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Conference 10016: High-Power Lasers and Applications VIII

Wednesday - Friday 12–14 October 2016

Part of Proceedings of SPIE Vol. 10016 High-Power Lasers and Applications VIII

10016-1, Session 1

Progress on development of two-micron solid-state laser for space-based remote sensing of wind and carbon dioxide

Upendra N. Singh, Mulugeta Petros, Tamer F. Refaat, Brian M. Walsh, Jirong Yu, Michael J. Kavaya, NASA Langley Research Ctr. (United States)

The societal benefits of improved weather forecasting and severe weather warning, and better understanding of climate change through identification of global carbon dioxide sources and sinks led to the desired NASA space missions of global wind and carbon dioxide measurements. Studies of both desired missions led to laser remote sensing solutions. The favored solutions for wind and carbon dioxide are pulsed hybrid Doppler lidar and Integrated Path Differential Absorption lidar, respectively. NASA LaRC identified the desired pulsed laser attributes and wavelength regions for the coherent-detection portion of the pulsed hybrid Doppler and for the carbon dioxide laser remote sensors. NASA Langley Research Center (LaRC) has a long history of developing pulsed 2-micron lasers. From fundamental spectroscopy research, theoretical prediction of new materials, laser demonstration and engineering of lidar systems, it has been a very successful progress spanning around two decades. This presentation will cover the 2-micron laser development from early research to current state-of-the-art instrumentation and projected future space missions. This applies to both global wind and carbon dioxide active remote sensing.

10016-2, Session 1

High-power DUV lasers for material processing

Toshio Mimura, kouji Kakizaki, Hiroaki Oizumi, Junichi Fujimoto, Takashi Matsunaga, Hakaru Mizoguchi, Gigaphoton Inc. (Japan)

A frontier in laser machining has been required by material processing in DUV region because it is hard to get high power solid-state lasers in this spectral region. DUV excimer lasers are the only solution, and now the time has come to examine the new applications of material processing with DUV excimer lasers. We have developed three types of DUV excimer lasers. The first is an injection-locked 193 nm excimer laser of 120 W with an ultra-narrow spectrum below 0.3 pm. The excimer lasers at 193nm as well as 248nm have been used in the semiconductor manufacturing for long years, and have field-proven stability and reliability. One of the important features will be the ability to support green operations while improving performance. The second is a high power 351 nm laser with free spectrum operation. A newly developed excimer laser of 450 W with low cost of ownership is applied to the new annealing process of FPD successfully. It can be highly reliable, because it was designed on the DUV excimer laser for semiconductor manufacturing. The third is an 193 nm “hybrid” laser, which is the combination of a solid-state seed laser and an excimer laser amplifier. High light-harvesting efficiency and high coherence of the hybrid laser has been achieved, which has M2 value of 1.6, and an average power of 110 W with three-pass amplifications. An interference exposure test demonstrated the high beam quality. The high photon energy of 6.4 eV at 193nm is expected to interact directly with the chemical bond of hard-machining materials, such as CFRP, diamond and reinforced glasses. We will report the latest results of performance of these high power DUV lasers and material processing.

10016-3, Session 1

Research of high-power all-solid-state laser and its applications in laser cutting and laser processing

Xue-Chun Lin, Institute of Semiconductors (China)

High-power all-solid-state laser has the significant advantages of small size, light weight, high efficiency, good beam quality, high reliability, and so on. It was widely used in scientific research, industrial processing, military and other fields. Laser processing with high precision, small deformation, high speed has become one of the most advanced processing technologies.

All-solid-state light source laboratory focuses on the research of high-power all-solid-state laser and its applications. A series of key technologies of high efficient pumping, depolarization compensation, cascade amplification, high beam quality control, and fiber coupling were broken through. In 2012, we successfully achieved 7.13kW laser with electro-optical efficiency of 18.4% and beam quality of 50.3mm • mrad through master oscillator power amplifier. Using orthogonal dual acousto-optic Q-switching, average output power of 1023W quasi-continuous laser with 82ns pulse width, 20kHz repetition rate was generated. The high-power all-solid-state lasers were successfully used in laser welding, cladding, quench, cleaning and other fields. Cooperation with domestic brand Chery Automobile, laser welding in critical components of CVT automatic transmission has been successfully used in the new Chery Tiggo SUV. The processing effect is good. Cooperation with the world’s third-largest oil supplier Weatherford, the laser cladding of the drilling unit was carried out. The quality of laser cladding is very good. This is the first time that this kind of components developed and produced by China instead of Europe and America.

10016-4, Session 1

Application of adaptive optics in laser weapon

Dong Zhao, Xiaofang Zhang, Beijing Institute of Technology (China)

In recent years, more and more countries pay attention to laser weapons in military research, the laser weapons era has arrived, but on the one hand, the heat deposition of laser weapons cavity medium causing laser temperature uneven results in the wavefront heat aberration,which will lead to the decline of the quality of light; On the another hand, it is the atmospheric effects on laser weapons, when the light beam transmitted through the atmosphere, besides atmospheric absorption and scattering,the atmosphere turbulence disturbance will also cause the beam wavefront aberration and scintillation effect, laser beam wavefront aberration made by the two aspects severely affect the performance of laser weapons. Adaptive optics as an real-time wavefront compensation technology, with the advantages of simple structure, good correction effect, closed loop operation and so on, has been widely used for correction of wavefront aberration in high-energy laser weapon system.This paper briefly introduces the basic priciples of adaptive optics and the progress of domestic and foreign adaptive optical research for laser beam quality correction, analyzes the key technology of laser weapon adaptive optics, and finally summarizes some existing technical problems, and presents the application prospect of adaptive optical system in the laser weapon

10016-5, Session 1

Research of silicon solar cells' minority-carrier lifetime after irradiated by high-power laser

Yu Zhang, Yunfei Li, Yanjie Li, Northwest Institute of Nuclear Technology (China); Guomin Zhao, Min Sun Chen, National Univ. of Defense Technology (China)

Compared with traditional methods of energy supply, there is a great possibility to get a more remarkable enhancement of conversion efficiency for laser power (of proper wavelength and intensity) beaming to silicon solar cells. However, it should be noticed that cells may be damaged by high power laser.Based on the background, this essay explored high-power-laser's possible damage to the cells by analysing IV curves and minority carrier lifetime, which was measured by open-circuit-voltage-decay method. Research shows that,for 30 seconds' irradiation, minority-carrier lifetime could be reduced when irradiated by laser of over 5.5W/cm2 and the higher laser power density, the more degradation, which is similar to the variation trend of IV curves. However, the degradation degree has a close relation with equilibrium temperature. The prolonged illumination would not bring about a more serious damage if the temperature had already reached a balanced point.

10016-6, Session 2

The research progress and application of single-frequency laser *(Invited Paper)*

Haiwen Cai, Kang Ying, Dijun Chen, Fang Wei, Qing Ye, Zhengqing Pan, Fei Yang, Ronghui Qu, Shanghai Institute of Optics and Fine Mechanics (China)

The report gives an introduction about the research progress of different kinds of narrow-linewidth single frequency lasers, including semiconductor laser, external-cavity diode laser, fiber laser, etc. A review is also presented about the application of single frequency laser on the optical sensing and optical communication areas.

10016-7, Session 2

16.8W diode-pumped rubidium vapor laser by using Brewster angle structure

Yannan Tan, Yimin Li, Chunyan Jia, Zhi Xu, Hu Shu, Jingwei Guo, Wan-fa Liu, Dalian Institute of Chemical Physics (China)

A high efficiency diode pumped alkali metal vapor laser is demonstrated by using a gain cell with Brewster angle structure. The one-trip transmittance of the laser in p-polarization is 97%, which is improved effectively. A gain cell with length of 1 nm is used. It is filled with alkali metal rubidium vapor as gain medium and methane with pressure of 600 Torr as buffer gas. Two diode lasers are used as the pump source with the power of 48 W and the central wavelength of 780 nm. The linewidth of the diode lasers is narrowed to 0.1nm with volume bragg gratings. In order to reduce the thermal effect of gain cell, a mechanical chopper is used to change the continuous pump laser to pulse output with pulse width of 1.85 ms , repetition frequency of 15 Hz and duty ratio of 2.77%. The experiment is optimized by using the output mirrors with output coupling rate of 41%, 58%, 76%. When the temperature of the cell is 160 ?, using the output mirror of 76%, the rubidium laser with wavelength of 795 nm and highest peak power of 16.8 W is obtained. The optical to optical efficiency is about 35%, and the slope efficiency is 44.2%.

10016-8, Session 2

Low-threshold and high-efficiency solar-pumped laser with Fresnel lens and a grooved Nd:YAG rod

Zhe Guan, Changming Zhao, Suhui Yang, Yu Wang, Jieyao Ke, Fengbin Gao, Haiyang Zhang, Beijing Institute of Technology (China)

Solar has attracted widespread attention as relative boundlessness of clean energy. Therefore, sunlight is considered as a new efficient source for direct optical pumped solid state lasers. High-efficiency solar pumped lasers with low threshold power would be more promising than semiconductor lasers with large solar panel in space laser communication. Here we report a significant advance in solar-pumped laser threshold by pumping Nd:YAG rod with a grooved sidewall. Two-solar pumped laser setups are devised. In both cases, a Fresnel lens with a surface of 1.03m2 is used as the primary sunlight concentrator. The gilding conical cavity with a liquid light guide lens is used as the secondary concentrator to further increase the solar energy concentration.

In the first setup, solar pumping a 6mm diameter Nd:YAG rod, maximum laser power of 30.7W/m2 cw at 1064nm is produced, which is higher than the reported record, the slope efficiency of laser output power with solar power is 4.3%. In the second setup, a 5mm diameter laser rod output power is 29.8W/m2 with a slope efficiency of 3.9%. The threshold power of 102W is obtained, which is 38% lower than the former. At the same time, the theoretical calculating of the threshold power and slope efficiency of the two setups has been established based on the rate-equation of four-level system. The analysis results are verified by using the finite element software (LASCAD) and experiment. The experimental results agree with theoretical analysis. So the optimization of the geometry of the copper cavity pumping system and resonator are useful for the design of a miniaturization solar pumped laser.

10016-9, Session 2

Amplified spontaneous emission of a diode pumped cesium vapor laser with consideration of deleterious processes

Guofei An, You Wang, He Cai, Shunyan Wang, Kepeng Rong, Hang Yu, Liangping Xue, Wei Zhang, Juhong Han, Hongyuan Wang, Jie Zhou, Southwest Institute of Technical Physics (China)

Diode pumped alkali laser (DPALs) provide a significant potential for construction of high-powered lasers. A series of models have been established to analyze the DPAL's kinetic process and most of them are based on the algorithms in which the amplified spontaneous emission (ASE) effect and deleterious processes have not been considered. However, ASE is harmful in realization of a high-powered DPAL since the gain is very high. Usually, ASE becomes serious when the volume of the gain medium is large and the pump power is high. In addition, alkalis are the most easily ionized atomic species, especially for rubidium and cesium. Under the condition of strong pump, the electrons will be excited to the higher levels, such as n2D5/2,3/2 and (n+2)2S1/2, by energy pooling collisions. Then, ionization processes including photo-ionization and Penning ionization will occur in the n2D5/2,3/2 and (n+2)2S1/2 levels resulting in decrease of the density of neutral alkali atoms. In this paper, a mathematic model is introduced for examination of the kinetic processes of a diode pumped cesium vapor laser, in which the cesium vapor and the buffer gases are beforehand filled in a sealed glass cell. ASE effects along both the longitudinal and the transverse directions

are taken into account in this model. The influence of deleterious processes of energy pooling, photo-ionization, and Penning ionization on the physical features of a DPAL is also studied at the same time. It has been theoretically demonstrated that the ASE effect can not be ignored in a high-powered DPAL system. Basically, the conclusions we obtained in this study can be extended to other kinds of laser configurations.

10016-10, Session 2

Measurement of thermally-induced distortion inside an alkali vapor with a quasi-Hilbert-transform algorithm

Wei Zhang, You Wang, He Cai, Juhong Han, Shunyan Wang, Kepeng Rong, Hang Yu, Liangping Xue, Guofei An, Hongyuan Wang, Jie Zhou, Southwest Institute of Technical Physics (China)

Diode-pumped alkali lasers (DPALs) have undergone rapid development to become one of the most promising candidates as very hopeful high-powered laser sources in recent years. Since the gas-state laser medium has very low thermal conductivity than that for a normal solid-state laser crystal, a very complicated phenomenon of thermally-induced lens should be brought about in a DPAL system. To evaluate such a complicated thermally-induced lens, we measure the thermally-induced distortion inside an alkali vapor cell by employing a quasi-Hilbert-Transform algorithm in this study. A probe He-Ne beam propagates through a sealed cesium vapor cell which is placed in one arm of a Mach-Zehnder interference setup. In the procedure, the extraction of cosine term, fast Fourier transform (FFT), inverse fast Fourier transform (IFFT), unwrapping process, and incline correction are successively carried out to obtain the phase information. Then, we deduce the distributions of focal lengths of a thermally-induced lens from the wavefront distributions after eliminating the effects of two cell side-windows. The results supply a valuable tool for design of a high-powered DPAL with good beam quality.

10016-11, Session 2

Enhanced visible supercontinuum generation in seven-core photonic crystal fiber

Xue Qi, Sheng-Ping Chen, Tong Liu, Jing Hou, National Univ. of Defense Technology (China)

The visible supercontinuum (SC) sources has played an important role in biomedical applications. However, the small core size of photonic crystal fiber (PCF) restrict the development of high power SC by its small mode field area. In addition, the zero dispersion wavelength (ZDW) of the PCF with small core diameter is usually below 1 ?m, which is far away from the 1.06 ?m laser which is the most commonly used pump source. As the ZDW of PCF shifts away from the pump, the intensity of visible light decreases correspondingly. To get an enhanced visible SC with high output power, we promote a new technique, which involves an enhanced visible SC generation in seven-core photonic crystal fiber pumped by a high power 1016 nm fiber laser. Muti-core PCFs offer a possibility of scaling up the mode field area to a large extent without remarkable change in dispersion properties, which show great potential in high power SC generation. Using a 1016 nm fiber laser as the pump makes the pump is closer to the ZDW of PCF, which could raise the intensity of visible light. In this paper, we report an enhanced visible SC generation ranging from 400 nm to 2300 nm in a seven-core PCF pumped by a 1016 nm picosecond fiber laser. The visible light (350-800 nm) occupies 25% of the total SC power 24 W and the power of the visible light is about 6 W.

10016-12, Session 3

Progress on high-power slab lasers *(Invited Paper)*

Qinjun Peng, Technical Institute of Physics and Chemistry (China)

No Abstract Available

10016-14, Session 3

Pathway towards second harmonic generation of a 100J 10hz diode-pumped solid-state laser

Jonathan Phillips, Saumyabrata Banerjee, Michael Fitton, Tristan Davenne, Paul D. Mason, Klaus G. Ertel, Thomas J. Butcher, Jodie M. Smith, Mariastefania De Vido, Oleg V. Chekhlov, STFC Rutherford Appleton Lab. (United Kingdom); Martin Divoky, HiLASE Ctr. (Czech Republic); Jan Pilar, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Andrew Lintern, Chris J. Hooker, Cristina Hernandez-Gomez, STFC Rutherford Appleton Lab. (United Kingdom); Tomas Mocek, HiLASE Ctr. (Czech Republic); Chris Edwards, John L. Collier, STFC Rutherford Appleton Lab. (United Kingdom)

High energy and high average power nanosecond diode pumped solid-state laser (DPSSL) systems operating at 100J-level and 10 Hz pulse repetition rate are required for new scientific applications, including material processing, advanced imaging and laser pumping of short-pulse amplifiers. To increase the functionality of these DPSSL systems efficient second harmonic generation (SHG) is a requirement. Recently, we have successfully demonstrated a 100J-scale (beam size 75 mm square) DPSSL based on cryogenic gas cooled, multi-slab ceramic Yb:YAG amplifier technology. DiPOLE100 has been operated at 1 Hz with pulse energy of 107 J and pulse duration of 10 ns with an optical-to-optical conversion efficiency of 21%, when pumped with 940 nm diode sources. Owing to the limited availability of large aperture non-linear crystals, we have used a scaled-down 10J DiPOLE cryo-amplifier system (beam size between 18 mm and 10 mm square) operating at 10 Hz to investigate SHG of high energy DPSSL systems. In this paper we will provide details of the 100 J laser system and the salient performance parameters of the DiPOLE 10J laser system. We will present results of SHG experiments for three candidate crystals, reporting conversion efficiency (45% DKDP, 50% YCOB, 82% for LBO) at varying intensity (>0.7 GW/cm2) levels, comparable to those expected in a 100J-level system, and short-term energy stability in YCOB and LBO for operation over 10 minutes. We present theoretically calculated temperature maps for both 10 J and 100 J operation at 10 Hz and compare the merits of each crystal for energy and power scaling. LBO represents the most promising candidate for SHG of a 100J-scale DPSSL system, where recent advances in crystal growth should soon overcome current limitations in available crystal size.

10016-15, Session 3

An edge-pumped multislab amplifier for Inertial Fusion Energy (IFE)

Min Li, Xiaomin Zhang, Mingzhong Li, Xudong Cui, Zhenguo Wang, Xiongwei Yan, Xinying Jiang, Jiangang Zheng, China Academy of Engineering Physics (China)

We proposed a novel laser amplifier for inertial fusion energy (IFE) based on an edge-pumped, gas-cooled multi-slab architecture. Compared to the face-pumped laser amplifiers for IFE, this architecture enables the pump, coolant and laser propagating orthogonally in the amplifier, thereby decoupling them in space and being beneficial to construction of the amplifier. To satisfy the high efficiency required for IFE, high-irradiance rectangle-waveguide coupled diode laser arrays are employed in the edge-pumped architecture and the pump light will be homogenized by total internal reflection. A traverse gradient doping profile is applied to the gain media, thus the pump absorption and gain uniformity can be separately optimized. Furthermore, the laser beam normal to the surfaces of the gas-cooled slabs will experience minimum thermal wavefront distortions in the amplifier head and ensure high beam quality. Since each slab has its own pump source and uniform gain in the aperture, power scaling can be easily achieved by placing identical slabs along the laser beam axis. Our investigations might provide an efficient and convenient way to design amplifiers for IFE.

10016-17, Session 3

High-power far-infrared optical parametric oscillator with high beam quality *(Invited Paper)*

Yingjie Shen, Chuanpeng Qian, Tongyu Dai, Xiaoming Duan, Baoquan Yao, Harbin Institute of Technology (China)

A high power ZnGeP2 (ZGP) optical parametric oscillator (OPO) with good beam quality pumped by a Q-switched Ho:YAG laser was demonstrated. The maximum output power of the ZGP OPO with a four-mirror ring cavity was about 5.04 W around 8.1 ?m with 83.9 W Ho incident pump power, corresponding to a slope efficiency of 9.2 %. The ZGP OPO produced 36.0 ns far-IR pulse laser in the 8.0-8.3 ?m spectral regions. The beam quality was measured to be M2~1.6 at the highest output power.

10016-16, Session 4

Large-aperture laser beam alignment system based on far-field sampling technique

Jiachen Zhang, Shanghai Institute of Optics and Fine Mechanics (China) and Univ. of Chinese Academy of Sciences (China); Daizhong Liu, Xiaoping Ouyang, Jun Kang, Xinglong Xie, Shanghai Institute of Optics and Fine Mechanics (China); Lei Gong, Shanghai Institute of Optics and Fine Mechnics (China); Jian Zhou, Baoqiang Zhu, Shanghai Institute of Optics and Fine Mechanics (China)

The inertial confinement fusion (ICF) facility is the largest and most complex of high-power lasers, large-aperture laser beams in these lasers, propagating from the master oscillator driver to the target, interact with more than 100 near-field optics and pass through several spatial filter pinholes over a distance exceeding 100 m. For purpose of high-power optical performance, alignment system for large-aperture laser beam becomes essential parts of this kind of laser. General alignment system for large-aperture laser beam is long in distance and large in volum because of taking near-field sampling technique. With the development of laser fusion facilities, beam diameter, paths and components increase greatly. Therefore, the space for alignment system is limited. General alignment system for large-aperture laser beam cannot meet the space requirements anymore. A new alignment system for large-aperture laser beam is designed to save space and reduce operating costs. The new alignment for large-aperture laser beam with a wedge is based on far-field sampling technique. The wedge is placed behind the spatial filter to reflect some laser beam as signal light for alignment. Therefore, laser beam diameter in alignment system is small, which can save space for the laser facility. This alignment for large-aperture laser beam has been demonstrated well on the SG-? Muliti-PW Facility. Comparing to general alignment system for large-aperture laser beam, large-aperture lens, long distance laser path and baffles with stepper motor is unnecessary for proposed alignment system, which saves cost and space greatly.

10016-18, Session 4

Title to be determined *(Invited Paper)*

Guoying Feng, Sichuan Univ. (China)

No Abstract Available

10016-20, Session 4

Correction of the phase distortion for high-power laser by freeform shape mirror

Gang Wang, Science and Technology on Solid State Laser Lab. (China)

The wavefront can keep stable while the laser system is adjusted well. Based on this characteristic, in order to improve the beam quality, we suggest to make mirror of free-form surface to compensate for the laser wavefront aberration. First, the theory of aberration compensated with free-form shape mirror is introduced, then through computer simulation, the mirror's capability of is discussed, lastly, the mirror is used by laser system which the average output power is 12.5KW. By the using of free-form shape mirror, laser's wavefront, beam quality of farfield and intensity of nearfield are improved obviously: the intensity of nearfield F is improved from 0.15 to 0.39; the wavefront's PV is improved from 6.3?m to 1.7?m; the wavefront's rms is improved from 2.0?m to 0.4?m; the beam quality of farfield ? is improved from 5.25 to 1.8. Compared with deformable mirror of adaptive optics, the free-form shape mirror has its own advantage: low cost; with no increase to laser system complication; the free-from shape mirror can be used to compensated for high order wavefront aberration effectively.

10016-21, Session 4

Investigation on the formation of intense fringe near Kerr medium slab in nonlinear imaging

Yonghua Hu, Yaoqiong Qiu, Xue Peng, Hunan Univ. of Science and Technology (China)

It is well known that hot-image can be produced by small-scale scatterers. For phase-typed scatterers, hot-image and second-order hot-image can be produced. However, when the number of scatterer is larger than one, the interaction between the

scatterered waves will lead to new nonlinear propagation results. In this paper, the nonlinear propagation of flat-topped intense laser beam through Kerr medium slab is investigated through computer simulation, where the beam is modulated by two parallel wirelike phase-typed scatterers with certain parameters. We demonstrate that an intense fringe together with hot image and second-order hot image can be formed when the distance of the two scatterers is several millimeters. It is found that the on-axis position of the plane of this intense fringe is in the middle part between the exit surface of the Kerr medium slab and the second-order hot image plane. This intense fringe shows the following basic properties: firstly, its intensity is apparently higher than that of corresponding second-order hot image and can be comparable with that of corresponding hot image; secondly, the distances between it and the in-beam positions of the two scatterers are the same. Besides, the beam intensity profile shows that this intense fringe is the only prominent bright fringe in its plane, and thus it is not a nonlinear image of any scatterer. It is found that, as the phase modulation depth increase, the intensity of it increases at first and reaches its maximum when the phase modulation depth is 3 rad, and then decreases, while the corresponding scatterer distance basically keeps decreasing slowly.

10016-13, Session Post

The influence of combined guiding effect on the beam quality in MOPA Nd:YVO4 lasers

Xingpeng Yan, Academy of Armored Force Engineering (China); Qiang Liu, Tsinghua Univ. (China); Xi Wang, Department of Information Engineering, Academy of Armored Forces Engingeering (China)

The effect of the combined guiding, the thermal induced guiding and gain guiding, on the beam quality in Nd:YVO4 MOPA laser is studied experimentally and theoretically. The beam quality enhancement is achieved during the power-amplification process in a 4-stage MOPA Nd:YVO4 MOPA laser. 195 W TEM00 mode laser is achieved while its beam quality enhanced from M2=3.2 to 1.2 after power amplification. This is an interesting phenomenon since the beam quality is always deteriorated during the laser amplification. To explain the phenomenon of beam quality improvement, a theoretical model is established with the thermal induced guiding effect and gain guiding effect is considered, and a nonlinear dynamical equation of the laser mode in laser amplifier is derived. The wave equation is a Schrödinger-like two order nonlinear partial differential equation, and a symmetrical split-step Fourier mothed is developed to analyze the wave equation. Both experimental and theoretical results show that the combined guiding effect dominates the evolution of beam quality in the insensitive pumping Nd:YVO4 MOPA lasers, and the combined guiding effect can be employed to improve the performance of beam quality in MOPA lasers.

10016-24, Session Post

63W output tandem-pumped thulium-doped silica fiber laser at 1980 nm

Yingbin Xing, Wuhan National Lab. for Optoelectronics (China)

We have demonstrated a high power and high efficiency thulium-doped silica fiber laser using a cascade tandem pumping method. A 1915nm Tm-doped fiber laser was used as a pump source for another Tm-doped fiber laser with the output power of 63W at 1980nm, corresponding to the slope efficiency of ~80%, which is the highest power to our best knowledge. And the 3dB bandwidth was 0.24nm. The 1915nm Tm-doped fiber laser was pumped by 793nm diode laser and the slope efficiency was 51%. The preform of double cladding Tm-doped fiber for the tandem pumped fiber laser was manufactured by MCVD with using the vapor-solution hybrid doping method. The fiber has a ~25?m diameter, 0.098 NA(numerical aperture) core and 400?m diameter, 0.46 NA inner cladding. In the tandem pumped fiber laser, the resonant cavity consist of a pair of FBGs at 1980nm and the homemade Tm-doped silica fiber. And the pigtail were angle cleaved by ~8° to eliminate end reflection. The optimal active fiber length was presented and it is found that when the length of homemade Tm-doped silica fiber was 7m, the efficiency was the highest. The influence of Tm concentration and ratio of Tm ion and Al ion on the efficiency was also explored. And it is found that the thulium-doped silica fiber with lower Tm concentration and higher Tm:Al ratio had lower optical efficiency. Meanwhile, the optimal fiber length became shorter.

10016-36, Session Post

Research on the effect of environment on the energy coupling coefficient of 45# steel under laser irradiation

Xiangyu Zhang, Guomin Zhao, Minsun Chen, Tianyu Zhang, National Univ. of Defense Technology (China)

Experimental research on the energy coupling characteristic of 45# steel under mid- infrared CW laser irradiation is carried out. In order to obtain the energy coupling coefficient, an experimental system for reflectance measurement is set up by an integrating sphere. The curves about reflectance along with the temperature variation are measured respectively in nitrogen and air atmosphere. Based on the classical electromagnetic theory and the Fresnel Formula, the theoretical value of the energy coupling coefficient is derived under ideal condition. Combined with the experimental phenomena and experimental conditions, the qualitative analysis about the differences between the theoretical value and experimental data is presented. The mechanism about the variation of reflectance of 45# steel under mid-infrared CW laser irradiation is also discussed. The experimental results show that the energy coupling coefficient of 45# steel increased with temperature rising?but the curve in the heating stage is not consistent with the curve in the cooling stage, which means that the change of the energy coupling coefficient is not a reversible process. Additionally, the oxidation reaction has an significant effect on the laser interaction with 45# steel. In air atmosphere, the laser heating induces the oxidation reaction of the 45# steel. As the temperature rises, the oxidation reaction become more vigorous and the energy coupling coefficient increases. However, in nitrogen atmosphere, the material is almost not oxidized. Accordingly, the energy coupling coefficient in air is larger than that in nitrogen environment.

10016-46, Session Post

The outgassing characteristic research of the silicone rubber in high-power laser system

Qipeng Wu, Lanzhou Institute of Physics (China)

The outgassing characteristic of the silicone rubber which is the main material of non-metallic materials in high power laser system was studied?outgassing rates of the silicone rubber and the baked-out silicone rubber which was performed at 80? 4 hours were measured by the constant volume process method and outgassing properties of them were analyzed by the quadrupole mass spectrometer. The results show that the outgassing rate of the silicone rubber and the baked-out silicone

rubber is 2.69?10-7Pam3s-1cm-2 and 6.47?10-8Pam3s-1cm-2?respectively. All of them give out condensable volatile matter in vacuum. The outgassing rate and condensable volatile matter of the baked-out silicone rubber are less an order of magnitude compared with the silicone rubber, and the outgassing rate of the silicone rubber is less than 1?10-7Pam3s-1cm-2, which is fit for non-metallic material of the high power laser system. This paper also discusses the method of reducing the outgassing rate and condensable volatile matter of the silicone rubber in high power laser system.

10016-47, Session Post

Numerical modeling of three-level system in ytterbium-doped photonic crystal fiber laser

Cheng Zhou, Univ. of Jinan (China)

In order to investigate the power characteristics of the Yb-doped PCF laser, we have represented a simple three-level system modeling based on a rate equation model. According to our theoretical modeling, the variation of the output power Pout via the pump power Pp is theoretically studied, which agrees well with experimental data. Then, we have investigated the effects of the doped concentration of Yb ions, the length and the effective mode field area of the PCF on the output power Pout of the Yb-doped PCF laser, respectively. The results show that the output power Pout first increases and then decreases when the doped concentration of Yb ions N0 increases and when the pump power Pp and the length of the PCF L are constant. And the optimal doped concentration Nm exponentially decreases when the length L of the PCF increases and the slope of the optimal doped concentration Nm also decreases when the length L of the PCF increases. The output power Pout first increases and then decreases when the length of the PCF L increases and when the pump power Pp and the doped concentration N0 are constant. And the optimal length Lm of the PCF exponentially decreases when the doped concentration N0 increases and the slope of the length of the PCF also decreases when the doped concentration N0 increases. The output power Pout linearly decreases when the effective mode field area A increases.

10016-48, Session Post

Structural-optical integrated analysis on the large aperture mirror with active supporting

Zhiyuan Ren, jianqiang zhu, zhigang liu, Shanghai Institute of Optics and Fine Mechanics (China)

Deformation of the large aperture mirror caused by the external environment load seriously affects the optical performance of the optical system, and there is a limit to develop the shape quality of large aperture mirror with traditional supporting method. It is effective way to reduce the optical mirror distortion with active support method, and the structural-optical integrated method is the effective means to assess the merits of the supporting for large aperture mirror. Firstly, we proposes a new support scheme that uses specific boundary constraints on the large lens edges and imposes flexible torque to resist deformation induced by gravity to improve surface quantity of large aperture mirror. We calculate distortion of the large aperture mirror at the edges of the flexible torque respectively with the finite element method; secondly, we extract distortion value within clear aperture of the mirror with MATLAB, solve the corresponding Zernike polynomial coefficients; lastly, we obtain the peak-valley value (PV) and root mean square value (RMS) with optical-structural integrated analysis . The results for the 690x400x100mm mirror show that PV and RMS values within the clear aperture with 0.4MPa torques than the case without applying a flexible torque reduces 82.7% and 72.9% respectively. The active supporting on the edge of the large aperture mirror can greatly improve the surface quality of the large aperture mirror.

10016-49, Session Post

Design and fabrication of transmission gratings with high diffraction efficiency for pulse compression

Chaoming Li, Soochow Univ. (China)

Fused silica transmission grating plays an important role in the ultra-short laser pulse compression system. Fused silica transmission grating have the advantages of high diffraction efficiency, high damage threshold, long life and no shelter,etc. The design and fabrication of pulse compression grating are investigated theoretically and experimentally in this paper. Rigorous coupled wave theory is used to design transmission grating with trapezoidal microstructure. In the past, the microstructure of transmission grating for pulse compression is designed using rectangular structure. Through theoretical analysis, we find that the trapezoidal structure has better diffraction efficiency than that of the rectangular structure. The fused silica transmission grating based on trapezoidal structure is studied in the paper. The deep-etched fused silica transmission grating (1250lp/mm) is fabricated by holographic lithography and ion beam etching technologies. The aperture of transmission grating is ?65mm, and its thickness is 1mm.The absolute -1st diffraction efficiency is over 98%(@808nm). Experimental results are coincident with the theoretical analysis.

10016-50, Session Post

Analysis research on transmitting and attenuating characteristics of non-lethal laser weapon in the fog

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Laser has been used in the military field widely because it has some advantages, such as strong directional, fast speed, high energy and flexible accurate. Non-lethal laser weapon does not directly lead to death and equipped with destruction and the destruction of the ecological environment. It has a broad application prospect in the field of counter-terrorism ChuTu. But the laser transmission should be affected by atmospheric environment. These will affect the operational effect of non-lethal laser weapons seriously. In this paper, the influence of fog visibility of laser attenuation characteristics is studied using Mie theory based on analysis of the laser atmospheric transmission theory. Different wavelengths laser attenuation coefficient in the fog are simulated and calculated. Different wavelengths laser's Kim attenuation model are deduced when they propagate in the fog. The relationship between attenuation coefficient and transmittance and the fog particle concentration and the transmission distance of 532nm laser are studied by simulation. The simulation results show that different wavelengths laser attenuation was sharply increased with the decreasing of fog visibility. Attenuation coefficient is as high as 40dB/km under the condition of the fog. The laser transmittance with concentration of fog drop speed greatly reduced. The laser transmittance is 40% in the 100m distance when the fog particle concentration is 20/m3. And the laser transmittance is 10% in the 200m distance. The laser transmittance is only 5% when the fog particle concentration is 100/m3.

10016-51, Session Post

Coherent combining efficiency improvement based on a focused conformal projection fiber laser array

Dong Zhi, Yanxing Ma, Xiaolin Wang, Pu Zhou, Lei Si, National Univ. of Defense Technology (China)

In this paper, we present a series of coherent beam combining (CBC) experiments of home-made FCPS to show the coherent combing efficiency improvement of FCPS comparing with CCPS for the first time to the best of our knowledge. We setup a CBC experiment system of two-dimensional home-made FCPS. We choose three channels, each with an end-cap for laser output, for the CBC experiment. Here we should point out that 20/400 fiber has greater power handling capacity, usually up to several kW, than the fiber with small core diameter of 6/7 μm. A lens with focal length of 2 m is used to focus the three laser beams to the far field. The first part of the combined beam is imaged by a CCD camera to observe the combined beam patterns. The second part of the passing light is detected by a photonic detector (PD) to provide feedback data. The signal processing accomplished in a signal processor for phase-locking control and a field programmable gate array (FPGA) processor for end-cap/tilt control. In our experiments, the filling factor is calculated 0.29, which is defined as the single beam diameter divided by the distance of adjacent beamlets. Throughout the whole experiment, single frequency dithering algorithm and SPGD algorithm are used to perform the phase-locking control and the end-cap/tilt control respectively. Experiments results satisfy the numerical calculations with system efficiencies above 80%. Comparing with CCPS, the CBC efficiency of FCPS improves from 59.0% to 84.7%.

10016-52, Session Post

Longitudinally-excited CO2 laser with short-laser-pulse operating at high-repetition rate

Jianhui Li, Kazuyuki Uno, Tetsuya Akitsu, Univ. of Yamanashi (Japan); Takahisa Jitsuno, Osaka Univ. (Japan)

A longitudinally excited CO2 laser has been developed with a short laser pulse at high repetition rate. In our previous study, the characteristics of the CO2 laser were investigated at a repetition rate of 1 Hz. In this study, the repetition rate of the CO2 laser was increased up to 300 Hz. The dependence of laser characteristics, such as output energy, waveform and beam profile on the repetition rate were investigated. The discharge tube was made of a 45-cm-long dielectric tube with an inner diameter of 9 mm or 16 mm. The optical cavity was formed by a ZnSe output coupler (reflectivity of 85%), and a high reflection mirror. The mixed gas (CO2:N2:He=1:1:2) was flowed into discharge tube. A fast rising voltage was applied to the discharge tube at 30 kV with a rising time of 0.2 micro-s. At a repetition rate of 300 Hz and a gas pressure of 3.4 kPa, the 9-mm discharge tube produced a short laser pulse with an output energy of 17.3 mJ, a spike pulse energy of 0.3 mJ, a spike width of 205 ns, and a pulse tail length of 113 micro-s. The output power was 5.1 W. At a high repetition rate, the laser beam formed a strong point in the center of a ring shape. However, at a low repetition rate, the laser beam formed a ring shape only. We thought that the laser beam was concentrated by improving the repetition rate up to 300 Hz.

10016-53, Session Post

Vortex beam based more stable annular laser guide star

Hongyan Wang, Ruiyao Luo, Wenda Cui, Lei Li, Quan Sun, Yulong He, Yu Ning, Xiaojun Xu, National Univ. of Defense Technology (China)

When generating laser guide star (LGS), sodium laser beam travels up through the turbulent atmosphere before generating LGS, resulting LGS spot wandering in the mesosphere. This introduces complications when using a LGS and needs a tip-tilt mirror in the laser launch optics to stabilize laser pointing. In this paper, we presented a more stable annular LGS for adaptive optics (AO) assisted ground based large telescopes. The more stable annular LGS is generated by a vortex beam rather than a Gaussian beam. In the uplink, a vortex beam tends to wander more slightly than a Gaussian beam does in atmospheric turbulence. This would reduce spot wandering of annular LGS in the mesosphere and ease the burden of uplink tip-tilt mirror. We conducted numerical simulation to validate the feasibility and merits of this concept. Our modeling follows three steps including setting parameters of launch telescope and atmosphere, simulating atmospheric propagation of a 20 W single-mode CW laser, and giving saturation corrected fluorescent LGS based on spatial intensity distribution of the arrival laser beam in the mesosphere. We quantitatively estimated the wandering of generated LGS and got a 37% reduced rms spot wandering of annular LGS, which is beneficial to a closed-loop AO system. Preliminary experimental results will also be presented. To the best of our knowledge, it is the first time this concept is formulated.

10016-54, Session Post

Effect of nonlinearity saturation on hot-image formation in cascaded saturable nonlinear medium slabs

Youwen Wang, Xiaohui Ling, Liezun Chen, Zhiping Dai, Shizhuan Lu, Hengyang Normal Univ. (China)

In high-peak-power laser system, nonlinear effect can cause hot image to be formed, hot image can be so intense to damage some components in its element chain. With the development of laser technologies, nowadays, the operating power of high-power lasers can reach enough high to result in the nonlinear refraction index saturation of the media of the components. We present analytical and simulative investigations on the hot-image formation in cascaded saturable nonlinear medium slabs based on spatial modulation instablity analysis and the standard split-step Fourier method, to disclose the effect of nonlinearity saturation on the distribution and intensity of hot images. It is shown that, saturable nonlinearity does not change the distribution of hot images, while may greatly affect the intensity of hot images, i.e., for a given saturation light intensity, with the intensity of the incident laser beam, the intensity of hot images firstly increases monotonously and eventually reaches a saturation; for the incident laser beam of a given intensity, with the saturation light intensity lowering, the intensity of hot images decreases rapidly, even resulting in a few hot images too weak to be visible. The results can help operators of high-power laser system to lower risk of the optic elements damage of hot images.

10016-55, Session Post

Formation of hot image in an intense laser beam through a saturable nonlinear medium slab

Youwen Wang, Xiaohui Ling, Shizhuan Lu, Zhiping Dai, Liezun Chen, Hengyang Normal Univ. (China)

In high-peak-power laser system such as Petawatt lasers, the laser beam can be intense enough to lead to saturation of nonlinear refraction index of medium. In additon, scattered light by contaminants on optic components through nonlinear medium can result in hot images which can be intense enough to damage optic components, and therefore limit the output powers of the system. We present analytical and numerical investigations of hot image formation in an intense laser beam through a saturable nonlinear medium slab based on Fresnel-Kirchhoff diffraction integral and the standard split-step Fourier method. The analytical results are found in agreement with the simulation ones. It is shown that, hot images can still form in an intense laser beam through a saturable nonlinear medium slab; and the saturable nonlinearity does not change the location of hot images,while the nonlinearity saturation may lower the intensity of hot images; furthermore, for the laser beam of given intensity, the intensity of hot images monotonously increases with thickness of the nonlinear medium slab, and the intensity of hot images monotonously increases to reach a maximum at first, then monotonously decreases to reach a minimum with the phase shift induced by the phase obscuration. Our results may be helpful to improve operation safety of high-power laser syetem.

10016-56, Session Post

Design of high-efficiency broad-bandwidth unpolarized transmission grating for femtosecond laser

Xinrong Chen, Chaoming Li, Soochow Univ. (China)

An unpolarized transmission grating with 1250lp/mm has been designed at 780nm center wavelength with 740nm~840nm bandwidth. By using the rigorous coupled-wave theory, computer optimization shows that: by the proper choice of structure parameters of groove depth and duty cycle, the first-order diffraction efficiency of a lossless-transmission surface-relief grating with a rectangular surface profile can be made very large (>90%) simultaneously for light of TE and TM polarizations incident near the Littrow angle. Be made of fuse silica, this unpolarized transmission grating possesses high laser damage threshold and therefore it is very suitable to apply in high-power laser systems such as femtosecond laser. The process tolerance of structure parameters of groove depth and duty cycle are analyzed in detail. As an important factor which is needed to be considered in practical applications, the influence of incident angle deviation to the Littrow angle for the first-order diffraction efficiency is discussed and the adjustable range of incident angle is present subsequently. Across the spectral region of 740nm~840nm, the process tolerance of groove depth is about 1.57um~1.61um and the process tolerance of duty cycle is about 0.54~0.62. The adjustable range of incident angle is 29.2°±1°.

10016-57, Session Post

Rippled area formed upon multi-pulse femtosecond laser ablation on silicon

Zhiming Li, Jingsong Nie, Yuze Hu, Lei Wang, Electronic Engineering Institute (China)

The numerical simulation of multi-pulse femtosecond laser ablation on silicon are introduced in this paper. Firstly, the two-temperature model of the femtosecond laser interaction with silicon including the band electron excitation, Auger recombination effect and two photon excitation etc. are introduced. The optical intensity inside the material which can be derived using the electric field obtained with Maxwell's equations in every optical half-cycle is used as an input condition to the material equations that describe the response of the material to the intensity. By solving the material equations, parameters of the excited material, such as electron density and electron temperature, are obtained.A single pulse laser damage threshold is 0.26J/cm2 in the model by using 800nm femtosecond laser and the heat accumulation effect is predicted with multi-pulses shooting. What's more, the irradiation of silicon with multiple linear polarized femtosecond laser pulses at fluence close to the damage threshold leads to the formation of laser-induced periodic surface structures (LIPSS) on the surface. For laser fluence near the ablation threshold, the finite-difference time-domain (FDTD) technique is used to calculate the electric field distribution on the surface of the silicon and its evolution with the formation of various nanostructures. It was found that the ripples formed in the initial stage facilitate the ablation along the direction perpendicular to the ripples, leading to the formation of an elliptical ablation area. With increasing number of pulses, the ablation area is gradually changed to a circular under the high fluence of femtosecond laser.

10016-58, Session Post

Experimental investigation of the thermally-induced core laser leakage in large-mode-area single-trench fiber

Lingchao Kong, Liangjin Huang, National Univ. of Defense Technology (China); Shaoyi Gu, China Electronics Technology Group Corp. (China); Jinyong Leng, Shaofeng Guo, Pu Zhou, Zongfu Jiang, National Univ. of Defense Technology (China)

We demonstrate the thermally-induced core laser leakage in single trench fiber (STF). The STF provides very high loss and power delocalization of higher order mode (HOM) and therefore maintain the single mode operation. However these properties are investigated under low power situations. In this paper we pump the STF in a high power co-pumping fiber amplifier. The maximum output power of 1022W was achieved with a slope efficiency of 76%. Further increase the pump power led to the output power decrease. Meanwhile, noise like power fluctuation at ms level was observed when the power started to decrease. However, no resonance frequency was observed in frequency domain indicating the mode instability was not triggered. We believe that it is the thermally-induced waveguide index profile change due to the excessively heat load in the front section of STF that leads to the failure of HOM suppression and the power of FM was coupled into the HOM. However the heat load in the rear section of STF was relatively low and the HOM started to leak into the cladding due to the bending loss. We provide a solution to mitigating this problem by pumping STF with pump light of smaller absorption coefficient. A maximum power of 1330W was achieved without power decrease via pumping with 905nm and 976nm pump light (the same amplifier). To our best knowledge, this is the first demonstration of thermally-induced core laser leakage in STF and the pertinent results can provide significant reference for future optimization.

10016-59, Session Post

Longitudinally-excited CO2 laser with multiple laser tubes

Kazuyuki Uno, Tetsuya Akitsu, Univ. of Yamanashi (Japan); Takahisa Jitsuno, Osaka Univ. (Japan)

We developed a longitudinally excited CO2 laser system that was constituted of multiple laser tubes and a single driver circuit. The driver circuit had a high-voltage pulse power supply with the input energy of 2.18 J, a spark gap, and a storage capacitor of 1400 pF. The driver circuit excited two laser tubes. 30-cm-long discharge tubes with the inner diameter of 13 mm and 16 mm were used. In the two-laser-tubes system at a gas pressure of 4.2 kPa (CO2: N2: He= 1: 1: 2), the 13-mm-tube produced a short laser pulse with the output energy of 23.3 mJ, the spike pulse energy of 0.72 mJ, the spike pulse width of 140 ns, and the pulse tail length of 82.8 ?s. The 16-mm-tube produced a short laser pulse with the output energy of 21.9 mJ, the spike pulse energy of 1.10 mJ, the spike pulse width of 200 ns, and the pulse tail length of 60.6 ?s. Therefore, in the two-laser-tubes system, the total output energy was 45.2 mJ. In a one-laser-tube system with the input energy of 2.18 J and the storage capacitance of 1400 pF at a gas pressure of 4.2 kPa, the 13-mm-tube produced 29.6 mJ and the 16-mm-tube produced 25.3 mJ. Therefore, in the same input energy of 2.18 mJ at the same gas pressure of 4.2 kPa, the two-laser-tubes system was more efficiently than the one-laser-tube system. Moreover, we investigated the three-laser-tubes system.

10016-60, Session Post

Spectral temporal characteristics of the radiation Ba I by femtosecond laser breakdown on the surface of aqueous solutions

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The characteristics of spectral lines of Ba I (413,2 nm and 553,54 nm) femtosecond laser breakdown on the surface of an aqueous solution BaCl2•2H2O was investigated. The transition probabilities 6s21S 0 – 5d6p 3D0 1 ? 6s21S 0 – 6s6p 1P0 1 for Ba I lines for wavelengths 413,2 553,54 nm and nm, respectively. The obtained experimental dependences of the intensities of spectral lines of Ba I from the time of registration delay relative to the laser pulse. Shows the change in the attitude of the population of the 5d6p 3D and 6s6p 1P levels Ba I from time delay. All experimental data were obtained on a laser complex SpitfirePro 40F, Spectra-Physics with a Central wavelength of 800 nm, pulse duration 45 fs, pulse energy - 0,82 mJ. 800-nm beam is frequency doubled in a nonlinear BBO crystal to produce the 400-nm laser pulses of duration ~100 fs. . ICCD cameras (PicoStar HR, LaVision and PI-MAX3, Princeton Instruments) coupled with 2500i or 2300 Acton SpectraPro spectrographs were used as a detectors. The technique temporary gating was used, when a gate delays were varied from 10 to 210 ns. The experimental data were performed in the software package WinSpec 2.6.5.

10016-61, Session Post

Thermal effects of the gradient doping gain fiber in all-fiber MOPA

Zichao Zhou, Xiaolin Wang, National Univ. of Defense Technology (China)

Thermal effect in the gain fiber is one of the main factors which restrict the power improvement of high power fiber amplifiers. Previous studies have shown that the thermal effect is closely related to the doping concentration in the gain fiber. In order to reduce the temperature at the fusion point and the maximum temperature of the gain fiber, we propose to use doping concentration varying along the gain fiber as a method to disperse the thermal effect of the gain fiber. A two stage single frequency all-fiber-integrated MOPA is demonstrated, the second stage of which has a hybrid gain fiber composed of high-doped and low-doped Yb fibers. The temperature of the gain fiber is measured by a thermal imaging camera. It is shown that compared with the constant doping fiber, temperature in the gradient doping fiber is greatly reduced when the output powers are approximately the same, especially at the fusion point. The corresponding theoretical study also verifies the accuracy of the experimental results. Based on rate equation model and thermal conduction model, the thermal distribution and output power of the fiber laser amplifiers with corresponding constant and gradient doping gain fiber in the experiment are simulated, which agrees well with the experimental results. Results indicate that the gradient doping of the gain fiber is an effective way to alleviate the thermal effect in high power fiber lasers.

10016-62, Session Post

Theoretical study of transverse mode selection with volume Bragg grating in laser resonator

Jing Hu, Soochow Univ. (China)

Volume Bragg grating (VBG) can be used in resonator to control the transverse distribution due to its excellent Bragg selectivity. Kogelnik's coupled-wave theory is used to analyze the VBG's angular selectivity, and the output modes of the volume Bragg resonator are simulated using the fast Fourier transform (FFT) method and the coupled-wave theory. In this paper, the volume Bragg grating is inserted into a plane-parallel resonator, the intensity distribution and diffraction losses of TEM00, TEM10 and TEM20 are simulated, and the loss difference for different modes at different angular selectivity of VBGs are discussed. At the angular selectivity of VBG is of 3 mrad, the diffraction loss for fundamental mode is of 6.3%, while the diffraction loss for TEM10 mode the TEM20 are 19.8% and 32.7%, respectively. Therefore, TEM10 and TEM20 can be easily suppressed if the gain is between 6.3% and 19.8%, and a fundamental transverse mode can be obtained.

Besides, the simulation results show that the intensity distribution profile of the transverse modes become smooth with the insertion of VBG, but the diffraction losses of transverse modes are increasing and the diffraction loss increases with the order number of transverse modes increasing. Moreover, the loss difference between different modes is getting large with the angular selectivity of the VBG. The higher loss difference between different modes is good for transverse mode selection so VBG with reasonable angular selectivity in laser resonator will force the multi-mode to operate in a single transverse mode, which may has potential applications in lasers.

10016-63, Session Post

Output characteristics of diode-pumped Yb:YAG mode-locked laser with a dual-core fiber

Yan Yan, Li Wang, Beijing Univ. of Technology (China)

The self-starting soliton generate in a dual-core fiber without any external mode-locking mechanism with the numerical simulated and demonstrated.The low-intensity light can be transferred to the other and ejected from the laser cavity in the nonlinear coupling between the two cores.Then we propose and analyze a diode-pumped Yb:YAG solid mode-locked laser based on an dual-core fiber, at the same time, the higher intensity light keep propagation and remains largely unaffected have contrasted, and the impact of the cavity characteristics on output parameters has analyzed in order to obtain a better application in the actual experiment.

10016-64, Session Post

Study on variations of transverse electromagnetic distribution after the linewidth narrowing of a LD

Liangping Xue, You Wang, Wei Zhang, Hang Yu, Shunyan Wang, Kepeng Rong, Hongyuan Wang, He Cai, Juhong Han, Guofei An, Jie Zhou, Southwest Institute of Technical Physics (China)

Because there are different wavelengths in the gain curve of a laser medium, the transverse electromagnetic (TEM) distribution of a diffracted beam must be greatly affected by a plane diffraction grating (PDG) or a volume-Bragg-grating (VBG) with an intrinsic wavelength which might be somewhat different from that of the peak value of the gain curve. In practical, such a phenomenon will become complicated during the process of self injection locking (SIL) in narrowing the linewidth of a high-powered laser diode (LD). Thus, it is important to study variations of the transverse electromagnetic distribution after narrowing the linewidth of a LD from 1000 GHz to about 10-100 GHz for realization of a high-powered diode pumped alkali laser (DPAL). In this paper, we experimentally investigated the beam propagation factor (M2-factor) and the transverse electromagnetic distribution of an output laser beam after the linewidth narrowing by employing a PDG with the different incident angles. Light emitted from a 1-bar LD was collimated by a pair of cylindrical lenses along the slow-axis. The results reveal that the transverse electromagnetic mode of the output laser beam with the narrowed linewidth becomes worse and an obvious smearing can be observed after using a diffractive element such as a PDG, which are thought to be harmful in improving the pump uniformity and extractive efficiency. The results should be significant in designing and constructing the optical system of a high-powered DPAL. Until now, there have been no relevant reports to the best of our knowledge.

10016-65, Session Post

Research on polarization vector characteristics in a microfiber-based graphene fiber laser

Mengmeng Han, Hebei Normal Univ. (China)

We experimentally investigated the polarization vector characteristics in an Er-doped fiber laser based on graphene that was deposited on microfiber. A rich variety of dynamic states, including polarization locked fundamental soliton, bound states, condensed phase, soliton bunching, harmonic mode locking, and different types of polarization domain wall square pulses and their harmonic mode locked counterparts have all been observed with different pump powers and polarization states.These results indicated that the microfiber-based graphene not only could act as a saturable absorber but also could provide high nonlinearity, which is favorable for the cross coupling between the two orthogonal polarization components. It was worth to mention that it is the first time to obtain the polarization domain wall solitons in a mode locked fiber laser.

10016-66, Session Post

Formation of noise-like square-wave pulses in a microfiber-based topological insulator fiber laser

Jingmin Liu, Hebei Normal Univ. (China)

We have demonstrated the formation of noise-like square-wave pulses in an Er-doped fiber laser for the first time, using a microfiber-based topological insulator as a saturated absorber (SA), which guaranteed both excellent saturable absorption and high nonlinearity. The pulse duration of the square-wave pulses could be increased obviously from 1 to 5.4 ns when the pump power was increased from 212 to 284 mW while the corresponding spectral bandwidths showed slightly change. With the pump power fixed and the polarization controllers of intra-cavity adjusted, harmonic mode locking with different orders could also be obtained. The pulse possessed a low temporal coherence, which was demonstrated by its double-scaled autocorrelation trace.

10016-67, Session Post

Experimental investigation of high-energy noise-like pulses from a long-cavity erbium-doped fiber laser

Kexuan Li, Beijing Univ. of Technology (China) and Chinese People's Armed Police Force Academy (China); Heyang Guoyu, Jinrong Tian, Yanrong Song, Beijing Univ. of Technology (China)

The high energy noise-like pulses (NLPs) were experimentally investigated in a passively mode-locked erbium-doped fiber laser with a long ring cavity by using nonlinear polarization rotation technique. Large net normal group-velocity dispersion of the cavity is estimated as high as 6.46 ps2, which is beneficial to formation of high-energy pulses. With the total pump power of 970 mW (the pump powers of forward pump and backward pump are set at the value of 455 mW and 515 mW, respectively), a stable ultrahigh energy rectangular-shape pulse emission with the pulse duration of 35 ns is observed. The energy of square packet with a fundamental repetition rate of 141.6 kHz is as high as 840 nJ. The signal-to-noise is higher than 60 dB in RF spectrum. The feature of NLPs is confirmed by the coherent spike of autocorrelation trace. When the pump power is beyond 970 mW, the mode locking operation with fundamental repetition rate cannot be achieved despite of the large range variation of polarization controller settings. However, the forth-order harmonic mode locking can be observed, the square pulse packet duration still remains at ? 35 ns. The experimental results demonstrate that the ultrahigh energy NLPs is only realized at the condition of special physical parameters and it is restricted by the numbers of ultra short pulses within the envelope to some extent.

10016-68, Session Post

Dynamic measurement of reflectance/ emissivity in mid-infrared band

Tianyu Zhang, Min Sun Chen, Houman Jiang, Xiangyu Zhang, National Univ. of Defense Technology (China)

In order to measure the change of laser energy coupling coefficient with temperature in mid-infrared wave band, reflectance integrating sphere experiment system was designed and set up. 915nm CW laser was used to heat samples and the wavelength of probe laser is 3.8?m. Chopper and phase-locked amplifier were adopted in the system. Thermal imager was used to measure and record the temperature of samples during laser irradiation. The reflectance of steel and aluminum plates to 3.8?m was measured during 915nm laser irradiation. According to Kirchhoff's law, the emissivity of opaque samples is equal to the absorption rate, namely the coupling coefficient. Thus, the emissivity of samples was obtained at the same time. And radiation temperature measured by the thermal imager was adjusted through the curves of emissivity. EDS analysis was done to investigate the change of elemental composition in the samples respectively. The experimental results show that, the results of reflectance and radiation temperature measured by this system are relatively accurate. In the process of temperature rising from 25 to 500 degrees, the color of steel plates turns black, while the color of aluminum plates is basically unchanged. When temperature reaches about 350 degrees, reflectance of steel decreases obviously with the increase of temperature, while reflectance of aluminum is almost constant. The reflectance is probably determined by the oxide in the surface of samples which is consistent with the results of EDS analysis. Reflectance decreases with the increase of the content of oxygen in the surface. The reason of why the reflectance of aluminum is almost constant is that aluminum oxide is not generate massively under 500 degrees.

10016-69, Session Post

Simulation of wavefront optimization by volume Bragg grating in photothermorefractive glass

Xiaojie Sun, Fan Gao, Xiang Zhang, Xiao Yuan, Soochow Univ. (China)

Wavefront distribution becomes one of the important parameters for high power laser systems, since it influences the beam quality, the focusing property and the triple frequency conversion effect from 1053nm to 355nm of laser beams. Wavefront distortion can be introduced by many factors, such as the surface of large-scale optical elements, thermal effect in laser systems, etc. Currently, the adaptive optics system and the traditional spatial filter are used to suppress the wavefront distortions in high power laser system. However, both of them require large space and time to maintain.

In this paper, optimization for the wavefront distortion based on volume Bragg gratings (VBGs) recorded in photo-thermo-refractive glasses (PTR) is simulated. A beam with different wavefront distortions is the incident beam on VBGs at the Bragg angle. The wavefront distribution of diffracted beam through two orthogonal VBGs is simulated based on the angular spectrum theory and Kogelnik's coupled wave theory. Four VBGs with different angular selectivity at 2.0mrad, 1.5mrad, 1.0mrad, and 0.5mrad are used to simulated and optimize the wavefront distribution. The simulation results show that the wavefront distribution can be optimized with the VBGs due to its angular selectivity. The PV value of wavefront distribution is reduced from 2.51? to 1.77?, 1.71?, 1.68?, 1.47?, respectively. And the RMS value is reduced from 0.207? to 0.0946?, 0.0942?, 0.0940?, 0.0935?, respectively. The wavefront PSD shows the distortion of medium and high frequencies can be filtered with the VBGs.

10016-70, Session Post

Detection of laser-induced damage on fused silica with photo-acoustic method

Muyu Yi, Xiang Zhang, Xiao Yuan, Soochow Univ. (China)

Detection of laser-induced surface damage on fused silica and other optical components is important for high power lasers. Since influenced by the subjective factors, the traditional method of phase contrast microscope observation is difficult to obtain an accurate, consistent laser damage threshold of optical components. The method of photo-acoustic detection, based on changes in the waveform and amplitude of acoustic signals, can obtain a real-time and low personal-error damage threshold of optical components, which has potential applications in high-power laser development.

In this paper, we design a new photo-acoustic probe which is Anti-Emi (Electron-Magnetic Interference), easy-adjusted and non-damage for the samples. Based on the photo-acoustic detection system, the damage processes of fused silica samples are detected according to the rapid increase of the acoustic signals. The samples are irradiated under the laser beam with the wavelength of 1064 nm and pulse width of 10 ns. Experimental results show that the damage thresholds of fused silica samples are 13.86 J/cm2 at the wavelength of 1064 nm and the pulse width of 10 ns. The above work may provide an effective technical support for the laser-induced damage detection

.10016-71, Session Post

Optimization of key parameters of a laser ablation ion mobility spectrometer

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Ion mobility spectrometry (IMS) is an atmospheric pressure detecting technique adept in real-time and on-line detection. Molecules could be ionized by sets of methods including radioactive ionization, electric field ionization, ultraviolet ionization and so on. But these methods could not apply to metal. Laser ablation ion mobility spectrometry (LA-IMS) is a new application which emphasize on metal detection with the combination of IMS technology and laser ablation sampling.

In this work, with a home-made ion mobility spectrometer, we investigated copper sheet signal intensity in different electric field. The migration characteristics of metal ions match the formula: l_d/K?1/E_d =t_dwhen the electric field intensity is stronger than 500v/cm. The relationship between signal intensity and sampling angle (the angle between drift tube and the tangent plane of the sample) was studied. With the increasing of the sampling angle, signal intensity had a significant increase; while the laser incident angle had no significant influence on it. The signal intensity increased 140% when the sampling angle varied from 0 to 45 degree with the angle between the drift tube and incident laser beam keeping 90 degree. Influence of the position of ion gate is also studied in this work. And results indicated that ion gate should be more than 2.5 cm to sample point or no signal was acquired. SNR was improved by a subtraction of acquired signal with a background signal acquired afore by opening the ion gate. After the subtraction, shockwave and electrical field perturbation produced during the interaction between laser beam and samples, two main noise of the signal could be eliminated. We also found that the distance between the boundary of the copper sheet and the sampling point has influence on the signal intensity.

10016-73, Session Post

Influence of soft bonding layer material viscoplasticity on thermal lens and aspherical aberration of high-power thin disk laser

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An viscoplasticity model is developed to analyze the deformation of laser disk with pumping. The characteristic of soft bonding material is described with Anand model. Transient analysis for laser disk with pumping considering bond solder viscoplasticity is within 100 hours. An finite element analysis software COMSOL is applied. Soft solder in this model is indium. Thin laser disk bonded to copper tungsten alloy, thermal expansion coefficient of which match with the crystal. In analysis back surface of laser disk is separated to spherical part and aspherical part. Thus thermal lens and aspherical OPD induced by laser disk back side can be obtained. Result show that, after 100 hours, refraction power of disk module with large pump spot(8mm diameter) will change more, but for disk module with small pump spot(4mm diameter), surface aspherical part will change more. This two parameter is important for high power fundamental mode disk laser design.

10016-74, Session Post

The design of thin disk laser multi-pass amplifier

Enmao Song, Guangzhi Zhu, Xiao Zhu, Jinbo Yu, Wenguang Zhao, Huazhong Univ. of Science and Technology (China) and National Engineering Research Ctr. for Laser Processing (China)

Thin disk laser is a successful design for realizing high output power, high efficiency, and good beam quality, simultaneously. Typically, the thickness of the thin disk crystal is between 100 microns and several hundred microns. The diameter of the disk is, depending on the desired laser power, between some mm and a few cm. The disk crystal is soldered on the CuW heat sink to provide an effective support. The most important advantages of the thin disk laser are efficient cooling and the possibility of reducing thermal aberration, which will be better to sustain good beam quality of seed laser after multi-pass amplification. However, the thinner thin disk crystal only provides very small single gain. The multi-pass amplification technology and regeneration amplification technology are widely used to improve the energy extraction efficiency. Comparing with regenerative amplification technology, multi-pass amplification structure can accept laser pulses range from continue wave to femtosecond wave and can be operated in burst mode At the same time, the amplification structure avoids complicated electronically controlled optical switch and improves average output power.

In this paper, a thin disk multi-pass amplification system is designed based on the conjugated double parabolic mirror pumping thin disk laser module, which realizes 40 passes transmitting through the thin disk crystal. The light transmission matrix is used to optimize optical mode matching of seed laser spot size and pumping spot size during the multi-pass transmission. At the same time, anti-stability of the thin disk multi-pass amplification system and the aberration of output laser beam are analyzed in deeply.

Acknowledgements

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10016-75, Session Post

New type of fiber mode stripper with quartz tubes

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Fiber cladding mode stripper is one of key devices in high-power fiber lasers and high-power transmission fiber. We report a new kind of mode stripper using quartz tubes with etched dots on the surface. We studied the waveguide property of the mode stripper both the dots on the outer surface and on the inner surface of the tube. Then we produced some quartz tubes using green laser for the experiments, which demonstrated that the new model strippers can reduce the cladding light and improve the axial temperature distribution obviously.

10016-22, Session 5

Recent advances in Raman fiber lasers *(Invited Paper)*

Yan Feng, Shanghai Institute of Optics and Fine Mechanics (China)

Stimulated Raman scattering is an effective and efficient nonlinear frequency conversion process inside optical fibers. In recent years, Raman fiber lasers have advanced greatly in terms of output power, spectral coverage, and field of applications. New schemes of Raman fiber lasers are emerging with technical innovation and interesting new physics.

10016-23, Session 5

Recent development on high-power tandem-pumped fiber laser *(Invited Paper)*

Pu Zhou, Hu Xiao, Jinyong Leng, Hanwei Zhang, Xueyuan Du, Jiangmin Xu, Jian Wu, National Univ. of Defense Technology (China)

High power fiber laser is attracting more and more attention due to its advantage in excellent beam quality, high electric-to-optical conversion efficiency and compact system configuration. Power scaling of fiber laser is challenged by the brightness of pump source, nonlinear effect, mode instability and so on. Pumping active fiber by using high-brightness fiber laser instead of common laser diode may be the solution for the brightness limitation. In this paper, we will present the recent development of various kinds of high power fiber laser based on tandem pumping scheme. According to the absorption property of Ytterbium-doped fiber, Thulium-doped fiber and Holmium-doped fiber, we have theoretically studied the fiber lasers that operate at 1018 nm, 1178 nm and 1150 nm, respectively in detail. Consequently, according to the numerical results we have optimized the fiber laser system design, and we have achieved (1) 500 watt level 1018nm Ytterbium-doped fiber laser (2) 100

watt level 1150 nm Ytterbium-doped fiber laser, 100 watt level Ytterbium/Raman hybrid fiber laser and 100 watt level random fiber laser (3) 30 watt 1178 nm Ytterbium-doped fiber laser, 200 watt-level random fiber laser. All of the above-mentioned are the record power for the corresponded type of fiber laser to the best of our knowledge. By using the high-brightness fiber laser operate at 1018 nm, 1178 nm and 1150 nm that we have developed, we have achieved the following high power fiber laser (1) 3.5 kW 1090 nm Ytterbium-doped fiber amplifier (2) 100 watt level Thulium-doped fiber laser and (3) 50 watt level Holmium -doped fiber laser.

10016-25, Session 5

1-MW peak power 574-kHz repetition rate picosecond pulses at 515 nm from a frequency-doubled fiber amplifier

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High-peak-power infrared and green picosecond pulses are important sources for laser machining, optical parametric oscillators, and so on. In this paper, we present the direct amplification of 30-ps pulses at 574-kHz repetition rate by using a large mode area rod fiber amplifier. A peak power of 2.3 MW at 1030 nm is generated and converted into 1 MW green peak power through second harmonic generation (SHG). Both infrared and green pulses exhibit diffraction-limited beam quality. The amplifier is seeded by a SESAM mode-locked laser with 30-MHz repetition rate. After a Yb-doped single-clad fiber pre-amplifier, an acoustic-optic pulse-picker is used to pick out pulses with a repetition of 574 kHz. To obtain high-peak-power output as well as avoid the self-phase modulation (SPM), we take use of flexible single-mode ytterbium photonic crystal fiber (NKT DC-200/40-PZ-Yb) and ultra-large-mode-area rod-type photonic crystal fiber (NKT aeroGAIN-ROD-PM85). We also optimize every stage's gain to control the spectral width introduced by SPM. Then second harmonic generation with a LBO crystal under type-? temperature-tuned interaction is investigated. The highest SHG efficiency is 60%. 1-MW peak power, 574-kHz repetition rate picosecond pulses with diffraction-limited beam quality is generated at 515nm.

10016-26, Session 5

Efficient 1.5-um Raman generation in ethane-filled hollow-core fiber

Yubin Chen, Bo Gu, Zefeng Wang, QiSheng Lu, National Univ. of Defense Technology (China)

Eye-safety fiber sources operating in 1.5 μm regions have attracted considerable attentions in the past decade, due to their extensive applications in the fields of communication, sensing, medicine, scientific research, and so on. Due to the spectrum broadening induced by varieties of non-linear effects in the solid core fiber at high power, it's a great challenge to achieve both high peak power and narrow linewidth 1.5μm fiber sources, which are required in some applications, with traditional Er-doped fibers or Er-Yb co-doped fibers. In contrast with solid core fibers, stimulated Raman scattering (SRS) of gas in hollow core fiber provide an effective method for obtaining both high peak power and narrow linewidth 1.5μm fiber source. We demonstrate here, for the first time to the best of our knowledge, a both high peak-power and narrow linewidth 1.5 ?m fiber gas Raman source. Using a 1064 nm microchip laser as the pump source, pulses of ~400 kW peak power, ~7.5 GHz linewidth, ~123 ps pulse duration, 1552.7 nm center wavelength are obtained with a 6 m ethane-filled negative curvature hollow-core fiber at 2 bar pressure by SRS. Comparing with the 1.5 ?m Er-doped or Yb-Er co-doped fiber laser, the peak power is increased 1~2 order of magnitude, meanwhile the linewidth is decreased 1~2 order of magnitude. If using a tunable pump source, this kind of fiber source can easily achieve broad tuning range near 1.5 ?m.

10016-27, Session 5

A systematic analysis of nanosecond pulse amplification in ytterbium-doped double-clad fiber amplifiers by considering inelastic scatterings and different operation regimes

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Dynamic characteristics of Ytterbium-doped double-clad fiber amplifiers during the amplification of nanosecond pulses have been extensively analyzed by a number of researchers and Dr. Wang is considered the first pioneer in this field. Although in his works he studied different aspects of this process, they are mainly limited to specific repetition rates (mainly tens of kilohertz), input temporal pulse widths (mainly tens of nanoseconds), input pulse peak powers and input pulse bandwidths (not mainly narrow bandwidths). Also effect of input pulse shape on threshold of inelastic scatterings has not been analyzed, to the best of our knowledge, that's a common phenomena in some amplifiers. On the other hand, in some applications we need specific pulse widths that are less than ten nanoseconds that's comparable to the phonon lifetime or some pulses with repetition rates of less than ten kilohertz that require us to consider special aspects such as pumping and inelastic scatterings. In our work based on numerical modeling we systematically discuss these parameters from temporal pulse widths to repetition rates and pumping configurations and analyze when to consider inelastic scatterings and change pumping configuration from CW to pulsed pumps. Also for the first time, to the best of our knowledge, we shed light on the effect of input pulse shape on threshold of inelastic scatterings and importance of using pulse shaping methods to suppress these detrimental effects. Our results can give a better understanding of nanosecond pulse amplification in Ytterbium-doped double-clad fiber amplifiers.

10016-28, Session 5

Theoretical and experimental analysis of double-pass ytterbium-doped fiber amplifier

Pengfei Zhang, National Univ. of Defense Technology (China)

We theoretically and experimentally demonstrated a double-pass ytterbium-doped fiber amplifier. First, we numerically analyze the impact of pump regime and fiber length on the amplifier. In our experiment, a laser seed with output power of ~100 ?W and wavelength of 1064 nm is amplified to 70.3 mW with a signal gain of 28.5 dB. With this double-pass configuration, amplified spontaneous emission (ASE) is effectively suppressed to more than 30 dB. Comparing with single pass configuration, it is found

that double-pass amplification configuration enhances the gain coefficient and improves the signal-to-noise ratio.

10016-29, Session 5

Passive harmonic mode-locking in a monolayer graphene-based long-cavity fiber laser with high pulse energy

Xiaoying He, Fudan Univ. (China); Dongning Wang, China Jiliang Univ. (China)

Passive mode-locking fiber lasers have attracted strong research interest during the past decade, especially in the context of producing high repetition rate pulses with short duration and high energy. To obtain the higher repetition rate pulses, the passive harmonic mode-locking (HML) technique has been employed, in which the fiber laser operates at a multiple of its fundamental frequency. The first experiment of the HML in an Erbium-doped fiber laser was implemented in 1993 by Grudinin et al. Up to now, many approaches have been reported in producing HML by use of nonlinear polarization rotation (NPR) [4-5], nonlinear amplifying loop mirrors (NALMs), semiconductor saturable absorber mirror (SESAM), carbon nanotubes SESAM combined with nonlinear polarization evolution and graphene. In all the aforementioned HML fiber lasers based on saturable absorber, the maximum output pulse energy achieved is very low, below 30 pJ. Such low energy pulses are liable to be distorted by the noise when propagating in the optical communication system.

In this paper, we experimentally investigated a dispersion-managed HML fiber laser based on the polymer-supported monolayer graphene film for high pulse power output. A larger light-graphene interaction has been achieved by using the MMF with a larger fiber core to replace the SMF, thus leading to a large output pulse energy. Single pulse energies achieved at the fundamental, the 2nd and the 3rd harmonics are ~1.55, ~1.13, ~1.04 nJ, respectively, by the use of the dispersion-managed system and large light-graphene interaction area to improve single pulse energy. The stable 3rd HML is obtained with ~603 fs pulse width, repetition rate of 20.26 MHz and SNR of 53 dB. With sufficient pump power, higher order of HML pulses of large energy would be generated. Such large energy ultrashort pulses would make the fiber laser proposed be a potential light source for fiber access network, material processing, optical frequency metrology and sensing.

10016-30, Session 5

All-fiberized single-frequency polarization-maintained fiber amplifier with record power

Long Huang, Pengfei Ma, Rongtao Su, Xiaolin Wang, Hanwei Zhang, Pu Zhou, National Univ. of Defense Technology (China)

Narrow-linewidth fiber lasers have wide and promising applications in gravitational wave sensing, nonlinear frequency conversion, laser radar, coherent beam combining and so on. Particularly, all-fiberized single frequency fiber laser with linear polarization is rather attractive due to its extreme narrow linewidth, high polarization degree, compact configuration and robust property. The output power of single frequency fiber laser oscillator is limited and by using cascade power amplification scheme, single frequency linearly polarized fiber have realized output power from several watts to several hundred watts in the past decade. In the present work, a 400 W-level single frequency fiber amplifier with linear polarization is demonstrated based on the master oscillator power amplifier configuration, which consists of a single frequency seed laser based on ultra-short cavity, two pre-amplifiers and a main amplifier.. A short piece of polarization-maintaining active fiber with a core diameter of 30 um and a high pump absorption coefficient is adopted in the main amplifier. The slope efficiency of the main amplifier is about 80%. No sign of SBS is observed at the maximal power. The near-diffraction-limited beam quality is realized with M2 < 1.5. To the best of our knowledge, this is the highest output power of single frequency fiber amplifier based on all-fiber structure.

10016-31, Session 5

Linear inner-cladding fiber amplifier suppressing mode instability

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For Small power system and hundreds of watts system, gain saturation is considered and increases mode instability (MI) thresholds. In fact, only signal power saturation is included and pump power saturation is neglected, which is small enough respect to signal power saturation numerically and has little effect in these systems. However, for output power of multi-kW-class and 10 kW-class lasers, pump power saturation makes a significant effect on calculation accuracy. Moreover, we use a semi-analytical model considering pump power saturation to compute mode instability threshold, ensuring computation accuracy and speed.

State of the art, fiber of 20 μm diameter core hasn't reached 10 kW in single mode regime. Linear cladding fiber (LCF) laser of 20 μm diameter core can generate 10 kW-class power pumped at 915 nm without MI effect in theory. Compared with other MI suppressing strategies, LCF improves heat profile of fiber both transverse and longitudinal direction. LCF smoothes the heat profile with stronger pump absorption and decreases nonlinear coupling coefficient by shrinking inner-cladding diameter, leading to the MI threshold scaling. Vignetting effect can be alleviated by reducing tapering ratio or increasing fiber length, noted that 915 nm pumping scheme need relatively long fiber compared to that of 976 nm pumping scheme. Fiber manufacture tapering inner-cladding and maintaining the fiber core uniform should be developed for this kind of fiber. LCF having a significant effect on MI need to be verified in experiment.

10016-32, Session 5

Phase modulation signals optimization automatically for suppression of stimulated Brillouin scattering

Min Jiang, National Univ. of Defense Technology (China) and Hunan Provincial Collaborative Innovation Ctr of High Power Fiber Laser (China); Yang Ran, Rongtao Su, Pu Zhou, National Univ. of Defense Technology (China) and Hunan Provincial Collaborative Innovation Ctr. of High Power Fiber Laser (China)

In high power narrow linewidth fiber amplifier system, phase modulation of the signal laser into multiple laser-lines is one of the common methods to suppress the stimulated Brillouin scattering (SBS) effect, which is the main limiting factor to achieve high power. In order to achieve optimal suppressing effect, the multiple laser-lines should have equal symmetrical amplitude. To the best of our knowledge, detailed studies of the efficient generation of equal amplitude symmetrical spectrum

with a certain number of lines within a limited linewidth and limited peak spectral power density have not been reported. In this paper, we use the phase modulation signal,which is the sum of a finite number of sinusoidal signals with different initial phases and different weights,to generate equal amplitude symmetrical spectrum. The stochastic parallel gradient descent (SPGD) algorithm is introduced the first time to search for the optimal initial phases and weights through iterations, thus obtaining the optimal modulation signal. We generate homogeneous symmetrical spectra with 11 lines and 19lines within 2 minutes and 29 lines within 6 minutes. Simulation results show that the method works well. Compared with other nonlinear algorithm, the SPGD algorithm holds the advantage of easy control strategy and rapid optimization process. Based on this method, the details of the spectrum can be controlled, such as the linewidth of signal laser and the peak power density.

10016-33, Session 6

Recent progress on high-field physics *(Invited Paper)*

Baifei Shen, Shanghai Institute of Optics and Fine Mechanics (China)

This talk is about recent theoretical and experimental progress on high-field physics in our group. It includes three parts. First, the physics of relativistic vortex laser is explored. The concept of high OAM (orbital angular momentum) physics is proposed. High order harmonics, electron jet producing and reflection of intense vortex laser are discussed. Second, the QED effects, X and gamma ray radiation is studied. Third, recent experimental progress is introduced. They are laser driven proton and heavy ion acceleration, proton radiograph, positron production, and gamma ray production.

10016-34, Session 6

Interaction of high-power laser beams with plasma in ICF hohlraum using the FDTD method

Zhili Lin, Huaqiao Univ. (China)

In the indirect-drive Inertial confinement fusion (ICF) system, groups of laser beams are injected into a gold cylindrical hohlraum and plasma is stimulated with the ablation of the wall of hohlraum by the high-power pulsed laser beams. In our work, the powerful finite-difference time-domain (FDTD) method is used to numerically examine the high-power laser beam injection and propagation in the high-intensity plasma. With the developed dielectric constant model of plasma, the Maclaurin series expansion (MSE) is applied to implement the dispersive model in the frame of FDTD method. The state-of-the-art approaches for generating the laser beams with a variety of parameters such as angles of incidence, temporal waveform, polarization state and intensity pattern are presented and realized according to the full utilization of the TF/SF source condition. Base on the previous technologies, the quantitatively numerical analysis of the energy scattering of laser beams from the vacuum-plasma interface at the entrance hole of hohlraum and the propagation characteristics of laser beams in the plasma are further conducted and investigated. Results are obtained, illustrated and discussed that are helpful for optimizing the laser beam parameters for the ICF system.

10016-35, Session 6

Nonadiabatic electron dynamics in orthogonal two-color laser fields with comparable intensities *(Invited Paper)*

JiWei Geng, Peking Univ. (China)

We theoretically investigate the nonadiabatic subcycle electron dynamics in orthogonally polarized twocolor laser fields with comparable intensities. The photoelectron dynamics is simulated by exact solution to the 3D time-dependent Schrödinger equation, and also by two other semiclassical methods, i.e., the quantum trajectory Monte Carlo simulation and the Coulomb-corrected strong field approximation.

Through these methods, we identify the underlying mechanisms of the subcycle electron dynamics and find that both the nonadiabatic effects and the Coulomb potential play very important roles. The contribution of the nonadiabatic effects manifest in two aspects, i.e., the nonadiabatic ionization rate and the nonzero initial velocities at the tunneling exit. The Coulomb potential has a different impact on the electrons' trajectories for different relative phases between the two pulses.

10016-37, Session 6

Studies on high-quality electron beams and tunable X-ray sources produced by laser wakefield accelerators *(Invited Paper)*

Ming Zeng, Horia Hulubei National Institute of Physics and Nuclear Engineering (Romania) and Shanghai Jiao Tong Univ. (China); Ji Luo, Min Chen, Shanghai Jiao Tong Univ. (China); Zheng-Ming Sheng, Shanghai Jiao Tong Univ. (China) and Univ. of Strathclyde (United Kingdom)

Intense femtosecond mid-infrared laser sources are attracting broad interests due to their potentials for a variety of applications. We propose to drive laser wakefield acceleration with mid-infrared high power lasers to achieve both high charge and high quality electron beams. In order to obtain high-quality electron beam injections, we adopt the ionization injection scheme with square-wave like bichromatic lasers (SWBL), which are composed of a laser at the fundamental frequency (or 2.4 um) as the driving laser of the wakefields and another at its third harmonic frequency (or 0.8um) as the injection laser [Phys. Rev. Lett. 114, 084801 (2015)]. The injection laser is a 10 fs, 0.8um laser pulse, which can trigger intermittent ionization injections by beating with the driving pulse. Based upon three dimensional particle-in-cell simulations, we show the production of electron beams with energy of ~700 MeV, energy spread of ~1% and charge of ~50 pC by a SWBL laser pulse with the peak power of ~80 TW. This proposal may pave a way for applicable high quality laser wakefield accelerators.

10016-38, Session 7

Self-starting and ultra-stable femtosecond fiber lasers for industrial applications *(Invited Paper)*

Zhigang Zhang, Peking Univ. (China)

No Abstract Available

10016-39, Session 7

Measurement and compensation schemes for the pulse front distortion of ultra-intensity ultra-short laser pulses

Fenxiang Wu, Yi Xu, Linpeng Yu, xiaojun yang, Jun Lu, Wenkai Li, Yuxin Leng, Shanghai Institute of Optics and Fine Mechanics (China)

Pulse front distortion (PFD) is mainly induced by the chromatism of the employed lens-based beam expanders in femtosecond high-peak-power laser systems, and it can temporally distort the pulse in the focus and therefore decrease the peak intensity. A novel measurement scheme based on self-reference and second-order cross-correlation technologies is proposed to directly measure the PFD of ultra-intensity ultra-short laser pulses, which is often associated with large beam size. The measurement scheme is applied in an existed 200TW/1Hz/27fs Ti:sapphire laser system, and the measured result of PFD is in good agreement with the theoretical calculation, which also demonstrates the validity and feasibility of this measurement method. This method can work not only without any extra struggle for the desired reference pulse, but also largely reduce the size of the required optical elements in the measurement, and it is the first time to realize the direct PFD measurement of ultra-intensity ultra-short laser pulses to our knowledge. In addition, in order to ensure optimum performance of such ultra-short high-peak-power laser systems, a simple combination of concave lens and parabolic lens is also designed to compensate the PFD. According to the theoretical calculation, the residual PFD of this laser system is smaller than 0.5fs after compensation, which can be ignored with respect to the pulse duration. Moreover, this direct PFD measurement and compensation schemes can also be applied in PW even 10PW ultra-short laser system with larger beam diameter, in which the PFD issue is more significant generally for larger lens-based expanders.

10016-40, Session 7

Accurate single-shot measurement of the femtosecond pulse duration in the multi-petawatt laser facility

Qingwei Yang, Xinglong Xie, Shuaixu Shi, Jianqiang Zhu, Jun Kang, Ailin Guo, Meizhi Sun, Haidong Zhu, Shanghai Institute of Optics and Fine Mechanics (China)

At the Shen Guang II (SGII) femtosecond 5PW laser facility, the single shot femtosecond laser pulse diagnostic results is affected by many factors, such as different attenuation under different target energy condition, the beam divergence of incident pulse, the distance between frequency doubing crystal and detector in the autocorrelator, material dispersion of the autocorrelator, etc., causing uncertainty in the measurement of the femtosecond pulse. In order to meet the requirements of single shot femtosecond laser pulse diagnostic in the SG II 5PW laser facility, some methods have taken. For example, a dispersion compensator is used to compensate the dispersion of attenuation before autocorrelator, and an imaging system is used to overcome the effect of the incident pulse divergence in the autocorrelator. Through carefully design and a series of experiment, a single shot autocorrelator suit for the SGII 5PW laser facility is achieved.

10016-41, Session 7

58W LD side-pump Nd:YAG picosecond laser system at 1KHz with double length of regenerative cavity

Mingliang Long, Gang Li, Meng Chen, Beijing Univ. of Technology (China)

An average power of 58W, pulse width of 40ps at 1KHz repetition rate of Nd:YAG picosecond laser is reported. It used an etalon to directly get pulse width of 135ps from Nd:YVO4 mode locked laser in 1064nm, which repetition rate was 88MHz. When the seed pulses were injected into the double length of regenerative LD side-pump Nd:YAG cavity at 1KHz repetition rate, the single pulse energy was amplified to 3mJ, the pulse width was compressed to 99ps, beam quality of M^2 factor was 1.3. The single pulse energy was amplified up to 58mJ, the pulse width was self compressed to 40ps, beam quality of M^2 factor was approximately 3.5 after single passing three stages of double high gain LD side-pump Nd:YAG module. Beam pointing was about 40urad. The stability for pulse to pulse RMS was less than 3%. A thin-film polarizer and a quarter-wave plate was inserted into the regenerative amplification cavity to let pulses double travel the same geometric path basis on pulse polarization. Serrated aperture were used in the amplification. That's beneficial to decrease the nonlinear effect for the high power in the crystal. High gain LD side-pump Nd:YAG module could lead the pulse energy amplify more and self compress the pulse width. Double length of regenerative cavity was used to enhance the optical cavity length, it greatly decreased the laser's volume and improved stability of picosecond laser. It's a nice way for high power picosecond laser and the laser system would be more simple and smaller.

10016-42, Session 7

The filamentation of femtosecond laser pulse in air with various orders of super-Gaussian beam

Yuze Hu, Jinsong Nie, Lei Wang, Xianan Dou, Zhiming Li, Electronic Engineering Institute (China)

The filamentation of femtosecond laser pulse in air are studied numerically with various orders of super-Gaussian beam based on the Nonlinear Schrödinger Equation. In order to investigate the characteristics of filaments pertaining to filament length, few-cycle pulses and supercontinuum which have high values of potential applications, we use three orders of super-Gaussian beams in both temporal and spatial regimes as initial conditions with the same energy, waist and pulse width. For the length of filaments, when the order of spatial super-Gaussian beams becomes higher, the onset of filaments would be earlier while the length becomes slightly shorter. With the order of temporal super-Gaussian beams becoming higher, the onset of filament would be delayed and the length are slightly shorter too. With further study, spatial and temporal orders of super-Gaussian play equal roles on the onset of filament, while the length is almost dependent on the temporal order. For the few-cycle pulses generation, after the filament is formed, the femtosecond pulse will be divided into several shorter sub-pulses. The front part of few-cycle sub-pulse will be prolonged by increasing the spatial order and the even shorter sub-pulses will be formed with the higher temporal order. For the supercontinuum generation, the spectrum broadening seems to be tightly related to the temporal order of super-Gaussian beam, which shows more intensive broadening with higher temporal order. The underlying physics behind these phenomena are optical Kerr-effect together with background energy reservoir in the spatial domain and self-phase modulation together with plasma effect in the time regime.

10016-43, Session 7

Mode-locked femtosecond all polarization-maintaining erbium-doped dispersion managed fiber laser based on a nonlinear amplifying loop mirror

Wenjue Wu, Yue Zhou, Ji Sun, Yitang Dai, Feifei Yin, Jian Dai, Kun Xu, Beijing Univ. of Posts and Telecommunications (China)

In recent years mode-locked fiber lasers are well developed as some optical devices which can be used in a lot of fields such as optical imaging, theoretical physics and high precision metrology. In general the soliton laser is limited in output power because of it usually worked in the anomalous dispersion regime, the wave breaking effect lead the laser to reduce the energy[1]. The laser can adopt dispersion managed cavity to overcome the limitation of energy, higher energy can be achieved as the net dispersion is positive and near the zero. In addition The NALM has more advantages than NOLM, such as better control, shorter cavity length, easier mode-locking[2-4]. If all elements and fiber in cavity are polarization maintaining it will increase the stablility of temperature and stress and the laser can work stably for a long time.

In this paper, we proposed a mode-locked all-PM-Er fiber laser base on NALM(nonlinear amplifying loop mirror). This configuration can better control and easier mode-locking. The laser can generate 1.6 ps pulses with the energy of 1 nJ that can be compressed down to 350 fs with the single mode fiber(SMF) outside the cavity.

10016-44, Session 7

Stable linear SESAM femtosecond fiber laser by use of Faraday rotator mirrors

Mohammad J. Hekmat, Asghar Gholami, Masood Omoomi, Mohammad Kanani, Mohammad Abdollahi, Narges Shahriari, Hossein Normohammadi, Isfahan Univ. of Technology (Iran, Islamic Republic of)

Fiber based femtosecond lasers are rapidly growing in recent years. For several applications, long stability of ultrashort pulsed source is desirable. In this research by use of commercial fiber components such as Batop SESAM, Thorlabs Faraday Rotator Mirrors and nLight Er doped fibers, a stable femtosecond fiber laser is achieved. In previous studies, PM fibers or Polarization Controller (PC) was used to increase laser stability which are replaced with Faraday Rotator Mirror at this research. Another strength of this research, unlike the other studies in the field of SESAM femtosecond fiber laser, no Kelly Sideband is observed in output spectrum. With addition of Erbium-Doped fiber amplifier, the output power 100mW with 155 fs and 45.5 MHz repetition rate is acquired.

10016-45, Session 7

Integration of a directly chirped laser source into a high-energy OPCPA system

Ran Xin, Univ. of Rochester (United States) and Cymer LLC (United States) and ASML (United States); Jonathan D. Zuegel, Univ. of Rochester (United States)

Chirped-pulse–amplification (CPA) technology is widely used to produce ultra-short optical pulses (sub picosecond to femtoseconds) with high pulse energy. A chirped pulse laser source with flexible dispersion control is highly desirable as a CPA seed. This work presents an all-fiber, directly chirped laser source (DCLS) that produces nanosecond, linearly-chirped laser pulses at 1053 nm for seeding high energy CPA systems. DCLS produces a frequency chirp on an optical pulse through direct temporal phase modulation. It provides programmable control for the temporal phase, high pulse energy and diffraction-limited beam performance, which are beneficial for CPA systems. A DCLS has been built and its integration into a high energy OPCPA system is experimentally demonstrated. DCLS produces a 1-ns, linearly-chirped pulse with a 3-nm bandwidth by applying a ~1000-rad quadratic temporal phase. This chirped pulse is amplified to 76 mJ in an OPCPA system and compressed to close to its Fourier transform limit, producing an intensity autocorrelation trace with a 1.5-ps width. The intensity correlation trace corresponding to the Fourier transform limit is 1.4 ps as calculated using simulation. In this paper the DCLS concept is first described. Its key enabling technologies are identified and discussed. These include high-precision temporal phase control using an arbitrary waveform generator, multi-pass phase modulation to achieve high modulation depth, regenerative amplification in a fiber ring cavity and a negative feedback system that controls the amplifier cavity dynamics. The key DCLS experimental results are then presented. These include the measured DCLS temporal phase and its compression results.

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10017-1, Session 1

Recent progress in 1.3- and 1.5-um waveband wafer-fused VCSELs *(Invited Paper)*

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Vertical cavity lasers emitting in the 1.3- and 1.5-μm wavebands are important for a wide range of applications in optical communications, sensing, illumination, optical pumping and spectroscopy. We discuss recent progress in the design, fabrication and industrialization of such devices made by using wafer fusion, which allows integration of GaAs-based DBRs with InP-based active structures and an independent optimization of the mirror and cavity properties before the fusion. Both the GaAs-based mirrors and InP-based optical gain structures are grown by MOVPE. The VCSEL structure comprises an InP-based active region with InAlGaAs compressively strained quantum wells (QWs) as the gain medium and tunnel junction aperture for current and optical confinement, double-fused to two GaAs/AlGaAs-based Bragg mirrors. By epitaxial growth, device design and processing optimization 1.3- and 1.5-μm waveband VCSELs emitting single mode power of 6-8-mW at room temperature and up to 3-mW at 80°C were demonstrated. Moreover, industrially manufactured 10-Gb/s full wavelength-set VCSEL devices for coarse wavelength division multiplexing systems with high yield and Telcordia-reliability have been developed. More recent results showed that, by increasing the compressive strain in the InAlGaAs QWs to 1.6% for higher gain, and by reducing the cavity photon lifetime by decreasing the number of pairs in the top DBR, it is possible to significantly improve both the static and dynamic performance of wafer-fused VCSELs emitting at 1.3-?m. Thus, the modulation bandwidth was increased to 11.5-GHz and large-signal modulation response experiments show open eye diagrams from 25 to 35 Gb/s for both B2B and after 10-km.

10017-2, Session 1

Green VCSELs based on InGaN QDs *(Invited Paper)*

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Green VCSELs emitting in the spectral range from 491.8 nm to 565.7 nm are demonstrated. These devices are featured with low threshold current of less than 1 mA, CW lasing at room temperature. The fabrication procedure includes laser liftoff of sapphire substrate of the original epitaxial wafer, the removal of high-defect GaN buffer to suppress the dislocation-induced light scattering, metal bonding to increase the heat dissipation. Two dielectric DBRs were adopted as the cavity mirrors.

For these VCSELs emitting at different wavelengths, the same QDs active region was used while the wavelengths were controlled by adjusting the cavity length, which is difficult for edge emitting lasers. Moreover, the emission wavelengths cover most of the so-called “green gap” where the emission efficiency is low due to the higher indium content in conventional QW optoelectronic devices. Our results provide an effective approach to overcome the “green gap”.

Green VCSELs are still at their initial stage of research. Up to now, green VCSELs have been demonstrated under pulsed injection by Nichia in 2011. The results presented here open up opportunities to design and fabricate semiconductor green lasers with excellent performance that may lead to wide-gamut, low consumption power and compact displays and projectors. The VCSELs could also be bonded on to Si for integration with other optoelectronic devices/circuits.

10017-3, Session 1

980-nm ultra-high-speed VCSELs exceeding 30-GHz Bandwidth *(Invited Paper)*

Wissam Hamad, Werner H. Hofmann, Technische Univ. Berlin (Germany)

With the increasing bandwidth demand of optical interconnects, directly modulated VCSELs with ultimate speed ratings are needed [1]. For serial 100 Gbps solutions today´s VCSELs have to increase their high speed performance. Here we report about our next generation devices.

The devices discussed here are an optimized version of our very successful high-speed, temperature-stable 980 nm VCSELs featuring a very short half-lambda cavity and a binary bottom-mirror with 32 pairs, levels were further optimized in order to minimize internal loss. Like previously, parasitics are controlled by two oxide apertures and highly conducting current-spreading layers. InGaAs MQW active layers with with strain compensated GaAsP barriers were utilized for high differential gain. The 22 -pair Al12Ga88As/Al90Ga10As top-mirror was replaced by a 18-pair GaAs/Al90Ga10As mirror for lower photon lifetime, better confinement and better heat extraction. The epi-structure was grown by IQE Europe.

As single-mode fitting showed poor overlap with the small-signal modulation response data, a rate-equation analysis was performed as suggested in [2]. Unlike longer-wavelength devices, short-wavelength high-speed VCSELs emit multiple modes. Therefore, a multi-mode rate equation analysis is necessary. However, if the modes share the same carrier-reservoir, the multi-mode solution has the same algebraic shape. This is why single-mode rate-equation analysis usually works well even applied on multi-mode devices. In case of non-linear effects like spatial hole burning, creating two or more coupled carrier reservoirs, different solutions are possible.

The VCSELs showed modulation bandwidth around and exceeding 30 GHz. The common set of figures of merit is expanded consistently to explain dynamic properties caused by carrier fluctuations. This new model allows the consistent extraction of figures of merit and can explain mode-dependent dynamics.

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10017-4, Session 1

Narrow-linewidth photonic microwave generation based on an optically-injected 1550-nm VCSEL subject to optoelectronic feedback

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Radio-over-fiber (RoF) has a promising application prospect in modern communications since it can effectively combine the optical fiber communication and the wireless microwave communication. As one of key techniques for supporting RoF, the acquisition technique of photonic microwave has received much attention in recent years. At present, several schemes for photonic microwave generation have been demonstrated including direct modulation, external modulation, optical heterodyne, double mode beating frequency based on dual-mode lasers of multi-segment integration, dual wavelength beating frequency of dual-wavelength fiber lasers by incorporating a delay interferometer and a saturated absorber, and so on. Each of these schemes mentioned above has its distinctive advantages and limitations, and these limitations still need to be further improved.

In addition to above mentioned methods, the photonic microwave generation technique based on the period-one (P1) nonlinear dynamics of optically injected semiconductor lasers has also been paid more attention due to following advantages. First, the microwave frequency generated by P1 oscillation is widely tunable beyond the relaxation resonance frequency. Second, single sideband (SSB) optical spectrum structure can be achieved by adjusting the injection parameters, which has the advantage of minimizing the microwave power penalty caused by chromatic dispersion of the optical fiber. Moreover, the optically injected semiconductor laser system can be used as an AM-to-FM conversion module to reduce the fading effects induced by AM modulation in the RoF system. Even so, the generated microwave usually has a relatively large linewidth and poor frequency stability, which may limit its applications. As a result, further improvement methods have been introduced to obtain high performance and narrow linewidth photonic microwave. We have noticed that the used semiconductor lasers in most of relevant investigations on photonic microwave generation by using the period-one (P1) nonlinear dynamics of optically injected semiconductor lasers usually are edge emitting semiconductor lasers (EELs). Compared with EELs, vertical-cavity surface-emitting lasers (VCSELs) are promising devices with such unique virtues as small size, low threshold current, compactness, single-longitudinal-mode and so on. Based on this consideration, in this work, we have experimentally demonstrated high-quality photonic microwave generation based on the P1 dynamical state output from an optically injected 1550 nm vertical-cavity surface-emitting laser (1550 nm-VCSEL) subject to optoelectronic negative feedback. The experimental results show that, under an optical injection with parallel polarization, a 1550 nm-VCSEL can exhibit rich nonlinear dynamical behaviors such as stable injection locking (SIL), P1, period-two (P2), chaos (CO) through adjusting the injection strength and frequency detuning. Under suitable injection condition, the 1550 nm-VCSEL can generate a photonic microwave signal with single sideband optical spectrum structure, but the linewidth of the microwave signal is relatively wide (on the order of MHz). After further introducing optoelectronic negative feedback, the linewidth of the microwave signal can be narrowed to 105.7 kHz (reduced to more than two orders of magnitude). Furthermore, under the case that the feedback strength is set at an optimized value, the frequency of the microwave signal can be tuned continuously within a certain range through simply varying the injection strength.

10017-5, Session 1

Polarization and dynamical properties of VCSELs-based photonic neuron subject to optical pulse injection *(Invited Paper)*

Shuiying Xiang, Aijun Wen, Hao Zhang, Jiafu Li, Xingxing Guo, Xidian Univ. (China)

The polarization switching (PS) properties and nonlinear dynamics of vertical-cavity surface-emitting lasers (VCSELs) subject to orthogonal polarization optical pulse injections are investigated numerically based on the spin flip model. The responses of VCSEL under the arrival of external stimuli of orthogonal pulse injection are mainly discussed. The effects of pulse width, pulse repetition frequency, pump current, injection strength, as well as the frequency detuning on the PS properties and nonlinear dynamics are considered. It is found that, the PS can be obtained by the optical pulse injection. Moreover, the frequency detuning induced PS can also be achieved for optical pulse with given strength, width and repetition frequency. The frequency detuning modifies the response properties significantly. For negative frequency detuning, the optical pulse injection cannot lead to PS. For positive frequency detuning, different spiking patterns, limit cycle and chaotic dynamics can be obtained under different operating condition of pulse width and repetition frequency. In particular, under the condition of external optical pulse injection with positive frequency detuning, many dynamics of biological neurons can be optically mimicked successfully, such as phasic spiking, tonic spiking, phasic bursting, which extend the application of VCSELs for the emulation of the dynamics of neuron. These simulation results are also similar to those obtained by several experimental demonstrations of long wavelength VCSELs. The parameter regions leading to different spiking patterns are further identified. Thus, the numerical model and simulation results of VCSEL-based neuron are very useful and interesting for the ultrafast brain-inspired neuromorphic photonics systems.

10017-7, Session 2

Room-temperature continuous-wave operation of GaN-based green laser diodes *(Invited Paper)*

Jianping Liu, Suzhou Institute of Nano-Tech and Nano-Bionics (China)

We have demonstrated GaN-based green laser diodes with output power of 58 mW under room temperature continuous-wave operation, which is made possible since a low threshold current density of 1.8 kA/cm2 and a low threshold voltage of 4.5 V have been achieved.

The low threshold current density is attributed to improved material quality of InGaN multiple quantum wells(MQWs), which is a challenge for green LDs due to green gap problem, i.e. reduced quantum efficiency in the green spectrum range. By suppress the In-rich cluster and reducing growth temperature of p-AlGaN:Mg cladding layer, the dark spot in green InGaN MQWs is eliminated, and therefore the quantum efficiency of green LD structures is improved by 4.5 fold.

However, when growth temperature is reduced, AlGaN:Mg layers are found to have high electrical resistance since increased carbon impurity exists and carbon acts as compensating donor in AlGaN:Mg layers. By tuning MOCVD growth conditions to suppress carbon concentration, the electrical resistance of low-temperature grown AlGaN:Mg layers is reduced, and therefore low threshold voltage is achieved for green LDs.

GaN-based green LDs are desired to replace solid state lasers for laser display and pico-projectors. Therefore a great deal of

attention have been paid to improve their performance to meet the demand.

10017-8, Session 2

Investigation of single lateral mode for 852nm diode lasers with ridge waveguide design

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852nm Narrow linewidth lasers can be widely used in the field of ultra-fine spectrum measurement, Cs atomic clock control, satellite and optical fiber communication and so on. Furthermore, the stability of the single lateral mode is a very important condition to guarantee the narrow linewidth lasers. Here we investigate experimentally the influence of the narrow ridge structure and asymmetrical waveguide design on the stability single lateral mode of an 852nm diode laser. According to the waveguide theoretical analysis, ridge mesa etch depth (, related to the refractive index difference of parallel to the junction) and ridge mesa width (the narrower the more control force to low order mode) are the main elements for lateral modes. In this paper, we designed different structures to investigate and verify major factors for lateral mode by experiment, and to confirm our thought. Finally, the 5 ?m mesa ridge laser, 800nm etch depth, with groove structure obtains excellent steady single lateral mode output by 150mA operating current and 30? temperature. The optical spectrum FWHM is 0.5nm and side mode suppression ratio is 27dBm with uncoated. The laser with 1mm cavity length showed the threshold current of 50mA, a lasing wavelength of ? = 852.6 nm, slope efficiency of above 70%. We accomplished single lateral mode of ridge waveguide edge-emitting lasers which can also be used as a laser source in the ultra-narrow linewidth external cavity laser system.

10017-9, Session 2

To packaged 650nm red semiconductor laser with transparent window

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In order to improve the characteristics of the AlGaInP/ GaInP red semiconductor laser diode, we design an asymmetric cladding structure, optimize the epitaxy growth condition and fabricate a transparent window facet by zinc diffusion method. After chip process manufacture, the laser chip with 12-μm stripe is bonded on TO18 package. Under continuous-wave (CW) operation condition, the typical threshold current is 42 mA, the slope efficiency is 1.12W/A, the wall-plug efficiency reaches 39.8%, and the maximum output power reaches higher than 320mW. Also, the character temperature reaches 75K.

10017-10, Session 2

830-nm InGaAs quantum-well lasers with very low beam divergence

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We report on our design and fabrication of 830 nm high power semiconductor lasers with extremely low beam divergence. 830 nm semiconductor lasers are widely used in digital printing and 3D sensing. Due to the intrinsic small size of the active region in the wafer growth direction, laser beam from a semiconductor quantum well structure is highly asymmetric in the two orthogonal directions. In many applications, particularly in low cost applications, it is highly desirable that a laser has a roughly circular beam profile as this would greatly reduce the cost associated with beam shaping and packaging. Conventional design by manipulating the waveguide thickness or/and the index profile does enable one to achieve low beam divergence to some extent. However this approach not only has detrimental effects on the other parameters such as threshold current, quantum efficiency, but also quite often becomes impractical as the growth tolerance becomes too small. Here we propose a novel approach in which by combining asymmetric waveguide and a feature called “pins” together, we are able to design an optimized epi structure which not only produces a beam divergence of less than 16 °, but also has very good growth tolerance as well. Tested devices show the beam divergence is as small as 13.5°, yet they still retain very high slope efficiency of around 1.26 W/A and low threshold current.

10017-27, Session 2

Directly-modulated laser-based 100G-PON demonstration *(Invited Paper)*

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As the demand for broadband applications continues rising, low cost and high capacity PON system has attracted more attention to keep up with the increasing demand in the future access network. Recently, the IEEE 802.3 Ethernet Working Group has already sponsored the discussion of next generation Ethernet passive optical network (NG-EPON) to provide 25-Gb/s per wavelength. In order to upgrade current 10-Gb/s PON to realize the capacity of 100 Gb/s PON with 25 Gb/s per wavelength, a variety of experimental demonstrations have shown the feasibility of 25-Gb/s per wavelength using the modulation schemes of four-level pulse amplitude modulation (PAM-4) [1-3] or electrical duobinary (EDB) [4] or optical duobinary (ODB) [5] or non-return-to-zero on-off-keying (NRZ-OOK) [6] for high speed transmission. However, different modulation formats have different advantages and disadvantages. For PAM-4 and duobinary modulation schemes, high speed duobinary-to-binary conversion circuit is required for the demodulation of such advanced modulation formats. And for the ODB and NRZ-OOK modulation schemes, high bandwidth transmitter and receiver are required, which can increase the cost. In order to achieve higher performance, these transmission schemes are always combined with the advanced digital signal processing (DSP) which increases the technical complexity and the cost as well. Most of the previous demonstration are based on the off-line processing, therefore requires more time for the practical deployment.

In this paper, we demonstrate the first field trial a real-time 100Gb/s TWDM-PON system with 4?25-Gb/s downstream and 4?10-Gb/s upstream transmission using 10G-class directly-modulated lasers (DMLs) and APD/PIN receivers. A single delay-interferometer (DI) is used to achieve frequency equalization as well as chirp management to increase the high frequency components of the system response and combat the chromatic dispersion (CD) during the fiber transmission. Note that there is no DSP applied for the whole system. Electrical clock/data recovery (CDR) chips are integrated on the main board for data generation, recovery and real-time bit error rate (BER) measurement. We obtained a power budget of 33 dB with 0-40km of standard single mode fiber based on NRZ-OOK modulation format for the downstream. The system stability is also verified using deployed 40-km fiber infrastructure over 67-hour real-time measurement.

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10017-11, Session 3

SBS-assisted microwave photonic signal processing *(Invited Paper)*

Wei Li, Institute of Semiconductors (China)

Stimulated Brillouin scattering (SBS) is widely used in microwave photonic signal processing applications. Many SBS-based microwave signal processing functions have been realized with extremely high performance. Microwave photonic signal processing are generally realized by manipulating the amplitude, phase, and state-of-polarization (SOP) of the optical signal. The microwave signal are recovered by beating between two optical signals in a photodetector (PD). The change of the amplitude, phase, and SOP of the optical signal will transfer to the corresponding microwave signal. SBS effect is possible to impart gain/loss and phase change on optical signal. Moreover, the SBS can also pull or push the SOP of the optical signal because the SBS provide different gain/loss on two orthogonal polarization states. The SBS working bandwidth is related to the bandwidth of the pump wave. Thus, the SBS bandwidth can be varied by tailoring the pump wave. Applying both the SBS gain and loss on the optical carrier, the amplitude of the optical carrier is unchanged but the phase of the optical carrier varies with the pump power and wavelength of the optical carrier. By beating between the optical carrier and sideband, a broadband microwave photonic phase shifter is realized. The SBS-based slow light is limited by the SBS interaction bandwidth. To overcome this limitation, we used a separate carrier tuning method to realize true time delay of microwave signal with high carrier frequency. Actually, the carrier frequency of the microwave signal is independent on the SBS effect. Moreover, we have also applied SBS to the microwave frequency measurement system. The SBS enables the tuning of the measurement range and resolution, which is realized by introducing a tunable phase to the optical carrier in a narrow bandwidth. In addition, the SBS can also find application in optical vector network analyzer (OVNA). The accuracy of the OVNA is improved using polarization modulation and SBS-assisted polarization pulling effect. Recently, on-chip SBS has been intensively studied. The on-chip SBS is promising since it is possible integrated with other optical components.

10017-12, Session 3

Sensing, measurement, and detection enabled by optoelectronic oscillators *(Invited Paper)*

Xihua Zou, Southwest Jiaotong Univ. (China)

Recently, optoelectronic oscillators (OEOs) have also been rapidly developed as emerging techniques towards sensing, measurement, and detection. A comprehensive overview to latest advances in OEO-based sensing, measurement, and detection applications is presented, including length change and distance measurement, refractive index estimation, load and strain sensing, temperature and acoustic sensing, optical clock recovery, and low-power RF signal detection. As a new application example, a novel approach for in-line position finding is proposed. When a long fiber Bragg grating inserted into OEOs is locally heated to slightly broaden its reflection spectrum, the target position heated is mapped into the oscillating frequency shift with a sensitivity of 254.66 kHz/cm in the experiment.

10017-13, Session 3

A novel approach for high-speed super-resolution imaging *(Invited Paper)*

Hongwei Chen, Yuxi Wang, Qiang Guo, Minghua Chen, Tsinghua Univ. (China)

Ever since Ernst Abbe proposed the theory of optical diffraction limitation in 1873, efforts have never stopped to make to challenge this iron law. Until recent, several methods find their way to go well beyond this lateral resolution limit. Most of them are mainly based on localization or point-scanning strategy, which always means that they require very large number of raw image data to reconstruct one resultant image and therefore limits the imaging speed. However, among all these methods, a technique known as structured illumination microscopy (SIM) is reported to achieve a frame rate of some tens Hz, besides it has the advantage of being label-free. Though the imaging speed of SIM can still hardly meet some extreme application such as super-resolution video for live cells, there shows a great potential to further improve the imaging speed of SIM.

Here we propose a new imaging strategy combing SIM with a recently developed high-speed imaging technique known as optical pulse laser time-stretch imaging which has been proven an effective tool for high-throughput screening for living cells, for short TS-SIM. This new method can help to improve the pattern generation rate, one of the key barrier towards higher-speed SIM, to tens of MHz, four orders of magnitudes faster than contemporary methods. A principle-proven experiment is conducted, and at the high pattern generation speed of 50MHz, super resolution imaging result is acquired which surpassed the diffraction limit by a factor of 1.4.

10017-14, Session 3

All-optical modulation conversion characteristics of an optically-injected semiconductor laser with external modulation of the master laser *(Invited Paper)*

Yali Zhang, Jiacheng Li, Zhiyao Zhang, Shangjian Zhang, Yong Liu, Univ. of Electronic Science and Technology of China (China)

The nonlinear dynamics of optically injected semiconductor lasers have been intensively investigated. Notably, among these various nonlinear dynamics, period-one (P1) oscillation state is a special one due to not only its large distribution area in the space of injection parameters, but also its nearly single sideband (SSB) of optical spectral. Therefore, it has drawn increasing interest. Generations of millimeter waves and all-optical modulation conversion have been reported. Potentially, this will contribute to the energy-efficient radio-over-fiber (RoF)

systems. Alternatively, it can be used to produce pure frequency modulation (FM) through intensity modulation (IM) suppression and conversion, which is expected to offer many benefits such as simple configuration, and wide frequency tunability with high modulation frequencies.

In this paper, we focus on study of all-optical modulation conversion characteristics, from intensity modulation (IM) to frequency modulation (FM), of an optically injected semiconductor laser with external modulation of the master laser (ML). We present a numerical simulation on the field amplitude time series with and without modulation data, and thus optical and power spectra of the P1 oscillation state. The optical spectra with data clearly show that the IM optical signal is converted into FM one. The frequency tunability of the generated microwave signal is shown to depend on frequency detuning between the master and slave lasers. Based on the above quantitative information, we numerically and experimentally carry on a systematic study on the efficiency of IM-to-FM conversion. The numerical simulation results prove the nature of the optically injected semiconductor laser as an IM limiter. We found that IM can be effectively suppressed and actually converted to FM by controlling injection conditions and modulation index. Then different output modulation indices can be obtained. Further, the FM is detected and demodulated through a FM discriminator. The efficiency of IM-to-FM conversion is hence experimentally characterized by comparing the eye diagrams before and after conversion. Correspondingly, the experimental results show the fact of the optically injected semiconductor laser as a perfect IM limiter.

10017-15, Session 4

Photonic microwave signal generation using an optically-injected semiconductor laser *(Invited Paper)*

Shilong Pan, Pei Zhou, Fangzheng Zhang, Nanjing Univ of Aeronautics and Astronautics (China)

When a semiconductor laser is subject to an incoming optical carrier, it can exhibit rich dynamical states including stable injection locking, periodic oscillations and chaos. Importantly, period-one (P1) dynamics of an optically injected semiconductor laser can be excited by undamping the relaxation resonance of the semiconductor lasers through Hopf bifurcation. Since the mid 2000's, the P1 dynamic state of the optically injected laser has received increased attention for diverse applications. For instance, by simply varying the injection strength, the detuning frequency, or both, a continuously tunable microwave signal over a frequency range up to 100 GHz can be generated. In this report, we first introduce a dual-loop optoelectronic feedback structure to improve the spectral purity of the generated microwave signal in the optical injection laser system, and optical pulse compression technique is also incorporated to generate frequency tunable short optical pulses. Since the dynamical behavior of a semiconductor has a sub-nanosecond time scale and the P1 frequency varies with the injection strength, it provides a convenient way to dynamically control the instantaneous frequency of the generated microwave signal, by simply manipulating the injection strength. Such a method can be used to generate various waveform for different applications. Experimental demonstrations of photonic generation of linearly chirped microwave waveform and frequency hopping microwave waveform are introduced. Compared with other photonic schemes, the proposed method features low cost, simple structure, large time-bandwidth product (TBWP) and high tunability, which may find applications in radar systems, electronic warfare and other applications.

10017-16, Session 4

Self-calibrated spectrum analysis for extracting frequency response of high-speed phase modulators *(Invited Paper)*

Shangjian Zhang, Yali Zhang, Heng Wang, Xinhai Zou, Yong Liu, Univ. of Electronic Science and Technology of China (China)

High-speed electrooptic phase modulators are essential elements in the high-speed optical communication system and microwave photonic system, due to their advantages of bias voltage free and linear modulation. As an intrinsic parameter, the half-wave voltage of an optical phase modulator, was often characterized by using the electrical spectrum methods and the optical spectrum methods in last two decades. The optical spectrum methods are generally limited by the linewidth of the laser source and the resolution of the available optical spectrum analyzer (OSA), while the electrical spectrum methods require the conversion from phase modulation to intensity modulation before photodetection. The major difficulty of the electrical spectrum methods lies in the extra calibration for the responsivity fluctuation in the photodetection.

In this talk, we will demonstrate self-calibrated spectrum analysis for characterizing high-speed phase modulators based on the frequency-shifted heterodyne, which avoids the effect of the responsivity fluctuation in the photodetection. Compared to the optical spectrum method, the proposed method achieves very high frequency resolution, and avoids the line-width influence of laser source. Different from the traditional electrical method, our method works without any small-signal assumption and photodetection calibration, and eliminates the limit of electrical driving amplitude and operating wavelength. Moreover, it alleviates at least half bandwidth requirement for the photodetector and spectrum analyzer. The proposed measurement method provides very simple method for the microwave characterization of high-speed electrooptic phase modulators, which is also a reference for other high-speed optoelectronic devices.

10017-17, Session 4

Stable RF signal distribution based on passive post phase correction with only one-stage frequency mixing

Zhiyao Jia, Ling Wang, Weiyu Wang, Chengwu Yang, Wei Li, Ninghua Zhu, Institute of Semiconductors (China)

In this letter?we propose and demonstrate a phase stabilization approach to distribute a radio frequency?RF?signal from remote antenna to local station with passive post phase correction. Simplified remote antenna structure makes it more cost-effective for system maintenance. Without local oscillator (LO) source involved, the system is easier to implement since there is no need for frequency locking between the LO signal and the received RF signal. The key advantage of our method is that only one-stage frequency mixing is used, which releases the system complexity and reduces the conversion loss. Theoretical analysis shows that the phase of the obtained signal at the local station is proportional to the received RF signal, which means the phase delay and its fluctuations induced during the fiber transmission is corrected. A proof-of-concept experiment is performed by transferring a RF signal through a single-mode fiber. A tunable optical delay line (TODL) inserted between the remote antenna and local station is used to simulate the fiber-length vibrations. The results verifies that the phase drift of the RF signal is effectively compressed using the proposed scheme.

10017-18, Session 4

Broadband x-band optically-steered PAA with large beam-steered angle

LiHong Zhang, NuanNuan Shi, Ye Deng, Shuqian Sun, Jian Tang, Ming Li, Ninghua Zhu, Institute of Semiconductors (China)

A broadband optically-steered phased array radar (PAA) is proposed and demonstrated at X-band with a large beam swept angle. In the proposed photonics-based PAA, eight groups of the true-time delay (TTD) line is designed to implement the time delay technique of the PAA based on the optical fiber with high dispersion coefficient.. By using the TTD networkthe, it can resolve these problems with traditional all-electronic methods for array control,such as bandwidth, loss, susceptibility to electro-magnetic interference,beam-squintand. Although, the dispersion value of the photonic crystal fiber (PCF) is -600 ps/nm/km,the connect between the PCF and the SMF is adopted fiber adapter. It increases the difficulty in the magnitude equalization and makes the architecture instability.The dispersion coefficient of the dispersion compensation fiber (DCF), as high as -140ps/nm/km,is a better choice than PCF to remove the above problem. In this paper, the DCF-based beam forming is proposed and demonstrated based on the wavelength-swept technique. The power deviation of ±0.5 dB and the delay error of 0.13 ps/nm are realized by the precise calibration both the magnitude and the phase. By tuning the optical wavelength over C band, the beam steered angle scans from -54° to 54° with the error of 7° with the frequency from 8 GHz to 12 GHz. The beam-forming patterns are measured and the beam deviations are within 3° in the wavelength of 1545 nm and 1538.5 nm. It is proved that the photonics-based technique can greatly resolve the beam squint problem and improve the swept angle.

10017-32, Session Post

Double optical feedback self-mixing interferometry for measurement of Young's modulus

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Young's modulus is of paramount importance for evaluating material performance in industrial design and material engineering. This paper presents a novel approach for determining Young's modulus by using double optical feedback self-mixing interferometry (DOFSMI). The DOFSMI system mainly consists of a laser diode (LD), a lens, a 1x2 graded-index multimode fiber optic coupler (GIMFOC), and a specimen. After being focused by the lens, the light emitted by the LD is split into two beams by the 1x2 GIMFOC. The two beams simultaneously hit on the specimen and then are reflected by the specimen which is manually excited by an impulsive excitation. The two reflected beams re-enter into the laser cavity, thus leading to the modulation in both amplitude and frequency of the LD output power. The modulated power can be detected by a photodiode (PD) as a DOFSMI signal which resonant frequency can be used for determining Young's modulus. In this paper, starting from the well-known Lang and Kobayashi (LK) equations, we firstly derive the theoretical model for describing the DOFSMI, based on which an effective algorithm is developed for retrieving the resonant frequency of the DOFSMI signal, thus for determining Young's modulus. The results presented in this paper show that Young's modulus retrieved from the DOFSMI signal is more accurate than from the conventional single OFSMI.

10017-36, Session Post

Numerical analysis of thermal effects in semiconductor disk laser with TEC cooler

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Thermoelectric cooler (TEC) has wide applications in the semiconductor disk laser thermal management, and analysis of the temperature field help to improve package performance. By separating the responding area of Peltier effect and Joule effect in TEC, the new TEC transfer model has been established without depending on both hot and cold side temperature to adapt to non-uniform heat flux distribution in TEC. With finite element method, this article has calculated the temperature distribution characteristics, and studied the effects of TEC current, heat exchange coefficient, the heat sink and the pump laser for the maximum temperature of quantum wells. Calculations show that the heat transfer coefficient significantly affects the ability of the TEC temperature shift, and cooling system performance which is nearly inversely proportional to the heat sink thermal conductivity is not sensitive to its the thickness variation, and the performance of oxygen-free copper with optimization of the area is close to diamond heatsink. Meanwhile the maximum temperature of the quantum well has a linear relationship with the pump power, and increasing the pump spot size is an effective way to increase the laser power.

10017-37, Session Post

Short-term frequency stability measurement for narrow linewidth laser by time domain self-heterodyne method

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For the laser short-term frequency stability measurement, it is important to find a relatively ideal single frequency source with long duration time. For this purpose, the time domain self-heterodyne method is proposed and experimentally demonstrated. In the method optical pulse with pulse width of 100?s is launched into a fiber with length of 125km, and then the Rayleigh backscattering signal of the propagating pulse is used as the ideal local frequency to heterodyne with the laser frequency generated in a short term of about 1.25ms. Then the time domain data of the heterodyne intermediate frequency (IF) are extracted by an oscilloscopeand through short time Fourier transform the frequency from the laser in different time is obtained.The narrow linewidth laser is adopted as the single frequency source for it possesses excellent monochromaticity, and the backscattering Rayleigh frequency of the light pulse propagating in the fiber delay line helps increase the duration of the frequency source. So by time domain self-heterodyne and (short time Fourier Transform) STFT, the variation of laser frequency in that duration time can be measured. Experimental results show the laser linewidth has relationship with the short-term stability of the laser, and in short-term the laser frequency is randomly fluctuating with a range less than triple of the laser linewidth.The measurement and evaluation of laser short-term frequency stability benefits the application of narrow linewidth lasers in distributed optical fiber sensing area.

10017-38, Session Post

Spectrum analysis of rectangular pulse in the atmospheric turbulence propagation

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Atmospheric turbulence has a great influence on the performance of the atmospheric laser communication system reducing the signal to noise ratio (SNR) and increasing the bit error rate (BER). However, there is rarely study on the effect of atmospheric turbulence on the power spectrum of the rectangular pulse. In this paper, a spectral analyzing method is used to analyze the influence of atmospheric turbulence on the signal. An experiment of laser beam propagation characteristic is carried out on a 6km horizontal atmospheric link, the wavelength is 808 nm. The signal is 100MHz rectangular pulse. The waveform of the rectangular pulse is collected by the oscilloscope, and the power spectral density of the signal is calculated and analyzed by the method of periodogram. Experimental results show that the response and noise characteristics of the laser and photoelectric detector have a great influence on the signal power spectrum distribution which can increase the noise component in the 10^6 Hz frequency range. After the atmospheric turbulence propagation, the signal power decreases in the whole frequency range. However, as the existence of atmospheric turbulence, the signal power increases in the atmospheric turbulence characteristic frequency (tens to hundreds of Hz). The noise power increases in the high frequency range (10^7~10^8 Hz).

10017-39, Session Post

Molecular dynamics study on the thermal conductivity of multiple layers in semiconductor disk laser

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Thermal properties of multiple layers including distributed Bragg reflector (DBR) and multiple quantum wells (MQWs) used in semiconductor gain element are crucial for the performance of vertical-external-cavity surface-emitting lasers (VECSELs). For the purpose of more reasonable semiconductor wafer designing, so to improve the thermal management of laser, accurate thermal conductivities of DBR and MQWs are under considerable requirement. Whereas the diameter of pump spot is much larger than the total thickness of DBR and MQWs, and heat flow in a vertical-external-cavity surface-emitting laser is mainly axial and quasi-one-dimension, therefore cross-plane thermal conductivities of DBR and MQWs are focused. By the use of non-equilibrium molecular dynamics (NMD) method, cross-plane thermal conductivities of DBR and MQWs were calculated, and simulated results were compared with reported data. The cross-plane thermal conductivity of AlAs/AlGaAs DBR, as an example, was computed, influences of the Al composition, the interfacial roughness, and the total number of interfaces on the cross-plane thermal conductivity were analyzed, and an optimized DBR configuration was proposed. For the strained InGaAs/GaAs MQWs, which not only provides gain to the laser wavelength, but also works as the heat source in the active region, the cross-plane thermal conductivity was modeled, the effects of the stress, the strain compensate layer, and the depth of barrier on the cross-plane thermal conductivity were discussed. Using the calculated thermal conductivities, temperature rise of a vertical-external-cavity surface-emitting laser was simulated, and the theoretical results were in good agreement with experiment.

10017-40, Session Post

Analysis of laser energy characteristics of laser-guided weapons based on the hardware-in-the-loop simulation system

Yawen Zhu, Xiaohong Cui, Qianqian Wang, Qiujie Tong, Xutai Cui, Chenyu Li, Le Zhang, Zhong Peng, Beijing Institute of Technology (China)

The hardware-in-the-loop simulation system, which provided a precise, controllable and repeatable test conditions, was an important part of the development of the semi-active laser (SAL) guided systems. In this paper?laser energy chain characteristics were studied, which provided a theoretical foundation for the SAL guidance technology and the hardware-in-the-loop simulation system. Firstly, according to the principles of the hardware-in-the-loop simulation system, a parameter Z was proposed to simplify the radar equation. Secondly, the theoretical model and calculation method were given about the energy chain characteristics based on the hardware-in-the-loop simulation system. Then, the major factors included weather factors, the reflection characteristics of targets and the distance between the missile and target were studied. Finally, theoretical results agree well with the values measured experimentally?the accuracy of modeling was verified by experiments. And experimental results showed that laser energy exhibited a non-linear change vs time-varying, which were in accord with the actual condition.

10017-41, Session Post

Design and implementation of the hardware-in-the-loop simulation system based on LabWindows/CVI and RTX

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In order to satisfy the requirements of the real-time and generality, a semi-physical simulation system based on RTX+LabWindows/CVI platform is proposed in this paper. This system runs on the Windows platform, using Windows RTX real-time extension subsystem to ensure real-time performance of the system combining with the reflective memory network to complete some real-time tasks such as calculating the simulation model, transmitting the simulation data, and keeping real-time communication. The real-time tasks of simulation system are run under the RTSS process. At the same time, we use the LabWindows/CVI to compile a graphical interface, and complete some non-real-time tasks in the process of simulation such as man-machine interaction, display and storage of the simulation data which are run under the Win32 process. Through the design of RTX Shared memory and task scheduling algorithm to complete the data interaction between the real-time tasks process of RTSS and non-real-time tasks process of Win32. The experimental results show that this system has the strongly real-time performance, highly stability, and highly simulation accuracy. At the same time, it also has the good performance of human-computer interaction.

10017-42, Session Post

All-optical sampling based on quantum-dot semiconductor optical amplifier

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With the rapidly growing communication needs, the all-optical signal processing system has become a hot research field of optical communication. This paper focused on the basic research and practical application of quantum-dot (QD) semiconductor optical amplifier (SOA) in all-optical sampling, and provided critical technical support for all-optical signal processing of ultrafast optical communication system.

Compared with bulk SOA, QD-SOA has various advantages such as faster gain recovery time, low linewidth enhancement factor, high saturated output power and low temperature sensitivity, so that it is more suitable for high-speed all-optical signal processing. This paper established a multi-level dynamic physical model of QD-SOA and studied its ultrafast dynamic characteristics through theoretical and simulation research.

For further study, an all-optical sampling scheme based on the nonlinear effect of QD-SOA is also proposed. Combining the simulation model of QD-SOA, we analyzed the characteristics of optical switch window and investigated the influences of different control light pulse peak powers, pulse widths and other factors on switch performance. The results show that, in order to get a better sampling effect, a control light pulse of appropriate peak power and narrow pulse width is needed. Through simulation, this paper achieved sampling of analog signal to high frequency pulse, in which a narrow Gaussian pulse sequence is as a probe light, and a sinusoidal optical signal of different wavelength from probe light is as a pump light, incident analog signal light modulates the carrier density and gain of QD-SOA to rotate the polarization state of sampling pulse light. The presented optical sampling method has an important role in promoting the improvement of all-optical signal processing technology.

10017-43, Session Post

All-optical D and T flip-flops based on polarization switch of SOA

Lina Wang, Yongjun Wang, Chen Wu, Beijing Univ. of Posts and Telecommunications (China)

The semiconductor optical amplifier (SOA) plays an important role in the development of the all-optical signal processing because of the advantages of simple structure, easy integration and strong non-linearity. Especially the nonlinear polarization rotation effect of SOA is receiving considerable interest by many researchers nowadays. The all-optical flip-flop using the properties of SOA also obtains widespread attention by researchers, as all-optical flip-flop is an important part in the field of all-optical signal processing. In this paper, a new all-optical flip-flop structure using polarization switch (PSW) based on polarization rotation effect of SOA is presented.

The main work of the paper is the simulation of all-optical logic gates and optical SR latch. The logic gate setup only uses one SOA, but it can get two different logic gates through a simulation. The extinction ratio of the logic gate is about 30dB. The structure of optical SR latch utilizes the two coupled polarization rotation switch of SOA. The structure of the flip-flop is based on these two parts. To demonstrate the feasibility of the structure, we analyze two types of flip-flops, including all-optical D and T flip-flops, whose clock pulse repetition rate is 1GHz with the pulse width of 0.3ns. The quality of all-optical flip-flop in this paper is measured by the falling and rising edge time. In the simulation, the falling edge time is about 50ps, while the rising edge time is higher than the falling edge time, because the gain increases slowly to the recovery time after the decrease of the gain of SOA. The results are useful for the development of all-optical flip-flop based on SOA.

10017-44, Session Post

A smokescreen model of laser attenuation based on MATLAB

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The model of laser through a smokescreen is built by Monte Carlo modeling. In a traditional Monte Carlo modeling, the initial direction cosine of photons is fixed and the radius of particles is set the same. But the laser will diverge while traveling in the air, so changes to the traditional Monte Carlo modeling method in photons initial motion is presented in this paper. The new model is compiled with MATLAB. It realized laser transmission in mixed particles smokescreen for the first time, which can simulate different size of particles uniformly mixed in the smokescreen. It can be applied to smoke in the simulator of attenuation characteristic simulation, and make the results close to the real battlefield environment. Results show that the model after changing the photons initial state of motion agree with the original model, but the overall decrease about 10%, and mixed smoke simulation results agree with the measured transmittance under the same experimental conditions with the error within 5%.

10017-45, Session Post

Dual-wavelength external-cavity laser device for fluorescence suppression in Raman spectroscopy

Zhang Xuting, Zhijian Cai, Jianhong Wu, Soochow Univ. (China)

Portable Raman spectrometers have been widely used in the detection of drugs, pesticides, explosives, food additives and environmental pollutants. However, fluorescence disturbance is a common trouble for these applications. Shifted excitation Raman difference spectroscopy (SERDS) method can effectively suppress the fluorescence background and can be easily applied onto portable Raman spectrometers. The key of SERDS method is to obtain a dual-wavelength laser source with narrow line-width and small wavelength gap. In this paper, we designed such a dual wavelength laser device based on the principles of external cavity diode laser (ECDL). The device consists of two laser diodes and a home-made blazed grating with two regions of different periods. The beams of the laser diode modules were projected onto the two grating regions and diffracted back into the diodes, introducing strong external-cavity feedback and suppressing invalid longitude modes. Since the grating regions have different periods, the device can emit two wavelengths. The wavelength gap can be controlled by changing the fabrication parameters of the home-made grating. By switching on/off the drive circuits of the laser diodes, we can conveniently enable or disable each of the two wavelengths in the output laser beam. The dual wavelength device proposed in this paper is low-cost and compact. It also has good mechanical stability because of no moving parts. These features make it an ideal laser source for SERDS technique. The experiment results showed that the dual-wavelength device could emit two wavelengths with the gap smaller than 2 nanometers, and the laser power for each wavelength could exceed 100mW.

10017-46, Session Post

A 60GHz RoF(radio-over-fiber) transmission system based on PM modulator?

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As one of the most important applications of microwave photonic?ROF (Radio over Fiber)system?which combines the advantages of optical communication and wireless communication?is a good candidate for broadband mobile Communication?In this paper, we built and simulation a 60GHz RoF(Radio-over-Fiber) transmission system based on PM modulator. First, we introduce the PM-IM(Phase modulation to intensity modulation) modulation mechanisms by the breaking the phase balanced approach. Using standard single-mode fiber input to the F-P(Fabry-Perot) optical filter to achieve the PM-IM modulation conversion by changing the wavelength of the laser or the frequency of the modulation factor of the F-P optical filter to adapt to different fiber lengths and the signal transmission rate. These two methods which changing the phase relationship between the optical carrier and the optical side band can realizing the ideal phase transition to obtain efficient and low loss modulation conversion. Finally, the simulation results show that different fiber lengths and the signal transmission rate configuration of different wavelength of the laser or the frequency of the modulation factor of the F-P optical filter?the BER performance and the eye diagram of the 60GHz RoF transmission system signals has been improved based on these PM-IM modulation methods.

10017-47, Session Post

4W high-performance 1470-nm InGaAsAs lasers

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We report on our design and fabrication of 1470 nm high power semiconductor lasers based on an InGaAlAs strained quantum well structure. Quantum well parameters were carefully optimized to achieve optimum performance. In addition, a novel far field reduction structure was incorporated into our epi structure to obtain low beam divergence and in the mean time to be without negatively impacting the threshold current. Device characterization was made by measuring the light-current-voltage (L-I-V) characteristics under continuous wave conditions. From the measurement, it is found our 2 mm-cavity devices with aperture size of 96 μm reach maximum power of around 4.2 W, and the slope efficiency is about 0.42 W/A. The devices display excellent thermal performance, with the characteristic temperature parameters T0 and T1 being 70 K and 600 K,respectively. Apart from the excellent external quantum efficiency and thermal performance, devices also show reduced beam divergence and low threshold current compared to the conventional designs. The threshold current density is only about 240 A/cm2 for the 2 mm long cavity and is reduced to 170 A/cm2 for the 5 mm long cavity. The beam divergence (FWHM) in the wafer growth direction is only 30 ° which is significantly smaller than the typical value of around 40 ° of the 1470nm lasers available commercially. Life-time test has also been performed to determine the reliability performance. Thus far more than 9000 life-test-hour has been accumulated, and there is no detectable sign of the power degradation, indicating our devices are extremely reliable.

10017-19, Session 5

Mode control and direct modulation for waveguide-coupled square microcavity lasers *(Invited Paper)*

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Lasing mode control and direct modulation characteristics have been investigated for waveguide-coupled unidirectional-emission square resonator microlasers. A quasi-analytical model is introduced to analyze the mode field distributions and quality (Q) factors for the confined modes inside the square optical microresonators with directly coupled waveguide, where high-Q whispering-gallery-like (WG-like) modes are induced by the mode coupling between doubly-degenerate modes. AlGaInAs/InP waveguide-coupled unidirectional-emission square resonator microlasers are fabricated by using standard planar technology, and electrically-injected lasing is realized at room temperature. The lasing modes are controlled by properly designing the lasing resonator, output waveguide and injection pattern. Dual-transverse-mode lasing with a tunable wavelength interval from 0.25 to 0.39 nm is realized by using a spatially selective current injection to modulate the refractive index, as the mode field distributions of different transverse are spatially separated. A corresponding tunable microwave signal from 30 GHz to 48 GHz is obtained with a high-speed photodetector. The wavelength interval can be further increased to a few nanometers by reducing the resonator size and replacing the flat sidewalls with circular arcs. The free spectra range in square microresonator can also be enhanced, and a mode-hopping-free single mode operation with a continuous tuning range of 9.2 nm is realized. The field distributions of WG-like modes distribute uniformly in square microresonator, which avoid the burning-induced carrier diffusion in high-speed direct modulation. A small-signal modulation 3dB bandwidth exceeding 18 GHz, and an open eye diagram at 25 Gb/s are demonstrated for the high-speed direct modulated square microlaser.

10017-20, Session 5

Fabrication and performance of In0.66Ga0.34As0.73P0.27/ In0.89Ga0.11As0.23P0.77 multiple-quantum-well lasers

Jia Chen, Qi Wang, Hao Liu, Zhiming Li, Xiankun Wang, Bingfei Liu, Beijing Univ. of Posts and Telecommunications (China)

We fabricated an InP-based In0.66Ga0.34As0.73P0.27/ In0.89Ga0.11As0.23P0.77 multiple-quantum-well (MQW) laser at 1.3 ?m wavelength. The device active region consists of six 5 nm thick In0.66Ga0.34As0.73P0.27 QWs separated by 10 nm thick In0.89Ga0.11As0.23P0.77 barrier layers. The un-doped active region is sandwiched between 90 nm thick lattice-matched In0.89Ga0.11As0.23P0.77 separate confinement heterostructure layer. The waveguide core is later covered with 1.5 ?m and 1.5?1.6 ?m thick n- and p-type InP cladding layers with Si and Zn dopant, with doping concentration varying from 5 ? 1018 cm-3 and 5 ? 1017 and 1 ? 1018 cm-3, respectively. The cladding

layers are lattice-matched to the n-doped InP substrate and the metal-oxide chemical vapor deposition (MOCVD) grown device structure is completed by a 230 nm thick highly doped (1.5 ? 1019 cm-3) In0.53Ga0.47 as contact layer. The MQW lasers are fabricated utilizing the standard fabrication process. The 100 ?m ridge-width lasers are later cleaved to 500 ?m length. Under quasi-continuous wave condition, a threshold current of 400 mA and the single side slope efficiency of 0.18 mW/mA are achieved for a broad area device with 100 ?m-wide strip and 500 ?m-long cavity at room-temperature.

10017-21, Session 5

High-performance 808-nm GaAsP/InGaP quantum-well lasers

Hai M. Hu, Bocang Qiu, Weimin Wang, Research Institute of Tsinghua Univ. in Shenzhen (China); Chunyu Miao, Raybow Optoelectronics Ltd. Inc (China); James Ho, Research Institute of Tsinghua University Shenzhen (China); Wenbin Liu, Chengpeng Li, Raybow Optoelectronics Ltd. Inc (China)

High power semiconductor lasers emitting at the wavelength of 808 nm have a number of important applications, including solid pumping and material processing. In this paper, we report on our design and fabrication of very high power semiconductor lasers based on an aluminium (Al) free core active structure. Al-free core has an advantage of higher catastrophic optical mirror damage (COMD) threshold, and thus offers improved device reliability compared to the AlGaAs-based devices. Asymmetric waveguide structure was employed in our design, which allows one to achieve high energy conversion efficiency (ECE). In addition, a far field reduction structure was also incorporated into our epi structure to obtain low beam divergence without impacting the other parameters. From extensive modeling, 2 mm long cavity with different aperture sizes was chosen for single emitter design, and 2 mm long cavity with fill factor of 50% was used for bar design. 45 W of optical power?limited by thermal roll-over, is obtained when the single emitter devices were tested under QCW conditions, and more than 10 W is acquired at the operation current of 10 A under the CW conditions. Under QCW operation conditions, Bar power of up to 200 W is attainable for the operation current of 200 A. In addition to the extremely high emission power, the lasers have excellent slope efficiency of about 1.3 W/A and beam property which is about 25 degree measured at the full width at the half maximum (FWHM).

10017-22, Session 6

Two-section REC-based DFB laser/laser array for RoF applications *(Invited Paper)*

Xiangfei Chen, Nanjing Univ. (China)

Distributed feedback (DFB) semiconductor lasers and multi-wavelength DFB laser arrays (DFB-MLAs) are key components in wavelength division multiplexing networks, photonic integrated circuits (PICs) and analogue communication systems to serve as optical source with excellent wave-length stability, high spectral purity and high linearity. However, the conventional DFB lasers and DFB-MLAs suffer from low single-longitudinal-mode (SLM) yield, poor wave-length accuracy (especially for DFB-MLAs) and high fabri-cation cost. In order to improve the wavelength precision and SLM yield, ?/4 phase-shifted grating combined with an-tireflection/antireflection (AR/AR) coatings are employed. Nevertheless, DFB lasers with ?/4 phase-shifted grating and AR/AR coatings also suffer from several drawbacks, including hight fabrication cost, low output efficiency and low operation bandwidth.

In this paper, we present a cost-efficient fabrication of two-section DFB (TS-DFB) lasers and four-channel TS-DFB laser arrays (TS-DFB-LAs) based on the reconstruction-equivalent-chirp (REC) technique. In the TS-DFB lasers, one section acts as a conventional DFB laser, and the other section works as a grating reflector. Compared with one-section DFB (OS-DFB) lasers fabricated by the REC technique, most of the characteristics of the TS-DFB lasers are improved, such as the slope efficiency, side-mode suppression ratio (SMSR), small-signal frequency response, relative intensity noise, and spurious-free dynamic range. A radio-over-fiber link utilizing the TS-DFB laser as directly modulated light source is experimentally achieved. About 50 MSym-bol/s 64-QAM signal with 10 GHz carrier is transmitted from the TS-DFB laser. After 40 km transmission in single-mode fiber, the signal quality is kept well with the average EVM of 2.97%.

10017-23, Session 6

Selective epitaxy of InP nanocrystals on Si nano-tips for hybrid graphene/InP/Si photodetectors *(Invited Paper)*

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The monolithic integration of III-V semiconductors having superior (opto-)electronic properties onto the mainstream Si technology platform presents a long-standing vision for scientists and engineers owing to a variety of device applications, which is, however, hindered by the fundamental materials issues such as lattice and thermal expansion mismatch and the formation of antiphase domains. InP could open new avenues for the realization of novel devices such as high mobility transistors in next generation CMOS (as a substrate) or efficient lasers for light distribution in silicon photonics circuitry. We presented here a CMOS compatible Si nanotip method to epitaxially grow high quality InP nanocrystals (NCs) with no threading defects, obtaining thus substrate-like optoelectronic properties on highly heterogeneous Si substrates. Fully relaxed, site and size controllable InP NCs were selectively grown on Si-tip wafers due to an In-desorption dominated growth mechanism. Defects like micro-twins and stacking faults existing in InP NCs do not severely degrade the optical properties. A prototype hybrid photodetector based on graphene/InP/Si device was realized and shows promising photodetection. The results demonstrated in this work will open up exciting opportunities for the heteroepitaxy of highly-mismatched III-V materials and thus the integration of various high performance (opto-)electronic hybrid devices on Si.

10017-24, Session 6

Infrared pulsed fiber lasers employing 2D nanomaterials as saturable absorbers *(Invited Paper)*

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We report infrared pulsed fiber lasers using MoS2 and topological insulator (TI) as saturable absorbers. An erbium-doped fiber laser mode-locked is presented by a MoS2-based saturable absorber. The chemical vapor deposition method is employed to grow high-quality multilayer MoS2. Stable mode-locked soliton pulses are achieved with central wavelength, spectral width, pulse duration, and repetition rate of 1568.9 nm, 2.6 nm, 1.28 ps, and 8.288 MHz, respectively. We also report a high energy passively Q-switched Ho3+-doped ZBLAN fiber laser at 2979.9 nm using TI: Bi2Te3 as the saturable absorber. Stable Q-switched pulses at 2979.9 nm were obtained with the repetition rate of 81.96 kHz and pulse duration of 1.37 μs. The achieved maximum output power and pulse energy were 327.4 mW at a slope efficiency of 11.6 % and 3.99 μJ, respectively only limited by the available pump power. Experimental results show that 2D nanomaterials are promising to act as saturable absorbers for realizing passive pulsed lasers at infrared waveband.

10017-25, Session 6

A review on the development of DML-based underwater wireless optical communication systems *(Invited Paper)*

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Among many vital technologies for ocean exploration, the underwater communication technology is a key enabler. Recently, underwater wireless optical communication (UWOC) has gained a renewed interest from both academic and industrial communities. UWOC features sufficient bandwidth, high security and low time latency, and consequently offers many intriguing opportunities for a variety of applications such as communication with seafloor sensors during a “fly-by” mission of an underwater vehicle, real-time video transmission, underwater sensor networks, etc. In this contribution, we will review the recent development of DML-based UWOC systems, especially the results obtained by Ocean College of Zhejiang University. We have achieved a 6-m, 1.324-Gb/s underwater transmission at a BER of 2.02?10-3, by using 128-QAM OFDM signals and a low-cost PIN photodetector, with a record spectral efficiency higher than 7.32 bits/Hz. By using an APD and 32-QAM OFDM signals, we have achieved a record bit rate of 4.883 Gb/s at a BER of 3.20?10-3 over a 6-m underwater channel.

10017-26, Session 6

Nanophotonic metasurfaces-assisted structured light manipulation for lasing applications *(Invited Paper)*

Jian Wang, Huazhong Univ. of Science and Technology (China)

Metamaterials are materials engineered to have tailored properties that have not yet been found in nature. Photonic metamaterials interact with optical frequencies. The two-dimensional equivalents of metamaterials, also referred to as metafilms or metasurfaces, is a new type of optical interfaces with patterned nanostructures, which can provide great flexibility in structured light manipulation. Plasmonic and dielectric metasurfaces can facilitate flexible manipulation of structured light. In this paper, we review our recent research progress in structured light manipulation using plasmonic and dielectric metasurfaces and its potential applications in lasing: 1) metasurfaces-based broadband generation of orbital angular momentum (OAM) carrying vector beams; 2) on-chip N-fold OAM multicasting using V-shaped antenna array metasurfaces; 3) chip-scale OAM beams generation and detection using nanophotonic dielectric metasurface array; 4) design and fabrication of metasurfaces on conventional optical fiber facet for linearly polarized mode (LP11) generation at visible light wavelength; 5) proposal and simulation of metasurfaces-assisted OAM-carrying Bessel laser; 6) experimental demonstration of a wavelength tunable directly excited OAM laser operating in the C-band.

10017-6, Session 7

High-performance mode-locked and Q-switched lasers based on 2D transition metal dichalcogenides *(Invited Paper)*

Kan Wu, Weiwen Zou, Jianping Chen, Shanghai Jiao Tong Univ. (China)

The discovery of graphene since 2004 has triggered great interest in two-dimension (2D) materials for their abundant photonic and electronic properties. Among various demonstrations with different 2D materials, transition metal dichalcogenides (TMDs) have caught researches’ attention because their optical nonlinearity are estimated to be even larger than graphene. Meanwhile, pulsed lasers including mode-locked and Q-switched lasers are important photonic platform for both scientific research and industrial application. Using the TMD materials as saturable absorbers which provide pulse shaping mechanism in a pulsed laser, one can obtain high-precision low-timing-jitter mode-locked pulse output as well as high-energy tunable repetition-rate Q-switched pulse output in fiber lasers. In this work, we will present our recent advances in TMD based pulsed laser application. Four TMD materials MoS2, WS2, MoSe2, WSe2, have been demonstrated to achieve pulsed lasers. The first demonstration on WS2 based mode-locked and Q-switched lasers has become ESI hot paper and highly cited paper (Optics Express 23, 26723, 2015). Mode-locked based on MoS2 has also been used to generate low-phase-noise microwave signals with wide frequency tuning range and high stability. In addition, we will also discuss the technology to achieve optical driven deposition with ultralow threshold of 3 dBm which is 10 dB lower than the typical threshold of this technology.

10017-28, Session 7

Optical super-resolution data storage inspired by nanoscopy *(Invited Paper)*

Yaoyu Cao, Jinan Univ. (China)

Data storage technique is expected, ever than before, to back up continued growing demands on big data processing that confronts great challenges in cost and energy consumption with current hard-disk-based big data centres. Compared with data storage techniques based on electromagnetic or electronic manipulation, such as hard disk and solid state disk, optical data storage exhibits exceptional advantages in energy-saving and long-time information preservation, which affords superior near-line storage and data archiving. However, the digital versatile disc (DVD) and blu-ray DVD based optical data storage techniques are suffering from theoretical capacity limit due to the physical barrier, well known as the diffraction limit of light. For that Ernst Abbe’s law gives the smallest recording bit size on the order of

the wavelength, the storage capacity is limited down to tens of Gigabytes per disc.

Here we report on our recent progress on the development of optical solutions to enable nanoscopy inspired optcial super-resolution data storage. This approach can directly break the diffraction limit by employing an optical dual-beam protocol. The super-resolution storage is achieved by producing an effective focal spot in the nanoscale for both of recording and reading to boost the data storage capacity per disc. For the recording, we have demonstrated the bit feature size as small as 33 nm, which leads to an equivalent storage capacity approaching 1 PB per disc. For the reading process, optically active quantum dots with engineered energy levels facilitate the luminescence signal retrieved in a super-resolved manner by reversible saturable optical fluorescence transitions (RESOLFT) process, which allows for resolving the bit size far less than the wavelength of the laser beam.

10017-29, Session 7

976-nm passively mode-locked ytterbium-doped fiber laser core-pumped by 915-nm semiconductor laser diode *(Invited Paper)*

Yue Zhou, Beijing Univ. of Posts and Telecommunications (China)

Within the past few years, femtosecond fiber lasers emitting around 976 nm have aroused some researchers' interest owing to their attractive applications as seed sources in fiber amplification systems and high power solid state amplifiers. Potentially, fiber lasers operating around 976 nm could be further converted to 488 nm via frequency doubling, which is highly desirable to provide a compact replacement for bulk and inefficient argon ion lasers in applications such as communications and underwater exploration of marine resources.

Remarkable progress has been made in ytterbium-doped fiber lasers (YDFL) emitting around 1 μm in the past few decades. The pulse duration and pulse repetition rate could be decently improved if implementing passive mode-locking method. Previous work demonstrated a double clad YDFL emitting at 976 nm. The laser is double clad multi-mode pumped, which suffers from relatively low conversion efficiency. Pumping with single-clad single-mode fibers (SMF) could obtain a higher slope efficiency.

In this paper, we demonstrate an all-normal dispersion (ANDi) femtosecond YDFL. The laser operates around 976 nm via single-clad single-mode core-pumped method, which could enhance the slope efficiency up to 19% compared to that of 14% via double-clad multi-mode pumped method [4]. The pulse repetition rate is 44.3 MHz, and pulse energy is approximately 1 nJ. Through external cavity pulse compression by a pair of gratings, the pulse duration can be compressed to 250 fs, nearly transform-limited.

10017-30, Session 7

Bandwidth enhancement and time-delay signature suppression of chaotic signal from an optical feedback semiconductor laser by using cross phase modulation in a highly nonlinear fiber loop mirror

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Optical chaos generated by semiconductor lasers attracted much attention for its extensive applications in secure communications, chaotic lidar, optical time domain reflectometer and fast random bit generator etc. Among various methods to obtain optical chaos signals, optical feedback is widely adopted for its simple configuration, low cost and feasible controllability. However, on one hand, the bandwidth of chaotic signal generated by optical feedback semiconductor laser is usually at a level of ~10 GHz, which is mainly restricted by the relaxation oscillation frequency of the laser. On the other hand, the time-delay signature (TDS) originated from the optical round-trip in an external cavity may be identified by some time-series analysis techniques and then deteriorates the performances of optical chaos system in some potential applications. For example, the limited chaotic bandwidth will restrict the transmission rate of optical chaos based secure communications, and the obvious TDS may degrade the security of the system. Therefore, it is significant to optimize both the bandwidth and the TDS of optical chaos signals from an external cavity optical feedback semiconductor laser. Recently, delayed self-interference and electrical heterodyning have been successively proposed to enhance the bandwidth of chaotic signal and suppress the TDS. In this work, we proposed to take advantage of cross phase modulation (XPM) in a nonlinear optical loop mirror for enhancing the bandwidth of chaotic signal and suppressing the TDS. The influences of input light power, power division ratio, and highly nonlinear fiber length on the chaotic bandwidth and TDS are numerical investigated. Detailed mappings of chaotic bandwidth and TDS evolution show that the bandwidth of chaotic signal can be enhanced dramatically and the TDS can also be suppressed with suitable operation parameters, simultaneously.

10017-31, Session 8

Narrow-linewidth hybrid integrated external-cavity diode laser for precision applications

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Narrow linewidth laser sources with low frequency noise are key tools in broad range of precision applications including high-resolution spectroscopy, interferometric optic sensing and phase coherent laser communication. In this report, we carefully construct a compact packaged hybrid external cavity diode laser (ECDL) to operate with high spectral purity and outstanding stability. The cavity is comprised by the single angled facet (SAF) InP gain chip and the polarization maintaining single-mode (SM) FBG (central wavelength near 1550 nm, reflectivity of 60% and 3dB FWHM of 0.1 nm). All the parts are either soldered or adhesively bonded on top of a baseplate soldered to the thermoelectric cooler (TEC) and then integrated in a 14-pin butterfly package (31 mm?18 mm?13 mm). The module emits at the wavelength of 1550 nm and provides 21 GHz of continuous tunability, it produces ≥ 30 mW of polarization maintaining fiber-coupled output power with intrinsic Lorentz linewidth ≤ 3 kHz and RIN ≤140 dB/√Hz@100 kHz. Moreover, no degradation of the power current characteristic is observed after the random vibration (12.8gRMS) and Sine vibration test. The laser module we reported offers superior performance, low-cost and reliable solutions for the above mentioned precision applications.

10017-33, Session 8

Self-referenced electrical method for measuring frequency response of high-speed Mach-Zehnder modulators based on two-tone modulation

Heng Wang, Shangjian Zhang, Xinhai Zou, Yali Zhang,

Yong Liu, Univ. of Electronic Science and Technology of China (China)

The frequency response of Mach-Zehnder modulators (MZMs), including modulation index and half-wave voltage, is critical to the overall performance especially in the microwave and millimeter-wave regime, which should be critically characterized for the purpose of system evaluation and optimization. The conventional optical spectrum analysis method and the swept frequency method based on vector network analyzer (VNA) are efficient in characterizing MZMs. However, the optical spectrum analysis method is limited by frequency resolution of the commercial grating-based optical spectrum analyzer, which only has a frequency resolution of about 1.25 GHz (0.01 nm at 1550 nm). The widely VNA-based swept frequency method relies on de-embedding the contribution of the PD since the measured results are always contributed to by both the MZM under test and the PD. The major difficulty for VNA-based swept frequency methods when the absolute frequency response is involved is the extra calibration required for the absolute responsivity of the PD. To solve this problem, we propose and demonstrate a self-referenced electrical method for measuring frequency response of MZMs based on two-tone modulation. The modulation index and half-wave voltage can be extracted from the heterodyne ratio of two desired components by properly adjusting bias voltage. The method avoids any roll-off calibration for the PD responsivity in spite of the involved photodetection. Moreover, the method reduces the half bandwidth requirement for PD and electrical spectrum analyzer (ESA) by setting a specific frequency relationship of two-tone microwave signals. Theoretical description and experimental demonstration are presented to elaborate our method. The frequency-dependent modulation indices and half-wave voltages are experimentally measured for a commercial MZM, and the optical spectrum analysis method is also demonstrated for verifying the self-referenced measurement of our method.

10017-34, Session 8

Automatic range-gated laser imaging

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Range-gated laser imaging is important for the applications of remote surveillance, object tracking, and spatial obstacle avoidance. For counterterrorism security, military recognition, the user has the demand for convenient use; for Underwater Unmanned Vehicles, drones require independent imaging. So we present a technique to accomplish automatic imaging and solve inconvenient use problem. Firstly, the distance information of the observed target s obtained by the laser range finder. Then, the field of view (FOV) for target detection, recognition and identification (DRI) is calculated referring to closed-circuit television DRI standards. Applying equivalent number of line pairs instead of the target-screen ratio in traditional analog video surveillance DRI standards, an absolute quantitative evaluation is unified and convenient for digital video surveillance systems. And multi-resolution mountain climb servo (MCS) auto focus method is applied to obtain high detailed high quality image, guaranteeing the auto focus speed and accuracy and improving the real-time, accuracy and robustness. This focus accuracy is 5 times better and time consuming is half less than classical focus. Combined with observed target distance information and FOV depth, we demonstrate a timing and spatial matching for range-gated depth and FOV depth, those system parameters including the delay of the range time?the lase pulse width and intensifier gate is settled automatically. Finally, The repeated experimental verification of range-gated imaging system shows this technique can meet object's DRI testing requirements, ensure the auto focus speed, precision and accuracy, set timing and spatial matching, achieving the convenient use of the system and automatic imaging for object observation.

10017-35, Session 8

Light emitters on SOI platform for optical interconnects

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We discuss light emitters in silicon photonic interconnects in this paper. Silicon-based optical interconnect is now considered as a promising solution to overcome the limited bandwidth and high power consumption of traditional electric interconnects. However, silicon based light source is still a major challenge due to the indirect band gap of bulk silicon. Ge self-assembled quantum dots (QDs) have attracted much attention to realize silicon light emitters. The advantages of Ge QDs include: easy fabrication, light emission between 1.3 ?m and 1.6 ?m in the telecom band and compatibility with complementary metal-oxide semiconductor (CMOS) processes. Firstly, a light emitter based on Ge QDs embedded in a photonic crystal ring resonator is designed and fabricated. Six sharp resonant peaks are present in a photoluminescence spectrum ranging from 1500 to 1600 nm at room temperature. Next, we observe strong resonant luminescence from Ge QDs embedded in modified PhC L3 cavities at room temperature. Five emission peaks corresponding to the five cavity modes of modified L3 cavity, which cover a 250-nm-wide wavelength range, are observed simultaneously in one device. Finally, a freestanding one-dimensional PhC nanobeam cavity embedded with Ge self-assembled QDs is fabricated. Only one photoluminescence peak is observed in the wavelength range of 1000 ~ 1600 nm at room temperature. The emission peak dominates the photoluminescence spectrum over an almost flat and weak background emission, indicating that single-mode emission is realized. These results show a possible direction to realize effective Si-based integrated light emitting devices based on Ge QDs in silicon cavities.

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10018-1, Session 1

Femtosecond laser nanojoining: the process, interface, filler metal, and its application *(Invited Paper)*

Lei Liu, G. Zou, L. Lin, Yingchuan Zhang, Tsinghua Univ. (China); Y. Norman Zhou, Tsinghua Univ. (China) and Univ. of Waterloo (Canada)

Further down the road of miniaturization to nanoscale, there is an emerging need to join nanoobjects to form nanoscale devices and systems.[1, 2] The nanojoining methods include laser beam, electron beam, soldering, sintering, resistance welding etc. Femtosecond laser is a promising tool for nanojoining because of its precise controlling of heat input, outstanding focusing ability, non-linear absorption and ultra-high peak power. Femtosecond laser induced nanojoining is also highly related to the plasmonic thermal effect,[3] due to the localized plasmon focusing the laser energy to a specific area and induce local melting.[4] In this work, femtosecond laser induced nanojoining, including the process,[5] interface,[6] filler metal,[7] and its applications are investigated and the future trend is discussed.

Acknowledgements

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10018-2, Session 1

Photocatalytic activity of three-dimensional micro-/nanostructured TiO2 fabricated by femtosecond laser-hybrid method *(Invited Paper)*

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As one of the most important semiconductor functional materials, TiO2 is widely used in photocatalysis, dye-sensitized solar cells, lithium-ion batteries and gas sensors. The three-dimensional micro-/nanostructured TiO2 grown on a titanium substrate (3D-TiO2-Ti) possesses such advantages as large specific surface area, superior light harvesting, and excellent electron conductivity, which can effectively improve its application performances. This study reports a novel laser-hybrid approach to fabricate 3D-TiO2-Ti. First, the primary microarrays were fabricated on the surface of titanium substrate by a femtosecond laser (3D-Ti). Next, the secondary TiO2 nanostructure was grown on 3D-Ti surface by chemical treatments to form 3D-TiO2-Ti. A variety of 3D-TiO2-Ti has been achieved recently in our group, such as nanopore, nanowire, and nanosheet. The as-fabricated 3D-TiO2-Ti exhibited better performances in light harvesting and absorption ability than nanostructure TiO2 grown on flat titanium surface (nanostructure-TiO2). The photocatalytic degradation of methyl orange revealed that the size and morphology of the primary microarrays and the secondary nanostructures affected the photocatalytic activity of 3D-TiO2-Ti synergistically. The photocatalytic efficiency was improved by a maximum of 50% compared to that of nanostructure-TiO2. Additionally, the photodegradation rate remained constant over several consecutive cycles, indicating that the 3D-TiO2-Ti was mechanically stable. The insights from the study on the fabrication of our 3D-TiO2-Ti can be extended to guide the fabrication of other functional metal oxides on metallic substrates.

10018-3, Session 1

Fabrication of 3D-embedded hollow structures inside polymer dielectric PMMA with femtosecond laser *(Invited Paper)*

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Recent progresses in femtosecond laser (fs) manufacturing have already proved that fs laser is a powerful tool in three dimensional internal structure fabrication. However, most studies are mainly focused on realize such structures in inorganic transparent dielectric, such as photosensitive glass and fused silica, etc. In this study, we present a method to create embedded internal 3D structures in a polymer dielectric material polymethyl methacrylate (PMMA). Both continues hollow structure such as microfluidic channels and discrete hollow structures such as single microcavities are successfully fabricated with the help of femtosecond lasers. Among them, complicated 3D microchannel with a total length longer than 10mm and diameters around 80?m to 200?m are fabricated with a low repetition rate Ti: sapphire femtosecond laser by direct laser writing at a speed ranging from 25?m/s to 200?m/s; microcavities which function as concave microball lenses (CMBLs) and can be applied in super-wide-angle imaging are fabricated with a high repetition rate femtosecond fiber laser due to the distinct accumulated heat effect after 5s irradiation with the tightly focused laser beam. These new approaches proved that femtosecond laser direct writing technology has great application potential in 3D integrated devices manufacturing in the future.

10018-4, Session 1

W/Cu joining strengthened by femtosecond laser-induced micron-scale interface structure

Jiang Dafa, Dingwei Gong, Jiangyou Long, Fan Peixun, Hongjun Zhang, Minlin Zhong, Tsinghua Univ. (China)

W/Cu joining is key for the fabrication of high heat load components for thermal-nuclear reactors, which however suffers from the low W/Cu bonding strength due to the immiscible nature of W-Cu system. In this study, we proposed a method for strengthened W/Cu joining based on femtosecond (fs) laser induced micron-scale W/Cu interface structure. W surfaces were irradiated by fs laser ablation to form micron-scale cube arrays, and then joined to Cu by vacuum hot pressing at 1000 ºC, 80 MPa for 2.5 hours. The tensile strength of the W/Cu joining sample was investigated. The results show that the micron-scale cube arrays were successfully introduced into W/Cu interface without any cracks or voids. The interface structure helps to increase the W/Cu bonding strength to as high as 59.6 MPa, increased by about 50% as compared to W/Cu joining with a flat interface (bonding strength 40.1 MPa). The W/Cu bonding strength shows positive correlation with the height of the cubes and the W/Cu interface area, indicating the possibility to control the W/Cu bonding strength by simply adjusting the fs laser ablation parameters for the fabrication of cube arrays on W surface. Our research provides a method for strengthened joining between intrinsically immiscible materials, including but not limited to W and Cu.

10018-5, Session 1

Heterogeneous nanowires interconnection using femtosecond laser radiation for integrated nanoelectronics

Luchan Lin, Lei Liu, Guisheng Zou, Tsinghua Univ. (China); Walter W. Duley, Univ. of Waterloo (Canada); Y. Norman Zhou, Tsinghua Univ. (China) and Univ. of Waterloo (Canada)

Surface plasmon resonance (SPR), which originates from the excitation of coherent oscillations of electrons, has been used in tailoring heat input in nanosystems [1]. And intense heat generation due to strong plasmon effects under optical excitation can be confined at the localized area around nanowires structures [2, 3]. Therefore, nanowires structures can be manipulated by these controllable plasmon effects. Femtosecond (fs) laser, with high pulse intensity, can further enhance these effects. Besides, due to the non-thermal nature of fs laser materials interaction, low damage on base materials can be achieved.

Ag and Ag nanowires can be joined together after femtosecond laser radiation and branched metal nanowire structure can be achieved. And it can also be known that silver has a bad wettability on TiO2 surface. But under the localized plasmonic effect generated at the metal (Ag)-oxide (TiO2) junction, surface structure of TiO2 has been modified and silver gets a better wetting on TiO2 as a result. Joint was formed between Ag and TiO2 without much damage found in other parts adjacent to the junction. Besides, high field intensity generated around the nanowires can also result in non-linear photon absorption (multi-photon absorption) in the dielectrics. As can be demonstrated, nanowire networks of TiO2 were formed with joined nanowires structures after femtosecond laser radiation. And surface structure of nanowires has been changed accordingly under high laser fluence. This femtosecond laser induced nanowires interconnection between different materials (metal and oxide) shows great potential in integrating functional nanowire units which can be used in the nanowires-based electronics.

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10018-7, Session 2

Ultrafast laser enabling versatile micro-nano scale material processing *(Invited Paper)*

Minlin Zhong, Tsinghua Univ. (China)

Ultrafast laser, with ultra-short pulse duration and ultra-high energy density, is an emerging powerful and advanced tool for micro-nano scale materials processing. The unique features when an ultrafast laser interacts with materials include: (1) beyond the diffraction limit via near-filed optics principle etc. to form sub-micro scale or nano-scale fabrication; (2) beyond the heat-affect zone limitation via extremely non-equilibrium energy transfer and dissipation to form high fabrication accuracy; and (3) materials independence via nonlinear effects like multi-photon absorption and avalanche ionization to process almost any kind of materials. In recent years, ultrafast lasers in sub-ps regime and MHz repetition rate deliver average power up to multi 100W and even over 1KW, which enables not only versatile micro-nano scale material processing for fundamental research, but also capable technologies for industrial applications.

This presentation reports our recent research by using high average power high repetition rate ultrafast lasers: (1) ultrafast laser enabling brand band anti-reflection surface micro-nano structures. On laser structured micro-nano Cu surface, we further introduce thermal oxidation to grow an kind of macro-micro/nano-nanowire structure, showing a reflectance of 0.6% at infrared 17 ?m and below 3% over 14?18 ?m (Nano Letters, 8/2015). (2) ultrafast laser enabling flexible patterning and thinning of graphene with precise layer control. Desired number of layer was obtained by single process from original multi-layer graphene when appropriate pulse threshold energy was adopted (Scientific Report, 6/2016). (3) ultrafast laser enabling smart superhydrophobic surfaces. Almost any kind of metal or alloy surfaces and many organic materials can be structured to form superhydrophobicity, colorful superhydrophobicity and superhydrophocity with tunable adhesion (ACS Applied Materials & Interfaces, 4/2015?J. Colloid and Interface Science, 3/2015).

10018-8, Session 2

Contrastive study on micromachining technology of sapphire substrate by 355nm nanosecond laser and 1064nm picosecond laser

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A 355nm Nanosecond Laser and a 1064nm Picosecond Laser are used for processing the 0.55mm thick rough sapphire substrate respecitively.By investigated and analyzed the effect of the two lasers on the sapphire,experimental results show that: the interactions of 355nm Nanosecond Laser with sapphire is the photo-thermal interactions and the thermal effects limits its capability to graphics cutting on sapphire; the interactions of 1064nm Picosecond Laser with sapphire is the photo-chemical interactions and it can be cold-worked cut sapphire. Through further experimental studies,we obtained that the power density value of the laser cutting sapphire is 1012W/cm2 and using 1064nm Picosecond Laser successfully sapphire graphics cutting and the complete set of process parameters were obtained,i.e.,repetition frequency at 1kHz; pulse width at 15ps; average power at 1W; single pulse energy at 1mJ; scanning velocity at 0.5m/s and scanning 50 times.

10018-9, Session 2

High-resolution laser lithography based on vortex laser and composite layer

Shichao Zhan, Yiyong Liang, Xiongfeng Li, Zhejiang Univ. (China)

Traditional laser lithography systems cannot write sub-wavelength patterns due to the diffraction limit. In this paper, a novel super-resolution laser direct writing method is proposed to break through the diffraction limit. Compared with conventional lithography systems, the photoresist layer in this method is overlaid by an extra photochromic layer which is a mixture of metanil yellow and aqueous PVA solution. Then a vortex beam with a hollow energy distribution is used to expose the photochromic layer and make an annular region of the photochromic layer opaque to the writing beam. Thus, a virtual aperture is formed in the photochromic layer which can confine the diameter of the writing beam and reduce the linewidth exposed in the photoresist layer. Lithography process of this new method was modeled and a corresponding simulation was made. In this simulation, the intensity ratio of the two beams, relative absorption coefficients and other parameters were changed to study their influence to linewidth in the photoresist. An experimental setup was designed to validate the simulation, where the wavelengths of the writing beam and the vortex beam are 405 nm and 532 nm, respectively. These two beams are strictly coaxial when they are incident to the photochromic layer. The experimental results agree quite well with the model simulation, showing that the linewidth could be reduced by increasing the intensity ratio of the vortex beam to the writing beam. They also indicate that the vortex beam could effectively reduce the lithography linewidth to 300 nm or even smaller.

10018-10, Session 2

A blue-ray laser-diode-based dual-beam interference lithography for fabrication of diffraction gratings for surface encoders

Xinghui Li, Xiangwen Zhu, Qian Zhou, Xiaohao Wang, Kai Ni, Graduate School at Shenzhen, Tsinghua Univ. (China)

The paper presents a dual-beam interference lithography technology for fabrication of diffraction gratings for surface encoders by using cost-effective 405 nm blue-ray laser diodes. In this system, a dual-beam interferometer system is employed. A laser beam raying from a compact 405 nm blu-ray laser diode is collimated and then divided into two beams by a beam splitter. These two beams are changed their propagation directions and interfere with each other. Generated interference fringes are exposed on the photoresist coated substrate. Grating line spacing d can be adjusted by changing the incident angle between these two beams. Grating width Wc that determines the measurement of the surface encoder is decided by the coherence length Lc of the laser diode and the grating line spacing d. Calculation and simulation were carried out to decide the grating width. Lc was experimentally obtained. A fabrication system was constructed to verify the feasibility of this technology. Diffraction gratings with a 2.5 micron line spacing and a 7 mm width was obtained. Experimental results show that this method is feasible for fabrication of gratings for surface encoders. This fabricated area can be stitched for a 100 mm order Wc by using a precision linear stage to move the coated grating substrate.

10018-6, Session 3

Energy-based approach as an example for a process signature for laser microprocessing

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A given part geometry can be fabricated reproducibly with the current manufacturing technology, but except for the geometric dimension at the macroscopic scale, the surface integrity is still not systematically predictable based on the processing conditions, and vice versa. In laser ablation process, workpiece material is heated by electromagnetic energy and removed by the thermodynamic effects induced by phase change such as melting, vaporization or sublimation, while laser chemical machining process does not heat the material beyond the melting point and the material is removed by (electro)chemical reaction. According to the main idea of process signature, the generated surface integrity is not process-dependent but simply energy-dependent. Taking these two kinds of laser micro machining processes as examples, this paper explores the challenges to implement the energy-based concepts of process signature in laser micro processing. It is expected that laser processes and specific materials independent mechanisms can be found, which are behind the interactions among the specific energy sources, mediums, surface, subsurface and base material. Moreover, as a guideline, this paper discusses also the roadmap and technical methods which can be used to realize this idea, from the monitoring of the process loadings to the evaluation of representative material modifications, and introduces the concept of a general laser process signature concerning the total effects of laser processes.

10018-11, Session 3

Recent research in laser surface processing and its applications in aerospace manufacturing *(Invited Paper)*

Yingchun Guan, BeiHang Univ. (China)

Laser surface processing has been considered as promising technique to enhance surface performance of materials or components in various applications of aerospace manufacturing. This work presents some recent applications of laser cleaning and polishing techniques on metallic substrates in our group. We firstly demonstrate a one-stop method in minimizing oxides layer and removing surface contaminates of Al alloy for TIG welding. Comparison of the performance between conversional cleaning method and laser cleaning method were examined carefully to identify changes in microstructure and chemical analysis of Al alloy welds. Special attention is paid to porosity distribution in the fusion zone after laser cleaning. It is further proposed that laser cleaning can refine microstructure of the interface between filter wire and the substrate during TIG welding, which may play a significant role in affecting the weld quality. Moreover, we show

both oxide removal and low surface roughness achieved at hot rolled Ni-55.0at.%Ti shape memory alloy (SMA) surface using a nanosecond pulsed Nd:YAG laser. Results show that as-received oxides with thickness of 10 micron had been removed completely after laser cleaning, and surface roughness of laser-cleaned surface was achieved as less than 1?m. No obvious change occur for phase analysis and transformation temperatures of the SMA, indicating that the influence of laser irradiation on shape memory effect of hot rolled Ni-55.0at.%Ti SMA was negligible. Finally, we employ laser polishing method to reduce surface roughness of laser deposited Ti alloys. Three dimension surface profile, residual stress, microstructure and micro hardness of laser-polished regions are examined carefully on both as-received surface and electrical discharge machined surface to investigate the effect of laser polishing on the substrate.

10018-12, Session 3

Synthesis of nanoparticles by pulsed laser ablation in air: a versatile means for flexible synthesis and separation from Xiamen University *(Invited Paper)*

Rui Zhou, Tingting Huang, Shengdong Lin, Xiamen Univ. (China)

To make the optical limiting effect into practical applications, such as for high-speed data-processing communication systems and broadband optical limiting devices, plasmonic nanocomposites are explored for their strong scattering cross-section and absorption of incident optical energy at different resonant frequencies, aiming to lower the energy threshold and broaden the optical limiting range. To synthesize pure nanocomposites dispersed in colloids, the laser ablation is applied as a physical and environmentally friendly approach to generate a variety of nanoparticles at different shapes, sizes, size distributions and concentrations in liquid-based environments by controlling laser parameters, including laser fluence, repetition rate and light wavelength. In this work, the formation mechanism of nanoparticles by laser ablation and their nonlinear optical limiting performance will be briefed. Metallic nanoparticles and their alloys are fabricated for surface plasmon resonance (SPR) enhanced nonlinear extinction properties with large light scattering cross sections at different sizes and concentrations by pulsed laser ablation in liquid. Laser-synthesized colloids of mixed nanoparticles at different sizes provide more opportunities to generate and enhance different nonlinear optical process in a disordered nanosystem. To further improve the broadband performance of optical limiting, hybrid systems are designed by combing different sizes and compositions' nanoparticles dissolved in deionized water to attenuate more incident laser light intensity. By controlling the laser ablation of different types of solid targets, an enhanced optical limiting hybrid system based on the use of plasmonic nanoparticles can be flexibly designed and fabricated over a broadband range.

10018-13, Session 3

Laser-induced deposition metal from solution and sensory properties of copper microstructures obtained by this method

Ilya Tumkin, Vladimir A. Kochemirovsky, Maxim S. Panov, Sergey Ermakov, Saint Petersburg State Univ. (Russian Federation)

Laser-induced chemical liquid-phase deposition of metals (LCLD) is one of the promising and effective methods for patterning of the microelectronic devices. This technique deals with metal reduction which proceeds in local volume of solution within the laser beam focal point and leads to deposition of small-sized metal structures on the surface of dielectric substrate. These structures which have the developed surfaces and exhibit high electrical conductivity properties can be applied for fabrication of extra small metallic conductors on dielectric surfaces without using photomask in contrast to photolithography.

Thus, the main aim of the current work is to obtain the small-sized copper electrodes and study their sensory properties. In order to achieve this goal we conducted the laser-induced synthesis of porous copper deposits using the LCLD technique and studied the sensory activity of these structures towards D-glucose and hydrogen peroxide detection.

The high conductive porous copper microstructures with a dispersion of pore size ranging from 50 nm to 50 ?m were synthesized using laser-induced metal deposition method. These structures have a developed effective surface area which is 30 times higher than that observed for a pure bulk copper with similar geometric parameters. The electrochemical studies revealed that an analytical response of the fabricated copper electrode is 15 times higher than those observed for a pure bulk copper. The sensory properties towards hydrogen peroxide and D-glucose showed that the value of Faraday current at the fabricated copper electrode is 2-2.5 orders of magnitude higher than for a pure bulk copper used as the etalon electrode.

10018-14, Session 3

Fabrication of micro holes in single-crystal SiC wafers using mid-UV solid-state laser

Litao Qi, Fangzhou Li, Heilongjiang Institute of Science and Technolology (China)

This paper provides an investigation of the ablation behavior of single crystal SiC to improve the manufacturability and high-temperature performance of SiC using laser applications. A 266nm mid-ultraviolet pulsed laser is used to investigate the micromachining of SiC wafer. The purpose is to find suitable laser parametric regime for the fabrication of high accuracy, high spatial resolution and thin diaphragms for MEMS high-temperature pressure sensor applications. Etch rate, ablation mechanism and quality of micromachining micro-holes are evaluated. Micro holes exhibits ripple patterns, micro-cracks and recast layers, most of which could be eliminated by a subsequent chemical cleaning process. The ablation process is characterized by four types of ablation mechanism, such are photomechanical fragmentation, thermal vaporization, explosive boiling and plasma shield, which are either singly or in combination occur as a function of pulse energy. The etch rate is obtained with mid-ultraviolet solid-state pulsed laser ablation experiments. Results shows mid-ultraviolet pulsed solid-state laser ablation is a high-efficiency material removal process for micromachining of SiC-based MEMS devices. In addition, the etch rates are substantially high for mid-ultraviolet pulsed laser compares to other conventional fabrications such as reaction ion and electrochemical etching. It has been found that excellent quality of machined features with little collateral thermal damage is obtained in the lower pulse energy range.

10018-15, Session 3

Fabrication of three-dimensional photonic crystal template using micro-projection stereo lithography

Jian-Wen Dong, Yigui Chen, En-Tao Liang, Wei-Xing Zhang, Sun Yat-Sen Univ. (China)

Photonic crystal is a material with periodic change of dielectric constant. There exists the photonic band gap in photonic

crystal, which can hold back the propagation of light in a certain frequency range. The photonic crystal has widely studied in science and technology such as integrated optoelectronic devices, the control of spontaneous emissions, optical communications, and sensor. Three dimensional (3D) photonic crystal is extremely concerned as it has many predominant characteristics, in particular for the realization on backscattering-immune topological propagation. Such special functionality needs to construct a 3D chiral channel in the structure of photonic crystals which is not compatible to the nowadays lithography. Because those lithography technologies like chemical self-assembly technique?holographic lithography can only fabricate the structure of complete periodicity either in two-dimensionally or three dimensionally.

A micro-projection stereo lithography method is put forward in this paper for the advantages of high customization, simple production process, low manufacture cost and rapid prototyping. Micro-projection stereo lithography method can actually be regarded as one kind of additive manufacturing. It is a highlight point that combines such booming additive manufacturing technology with the fabrication of three-dimensional photonic crystal. We utilized digital micro-mirror (DMD) device and a 405nm LED array to solidify the photosensitive resin in a bottom-up and layer-by-layer fashion. There are two subsystems in the method: one is reduction optical imaging subsystem for improving the horizontal printing resolution and adjusting the printing size as required, and the other is feedback subsystem on the purpose of positioning where the image is in focus.

In the paper we firstly study the light uniformity of projection spot in micro-projection stereo lithography system, and then we discussed on resin about its solidification resolution in horizontal plane as well as the relationship between polymerization depth and light exposure dose. By using such micro-projection stereo lithography method, a 3D photonic crystal template with chiral channel in the center has been fabricated and the lattice constant is about 390 μm. At the same time, measuring analyses and a Fourier diffraction pattern for characterizing the 3D photonic crystal template are presented.

10018-16, Session 3

Optical methods for correction of surface acoustic wave sensors topology

Sergey Y. Shevchenko, Daniil V. Safronov, Alexander S. Kukaev, Dmitry P. Lukyanov, Saint Petersburg Electrotechnical Univ. “LETI” (Russian Federation)

Sensors based on surface acoustic waves (SAW) are becoming more popular nowadays due to possibility of wireless implementation and creation of new types of these sensors, i.e. inertial ones. Originally, a photolithography process is used for that purposes. However, production of a photo mask, which degrades in just a several months, is a difficult and expensive process. In addition, sensing element properties change after the packaging is done. Therefore, it is promising to find a method to correct topology of packaged sensing elements (SE) and even to produce them without photomasks.

The problem might be solved using a high-precision laser. The essence of proposed method is to evaporate unneeded material from a fully metallized wafer, leaving only desired topology. Thus, it is possible to change SE topology configuration without any essential expenses of time and money that will allow simplifying technological process of SAW-based sensors production.

As the substrate of SAW-based SE is usually made of optically transparent material, the proposed method allows bilateral topology creation. In case of a photolithography it is not possible to form absolutely identical topologies and place them to exactly same positions on two sides of a wafer.

A number of low-frequency experimental delay lines and resonators were produced using a laser ablation technique for research purposes. Quality of produced topology is examined. Spectral characteristics of these elements are carried out and compared with theoretical predictions. The received results will be presented in the report.

10018-17, Session 3

Switchable repetition-rate bound solitons passively mode-locked fiber laser

Xu Qin Wang, Yong Yao, Harbin Institute of Technology Shenzhen Graduate School (China); Yanfu Yang, Harbin Institute of Technology Graduate School (China); Ying Long Gu, Harbin Institute of Technology (China)

The repetition rate switchable laser has a great potential in measurement detection, femtosecond machining and others. And they required a stable laser and avoid the side effects, limited pulse repetition frequency to a few kilohertz. In this case harmonic mode-locking and suitable repetition rate fiber laser offers advantages. Harmonic wave definitely which the repeat frequency is integer times of the foundation frequency. Thus, significant lengths of gain fiber are required, resulting in long cavities and low fundamental repetition rates. We demonstrated a repetition rate switchable mode-locked fiber laser based on high nonlinear fiber and Bi2Se3 saturable absorbing unit which the output is ultra-short pulse laser, and the amount of the harmonic is continuous adjustable beetween 1st and 14th obtained that the polarization controller carefully rotated. And we know the role of high nonlinear fiber in the ring cavity to appear muilt-wavelength. The central of multi-wavelength of optical spectrum is 1550 nm, and the pulse width of fundamental pulse is 873 fs. The repetition rate varied from 193 kHz to 2.7 MHz.

10018-18, Session 3

Research of the suppression of the phase noise in DFB fiber laser by self-injection locking

Jianfeng Tang, Yinfa Zhang, Zhenglong Yu, Xi’an Communication Institute (China); Shuidong Xiong, Lina Ma, National Univ. of Defense Technology (China)

The intrinsic phase noise of distributed feedback fiber laser (DFB-FL) greatly reduces the signal to noise ratio (SNR) of unbalanced interferometric fiber sensor system, which has a negative influence on the demodulation of tiny signal. In order to suppress the phase noise of DFB fiber laser, a self-injecion locking DFB-FL based on an optical circulator was presented. Using an unbalanced Michelson interferometer with one meter optical path difference (OPD) unequal arms, we measured the phase noise of the unlocked DFB fiber laser and self-injection locking DFB fiber laser with one meter, one point five meter, two meters length. Result of experiment demonstrated that the phase noise of DFB-FL was suppressed by the self-injection locking structure, and the effect of suppression was improved with the increase of the locking ring length. When the length of locking ring is two meters, the phase noise above 500Hz decreases by 8 dB and some outstanding low frequence noise decrease obviously demodulated by an one meter OPD unbalanced Michelson interferometer, and the mode was not hoping in eight hours. Contrast with the unlocked DFB-FL, the pump efficiency of self-injection locking DFB-FL was increased by 30%. In addition, the mode of DFB-FL was not stable with the changing of the temperature if the length of locking ring was above 2.5m.

Conference 10019: Optoelectronic Devices and Integration VI

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10019-1, Session 1

Compact silicon photonic devices and high-density waveguide integration *(Invited Paper)*

Wei Jiang, Nanjing Univ. (China)

Silicon photonics can potentially transform the photonics technology owing to its low-cost fabrication and large-scale integration advantages. Miniaturized devices and high-density integration are the trends for future development of silicon photonics. This talk will review our recent work on compact silicon photonic devices based on photonic crystals and micro-resonators as well as emerging high-density waveguide integration technology. Particularly, ultra-high-density waveguide integration based on a novel waveguide superlattice concept will be discussed. Half-wavelength pitch waveguide arrays with very low crosstalk have been demonstrated experimentally. We will show how physics insight can be employed to overcome some crucial limitations of integrated photonics. Potential applications of our work in optical interconnects, space-division multiplexing, mode-division multiplexing, wavelength-division multiplexing, and optical phased arrays will be discussed.

10019-2, Session 1

The application of double-layer gold gratings in biosensors and unidirectional couplers *(Invited Paper)*

Chongjun Jin, Yang Shen, Sun Yat-Sen Univ. (China)

In this presentation, the progress of the applications of double-layer gold gratings in biosensing and integrated optics is reviewed. Then we report our efforts on the fabrication of double-layer gold gratings, their applications in surface enhanced Raman scattering spectroscopy, refractive index sensors, label-free biosensors, unidirectional couplers for surface plasmon polariton, optical switchers and routers.

10019-3, Session 1

Measurement of the roughness of smooth glass surfaces using optical waveguides

Katerina Kaslova, OAO VimpelCom (Russian Federation); Anatoly N. Osovitsky, Peoples' Friendship Univ. of Russia (Russian Federation); Nikolai D. Espinosa Ortiz, Univ. de las Fuerzas Armadas (Ecuador); Jesus A. Vila M., Univ. del País Vasco (Spain)

Are presented the results of measurements of surface roughness of fluorine-containing glasses, using a new methodology for gradient waveguide propagation of the laser radiation.

This new method also allows the measurement of the attenuation of optical radiation in the surface layer of glass

The development of multiple experimental investigations confirm the advantages of the method - high sensitivity and simplicity in development.

10019-4, Session 1

Accuracy evaluation of the surface integration of micro-POFs using a micro-dispensing process

Bechir M. Hachicha, Ludger Overmeyer, Leibniz Univ. Hannover (Germany)

Integrated waveguides are used for communication as well as for sensing applications. They are present in PCB's for high transfer rate and in civil buildings for health monitoring. However, the use of integrated waveguides in simple mechanical parts is not yet established. We are contributing to the research in this field by developing an automated surface integration process of micro-polymer optical fibers (μ-POF) into metallic surfaces. The developed method uses the micro-dispensing process. We functionalize UV-curing adhesives as cladding for micro-optical cores as well as for inherent bonding to the substrate surface.

We evaluated the repeat accuracy of this process in this article. A high accuracy of geometry and position of the integrated μ-POF facilitates the handling in the next step. After the surface integration, optical axes of sender and receiver have to be aligned with the optical axis of the surface integrated μ-POF. A high repeatability of the process allows the use of the "fit into place" strategy to align the optical axes of beam sender and receiver. This choice reduces the coupling process complexity as well as its cycle time.

In this article we present the method as well as the experimental set-up used for the accuracy evaluation. Furthermore, possibilities to increase the accuracy are investigated and discussed.

10019-5, Session 1

Silicon nitride grating waveguide based directional coupler

Jijun Feng, Univ. of Shanghai for Science and Technology (China); Ryoichi Akimoto, National Institute of Advanced Industrial Science and Technology (Japan); Heping Zeng, East China Normal Univ. (China)

Silicon nitride is a promising wave-guiding material for integrated photonics applications with a wide transparency bandwidth from visible to mid-infrared, with the superior performance in fiber-coupling and propagation losses, the fabrication process more tolerant to the structure parameters variation and compatible with the CMOS technology. Directional coupler (DC) is very popular for realizing beam splitter because of its structural simplicity and no excess loss intrinsically. Here, a conventional silicon nitride directional coupler, three-dimensional vertical coupler, and grating waveguide assisted coupler are designed and fabricated, and compared with each other. A grating waveguide based coupler with a period of 300 nm and coupling length of 26 um, can realize a wideband 3-dB splitter for the wavelength in the range from 1540 to 1620 nm, for a transverse electric (TE) polarized wave. With further optimization of the grating period and duty cycle, the device performance can be further improved with wider bandwidth.

10019-6, Session 2

Recent developments of fiber Bragg gratings induced by femtosecond laser *(Invited Paper)*

Yiping Wang, Changrui Liao, Jun He, Qiao Wang, Ying Wang, Congzhe Zhang, Shen Liu, Shenzhen Univ. (China)

We reported recent developments of fiber Bragg gratings (FBGs) induced by use of a femotosecond laser in Shenzhen University. We demonstrated a method for the preparation of negative-index fibre Bragg gratings using 800 nm femtosecond laser overexposure and thermal regeneration. A positive-index type I-IR FBG was first inscribed in H2-free single-mode fibre using a femtosecond laser directed through a phase mask, and then a highly polarization dependant phase-shifted FBG (P-PSFBG) was fabricated from the type I-IR FBG by overexposure to the femtosecond laser. The fabrication of fiber Bragg gratings was here demonstrated using ultrashort pulse laser point-by-point inscription. Fiber Bragg gratings were formed into D-shaped fibers for use as refractive index sensors. A nonlinear relationship was observed between the Bragg wavelength and liquid refractive index. We have successfully fabricated a series of sampled fiber Bragg gratings with easily adjustable sampling periods and duty cycles using an 800 nm femtosecond laser point-by-point inscription. The thermal stability of the fabricated fiber gratings was investigated using isochronal annealing tests, which indicated that the fiber gratings are capable of maintaining high reflectivity at temperatures of up to 1000°C for 8 h. We present a type of phase-shifted fiber Bragg gratings based on an in-grating bubble fabricated by femtosecond (fs) laser ablation together with a fusion-splicing technique. A microchannel vertically crossing the bubble is drilled by fs laser to allow liquid to flow in or out. By filling different refractive index (RI) liquid into the bubble, the phase-shift peak is found to experience a linear red shift with the increase of RI, while little contribution to the change of phase shift comes from the temperature and axial strain. Therefore, such a PS-FBG could be used to develop a promising tunable optical filter and sensor. Moreover, parallel integrated FBGs have beeb successfully fabricated in SMFs by using femtosecond laser point-by-point inscription. More than one FBG can be parallel inscribed in the same region of fiber and this new grating exhibits many unique properties, such as multi-wavelength operation, ultrashort grating length and outstanding thermal stability.

10019-7, Session 2

980nm tapered lasers with photonic crystal structure for low vertical divergence

Xiaolong Ma, Yun Liu, Pengchao Zhao, Wanhua Zheng, Institute of Semiconductors (China)

High power tapered lasers with nearly diffraction limited beam quality have attracted much attention in numerous applications such as nonlinear frequency conversion, optical pumping of solid-state and fiber lasers, medical treatment and others. But the large vertical divergence of traditional tapered lasers is a disadvantage, which will make it expensive and difficult for beam shaping in some applications. A novel waveguide based on photonic band crystal (PBC) concept can expand mode size and thus narrow vertical far field divergence.

In this paper, we present tapered lasers with PBC structure emitting at 980 nm. The epitaxial layer is grown using metal organic chemical vapor deposition. The devices have a total length of 2 mm with 400 um long ridge waveguide and 1600 um long tapered section. The taper angel is 4o. Under quasi-continuous wave operation an output power of 3.3 W is achieved with peak conversation efficiency of 35%. The threshold current is 240 mA and the slope efficiency is 0.78 W/A. In continuous wave mode, the output power is 2.87 W, followed by suddenly failure resulting from catastrophic optical mirror damage (COMD). The vertical and lateral far field divergences are 12.3o and 2.9o with full width at half maximum (FWHM) at 0.5A. At high injection level the vertical divergence doesn't exceed 16o FWHM. Beam propagation ratio M2 is measured based on second moment definition. High beam quality is confirmed by M2 value of less than 2.

10019-8, Session 2

Tunable multi-channel dropping filters based on double-waveguide parallel-coupled microring resonators

Chunyu Zhang, Harbin Institute of Technology (China); Xuenan Zhang, Northeastern Univ. (China); Yong Feng Wu, Chang Qiu Yu, Yundong Zhang, Harbin Institute of Technology (China)

The filtering characteristics of double-waveguide parallel-coupled microring resonators are theoretically investigated in this paper.

The structure is described as follows. It consists of an input-through waveguide, a drop waveguide, and N rings coupled to both waveguides. Each ring increases in radius by increment of a small radius difference between adjacent rings compared to the radii of each ring. A heater is embedded on the cladding to impose a continuously changeable additional phase shift between adjacent rings using thermo-optic tuning.

We theoretically analyze the following characteristics of the structure. Transfer matrix of the structure with arbitrary number of rings is deduced in detail. Number of the very narrow coupled resonators induced transparency (CRIT) channels, generated within a side-coupled integrated spaced sequence of resonators (SCISSOR) stop-band via constructive interference between adjacent slightly frequency-detuned rings, can be any desirable integer by fabricating corresponding number of rings in the structure. Any one or any number of arbitrary channels can be continuously tuned and selectively switched on/off, by modulating the additional phase shift between corresponding pairs of rings, minimally red shifting and widening the tuned channel when switching off, without moving or lowering the other channels greatly. In addition, numerical simulation shows that, under inevitable tolerances of parameters, performance of the structure remains basically stable. The structure is compact, reliable, flexible and tunable, and has potential vital applications for optical switches in dense wave division multiplexing (DWDM) systems.

10019-9, Session 2

The realization of optical switching generated from the combination of Ag/a-Si/p-Si memristor and silicon waveguide

Dongyang Li, Univ. of Electronic Science and Technology of China (China) and Southwest Univ. for Nationalities (China); Anran Guo, Qinjian Song, Guohui Guo, Wei Li, Univ. of Electronic Science and Technology of China (China)

Much attention has been attracted by applications of memristor in data storage, unconventional computing, and logic circuit since 2008, but very few have been focused on applications in optical switches and optical modulators. Here, by combining a silicon waveguide with a memristor of Ag/a-Si/p-Si structure, a novel

optical switch (OS) for use at 1.55 ?m has been set up. The device consists of a bottom p-Si waveguide, an upper a-Si layer and a top Ag electrode, i.e. a sandwich structure named as Ag/a-Si/p-Si. The light signal transmitting through the silicon waveguide can be modulated by changing optical parameters of a-Si dielectric layer in which the formation and annihilation of Ag filament can be adjusted by an alternately electrical field between Ag and p-Si electrodes. The distribution of optical field intensity dependence on the thickness and refractive index of a-Si layer as well as the geometric size of waveguide have been studied by numerical analysis. The optical switching behavior has been simulated and the effect of area size of Ag layer on the light signal through the OS has also been studied. Finally, based on Ag/a-Si/p-Si sandwich structure and the simulated results, we have proposed a novel variable optical attenuator (VOA) and demonstrated its function by numerical simulation.

10019-10, Session 2

High efficiency single transverse mode photonic band crystal lasers with low vertical divergence

Shaoyu Zhao, Hongwei Qu, Aiyi Qi, Yun Liu, Xuyan Zhou, Yuzhe Lin, Wanhua Zheng, Institute of Semiconductors (China)

High efficiency 980nm longitudinal photonic band crystal (PBC) edge emitting laser diodes are studied. The calculated results show that eight periods of Al0.1Ga0.9As and Al0.25Ga0.75As layer pairs can reduce the vertical divergence to 10.5° full width at half maximum (FWHM). The broad area devices show a high internal quantum efficiency ?i of 95% and low internal loss ?i of 1.38 cm-1. Ridge waveguide (RW) lasers with 4um and 5um strip width are fabricated. Both of them achieve good lateral beam quality factor M2 less than 2 at 500 mA, measured using the second moment method as recommended in ISO 11146. The light current voltage (LIV) characteristics of 5 um strip width uncoated devices with different cavity length are measured, and the continuous wave (CW) threshold at room temperature are 40 mA, 48 mA and 55 mA for 1 mm, 2 mm and 3 mm cavity length devices, respectively. Due to the high internal quantum efficiency and low internal loss, the per-facet power conversion efficiency (PCE) exceeds 25% for each cavity length device. In order to achieve high power and high efficiency at the same time, the 3 mm RW lasers are coated with 99% high reflection (HR) and 4% anti reflection (AR). The coated devices obtain 425 mW single transverse mode output power at 500 mA CW operation with high PCE of 46%, narrow vertical divergence 11.1° and lateral divergence 6.8° (FWHM). The slope efficiency and threshold are 0.94 W/A and 44 mA, respectively.

10019-19, Session 2

Preparation and evaluation of perovskite solar cells in the absolute atmospheric environment

Xiaohui Wang, Univ. of Science and Technology of China (China)

The methylammonium lead halide (CH3NH3PbX3, X = halogen; CH3NH3: MA) based perovskite solar cells stand out from many new solar cells in recent years, and attract the attention of many scientific researchers. The PCE of perovskite solar cells are very good even compared with the traditional solar cells, but it is very difficult to fabricate perovskite solar cells in the ambient air condition, especially when they interact with moisture in air. In this paper, we report fabrication of perovskite solar cells completely in air using a two-step technique without using a glove box, and all materials were just stored in ambient air. The current density (Jsc), open circuit voltage (Voc), fill factor (FF), and PCE of the solar cells are tested and studied.

The cross-section SEM image of the perovskite solar cells exhibits a well-defined layer-by-layer structure with clear interfaces. The thicknesses of the compact TiO2, perovskite, and the HTM layer are 60, 310, and 220 nm, respectively. As reported before, the thickness of the perovskite layer around 310 nm is optimal and sufficient to serve as the light-absorbing layer. XRD pattern shows main diffraction peaks centred at 14.2° (110) and 28.5° (220), which can be assigned to the CH3NH3PbI3 phase, suggesting a crystal structure, and the peak centred at 12.7° is attributed to PbI2. We observed unreacted PbI2 remained, which means the conversion of PbI2 to perovskite on exposure to the MAI solution is incomplete. Our best Jsc is 19.2 mA/cm2, the best Voc is 1.0 V, the best FF is 0.65, and the best PCE is 10.2%.

10019-12, Session 3

Investigation of advanced pre- and post-equalization schemes in high-order CAP modulation-based high-speed indoor VLC transmission system *(Invited Paper)*

Yiguang Wang, Nan Chi, Fudan Univ. (China)

Light emitting diodes (LEDs) based visible light communication (VLC) has been considered as a promising technology for indoor high-speed wireless access, due to its unique advantages, such as low cost, license free and high security. To achieve high-speed VLC transmission, carrierless amplitude and phase (CAP) modulation has been utilized for its lower complexity and high spectral efficiency. Moreover, to compensate the linear and nonlinear distortions such as frequency attenuation, sampling time offset, LED nonlinearity etc., series of pre- and post-equalization schemes should be employed in high-speed VLC systems. In this paper, we make an investigation on several advanced pre- and post-equalization schemes for high-order CAP modulation based VLC systems. We propose to use a weighted pre-equalization technique to compensate the LED frequency attenuation. In post-equalization, a hybrid post equalizer is proposed, which consists of a linear equalizer, a Volterra series based nonlinear equalizer, and a decision-directed least mean square (DD-LMS) equalizer. Modified cascaded multi-modulus algorithm (M-CMMA) is employed to update the weights of the linear and the nonlinear equalizer, while DD-LMS can further improve the performance after the pre-convergence. Based on high-order CAP modulation and these equalization schemes, we have experimentally demonstrated a 1.35-Gb/s, a 4.5-Gb/s and a 8-Gb/s high-speed indoor VLC transmission systems. The results show the benefit and feasibility of the proposed equalization schemes for high-speed VLC systems.

10019-13, Session 3

Flexible metallic transparent conductive networks for optoelectronic applications *(Invited Paper)*

Bing Han, Jinwei Gao, South China Normal Univ. (China)

Transparent conductive electrodes are essential components in many modern optoelectronic applications, such as, touch-screen displays, LCDs, OLEDs, wearable electronics, and solar cells etc. New optoelectronic devices need materials with not only high optical transmittance and electrical conductivity, but also mechanical stability and flexibility. Traditionally, doped metal oxides play an important role in this field. However, doped metal oxides could not meet the demand of new optoelectronic devices due to their highly brittle and the increasing cost. Recently, we

propose two new strategies. In first one, we demonstrated a novel approach, based on the “cracking phenomenon” to fabricate metallic networks, which mainly includes four steps: synthesis and deposition of TiO2 film (as a crack material), self-cracking, metallic film deposition, and template film lift-off. The metallic network electrodes with micrometer pitch and sub-micrometer metallic lines, showing good electro-optical properties (with transmittance ranging from 82 % (with ~4.2 ?/sq sheet resistance) to 45% (with ~0.5 ?/sq sheet resistance)) and good flexibility.1 In another case, we studied two bio-inspired networks for two specific optoelectronic applications. The first network, intended for solar cells, light sources, and similar devices, has a quasi-fractal structure and is derived directly from a chemically extracted leaf venation system. The second network is intended for touch-screens and flexible displays, and is obtained by metalizing a spider’s silk web. We demonstrate that each of these networks attain an exceptional optoelectronic and mechanical performance for its intended purpose, providing a promising direction in the development of more efficient optoelectronic devices.2

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10019-14, Session 3

Optical implementation of neural learning algorithms based on cross-gain modulation in a semiconductor optical amplifier

Qiang Li, Zhi Wang, Yansi Le, Chonghui Sun, Xiaojia Song, Chongqing Wu, Beijing Jiaotong Univ. (China) and Key Lab. of Luminescence and Optical Information (China)

Neuromorphic engineering has a wide range of applications in the fields of machine learning, pattern recognition, adaptive control, etc. Photonics, characterized by its high speed, wide bandwidth, lower power consumption and high parallelism, is an ideal way to realize ultrafast spiking-based information schemes. Synaptic plasticity is believed to be critical for learning, memory and development in neural circuits. Experimental results have shown that changes of synapse are highly dependent on the relative timing of pre- and postsynaptic spikes. Synaptic plasticity in which presynaptic spikes preceding postsynaptic spikes results in strengthening, while the opposite timing results in weakening is called spike-timing-dependent plasticity (STDP) learning rule. And synaptic plasticity has the opposite effect under the same conditions is called anti-STDP learning rule. We proposed and experimentally demonstrated an optical implementation of neural learning algorithms, which can achieve both of STDP and anti-STDP learning rule, based on the cross-gain modulation (XGM) within a single semiconductor optical amplifier (SOA, IPSAD 1501C). The weight and height of the potentitation and depression window can be controlled independently, through the adjustment of the injection current of the SOA, to mimic the biological STDP and anti-STDP learning rule more realistically. As the injection current increases, the width of depression and potentitation window decreases and height increases, due to the decrease of recovery time and increase of gain under a stronger injection current. Based on the demonstrated optical STDP and anti-STDP circuit, ultrafast learning in optical spiking neural networks can be realized.

10019-15, Session 3

Detection of atmospheric boundary layer height in the plum rain season over Hangzhou area with three-dimensional scanning polarized lidar

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The atmospheric boundary layer can be directly influenced by the ground and it is closely related to human activities, so the detection and investigation of the atmospheric boundary layer is very important. Due to the abundant rainfall in the plum rain season in Southern China, the atmospheric boundary layer height (ABLH) is very different from any other time of the year. Lidar is an active remote-sensing instrument, and the advantage of high spatial and temporal resolution makes it very suitable for the detection of the atmosphere. In this paper, a three-dimensional (3D) polarized Lidar is introduced and the structure will be given in detail. Compared to traditional one-direction ground-based Lidar, the pointing of the 3D scanning Lidar is very flexible and can be adjusted to any direction within the up hemisphere (360 degrees by 90 degrees) in a very short time. The ABLH in the plum rain season (from May to June 2016) over Hangzhou area (30°16? N, 120°07? E) were observed and different derivation methods, such as the wavelet covariance method, the gradient method and the profile fitting method, were carried out and compared in detail. The results show that the wavelet covariance method shows better stability than the gradient method and better accuracy than the profile fitting method. This work brings a more flexible and accuracy way for the ABLH detection and will be of great importance to the atmospheric study during the plum rain season.

10019-16, Session 3

Design of real-time wireless and high-precision photoelectric autocollimator

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This paper presents the design of a real-time wireless and high-precision photoelectric autocollimator. Firstly, long exit pupil distance and no vignetting optical system is proposed. Compared with the conventional optical system of autocollimator, it solves the problem of ray cutting because of the limitation of objective lens diameter by adding an aperture in the optical system and selecting optical structure with long exit pupil distance. Besides, it eliminates the influence of stray light in the optical system by the use of polarization beam splitting system. Then, the design of photoelectric detection system is discussed. After emulational and experimental analysis, adoption of a camera with a high signal to noise ratio and high frame rate can improve the real-time measurement precision. The detection software uses the specific multi-frame superposition algorithm based on high speed CMOS camera. The centroid coordinates of multi-frame images are averaged according to the FIFO(first in first out) rule, and meanwhile adaptive thresholds and self-adapted matching windows are used for improving the real-time measurement accuracy. Furthermore, the measurement result can be transmitted wirelessly to a tablet personal computer which is convenient for the staff to adjust the instrument during the experiment. Finally, relevant test results of the instrument are given. The measurement accuracy of the autocollimator can reach up to 0.1? with the measurement range of 1200? and the single measurement time is less than 17 ms. In comparison to conventional autocollimator, the measurement accuracy and

measurement range have been improved. Meanwhile, it has the advantages of real-time and remote operation.

10019-11, Session 4

High-efficiency circular polarizer based on all-dielectric Huygens metasurface

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We demonstrate an all-dielectric circular polarizer with high efficiency and broadband response in the microwave region by leveraging the recently developed Huygens metasurface. Due to the symmetry breaking of the structure in the light propagation, one state of the circularly polarized light can pass through freely, while the other state is largely blocked. Specifically, the maximum transmission reaches 0.97 with a polarization suppression ratio of 911:1, which represents a major advance in the performance compared with previously reported circular polarizers. The circular polarization selectivity here originates from the simultaneous excitation of the Mie-type electric and magnetic dipole resonances within an all-dielectric rotationally twisted strips array. The proposed structure possesses the merits of high efficiency and simple inclusions and paves a way to construct polarization devices by cascading tensor Huygens surfaces with all-dielectric materials.

10019-17, Session 4

Development of next-generation nanolithography methods to break the optical diffraction limit *(Invited Paper)*

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Nanolithography is a key technique for nanoscale pattern definition. In the fields of photolithography, major advancements in resolution have historically been achieved through use of shorter wavelengths of light due to the optical diffraction limit. Using phase shift mask and immersion technology, it has already been demonstrated that 193 nm photolithography can produce sub-50 nm features. Along this path, such improvements come with an ever increasing cost for photolithographic tools. The escalating cost for photolithography tools is driven by the need for complex sources and optics. The cost for a single tool has exceeded $60M, a prohibitive number for many users. As a result, researchers are looking at low cost alternative methods for printing sub-50 nm features. Here we present two low cost high resolution lithography methods which could become the next generation lithography tool selection.

Recent studies have showed that extraordinary optical transmission and nanoscale spatial resolution could be achieved with the use of nanoscale antenna benefiting from the enhanced transmitted light confined in the tips. We demonstrated that laser direct writing with nanoscale antenna could achieve sub-50nm resolution with very low cost.

Nanoimprint lithography has made tremendous progress since its initial development. The number of technical hurdles that must be cleared before it is recognized as fully competitive with photolithography for sub-50-nm patterning is dwindling. Patterning resolution has been demonstrated down to 20 nm, with precision overlay/alignment requirements of multilevel device fabrication of better than 10-nm alignment resolution.

10019-18, Session 4

Modeling of current gain compression of a tin-incorporated group-IV alloy-based transistor laser

Ravi Ranjan, Prakash Pareek, Mukul K. Das, Indian School of Mines (India)

The transistor laser (TL) is a unique optoelectronic device that can be use simultaneously as a transistor and a laser [1]. In TL a quantum well (QW) is incorporated in base region for lasing action so, direct bandgap III-V material has been used in TL. Group IV semiconductor like Si and Ge are always a good choice of materials for devices, yet not suitable for light emitting devices because of their indirect bandgap nature. Bandgap engineering of Ge creates an opportunity for direct bandgap group IV material. So, silicon-germanium-tin (SixGeySn1-x-y) alloys have been attracting a great deal of attention in recent years. In this perspective, authors propose a simple theoretical model for mid infrared TL based on Tin incorporated group IV material and calculate its optical parameters in previous work [2].

In this work we obtain the collector currents as a function of collector-emitter voltage (VCE) for different injected base current in common-emitter (CE) mode for Si-Si0.12Ge0.73Sn0.15/Si0.11Ge0.73Sn0.14 n-p-n transistor laser (TL) with strain balanced Ge0.85Sn0.15 single quantum well (QW) in the base. The proposed TL structure and values of relevant material parameters are taken from [2]. Laser rate equation and continuity equation are used to calculate collector current (IC) and base current (IB) as a function of collector-emitter and base-emitter voltages. It is observe that for base currents smaller than the threshold base current (IBth=1.5 mA in given structure) the current gain (?≈131) is almost constant and it work as a normal transistor. However, as the base current exceeds IBth, the current gain decreases due to the stimulated recombination process in the QW. The variation of ? with respect to IB is also shown to illustrate gain compression above threshold base current.

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10019-20, Session 4

Gain-switched thulium-doped fiber laser with ultra-wide tuning range

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Lasers working in the nominally “eye-safe” 2 ?m region have attracted significant attention due to their wide range of applications in, for example, optical communications, remote sensing, material processing, medicine, as well as nonlinear frequency conversion. For many of these applications, a widely tunable source working in the pulsed regime is required or highly desired due to the flexibility it can provide in operation wavelength and temporal characteristics. The thulium-doped fiber laser (TDFL) is a promising candidate for achieving wideband tunable operation at ~2 ?m thanks to the distinctively broad emission spectrum of thulium doped in silica glass. In this contribution, we present a gain-switched ultra-wideband tunable TDFL built in an all-fiber format. A fiberized grating-based tunable filter is used to select the operation wavelength. Pulsed operation of the TDFL in the nanosecond regime is realized

through gain switching the system using a 1550 nm fiber master oscillator power amplifier (MOPA) seeded by an electrically modulated semiconductor diode laser. This TDFL features a remarkably wide tuning range spanning 1765 – 2055 nm (24 THz in frequency terms). The nearly 300 nm tunability doubles the record tuning range of existing gain-switched fiber lasers, and to the best of our knowledge, presents the broadest tuning range that has been reported for a monolithic pulsed fiber laser to date. The TDFL can operate at a repetition rate of 5 – 100 kHz with a pulse width as short as 300 ns. A modest compromise in the tuning range allows pulse width reduction to sub-100 ns.

10019-38, Session Post

Optical characteristic analysis of optical fiber near-field and far-field

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In this work, definitions of mode-field radius and divergence half-angle were analyzed according to different kinds of methods. Then, numerical calculation of these definitions was given for the LP01 mode in symmetrical step-index optical fiber and results proved that the matching efficiency method-based, entropy-based, power in the bucket-based and 1/e2-based mode-field radii and divergence half-angles are suitable for illuminating the near-field and far-field characteristic respectively compared to the two well-known second order moment-based and differential operator-based definitions. These conclusions may provide a theoretical groundwork for designing optical fiber devices and further researching the propagation characteristic of optical fiber.

10019-39, Session Post

Investigation on optical and acoustic fields of stimulated Brillouin scattering in As2S3 suspended-core optical fibers

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The optical and acoustic fields of stimulated Brillouin scattering (SBS) in the As2S3 chalcogenide suspended-core microstructured optical fibers (MOFs) are investigated by the finite-element method (FEM). The optical and acoustic fundamental modes are analyzed at 1550 nm. The core diameters of the MOFs vary from 1 to 6 μm. For each case, the holes of the MOFs are filled with different materials such as trichlormethane (CHCL3), alcohol and water. When the core diameter is 6 μm, the maximum peak intensity of the optical fundamental mode is in the case with air holes, while the minimum value is in the case filled with CHCL3. The ratio of difference is ~0.66%. The minimum peak intensity of the acoustic fundamental mode is in the case with air holes, while the maximum value is in the case filled with water. The ratio of difference is ~0.13%. The same rule occurs in the fiber cores of 4.5, 3 and 2 μm, where the decreases of ~0.97%, 1.48%, 1.94% for optical field and the increases of ~0.24%, 0.34%, 0.74% for acoustic field are obtained, respectively. When the core diameter is 1 μm, ratios of difference for optical and acoustic fields are much higher than those in the cases of 2-6 μm, which are ~3.55% and 29.13%, respectively. The overlap factors between optical and acoustic fields are calculated, which are changed with the core diameter and the filled material. Our results will be helpful to strengthen or suppress the SBS effect in practical applications.

10019-40, Session Post

A short-range optical wireless transmission method based on LED

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A short-range LED optical wireless transmission method is proposed in this paper. Furthermore achieved one to many images transmission through this method. The system makes MCU to be the mater controller. C# is used to convert the original data of file format to binary data matched USB. MCU encode the binary data getting from terminals by USB and modulate the encoded signal using PWM. Drive Circuit load the modulated signals to LED. Also, MCU control on-off of LED with signal. Optical signal is detected by PD, through amplified and filtered for shaping wavefrom on receiver, MCU demodulated and decoded the signal back to binary data. Then send to terminals like PC and reverted back to original image. Analysis the performance from power, power consumption of transmitter, relationship of bit error rate and modulation mode, compare modulation OOK with PWM, influence of ambient light, respectively. The results shows that both the images can be received accurately which uses this method. The transfer rate can get to 1Mbit/s using PWM modulation mode on stabilization system with transmitter LED source of 1w, and the ambient light effect little to the LED transmission method in normal light environment. The method is convenient to carry LED wireless short range transmission for mobile transmission equipment as a supplement of Bluetooth short-range transmission for its electromagnetic wave interfere problem, and the analysis method in this paper can be a reference for other similar systems.

10019-41, Session Post

High-efficient slanted grating coupler for perfectly-vertical coupling in optical integration

Yanan Guo, Yongqing Huang, Xiao-Min Ren, Beijing Univ. of Posts and Telecommunications (China)

A high efficient slanted grating coupler is proposed and demonstrated for perfectly-vertical coupling between optical fibers and silicon-on-insulator (SOI) waveguides. In the coupler, the gratings are periodically etched on the 8°slanted silicon layer of the SOI wafer ,the light from the fiber normally incidents on the coupler and then horizontally propagates to the planar waveguide layer. The properties of the slanted grating coupler are numerically studied with the eigenmode expansion method and simulated by COMSOL software based on the Finite Element Method (FEM). The calculated and simulated results indicate that the vertical-coupling slanted grating coupler offers a much higher coupling efficiency of 88.6% than the common planar grating coupler (~79%) under oblique incidence of the fiber at the wavelength of 1550 nm for transverse electric (TE) polarization, as well as a broad 1 dB bandwidth of 40 nm based on the optimized design parameters including grating period, etch depth, filling factor, buried oxide layer (BOX) thickness of SOI, the slanted angle of the grating layer and so on. It is noted that the device designed here not only enables a compact high efficient optical coupling process with a rather large fabrication tolerance, but also has great practically potentials in future optical interconnections and large-scale nanophotonic integrated circuits.

10019-42, Session Post

Directional emission microcavity lasers with different device structures

Chang-ling Yan, Changchun Univ. of Science and Technology (China)

Micro-cavity lasers, such as micro-disks, in which the lights are confined with a small mode volume and high quality factor (Q-factor), have been worldwide investigated. However several obvious disadvantages still impede their further development, such as low optical power output and isotropic far-field profile pattern due to their circular symmetric device structures. To overcome the intrinsic problems, the deformed structures were proposed, including stadium-shaped lasers, bow-tie mode lasers, spiral-shaped lasers, and so on. For the lasing material aspect, a wide material range from dye-doped polymer organic material to quantum well and quantum dots structure semiconductor material has been widely used in fabrication of the micro-cavity lasers. Among those materials, electrically pumped mid-infrared quantum cascade lasers (QCLs) are of special interest because they are unipolar devices and hence they are not sensitive to undesirable surface recombination. In addition, mid-infrared QCLs have a relatively long emission wavelength, therefore reducing scattering losses due to roughness along the etched sidewalls of the micro-cavity structures. In this paper we will present directional emitting micro-cavity lasers with different structures of limason, triangle and ellipse shaped cavities. The mechanism of directional emission for these deformed micro-cavity structures is investigated and compared. In experiment, mid-infrared InP based InGaAs/InAlAs quantum cascade laser material with about 10?m wavelength is employed to fabricate these micro-cavity lasers. Their lasing output characteristics such as light output power level, threshold current density, and far-field profile pattern are investigated and also compared.

10019-43, Session Post

The research of multi-alkali vacuum photodiode on heating and illuminating

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A novel concept for solar cell technology, photon-enhanced thermionic emission (PETE), was proposed for harvesting photonic and thermionic energy simultaneously. Researches show that the conversion efficiency of PETE is pretty high, calculated efficiencies for idealized devices can be above 50%, which is exceed the theoretical limits of single-junction photovoltaic cells. To explore whether the vacuum device can exhibit good performance under the conditions that combines illumination and heating, a multialkali vacuum photodiode is used as a quantum and thermal energy converter. The band gap of multialkali cathode is 1.1eV and the multialkali photocathode is employed at temperature below 100?.The current-voltage characteristic curve is measured under two different temperature conditions, so is the power-voltage curve. And the conversion efficiency of the multialkali vacuum photodiode is also calculated on the basis of experiment data. The experiment results show that the power converted by a heated and illuminated condition is greater than that obtained under illumination at room temperature or heating without illumination. The conversion efficiency of the multialkli vacuum photodiode is higher than that not be heated. This paper shows that the multialkali vacuum device presents better performance under the combined conditions. Although the power production and conversion efficiency are not very high in this research, the experiment demonstrates how the two forms of quantum and thermal of solar energy can be simultaneously utilized.

10019-44, Session Post

Chromatic dispersion and polarization-mode dispersion insensitive optical signal-to-noise ratio monitoring based on electronic variable optical attenuators and optical bandpass filter

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In this paper, an optical signal to noise ratio(OSNR) monitoring method is proposed based on radio-frequency(RF) power measurement of two signals in parallel connection. The signal is split into two parallel branches equally. One branch signal is filtered by a optical bandpass filter to remove out-band noise and the other transmits the electronic variable optical attenuators with power lock control loop to keep the output power costant. The RF power changes at the same position of the dual branch signal processed in different ways present falling and rising trends respectively with the increase of OSNR. The difference of RF power at the same position is used to monitor OSNR. The simulation results show that the proposed technique can monitor OSNR from 2 to 30 dB with less than 1.5dB error in a 40Gb/s non-return-to-zero differential quadrature phase-shift keying(NRZ-DQPSK) transmission system, which is insensitive to chromatic dispersion impairment and polarization mode dispersion impairment.

10019-45, Session Post

All-optical quantization by slicing supercontinuum in a Ge11.5As24Se64.5 rib waveguide

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All-optical Analog-digital-conversion (ADC) are widely investigated in photonic integrated highly nonlinear waveguide for all-optical signal processing. All-optical quantization, as the key part of ADC, has been researched in various fields. However, it urgently to improve the quantization resolution and power consumption due to the limitation of the low waveguide nonlinearity. Chalcogenide glass (ChG) waveguide as an attractive candidate is adopted in supercontinuum (SC) generation and integrated photonic circuit because of its excellent characteristics, such as high third-order nonlinearity and easy integration. In this paper, the geometrical parameters of Ge11.5As24Se64.5 rib waveguide are optimized, making it achieves the low positive dispersion and high nonlinear coefficient which equals to 137.8/W*m at 1550nm . The range of input pulse peak power is between 0.54W and 0.9W with 100 fs pulse width. The quantization is realized by slicing the generated highly coherent SC with an arrayed waveguide grating (AWG) on the anti-stoke side. A 4-bit quantization resolution along with an effective number of bits (ENOB) of 3.985 and a signal-to-noise ration of 23.99 dB are achieved by appropriate design of the AWG center wavelength.With this method, the maximum

difference error which is lower than 0.08 is achieved.Finally, we propose a schema of improving quantization resolution by using tunable optical attenuator which can adjust the output power of the AWG and demonstrate its feasibility by numerical simulation.

10019-46, Session Post

High-performance transparent conductive film with an embedded Ni metal mesh based on selected metal electrodeposition process

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An ultra-flexible and low-sheet resistance transparent conductive film is developed from nickel metal-mesh (Ni metal-mesh) embedded in a polyimide (PI) by exploiting selective deposition technique coupled with photolithography and subsequent inverted film-processing method. The novel fabrication process exploits a metal selective electrodeposition technique to substitute vacuum-based metal deposition, which is crucial for low-cost, large-area devices fabrication. The fabricated conductive film achieved sheet resistance values as low as 0.15 ?/sq, with corresponding optical transmittance as 80% at 550 nm. Those data indicate that the figure of merit for the conductive film can achieve to 1.1*10^4. Due to the embedded nature of the film, the film shows excellent adhesion and also preserves its structural integrity and good contact with the substrate for severe bending showing less than 4% decrease of conductivity even after 10^4 cycles. Finally, employing the fabricated Ni metal-mesh/PI conductive film, a hybrid transparent thin-film heater is demonstrated, which exhibited higher heating temperatures (110 oC) under the lower operating voltage (1 V), lower power consumption (79.1 oC cm^2 W^-1), and shorter response time (T < 2 s) than other exiting heaters, as well as stability after repeated test. With superior performance and the low-cost, large-area fabrication process, our results demonstrated the metal-mesh/PI hybrid conductive film has broad applications in flexible and stretchable optoelectronic devices.

10019-47, Session Post

Multimode fiber-focusing lens-based plasmonics

Chunying Guan, Harbin Engineering Univ. (China)

In recent years, the prospects for the application of the beam tailoring have attracted widespread attention for scientific research and commercial development. Plasmonics has emerged as a technology that enables the creation of a wide range of miniaturized and nanostructured photonic devices. A planar lens based on a nanoscale slit array was recently demonstrated experimentally. We can design different geometrical structures on the fiber ends. The surface plasmon wave is modulated by the micro structures, and the focusing lens of the all-fiber integrated beam can be realized. The use of metal provides the advantage of much higher index contrast over dielectric structures, resulting in a stronger focusing capability for lenses as well as a convenient planar geometry.

In the present work, a compact all-fiber plasmonic focusing lens is proposed and demonstrated in a conventional multimode fiber. Here, the focusing beam generator is composed of a single slit and a 1D groove array on the gold film deposited end facet of an optical fiber. The arrays of nanoscale slits with varying widths in a planar metallic film can be used to focus the light due to the modulated phase distributions. An all-fiber focusing beam generator provides many advantages, such as no need for alignment systems, high flexibility, lower insert loss, and easy portability, which is of importance to realize optical trapping, micromanipulation, beam shaping, and fiber integrated devices.

10019-48, Session Post

High-precision long-term stable fiber-based optical synchronization system

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A fiber-based?high precision long-term stable time synchronization system for multi-channel laser pulses is presented?using fiber pulse stacker combined with high-speed optical-electrical conversion and electronics processing technology. This scheme is used to synchronize two individual lasers including a mode-lock laser and a time shaping pulse laser system. The relative timing jitter between two laser pulses achieved with this system is 3.5ps(rms) in five hours. The synchronization system is low cost and can work at ~MHz of repetition rate.

10019-49, Session Post

A four-port vertical-coupling optical interface based on two-dimensional grating coupler

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In this work, a fiber-to-chip vertical-coupled optical interface with 4 ports is proposed. Lights incidences vertically from single mode fiber can be coupled into silicon photonic chips and split into 4 silicon waveguides. If incident light is circular polarized, the power of the light will be equally split into 4 wavguides with all lights travel in 4 channel converted into TE polarization, which is favored in silicon photonic integrated circuits. The optical interface is based on a 2-dimensional grating coupler with carefully designed duty cycle and period. When the fiber is placed perfectly vertical on the top of the grating region, the light beam launched from fiber is coupled in and split into 4 parts with opposite directions. And due to the symmetry of the grating, the split ratio will be a perfect 25:25:25:25 when the vertical fiber is placed right in the grating center. In this condition, the grating cannot only function as a coupler but also a 6-dB splitter at the input interface. Simulation results show that coupling efficiency of each port can reach 11.6% so that total coupling efficiency of the interface is 46.4%. And Lights coupled into 4 waveguides are all converted into TE polarization through the 2-dimensional structure.

10019-50, Session Post

RF spectral analysis for characterisation of mode-locked regimes in fibre lasers

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Mode-locked fibre lasers are known for their plethora of generation regimes with broadly different pulse parameters. Three types of measurements are traditionally used for identification of these regimes: mode-locked pulse train, autocorrelation, and optical spectrum of the mode-locked pulses. In this work, we present our results of RF spectral analysis applied to mode-locked lasers and propose a method of qualitative assessment of mode-locked operation, which allows differentiation of individual generation regimes by a parameter calculated from RF spectra of the fundamental and the n-th radiation harmonics. The proposed parameter is derived both from the signal-to-noise ratio and from width and amount of additional noise present in RF spectrum of inter-mode beats at the fundamental pulse repetition frequency and its harmonic.

The approach to assessment of mode locking quality in fibre lasers that we propose in the present work enables differentiation of pulsed generation regimes observed in fibre lasers with the aid of RF spectral analysis technique, while avoiding other, more complicated types of measurement.

10019-51, Session Post

Solar cells based on InP/GaP/Si structure

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Solar cells based on III-V semiconductors are reviewed. Presented work emphases on the QDs solar cells for next-generation photovoltaic, and questions of modeling, simulation and possibilities of manufacturing of the InP/GaP/Si solar cells are discussed. The challenges that arise from nanostructures technologies are, also, concerned.

10019-21, Session 5

Field trail of 1-tb/s real time single-channel optical transmission system over 1400km fiber link from Wuhan to Shanghai with on-line video service *(Invited Paper)*

Bo Liu, Xiangjun Xin, Lijia Zhang, Beijing Univ. of Posts and Telecommunications (China)

To our best knowledge, we firstly build a 1Tb/s real time single-channel optical transmission system with service. The transmission link is 1400km G.652 fiber link from Wuhan to Shanghai with dispersion management which deteriorates the nonlinear damage. We employ the Nyquist filter technology to improve the spectral efficiency while adopt the coding modulation FEC technology to improve the transmission performance. We find an effective way to manage the OSNR in a real employed fiber link which carriers 100G service. The 1Tb/s optical signal is carried on five subcarriers and modulated by polarization multiplexed 16QAM format. After 24 hour continuous monitor, the system has achieved no error transmission after FEC coding. The on-line video service is successfully carried on the system, which also supports the online chat.

10019-22, Session 5

Mode evolution in polarization maintain few-mode fiber and applications in mode-division-multiplexing systems *(Invited Paper)*

Yan Li, Xinglin Zeng, Jian Wu, Beijing Univ. of Posts and Telecommunications (China)

In the single mode polarization maintaining fiber (PMF), the existence of birefringence implies that the fiber supports two orthogonally degenerate polarized modes that have different effective indices and hence propagate with different group velocities. and the dynamic of combined polarization state can be completely characterized in terms of the Stokes parameters or Poincaré sphere, which have proved to be a useful tool in dealing with transformation of the polarization state. However, in a few mode polarization maintaining fiber (FM-PMF), the neff splitting between modes within a high-order mode group will also causes complex power sharing between elements of each LP mode set. Hence besides the polarization state evolution, the mode patterns in each LP set are need to be analyzed. In 1999, M. J. Padgett and J. Courtial developed a Poincaré sphere equivalent for light beams containing first-order orbital angular momentum (OAM+1/OAM-1) in LP11 mode set. Using this equivalent called the sphere of first-order modes, the analogy between free space cylindrical-lens converters performing mode transformation and wave plates performing polarization state transformation was theoretically investigated.

In this letter, the completed first-order mode (LP11 mode) evolution in PM-FMF is analyzed and represented by analogous Jones vector and Poincaré sphere respectively. Furthermore, with Jones matrix analysis, the modal dynamics in FM-PMFs is conveniently analyzed. The conclusions are used to propose a PM-FMF based LP11 mode rotator and an PM-FMF based OAM generator. Both simulation and experiments are conducted to investigate performance of the two devices.

10019-23, Session 5

Optical polarization detection using integrated metal gratings

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A semiconductor optical polarization detector based on a new lateral p-i-n diode architecture is described. This design provides enhanced responsivity and good blue light detection capability.

A polarizing metal grating was fabricated in the middle intrinsic part of the diode by evaporating aluminium through a grating structure defined in resist. Several thicknesses of aluminium films were investigated for this purpose. Some light managed to get through the thin films and because of the sensitivity of the lateral p-i-n architecture caused a reduction in polarization sensitivity.

Polarization measurements were performed using a goniometer holding a Kodak polarizing sheet. The light wavelength used in these measurements was centred at 630 nm with visible region as spectral width. The same light was used with three different filters to obtain blue, green and red wavelengths of light cantered at 470 nm, 550 nm, and 630 nm respectively. The output voltage of the device was measured for different relative angles between the grating lines and the direction of polarization for the polarizing sheet. The voltage that was measured was developed across a biasing resistor such that the larger photocurrents resulted in lower voltages being measured and vice versa. When the polarization direction of the polarizing sheet and the device grating were aligned, a larger fraction of the incident light would

be expected to get through, producing more photocurrent and thus a lower output voltage.

In conclusion, we have described a grating-integrated semiconductor polarization detector that makes use of a novel base device as the underlying light sensor. The lateral p-i-n junction architecture endows the device with enhanced sensitivity so that it can detect changes in linear polarization even when the incident light is quite week.

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10019-24, Session 5

Experimental measurement of effective refractive index difference for few-mode polarization-maintaining fibers using S2 method

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Polarization maintaining fibers (PMFs) can keep linear polarization state against external perturbations by inducing a high effective refractive index difference (?neff) along one polarization axis. For few mode polarization maintaining fibers (FM-PMFs), ?neff is applicable between both orthogonal linear polarization modes (e.g. LP01x and LP01y) and orthogonal degenerated modes (e.g. LP11a and LP11b), which can enable advanced functionalities in multiple-input-multiple-output-free spatial division multiplexing systems and optical fiber sensing systems. Therefore, the measurement of ?neff for polarization modes and degenerated modes is very important for determining the quality of a FM-PMF. However, measurement of the ?neff for FM-PMFs can be complicated due to the requirement for generating and demultiplexing of the higher order modes (HOMs).

Spatially and Spectrally (S2) resolved imaging method, have become a standard technique for mode content characterization in fibers. In this paper, we propose to measure the ?neff of FM-PMFs using S2 method for the first time. The presented method is simply by employing a tunable laser and an IR CCD camera, can avoid any mode converter or mode multiplexer/demultiplexer, featuring a rapid testing speed. A proof-of-concept experiment is carried out to measure FM-PMFs with a length of 1.1m and 5m. The ?neff between the orthogonal polarization modes (i.e. LP11ax-11ay, LP11bx-11by, LP21ax-21ay, and LP21bx-21by) are characterized as 7.05?10-4, 6.91?10-4, 1.02?10-3 and 1.04?10-3 respectively. The ?neff of the orthogonal degenerated modes (i.e. LP11ax-11bx, LP11ay-11by, LP21ax-21bx and LP21ay-21by) are also characterized to be 1.39?10-4, 1.24?10-4, 5.61?10-5 and 6.53?10-5respectively.

10019-25, Session 5

Uniform flat-top interleaver consisting of a two-stage cascaded Mach-Zehnder interferometer

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Since interleaver was applied in optical communication, its capability of splitting a set of densely spaced channels into several sets of channels with wide channel spacing has attracted much attention. We theoretically study a novel all-fiber asymmetric interleaver consisting of a two-stage cascaded Mach-Zehnder interferometer (MZI). The proposed interleaver has three single mode fiber couplers linked to two differential delays. Based on a comprehensive analysis, we demonstrate that a uniform flat-top spectral response can be obtained through changing the coupling coefficient rj (j=1, 2, 3) of the couplers. The light transmission distance is fairly short in the optical fiber device, thus we take no account of the transmission loss and dispersion in the whole process. First, we observe the change of transmission intensity as a result of altering coupling coefficient under the condition of fixing two coupling coefficient r1 and r2 with the different values of r3. The transmission spectrum of the two outports are comb line shape. Then, we adjust the length of two differential delays in order to achieve an all-fiber interleaver with unbalanced passband. is the physical length of the differential delays designed to be (is the basic value) , corresponding phase delay. The ratio of 1dB bandwidth and 3dB bandwidth at the outports is 71.91%. According to the research above, a near box-shaped spectral response can be generated when we set reasonable parameters, and the passband and stopband of optical interleaver are improved significantly. The degree of our structure is flexible which will be useful in fabricate. And we hope that the asymmetric interleaving features will provide a better solution for unbalanced dense wavelength division multiplexing networks (DWDM).

10019-26, Session 5

A distributed optical fiber sensing system for dynamic strain measurement based on artificial reflection array and rapid phase discrimination

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Phase sensitive optical time domain reflectometry (?-OTDR) has been widely used in many applications for its distributed sensing ability on weak disturbance all along the sensing fiber. However, traditional ?-OTDR cannot make quantitative measurement on the external disturbance due to the randomly distributed position and reflectivity of scatters within the optical fiber. Recently, an ultra-weak FBG (UWFBG) array enhanced ?-OTDR with active laser frequency sweeping has been proposed to realize quantitative measurement on fiber strain variation. Unfortunately, the sweeping scheme consumes too much time, which would limit its application to low frequency measurement only. In this paper, a novel distributed optical fiber sensing (DOFS) system based on artificial reflections array and rapid phase discrimination has been presented for dynamic strain measurement. Two adjacent reflectors in the fiber form a fizeau interferometer. If the interval between the two reflectors is changed, the phase of the interference signal will also be changed. A symmetric 3?3 coupler was introduced to discriminate the phase change through interference intensity. A software based table look-up scheme was proposed to calculate the phase value in real-time. The fiber length fluctuation between the two reflectors induced by external disturbance would then be obtained accordingly. An experiment has been made to demonstrate the validity of the proposed method. The fiber under test was composed by five spools of 20 meter long single mode fiber, which were cascaded with FC/PC connector via fiber flanges. Dynamic strain was applied by an ordinary baffle box on the center 10m section of the second fiber spool. Experimental results have shown that the proposed method has good frequency response characteristic up to 3.2 kHz and a 50dB dynamic range of linear intensity response was successfully achieved at 500Hz while the optical probe pulse width and repetition rate were 100ns and 10 kHz respectively.

Compared with previous sweeping scheme, the proposed method has improved the measurement speed by several orders of magnitude, which could extend the application realm of the DOFS systems to high frequency dynamic strain measurements.

10019-27, Session 5

Improved hybrid polymer/PbS quantum dot infrared phototransistors incorporating single-layer graphene

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Recently, bulk-heterojunction field effect phototransistors (BH-FEpTs) based on poly [2-methoxy-5-(2´-ethylhexyloxy-p-phenylenevinylene)] (MEH-PPV) and PbS quantum dot composites have shown low photo performance in infrared (IR) illumination, due to the inherit poor carrier mobilities of the blends. A good method to improve the performance is integrating the photosensitive blends with graphene, which have high carrier mobility up to 200,000 cm2V-1s-1. In this papers, we fabricated two type of IR FEpTs in solution process: GBH-FEpTs applying single layer graphene beneath the bulk layers and BH-FEpTs based on MEH-PPV and PbS quantum dot composites. The photo sensitive mechanism of GBH-FEpTs can be interpreted as follows. Photo induced carriers generate in blends in the illumination of 808nm laser. When the gate bias is applied on the device, a great number of photo induced carriers are dragged down and then transferred rapidly in the bottom graphene driven by the electric fields. As a result, holes and electrons mobilities in the GBH-FEpTs are promoted up to 2200 and 1890 cm2V?1s?1, two orders magnitude higher than that in BH-FEpT. As photo induced current is in direct proportion to carrier mobilities, higher value up to 0.18mA is achieved in the GBH-FEpTs. The GBH-FEpTs exhibit higher performances in terms of photo responsivity (R) ~ 108 A/W at a light intensity (4.9 mW/cm2), higher external quantum efficiency (EQE) (more than 1?104 %) and higher specific detectivity (D*) (2?1012 Jones). The cooperation of photosensitive organic and inorganic composites with graphene may provide a convenient route for IR photo detectors design with high performances.

10019-28, Session 5

A calibration method for photon counters using a customized standard light source

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Photomultiplier tubes (PMTs) are the most common photoelectric conversion apparatus used as photon counters. Because the dark count and other properties of PMTs are greatly influenced by temperature, photon counters need calibration. Traditional solutions for calibration of photon counters are either based on the inverse square law of illumination, or using light-emitting diodes (LEDs) as standard light sources. However, rigid experimental techniques are necessary for these solutions. And the emission spectrum of LEDs does not cover the entire spectrum of detection. This paper presents a calibration method for photon counters using a customized standard light source which can provide full spectrum of weak light from the dark count level to the saturation intensity of PMTs. The photon counter in a light-shielding cavity is connected, via an optical fiber, to the customized standard light source attached with an intensity monitor. The calibration process is discussed and experimental results with chemical reference substance are also presented for comparison.

10019-29, Session 5

Coupling between fiber-optic microring and lithium niobate microwaveguide chip towards photonic interlink devices.

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Lithium niobate (LN) is a key material for electro-optic modulators and various other linear and non-linear optical applications since it possesses a larger electro-optic coefficent and nonlinear optical properties. The most popular and conventional method to fabricate optical waveguide on LN substrate is through ion doping method such as Ti (titanium) indiffusion or annealed proton exchange (APE). Optical microfiber coil or loop or knot resonators have been attracted considerable attention as building blocks for optical micro and nanodevices in recent years. The micro and nanofiber (MNF) devices needs a relatively robust substract to support its stable performance. Therefore, it is meaningful and promising to build an interconnection plaform between fiber-optic micro and nanodevices (such as microfiber knot resonator (MKR)) and the robust LN waveguide chip. We propose a tunable add-drop filter based on MKR coupling into a LN APE waveguide. The width of the LN waveguide is of ~7?m and the adjacent of each LN waveguide distances of 140?m. The initial input light is injected into the input port. When the diameter of MKR (D) and the diameter of microfiber (d) are ~600?m and ~7.5?m respectively, the coupling experimental result shows a free spectral range (FSR) of 0.9 nm and Q value of 25710 at resonant wavelength of ~1594 nm with full width at half maximum (FWHM) of 0.062nm in the transmitted spectra of through port. And the FSR is of 0.6 nm and Q value of 14312.36 at resonant wavelength of ~1540.8 nm with FWHM of 0.089nm when the diameter of MKR and the microfiber are ~850?m and ~10?m respectively.

10019-30, Session 6

A simple and low cost method to fabricate well-controllable and organized silicon nanowire arrays

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We propose a simple and low cost method to fabricate well-controllable and organized silicon nanowire (SiNW) arrays avoiding complicated and expensive lithography techniques. We have performed a series of experiments combined deposition of a monolayer of polystyrene nanospheres, deposition of silver film, silver film annealing and a wet chemical etching to demonstrate the controllability of density, length and diameter of SiNWs. Our methods leads to a well-organized SiNW arrays which is preferable for specific optoelectronic applications compared SiNWs which are grown with random orientations. Our previous published work have studied Heterojunction of poly (o-toluidine) and SiNWs. Now we are aiming to replace the random growth of SiNWs by a well organized and controllable SiNW arrays. We believe that it will enhance the performance of our device as a heterojunction diode and also as a hybrid solarcell. Our controllable SiNW arrays are needed to enhance the performance of other optoelectronic devices.

10019-31, Session 6

Characterization of organic solar cells: challenges and applications

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Organic solar cells have been one of the hot spots for research. However, accurate characterization of organic solar cells is still a challenging task. There are lots of doubts concerned to the accuracy and reliability for its efficiency measurement, which is harmful to further research and application of organic solar cells. In this paper, we plan to begin with organic solar cells' own properties, to measure their quantum efficiency and photo-electric characteristic accurately. Firstly, main influencing factors will be analyzed by start with organic photovoltaic materials absorption and spectral response, etc. Study on the corresponding solutions to obtain data which demonstrate the true state for the tested samples. Secondly, measure the quantum efficiency for organic solar cells, choose spectral matched reference solar cells according to the spectral resposivity of organic solar cells, calibrate accurately to obtain its Isc-STC (short-circuit current under standard test conditions). Thirdly, choose finely calibrated and standard spectrum matched double light source solar simulator in A+ classification, then calculate the spectral Mismatch Factor (MMF) according to IEC 60904-7, to guarantee the value accuracy during measurement. Combining with metrology technologies for critical parameters, this paper will demonstrate accurate measurement method for organic solar cells, so that provide strong support for this field's healthy and effective development.

10019-33, Session 6

Organic semiconductor materials and devices for visible light communications

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Visible light communications (VLC), is an emerging area of wireless data communications, which takes advantage of solid-state lighting infrastructure to provide both illumination and high speed datalinks. Organic semiconductor materials and devices, which have unique properties of solution processability, compatibility with flexible substrates and with large-scale printing technology, enable a host of new practical applications including VLC and more importantly have the capability of addressing some of key challenges in VLC.

Here we report the demonstration of organic semiconductors as fast colour-convertors in hybrid semiconductor light sources for free-space VLC. We show that these materials can improve bandwidths up to 200 MHz, much higher than are possible with conventional LED phosphors. In addition, we report two datalinks based on organic optoelectronic devices, one using an OLED as the transmitter and the other using a PTB7:PC71BM solar cell as the receiver. Simultaneous functions of data communication and energy harvesting of the OPV devices have great implications for the connectivity of future smart devices, many of which could become self-powered units as part of the "Internet of Things" [1].

We also demonstrate large area, all-dielectric fluorescent antennas for spatially multiplexed VLC based on nanoimprinted polymer films. We show that these antennas can emit highly directional, broadband fluorescence through careful grating optimisation [2,3], and can be used as high data-rate transmitters, offering a route to multi-Gbps spatially multiplexed VLC.

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10019-34, Session 7

Electro-optical circuit boards with polymer optical waveguides: A scalable technology for in-chassis connections

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Industry is scaling current technologies with new innovations to enable 56-112Gbps short distance links with copper. Yet, increasing power consumption, design complexity, fabrication challenges and cost with requirements for higher packaging density are pushing industry to seek alternatives for copper. We have developed PCBs with integrated polymer waveguide optical layers [1-4]. In this paper, we present optical/electrical demonstrator with 96-optical channels totaling 2.4 Tb/s aggregate capacity. The demonstrator is tested with 300 Gb/s on-board transceivers, 10-cm- and 20-cm-long embedded waveguides, and connectors with 90° reflectors in a standard PCB. The results show BER 1E-12 at 25Gb/s, <0.1 dB/cm transmission loss and 2.5 dB connector loss. The waveguides were designed with nominal 50 μm core size and 250 μm spacing to match OM3/OM4 fiber ribbons from/to the engines. We show results from another demonstrator with bandwidth density (Gb/s/mm) on-board scaled further 2-4x by increasing optical channel density with 125 μm or 62.5 μm channel spacing. This minimizes real estate allocated for optical traces in the board. We envisage high density waveguides usable in SiPho packages. Furthermore, we show results for fabricating standard electrical interconnect structures e.g. tracing layers, vias, plated vias top/bottom and through new optical layers in PCB stack. Material stability and process compliance test were carried to investigate lamination impact to optical loss. We report results in different process conditions to evaluate new material robustness and long term reliability. Assembly process compliance test results show that O/E PCBs pass 4x T=240°C with stable optical loss measured from polymer waveguides.

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10019-35, Session 7

Novel long-wavelength mushroom-type vertical-illumination PIN photodiode

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We demonstrate a novel InP-based long-wavelength mushroom-type vertical-illumination PIN photodiode. The photodiode consists a PIN structure lattice matched to an InP substrate, it has five layers: p+ InGaAs contact layer, p+ InGaAsP electron diffusion barrier layer, intrinsic InGaAs absorption layer, intrinsic InGaAsP spacer layer and InP collection layer. The operation and performance of the photodiode have been studied using a two-dimensional, drift-diffusion approach utilizing numerical simulation software. We introduce the undercut mushroom-type geometry to overcome the trade-off between the capacitance and the contact resistance, thereby reducing the RC time constant.

First of all, we optimize the absorption layer thickness and the area of the conventional PIN photodiode with the proposed structure to achieve a higher bandwidth. After that, we optimize the absorption layer area of the mushroom-type PIN photodiode. Then we compare the bandwidth of the optimized mushroom-type PIN photodiode and the conventional PIN photodiode. These two types of photodiodes only differ in the area of i-InGaAs absorption layer.

The mushroom-type photodiode has shown 35.62% improvement in bandwidth comparing with the conventional photodiode. The result shows that at 3 V bias, 1.55 ?m wavelength, the optimized mushroom-type PIN photodiode and the conventional PIN photodiode both with 700nm absorption layer have achieved 3dB bandwidth of 29.81 GHz and 21.98 GHz, respectively. To get rid of the electron diffusion and band discontinuity problems, two InGaAsP layers are adopted above and below the absorption layer. The InP collection layer is made 500nm and Gaussian doped for increasing the electric field as well as minimizing the contact resistance.

10019-36, Session 7

Performance optimization of Pnp InGaAs/InP heterojunction phototransistors

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Development of high sensitivity photodetectors with high speed and low power consumption has been a main goal in device research for optical communication applications. Metal–semiconductor–metal (MSM) photodetectors or p-i-n photodetectors can provide high-speed, low noise operation but no internal gain. Avalanche photodiodes (APDs) can achieve high sensitivity due to large internal gain, however, they need high operation voltage and suffer from avalanche noise. It is therefore expected that heterojunction phototransistors (HPTs) can provide an exciting alternative to MSM, p-i-n photodetectors or APDs for the optical communication, which can offer large optical gain without the excessive noise resulting from avalanching.

In this paper, a two-terminal Pnp InP/InGaAs HPT with a floating base (2T-HPT) is fabricated, and numerical simulations are performed to investigate the gain and photoresponse characteristics. To optimize the optical gain and device performance, the precise adjustment of the base doping level, the base width and the compositional grading of base have been investigated. Properly reducing the base width or increasing the range of the compositional grading can greatly enhance the emitter injection efficiency. The effects of high-low doping in collector region and the insertion of a thin, undoped InGaAs layer in the base region of the HPT have also been investigated in detail. It is found the high-low doping in collector can form an electric field to aid carrier transport and the intrinsic layer between emitter and base has functions of reducing knee voltage and the dark current of HPT. Finally, the HPT under high voltages are also discussed.

10019-37, Session 7

On-chip integration for in-plane video transmission using visible light

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We demonstrate here a wafer-level process to fabricate a monolithic photonic integration of a light emitting diode (LED) with a waveguide and photodiode on a GaN-on-silicon platform. Both silicon removal and back-side thinning are conducted to achieve suspended device architecture. A highly confined waveguide that utilizes the large index contrast between GaN and air is used for the connection between the LED and the photodiode. Suspended waveguide is considered as an in-plane escape cone of the LED, and at the other end of the waveguide is the photodiode. The photons emitted from the LED are transported to the photodiode through the suspended waveguide parallel to the LED surface, leading to an in-plane data transmission using visible light. The proof-of-concept monolithic integration paves the way towards the in-plane visible light communication as well as photonic computation on a single chip. The highlights are achieved in our present work.

1, We demonstrate a wafer-level process for achieving monolithic photonic integration of a light-emitting diode with a waveguide and photodiode on a GaN-on-silicon platform. Both silicon removal and back-side thinning are conducted to achieve a suspended device architecture.

2, Experimental results verify that the light being guided in the suspended waveguides plays the dominant role in the induced photocurrent.

3, The integrated system can simultaneously realize light emission, transmission and photodetection. The photons emitted from the LED are transported to the photodiode through the suspended waveguide parallel to the LED surface, leading to in-plane data transport using visible light.

4, The wire-bonded chip can achieve in-plane video transmission via the light emitted from the LED, paving the way towards in-plane visible light communication as well as photonic computation on a single chip.

10020-1, Session 1

A high resolution imaging method used compressive sensing theory based on array detector applications *(Invited Paper)*

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The military and civil applications call for more stringent requirements for the accuracy, timeliness and diversity of information. As a key approach to acquire it, the imaging systems need a substantial performance increase, such as resolution enhancement. In the box of Shannon sampling theorem, raising the resolution means cutting the pixel size of sensor and increasing the number of pixels. This will enlarge the complexity and difficulty of system nonlinearly. Compressive sensing has given a revolutionary solution: Based on the sparsity of signal and sub-Nyquist non-coherent compressed sampling, one can recover the original signal by sparse optimization. It avoids the blind pursuit of an excessively high-resolution sensor.

The single-pixel camera which is developed by Rice University in America is just the limit condition used compressive sensing theory for high resolution imaging. Aiming at the practical application of the optical remote sensing based on array detectors, this paper founds a novel high resolution imaging framework with compressive sensing. The imaging mechanism of single-pixel camera can be contained in the framework. Then a novel compressive sensing reconstructed method with energy compensation is proposed in this framework. The method can overcome the heterogeneity of reconstructed images of single-pixel camera. The simulation experiments deeply discuss the sampling mechanisms with different sampling rates and different image patch sizes for reconstruction. The experimental results show that the image resolution is improved after reconstruction with a high sampling rate or with a big image patch size. The imaging method in this paper can supply a technology reference for compressive sensing application in remote sensing.

10020-2, Session 1

Large field-of-view range-gated laser imaging based on image fusion

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Laser range-gated imaging has great potentials in remote night surveillance with far detection distance and high resolution,even if under bad weather conditions such as fog,snow and rain. However,the field of view(FOV) is smaller than large objects like buildings,towers and mountains,thus only parts of targets are observed in one single frame so that it is difficult for target identification.Apparently, large FOV is beneficial to solve the problem,but the detection range is not available due to low illumination density in a large field of illumination matching with the FOV.Therefore, a large field-of-view range-gated laser imaging is proposed based on image fusion in this paper,first of all,the infrared laser range-gated system is used to acquire two groups of images with small FOV for five dummies under different scenarios in the night,one scenario the dummies are arranged in a row at the distance of 110m,another the dummies distributed in the distance range from 130m to 270m,and the building at 350m is captured as the third group.Then image fusion is used for generating panoramic through above three groups of pictures separately,which is based on the fuction about panoramic image mosaics in OpenCV 3.0 named Stitcher,and the Stitcher fuction is more effective to the night range-gated images by adjusting match confidence and feature extraction methods. Compared with the raw panoramic image obtained by range-gated system directly,the fused images have a larger FOV,and possess more detail information of objects,this illustrates that image fusion is effective to expand the view field of range-gated imaging.

10020-3, Session 1

compressive full-waveform LIDAR with low-cost sensors

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Full-waveform LIDAR is a method that digitizes the complete waveform of backscattered pulses to obtain range information of multi-targets. Compared to conventional LIDAR technique, recording the complete waveform is advantageous to create a dense point cloud for follow-up feature extraction. To obtain high-resolution ranging information, conventional full-waveform LIDAR system are equipped with high-bandwidth sensors, which are expensive. To avoid these expensive sensors, a new full-waveform LIDAR system based on compressive sensing is presented in this paper. Compressive sensing is a technique that can reconstruct sparse signal with a reduced number of measurements compared to conventional Nyquist-Shannon sampling technique. To obtain these measurements, pseudo-random sequences are generated by high-rate arbitrary waveform generator. Electro-optical modulator is utilized with these sequences to modulate the non-coherent continuous-wave laser. Then the backscattered signal becomes a convolution between the sequences and the range information of multi-targets. Finally a low-bandwidth detector and a low-bandwidth analog-digital converter are used to acquire the signal. To reconstruct the high resolution range information, split Bregman iteration algorithm is employed with the measurements using range signal's sparse property. With experiment, it has been proved that, to achieve 0.30 meter ranging resolution, the temporal sampling distance in a conventional full-waveform LIDAR system needs to be 2 nanosecond, which defines the sample rate as 500 Msps. However, using compressive sensing method, the same ranging resolution can be achieved with a 48 Ksps sensor. Experimental results are also discussed for a full-waveform LIDAR system with sub-centimeter resolution using inexpensive low-bandwidth optical sensors.

10020-4, Session 1

Iterative deconvolution methods for ghost imaging

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Ghost imaging (GI) is a new technique in single-pixel imaging. It has been demonstrated that GI has applications in various areas such as imaging through harsh environments and optical encryption.

Correlation is widely used to reconstruct the object image in GI. But it only offers the signal-to-noise ratios (SNR) of the reconstructed image linearly proportional to the number of measurements. Here, we develop a kind of iterative deconvolution methods for GI. With the known image transmission matrix in GI, the first one uses an iterative algorithm to decrease the error

between the reconstructed image and the ground-truth image. Ideally, the error converges to a minimum for Gaussian speckle patterns when the number of measurements is larger than the number of resolution cells. The second technique, Gerchberg-Saxton (GS) like GI, takes the advantage of the integral property of the Fourier transform, and treats the captured data as constraints for image reconstruction. According to this property, we can regard the data recorded by the bucket detector as the Fourier transform of the object image evaluated at the origin (k = 0). Each of the speckle patterns randomly select certain spectral components of the object and shift them to the origin in the Fourier space. One can use these constraints to reconstruct the image with the GS algorithm. This deconvolution method is suitable for any single pixel imaging models. Compared to conventional GI, both techniques offer a nonlinear growth of the SNR value with respect to the number of measurements.

10020-5, Session 1

Development of 36M-pixel x-ray detector for large field of view and high-resolution micro-CT

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Dramatic improvements in consumer-grade digital cameras with regard to the resolution and low light sensitivity, together with the use of synchrotron radiation, make possible a new cost-effective technique for large field-of-view and high-resolution x-ray micro-CT.

Imaging using conventional x-ray sources can only be performed on localized areas, which limits the application of three-dimensional (3-D) x-ray micro-CT in the field of lung specimens with sizes usually in the range of 5–30 mm. An alternative to conventional sources is synchrotron radiation, which can produce large area collimated beams.

In the x-ray imaging, a phosphor screen converts the x-rays into light, and the optical image is captured using a digital single-lens reflex camera with high numerical aperture lenses. The camera used was a 36M-pixel Nikon D800e. The camera's CMOS sensor has 7360 x 4912 pixels with a sensor active area of 35.9 mm wide x 24.0 mm high. Each pixel has dimensions of 4.88 x 4.88 μm. An equivalent pixel size projected onto the fluorescent screen area is an identical value of 4.88 μm. The x-ray field of view is also 35.9 mm x 24.0 mm. Image signals are converted to digital data with a 14-bit format.

Images of a human lung specimen in a plastic bottle with outer diameter of about 30 mm were obtained for studies of 3-D CT imaging. In a slice image, the whole cylindrical body of the plastic bottle was depicted and micro-architectures of the specimen were visualized with around 7 ?m spatial resolution.

10020-6, Session 2

Underwater three-dimensional range-gated laser imaging based on triangular-range-intensity profile spatial-correlation method *(Invited Paper)*

Xinwei Wang, Xiaoquan Liu, Pengdao Ren, Liang Sun, Songtao Fan, Pingshun Lei, Yan Zhou, Institute of Semiconductors (China)

Three dimensional (3D) underwater optical imaging with high resolution and good real time performance is important for marine automatic navigation, scientific research, aquaculture, engineering, archaeology, and natural resources exploration. Underwater 3D range-gated imaging can extend the detection range by a factor of about 3 over conventional underwater stereo cameras with suppressing water backscattering and filtering backgrounds, and also has greater potentials in real-time high-resolution imaging than 3D laser scanning. Up to now, there are two approaches of underwater 3D range-gated imaging. One is realized based on many gate images by time slicing, and the other is realized by spatial correlation of two gate images with trapezoidal range-intensity profiles. It has proved that the latter has a better real time capability. In this paper, a triangular-range-intensity profile spatial correlation method is used for underwater 3D range-gated imaging. Different from the trapezoidal method, in our method gate images have triangular range-intensity profiles by the convolution of laser pulses and gate pulses with equal pulse width and gate time, and the range resolution is improved by a factor of 3. A 3D underwater range-gated laser imaging system is established where a 532nm pulsed laser and an ns-scaled gated ICCD are respectively utilized as illuminator and detector. In experiment, 3D images of artificial fishes, fish net and balls are obtained with mm-scaled resolution, and thus target sizes and distances can be measured. In addition, 3D imaging with video frame rates can also be realized by inter-frame correlation. The research of this paper is beneficial to 3D real-time high-resolution underwater imaging.

10020-7, Session 2

Reflectivity and depth images based on TCSPC

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We described two optical imaging systems which were used to acquire the data for three-dimensional images including reflectivity and depth images of a target when it was illuminated by a MHz repetition rate pulsed laser source based on time-correlated single photon counting technique (TCSPC). The traditional one of which transmitted and received beams path are separated, and we proposed another one called transceiver system of which transmit and receive channels are coaxial. Experimental results produced by both systems showed that the transceiver system had more advantages of less noise from ambient light and no limitation about field area of view. Lack of objective lens for transceiver system, counts of collecting return photons was less, which was prejudicial to construction of 3D images, thus an advanced one named first photon system was presented. Structurally speaking, this one is the same as transceiver system, but the control system is different. As a result, the first return photon per pixel was recorded across system instead of overall return photons per pixel. That's to say only one detected return photon is needed for per pixel of this system to rebuild 3D images of target with less energy and time.

10020-8, Session 2

An Efficient Anti-occlusion Depth Estimation using Generalized EPI Representation in Light Field

Hao Zhu, Qing Wang, Northwestern Polytechnical Univ. (China)

Light field cameras have been rapidly developed and are likely to appear in mobile devices in near future. It essential to develop efficient and robust depth estimation algorithm for mobile applications. However, existing methods are either slow or lack of adaptability to occlusion such that they are not suitable to mobile

computing platform.

In this paper, we propose the framework of the generalized epipolar plane image (GEPI) representation in light field. In this framework, the EPI is obtained by shearing a 2D slice in 4D space and traditional obtention is just a special case sheared in horizontal or in vertical. We formulate the GEPI using two linear functions in mathematic, and the 2D slice in any angle which satisfies the conditions can be called a GEPI. Theoretically, each GEPI can be used for depth estimation, however it does not hold due to the occlusion. By modeling the occlusion in light field, there is at least one GEPI representation which is free of occlusion. We propose to select the best occlusion-free GEPI in light field, and applies an efficient local depth estimation method.

The performance of the proposed algorithm is evaluated in the most popular light field dataset, and compared to the state-of-the-arts. The experimental results demonstrate that the proposed algorithm outperforms the existing local methods especially in occlusion areas, and comparing to the global methods, our algorithm can achieve high-quality depth map under a low time complexity.

10020-9, Session 2

Realization of three dimensional thermal infrared imaging by structured light and binocular vision

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Thermal infrared imaging has broad applications in various fields. However, two dimensional infrared imaging has limited its applications for its lack of spatial information while the current three dimensional imaging in the visible spectrum does not provide thermal infrared information. By utilizing the coded structured light and binocular stereo vision, a 3D infrared imaging system is proposed and constructed with two visible-light cameras and one infrared camera together with a digital projector. Multimodal sensors are integrated to fuse the spatial and thermal infrared information that are acquired through the aforementioned three independent cameras, providing the geometrical size and surface temperature of the target simultaneously. The 3D shape is generated with the involvement of structured light technique, and the registration between different sensors is accomplished based on trifocal tensor and bilinear interpolation. Two sets of experimental investigations with a storage box and a rudder model respectively were undertaken with the system. The results show that the registration of 3D geometric information and 2D infrared image as well as dealing with the resolution difference between the three cameras is successful. The proposed system is non-contact and free of human-intervene, and provides technical reference to its potential applications in industrial detection and medical diagnosis alike.

10020-10, Session 2

Integral imaging-based optical refocusing of 3D objects on their full-depth by using local [delta]-periodic functions and subdivided-elemental images

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The need for the optical three-dimensional (3-D) refocusing method is getting strong since it allow us to optically reconstruct the refocused 3-D images on their real depth with the light fields captured from the input 3-D objects. A periodic ?-function array (PDFA) based method is proposed for 3-D refocusing by use of the inherent sifting property of the PDFA, however, this method has a critical problem that it works only for the 3-D objects located within a specific pickup range That is, the 3-D objects to be imaged should be positioned within a so-called effective-capturing-zone (ECZ).

Thus, an approach for optical refocusing of three dimensional (3-D) objects on their real depth without a pickup-range limitation based on subdivided-elemental image arrays (sub-EIAs) and local periodic ?-function arrays (L-PDFAs) is proposed. The captured EIA from the 3-D objects locating out of the conventional effective pickup-range, is divided into a number of sub-EIAs depending on the object distance from the lens array. Then, by convolving these sub-EIAs with each L-PDFA whose spatial period to that of the sub-EIA, arrays of spatially-filtered sub-EIAs (SF-sub-EIAs) for each object depth can be uniquely extracted. From these arrays of SF-sub-EIAs, 3-D objects can be optically reconstructed to be refocused on their real depth. Operational principle of the proposed method is analyzed based on ray-optics. In addition, to confirm the feasibility of the proposed method in the practical application, experiments with test objects are carried out and the results are comparatively discussed with those of the conventional method.

10020-11, Session 3

Single-pixel hyperspectral imaging *(Invited Paper)*

Jinli Suo, Yuwang Wang, Liheng Bian, Ziwei Li, Tsinghua Univ. (China)

Multispectral imaging is extremely useful and vital for surveying scenes and extracting detailed information. Conventional multispectral imaging methods detect photons of a 3D hyperspectral data cube separately either in the spatial or spectral dimension using array detectors, and are thus photon inefficient and spectrum range limited. Besides, they are usually bulky and highly expensive. To address these issues, this paper presents multispectral imaging techniques using a single bucket detector, to take full advantage of its high sensitivity, wide spectrum range, low cost and light weight. Two mechanisms are proposed: (i) utilizing the gap between the speed of the illumination structuring and single pixel recording, we multiplex the spectral information either in temporal or frequency manner. (ii) utilizing the relative redundancy of illumination patterns' resolution with respect to that of the reconstructed images, we multiplex the spectral information in different positions of a high resolution spatial light modulator. The effectiveness of these two strategies are both validated experimentally.

10020-12, Session 3

Spatial-spectral data redundancy requirement for Fourier ptychographic microscopy

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Fourier ptychographic microscopy (FPM) is a new computational super-resolution approach, which can obtain not only the correct object function, but also the pupil aberration, the LED misalignment, and beyond. Although many state-mixed FPM techniques have been proposed to achieve more accurate and efficient recovery in the past few years, little is known that their reconstruction performance highly depends on the data

redundancy in both spatial and spectral domains. Generally, at least 35% aperture overlapping percentage in the Fourier domain is needed for a successful reconstruction using ordinary FPM method. However, the data redundancy requirements for those state-mixed FPM schemes are largely remained unexplored until now. In this paper, we explore the spatial and spectral data redundancy requirements for the FPM recovery process to introduce spatial-spectral sampling criteria for the conventional and state-mixed FPM techniques. Moreover, an upsampled FPM method is proposed to solve the pixel aliasing problem, and an alternative spectral subsampled FPM scheme is introduced to get rid of the complexity of decoherence and achieve the expected recovery quality with reduced data quantity. All the proposed methods and spatial-spectral sampling criteria are validated with both simulations and experiments, and our results show that state-mixed techniques cannot provide a significant performance advantage since they are much more sensitive to data redundancy. This paper provides both the guidelines for designing the most suitable FPM platform and the insights for the capabilities and limitations of the FPM approach.

10020-13, Session 3

Reconstructing spectral reflectance from digital camera through samples selection

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Imaging spectrophotometers have been widely studied in the reconstruction of the spectral information of the samples. But they require shot several times and long exposure time. Digital cameras have the advantages of higher resolution, shorter exposure time. Researchers try to recovery spectral reflectance from digital camera outputs, such as pseudo-inverse method, wiener estimation, principal component analysis, and independent component analysis. Most of above methods, the camera's responsivity needs to be instrumentally measured while it is often inconvenient. The accuracy of reconstructed spectral reflectance is affected directly by the uniform characteristics of the training samples and test sample. In this study, we propose a method to reconstruct spectral reflectance from RGB images by averaging the selected reflectance of training samples group whose color difference are smaller with the camera outputs of each pixel (testing sample) respectively, and it doesn't require priori knowledge of camera's spectral responsivity. The odd and even sequence numbers of 1269 Munsell color chips were used as training samples and test samples respectively. Different selected numbers of training samples were investigated. The spectral reflectance estimation are evaluated with absolute error, root mean squared error, standard deviations, and Goodness-of-Fit Coefficient. Experimental results prove the reliability of the proposed methods. Especially due to the nature of the proposed method, the reconstructed spectral reflectances are among 0-1, which make them have actual physical meanings.

10020-14, Session 3

light field camera self-calibration and registration

Zhe Ji, Chunping Zhang, Qing Wang, Northwestern Polytechnical Univ. (China)

Monocular light field is famous for the post processing capability in 4D light field, but its limited field of view is a difficult issue to deal with. As the rise of the Multiview light field (MVLF), the registration of MVLF become a new solution and the calibration of MVLF is a key step before the registration. The previous work have studied the calibration of intrinsic parameters in monocular light field or the registration of multiple calibrated cameras, but the work in MVLF has not been concerned.

In this paper, we propose a self-calibrating method to get the pose of light field (LF) and the interval parameters of cameras at the same time. At first, we represent the LF structure as a two-parallel-plane (TPP) model with 5 intrinsic parameters, which describe the proportion and shift of the two planes. Then the 3D projective transformation from the rays to the reconstructed points in LF is studied. Next, with the constraints of ray-ray correspondence in different LFs, we can relate the pose information into the model. Based on all the constraints mentioned before, we can deduce the linear initialization of the parameters, and then a nonlinear refine process is added to optimal the solution. Finally, the different LFs are registered as one with the more accurate parameters. To validate the method, we employ the experiment on both simulated data and a physical light field camera. The stitching result and 3D point clouds registration error of MVLF demonstrate the high performance of the proposed model.

10020-15, Session 3

An effective rectification method for lenselet-based plenoptic cameras

Jing Jin, Yiwei Cao, Weijia Cai, Wanlu Zheng, Ping Zhou, Southeast Univ. (China)

The Lenselet-Based Plenoptic has recently drawn a lot of attention in the field of computational photography and the additional information inherent in a light field allows a wide range of applications. Some preliminary processing of the raw image is significant before further operations.

In this paper, we present a novel method for the rectification of the rotation of the raw image, caused by imperfectly position of microlens array relative to the sensor plane in commercially available Lytro plenoptic cameras. The key of our method is to locate each center of the macroimage, a small portion of the image projected by a microlens according to vignetting. A structuring element was applied to probe the raw image to find subimages where the centers of them have the maximum pixel values compared to the peripheries of the subimages. If the structuring element exactly fits inside a subimage, the brightest pixel -- the center of this subimage -- is regarded as the center of the corresponding macroimage. The error of the center coordinate estimates can be corrected and the angle of rotation can be computed via a subsequent line fitting. We apply our algorithm on two raw images captured with different Lytro cameras and the angle of rotation are -0.3600° and -0.0621° respectively. The rectified raw image is used in further operations, such as extraction of the sub-aperture Images and epipolar images. The experimental results show that our method can address the problem of rotation of raw image efficiently.

10020-16, Session 3

Design of optoelectronic imaging system with high resolution and large field-of-view based on dual CMOS

Hanglin Cheng, Qun Hao, Yao Hu, Jie Cao, Shaopu Wang, Lin Li, Beijing Institute of Technology (China)

With the advantages of high resolution, large field of view and compacted size, optoelectronic imaging sensors are widely used in many fields, such as robot's navigation, industrial measurement and remote sensing. Many researchers pay more attention to improve the comprehensive performances of imaging sensors, including large field of view (FOV), high resolution, compact size

and high imaging efficiency, etc. One challenge is the tradeoff between high resolution and large field of view simultaneously considering compacted size. In this paper, we propose an optoelectronic imaging system combining the lenses of short focus length and long focus length based on dual CMOS to simulate the characters of human eyes which observe object within large FOV in high resolution. We design and optimize the two lens, the lens of short focus length is used to search object in a wide field and the long one is responsible for high resolution imaging of the target area. Based on a micro-CMOS imaging sensor with low voltage differential transmission technology-MIPI (Mobile Industry Processor Interface), we design the corresponding circuits to realize collecting optical information with high speed. The advantage of the interface is to help decreasing power consumption, improving transmission efficiency and achieving compacted size of imaging sensor. Meanwhile, we carried out simulations and experiments to testify the optoelectronic imaging system. The results show that the proposed method is helpful to improve the comprehensive performances of optoelectronic imaging sensors.

10020-17, Session 4

Behavior analysis of video object in complicated background *(Invited Paper)*

Wenting Zhao, Shigang Wang, Wei Wu, Yang Lu, Yunpeng Hu, Jilin Univ. (China)

This paper aims to achieve robust behavior recognition of video object in complicated background.

Features of the video object are described and modeled according to the depth information of three-dimensional video. Multi-dimensional eigen vector are constructed and used to process high-dimensional data.

Stable object tracing in complex scenes can be achieved with multi-feature based behavior analysis, so as to obtain the motion trail.

Subsequently, effective behavior recognition of video object is obtained according to the decision criteria.

What's more, the real-time of algorithms and accuracy of analysis are both improved greatly. The theory and method on the behavior analysis of video object in reality scenes put forward by this project have broad application prospect and important practical significance in the security,terrorism, military and many other fields.

10020-18, Session 4

The efficient model to define a single light source position by use of high dynamic range image of 3D scene

Xu-yang Wang, Changchun Univ. of Science and Technology (China); Dmitry D. Zhdanov, Igor S. Potemin, ITMO Univ. (Russian Federation); Ying Wang, Han Cheng, Changchun Univ. of Science and Technology (China)

One of the challenges of augmented reality is a seamless combination of objects of the real and virtual worlds. One of the object types are light sources. In this paper we consider the solution to restore the coordinates of a light source in the real scene with use of High-Dynamic Range Image (HDRI). The first light source position algorithm was proposed by Zheng in 1991, in order to measure the azimuth angle of the light source, this algorithm analyzes the image containing the marker according to the shadow information of image contour line. In these days, the problem of determining the coordinates of the light source can be based on the research about light source reconstruction has been developing variously, for example, getting the dynamic luminance information from a video, taking a panoramic photo by a pair of fish-eye lens, what's more, classifying and segmenting the complex scenes by the point cloud data.

We suggest a measurement and computation models for reconstruction of light source position. The model is based on the dependence of luminance of the small size diffuse surface directly illuminated by point like source placed at a short distance from the observer or camera. The advantage of the computational model is the ability to eliminate the effects of indirect illumination. One more advantage is that only relative but not absolute values are necessary, and the measurement is worked easily. The paper presents a number of examples to illustrate the efficiency and accuracy of the proposed method.

10020-20, Session 4

X-ray technique application in evaluating the quality of tomato seeds

Xueguan Zhao, Xiu Wang, Beijing Academy of Agriculture and Forestry Sciences (China) and National Research Ctr. of Intelligent Equipment for Agriculture (China) and Key Lab. of Agri-informatics Ministry of Agriculture (China); Cuiling Li, Beijing Academy of Agriculture and Forestry Sciences (China)

The objective of this work was that to investigate the application of X-ray technique in evaluating the quality of tomato seeds and in verifying the effectiveness of the X-ray test to detect damage or abnormalities in tomato seed structure associated with germination. In this paper, using the x-ray camera directly to generate digital images, the radiation exposure condition of 18 Kv generated more precise seed images. The work was carried out with five seed lots each of Xia Lang were used, one hundred seeds per lot were exposed to X-radiation and visually classified into four categories according to the proportion between the area occupied by the embryo and endosperm in relation to the total cavity area in the internal seed structure, e.g. 0, < 40%, 40-65% and 100%. In addition, there is an damage internal structural. X-ray tested seeds were submitted to the germination test to detect possible associations between seed anatomy and its corresponding seedling, and non-germinated seed. Germination test at 25ºC for 20 days. The experiments show that crack in the cotyledon region negatively affected seedling shoot development. These parameters correlate well with the morphology of 14-day old seedlings, the percentage of seeds germination was 32% higher after hand selection based on X-ray evaluation. The results of this work showed an association between the morphological information provided by the X-ray test and the standard germination test, indicating its potential to be applied on tomato seed quality assay.

10020-19, Session Post

Research on key technology of yacht positioning based on binocular parallax

Wei Wang, Ping Wei, Beijing Institute of Technology (China)

Yacht has become a fashionable way for entertainment. However, to obtain the precise location of a yacht docked at a port has become one of the concerns of a yacht manager. To deal with this issue, we adopt a localization method based on the principle of binocular parallax in this paper.

Binocular parallax uses cameras to get multi-dimensinonal perspective of a yacht based on geometric principle of imaging. on access to image pixels between the location of deviation is evaluated to get spatial location information of the yacht.

In order to simplify the yacht localization problem, we install LED light indicators on a yacht. These LED flashes at a certain frequency during day time and night time. After getting the location of the LEDs, locating the yacht is easy. Compared with other traditional localization methods, this method is simpler and easier to implement.

In this paper,we study the yacht locating method using LED indicators. Simulation experiment is done for an object in the distance of 30 meters. We also analyze noise influence, and comparing our method with others using locating results.The experimental result shows that our method is feasible and easy to implement with a small 10% positioning error.

10020-29, Session Post

Propagation characteristics of orbital angular momentum for remote imaging

Li Lu, Air Force Early Warning Academy (China)

The research of orbital angular momentum (OAM) in light beam gradually is becoming an attractive area for quantum information, optical micromanipulation, and optical communication applications. Compared to other conventional methods, OAM can offer new degrees of freedom in addition to traditional linear momentum. Recent years, some researchers verified that OAM can promisingly be used in the low frequency radio domain and not be restricted to the optical frequency range. According to the classical electrodynamics theory, the electromagnetic (EM) field can radiate both energy and angular momentum. The energy of the EM field is associated with translational dynamics, referred to as linear momentum. The angular momentum is connected to rotational dynamics, which can be decomposed into two components: spin angular momentum (SAM) and OAM, the former is associated with polarization, the latter leads to helical phase fronts. L. Allen had studied detailed that generations and torque effects of orbital angular carried by a laser beam. Such beams usually have the characteristics on-axis phase singularity and amplitude nulls at the centers of beams, called optical vortex. Similar to optical vortex, angular momentum carried by the wave in microwave wavelength reveals EM vortex features. The studies on applying OAM to remote imaging have little been proceeded.

In this paper, the propagation charactistics of OAM in EM vortex waves are analyzed, and the applications of remote imaging required to detect OAM in EM vortex waves are descripted and discussed. The results show OAM has the capability to be used for remote imaging system and can be enhanced the performance of target detection.

10020-31, Session Post

Image preprocessing for vehicle panoramic system

Ting Wang, Liguo Chen, Soochow Univ. (China) and Collaborative Innovation Ctr. of Suzhou Nano Science and Technology (China)

The research on image preprocessing for vehicle panoramic system was carried out owing to the problem that distortion exist in panoramic image stitching. Firstly, the fundamental role that image preprocessing(distortion image's correction and bird-eye image transformation) played in panoramic vision was found out. Afterwards,the fisheye camera was calibrated with Hyperboloid model that proposed by Scaramuzza. Through the comparison with conventional perspective camera, a procedure for distortion image's correction was given. As four cameras were mounted in different positions(the front logo,the left and right rear-view mirror and the rear license plate), different field of view(FOV) and installation height may have effects in terms of image correction. Moreover, the central region of distortion image will get a better correction than border area from the imaging principal of fisheye camera. Therefore,through measuring one hundred household cars, the installation height for front logo:65cm, 95cm for rear-view mirror and 58cm,84cm,93cm for rear license plate respectively were taken as experimental installation height. Through the linear fitting for corrected calibration plate images which were taken at different installation angle,the suggested installation angle for different mounting position was given. Through analyzing the principal of current bird-eye image transformation,the factor that result in varying grid size was found out.Therefore,a bird-eye image transformation method that the first transformation made with central calibration plate while the second transformation was made by left and right plates was proposed. Experiment indicated that the proposed method can weaken the existing problem of bird-eye image effectively.

10020-32, Session Post

Simultaneous localization and mapping of mobile robot using a pose graph and a stereo camera

Junqin Lin, Baoling Han, Ming Zhao, Xinliang Zhong, Jiahang Zhao, Beijing Institute of Technology (China)

Localization algorithm based on machine vision is a hot topic in the field of intelligent mobile robot?Visual localization can help the mobile robot obtain the current position and orientation information accurately, ensuring that the mobile robot can accomplish the appointed task safely and efficient.

A fast method for mobile robot 3D SLAM was presented to address the problem of 3D modeling in complex indoor environment. Environment texture and 3D data were captured by sensor of Bumblebee2 that made in Canadian Point Grey Company. In this paper, through using the stereo matched SIFT features point as environmental visual landmarks. In order to reduce the complexity of matching in the SIFT algorithm, using 32-dimensional feature descriptors instead of the original 128-dimensional feature descriptors describes the SIFT image features.

According to the camera calibration model and the image feature extraction and matching procedure, the association between two 3D point clouds was established. On the basis of the RANSAC algorithm, the correspondence based iterative closest point arithmetic model was solved to realize the robot's precise localization effectively. With the key frame-to-frame selection mechanism, the 3D grid map method and the unique normal characteristic of a spatial point were used for maintaining and updating the global map. The global optimization is used to obtain the best position of the frames to reduce the accumulative error which caused by the matching error and the mismatching between two frames.

Experimental results demonstrate the feasibility and effectiveness of the proposed algorithm in the indoor environment.

10020-34, Session Post

Online multi-object tracking with behavior learning

Le Dan, Zinan Lin, Xiangyang Ji, Qionghai Dai, Tsinghua Univ. (China)

Multi-object tracking(MOT) which performs the tracking of multiple targets in video sequences plays an important role in numerous computer vision tasks. MOT draws more and more attention due to its wide applications in various scenarios, such as pedestrian surveillance, traffic safety, robot navigator and automatic drive. Online MOT can be stated as to associate the

noisy and ambiguous object detections in current frame with previously tracked objects. In order to resolve the ambiguity in data association, cues such as appearance and dynamics are employed. Though these cues have improved the MOT performance significantly, all these methods still suffer severe identity switch which is unacceptable in applications like pedestrian surveillance and robot navigator. Meanwhile, ID switch rarely happens in human tracking. People may lost the targets they track for a little while but merely confused with the objects they track under common scenarios. From this point of view, we try to improve MOT performance by addressing the difference between existed methods and human tracking. For example, targets tend to move smoothly and the bounding box tends to become larger when the object is heading towards the camera. Unfortunately, these behavior patterns are mostly semantic and hard to model directly. In this work behavior learning based on neural network is first introduced to provide a semantic feature other than traditional appearance and dynamics. We Perform behavior learning on both ground truth and specific tracking result to generate global and local prediction. Accurate prediction for each object is produced by combining global and local prediction. Our experimental evaluation on benchmark datasets confirms that, by using behavior learning, the ID switch numbers is significant reduced while the recall rate is improved or remained the same level.

10020-35, Session Post

Studies on filtered back-projection imaging reconstruction based on a modified wavelet threshold function

Zhong Ren, Jiangxi Science and Technology Normal Univ. (China) and Nanchang Univ. (China); Guodong Liu, Jiangxi Science and Technology Normal Univ. (China)

Although the filtered back-projection (FBP) reconstruction algorithm has been widely applied into the biomedical imaging, the complete data should be used in order to obtain the high quality of image. In practice, the original data are easily polluted by all kinds of noises, which will seriously impact the image reconstruction quality of the biomedical imaging. Therefore, the removing of noises interference is a key step of improving the image quality of imaging reconstruction. In this paper, the wavelet threshold denoising method was used into the filtered back-projection algorithm of imaging reconstruction. To overcome the drawbacks of the traditional soft- and hard-threshold functions, a modified wavelet threshold function was proposed. The modified wavelet threshold function has dual threshold values and dual factors. To verify the feasibility of the modified wavelet threshold function, the standard test experiments were performed by using the software platform of MATLAB. Experimental results show that the filtered back-projection reconstruction algorithm based on the modified wavelet threshold function has better reconstruction effect because of more flexible advantage. Moreover, the modified wavelet threshold function overcomes the drawbacks of pseudo Gibbs oscillation for the hard-threshold function, and reduces the deviation between the reconstructed image and the original image. Therefore, the filtered back-projection reconstruction algorithm based on the modified wavelet threshold function has great potential value in the image reconstruction of biomedical imaging.

10020-36, Session Post

Experimental study of polarization imaging characteristics on various materials

Sike Bai, Duan Jin, Changchun Univ. of Science and Technology (China); Yizhuo Lu, Jinlin Univ. (China); Xinxin Wang, Tianwei Chen, Changchun Univ. of Science and Technology (China) and Jinlin Univ. (China)

Polarization imaging has a series of advantages where ordinary imaging has no, especially to highlight target in a kind of special background, which is a good auxiliary means of studying the earth's surface and atmosphere. Under the three typical bands which are red light band, green light band and blue light band in the range of visible light, to adopt the method of calculating the stokes vector, polarization experiments are carried out in six kinds of materials which are lawn, stone, asphalt surface, glass, rubber and iron plate respectively, and degree of polarization and polarization degree of contrast are analyzed in details, the experimental results show that there is all a very big concern between the polarization imaging features and the material, imaging band, observing time, so polarization imaging has an important significance in target recognition and remote sensing detection.

10020-37, Session Post

Generation of high-dynamic range image from digital photo

Ying Wang, Changchun Univ. of Science and Technology (China); Igor S. Potemin, Dmitry D. Zhdanov, ITMO Univ. (Russian Federation); Xu-yang Wang, Han Cheng, Changchun Univ. of Science and Technology (China)

The traditional digital camera equipment can only capture two orders of magnitude range image. General image can only contain 256 levels which are far away to denote the dynamic range of the natural scene luminances. Thus it is very important to build the High Dynamic Range Image (HDRI). HDRI records the luminance of the real scene. It can be used in many modern applications such as digital photography, game development, medical imaging, remote sensing satellites imaging, virtual prototyping etc.

The task of conversion of ordinary 256 level image to HDRI has different solutions. For example, Mann and Picard used the linear function to simulate the response curve; Debevec and Malik employed a number of images with accurate exposure; Mistsunaga and Nayar used polynomial approximation to simulate the response curve. In any case, the response curve must be reduced to single units of the relative aperture and exposure time and then calibrated to standard light source.

The article proposes the camera calibration method based on the clear sky as the standard light source and takes sky luminance from CIE sky model for the corresponding geographical coordinates and time. The proposed method can be applied to any ordinary digital camera to convert the ordinary image to HDRI. The only requirement to the camera is to save values of the relative aperture and exposure time. The article considers base algorithms for getting real luminance values and corresponding programmed implementation of the algorithms. Moreover, examples of HDRI reconstructed from ordinary images illustrate the article.

10020-38, Session Post

A chest-shape target automatic detection method based on Deformable Part Models

Mo Zhang, Weiqi Jin, Li Li, Beijing Institute of Technology (China)

Automatic weapon platform is one of the important research directions at domestic and overseas, it needs to accomplish fast searching for the object to be shot under complex background. Therefore, fast detection for given target is the foundation of further task. Considering that chest-shape target is common target of shoot practice, this paper treats chest-shape target as the target and studies target automatic detection method based on Deformable Part Models. The algorithm computes Histograms of Oriented Gradient(HOG) features of the target and trains a model using Latent variable Support Vector Machine(SVM); In this model, target image is divided into several parts then we can obtain foot filter and part filters; Finally, the algorithm detects the target at the HOG features pyramid with method of sliding window. The running time of extracting HOG pyramid with lookup table can be shorten by 36%. The result indicates that this algorithm can detect the chest-shape target in natural environments indoors or outdoors. The true positive rate of detection reaches 76% with many hard samples,and the false positive rate approaches 0. Running on a PC (Intel(R)Core(TM) i5-4200H CPU) with C++ language, the detection time of images with the resolution of 640 480 is 2.093s. According to TI company run library about image pyramid and convolution for DM642 and other hardware, our detection algorithm is expected to be implemented on hardware platform, and it has application prospect in actual system.

10020-39, Session Post

Detection algorithm of single-frame small target based on NSCT

Wei Zhang, Wei Chen, Beihua Univ. (China)

The technique of small target detection is the key technique of the electro-optical detecting system, especially in low signal-to-noise and low contrast images. The temporal and spatial distribution features of the small target, noise and the contour are proposed in this article. A detection algorithm of single frame small target based on NSCT is proposed. The original image is decomposed by NSCT transform to obtain the details characteristics of multi-scale and multi-direction. Then, the low frequency image is filtered by median filter to remove residual target. In the finer scale, the noise coefficients will attenuate quickly but the contours and textures coefficients will be relatively stable, so the contours and textures can be distinguished by the correlation coefficient between adjacent scales. The weight coefficient of the high frequency sub-bands is adjusted according to the sub-bands correlation to suppress target. The background image obtained by inverse NSCT transform is subtracted from an original image. Finally, adaptive threshold and region growing is applied are used on background image. Through simulation experiment?the method can detect the single frame small target quickly and accurately.

10020-40, Session Post

A cartoon-texture decomposition-based image deburring model by using framelet-based sparse representation

Huasong Chen, Xiangju Qu, Ying Jin, Zhenhua Li, Anzhi He, Nanjing Univ. of Science and Technology (China)

Image restoration is a classical and crucial inverse problem in optical imaging. Images often inevitably suffer from the blurring effect due to atmospheric turbulence, an out of focus camera, or relative motion between the camera and the object in image acquisition or transmission processes. Conventional image deblurring methods often deal with the degraded images as a whole while ignoring that an image contains two different components: cartoon and texture. Recently, total variation (TV) based image decomposition methods are introduced into image deblurring problem. However, these methods often suffer from the well-known stair-casing effects of TV. In this paper, a new cartoon-texture decomposition based sparsity regularization method is proposed for non-blind image deblurring. Based on image decomposition, it respectively regularizes the cartoon with a framelet-domain-based sparse prior regularization and the texture with the sparsity of discrete cosine transform domain. Then an adaptive alternative split Bregman iteration is proposed to solve the new multi-term sparsity regularization model. Experimental results demonstrate that our method can recover both cartoon and texture of images simultaneously and therefore can improve the visual effect. In addition, the objective assessment indexes of the deblurred images show that our method can greatly improve both the PSNR and the SSIM values than TV decomposition methods and other undecomposed methods.

10020-41, Session Post

The design of red-blue 3D video fusion system based on DM642

Rongguo Fu, Hao Luo, Guiyuan Wang, YiFang Wei, Jin Lv, Hao Zhang, Shu Feng, YaFeng Qiu, Nanjing Univ. of Science and Technology (China)

Aiming at the uncertainty of traditional 3D video capturing including camera focal lengths, distance and angle parameters between two cameras, a red-blue 3D video fusion system based on DM642 hardware processing platform is designed with the parallel optical axis. In view of the brightness reduction of traditional 3D video, the brightness enhancement algorithm based on human visual characteristics is proposed and the luminance component processing method based on YCbCr color space is also proposed.The BIOS real-time operating system is used to improve the real-time performance. The video processing circuit with the core of DM642 enhances the brightness of the images, then converts the video signals of YCbCr to RGB and extracts the R component from one camera, so does the other video and G, B component are extracted synchronously, outputs 3D fusion images finally.The real-time adjustments such as translation and scaling of the two color components are realized through the serial communication between the VC software and BIOS. The system with the method of adding red and blue components reduces the lost of the chrominance components and makes the picture color saturation reduce to more than 95% of the original.Enhancement algorithm after optimization to reduce the amount of data fusion in the processing of video is used to reduce the fusion time and watching effect is improved. Experimental results show that the system can capture images in near distance, output red -blue 3D video and presents the nice experiences to the audience wearing red-blue glasses.

10020-42, Session Post

High-resolution three-dimensional imaging with compress sensing

Jingyi Wang, Beijing Institute of Technology (China); Jun Ke, Beijing Institute of Technology (China)

LIDAR three-dimensional imaging technology have been used in

many fields, such as military detection. However, LIDAR require extremly fast data acquisition speed. This makes the manufacture of detector array for LIDAR system is very difficult. To solve this problem, we consider using compress sensing which can greatly decrease the data acquisition and relax the requirement of a detection device. To use the compressive sensing idea, a spatial light modulator will be used to modulate the pulsed light source. Then a photodetector is used to receive the reflected light. A convex optimization problem is solved to reconstruct the 2D depth map of the object.

To improve the resolution in transversal direction, we use multiframe image restoration technology. For each 2D piecewise-planar scene, we move the SLM half-pixel each time. Then the position where the modulated light illuminates will changed accordingly. We repeat moving the SLM to four different directions. Then we can get four low-resolution depth maps with different details of the same plane scene. If we use all of the measurements obtained by the subpixel movements, we can reconstruct a high-resolution depth map of the sense. A linear minimum-mean-square error algorithm is used for the reconstruction.

By combining compress sensing and multiframe image restoration technology, we reduce the burden on data analyse and improve the efficiency of detectio. More importantly, we obtain high-resolution depth maps of a 3D scene.

10020-43, Session Post

Range-gated underwater laser imaging enhancement based on contrast-limited adaptive histogram equalization

Liang Sun, Xinwei Wang, Xiaoquan Liu, RuiRong You, Pengdao Ren, Pingshun Lei, Jun He, Yan Zhou, Yuliang Liu, Institute of Semiconductors (China)

Underwater range-gated laser imaging is widely used for underwater target detection with significantly suppressing seawater backscattering and improving the quality of underwater images. However, it still has some problems like un-uniform light, low brightness and contrast. To solve the problems, a variant of adaptive histogram equalization called contrast limited adaptive histogram equalization (CLAHE) is proposed in this paper. It differs from traditional histogram equalization (HE) in the respect that the adaptive method computes several histograms, corresponding to a distinct section of the image respectively, and uses them to redistribute the lightness values of the image. It is therefore suitable for improving the local contrast and enhancing the definitions of edges in each region of an image. In experiment, we get images with a standard plate and fishing net at the distance of 5 m by underwater range-gated laser imaging system. Then we use the CLAHE and HE to enhance the images, and evaluate the quality of enhanced images by peak signal to noise ratio (PSNR) and image contrast. The result shows that both the CLAHE and HE significantly enhances the brightness and contrast of images, but the HE gets the images over-enhanced, while the CLAHE has a good enhancement with compressing the over-enhancement and the influence of un-uniform light by the using of adaptive local enhancement, it also has higher value of PSNR and contrast than HE. The experimental results demonstrate that the CLAHE has a good result of image enhancement for target detection by underwater range-gated laser imaging system.

10020-44, Session Post

A novel representation and compression method in layered depth video

Zefu Li, Ran Ma, Shanghai Univ. (China)

Layered depth video (LDV), as a sparse representation of multi-view video plus depth (MVD), is considered as a promising 3D video format for supporting 3D videos services. This format consists of one full or central view and additional residual data that represent side views needed to be transmitted. However, the amount of residual data becomes larger when the distance between the central view and side views increases. This occurs when parts of the central view are not visible in the side views, leaving some holes called disocclussions. To address this problem, in this paper, a new inpainting-based residual data generation method is presented. The holes can be inpainted by using the available texture inside the central view. Then, the inpainting-induced artifacts are considered as new residual data and the residual data of two side views is merged into one buffer to further reduce the amount of data. For better coding efficiency, the block wise alignment is proposed to adapt to the block structure in current high efficient video coding (HEVC) coder firstly. Then in order to fit the shape or distribution of residual data, a proper code unit (CU) size and split pattern is proposed. The experiments show high compression efficiency of the proposed representation and compression method. The proposed method allows reduction of required bitrate of at least 30% comparing to classical LDV method, while they have the similar quality of intermediate virtual view in the terminal's display.

10020-45, Session Post

Pedestrian detection based on redundant wavelet transform

Lin Huang, Tie-Jun Yang, Li-ping Ji, Ping Hu, Guilin Univ. of Technology (China)

Intelligent video surveillance is to analysis video or image sequences captured by a fixed or mobile surveillance camera, including moving object detection, segmentation and recognition. By using it, we can be notified immediately in an abnormal situation. Pedestrian detection plays an important role in an intelligent video surveillance system, and it is also a key technology in the field of intelligent vehicle. So pedestrian detection has very vital significance in traffic management optimization, security early warn and abnormal behavior detection. Generally, pedestrian detection can be summarized as: first to estimate the moving area; then to extract the features of region of interest; finally to classify samples using a classifier. Redundant wavelet transform (RWT) overcomes the deficiency of shift variant of discrete wavelet transform, and it has better performance in motion estimation when compared to discrete wavelet transform. Addressing the problem of the detection of multi-pedestrian with different speed, we present an algorithm of pedestrian detection based on motion estimation using RWT, combining histogram of oriented gradients (HOG) and support vector machine (SVM). Firstly, three degrees of movement (DoM) are estimated using RWT and the corresponding areas are segmented. According to the different DoMs, a region proposal (RP) is generated. Then, the features of a RP is extracted using HOG. Finally, the features are fed into a SVM trained by pedestrian databases and the detection results are gained. Experiments show that the proposed algorithm estimates pedestrian with different speed more accurately than that of some state-of-art ones.

10020-46, Session Post

High-resolution image restoration algorithm of wavefront coding system based on Lucy Richardson algorithm and wavelet denoising

Qiang Li, Feng Xu, Soochow Univ. (China)

Abstract:The middle blurred image is received by the detector since the low modulation transfer function(MTF) of the wavefront coding(WFC) imaging system. However, using an appropriate filter, the middle blurred image can be restored with enough target information saved because there is no zero point in the passband of the MTF. While the signal has been amplified by the filter in the restoration process, the noise of the system is also enlarged and the signal to noise ratio(SNR) of the image is reduced. In order to solve the above issues, an improved algorithm has been proposed in the paper. The noise is controlled by the wavelet in the reconstruction process, and the middle blurred image is restored by the LR algorithm with a prior knowledge of the degradation function. Thus, the wavelet denoising are combined with LR algorithm to restore the middle blurred image of the WFC system. The test results show that the noise of the reconstructed image has been suppressed and the peak SNR and SNR has been improved, the restoration image with the diffraction limit level has achieved good results in image detail restoration and noise control.

10020-47, Session Post

Cross-center extraction with sub-pixel accuracy

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In order to achieve automatic measurement function, laser scanning measurement system need to ensure that measurement system of the cross and the target center overlapped. To develop the obtaining accuracy of the cross central coordinate, a novel algorithm based on the combination of two-step Hough Transform and Sub-pixel curve fitting was presented. Firstly, Hough Transform was used to detect the straight line of long axis of the cross, and then the central coordinate value of the cross can be deduced roughly through straight line equations. Secondly, take this coordinate as a center, and a certain number of pixel values as the edge length, a region of interest (ROI) can be defined. In this ROI, the two short axes of the cross were obtained to detect the straight line roughly using Hough Transform again. Then, the coordinate value of short axis was acquired in pixel level with canny edge detection algorithm. According to the equations of the straight line, rough errors were removed through 3 rule, and the coordinate values of short axis in sub-pixel level with curve fitting algorithm is obtained. Finally, based on the sub-pixel level of coordinate values, straight line equations of two short axes was presented with LSM, and thus the coordinate of cross center would be accurately detected with the intersection of two short axes. Experimental results showed that the accuracy of the central coordinates value of cross approaches to sub-pixel level and can satisfy the measurement system requirements of high precision.

10020-48, Session Post

Human body region enhancement method based on Kinect infrared imaging

Lei Yang, Zhongyuan Univ. of Technology (China); Yubo Fan, Xian Jiaotong Univ. (China); Xiaowei Song, Wenjing Cai, Zhongyuan Univ. of Technology (China)

To effectively improve the low contrast of human body region in the infrared images, a combing enhancement method is proposed to enhance the human body region. According to the characteristics of different kinds of noise in infrared images, a combing method with multiple enhancement methods is more efficient than a single processing method. Firstly, for the infrared images acquired by Kinect, in order to improve the overall contrast, an Optimal Contrast-Tone Mapping (OCTM) method with multi-iterations is applied to balance the contrast of low-luminosity infrared images. Secondly, to enhance the human body region better, a Level Set algorithm is employed to improve the contour edges of human body region. Finally, to further improve the human body region in infrared images, a Laplacian Pyramid decomposition is adopted to enhance the contour-improved human body region. Meanwhile, the background area without human body region is processed by bilateral filtering to improve the overall effect. The algorithm for human body region enhancement is different from that for background processing, so the enhancement effect is better. With theoretical analysis and experimental verification, the results show that the proposed method could effectively enhance the human body region of such infrared images. The proposed method shows an advantage in the infrared image processing of human body area under no light or dim light environment. It will help to recognize the human body region with clear human body shape and posture, and will be helpful in the development of infrared surveillance system.

10020-49, Session Post

Binocular stereo matching method based on structure tensor

Xiaowei song, Manyi yang, Zhongyuan Univ. of Technology (China); Yubo Fan, Xian Jiaotong Univ. (China); Lei Yang, Zhongyuan Univ. of Technology (China)

A main research area of computer stereo vision is to recover the 3d coordinates of the object from multiple 2d images, and the binocular vision technology based on two images is one of the research hotspots. In a binocular vision system, to recover the 3d information of the object, the most important thing is to acquire the matching points. In recent years, tensor theory develops rapidly. Tensor has two characteristics. One is the transformation rule of coordinate system, the other is multidimensionality. Structure tensor shows better detection performance in the local structure region, and is very suitable to find the specific shapes like pedestrians, cars and road signs in images. In this paper, the luminance information and the structure tensor are combined to form the extended structure tensor. The directional derivatives of luminance in x and y directions are calculated to highlight the local structure of the image. The Euclidean distance between feature vectors of key points is adopted as the similarity judgment metric of the key points in the two images. The coordinates of the matching points within the detected target in the images are precisely acquired by matching. Experiments were performed based on the left and right images of the captured road signs. Binocular calibration was followed by image matching for matching points, and the target depth was calculated according to the matching points. By comparison, it was proved that the structure tensor could accurately acquire the matching points in the binocular stereo matching.

10020-50, Session Post

A vertical parallax reduction method for stereoscopic video based on adaptive interpolation

Qingyu Li, Yan Zhao, Jilin Univ. (China)

The existence of vertical parallax is the main factor of affecting the viewing comfort of stereo video. Visual fatigue is gaining widespread attention with the booming development of 3D or stereoscopic video technology. In order to reduce the vertical parallax without affecting the horizontal parallax, a self-adaptive image scaling algorithm is proposed, which can use the edge characteristics efficiently. In the meantime, Levenberg-Marquardt (L-M) algorithm which is the nonlinear algorithm, is introduced in this paper to improve the accuracy of the transformation matrix. Firstly, the self-adaptive scaling algorithm is used to the original image for interpolation. When the pixel point of original image is in the edge region, the interpretation is implemented adaptively along the edge direction obtained by Sobel operator. Secondly the SIFT algorithm, which is invariant to scaling, rotation and affine transformation, is used to detect the feature matching points from the binocular images. Then according to the coordinate position of matching points, the transformation matrix, which can reduce the vertical parallax, is calculated using Levenberg-Marquardt algorithm. Finally, the transformation matrix is applied to target image to calculate the new coordinate position of each pixel from the view images. The experimental results show that comparing with the method that reduces the vertical parallax using linear algorithm to calculate two-dimensional projective transformation, the proposed method improves the vertical parallax reduction obviously, at the same time, in terms of the impact on horizontal parallax, the proposed method is more closer to the original image. Therefore, the proposed method can optimize the vertical parallax reduction.

10020-51, Session Post

Single face image reconstruction for super resolution using support vector regression

Haijie Lin, Qiping Yuan, Tianjin Univ. of Technology (China); Zhihong Chen, Xiaoping Yang, Tianjin Univ. (China)

In recent years, we have witnessed the prosperity of the face image super-resolution (SR) reconstruction, especially the learning-based technology. In this paper, a novel super-resolution face reconstruction framework based on support vector regression (SVR) about a single image is presented. Given some input data, SVR can precisely predict output class labels. We regard the SR problem as the estimation of pixel labels in its high resolution version. It's effective to put local binary pattern (LBP) codes and partial pixels into input vectors during training models in our work, and models are learnt from a set of high and low resolution face image. By optimizing vector pairs which are used for learning model, the final reconstructed results were advanced. Especially to deserve to be mentioned, we can get more high frequency information by exploiting the cyclical scan actions in the process of both training and prediction. A large number of experimental data and visual observation have shown that our method outperforms bicubic interpolation and some state-of-the-art super-resolution algorithms.

10020-52, Session Post

Pure-optical broadband photoacoustic detector based on total internal reflection

Xiaoyi Zhu, Wenzhao Li, Changhui Li, Peking Univ. (China)

Photoacoustic tomography (PAT) uniquely combines the optical absorption contrast and ultrasonic detection, which is superior for optical absorption detection. Over the past decade, PAT has gained significant progresses in both technical development and biomedical implementations. Due to the large scale difference in tissue optical absorbers, Photoacoustic (PA) signals could cover a very wide frequency range. Therefore, the photoacoustic detector desires not only high sensitivity, but also wide bandwidth. Due to the high detection sensitivity and the extreme wide bandwidth, several pure optical detection detectors based on different mechanisms have been studied, including the Mach-Zehnder interferometer [1], Fabry-Perot Polymer [2], micro-ring resonator [3], low-coherence interferometer [4], and surface plasmon resonance detector [5]. In this study, we proposed a new PA detection method that based on total internal reflection (TIR). The stength of the reflected light is modulated by the variation of media refractive index (RI) that caused by PA pressure waves. Our method can extract extreme weak signals. Both phantom and animal experimental results demonstrated this novel method can provide a broadband and sensitive PA imaging.

10020-53, Session Post

Research on free-space optical communication based on time-division multiplexing

Dan Wang, Jinan Univ. (China); Wenchao Zhou, The Second Compulsory Drug Rehabilitation Ctr. of Guangdong Province (China); Zhen Li, Zhenqiang Chen, Hao Yin, Siqi Zhu, Anming Li, Jinan Univ. (China)

Free-space optical (FSO) communication is a technology that can transfer sound, image and text information using laser beam as a data carrier. With the advantages of a huge resistance to electromagnetic interference, a wide range of available spectrum, ease of implementation and high data rate, FSO systems are widely used in scientific research, military, civilian and other fields. This paper reports an improved design for video and audio synchronous wireless transmission system. Video and audio signals are time division multiplexed and then are modulated by an acousto-optic modulator (AOM). The modulated signal propagates through the atmosphere and is received by the photoelectric convertor. The original signal is recovered by de-multiplexer. Video signal is showed by a monitor and audio signal is tested by a speaker. The 3dB bandwidth of this system is 6.7MHz. The system achieves the functions of signal multiplexing and wireless transmitting with the help of a designed circuit and microcontroller programming. The time-division multiplexer/de-multiplexer is provided by means of a microcontroller, switching chip and other auxiliary circuit. The photoelectric convertor is presented by making use of a photodiode and amplification circuit. Proved by experiments, this system perfectly meets the actual requirements with advantages of flexibility, practicality and low cost. And it provides an efficient scheme of synchronous wireless transmission of video and audio signals for monitoring system and TV access network.

10020-54, Session Post

Sinogram-based adaptive iterative reconstruction for sparse view x-ray computed tomography

Dragos Trinca, Yang Zhong, Y. Z. Wang, Talgat Mamyrbayev, Tomsk Polytechnic Univ. (Russian Federation); E. Libin, Tomsk State Univ. (Russian Federation)

With the availability of more powerful computing processors, iterative reconstruction algorithms have recently been successfully implemented as an approach to achieving significant dose reduction in X-ray CT. There are two ways of reducing the dose, either by (1) reducing the scanner flux, or by (2) decreasing the number of views. In this work, we propose an adaptive iterative reconstruction algorithm for X-ray CT, that is shown to provide results comparable to those obtained by proprietary algorithms, both in terms of dose reduction (using the second approach for reducing the dose) and execution time. One of the main advantages of the proposed algorithm, as compared to other non-proprietary algorithms that have been proposed, is that it is not only fast at the reconstruction process, but also fast at the scanning process, as it requires a significantly smaller number of views.

10020-55, Session Post

Research of nonlinear simulation on sweep voltage of streak tube imaging lidar

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When the streak tube imaging lidar is used to detecting and imaging the target, the range accuracy is influenced by the nonlinearity of the sweep voltage. In order to study the nonlinear sweep voltage, a nonlinear distance model of streak tube is proposed based on the principle of streak tube imaging lidar system and streak image is obtained, the nonlinear influences of the system are analyzed from multiple perspectives after comparing the simulation results with the ideal results. Firstly, the model of the parallel-plate deflection system is studied, and the mathematical relation between the sweep voltage and the position of the image point on the screen is obtained based on the movement rule of phoelectron. Then, the mathematical model of the sweep voltage is established on the basis of its principle and the nonlinear distance model of the streak tube is obtained. After that, the simulation of streak image is carried out for the selected staircase target, corresponding sweep voltage slope of the system can be calculated by the simulation result and the range image of the target can be reconstructed by extremum method. Comparing reconstruction result and actual target, the range accuracy caused by the nonlinearity of the sweep voltage is obtained.Under the principle of full screen sweeping, the curve of the errors varying with target ranges is also obtained. Finally,the influence of parameter relate to sweep time on the range accuracy of the system is analyzed. The results of research provide theoretical reference for optimal parameter selection to minimum range error and it can provide effect prediction for the design of streak tube imaging lidar.

10020-56, Session Post

Automatic identification of various spectral features at the time-resolved excitation emission matrix of dissolved organic matters and phytoplankton cells in seawater

Pavel A. Salyuk, V.I. Il'ichev Pacific Oceanological Institute (Russian Federation) and Far Eastern State Univ. (Russian Federation); Vladimir Krikun, V.I. Il'ichev Pacific Oceanological Institute (Russian Federation)

The variation of the different parameters of the exciting radiation and the registration of the fluorescence of the investigated object allows to obtain multidimensional spectral images: from three-dimensional (length of the exciting radiation, the wavelength of the emitted radiation, the fluorescence intensity) to eight and more dimensions (in addition to three of these dimensions: spatial coordinates x, y, z; time of measurements; the duration and the intensity of the exciting radiation and etc.). In the case of measurements in natural conditions is highly desirable that the result of the processing performed during a single measurement for the operation in real time.

In this paper we consider the approach described for the treatment of fluorescence measurements of dissolved organic matter and chlorophyll-a in seawater. Joint analysis of the various pairs of wavelengths of excitation / emission fluorescence, fluorescence analysis at different durations of the exciting radiation and the time-spatial analysis of the received signal allow identifying different types of fluorescent dissolved organic matter and estimate their stage of biodegradation, to study the functional state of phytoplankton cells. So it is possible to provide real-time investigation of environmental indicators of seawater.

10020-57, Session Post

The equipment for time-resolved measurements of excitation-emission matrix of seawater fluorescence in natural conditions

Ivan G. Nagorny, Far Eastern State Univ. (Russian Federation) and Institute for Automation and Control Processes (Russian Federation); Pavel A. Salyuk, Vladimir A. Krikun, V.I. Il'ichev Pacific Oceanological Institute (Russian Federation); Alexander Yu Mayor, Konstantin A. Shmirko, Institute for Automation and Control Processes (Russian Federation)

Excitation-emission matrix (EEM) technique is widely used in the last decade to study the properties of organic matter in seawater. Additional variations of the exciting radiation parameters (in addition to the wavelength), such as the duration and intensity, allow to get more spectral information about the object of research, and allow to identify some individual components of the tested sample or to study the dynamics of the molecular changes in the sample of analyzed liquid.

One of the main limitations of the EEM technique is that usually necessary to carry out research in the laboratory on the specialized equipment. In this paper describes the hardware system that allows to carry out measurements in the field studies.

The hardware system includes a set of light-emitted diodes (LEDs) working in the range from 245 to 600 nm, which produce sequential excitation fluorescence of the sample liquid, which is detected using a 32-channel photomultiplier tube (PMT). Number of LEDs can vary from 7 to 16. Through the use of multi-channel

photomultiplier reached the required measurement sensitivity and efficiency measurement is less than 1 minute for full cycle.

Some channels are set to ultra-variable fluorescence measurements of phytoplankton cells. Minimum 4 channel in excitation range of 350-600 nm support the work of variable duration excitation pulses from a micro seconds to seconds. This makes it possible to measure the fluorescence of the chlorophyll-a with closed or open reaction centers of phytoplankton cells. The use of multiple excitation radiation in channel allows to activate various mechanisms of energy transfer in the photosynthetic apparatus of phytoplankton cells, improves measurement accuracy, reduces dependence on the variation in species composition and functional state of phytoplankton cells.

10020-21, Session 5

Development of an atmospheric turbulence simulator for deformable mirror evaluation *(Invited Paper)*

Jun Ho Lee, Sunmi Shin, Kongju National Univ. (Korea, Republic of); Hyug-Gyo Rhee, Ho-Soon Yang, Korea Research Institute of Standards and Science (Korea, Republic of); Ho-Jae Lee, Korea Institute of Industrial Technology (Korea, Republic of)

Currently we are developing a 10cm silicon carbide (SiC) deformable mirror with 37 actuators operating at 500 Hz. The deformable mirror aims to be applied into a 1.5m telescope. The adaptive optics system capability with the deformable mirror was simulated and predicted based on the Kolmogorov atmospheric turbulence model. However, in order to confirm the prediction, a closed-loop adaptive optics system was constructed with an insertion of an atmospheric turbulence simulator. The atmospheric turbulence simulator consists of two point sources, a Boston deformable mirror and double random phase plates. In order to simulate a binary star, the two point sources are mounted on 3-axis micron meter stages, respectively and are optically merged into a single beam path by a beam splitter cube. Each light intensity of the source is adjustable to a corresponding stellar magnitude while the angular separation is precisely adjusted by moving the 3-axis stages. The atmospheric disturbance is generated by shaping the Boston deformable mirror and also by rotating double phase plates. The fried parameter of the generated the atmospheric disturbance corresponds from 7cm to 15cm at 500nm at the telescope pupil plane, which represents a typical seeing condition at Bohyun observatory, South Korea. At the first, the Boston deformable mirror has 12 x 12 actuator array with 400 ?m pitch and actuator control signals are generated based from the Kolmogorov atmospheric model and frozen layer theorem. At the second, the phase plates are glass plates with some residual aberrations. The rotating direction and velocity of each random phase plate is controlled to represent the atmospheric turbulence wind profiles.

10020-22, Session 5

Solutions to improve space-time adaptive systems resolution

Hua Liu, Science and Technology on Electro-Optic Control Lab. (China)

The principle approach, modeling, and error analysis are analyzed, and the system configuration based on SLM is advanced in algorithm analysis. For to improve the resolution of the imaging system, and achieve the theoretical limit, we introduced that the core methodology, which is that in the deep understanding and research of the photoelectric information control, the basic theory of the spatial light modulator and the algorithm based on space-time adaptive system is discussed deeply which used to the core of the photoelectric system configuration by which key components applied to solve the control function. This paper discusses the hardware system. Usually, an SLM modulates the intensity of the light beam. However, it is also possible to produce devices that modulate the phase of the beam or both the intensity and the phase simultaneously. Adaptive configuration, for a complicate sensor is accomplished by an implementation of structured programming, based on global optimization algorithm , which explores the available configuration space formed by powers of individual components and inter-component separations. Besides, the discuss includes the control on the SLM for spatial information of the amplitude, phase, frequency, polarization, and the intensity of energy research. A typical model is used to illustrate the feasibility, and the criteria is developed.The technology principle of super resolution restructure from the point of view on theory and engineering. Three kinds of restructure technologies, that prototype, micro scanning and sub pixel are described, and how to decrease their shortcomings are discussed in detail. Furthermore, to improve the band width by reconstruction without the spectral alias in super resolution technologies, a new coding technology combining a optical encoding and the sub pixel is proposed. With the global method, simulation results show that the system can meet the application requirements in MTF, REA, RMS and other related criteria.Results show that they are effective solutions.

10020-23, Session 5

Calculation of overlapping pixels for optical-butting focal plane

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The resolution and observing width of optical remote sensing camera can be enhanced by increasing the detector length of focal plane. Optical butting is used to increase the imaging length owing to its simple structure, low cost and the simultaneously-imaging detectors. But butting process is influenced by many factors, which result in imaging gaps, so overlapping pixels between adjacent detectors is the key. In this paper, the factors causing imaging gap are analyzed, and calculation of overlapping pixel number is given out based on the analysis. Firstly an optical-butting focal plane system is built on optical imaging principles. Then the factors causing imaging gap are listed and analyzed, under the consideration of telecentric and non-telecentric optical system. Based on the imaging gap analysis, a formula for overlapping pixel number calculation is obtained, with the MTF assurance in vignetting districts resulted from optical butting. Finally a calculation example of a camera is given.

10020-24, Session 5

Enhancing the actual operational performance of coaxial three-mirror anastigmatic optical system by wavefront coding

Zhang Binglong, Bin Hu, Jiangao Jin, Bo Li, Ningjuan Ruan, Yun Su, Beijing Institute of Space Mechanics and Electricity (China)

Coaxial Three-Mirror Anastigmatic (TMA) optics has been well known in remote sensing for excellent anti-astigmatic, but space environmental disturbances such as thermal field change, vibration often caused optical elements to deformation, tilt or position deviation, the degree of structure stability became the key factor to influence the actual performance when coaxial TMA

run in orbit. This paper presented the pupil phase distribution by which optical system became insensitive to defocus and defocus-related aberrations, the corresponding phase mask was designed and placed to pupil position of coaxial TMA, optimized the modified optics in ZEMAX, a filter was developed based on wiener filter, the filter could effectively restore the blur produced by phase mask and defocus, but magnify the image noise a little, finally, analyzed the actual performance of modified imaging system by the simulation, and result showed that, by using Wavefront Coding, the fabrication and assembly tolerance of coaxial TMA optical system could be relaxed to 2 times, the depth of focus of system could be extended to 16 times than before, and the imaging quality is almost invariant, actual performance in orbit was enhanced dramatically.

10020-26, Session 5

Break diffraction limit using nearest-neighbour pixel-modified optical transfer function

Yu Wang, GDS Optics (United States)

For images taken by a diffraction limited optical system; if the pixel pitch of the system's detector is much smaller than the diffraction limit, then the spatial resolution of the images can be enhanced by a method called nearest neighbor pixel modified optical transfer function. This method rewrites the point spread function in terms of the nearest pixels, and then develops a modified optical transfer function using the Shift Theory of Fourier Transform. Theoretical simulation shows that this method is able to enhance resolution of single frame images beyond the diffraction limit. Initial experiment results were in good agreement with the simulation. We have applied this method to two of NASA's space images, with many hidden details appearing in the processed images.

10020-27, Session 6

Colour image encryption using affine transform in fractional Hartley domain *(Invited Paper)*

Anil K. Yadav, Phool Singh, Kehar Singh, The Northcap Univ. (India)

A novel scheme for colour image encryption using the fractional Hartley and affine transforms is proposed. An input colour image is first decomposed in its RGB (red, green and blue) components. Each component is bonded with a random phase mask (RPM) and then subjected to a fractional Hartley transform followed by affine transform. Thereafter, a second random phase mask is applied to each component before the final transformation by inverse fractional Hartley transform resulting in component-wise encrypted image. Finally, the components are combined to give a single channel colour encrypted image. The process of decryption is just the reverse of encryption. The scheme is validated with numerical simulations performed on colour image of Lena of size 256x256 pixels using MATLAB 7.14. The use of affine transform along with fractional Hartley transform adds to the security. The scheme is evaluated for its sensitivity to parameters of the fractional Hartley and affine transforms. It is found to be highly sensitive to encryption parameters by analysing the plots of correlation coefficient (CC), mean-squared-error (MSE) and peak signal-to-noise ratio (PSNR). Also, it is evaluated for its robustness against the usual noise and occlusion attacks. The proposed scheme is found to be secure and robust owing to multiplicity of encryption parameters introduced through the type of transform used.

10020-28, Session 6

A multi-image super-resolution via hybrid registration with depth information

Shi Lei, Tsinghua Univ. (China)

Multi-image super-resolution (MISR) reconstructs a high-resolution image from a set of low-resolution images of the same scene. Precise alignment of the input images is an essential part of MISR. However, it is a great challenge to align corresponding images electively and efficiently. To address this problem, in this paper we propose a novel hybrid method to precisely register a set of low-resolution images of different views employing the corresponding depth information. Utilizing the geometric mapping relationship between depth and position in real world, depth information is employed to find the corresponding position in the reference image. A high-resolution image is then reconstructed using cubic interpolation. Our algorithm is compared to several multi-image super-resolution algorithms using six groups of images from HCI database. Results and analysis show that our method performs better than others registration methods.

10020-30, Session 6

Experimental research on showing automatic disappearance pen handwriting based on spectral imaging technology

Yi Su, National Police University Of China (China); Lei Xu, Yi Su, Institute of Forensic Science (China); Ningning Liu, People's Public Security University of China (China)

At present, more and more criminals utilize the automatically-disappeared pen for economic fraud?so that investigators cannot get a direct evidence of the disappearance of writing. However, the existing technology has unsatisfactory effect in term of completely disappeared handwriting. In this research, according to the principle of imaging spectrometer, and combined with the difference of absorption and reflection in various substances in different bands to identify the potential handwriting which left on the surface of different papers, that provides a new method for the inspection of disappeared handwriting. This paper adopt the visible spectrum imaging technique to inspect disappeared handwriting made by different disappeared pens in the same object or by the same disappeared pen in different objects. Good reveal effects could be obtained in both cases. Compared with the video spectral comparator and sodium hydroxide solution traditional methods, it is more simple, convenient, efficient and has higher sensitivity. Meanwhile, as the optical nondestructive testing, it can be used before the other methods, improving the inspection efficiency and offering important evidence for the detection of the disappeared handwriting cases.

10021-201,

Freeform optics opening up a bright future for imaging instrumentation

Jannick P. Rolland, R.E. Hopkins Ctr. for Optical Design and Engineering (United States) and NSF/IUCRC Ctr. for Freeform Optics (United States) and The Institute of Optics, Univ. of Rochester (United States)

Freeform surfaces in optical system design have already transformed the lighting industry and have started to revolutionize the imaging industry following recent advances that empower innovation in optical instrumentation. In the context of imaging, an historical highlight about freeform optics will be followed with a discussion of key concepts and discoveries in optical aberration theory that are currently guiding the design of freeform imaging systems for manufacturing with nanometer-class accuracy. Freeform manufacturing, enabled by maturing techniques that include polishing, ion beam finishing, diamond machining, milling, and magnetorheological finishing, will be discussed. Building on simultaneous theoretical as well as rapid technical advances across industries from design to assembly, three design case studies will be discussed to highlight the emerging benefits of freeform optics in imaging systems as well as the design for manufacture process. With the emergence of high definition displays and sensors, together with the constant quest for more compact and higher performance optical imaging technologies across a wide range of applications, freeform optics opens the path for a rich space of solutions that will enable the science of tomorrow.

10021-202,

Innovative large wide-field astronomical telescope: LAMOST

Xiangqun Cui, Nanjing Institute of Astronomical Optics & Technology (China) and National Astronomical Observatory (China)

LAMOST, Large Sky Area Multi-Object Fiber Spectroscopic Telescope, is one of the most innovative telescope configurations in the world with the both wide field-of-view and the large aperture, four-thousand optical fibers, and sixteen spectrographs equipped. LAMOST has the capability to observe and capture tens of millions of spectra of celestial objects such as stellar, galaxies, and quasars.

10021-1, Session 1

Efficient stimulated Raman scattering in hybrid liquid-silica fibers for wavelength conversion *(Invited Paper)*

Sylvie Lebrun, Lab. Charles Fabry, Institut d'Optique (France); Minh Châu Phan Huy, Philippe Delaye, Institut d'Optique Graduate School (France); Gilles Pauliat, Lab. Charles Fabry, Institut d'Optique (France)

For nearly 10 years, we have developed a new kind of fiber wavelength shifters based on Stimulated Raman Scattering in the liquid filling the hollow core of photonic crystal bandgap fibers or Kagome fibers. The liquid choice, the design of the photonic microstructure, the fiber length and diameter give us enough degrees of freedom to realize efficient and versatile shifters, each being optimized for a specific wavelength shift. Connecting such a fiber device to a fixed wavelength laser allows delivering a new wavelength. With the same laser, another wavelength can be readily obtained by connecting another shifter. Using various microlasers delivering 532 nm sub-nanosecond pulses of about 1 ?J, we already built a full series of shifters to reach any wavelength among: 556 nm; 561 nm; 582 nm; 595 nm; 612 nm; 630 nm; 650 nm; 667 nm; 772 nm. Other wavelengths could be reached by designing new shifters. In this presentation, we will detail how we design and optimize these new devices to reach the targeted wavelength with high conversion efficiencies (up to 80% of the initial photons are converted at the desired wavelength), narrow linewidths (typically less than 0.5 nm) and transverse single mode operation.

10021-2, Session 1

Diffractive optical elements for multi-dimensional subdiffraction-limit spot generation: design, demonstration, and characterization *(Invited Paper)*

Yusuke Ogura, Jun Tanida, Osaka Univ. (Japan)

We present diffractive optical elements (DOEs) for generating wavelength-multiplexing and three-dimensional (multi-dimensional) arrays of subdiffraction spots, which are smaller than the single diffraction limit spot. This method is based on the use of propagating light, and its superior features, including spatial parallelism and remote accessibility to matter, can be utilized in applications. In design, special constraints are introduced into the Gerchberg-Saxton algorithm to control the phases of spots and to disperse light energy to a surrounding area. In each iteration, the phase distribution of a wavelength-multiplexing DOE is synthesized from the phase distributions obtained tentatively for the individual wavelengths. As an example, a two-wavelength two-plane DOE was investigated. The design result showed that expected spot arrays were generated for two wavelengths on the individual output planes. We constructed an experimental system with a spatial light modulator and demonstrated that the generated spot arrays were in conformity with the design result. Spot sizes were reduced to less than 80% of that of the diffraction limit spot. Characteristics of this type of DOEs were also evaluated by numerical calculation. For example, the result shows that the focal depth is extended in subdiffraction-limit spot generation. We believe that this study contribute to expand application fields of DOEs.

10021-3, Session 1

The development of an adaptive optics system and its application to the biological microscope *(Invited Paper)*

Masayuki Hattori, Yosuke Tamada, National Institute for Basic Biology (Japan)

The improvement of the optical devices in this decade, such as the MEMS-SLM (Micro Electro Mechanical Systems-Spatial Light Modulator) and wave front sensor with micro lens device, is making adaptive optics commonly available. It also gives the new basis of the design of adaptive optics with the improved accuracy and the compactness. We have developed an adaptive optics bench from such a point of view, and the application to the optical microscope has attained effective results in the observation of the live cell samples. In this presentation, our recent results will be shown. The result includes analysis of blur by the fine structures in biological sample and result of the image correction by the adaptive optics.

10021-4, Session 1

Hybrid high-speed organic electro-optic modulator

Feng Qiu, Kyushu Univ. (Japan)

Inside optical transmission systems, electro-optic (EO) modulators are one of the vital building blocks. Among different types of materials used to construct modulators, EO polymer can offer intrinsic advantages such as a large EO coefficient (r33), high bandwidth, low dielectric constant and loss, and excellent compatibility with other materials and substrates. Here, we present several novel designed modulators based on the EO polymer / titanium dioxide (TiO2) hybrid structure 1-2. They includes: (1) vertical-stacked structure; (2) EO polymer covered TiO2 nano-line; (3) Compact ring resonators; (4) EO polymer filled slot waveguides. We give the design principle, describe the devices' fabrication process, and demonstrate the outstanding optical properties of the fabricated devices.

10021-5, Session 1

In-depth performance analysis of a novel R-ORMS (remote optical rainfall measurement sensor)

Muhammad Hassan Bin Afzal, Primeasia Univ. (Bangladesh)

A novel rainfall measuring sensor concept titled R-ORMS is being developed and proposed in this article. This specific sensor R-ORMS designed on the basis of tipping bucket rainfall accumulation concept integrated with hydreon sensor's highly sensitive rain intensity measurement process. This article systematically covered the comparative performance analysis between following three rain gauges such as R-ORMS, tipping bucket and hydreon sensor according to sensing principle, resolution, rainfall measurement, and function of data counter or data logger and battery shelf life. It is clearly observed that, R-ORMS performs much better compare to other techniques with better resilience. A comprehensive comparative study been carried out to evaluate the durability and feasibility of three techniques for rainfall measurement such as standard rain gauges, proposed R-ORMS, tipping bucket based hydreon sensor. These three methods are compared based on sensing principle, resolution, rainfall measurement, and function of data counter or data logger and it's battery shelf life. The R-ORMS designed in such pattern that can overcome the common drawbacks of all standard rain gauges. Some rain gauges are combined with wind speed detecting sensor, temperature detecting sensor but R-ORMS purely designed to measure the total rainfall by considering both accurate wind speed and temperature detection. This proposed sensing technology performs much better than other available rain gauges by providing accurate rainfall measurement.

10021-6, Session 1

Chromostereopsis in "virtual reality" adapters with electrically-tuneable liquid lens oculars

Maris Ozolinsh, Kristine Muizniece, Univ. of Latvia (Latvia); Janis Berzinsh, "Barona Optika" (Latvia)

Chromostereopsis is a visual illusion whereby an impression of depth is conveyed in two-dimensional color images. Chromostereopsis can be sight and feel also in "Virtual Reality" adapters, that induces the appearance of colour dependant depth sense and, finally, combines this sense with the source conceived depth scenarium. Previously we have investigated human tolerance to induced chromostereopsis, that depends on observer's pupillary distance, age, near heterophoria and used correction type - typical binocular vision parameters[1]. Our studies are devoted to investigation the induced chromastereopsis when using "Virtual Reality" adapters together with mobile devices as smartphones. We did observation of composite visual stimuli presented on the high spatial resolution screen of the mobile phone placed inside a portable "Virtual Reality" adapter. Separated for the left and right eyes stimuli consisted of two areas: a) identical for both eyes color chromostereopsis part, and b) additional conventional color neutral random-dot stereopsis part with a stereodisparity based on the horizontal shift of a random-dot segment in images for the left and right eyes, correspondingly, and the observer task was to equalize the depth sense for neutral and colored stimuli areas. Such scheme allows to determine actual observed stereopsis disparity value versus eye stimuli color difference. Additional to standard application in our adapter the tuneable "Varioptic" liquid lens oculars were incorporated additionally, that allowed stimuli eye magnification, vergence and disparity values control electrically[2]. At standard observation conditions for adapter with +2D ocular lenses for mobile blue-red stimuli , the chromostereopsis sensitivity was detected S?2.1[arcmin/(Lab-color difference)].

[1] Ozolinsh M and Muizniece K (2015).Front. Psychol., 6:337

[2] ARCTIC 39N FAMILY. http://www.varioptic.com/products/variable-focus/arctic-39n/

10021-7, Session 2

Aberration vignetting phenomena and its visualization in wide angular objectives *(Invited Paper)*

Marina Letunovskaya, Irina L. Livshits, Igor S. Potemin, Dmitry D. Zhdanov, Sergey Okishev, ITMO Univ. (Russian Federation); Heidi Ottevaere, Vrije Univ. Brussel (Belgium)

The term "vignetting" stands for a defect in which the brightness of the image decreases toward the periphery compared to its center.

There are different nature of vignetting, depending on which we differ geometrical, mechanical and aberration.

Vignetting depends on the field angle and it is most important for the wide angle objectives.

Aberration vignetting is produced by the pupil aberrations (mainly coma and distortion) and in some cases could be useful to compensate the fall of relative illumination from center to the periphery.

As a result of the action of different aberrations, aberration vignetting could be both positive and negative. So it is possible to compensate other types of vignettings and provide uniform illumination along the image plane, this is hardware compensation.

The requirement of obtaining uniform illumination in the image plane is especially important for cartography both aerial and underwater, lithography, and many other applications.

In spite that in modern devices the fall of relative illumination could be corrected by software, hardware compensation is important as it provides real time action.

The article presents a method of physically accurate simulation of the light propagation in optical devices. Method is based on stochastic ray tracing technics and can be applied to the imaging of three-dimensional objects under complex illumination conditions. These solutions were used for the analysis and visualization of the aberration vignetting effect. The article is

illustrated with a number of visual examples of these phenomena for different objectives like fish-eye lenses and eyepieces.

10021-8, Session 2

Single-pixel imaging by Hadamard transform and ghost imaging and its application for hyperspectral imaging *(Invited Paper)*

Yasuhiro Mizutani, Osaka Univ. (Japan); Kyuki Shibuya, The Univ. of Tokushima (Japan); Hiroki Taguchi, Osaka Univ. (Japan); Tetsuo Iwata, The Univ. of Tokushima (Japan); Yasuhiro Takaya, Osaka Univ. (Japan); Takeshi Yasui, The Univ. of Tokushima (Japan)

In this paper, we report on comparisons of single-pixel imagings using Hadamard Transform (HT) and the ghost imaging (GI) in the view point of the visibility under weak light conditions. For comparing the two methods, we have discussed about qualities of images based on experimental results and numerical analysis. To detect images by the TH method, we have illuminated the Hadamard-pattern mask and calculated by orthogonal transform. On the other hand, the GH method can detect images by illuminating random patterns and a correlation measurement. For comparing two methods under weak light intensity, we have controlled illuminated intensities of a DMD projector about 0.1 in signal-to-noise ratio. Though a process speed of the HT image was faster then an image via the GI, the GI method has an advantage of detection under weak light condition. An essential difference between the HT and the GI method is discussed about reconstruction process. Finally, we also show a typical application of the single-pixel imaging such as hyperspectral images by using dual-optical frequency combs. An optical setup consists of two fiber lasers, spatial light modulated for generating patten illumination, and a single pixel detector. We are successful to detect hyperspectrul images in a range from 1545 to 1555 nm at 0.01nm resolution.

10021-9, Session 2

See-through head-mounted display with geometrical waveguide: a review *(Invited Paper)*

Qichao Hou, Dewen Cheng, Yongtian Wang, Beijing Institute of Technology (China)

See-through Head-mounted displays (HMDs) are widely used in many field such as military, scientific research, assembly, medical treatment, navigation and entertainment. In recent years, researchers have introduced freeform optics, scanning technologies, holographic waveguide and geometrical waveguide into the system of the see-through HMDs. Among those technologies, the geometrical waveguide has tremendous advantage to achieve high resolution, ultra-thin thickness, light weight and full-color display. This talk reviews three types of ultra-thin geometrical waveguide applied in see-through HMDs.

In see-through HMDs, waveguide acts as a pupil expender, the waveguide can be divided into two sections: input-coupling structure and output-coupling structure. Input-coupling structure is similar in different geometrical waveguide, whereas, output-coupling structure varies much and directly determines the performance of see-through HMDs. Three types of output-coupling structures will be reviewed in this talk, partially-reflective mirrors array, trapezoidal microstructures and triangular microstructures, separately. Each kind of waveguide has its merits and demerits. The first type is easy to fabricate and can achieves an FOV of 36o with a thickness less than 2 mm, whereas, the energy efficiency is relatively low; The second type has a really high energy efficiency, but the inverted trapezoidal microstructures are difficult to manufacture; The last type improves the manufacturability and has an acceptable energy efficiency, but the mainly drawback is that a high refraction material is needed which makes it expensive.

The working principle of each output-coupling structure will be described in this paper, and then, we will give conclusions and recommendations for future work.

10021-10, Session 2

A novel type of high-resolution dual-channel Kirkpatrick-Baez microscope

Qing Xie, Baozhong Mu, Yaran Li, Tongji Univ. (China)

High resolution X-ray microscope is one of the essential diagnostic methods for ICF physical experiments. In the compressing phase, the target radiates wide brand X-ray during several nanoseconds. Using the streak camera combined with X-ray imager can measure time-resolved and high spatial resolution details of the target's ablation-front trajectory, imploding velocity and nonuniformity in compressing process. These diagnostic results will provide significant evidence to support the study about the energy absorption and inner surface Rayleigh-Taylor instability theory of the target, which is important for the target designing. It's urgently necessary to provide a microscopy system with high spatial resolution at several micrometers and in a large view field with enough light gathering power.

We designed a new type of X-ray microscope which can image separately at 2.5 keV and 4.3 keV energy points with high spatial resolution in large view field. This microscope is based on X-ray Kirkpatrick-Baez optical structure. In the tangential direction, a bi-mirror reflective form is investigated to reduce off-axis aberration and extend the view field with efficient resolution. In the sagittal direction, a spherical mirror is zoning coated with two kinds of multilayers to choose X-ray at different energy points. Meanwhile, using reflective mirror has also a function of focusing light to improve the gathering power effectively. The lab experiments show that, the spatial resolution can achieve 5?m at a large view field of 600?m. This system, combined with a streak camera, is also well applied in the implosion trajectory and RT instability experiments.

10021-11, Session 3

The angular divergence control of partially-coherent beams using a phase-only liquid spatial light modulator *(Invited Paper)*

Xiaolong Ni, Changchun Univ. of Science and Technology (China)

In order to reduce the complexity and cost of partially coherent optical system, increase the convenience of partially coherent laser beam application, in this paper, we presents a method to control the coherence width and angular divergence of laser beam complexly, using a phase-only liquid spatial light modulator. First, the basic theory and method to control the coherence width and angular divergence of laser beam using a liquid crystal spatial light modulator are introduced; Then, the experiment to test the coherence width and angular divergence controlling accuracy are carried out. The experiment results show that, for a partially coherent laser beam with the coherence width and divergence angle are 0.9mm, 7.5mrad and 1.5mm, 3.8rad, the error of coherence width is less than 5%, the root-mean-square error of the degree of coherence are 0.027386 and 0.031314,

and the peak-to-valley are 0.084658 and 0.089103, the error of divergence angle is less than 10%, the root-mean-square error of the degree of coherence are 0.032478 and 0.043186, and the peak-to-valley are 0.091201 and 0.102130. This method can control degree of coherence width and angular divergence with a high accuracy.

10021-12, Session 3

Multi-tool design and analysis of an automotive HUD *(Invited Paper)*

Bruce R. Irving, Steve Mulder, David M. Hasenauer, Synopsys, Inc. (United States)

Design and analysis of an optical system is often a multidisciplinary task, and can involve the use of specialized software packages for imaging, mechanics, and illumination. This paper will present a case study on the design and analysis of a basic Heads Up Display (HUD) for automotive use. The emphasis will be on the special requirements of such a visual system and on tools and techniques needed to accomplish the design. The first section will present an overview of the imaging design using commercially available imaging design software. Topics addressed include modeling the windshield, visualizing the imaging performance, using constraints and free-form surfaces to improve the system, and design/analysis methods for meeting specific visual performance specifications. The second section will address the use of a CAD program to design a basic mechanical structure to support and protect the optics. This section will also discuss some issues and limitations involved in translating data between a CAD program and an optical program. Typical issues that arise include the precision of optical surface prescriptions, surface and material properties, and the management of large data files. In the final section, the combined optical and mechanical package will be considered, using an illumination design program for stray light analysis. This analysis will be aimed at finding, visualizing and quantifying unexpected ray paths. Techniques for sorting optical ray paths by path length, power, and elements or materials encountered will be discussed, along with methods for estimating the impact of stray light on optical system performance.

10021-13, Session 3

Optical processing deep inside optical materials using counter-propagating pulse-shaped spatial solitons *(Invited Paper)*

Masaki Hisaka, Osaka Electro-Communication Univ. (Japan)

Optical processing using counter-propagating, pulse-shaped spatial solitons to control the molecular structure deep inside the optical material is investigated. A counter-propagating femto-second Ti:sapphire pulsed laser focused at the surface of a ferroelectric crystal such as a Ce-doped Sr0.75Ba0.25Nb2O6 (SBN75) single crystal induces a pulse-shaped, second-harmonic (SH) spatial soliton beam associated with the self-focusing fundamental laser. The counter-propagating SH beam collided with the collision position deep inside the crystal, resulting in the formation of a locally reversed crystal domain at the collision point. This collision process can be controlled using external threshold controls of electric field and crystal temperature. The depth position can be controlled by an optical delay in one optical path. Several domains at different axial positions can be reversed locally. The non-linear interaction between the soliton collision and the approximate periodic reversed domain of a random ferroelectric domain structure induces a change in the intensity of the transmitted beam, thereby enabling the detection of the reversed domains. We also simulated the nonlinear effect using a quadratic-soliton model, an associated fundamental beam, and a SH beam interaction.

10021-14, Session 3

An integrated solution for compression-molded glass lenses

Bo Tao, Ye Yuan, Xinlin Zhou, Hua Chen, Wuhan Univ. of Science and Technology (China)

In compression glass molding, residual stresses, refractive index variation and geometric deviation are inevitable, and can affect the optical performance of a molded glass lens, result in substantial amount of aberrations. In order to achieve optimal performance of molded glass lenses, residual stresses, refractive index variation and geometric deviation have to be taken into account simultaneously and be kept in a reasonable level. In this research, an integrated procedure of modifying molds with annealing step was proposed to reduce geometric deviation, refractive index variation and residual stresses. Geometric deviation predicted by the finite element method simulation was used to provide feedback to modify the model geometry design. Then, a post molding annealing step was followed. Residual stresses and refractive index variation before and after annealing step were measured. Residual stresses were measured and reconstructed by using a circular polariscope. Refractive index was measured and reconstructed by using an optical setup based on Mach-Zehnder interferometer. Measurement results confirmed that this post molding step is beneficial for lens design. The residual stresses and refractive index variation were reduced and controlled. This study demonstrated a suggestion for compression glass lens to achieve better performance while maintaining low cost.

10021-15, Session 3

Two-dimensional analytical modeling of a linear variable filter for spectral order sorting

Cheng-Hao Ko, Yueh-Hsun Wu, Symphony Chakraborty, Sheng-Yu Tsai, Chi-Tsung Hong, National Taiwan Univ. of Science and Technology (Taiwan); Bang-Ji Wang, Jih-Run Tsai, Chiu-Der Hsiao, National Space Organization (Taiwan)

A two dimensional thin film thickness model based on the geometry of the commercial coater which can calculate more effectively the profiles of LVFs has been developed by isolating the substrate plane as an independent coordinate (called local coordinate) from the geometrical coordinate (called global coordinate) whereas the rotation and translation matrix are used to establish the coordinate transformation between local coordinate and global coordinate and combine the characteristic vector with the step function to build a borderline on the surface of substrate in the local coordinate which can conclude that the local mask will block the deposition or not.

The height of the local mask has been increased from 1mm up to 40mm in the proposed model and two dimensional simulations are developed to obtain a thin film profile deposition on the substrate inside the evaporation chamber of the commercial coater to achieve the specific request of producing LVF zone width in a economical way than the previously reported.

10021-16, Session 3

Application of Q-type aspheric surface in the design of Wynne-Dyson projection lens

Cheng-Fang Ho, Wei-Jei Peng, Wei-Yao Hsu, Instrument Technology Research Ctr. (Taiwan)

ITRC dedicates in high precision optics for more than 40 years and focuses in lithography optics for projection system recently. The first project of the lithography optics in ITRC is an i-line Wynne-Dyson projection lens for 3D-ICs applications. The Wynne-Dyson projection lens is a classical design for unity magnification projection system. We take the advantages of the established benefits of Wynne-Dyson lens and modify it. ITRC's Dyson lens is a 0.16 NA system with unity magnification, which is designed in double telecentricity and long working distance. The projection lens comprises three lenses and one concave mirror. Two aspheric surfaces are deployed in lens 1 and concave mirror. A lens with aspheric surfaces can correct for aberration and deliver a higher performance with fewer lens elements, therefore it has advantages of compact and light. However, aspheres are more difficult to fabricate and higher cost than spherical surface. In order to control the testability and manufacturability of the aspheric surface, the Q-type aspheric surfaces are applied in our design phase and manufacture process. We optimize for both performance and manufacturability by Q-type aspheric surfaces. Not only a testable and manufacturable asphere can be approached but also an additional benefits of less sensitive and cost-effective to manufacture to the required specification. In this paper, the Q-type aspheric surfaces and slope constraint are applied to a Wynne-Dyson projection lens, and then it is compared to a design using standard power series aspheric surfaces. We estimate and compare the testability of both type aspheric surfaces by the departure from best-fit-sphere and fringe density of interferometry. Furthermore, subaperture stitching interferometer system (ASI, from QED technologies) is also applied for testability comparison. The tolerance and sensitivity are also discussed. Finally, the results show a diffraction limit approached lens with testable aspheric surface is designed using Q-type aspheric surface. One of the asphere is 150 um departure from best-fit-sphere in 226 mm clear aperture, that can be tested by subaperture stitching interferometer system (ASI). The alignment tolerance of lens in decenter and tilt can be controlled in the range of ±30 micron and 20 arc-second, respectively.

10021-17, Session 4

Direct design of laser-beam shapers, zoom-beam expanders, and combinations thereof *(Invited Paper)*

Fabian Duerr, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

Laser sources have become indispensable for industrial materials processing applications like surface treatment, cutting or welding; but also for medical applications like corneal surgery to name a few examples. Many of these applications pose different requirements on the delivered laser irradiance distribution. Some applications might not only favor a specific irradiance distribution (e.g. a flat-top) but can additionally benefit from time-varying distributions.

We present an overview of a recently developed design approach that allows direct calculation of virtually any refractive or reflective laser beam shaping system. The derived analytic solution is fully described by few initial parameters and does allow an increasingly accurate calculation of all optical surfaces. Unlike other existing direct design methods for laser beam shaping, there is almost no limitation in the number of surfaces that can be calculated with this new approach. This is of particular importance for optical designs of dynamic systems such as variable optical beam expanders that require four (or more) optical surfaces. Besides conventional static beam shapers, we present direct designs of zoom beam expanders, and as a novelty, a class of dynamic systems that shape and expand the input beam simultaneously. Such dynamic zoom beam shapers consist of a minimal number of optical elements and provide a much more compact solution, yet achieving excellent overall optical performance throughout the full range of zoom positions.

All presented ray tracing results confirm the high accuracy of the derived solutions and highlight the potential of this design approach for various beam shaping applications.

10021-18, Session 4

Design of aspheric multifocal contact lens using spline curve *(Invited Paper)*

Lien T. Vu, National Taiwan Univ. of Science and Technology (Taiwan)

This paper presents a solution for the design of aspheric multifocal contact. The aspheric multifocal contact lenses consist of a zonal aspheric surface to increase add power values and reduce dependence on pupil diameter. However, the refractive power distribution is continuous over a selected range but not smooth, the visual acuity is still limited. In this research, the multi-aspheric curve on the optical surface profile of the aspheric multifocal contact lens is replaced by a single freeform spline curve. A cubic spline curve is optimized to obtain the smooth connection of the different vision correction zones and still satisfy the power distribution of the aspheric multifocal contact lens. The result shows that the contact lens using a cubic spline curve could provide not only a smooth lens surface profile but also a smooth power distribution. This method can be extended to the design of multifocal contact lens with complex requirements of the power distribution. The proposed contact lens is easily transferred to CAD format for analysis or manufacture. Results of this study can be further applied for progressive contact lens design.

10021-19, Session 4

Design and verification of a flat-field aberration-corrected concave blaze grating for hyperspectral imaging

Cheng-Hao Ko, Sheng-Yu Tsai, Yueh-Hsun Wu, Chi-Tsung Hong, National Taiwan Univ. of Science and Technology (Taiwan); Jih-Run Tsai, Bang-Ji Wang, Chiu-Der Hsiao, National Space Organization (Taiwan)

A flat-field aberration corrected concave blaze grating for 400-1100nm is designed and fabricated. An optical system is setup to measure the focused spot size, spectral resolution and diffraction efficiency to evaluate the performance of aberration-corrected concave grating. The blaze grating reaches a diffraction efficiency of 70%. For an input point source at z = 0, the focused vertical spot size is 50μm, which indicates a 50μm spatial resolution at the image plane. The focused horizontal spot size is 300μm, which converts to a spectral resolution of 6nm. The design methodology can be applied to an Offner type hyperspectral imager with a free-form convex grating and variable line spacing to achieve high efficiency and high spatial and high spectral resolving power.

10021-20, Session 4

Aspheric and freeform surfaces test with non-null subaperture stitching interferometry

Dong Liu, Lei Zhang, Yongying Yang, Tu Shi, Jian Bai, Yibing Shen, Zhejiang Univ. (China)

A non-null subaperture stitching interferometry (NSSI) is proposed for steep aspheric and free form surfaces testing. A partial null lens (PNL) is employed as an alternative to the transmission sphere, to generate different aspherical wavefronts as references. In NSSI, aspheric surfaces are tested with annular subapertures while free form surfaces with irregular ones. For aspheric surfaces in NSSI, the coverage subaperture number would thus be reduced greatly for the better performance of aspherical wavefronts in matching the local slope of aspheric surfaces. For free form surfaces, irregular subapertures are employed to reduce subaperture number and take full advantage of resolution of interferometer due to the surface asymmetry. A multi-subaperture simultaneous reverse optimizing reconstruction (MSROR) method based on system modeling and ray tracing is proposed for full aperture figure error reconstruction, instead of various mathematical stitching algorithms. All the subaperture measurements are simulated simultaneously with a multi-configuration model in a ray-tracing program, including the interferometric system modeling and subaperture misalignments modeling. With the multi-configuration model, full aperture figure error would be extracted in form of Zernike polynomials from subapertures wavefront data by the MSROR method. This method concurrently accomplishes subaperture retrace error and misalignment correction, requiring neither complex mathematical algorithms nor subaperture overlaps. A numerical simulation exhibits the performance of the NSSI, which demonstrates its high accuracy in testing steep aspheric and free form surfaces. Test results of an aspheric in NSSI are shown to be in good agreement with those of Zygo Verifire Asphere interferometer while results of a bi-conic surface in NSSI are identical with those of Taylor Hobson contourgraph.

10021-21, Session 4

Design of freeform unobscured reflective imaging systems using CI method

Tong Yang, Tsinghua Univ. (China); Wei Hou, Tsinghua University (China); Xiaofei Wu, Guofan Jin, Jun Zhu, Tsinghua Univ. (China)

In this paper, we demonstrated the design method of freeform unobscured reflective imaging systems using the point-by-point Construction-Iteration (CI) method. Compared with other point-by-point design methods, the light rays of multiple fields and different pupil coordinates are employed in the design. The whole design process starts from a simple initial system consisting of decentered and tilted planes. In the preliminary surfaces-construction stage, the coordinates as well as the surface normals of the feature data points on the freeform surface can be calculated point-by-point directly based on the given object-image relationships. Then, the freeform surfaces are generated through a novel surface fitting method considering both the coordinates and surface normals of the data points. Next, an iterative process is employed to significantly improve the image quality. In this way, an unobscured design with freeform surfaces can be obtained directly, and it can be taken as a good starting point for further optimization. The benefit and feasibility of this design method is demonstrated by several design examples of high-performance freeform unobscured imaging systems. All these systems have modulation-transfer-function (MTF) curves which are closed to the diffraction-limit.

10021-31, Session Post

Spatial distribution of current density and thermal resistance of high-power AlInGaN “vertical” and “face-up” light-emitting diodes

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Despite the continuous improvement of luminous efficiency of modern light-emitting diodes (LED), especially based on AlInGaN quantum-wells system, self-heating and heat dissipation remain important and often critical for the proper functioning of such devices. This paper presents a comprehensive analysis of the electroluminescence (EL) and current distributions in connection with thermal resistance in high-power “vertical” and “face-up” AlInGaN light emitting diodes. The study was carried out using a combination of high-resolution EL mapping techniques giving information on the lateral distributions of near-field light emission intensity and thermal transient measurements for evaluation of thermal resistance of LEDs and its elements. It was shown that the “vertical” LEDs with the upper n-contact and a relatively thick n-GaN contact layer maintain better uniformity of the current distribution up to currents greater than 1A, and accordingly have better energy efficiency (conversion efficiency and output optical power). Also, more uniform current distribution and the resulting absence of significant thermal gradients improve reliability and prolong service life. A good correlation was established between the current distribution and thermal resistance of LEDs. Localization of current near the contact pads at high current levels results in the increase of thermal resistance because of the reduced cross section for heat flow from the active region to the radiator. The slope of current vs. thermal resistance curve at the transition region from small to large currents can be used to estimate the dependence of LED’s efficiency and the nonuniformity of the current density and temperature distribution on current and temperature.

10021-32, Session Post

Single camera stereo vision recognization method for Parts’ pose on CMM

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Objective: In order to recognize parts’ pose on Coordinate Measuring Machine (CMM) correctly and fast, a single camera stereo vision recognization method based on the translation of (CMM) is proposed, and its principle, the pose parameters solution and recognization procedure are studied. Method : According to the double cameras stereo vision principle, a image of the part to be measured is captured by the CCD camera, which is driven by CMM along the its X or Y axis, on two different position correspondingly. Thus, the part’s single camera stereo vision measurement is realized with the proposed matching method on two images of the same feature point to be measured on the part, and each feature point’s 3D coordinates in the camera coordinate system can be obtained. Then, using the camera calibration parameters, each feature point’s 3D coordinates in the machine coordinate system can be calculated. At last, combining with each feature point’s 3D coordinates in

the part CAD coordinate system, the part's pose parameters can be solved. Result&Conclusion:The recognization system is set up, and the experiment is conducted?Experiment result shows that the recognization method discussed above is correct and practical, and the recognization time of is 1.818s which meets the real-time measuring requirement .

10021-33, Session Post

Study on the characteristics of a novel optical phased array based on waveguide

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A novel scheme of optical phasea array(OPA) based on wave-guide is represented in this paper. Fiber paths is main design of system, the single mode fibers are used as transmission paths, photonic crystal fibers(PCF) are adopted as the output array, LiNbO3 wave-guide is used as the phase modulator. The system configuration have been given in the paper, performance of main device such as LiNbO3 wave-guide and PCF array are analyzed. According to the theory of OPA and electro-optical effect of LiNbO3 wave-guide, the feasibility of system have been demonstrated.By adjusting the phase shift of each LiNbO3 wave-guide, the beam deflection have been observed. Simulation experiments have been implemented to study the influence of its structure parameter on output diffraction characteristics. The results show that the inter-elements distance, the quantity of fiber core and arrangement of fiber core affect the beam scanning quality including full width at half-maximum(FWHM), output intensity distribution and normalized amplitude distribution. The grating lobes can be suppressed by smaller distance, the beam scanning accuracy is improved by more units of fiber core. Then two-dimension arrangements of fiber core is analyzed. By adjusting the arrangements of the fiber core, the coupling coefficient and the coupling length between two fiber core in the PCF array are changed, which conduct the different output amplitude distribution. So the structure parameter of PCF array is main factor to the beam steering. With the development of craft for PCF, the research result will provide assistance for the design of OPA in the future.

10021-34, Session Post

Stray light analysis on helicopter optical landing guidance system

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Shipboard helicopter optical landing guidance system can ensure the safety of landing when the helicopter completed missions. Stray light has a great influence on positional accuracy of the optical landing guidance system. In order to improve the imaging quality of the optical system, the sources of stray light in optical landing guidance system were studied in this paper. Moreover, the effects of stray light on the system were analyzed in detail.The model of the optical landing guidance system was established in the TracePro software, 16 different off-axis angles were selected to carry out the ray tracing. Through modeling and simulation, the irradiance of stray light in the imaging plane and the point source transmittance (PST) of the system were obtained, they were used to evaluate the level of stray light. Results show that PST of the optical landing guidance system can achieve a level of 10-5~10-8 when the off-axis angle is equal to or greater than 50°. At the same time, the solar stray light energy that gets to image plane can achieve a level of 10-4W/m2. So the optical landing guidance system can work regularly in this range.

10021-35, Session Post

Improved algorithm of ray tracing in ICF cryogenic targets

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The high precision ray tracing inside inertial confinement fusion (ICF) cryogenic targets plays an important role in the reconstruction of the three-dimensional density distribution by algebraic reconstruction technique (ART) algorithm. The traditional Runge-Kutta methods, which is restricted by the precision of the grid division and the step size of ray tracing, cannot make an accurate calculation in the case of refractive index saltation. In this paper, we propose an improved algorithm of ray tracing based on the Runge-Kutta methods and Snell's law of refraction to achieve high tracing precision. On the boundary of refractive index, we apply Snell's law of refraction and contact point search algorithm to ensure accuracy of the simulation. Inside the cryogenic target, the combination of the Runge-Kutta methods and self-adaptive step algorithm are employed for computation. The original refractive index data, which is used to mesh the target, can be obtained by experimental measurement or priori refractive index distribution function. A finite differential method is performed to calculate the refractive index gradient of grid nodes, and the distance weighted average interpolation methods is utilized to obtain refractive index and gradient of each point in space. In the simulation, we take ideal ICF target, Luneberg lens and Graded index rod as simulation model to calculate the spot diagram and wavefront map. Compared the simulation results to Zemax, it manifests that the improved algorithm of ray tracing based on the fourth-order Runge-Kutta methods and Snell's law of refraction exhibits high accuracy. The relative error of the spot diagram is 0.2%, and the peak-to-valley (PV) error and the root-mean-square (RMS) error of the wavefront map is less than ?/35 and ?/100, correspondingly.

10021-36, Session Post

An improved NAS-RIF algorithm for image restoration

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Space optical images are inevitably degraded by atmospheric turbulence, error of the optical system and motion. In order to get the true image, a novel nonnegativity and support constants recursive inverse filtering (NAS-RIF) algorithm is proposed to restore the degraded image. Firstly?the image noise is weaken by Contourlet denoising algorithm. Secondly, the reliable object support region estimation was used to accelerate the algorithm convergence. We introduce the optimal threshold segmentation technology to improve the object support region. Finally, an object construction limit and the logarithm function were added to enhance algorithm stability. Experimental results demonstrate that, the proposed algorithm can increase the PSNR of the restored images, improve the quality of the restored images. The convergence speed of the proposed algorithm is faster than that of the original NAS-RIF algorithm.

10021-37, Session Post

Optimization technique of wavefront coding system based on ZEMAX externally-compiled programs

Libo Han, Yuejin Zhao, Liquan Dong, Ming Liu, Xiaohua Liu, Beijing Institute of Technology (China)

Wavefront coding technique as a means of athermalization applied to infrared imaging system, the design of phase plate is the key to system performance. This paper apply the externally compiled programs of ZEMAX to the optimization of phase mask in the normal optical design process, namely defining the evaluation function of wavefront coding system based on the consistency of modulation transfer function (MTF) and improving the speed of optimization by means of the introduction of the mathematical software. User write an external program which computes the evaluation function on account of the powerful computing feature of the mathematical software in order to find the optimal parameters of phase mask, and accelerate convergence through generic algorithm(GA), then use dynamic data exchange (DDE) interface between ZEMAX and mathematical software to realize high-speed data exchanging. The optimization of the rotational symmetric phase mask and the cubic phase mask have been completed by this method, the depth of focus increases nearly 3 times by inserting the rotational symmetric phase mask, while the other system with cubic phase mask can be increased to 10 times. The maximum operating temperature of optimized system range between -40?-60? and the consistency of MTF is better within this range. Results show that this optimization method can be more convenient to define some unconventional optimization goals and fleetly to optimize optical system with special properties due to its externally compiled function and DDE, there will be greater significance for the optimization of unconventional optical system.

10021-38, Session Post

Research on characteristic of radiometric imaging quality for space-borne camera with super-wide field of view

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In order to ensure the radiometic imaging quality for the space borne camera with super-wide field of view, we put forward a new method, with which the apparent spectral radiance for any field of view can be precisely calculated. Firstly, building the imaging model for the space borne camera, and the parameters of the orbits and attitudes of satellite, the line of sight for the given field of view, the characteristics of different ground objects, the state of the atmosphere, et al.. Secondly, calculating the geometrical observation parameters for the given line of sight of the space borne camera. Finally, using the radiative transfer model to calculate the value of the apparent spectral radiance. Then, we use this method to calculate the apparent spectral radiance for the space borne camera with the FOV of 75°based on freeform mirror on a small remote sensing satellite. And the results shows that the difference of the apparent spectral radiance between the center of the FOV and the edge of the FOV can be 26.9% at the reference of the apparent spectral radiance for the central image pixel, when the satellite takes the imaging of the area of North Atlantic. And we should greatly consider the characteristic of the radiometric imaging quality for the space borne camera with super-wide field of view.

10021-39, Session Post

Multifocal intraocular lens to correct presbyopia

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Due to the loss of the flexibility of the crystalline lens, presbyopia is the most common vision dysfunction for adults after 40. To correct presbyopia, this paper presents a design of a multifocal intraocular lens(MIOL), which can give extended clear vision range both in photopic vision(3mm pupil diameter) and in the mesopic vision(4.5mm pupil diameter). With a pseudophakic eye model, a multi-configuration with object distance covering a full range for normal visual task from 8m to 0.4m were applied. The surfaces of MIOL are aspherical diffractive surface. MIOL was divided into two regions: the inner zone was optimized when the pupil diameter was 3mm and the outer zone was optimized when the pupil diameter was 4.5mm. Finally, we got a 22 diopters(D) MIOLwith a central thickness of 0.652mm and an optical diameter of 4.5mm. By evaluating the modulation transfer function, we got optical performance of the pseudophakic eye with this MIOL. When the pupil diameter of pseudophakic eye was 3mm, MTF at 50c/mm and 100c/mm were above 0.4 and 0.15 for the object distance from 8m to 0.4m. When the pupil diameter of pseudophakic eye was 4.5mm, MTF at 50c/mm and 100c/mm were above 0.25 and 0.09 for the object distance from 8m to 0.4m.The visual acuity was above 0.9 for the whole visual range at both two pupil diameters. Therefore it is safe to say that the new MIOL design provides good optical performance for whole visual range under both the photopic vision and the mesopic vision.

10021-41, Session Post

Simulation of the BSDF measurement capabilities for various materials with GCMS-4 gonio-spectrophotometer

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For the physically accurate lighting simulation of various types of objects it is necessary to consider the optical properties of these objects, which are usually defined by means of measuring the Bi-directional Scattering Distribution Function (BSDF) using gonio-spectrophotometer.

However the simulation results (image rendering or lighting calculations) are to a certain extent differed from those actually observed picture or photometric measurement result. One of the main reasons for this discrepancy is the inaccuracy of BSDF measurements for particular sample. The magnitude of error depends on both the characteristics of gonio-spectrophotometer used for measurement and the combination of optical properties of the sample surface and material. In particular, in case of BSDF measurements for the mirror like sample, the error will be determined mainly by the angular size of detector, which has a finite size, unlike infinitesimal angle of specular reflection. In case of the sample with volume scattering material, some part of scattered light misses the detector and thus not included in the measurement results.

In this paper, the authors analyzed the accuracy of BSDF shape measured for later use of measurements in special software for photorealistic visualization and virtual prototyping. Visual

and numerical analysis were done. In the first case we look at the sample image rendered under specified lighting conditions, replacing its properties on the measurement results and visually estimate the similarity (or difference). In the second case we compare the results of simulation of spatial or angular radiance distribution with results of corresponding radiometric measurements.

10021-42, Session Post

Image amplification-based super-resolution reconstruction procedure designed for wavefront-coded imaging system

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Wave-front coding, proposed by Dowski and Cathey in 1995, is a widely known powerful technique which is capable of extending the depth of focus (DOF) of incoherent imaging systems. Since then, many studies have been conducted but the possibility of using wave-front coding to obtain super-resolution has rarely been investigated. By adding a suitably designed phase mask to the aperture plane, the point spread function (PSF) becomes almost invariant regardless of the defocus value.

Compared to the PSF of conventional imaging systems, the PSF corresponding to wave-front coded imaging systems has a much wider effective width. However, benefiting from its very large PSF generated by the suitably designed phase mask, wave-front coding could also be used to achieve super-resolution without replacing the current sensor with one of smaller pitch size which has many limitations for digital imaging systems.

In this paper, an image amplification based super-resolution reconstruction procedure has been specifically designed for wave-front coded imaging systems and a simple Cooke triplet-based prototype system was established to verify the effectiveness of the procedure. As a result, the effectiveness of the procedure has been tested by experiment. For instance, for a focal length of 50 mm and f-number 4.5, objects within the range [5 m, ∞] are clearly imaged with the help of wave-front coding, which indicates a DOF extension ratio of approximately 20. The proposed super-resolution reconstruction procedure produces at least 3? resolution improvement, with the quality of the reconstructed super-resolution image approaching the diffraction limit.

10021-43, Session Post

Development of miniature high-collimated solar simulator

Pengsong Zhang, Beijing Institute of Spacecraft Environment Engineering (China); Danyi Wang, Beijing Institute of Spacecraft Environment Engineering (China); Bolun Zhang, Linhua Yang, Beijing Institute of Spacecraft Environment Engineering (China)

The solar simulator is used to simulate the outer space solar radiation characteristics. The beam angle of so-called high collimated solar simulator is consistent with that of the outer space solar radiation, which is widely used in the ground test and accuracy calibration of sun sensors. Commonly the irradiance can achieve a solar constant if the collimation angle of solar simulator is between 1° and 2°. However, due to the restriction of the design of the solar simulator, the irradiance is only about 0.1 to 0.3 solar constant when the collimation angle is 32'.

This study optimizes the energy efficiency of optical integrator and the collimator system using theoretical calculations and the optical simulation software. The difficulty to get the real collimation angle and high solar radiation at the same time is overcome. So the veritable simulation of space solar characteristics is possible. The irradiation on target surface should possess the characteristics of real solar radiation, solar angle, spectral distribution, irradiation stability, uniformity.

The miniature high collimated solar simulator discussed in this study is mainly composed of optical system, mechanical system, electronic control system and cooling system. The coaxial optical system with vertical light Xenon lamp is used. After being converged by ellipsoidal condenser, the beam from Xenon lamp is deflected to the optical integrator by the reflecting mirror, and then the field lens of optical integrator images the ellipsoidal condenser on the projector lens of optical integrator, while the projector lens images the field lens at infinity. The collimating lens images the field lens to the irradiation surface, so realizes accurate collimation beam simulation. In addition, the opto-mechanical system ensures reliable position of optical system, and the electronic control system provides the current required by Xenon lamp to control the irradiance, and the cooling system is used to cool the optical system and opto-mechanical system.

As a result, an irradiance of 0.8 solar constant at the collimation angle of 32.2', with 4.65% irradiation uniformity, and 1.93%/h irradiation stability in ?200mm irradiation surface are realized in the miniature high collimated solar simulator developed in this study, which effectively overcomes the technical problem to get the real solar angle and high irradiance at the same time, and provides a reliable test platform for the high precise calibration of the sun sensor in the satellite control system.

10021-44, Session Post

Full-field calibration and compensation of lateral chromatic aberration based on unwrapped phase

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Optical measuring technique, such as 3-D shape measurement and machine vision have been widely studied in academics and applied in industries due to its advantages of non-contact, fast acquisition and high accuracy. Cameras are the dispensable devices in these techniques, especially color cameras can capture color texture and shape data simultaneously. However, images captured by color camera have the phenomenon of chromatic aberrations (CA) and lead to lower precision. Therefore, it is vital how to compensate for CA of a color camera.

This paper presents a novel method to full-field calibrate lateral CA between color channels by using unwrapped phase data. Closed circle sinusoidal fringe patterns having the optimum three-fringe numbers are generated and displayed on a liquid crystal screen consecutively through red, green and blue channels. These closed fringe patterns are captured by a color camera. The wrapped phase and unwrapped phase of each pixel can be calculated by using four-step phase shifting algorithm and optimum three-fringe number method, respectively. The pixel deviations produced by lateral CA are computed by comparing the obtained absolute phase data between red, blue, and green channels in polar coordinate system and calibration is accomplished in cartesian coordinate system. Lateral CA between

color channels of the color camera can be compensated by using the calibrated data. Simulated and experimental results show the validity of the proposed calibration method.

10021-45, Session Post

A design of panoramic lens system to realize the projection from the local annular object field to rectangle image field by using freeform surfaces

Xuqi Bian, Tao Ma, Jun Zhang, Soochow Univ. (China)

Since the early 1980s, people around the world began to study the Panorama Imaging System. Panoramic Imaging System can be defined as an optical system whose field of view is greater than 180° or equal to 360° in the vertical or horizontal direction. Nowadays, a panoramic annular lens (PAL) applies in aerospace, robotics vision, industrial pipeline endoscope and corporate video conferencing. A cylinder-to-plane projection which called the Flat Cylinder Perspective(FCP) is adopted in PAL. The FCP projected the three-dimensional cylindrical field object onto a two-dimensional annular image plane. The optical system has fade zone in the center of detector. Based on the structure of the PAL system, this paper shows that an annular lens is designed with free-form surfaces. In the designed optical system, the local annular object field of view is projected onto a rectangular image plane. The annular lens has a wide field of view of 180° in horizontal direction and a field of view of 40° in vertical direction. The design of the annular lens can maximize the use of area and have no fade zone in rectangular detector.

10021-46, Session Post

Measurement of optical return loss based on optical time domain

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As laser communication technologies and dense wavelength-division multiplexing (DWDM) systems evolve rapidly, the bandwidth of optical fiber communication is much broader than before. To ensure the stable propagation, we should characterize all the optical components, including connectors, couplers, switches and so on. Among the component characteristics, backreflection contributes to overall power loss, degrades laser performance and interferes with voice and video signal processing. Optical return loss (ORL) can be used to describe the characteristic of backreflection. Several measurement principles and methods are introduced to measure ORL. Among them, the technique based on optical time domain is widely used. The technique can be divided into two categories, one is using optical time domain reflectometer (OTDR), and the other is using optical reflection discrimination (ORD). This paper will describe the differences between these two methods in measurement principle, sensitivity and measurement result. OTDR method measures the backscatter level of the fiber media itself and the reflection peak level of reflective events along the fiber link. It offers an estimate of the strength of a reflection at a given distance based on its peak height. OTDR method is suitable for characterizing long distance fiber links with sufficient space between the multiple reflections. ORD method measures the incident and reflected optical powers of reflected events. It can eliminate the influence of the backscatter signals of the fiber media itself, so the measurement result can reach up to 80dB. ORD method is typically optimized for measuring short-length optical links like patch cords, pigtails, and other discrete components. Conclusions of this paper can be the guidance for selecting the proper optical return loss meter for ORL measurement.

10021-47, Session Post

Analytical calculation of light scattering from randomly rough Gaussian surfaces according to slope probability

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As light scattering from randomly rough surfaces is of great importance in wide fields such as remote sensing, polarized imaging and target identification, etc., both experimental and numerical approaches are used to describe the details of the light scattering process. Among these approaches, numerical calculations can simulate the scattering distribution without complex experimental setups and complicated operations, thus they become important tools in light scattering studies. Method of moments and Kirchhoff approximation methods are representatives of these approaches, as they can provide extremely accurate light scattering, however, they still suffer from the long time-consuming and large calculation load. These disadvantages limit their future applications in dynamic measurements and high speed detections. Here, in order to overcome these disadvantages, analytical calculation of light scattering from randomly rough Gaussian surfaces according to slope probability is presented in this paper. Compared to other light scattering numerical approaches, the proposed technique uses the statistical parameters of randomly rough surfaces directly without computing the ensemble average from numerous scattered fields, which can obtain light scattering parameters with high accuracy, but much less time consuming. Additionally, not only the light scattering distributions can be obtained, the polarization parameters as Mueller matrix can also be retrieved, indicating the proposed method can provide more details of the randomly rough surface information. We believe the paper provides a useful approach for light scattering study and offers potentiality in real time light scattering testing.

10021-48, Session Post

Three-dimensional illumination system for tomographic particle image velocimetry

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Tomographic particle image velocimetry (Tomo-PIV) is a new developed technique for three-component three-dimensional (3C-3D) velocity measurement of the flow field based on the optical tomographic reconstruction method , and received extensive attention of the related industries at home and abroad. Three-dimensional light source illuminates tracer particles of flow field is a critical application for tomographic particle image velocimetry. Three-dimensional light source not only determines the size of measurement volume which corresponding to the scope of application, but also has a great influence on the image quality.In this work, we proposed a rectangular light amplification system based on prisms combination and two reflectors.The rectangular light amplification concept is verified experimentally by measuring the cross section size of the illuminated light source.The system can be optimized through the basis of theoretical model research and provides an estimation of some important system parameters. A 60mm*25mm cross section of rectangular three-dimensional light source can be obtained by

using the rectangular light amplification system .The results show the feasibility and advantages of the system.

10021-49, Session Post

Design of precise assembly equipment of large optical components

Pei Guoqing, Xu Xu, Xiong Zhao, Weifeng Du, Yan Han, Ye Lang, Zhou Hai, Xiaodong Yuan, China Academy of Engineering Physics (China)

High-energy solid-state laser is an important way to achieve inertial confinement fusion research. With the development of high power laser technology, the optical components of modern high-energy solid-state laser has become larger and larger. Laser fusion facility includes thousands of various types of large optical components. To make sure the device works safely and reliably, these large optical components should be installed with high precision and high efficiency. Currently the assembly of large optical components is by man's hand which is in low level of automation and labor-intensive.

The large optical components are very fragile, heavy and expensive. We analyzed the actual operating conditions and technical principles of the assembly of large optical element. According to the characteristics of the precision assembly of large optical components. We designed a new kind of grasping device which are used to complete the assembly of large optical components. Flange, vacuum chuck, chuck installation and connection components, the clamping cylinder and translation cylinder, vacuum pump, filter, solenoid valves, vacuum line were designed. The layout of pneumatic system is arranged. We simulated the impact of the grasping device on the PV value and the RMS value of the large optical components which indicated that the deformation of the large optical components were within a reasonable range. The structural strength of the grasping device's key parts were analyzed which indicated that the strength of the main support plate was enough to keep the device safely. An experiment was performed to illustrate the reliability and precision of the grasping device.

10021-50, Session Post

On freeform configuration to improve system resolution

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Freeform system theory and its influence on aberration and control, is the basis to develop such a system design, which has application value in engineering aspects. The principle approach, modeling, and error analysis are analyzed, and the system configuration based on freeform is advanced in algorithm analysis. For to improve the resolution of the imaging system, and achieve the theoretical limit, we introduced the technology principle of super resolution restructure from the point of view on theory and engineering. Several methods to realize high resolution restructure configurations are introduced based on theoretical analysis and engineering practice. Then, three kinds of restructure technologies, that prototype, micro scanning and sub pixel are described, and how to decrease their shortcomings are discussed in detail. Furthermore, to improve the band width by reconstruction without the spectral alias in super resolution technologies, a new coding technology combining a optical encoding and the sub pixel is proposed. With the global method, the bandwidth has been amplified by ten times as compared with that of traditional ones. Simulation results show that the system can meet the application requirements in MTF, REA, RMS and other related criteria. Compared with the conventional design, the system has reduced in volume and weight significantly. Therefore, the determining factors are the prototype selection and the system configuration combined optical, electronic and signal processing technologies, and as an important developing trend.

10021-51, Session Post

Slope error tolerance analysis for candela distribution of total-internal-reflection collimating lens

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The total internal reflection (TIR) lens is one of the most widely used collimating optical devices for LED with small beam angles and high CLIs. Little work is concerned with how the slope-error distribution impacts the performance of certain LED collimators, especially the angular candela distributions.

This paper presented a general concentration standard index (GCSI) which is introduced as a metric for analyzing the luminous intensity at certain angle, both locally and globally.

Firstly, a Three-Dimensional (3D) slope error tolerance model for TIR lens is constructed as the extended work of the 2D model proposed by the authors, and then the local concentration standard index (GCSIL) for various angles and locations on TIR curve are calculated.

Secondly, the slope error sensitivities for luminous intensity for different angels is derived by integration from GCSIL with all positions at the TIR curve and how the slope error impact on the angular candela distribution can be obtained.

Thirdly, the slope error impact on the Beam angle (the Full Width at Half Maximum luminous intensity (FWHM)) and the Filed Angle (the Full Width at 10% Maximum luminous intensity) , are also considered by this theory. The results revealed that the Beam Angle is decreased at first and then increased with the increased slope error, whereas the Filed angle is monotonically increasing with the slope errors.

According theory has been well demonstrated with Monte Carlo ray tracing due to RMS uniformity as low as 1.8% for Beam angle and 2.23% for Filed angle.

10021-52, Session Post

calibration research of focal length measurement using Talbot interferometer

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In this paper, the math model is built for focal length measurement using an interferometer based on the Talbot effect and the Moiré technique. From this model, a series of methods is presented to calibrate primary systemic parameters of which measurement uncertainty composes mainly. These parameters include the distance between the first grating and the tested optical system, the distance between the two gratings, the angle between the grating ordinate and the camera ordinate, the angle of two gratings, the angle of moiré fringes, and the rate of two grating pitches. The calibrating procedure of a certain interferometer has been practised, getting a certain result of measurement uncertainty of 2% (k=2) in the scale of 500 meters. An experiment designed for validating the measurement uncertainty is described. A knife-edge instrument also with the measurement uncertainty of 2% (k=2) is applied to affirm the real focal spot of 30 meters to 500 meters. The experiment shows that the measurement results of calibrated Talbot interferometer and that of knife-edge instrument satisfy the comparison equation. As a result, the analysis of the measurement uncertainty is rational, the method is practicable, and the measurement results are traceable.

10021-53, Session Post

Simultaneous null test of primary mirror and three mirror in off-axis three mirror

Yajun Niu, Jun Chang, Weilin Chen, Benlan Shen, Beijing Institute of Technology (China)

The null test of off-axis mirror plays a very important role in off-axis three mirror design. The detection device depends on either complex detection optical system designs or high-precision null lens design. Both can only test one off-axis mirror and are not non-universal. In order to increase the detection efficiency, we innovatively propose a simultaneous null test method of primary mirror and three mirror in off-axis three mirror. The simultaneous null test device is composed of a zoom null lens and a special computer generated hologram (CGH) plate. The special CGH plate has two sub-regions which are corresponding to the two off-axis mirror. The simulation result of an off-axis three mirror detection example show that the simultaneous null test method is feasible.

10021-54, Session Post

Polarization properties of cat's eye retroreflector with three-dimensional Jones matrix method

Yuegang Fu, Yahong Li, Wenjun He, Jiayuan Liu, Changchun Univ. of Science and Technology (China)

We presents the geometrical performance analysis of Cat's-eye retroreflector (CER) in this paper, including the relationship to refractive index, normalized incident height and divergence angle, which provides tips for optimizing the design of CER. Furthermore, the polarization property of CER plays a critical role in related engineering application. For example, when it is used in polarization interferometer, it's polarization property will reduce the signal-to-noise ratio. If CER is applied in laser resonator, the polarization degree of emitted laser is directly influenced, even producing the phenomenon of depolarization. In this paper, we have studied a detailed three- dimensional polarization ray tracing of CER based on the three-dimensional Jones matrix and vector Snell's law, and the layouts of output polarization state, retardance and diattenuation of CER in the exit pupil have been investigated. The calculated results have showed that the maximum retardance is 0.3°, the maximum diattenuation is 0.027, which have had almost no influence on the output polarization state. Finally, We have made some simulations of the output polarization states of CER with different input polarization states. For example, horizontal Linear, 45° linear, circular and elliptical polarization state have been analyzed by using simulation software FRED. The simulation results have indicated that the output polarization state remains unchanged with different input polarization states of CER, which is consistent with the theoretical analysis. Therefore, CER can be equivalently viewed as a polarization maintaining component.

10021-55, Session Post

Characterization on the effect of linear stress birefringence in a total reflection prism (TRP) ring resonator

Dong Li, Chao Bi, Yajun Jiang, Jianlin Zhao, Northwestern Polytechnical Univ. (China)

By using the total reflection prisms with the reflectivity close to one hundred percent instead of the stack of alternated high-index and low-index multi-dielectric layers, the total reflection prism (TRP) ring laser gyroscope can motivate the ongoing interest in inertial navigation systems (INS) community and promote an increase in the service life and a reduction in the start-up time of a laser gyroscope. However, the TRP resonator put forward higher requirements on the co-planarity of the beam reflective point on the four prisms. The resonator consisted of the prisms is the core component of the gyroscope whose precision can be affected by the slightly residual stress and the errors of structure parameters during the processing and adjustment of the resonator and prisms, etc. In this paper, based on the theory of Jones matrix and the condition of eigenmode self-consistency, we analyze the effect of linear stress birefringence of prism on the beam polarization (described with the ellipticity and loss of the eigenmodes) and null drift (described with the output frequency difference of the eigenmodes) in a TRP resonator. The results show that the linear stress birefringence of prisms can cause larger polarization ellipticity for both CW (clockwise) and CCW (counter clockwise) beams, which has nothing to do with the nonplanar angle. Meanwhile, the direction of stress has some influence on beam polarization ellipticity and null drift. These interesting results are useful for the designing and optimizing the structure of super high precision TRP ring laser gyroscopes.

10021-56, Session Post

Measurement for diffraction efficiency of convex gratings

Peng Liu, Xinhua Chen, Jiankang Zhou, Zhicheng Zhao, Quan Liu, Chao Luo, Xiaofeng Wang, Weimin Shen, Minxue Tang, Soochow Univ. (China)

Imaging spectrometers with convex gratings which can offer fast apertures and small volume systems synchronously have received a great deal of attention both in China and abroad, because of the increasingly development of convex grating manufacture techniques. They can be applied as remote sensing instruments in the areas of mineral exploration, agriculture, forestry, environment hazards assessment, urban study and so on.

As one of the most important properties of convex gratings, diffraction efficiency has a direct impact on energy transmission characteristics of imaging spectrometers. Compared with plane gratings, convex gratings are formed upon convex substrates that results in different measurement methods of diffraction efficiency which have been rarely reported in China.

In this paper, a new measuring system for diffraction efficiency of convex gratings and its principle are proposed and described. This system mainly consists of a stable light source, relay system, Offner spectrometer, and data-processing system. By using this system, the intensity of diffraction signals over an extended spectral range from a convex grating can be detected during one exposure cycle. After setting up the measurement system and accomplishing the laboratory spectral calibration, the diffraction efficiency of a convex grating with an aperture of 35 mm, curvature-radius of 72mm and a grating period of 5 ?m is tested. In the end, the comparison and error analysis between the theoretical calculations and the testing data are carried out to provide the technical basis for the further manufacture of convex gratings and imaging spectrometers.

10021-57, Session Post

Research on detecting plankton based on darkfield microscopy

Buyu Guo, Jia Yu, Ocean Univ. of China (China)

Plankton is an important part of the marine life, which plays a significant role in studying the change of global climate and the marine ecological environment. However, once plankton leaves

the original living environment, it is extremely vulnerable to death and the refractive index of plankton is highly close to the refractive index of the ocean. This makes it very difficult to detect plankton by the bright field microscopy.

This problem can be resolved by the darkfield microscopy, which allows only oblique rays from every azimuth to "strike" the specimen and let the field of view appear dark. Meanwhile the darkfield microscopy with high resolution can help to detect the plankton in a smaller size. To achieve accurate and effective detection of plankton, we build the Underwater Darkfield Microscopy Detection System. This system is composed of two parts: light cabin and receiver cabin that are connected through a cable. The battery is located in the light cabin to generate hollow light cone for illuminating. The receiving compartment includes microscopic imaging amplification unit and storage unit, capturing the image by CCD.

We start by collecting samples from the coast of Qingdao and then use the resolution board to confirm the performance and resolution of the underwater darkfield microscopy detection system. We detect plankton from the collected sample to obtain their shape information. The resolution of our system is about 181lp/mm.

10021-58, Session Post

Design, assembly, and metrology of an oil-immersion microscope objective with long working distance

Wei-Jei Peng, Wen-Lung Lin, Hui-Jean Kuo, Cheng-Fang Ho, Wei-Yao Hsu, Instrument Technology Research Ctr. (Taiwan)

The design, fabrication, assembly, and optical metrology for an oil-immersion microscope objective with long working distance employed in a lattice light-sheet microscope are presented. In this application, the orthogonal excitation and detection objectives are dipped in an oil medium. The excitation objective focuses incident laser beam to excite fluorescence on specimen for collecting by detection objective. The excitation objective in our study is custom-designed to meet the requirement specification of oil-immersion, long working distance, and numerical aperture (NA) of 0.5, etc. To produce an acceptable point spread function (PSF) for efficient excitation, the performance of the objective needs to be close to diffraction limit. Therefore modulation transfer function (MTF) at high spatial frequency should be kept after assembly. It is difficult because the tolerance is much more sensitive at higher spatial frequency. Consequently, tolerance budget must be considered in the design phase, the criterion of optical design is based on as-built optical performance in our study for ensuring quality after fabrication and assembly. Furthermore, the opto-mechanical design and assembly method are also discussed. Afterward, the objective with five spherical lenses was fabricated and assembled. In optical metrology, the focus of the objective is immersed in the oil, so it leads to measured result sensitive to the depth of oil medium. For solving the issue, we made an index-matching lens to replace oil for ensuring accuracy measurement and avoiding complex mechanical adjustment. Finally, the measured optical performance of the excitation objective in our study can accomplish the requirement specification and successfully used in a lattice light-sheet microscope.

10021-59, Session Post

Tilt displacement range testing for a piezoelectric deformable mirror

Dongdong Wang, Qun Hao, Yong Song, Beijing Institute of Technology (China); Xuemin Cheng, Graduate School at Shenzhen, Tsinghua Univ. (China); Fan Fan, Heng Li, Beijing Institute of Technology (China)

In our previous works, we presented a zoom system and image stabilization design based on deformable mirrors (DMs). According to the high bandwidth and free edge characteristics of the piezoelectric deformable mirror (PDM), we tested the system's image-stable capability. We found the PDM could realize some tilt displacements while keeping a certain stable surface shape, it could obtain higher image stabilizing precision when integrated with the traditional mechanical image stabilization systems. In the design of the image stabilization system, the PDM's tilt displacement range is a key factor for consideration. So in this paper, we carried out a tilt displacement range testing experiment by using the OKO's 37-channel PDM. We measured and analyzed the variation of the tilt displacements in optical image stabilization process, and calculated the maximum tilt angle as the PDM surface shape was stabilized. We built an experimental platform consisting of a fixed target, an imaging system based on PDM, and a CCD camera. We used the ZYGO interferometer as an evaluation instrument to measure the surface shape stability. When the PDM surface had a tilt displacement, the image point of the fixed target on the camera sensor shifted correspondingly. The tilt angle of the PDM could be obtained by calculating this shift. The results showed that the maximum tilt angle of the PDM was 0.2mrad. The paper also analyzed the experiment errors when concerning about the off-axis error of the PDM deflection center.

10021-60, Session Post

Optical design of Offner-Chrisp imaging spectrometer with freeform surfaces

Lidong Wei, Jinsong Zhou, Juanjuan Jing, Lei Feng, Yacan Li, Academy of Opto-Electronics, CAS (China)

Imaging spectrometers are novel radiation sensors that provide a collection of spectral images of inhomogeneous scenes. The Offner-Chrisp spectrometer is the preferred optical configuration in many spectroscopic imaging applications because it has several advantages over other similar instruments. However, the diffraction grating makes the Offner-Chrisp imaging spectrometer asymmetric in the meridional plane, and the astigmatism becomes the dominant residual aberration. Moreover, the images of different wavelengths are not flat along the slit can decrease the imaging quality and difficult for assembly.

Freeform surfaces enable imaginative optics by providing abundant degrees of freedom for an optical designer as compared to spherical surfaces, and offer many advantages in imaging application, e.g. superior image quality, compact and lightweight designs. An Offner-Chrisp imaging spectrometer with freeform surfaces is designed in this paper. The imaging spectrometer works at the wavelength range from 200 to 1000nm. The freeform surfaces are used to reduce the residual aberration over the large wavelength range and achieve a large flat field simultaneously. The design starts from a sphere Offner-Chrisp system, and then the freeform surfaces are applied to optimize the initial configuration by the use of an optical software package. Different types of freeform surfaces are considered to evaluate their potential, e.g. anamorphic aspheres, Q-polynomials of Forbes, X-Y polynomial and Zernike polynomial. Benefits from the freeform surfaces, the residual aberrations are well corrected, especially in the UV region and a flat field over the wide wavelength range is also obtained. The image quality is near diffraction limits. For evaluating the manufacturability of the freeform surfaces system, the aspheric departures of each freeform surface are also evaluted which meet the current manufacturing capacity.

10021-63, Session Post

Design of a holographic waveguide with L configuration

Guangxin Xiang, Wenqiang Li, Luoyang Institute of Electro-Optical Equipment (China)

In order to decrease the complexity to design and manufacture the gratings of single plate with single reflecting surface, an L-shape two-dimension extended configuration with single plate is given in the paper. This configuration consists of two specular reflecting surfaces and three holographic gratings of which period and the groove orientation are totally same, which makes gratings design and fabrication easier. According to the calculation and analysis to the optical path of configuration, the dimension of the turning grating is no larger than 40mm?40mm. The simulation result demonstrates the display configuration is reasonable and correct and can realize the display effect with 30°?30° field of view and ?30mm large exit pupil. This configuration can be applied to an Augmented Reality Display (AR) or a Head-Mounted Display (HMD).

10021-65, Session Post

Design and Analysis of Conical Diffraction Imaging Spectrometer with High Spectral Resolution

Qiao Pan, Qinghan Liu, Zhicheng Zhao, Weimin Shen, Soochow Univ. (China)

Owing to the use of CCD linear image sensor of rectangle pixels, the spectral dispersive width of spectrometer is usually much longer than the spatial one, sometimes up to dozens of or hundreds of times. In this case, traditional in-plane Offner mounting is no longer satisfied because of dramatic increasing astigmatism and distortion. To meet these special needs, conical diffraction Offner mounting, one kind of off-plane Offner mountings, in which the incident light plane parallel to the direction of the grooves of the grating, is presented. Wave aberration theory is applied when analyzing the initial parameters related to the structure of spectrometer. Consequently, an optimal design is proposed later by utilizing the formal results, of which the focal ratio is 4 at the spectral region of 400?1000nm while slit length 500?m and dispersive width 21mm. To evaluate the overall image quality changing along with the angles between incident and diffractive plane, the entrance slit length and the spectral width, the merit function and spectral response function are considered under no obvious changes in the spectrometer's total volume. At the end of the design instance, comparative analyses between in-plane and conical diffraction Offner mountings are presented as well. Finally, conclusions are given about the application scopes of these two configurations.

10021-66, Session Post

Design of refractive fore-optics with wide field-of-view and waveband for miniature imaging spectrometer

Jingchao Mao, Minyi Xu, Qinghan Liu, Weimin Shen, Soochow Univ. (China)

With the development of UAV remote sensing technology? compact high-resolution imaging spectrometer will be more and more popular. It is urgent to design and develop fore-optics with wide field of view for miniature broad spectrum imaging spectrometer which can improve the efficiency of remote sensing and get wider coverage. The refractive system has high luminous flux and it is conducive to manufacture and assemble. Our focus is on the correction of secondary spectrum and meeting the requirement of imagery telecentricity which is appropriate for linear pushbroom imaging system. Based on the third-order aberration theory, it calculates the power of individual elements of the objective lens with minimized longitudinal chromatic aberration in a broad spectral range. Moreover, this paper derives equations to calculate the radii of curvature of superachromatic optical system with a required value of spherical aberration and coma. Finally, optimized refractive SWIR fore-optics working in 1-2.5?m with effective focal length (EFFL) of 11mm is reported. Its full field, F-number are respectively 40°, F/2.8. The system has many advantages such as simple and compact structure?near diffraction-limited imaging quality?small secondary spectrum?and imagery telecentricity. Especially it consists of spherical surfaces that can greatly reduce the difficulty and cost of manufacture and test, which is applicable for SWIR imaging spectrometer with wide field of view.

10021-67, Session Post

Afocal three-mirror anastigmat with zigzag optical axis for widened field-of-view and enlarged aperture

Qi Li, Han Lin, Yangming Jin, Weimin Shen, Soochow Univ. (China)

In order to improve the detection accuracy and range of new generation of Forward Looking InfraRed (FLIR) system for distant targets, its optical system, which usually consists of a fore afocal telescope and rear imaging lenses, is required to has wide spectral range, large entrance pupil aperture, and wide field of view (FOV). In this paper, a new afocal Three-Mirror Anastigmat (TMA) with widened field of view and high demagnification is suggested. Its mechanical structure remains coaxial, but it has zigzag optical axis through properly and slightly decentering and tilting of the three mirrors to avoid its secondary obscuration due to the third mirror as FOV increase. Compared with conventional off-axis TMA?the suggested zigzag-axis TMA is compact, easy-alignment and low-cost.

The design method and optimum result of the suggested afocal TMA is presented. Its initial structural parameters are determined with its first-order relationship and primary aberration theory. Slight and proper decentration and tilt of each mirror is leaded in optimization so that its coaxial mechanical structure is held but attainable FOV and demagnification are respectively as wide and as high as possible. As an example, a 5.5-demagnification zigzag-axis afocal TMA with a wavelength range, an entrance pupil diameter, and FOV respectively from 3 um to 12 um, of 320mm, and 2?4 degrees and with real exit pupil, is designed. Its imaging quality is diffraction limited. It is suitable for fore afocal telescope of the so-called third generation FLIR.

10021-68, Session Post

Assembly and alignment of high-resolution spaceborne optical system

Wang Kai Guo, Min Wang, Feng Lin, Fujian Normal Univ. (China)

Based on a high-resolution spaceborne optical system researched and developed independently, this paper puts forward a method called detecting instrument and computer aided separated assembly and alignment. It uses a variety of high-precision detecting instruments to test the parameters of optical components and system, and then select the qualified component to match in groups. Adjust the main errors what are the air gap error between lenses and the eccentric error in

assembly. Divide the optical system into some small lens groups and their residual error can be compensated by adjusting the air gap between lenses. Use the detecting instrument to measure the MTF after assembly and alignment. The result shows that the optical system meets the design requirements and its pixels are more than 20 million. This alignment method is also suitable for other high-resolution coaxial optical system.

10021-70, Session Post

Optical design of a dual-channel two-focal-length system by utilizing azimuth property of PAL structure

Chen Xu, Dewen Cheng, Yongtian Wang, Beijing Institute of Technology (China)

An approach to design a dual-channel two-focal-length lens based on the panoramic annular lens (PAL) structure is presented in this paper. The method of establishing the second channel to eliminate the blind area has been explored in some documents, and mostly it is achieved by utilizing the front surface of the PAL block. But in this paper, we modified the PAL block and divided it into two channels according to their different azimuth direction. These two channels have different focal lengths. Thus, by rotating the system around its axis, optical step-zoom effect can be obtained. Finally, a dual-channel system with a zoom ratio of 3? is designed, of which the wide-angle channel has a field-of-view (FOV) of 60° (radial) ?90° (azimuthal) and the long focal length channel has a FOV of 20° (radial)?20° (azimuthal). These two channels share the same stop surface, relay lens, and the image sensor. And a thin glass plate with diffractive structure is placed before the image plane to further correct aberration and obtain a common back focal length for the two channels. This system may have applications in many fields, such as surveillance, robot vision, and foveal imaging.

10021-71, Session Post

Study of 700mm-diameter primary mirror based on topology optimization and sensitivity analysis

Xin Wang, Xiaoying He, Lei Feng, Juanjuan Jing, Jinsong Zhou, Academy of Opto-Electronics, CAS (China); Wei Wang, Xi'an Institute of Optics and Precision Mechanics, CAS (China); Yacan Li, Academy of Opto-Electronics, CAS (China); Wei Lidong, Academy of Opto-Electronics, Chinese Academy of Sciences (China) and Academy of Opto-Electronics, CAS (China)

The primary mirror is an important optical component of space camera. It's performance related to the optical image quality, and it's weight directly affects the camera weight. The traditional method of designing primary mirror relies on much experience, and many design parameters obtained by empirical formulas. The method lacked precise theory, and the performance of the result is unstable. Therefore, the method of designing primary mirror should be optimized. For this study, a primary mirror made of SiC with a diameter of 700mm was conceptual designed in the method of topological optimization firstly. The design goal is to fully guarantee the quality of the structural strength and also the shape of mirror surface under the premise of minimum weight.

The structure of topology optimization has completely met the design requirements. But due to the topological optimization is conceptual design, which cannot determine the specific size of configurations. In order to further enhance the performance of the mirror, sensitivity analysis is carried out to determine the optimum thickness of the back muscles. Divided back tendons into three categories according to the distribution location. The sensitivity of primary mirror stiffness to the three categories tendons was analyzed, and then the optimum thickness of the tendons was found. Finally, the optimum primary mirror fully satisfied the required optical performance was designed, which has better mechanical performance and the lighter weight. A companion between the optimum primary and traditional primary was made and the results showed that, the optimum primary has higher lightweight ratio increased by 5%, higher modal frequency increase by 81Hz.The maximum deformation under gravity parallel to the optical axis reduced by 48nm, PV of the mirror surface reduced by 8.1nm and RMS reduced by 3.1nm. Put forward the target of temperature control through the thermal analysis.

All the result data indicates that this optimization method in the paper is reasonable and effective, which gives a reference to the primary mirror design in the future.

10021-72, Session Post

Wavefront sensing for sparse aperture imaging system based on sub-aperture phase diversity

Junliu Fan, Quanying Wu, Jun Wang, Suzhou Univ. of Science and Technology (China); Baohua Chen, Soochow Univ. (China)

The phase diversity wave-front sensing (PDWFS) technique is a posteriori image-based wave-front sensing method which has been successfully implemented to the Hubble Space Telescope, it utilizes two images collected simultaneously whose pupil phase differs from each other in a known manner, typically the focus diversity. Here, we introduce a new method of implementing phase diversity on sparse aperture imaging system that utilizes control of the sub-apertures. Instead of adding defocus phase to the image, intentional piston or tilt errors are introduced to one sub-aperture with respect to the others, the objective function is firstly derived for the sparse aperture imaging system, then the genetic algorithm is used to minimize the objective function to estimate the errors of the sub-apertures. Digital simulations are conducted for varying amounts of diversity and levels of noise. The performance of sub-aperture phase diversity is evaluated by comparing with the conventional focus diversity. The results show that the sub-aperture phase diversity performs better than the conventional focus diversity at low noise level, while focus diversity performs better at high noise level, in the computational burden aspect, the sub-aperture phase diversity takes less iterations than conventional focus diversity and therefore achieves higher computational efficiency. Sub-aperture phase diversity may be an useful alternative if the primary focus phase diversity method fails.

10021-73, Session Post

Depolarization of laser beam propagating through atmosphere based on multiple Rayleigh scattering model

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An analytical formula model which is used to describe laser beam's depolarization characteristics is solved based on multiple Rayleigh scattering model. Firstly, by using Stokes vector to characterize intensity and polarization, while at the same time using Mueller matrix and rotation matrix to characterize polarization changing in scattering procedure, a single scattering

model is built. Then, a multiple scattering model is built considering the effects of atmospheric absorbing and scattering attenuation. The received light's Stokes vectors through multiple scattering procedure are separately solved. At last, on the basis of multiple scattering vectors, the depolarization characteristics of laser beam propagation through atmosphere are estimated though calculating ratio of depolarization and polarizing angle shifting. The numerical analysis based on analytical conclusion of this paper shows that for a horizontal polarized laser beam, its ratio of depolarization is about 1% and polarizing angle shifting is about 0.3? when propagates through atmosphere and arrives into the receiver on the ground and both the above characteristics have only a small change compared with the change of cloud's depth. The findings of these research show that Rayleigh scattering from atmosphere has a weak effect on the laser beam's polarization status. The multiple scattering model and Stokes vector analytical formulas raised in the paper could also be used to study the depolarization characteristics of ellipse polarized laser beam and partially polarized laser beam propagating through atmosphere. The research findings of this paper will have theoretical guiding significances in the domain of laser communication, laser detection and laser imaging.

10021-74, Session Post

Mean likelihood estimation of target micro-motion parameters in laser detection

Liren Guo, Yihua Hu, Yunpeng Wang, Institute of Electrical Engineering (China)

First of all,a closed-form expression to evaluate the parameters which maximize the cost function is derived based on the thiory of mean likelihood function. Then the compressed likelihood function is designed to obtain the global maximum, mainly through exponeniating the cost function and adjust the constant factor. This compressed likelihood function acts like a probablity density function that ensures the global convergence. Finally?the Monte Carlo sampling method is used to generate the random variables subject to the distribution obtained from the compressed likelihood function. The parameters are ultimately estimated by calculating the circular mean of the random variables. Simuation and experiment results show that this method is able to reach the Cramer-Rao Bound and acquire similar performance as Maximum Likelihood Estimation with less computational amount.

10021-75, Session Post

Research on focusing properties of multi-vortex phases vector beam loading with different topological charges

XianYi Zhang, Xiaoping Yang, Tianjin Univ. of Technology (China)

The inhomogeneous polarization distribution of vector field makes a great impact on the spatial-temporal evolution and leads to many novel phenomena and effects, which is different with the scalar beam, such as that the radially polarized field could be highly focused into a sharper spot with strong longitudinal component, the azimuthally polarized field could be highly focused into two-dimension and three-dimension hollow focal field. In addition, we also can adjust and control the light field, which mainly involves the polarization and phase control. In this paper, the phase control of vector beam namely load vortex phase is researched and simulated.

In this paper, we deduced the focusing field formula of the multi-vortex phase vector beams loading with different topological charges based on the Richards-Wolf vector diffraction theory. It is found that when the Gaussian radial vector field symmetric loading double vortex, three vortex and four vortex along the x axis, it can generate one, two and three optical dark-field in the focusing field respectively.and it can be used in the multi particle capture.We loaded different topological charges on the vortex phases,and adjusted the energy distribution of the focusing spot by changing the topogical charges.This feature can be used in the field of multi particle manipulation and fine control of laser micro maching

10021-76, Session Post

Design of photonic crystal Fizeau interferometer using self-collimation effect

Jun Wang, Suzhou Univ. of Science and Technology (China) and Soochow Univ. (China); Xiao Yuan, Soochow Univ. (China)

A Fizeau interferometer based on the self-collimation effect of two-dimensional air-cylinder photonic crystal (2D PhC) is demonstrated theoretically. The back ground index of the square-type lattice PhC is 3.5 and the radius of the air holes r0 = 0.26a, where a is the lattice constant. The structure of PhC leads to its self-collimation effect, by which the lights propagate in the interferometer. The Fizeau interferometer includes one total reflection PhC mirrors and two defect row splitter, shown in Fig.1. Compared with non-common optical path interferometer (e.g. Michelson and Sagnac), Fizeau is a type of common optical path interferometer, therefore the machining errors of optical paths lead to little influence on the interference intensities. The equi-frequency contours (EFCs) of the PhC are calculated by using the plane-wave expansion(PWE) method, and interference properties are investigated by using the finite-difference time-domain(FDTD) method. The transmission spectra at output port is in the shape of sinusoidal curves in the frequency range from 0.26c/a to 0.27c/a shown in Fig.2, whose peak spacing is determined by the optical path difference of the interferometer. For the operating wavelength around 1550nm, the dimensions of this interferometer are only tens of microns. The proposed interferometer is sensitive to the refraction index changes in the optical path, which make it possible to be sensors.

10021-77, Session Post

Light concentrator of the wide field-of-view Cherenkov telescope

Rui Yang, Xiyi Sheng, Bollin Liao, Yunnan Univ. (China)

The Wide Field of View Cherenkov Telescope (WFCT) is an important components of the project of Large High Altitude Air Shower Observatory (LHAASO) in Gamma ray astronomy. WFCT is mainly constituted by optical reflector and photomultiplier (PMT) array camera located on the focal plane of optical system. In order to avoid loss of Cherenkov signal resulting from the dead area between circular PMT tubes and invalid fringe of each PMT, the light concentrator used as front window of PMT array is considered to improve detective efficiency. Basing on the edge-ray principle and features of WFCT, four types of single concentrator, such as circular light cone, hexagonal light cone, compound parabolic concentrator (CPC) and hexagonal CPC are designed and simulated in the non-sequential mode of ZEMAX. Furthermore, the focusing effect of the light concentrator arrays in practical optical path of WFCT is also simulated in the mixed-sequential mode of ZEMAX. The result shows that the hollow hexagon CPC has good performance in focusing and collecting light. Moreover, the samples of the hollow hexagon CPC have been manufactured and tested. The experiment result turns

out that 30% collection efficiency has been promoted with the hollow hexagonal CPC, comparing with the detector without light concentrator.

10021-78, Session Post

Research on simulation and analysis of the parallax of visual optical system

Qiang Ji, You Long, Xiaoxia Li, Xiaohong Liu, Haijun Zhang, Liang Zhou, AVIC Luoyang Institute of Electro-Optical Equipment (China)

The features of visual optical system used for the near-eye display device is that the images at position of human eyes are formed to infinity. The parallax of visual optical system will affect the observation comfort and display accuracy in particular situation. In this paper, we proposed a simulation calculation program of parallax with tunable accuracy and rapid convergence according to the the theoretical analysis of parallax mechanism. The autonomic computing of parallax and position accuracy at any field of view within the range of exit pupil was achieved by such calculation program. The validity and accuracy of the calculation program were verified by calculating and simulating the typical off-axis visual parallax optical system.

10021-79, Session Post

The water colority measurement based on HSV chromaticity

Jun Wang, Yang Pan, Quanying Wu, Fan Wang, Suzhou Univ. of Science and Technology (China); Fan Jun liu, Suzhou Univ of Science and Technology (China)

A method of measuring water colority based on HSV chromaticity (H hue, S saturation, V value) system is proposed. The measurement system is composed of halogen lamp, sample cell and spectrometer. The spectrum data of transmission light captured by spectrometer is used to calculate the XYZ tristimulus values which is then converted to HSV chromaticity. The colority and saturation value are studied, which shows a good linear relationship between them. Therefore the colority can be calculated by the saturation. Since the hue value is acquired at the same time, the method is adopted to water sample with different hue. Moreover, the V value is an independent component, so the instability of light source has no influence on the measurement. The linear relationship is calibrated in the experiment, and the colority obtained by the calibrated linear function coincides with the standard solution.

10021-80, Session Post

Tomato seeds maturity detection system based on chlorophyll fluorescence

Cuiling Li, Zhijun Meng, Xiu Wang, Beijing Academy of Agriculture and Forestry Sciences (China)

Seeds chlorophyll fluorescence intensity can be used as seeds maturity and quality evaluation indicator, in order to judge the chlorophyll content of high and low level in seeds, and further to judge seeds maturity, chlorophyll fluorescence intensity of seeds epidermis is measured and analyzed. This research developed a tomato seeds maturity detection system based on chlorophyll fluorescence including an excitation light source unit, a fluorescent signal acquisition unit and a data processing unit. Excitation light source unit was used for tomato seeds fluorescence excitation, which was made up of high power LEDs, radiators and constant current power supplies. Fluorescent signal acquisition unit consisted of a fluorescence spectrometer, an optical fiber, an optical fiber holder and a narrowband filter. Data processing unit included a computer. This study harvested tomato fruits at different ripeness periods and used them directly to produce seeds of different maturities. This research used the developed tomato seeds maturity testing system to collect fluorescence spectral information of tomato seeds of different maturities, first derivative (FD), Savitzky-Golay (SG) convolution smoothing methods were utilized to pretreat fluorescence spectrum data. Principal Component Analysis (PCA) method was adopted to reduce the dimensions of spectral data, extract principal components, and it was combined with linear discriminant analysis (LDA) to establish discriminant model of tomato seeds maturity, discriminant accuracy was above 90%. Research results showed that using chlorophyll fluorescence spectroscopy is feasible for seed maturity detection, and the developed tomato seeds maturity testing system has high detection accuracy.

10021-81, Session Post

Effect of mixed atmosphere on the properties of InGaZnO thin-films

Chenghan Li, Li Wang, Beijing Univ. of Technology (China)

The effect of oxygen and argon on amorphous indium-gallium-zinc-oxide(IGZO) thin films is investigated. IGZO ceramic target was prepared by mixing the In2O3, Ga2O3, and ZnO powders at a mol ratio of 0.8:0.05:0.15, the target obtained by solid-state reactions in atmospheric pressure, pulsed laser deposition(PLD) method was applied to grow amorphous IGZO films. IGZO thin films on Al2O3 substrates in a mixed atmosphere of Ar and O2 at fixed 10Pa working pressure. X-ray diffraction (XRD) patterns show that both films with an amorphous structure independent of the atmosphere composition. The transmitted spectrum shows a clear Burstein-Moss shift dependent on the change of mixed atmosphere. The average transmittance in visible wavelengths of all films is higher than 90%. The maximum carrier mobility was found to be 10.42 cm2 V?1 s?1 in thin film with mixing the Ar and O2 gas ratio of 1: 3

10021-82, Session Post

Space-time adaptive system: architecture method and operation support

Hua Liu, Luoyang Institute of Electro-Optical Equipment (China)

Along with the development on the artificial intelligence, augmented reality of academic research and business, to the requirement of the multidisciplinary integrated is becoming more deeply. Space-time adaptive methods, and their expansion of the aspects of application and operation platform, are extending from the traditional space-time system design to the structured devices, augmented reality, virtual reality, artificial intelligence and open Internet and so on, while with the physical system, social system more closely together. This kind of system configuration, development method and running environment has some typical characters, such as open, dynamic and difficult to control, and requires that the software and hardware systems need to have a certain degree of adaptive capacity. That is to say that software and hardware systems should be able to take the initiative to perceive the change of the environment and the demand, and adjust their own structure and behavior, according to this with continued low offering services to meet users expect (or even exceed). In this report, based on the holographic beam tracing technology, the core technology system on real scene was built, which can not only provide realistic reappearance effect,

but also confirmed a practical application. By predicting the framework of reproduction and how to apply the tracing process, the key problems of technology are analyzed, summarized and predicted. In recent years, the space-time adaptive software and hardware system of related theory, method, technology and application is getting attention of academia and industry. We set up the space-time adaptive theory based on space photoelectric control method of the purpose is to integrated our research and ideas in the development of space-time adaptive system method and the latest achievements in aspects of operation support and to promote further work.

10021-83, Session Post

Demonstration of DFTS-OFDM and equalization technology using in VLC communication via the headset port of android device

Fumin Wang, Meng Shi, Nan Chi, Fudan Univ. (China)

Visible light communication (VLC) is one of the hottest research directions in wireless communication. It is safe, fast and free of electromagnetic interference. We carry out the visible light communication using DFTS-OFDM modulation mode through the headset port to and take equalization technique to compensate the channel. In this paper, we first test the feasibility of the DFTS-OFDM modulated VLC system by analyzing the constellation and the transmission error rate via the headset interface of the smartphone. Then we change the peak value of the signal generated by the AWG as well as the static current to find the best working point. We tested the effect of changing the up-sample number on the BER performance of the communication system, and compared the BER performance of 16QAM and 8QAM modulation in different equalization method. We also do experiment to find how distance affect the performance of the communication and the maximum communication rate that can be achieved. We successfully demonstrated a visible light communication system detected by a headset port of a smart phone for a 32QAM DFTS-OFDM modulated signal of 27.5kb/s over a 3-meter free space transmission. The light source is traditional phosphorescent white LED. This result, as far as we know, is the highest data rate of VLC system via headset port detection.

10021-84, Session Post

An interactive VR system based on full-body tracking and gesture recognition

Xia Zeng, Xinzhu Sang, Duo Chen, Peng Wang, Nan Guo, Binbin Yan, Beijing Univ. of Posts and Telecommunications (China)

Most current virtual reality (VR) interactions are realized with the hand-held input device which leads to a low degree of presence. There has been other solutions using sensors like Leap Motion to recognize the gestures of users in order to interact in a more natural way, but the navigation in these systems is still a problem, because they fail to map the actual walking to virtual walking only with a partial body of the user represented in the synthetic environment. Therefore, we propose a system in which users can walk around in the virtual environment as a humanoid model, selecting menu items and manipulating with the virtual objects using natural hand gestures. With a Kinect depth camera, our system tracks the joints of the user, mapping them to a full virtual body which follows the move of the tracked user. The movements of the feet can be detected to determine whether the user is in walking state, so that the walking of model in the virtual world can be activated and stopped by means of animation control in Unity engine. This method free the hands of users comparing to traditional navigation way using hand-held device. We use the point cloud data getting from Kinect depth camera to recognize the gestures of users, such as swiping, lifting and manipulating virtual objects. Combining the full body tracking and gestures recognition using Kinect, we achieve our interactive VR system in Unity engine with a high degree of presence.

10021-22, Session 5

The optical legacy of Imperial College London *(Invited Paper)*

Tina E. Kidger Webb-Moore, Kidger Optics Associates (United Kingdom)

The Industrial Revolution, incubated primarily in the UK, generated an increasing need for highly skilled technical people. Throughout the 19th century, technical instruction increased dramatically and the formation of schools specializing in science and technology grew simultaneously. In England, there was much motivation in favour of a national prestige center for science and technology centered in London. Central among the motivating forces was Queen Victoria's husband, Prince Albert. Although there were already existing specialist science and technology institutions in major English cities, the growth of superior institutions in other countries within Europe, especially Germany and the Charlottenburg area of Berlin (e.g., the Berlin Technical High School), encouraged important English dignitaries to become more competitive with continental Europe. As a result of this strong continental motivation several science and technology institutions were built in the South Kensington part of London during the latter half of the 19th century. Imperial College, founded at the start of the 20th century, was a culmination and consolidation of several of these 19th century English institutions. Optical science and technology was an early beneficiary of the founding of Imperial College.

One important way to experience the development and influence of Imperial College in the discipline of optics is through its exceptional scientists and engineers. We look at the people who were instrumental in the founding of Imperial College London in the late 19th and early 20th century, who saw the need for a university which would advance technical training. The reasons for the formation of the Optics Section in1917 followed in 1919 by the first course in technical optics in Britain to be set up at Imperial College. This paper seeks to highlight IC's founders and early scientists who made this happen and illustrates the considerable permeation of their contributions throughout international optics today.

10021-23, Session 5

Illumination analysis of LAPAN's IR microbolometer

Bustanul Arifin, Andi M. Tahir, Irwan Priyanto, Indonesia National Institute of Aeronautics and Space (Indonesia)

We have since 2 years ago been doing a research in term of an IR Micrometer Bolometer which aims to fulfill our office, LAPAN, desire to put it as one of payloads into LAPAN's next micro satellite project, either at LAPAN A4 or at LAPAN A5. Due to the lack of experience on the subject, everything had been initiated by spectral radiance analysis adjusted by catastrophes sources in Indonesia, mainly wild fire (forest fire) and active volcano.

Based on the result of the appropriate spectral radiance wavelength, 3.8 – 4 ?m, and field of view (FOV), we, then, went through the further analysis, optical analysis. Focusing in illumination matter, the process was done by using Zemax software. Optical pass Interference and Stray light were two

things that become our concern throughout the work. They could also be an evaluation of the performance optimization of illumination analysis of our optical design.

The results, graphs, show that our design performance is close diffraction limited and the image blur of the geometrical produced by Lapan's IR Micro Bolometer lenses is in the pixel area range. Therefore, our optical design performance is relatively good and will produce image with high quality. In this paper, the Illumination analysis and process of LAPAN's Infra Red (IR) Micro Bolometer is presented.

10021-24, Session 5

Balancing deflection angles in the design of LED refractive optics with two freeform surfaces

Sergey V. Kravchenko, Kseniya Andreeva, Mikhail A. Moiseev, Leonid L. Doskolovich, Image Processing Systems Institute (Russian Federation)

The use of LEDs in the modern lighting devices makes the problem of designing secondary optics quite relevant. For the purpose of street, industrial and emergency lighting optical elements with two free-form surfaces are usually used. In this study the method for computation of such LED optics is proposed. In this approach the optical element surfaces are designed sequentially: firstly the inner surface is computed and then the outer one. At the beginning of each surface computation a piecewise smooth solution should be designed. Such a surface generates discrete intensity distribution that approximates the continuous one. In order to compute piecewise smooth solution we propose to utilize the supporting quadric method. After we have had piecewise smooth surface the smooth one is obtained by fitting NURBS-spline on it. Such a method allows controlling the balance of deflection angles between the inner and outer surfaces. It has been proven that in the case of point source, the maximal efficiency is obtained when each surface performs the half of the required ray deflection. As an example, the optical element with equal ray deflection part in each surface generating intensity distribution for ME1 class roadway lighting is designed. The simulation results of the luminance and illuminance distribution confirm good quality of the proposed method.

10021-25, Session 5

Analytical design of reflective optical element generating a prescribed intensity distribution

Egor V. Byzov, Samara State Aerospace Univ. (Russian Federation) and Image Processing Systems Institute (Russian Federation) and LED Optics Design LLC (Russian Federation); Evgeny S. Andreev, Mikhail A. Moiseev, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation) and LED Optics Design, LLC (Russian Federation); Leonid L. Doskolovich, Nikolay L. Kazanskiy, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation)

In this paper a new kind of source-target map for design mirrors generating prescribed two-dimensional line-shaped intensity distributions is presented. Line-shaped means that distribution is defined in region with a high aspect ratio, obtained from the line by direct replacement for each point on the segment perpendicular to the reference. This map is a generalization of the mapping, used in the well-known problem of reflective optical elements design generating one-parameter intensity distributions. Design examples show high performance of the proposed method, including for areas with a small aspect ratio. For rectangular and elliptical intensity distributions with angular dimensions from 80°x20° to 40°x20° the relative standard error does not exceed 8.5%

10021-26, Session 5

Visual analysis of the computer simulation results for both imaging and non-imaging optical systems

Boris K. Barladian, M. V. Keldysh Institute of Applied Mathematics (Russian Federation); Igor S. Potemin, Dmitry D. Zhdanov, ITMO Univ. (Russian Federation); Alexey G. Voloboy, Lev Z. Shapiro, Ildar V. Valiev, Elisey D. Birukov, M. V. Keldysh Institute of Applied Mathematics (Russian Federation)

Typical simulation results of the computer systems of the virtual prototyping and realistic rendering are images generated on the virtual sensors of various kinds. As a rule, these images represent two-dimensional distribution of the light values in Cartesian coordinates (luminance, illuminance) or in polar coordinates (luminous intensity). Using virtual sensors allows making the calculation and design of different kinds of illumination devices, providing stray light analysis, synthesizing of photorealistic images of three-dimensional scenes under the complex illumination generated with optical systems, etc.

Based on rich experience in the development and practical using of computer systems of virtual prototyping and photorealistic rendering the authors formulate a number of basic requirements for the visualization and analysis of the results of light simulations represented as two-dimensional distribution of luminance, illuminance and luminous intensity values. The requirements include the dynamic range compression, pseudo color imaging, visualization of the spherical panorama, regression analysis, the analysis of the image sections and regions, analysis of pixel values, the image data export, etc. All those requirements were successfully satisfied in designed software component for visual analysis of the light simulation results. The module "LumiVue" is an integral part of the "Lumicept" lighting simulation system and the corresponding plug-in of the CATIA computer-aided design product.

A number of visual examples of analysis of calculated two-dimensional distribution of luminous intensity, illuminance and luminance illustrate the article. The examples are results of simulation and design of lighting optical systems, secondary optics for LEDs, stray light analysis, virtual prototyping and photorealistic rendering.

10021-27, Session 6

Self-mixing interferometry and its applications *(Invited Paper)*

Yanguang Yu, Yuanlong Fan, Bin Liu, Univ. of Wollongong (Australia)

This paper reviews the self-mixing interfereometry (SMI) in terms of its operation principle, the features of SMI signals and its configuration. Self-mixing refers to a phenomenon that occurs when a small fraction of the light emitted by a laser is backscattered or reflected by an external target and re-enters the laser active cavity, thus leading to the modulation of the laser output power. This is a remarkably universal phenomenon, occurring in lasers regardless of type. A few application examples are presented based on the research work done in our group,

including SMI sensing for measuring displacement, material parameters and laser parameters. An SMI with the laser operating at the relaxation oscillation is also introduced which has potential for achieving more sensitive sensing.

10021-28, Session 6

Measurement of optical system aberrations based on randomly-encoded hybrid grating

Jiabin Jiang, Tong Ling, Yongying Yang, Rui Zhang, Zhejiang Univ. (China)

A lateral shearing interferometer based on randomly encoded hybrid grating (REHG) is proposed to measure the optical system aberrations. According to the theory of Fraunhofer diffraction, the REHG is designed to be a combination of a randomly encoded binary amplitude grating and a phase chessboard. Compared with the conventional cross-grating lateral shearing interferometer, the REHG is more suitable for the general aberration testing since no order selection mask is needed. Collimated beam for aberration measurement will converge after passing through the optics system under test. Then the quadriwave lateral shearing interferogram containing the wavefront aberration information is then recorded by the CCD. By selecting its +1 order of the Fourier spectrum in both X and Y directions, the shearing wavefronts in both two orthogonal directions can be obtained employing phase unwarping algorithm. Zernike polynomials are used as basic functions for the original wavefront, and the coefficients of Zernike polynomials can be obtained with shearing wavefronts. In the experiment, we employed a REHG with a grating pitch of 240 um to test a cemented doublet optics with an aperture of 50mm and a focal lengths of 90mm. The test results showed the peak-to-valley (PTV) aberration is 0.242?while the root-mean-square (RMS) is 0.064?. The test results by the REHG are very close to the results by the ZYGO GPI interferometer while the error of PTV is 0.003?and the error of RMS is 0.007?. The measurement of optical system aberrations by REHG can reach high precision and exhibit good immunity to environmental disturbance. The REHG can be applied to the optical testing of beam quality, optical system aberration and biomedical research.

10021-30, Session 6

An eight-channel Kirkpatrick-Baez microscope for plasma diagnostic

Yaran Li, Baozhong Mu, Qing Xie, Qiushi Huang, Zhanshan Wang, Tongji Univ. (China); Jianjun Dong, Zhurong Cao, Shenye Liu, Yongkun Ding, China Academy of Engineering Physics (China)

Kirkpatrick-Baez (KB)-type x-ray microscope proves to be an advantageous tool for plasma diagnostic in inertial confinement fusion (ICF) experiments. We have designed, manufactured and tested an 8-channel KB-type x-ray microscope for use at the Shenguang-?(SG?) laser facility. The reflecting elements are 3 pairs of concave spherical mirrors accurately arranged to reflect and focus x-ray emitted from laser plasma. Customized substrates and specially-made pyramid was fabricated and tested in order to materialize its strict optical design. The single superpolished substrate (<5 Å r.m.s roughness) has dimensions of 30?10?8mm and is coated with a C/W periodic mutilayer, providing high reflectivity at specific grazing incident angle at 8 keV. Laboratory results show its spatial resolution is ~3?m at best focus and better than 5?m over a 300-?m-diam region which agrees well with ray tracing. Combined with X-ray framing camera, the time evolution of the imploded target has also been recorded at SG? with a time interval of 80ps. The eight-channel KB microscope proves to be a high-resolution, high-throughput x-ray imaging system. This article provides detailed information about the optical design, assembly method and experimental results of the microscope.

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10022-1, Session 1

Common-path digital holographic microscopy and its applications *(Invited Paper)*

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Digital holographic microscopy (DHM) has become a novel tool with advantages of full field, non-destructive, high-resolution and 3D imaging, which captures the quantitative amplitude and phase information of microscopic specimens. Its applications are manifold and include biological microscopy, microstructures metrology, and so on. It's a well-established method for digital recording and numerical reconstructing the full complex field of wavefront of the samples with a diffraction-limited lateral resolution down to a few hundreds of nanometers depending on the numerical aperture of microscope objective. Meanwhile, its axial resolution through axial direction is less than ?/50 due to the interferometric nature in phase imaging.

In this paper, we summarize the principles of DHM, discuss some key technologies in its optical-mechanical design, analyze traditional optical configurations including Mach–Zehnder interferometer and Michelson interferometer, and apply this technology to measure microlens arrays, laser mark and pit, microcantilevers, MEMS devices, and so on. Besides this, to significantly increase the stability of the interferometer, common-path configurations with a piece of glass plate, calcite crystal or Lloyd mirror are introduced in DHM to make up a compact experiment system. Meanwhile, dual-wavelength technique and some numerical algorithms are also employed to improve the measurement accuracy. Experiment results of pollen and osteoblast cells show the feasibility of the proposed configuration.

10022-2, Session 1

Super-resolution imaging in optical scanning holography using structured illumination *(Invited Paper)*

Zhenbo Ren, Edmund M. Y. Lam, The Univ. of Hong Kong (Hong Kong, China)

As a specific digital holographic microscopy system, optical scanning holography (OSH) is an appealing technique that makes use of the advantages of holography in the application of optical microscopy. In OSH system, a three-dimensional object is scanned with a Fresnel zone plate in a raster fashion, and the electrical signals are demodulated into a complex hologram by heterodyne detection. Then the recorded light wavefront information contained in the hologram allows one to digitally reconstruct the specimen for multiple purposes such as optical sectioning, extended focused imaging as well as three-dimensional imaging. According to Abbe criterion, however, akin to those conventional microscopic imaging systems, OSH suffers from limited resolving power due to the finite size of the objective lens and the aperture, i.e., low numerical aperture. To bypass the diffraction barrier in light microscopy, various super-resolution imaging techniques have been proposed. Among those methods, structured illumination is an ensemble imaging concept that modulates the spatial frequency by projecting additional well-defined patterns with different orientation and phase shift onto the specimen. Computational algorithms are then applied to remove the effect of the structure and to reconstruct a super-resolved image beyond the diffraction-limit. In this paper, we introduce this technique in OSH system to scale down the spatial resolution below the diffraction limit. The performance of the proposed method is validated by simulation and experimental results.

10022-3, Session 1

Imaging characteristics of self-interference digital holography with structured illumination

Ying Han, Yuhong Wan, Beijing Univ. of Technology (China); Hongqiang Zhou, Beijing University of Technology (China) and Institute of Information Photonics Technology (China); Fan Wu, Tianlong Man, Beijing Univ. of Technology (China)

Self-interference digital holography enables hologram-recording of object illuminated with spatially incoherent light by special beam splitting methods. Among them, Fresnel incoherent correlation holography(FINCH) has great potential of super-resolution microscopic imaging. In order to achieve the goal of super-resolution, some techniques have been proposed, such as dual-lens FINCH, FINCH combined with confocal imaging system and so on. Structured illumination microscopy(SIM) is a kind of method that can achieve super-resolution imaging and optical sectioning imaging simultaneously. By introducing a sinusoidal fringe patterned light, it can record high frequency information beyond the diffraction limit of a system to achieve super-resolution imaging. In this paper, the imaging characteristics of FINCH with structured illumination are investigated in detail. The super-resolution imaging principal of FINCH with structured illumination are firstly demonstrated. The effects of structured light pattern, including the period, modulated direction and modulation depth of sinusoidal pattern on imaging lateral-resolution are also investigated. The resolution improved when increasing the frequency of sinusoidal pattern until it is equal to the cut off frequency of the system, and by increasing the modulation depth, the resolution also become better. The image reconstructed from two(like 0°and 90°) and four(like 0°, 45°, 90°and 135°) pattern orientation is shown in the paper at the same time. This work offers great reference for 3D super-resolution microscopy in the near future.

10022-4, Session 1

Digital in-line holographic microscope based on the grating illumination with improved resolution by interpolation

Shaodong Feng, Mingjun Wang, Jigang Wu, Shanghai Jiao Tong Univ. (China)

High resolution is always a pursuing target in the imaging field, as a newprospective technique in imaging applications, digital in-line holography has become a very active field for compactness, more information and low-cost. However, for compact system, the resolution is often limited by sensor pixel size. To overcome this problem, we propose an iterative reconstruction method with data interpolation based on the grating illumination. In our method, the Talbot self-image of a Ronchi grating is exerted in the sample plane as a priori constraint which lead to the convergence of the iteration, the iteration between the sample plane and the sensor plane can provide some extra information with interpolation in the sensor plane based on the a priori constraint, furthermore, the iteration

reconstruction can also eliminates the twin-image to improve the image quality. Numerical simulation has been conducted to show the effectiveness of this method. In order to make a further verification, we have developed a lensless in-line holographic microscope with a compact and wide field-of-view design. In our setup, the sample was under the Talbot image illumination of the Ronchi grating, which was illuminated by a collimated laser beam, and holograms were recorded by a digital imaging sensor. We can shift the grating laterally to get a wide-field image. We demonstrated the resolution of our imaging system by using the USAF resolution target as a sample, and the results shown the resolution improvement of the image.

10022-10, Session 1

Processing of digital holograms: segmentation and inpainting

Shuming Jiao, Wenbin Zou, Shenzhen Univ. (China)

In modern holography, a hologram can be acquired, processed, stored and reconstructed all in digital forms. Various hologram image processing techniques can be developed with regard to the specific image properties of digital holograms. In this presentation, the author will explore two novel hologram image processing issues, i.e., hologram decomposition and hologram inpainting.

By hologram decomposition, one hologram can be decomposed into several sub-holograms and each sub-hologram represents one individual item in the 3D object scene. In this presentation, a Virtual Diffraction Plane (VDP) based hologram decomposition scheme is proposed. By Otsu thresholding segmentation, morphological dilation and sequential scan labelling, a VDP back propagated from hologram can be divided into sub-VDPs and each sub-VDP can be reverted to be a sub-hologram. At the same time, an alternative VDP cutting approach is proposed as a supplementary method. This automatic hologram decomposition scheme is further employed for focus distance detection in blind hologram reconstruction. It is free of "Shading Effect" and has better accuracy and reliability.

By hologram impainting, a damaged hologram can be restored by filling in the missing pixels. In this presentation, an exemplar and search based image inpainting technique is applied for the restoration of heavily damaged digital off-axis Fresnel holograms. An intelligent search technique, Artificial Bee Colony algorithm, is employed to significantly increase the computation efficiency of the inpainting process. Experimental results reveal that with this proposed method, the pictorial information in heavily damaged holograms can be recovered with good fidelity. In addition, Morphological Component Analysis (MCA) inpainting algorithm is proposed for hologram restoration when the missing regions are noise-like separate missing pixels instead of scratch lines or holes. Three potential application cases of hologram inpainting are discussed including occlusion recovery, hologram watermarking and QR code restoration.

10022-5, Session 2

Digital holographic amplification of modified Jamin (Rozhdestvensky) interferograms

Dmitriy V. Venediktov, Sergey A. Pulkin, Saint Petersburg State Univ. (Russian Federation); Alexander A. Sevryugin, Ibragim M. Tursunov, Vladimir Y. Venediktov, Saint Petersburg Electrotechnical Univ. "LETI" (Russian Federation)

Digital holography provides a lot of opportunities for transformation of interferometric information. One can increase the interferometer sensitivity by "amplification" of holographic fringes' deformations, remove the distortions, imposed by interferometer elements, provide digital summation or extraction of interferograms, modify the spatial carrier frequency etc. However, to the moment this technique was applied mainly to the interferometers, measuring height of distortions, distance to the object or its movement parameters. We consider the prospects of applying similar approaches in the case of spectroscopy interferometery. This idea was investigated in the experiment with the use of modified Jamin interferometer, working together with spectrograph (this device is also known as Rozhdestvensky interferometer). The results of the experiment has shown that the use of holographic multiplication simplifies the analysis of interferograms, used investigation of fine structure of spectral lines.

10022-6, Session 2

Noise reduction performance of the compressive digital one-shot in-line holographic tomography *(Invited Paper)*

Hua Zhang, Liangcai Cao, Hao Zhang, Guofan Jin, Tsinghua Univ. (China)

Digital holography (DH) is recently applied to reconstruct 3-D datacube from a 2-D holographic data in the tomographic imaging. Digital one-shot in-line holography (DOIH) maintains the space-bandwidth product, compared with off-axis holography. However, DOIH suffers from intrinsic defects, such as twin-image restriction and the squared noise. In this work, compressive sensing (CS) is applied for DOIH in the tomographic reconstruction to overcome the above defects. The Fresnel propagation is employed in the algorithm, which keeps the 'incoherence' condition for CS measurement. The evaluation of the reconstructed images at different depths prove the validity of compressive DOIH, compared with the traditional back-propagation method. It is demonstrated that compressive DOIH has the great capability to strip both the squared noise and the constant noise from the 2-D hologram. The proposed method has great potentiality for dynamic imaging of moving micro-organic particles due to the fast sampling rate of DOIH.

10022-7, Session 2

Three-dimensional edge extraction in optical scanning holography

Yonghong Zong, Changhe Zhou, Jianyong Ma, Wei Jia, Jin Wang, Shanghai Institute of Optics and Fine Mechanics (China)

Edge extraction has found applications in various image processing fields where extracting the edge or shape of the object is of great interest, such as in pattern recognition. While the 4-f system with spectrum modulation is usually used for edge extraction, the objects being processed are in the same plane with little depth of field. In this paper, a new method is proposed for edge extraction of three-dimensional objects in optical scanning holography (OSH). OSH is a two-pupil heterodyne scanning optical system which traditionally uses a delta function or a point source and a uniform function or a plane wave as its pupil functions. Isotropic and anisotropic edge extraction of 3D objects is simulated using spiral phase plates in OSH operating in an incoherent mode. We propose to use a delta function and a spiral phase plate as the pupil functions to realize isotropic and anisotropic edge extraction. The interference of these two pupils creates a time-varying vortex beam which can be used to two-dimensionally scan an object to record its edge-only information. The isotropic edge extraction can be achieved by

using a spiral phase plates with its center on the optical axis. The anisotropic edge extracted object can be obtained by shifting the optical vortex in the pupil plane, by using two offset spiral phase plates of same charge, or by using two oppositely charged spiral phase plates. Our computer simulations show the capability of extracting the edges of a given 3D object by spiral phase filtering in OSH.

10022-8, Session 2

Resampling masks for noise reduction in phase-shifting digital holography

Wenhui Zhang, Liangcai Cao, Hao Zhang, Song Zong, Guofan JIn, Tsinghua Univ. (China)

Holographic imaging is degraded severely by the speckle or incoherent noise. Using multiple holograms to reconstruct the original image can decrease noise with an undesired time consumption. One-shot strategy to reduce noise in digital holography has been widely investigated recently. One hologram is enough for filtering noise by dividing it into sub-holograms during reconstruction. An image with lower noise can be acquired through the average of the reconstruction results of the sub-holograms. Before divided into multiple parts, the zero-order of the hologram is filtered in the frequency domain. The reconstruction results would also be subject to the interference of the conjugate term. It is difficult to filter the zero-order accurately if three orders of the hologram are overlapping. In this work, resampling masks on phase-shifting digital holography is proposed to reduce the noise and filter the zero-order and the conjugate term of the hologram. The post-propagated complex amplitude of objects acquired through four-step phase-shifting digital holography experiment using a phase-only spatial light modulator is encoded into several parts by resampling masks. A high quality reconstruction image with lower noise is achieved through the superposition of the individually reconstruction of coded complex amplitudes. Compared to direct reconstruction of the conventional digital holography, the peak signal to noise ratio of the results can be increased by 10 dB via the proposed approach and the reconstructed images become smoother. This method can be used for digital holographic imaging of the biological samples and microstructures. Experimental results prove the feasibility of this proposed method.

10022-9, Session 2

Pixel Super-resolution in digital in line holography

Mingjun Wang, Shanghai Jiao Tong Univ. (China); Wu Jigang, Shanghai Jiao TOng Univ, (China); Shaodong Feng, Shanghai Jiaotong Univ. (China)

In this paper, we report a new holographic microscope using pixel super-resolution algorithm. In our method, a sequence of low resolution images are acquired by a complementary metal oxide semiconductor (CMOS) sensor in digital in-line holography system and the resolution is limited by the sensor pixel size. Then the super-resolution algorithm is applied to the low resolution images toand get the image with much higher resolution that beyond the Nyquist criteria.

In our method, we carried outperform both numerical stimulation and experiments to demonstrate our method with US Air Force Target in experiment to validate our method used as the sample. The sample is randomly moved in the sample plane and a set of holograms are captured with by the camera in inline holographic system. We use two methods to reconstruct the sample image. Two experiments are done respectively. In the first method, super-resolution algorithm is processed applied with those the low resolution images holograms to getting the high resolution hologram. Then the high resolution hologram is reconstructed with using auto-forcusing algorithm to get the high resolution sample image. In the second method, the raw holograms are directly reconstructed to get a set of low resolution sample images, and then the super-resolution algorithm is processed applied to the reconstructed images to get the high resolution sample image. With comparisonWe observed that the abovementioned two methods can get similar results, the order of using super-resolution algorithm does not matter a lot to the resolution of reconstructed image in both numerical stimulation and experiments. We believe that the combination of pixel super-resolution algorithm and digital in-line holography can be very promising useful in life healthy protection and diagnosis to implement a compact low-cost microscope with high resolution.

10022-11, Session 2

Measuring a thermal expansion of thermoelectric materials by using in-line digital holography

Thanyarat Thong-on, Prathan Buranasiri, King Mongkut's Institute of Technology Ladkrabang (Thailand)

In this paper, the measuring a thermal expansion of thermoelectric material (TE) CuCrO2 was observed by using digital holography (DH) technique. In the experimental setup, diode laser, a digital camera and a sample on hot plate were set in the same alignment, then called in-line digital holography (DIH). A laser beam was expanded and been parallel through a thermoelectric sample, which was heated by a hot plate from a room temperature to 224 °C, then a set of expanded images of a TE sample were recorded by a digital camera and numerically analyzed data by imaging reconstruction. For the result of this research, thermoelectric material was founded infinitesimal expanding, and its thermal expansion coefficient (COE) was founded equal to 2.25 ? 10-6 °C-1.

10022-12, Session 3

A head-mounted compressive three-dimensional display system with polarization-dependent focus switching *(Invited Paper)*

Chang-Kun Lee, Seokil Moon, Byounghyo Lee, Byoungho Lee, Seoul National Univ. (Korea, Republic of)

A head-mounted compressive three-dimensional (3D) display system is proposed by combining polarization beam splitter (PBS), fast switching polarization rotator and micro organic emitting diode with high pixel density. According to the polarization state of image controlled by polarization rotator, optical path of image in the PBS can be divided into transmitted and reflected components. Since optical paths of each image are spatially separated, it is possible to independently focus both images at different depth positions. Transmitted p-polarized and reflected s-polarized images can be focused by convex lens and concave mirror, respectively. When the focal lengths of the convex lens and concave mirror are properly determined, two image planes can be located in the intended positions. The geometric relationship is easily modulated by the replacement of the components. The fast switching of polarization realizes the real-time operation of multi-focal image planes with single panel. Since it is possible to conserve the device characteristic of single panel, the high image quality, reliability and uniformity can be retained. For generating 3D images, the four-dimensional light field information for compressive 3D display between two image planes is calculated. Since the display panel with high pixel density is adopted and two optically separated image planes are

free from diffraction which limits resolution of layered 3D display system composed of physically stacked display panels, high quality 3D images are reconstructed. Simple optical configuration of the proposed system is integrated in the prototype of the head-mounted display system.

10022-13, Session 3

Volumetric display with holographic multi-photon excitations *(Invited Paper)*

Yoshio Hayasaki, Kumagai Kota, Utsunomiya Univ. (Japan)

Developments of three-dimensional (3D) displays are one of the dreams. The realization of a future visually sufficient 3D display will require some technological innovations. Holographic, stereoscopic head-mounted displays were the good candidates for producing effective 3D graphics, but they have a limited observation area and require users to wear special devices. Volumetric displays that render 3D graphics can be observed from any surrounding viewpoints without any wear devices. They are classified into two light-reflecting and light-emitting types, depending on the characteristics of the voxels. One of the light-emitting types was based on a laser addressing, which had a wide viewing angle and no requirement of wiring between the laser source and the display material.

We developed a volumetric display composed of a femtosecond laser for two- and multi-photon excitations to display materials, an LCSLM that displays a computer-generated hologram for parallel addressing, a 3D beam scanner composed of galvanometer mirrors and a varifocal lens for expanding an addressing area, and display materials. Some types with different display materials that were solid, liquid, and gas types were demonstrated. The solid material had multilayer structures composed of polymer plates with fluorescent dyes for multi-color display. The liquid material was glycerin for bubble display. The gas matter was an air for an interactive touchable display. The main purpose of the holographic parallel addressing was to increase the number of voxels per unit time, but it had an addition usefulness of the controls of voxel brightness and size.

10022-14, Session 3

Focus-tunable multi-view holographic 3D display using a 4k LCD panel *(Invited Paper)*

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A focus-tunable multi-view holographic three-dimension (3D) display system with a large size of 22.3cm?12.5cm and a resolution of 3840?2160 is presented. It is assumed that 3D image generation by holographic stereograms is similar to that of multi-view autostereoscopic displays, in that multiple parallax images are displayed with rays converging to corresponding viewpoints. If the multiple rays reconstructing the 3D images point enter the pupil simultaneously, the eyes can focus on that point according to the depth cue. To achieve the purpose, a method of synthesizing computer-generated holograms (CGHS) from multiple perspective projections (parallax images) is adopted in this paper. It does not require calculations of light diffraction. The spherical wave was adopted and the wavefront converging to a viewpoint on the hologram plane. It has the amplitude distribution of a parallax image and the phase distribution of the spherical wave. The wavefront of all multiple viewpoint images are calculated, then they are summed up to obtain the object wave on the hologram plane. A reference light is used to converge the central diffraction wave and the first order diffraction wave from the liquid crystal display (LCD). The viewing zone of holograms is between the central and first order diffraction wave. Because the distance of adjacent viewing points is smaller than the pupil diameter, therefore, the system provides smooth and continuous motion parallax. Experiment results shows that the proposed display can construct the 3D objects with focus cues: accommodation and retinal blur.

10022-15, Session 3

Vertical viewing angle expansion using lenticular lens sheet.

SooBin Kim, Hwi Kim, Korea Univ. (Korea, Republic of)

We propose lenticular lens for holographic display. Integral image displaying has wide viewing angle, but it has not depth expression. The lenticular lens is a great help in the vertical viewing angle. The asymmetric diffuser has expansion of vertical viewing angle. But, accommodation effect cannot be expected in asymmetric diffuser. The accommodation effect is important in hologram display. Our system has accommodation effect of important thing in the hologram display. The resolution is low, but displaying hologram with a narrow field of view will be a great contribution. We also made a simulation tool for everything in lenticular lens sheet. For example, the result of the interaction with spatial light modulator (SLM) and display panel and the hologram displaying. Our results of simulation shown demonstration in experimental results for same. But, lenticular lens sheet has critical problem in hologram displaying. It has interval that is not the field of observation window, it is called black term effect. We proposed a solution for black term effect to jittering effect. This paper demonstrates that all important thing in hologram displaying for simulation and experiment. The ultimate goal of this paper is perfect expansion of vertical viewing angle using lenticular sheet in hologram displaying.

10022-16, Session 3

Optimization of lens shape for autostereoscopic display

Jianshe Ma, Ping Su, Shu An, Graduate School at Shenzhen, Tsinghua Univ. (China)

Three-dimensional (3D) displays based on binocular parallax are drawing increasingly interests. Beam-splitting elements, which present separate images to the viewer's left and right eyes, play an important role in auto-stereoscopic display. Lenticular lens array is widely used as beam-splitting element. However, the crosstalk caused by the aberration caused by spherical surface decreases the 3D experience.

This paper devotes to the optimization of lens shape to obtain better beam splitting effect. It is determined that the most viable cross-sectional shape for the lenticular lenses is elliptical. Firstly, the formula of the surface, which is , is derived based on the ellipse equation and the requirement of display system. The semi-major axis is 17.99mm and the semi-minoraxis is 7.38mm. Then, the crosstalk is defined as the ratio of the disturbing light intensity to the total light intensity. A math model is constructed to simulate the imaging process and calculate the crosstalk. Simulation result shows that the crosstalk is reduced by 20%, which proves the cross section shape of elliptical is superior to

spherical. Besides, the minimum line width can be increased by 30%, which reduces the difficulty of machining greatly. In conclusion, the optimization of the surface has a significant effect on the improvement of stereoscopic depth and the reduction of ghost images.

10022-17, Session 3

High-aperture diffractive lens for holographic printer

Alexander Y. Zherdev, Sergey B. Odinokov, Dmitry S. Lushnikov, Bauman Moscow State Technical Univ. (Russian Federation); Chermen B. Kaytukov, FSUE "STC" Atlas (Russian Federation)

An optical schema of holographic printer for obtaining of holographic stereograms with increasing angle of view is proposed. Conventional holographic printers allows to obtain holographic stereograms with angle of view up to 90°. Proposed schema allows to increase angle of view up to 120°. The optical schema is based on diffuser and diffraction optical element namely high-aperture diffractive lens. The experience of using of composite holographic lens and binary Fresnel zone plate as a high-aperture diffractive lens is described. Samples of high-aperture diffractive lens with aperture f/0.3 are obtained and investigated. Samples of holographic stereograms are obtained using samples of high-aperture diffractive lens.

10022-18, Session 4

Development of scanning holographic display using MEMS SLM *(Invited Paper)*

Yasuhiro Takaki, Tokyo Univ. of Agriculture and Technology (Japan)

Holography is an ideal three-dimensional (3D) display technique, because it produces 3D images that naturally satisfy human 3D perception including physiological and psychological factors. However, its electronic implementation is quite challenging because ultra-high resolution is required for display devices to provide sufficient screen size and viewing zone. We have developed holographic display techniques to enlarge the screen size and the viewing zone by use of microelectromechanical systems spatial light modulators (MEMS-SLMs). Because MEMS-SLMs can generate hologram patterns at a high frame rate, the time-multiplexing technique is utilized to virtually increase the resolution. Three kinds of scanning systems have been combined with MEMS-SLMs; the screen scanning system, the viewing-zone scanning system, and the 360-degree scanning system. The screen scanning system reduces the hologram size to enlarge the viewing zone and the reduced hologram patterns are scanned on the screen to increase the screen size: the color display system with a screen size of 6.2 in. and a viewing zone angle of 11° was demonstrated. The viewing-zone scanning system increases the screen size and the reduced viewing zone is scanned to enlarge the viewing zone: a screen size of 2.0 in. and a viewing zone angle of 40° were achieved. The 360-degree scanning also increases the screen size and the reduced viewing zone is scanned circularly: the display system which has a flat screen with a diameter of 100 mm was demonstrated, which generates 3D images viewed from any direction around the flat screen.

10022-19, Session 4

Optical scanning holography for stereoscopic display *(Invited Paper)*

Jung-Ping Liu, Hsuan-Hsuan Wen, Feng Chia Univ. (Taiwan)

Optical Scanning Holography (OSH) is a nonconventional digital holographic recording technique. In OSH, a heterodyne structured light is applied to raster scan a 3D object target, and the scattered light is recorded and demodulated to generate a digital hologram of the 3D object. OSH can be operated in the incoherent mode. The incoherent-mode of OSH is able to record speckle-free complex hologram of a 3D object. In addition, multiple lighting effects can be simultaneously recorded in OSH, and thus the lighting of the hologram can be modified after the holographic recording. Because of the above unique features, the OSH is a good candidate to record a 3D scene for holographic display.

The shortcoming of OSH is that the scanning procedure is time-consuming. To solve the problem, we have proposed to use an asymmetry pupil in OSH system to limit the vertical bandwidth of the hologram, while the horizontal bandwidth is retained. Consequently, the vertical sampling rate as well as the scanning time is significantly reduced. Although the horizontal sampling rate can be much higher than the vertical sampling rate, it is still limited due to the unsteadiness of the scanner. As a result, the viewing angle is not large enough for optical display. To solve this problem, we record two OSH holograms with an angular separation. The two holograms are synthesized to a single stereoscopic hologram with two main viewing angles. Because both views can reconstruct full-depth-resolved 3D scenes, the problem of accommodation conflict in conventional stereogram is avoided.

10022-20, Session 4

Three dimensional Identification card and applications *(Invited Paper)*

Changhe Zhou, Shanghai Institute of Optics and Fine Mechanics (China)

Three dimensional Identification Card means that there are three-dimensional optical techniques are used, the personal image on ID card is displayed to be three-dimensional, so we can see three dimensional personal face. The ID card also stores the three-dimensional face information in its inside electronics chip, which might be recorded by using two-channel cameras, and it can be displayed in computer as three-dimensional images for personal identification. Three-dimensional ID card might be one interesting direction to update the present two-dimensional card in the future. Three-dimension ID card might be widely used in airport custom, entrance of hotel, school, university, as passport for on-line banking, registration of on-line game, etc..

10022-21, Session 4

Digital holographic imaging and sensing for biology and sound wave measurement *(Invited Paper)*

Osamu Matoba, Xiangyu Juan, Kobe Univ. (Japan); Yasuhiro Awatsuji, Kyoto Institute of Technology (Japan)

Since the invention of microscopes, countless studies and researches have been benefited from the ever-growing microscopic technology. However, it is still challenging to fully utilize microscopes in various field such as cell imaging.

One of the difficulties is diverse information often encounter with biological samples. It is caused by difference imaging methods that are often incompatible. For instance, fluorescence microscopes only provide information of substances tagged by fluorophores. Sometimes it is necessary, and other times we wish to obtain as many information as possible from a single object. Since digital holographic method and fluorescence imaging method are highly utilizable and providing different perspectives from a single biological object, we combined the two methods in one system to operate simultaneously. We named it multi-modal digital microscope. The system reconstructs phase images with extensive depth of field by transmission type Mach-Zehnder interferometry. Meanwhile, fluorescent intensity is acquired by epifluorescence microscopic configuration. The two types of recording can be synced by using the same trigger.

This invited presentation introduces digital holographic applications of bio-imaging and voice recording. We explain how the 4D digital holographic system works. Experiments focus on the cell reprogramming process by measuring distribution of chloroplasts from the fluorescent perspective, as well as membranes and nucleuses from the phase perspective. In the sound wave measurement, the temporal phase imaging caused by the propagation of the sound wave is presented. Experiment result shows the effectiveness of the proposed methods and presents the further application.

10022-22, Session 4

Temporal speckle method for measuring three-dimensional surface of large-sized rough glass

Chao Li, Shanghai Institute of Optics and Fine Mechanics (China) and ShanghaiTech Univ. (China); Changhe Zhou, ShaoQing Wang, Xin Fan, Shanghai Institute of Optics and Fine Mechanics (China); Boquan Yang, Shanghai Univ. (China); Yancong Lu, Shanghai Institute of Optics and Fine Mechanics (China)

Surface measurement of large-sized rough glass is always the key point be focused on during the production process. Traditional 3D measuring instrument like three-coordinate measurement machine, which relies on a sharp probe to contact rough surface, and directly measures the 3D shape. So inevitably there are some problems of it, such as low efficiency, long measurement period and limited spatial resolution, especially for large-sized rough glass. We propose an novel active fast 3D scanning setup to meet the demand of fast 3D profile measurement for a large-sized rough glass block. When it comes to rough glass, we have to face the surface scatting problem, especially for laser beams. In order to overcome this, band-limited binary random pattern is introduced. Unlike the original binary random pattern, the patterns we use are filtered out high frequency and low frequency parts, called band-limited binary random patterns, which proved to minimize the influence of scattering combined with temporal correlation technique (TCT). In our experiment, a series of N band-limited binary random patterns is used to encode the surface of the rough glass and two cameras capture N pairs of images strictly simultaneously as soon as each random pattern projected. Then at matching procedure, TCT is used to reduce the size of correlation windows to one pixel in spatial domain and extends the length of the correlation windows to N pixel in temporal domain. Finally, by using disparities and system parameters obtained from calibration, 3D reconstruction can be achieved. All the data acquisition process is controlled within 2s with 0.3mm absolute error or even less.

10022-44, Session Post

Holographic data storage recording system based on computer synthesis of Fourier holograms

Sergey S. Donchenko, Sergey B. Odinokov, Vladimir I. Bobrinev, Alexandr U. Betin, Evgenie Y. Zlokazov, Bauman Moscow State Technical Univ. (Russian Federation)

In this paper we present a Holographic data storage recording device, based on computer synthesis of Fourier holograms. Information is presented as a binary graphic information, and calculated into grayscale Fourier hologram (CGFH). CGFH are displayed on spatial light modulator (SLM) and projected via optical scheme to recording medium with required reduction. Hologram multiplexing is performed by rotation plane of 1D CGFH relatively to recording medium. Results of recovering information from holograms, recorded in Holographic data storage recording device is presented in paper.

10022-47, Session Post

The influence of diffraction gratings relief distortion on diffraction efficiency during authentication security holograms

Vasily V. Kolyuchkin, Sergey B. Odinokov, Bauman Moscow State Technical Univ. (Russian Federation); Ivan Tsyganov, Bauman Moscow State Technical University (Russian Federation)

The method of security hologram quality inspection, in which the relief phase parameters are determined by registering results of the intensity distribution in diffraction orders, is known. Deviation of a real from the ideal profile, another words phase relief noise, influence on the accuracy of this method. In the paper, on the assumption of homogeneity of the phase relief noise, the mathematical expressions for evaluating the influence of the phase relief noise on the intensity distribution in the diffraction orders are represented. Parameters of the correlation functions approximation describing the phase relief noise are determined. The dependence of the intensity values from the standard deviation of the phase relief noise is represented.

10022-57, Session Post

Microsphere microscopic imaging with the coherent light

Sha Guo, Yunxin Wang, Dayong Wang, Beijing Univ. of Technology (China); Qiaowen Lin, Lu Rong, Beijing Univ of Technology (China)

The microsphere has great potential to improve the resolution of imaging system, which can be applied in processing of surfaces materials and detection of nano-structure etc. The high frequency information can be collected by the microsphere; meanwhile, the object can be magnified. The magnification varies with the parameters of the microsphere. Many experimental studies have been presented by combining the white light microscopy with microsphere and obtained the fine structure of the Blu-ray disc and viruses etc. However, the curvature radius of the microsphere is from several microns to tens of microns, so the unavoidable the chromatic dispersion exists in microsphere incoherence imaging, which reduces the image quality. In this paper, the microsphere microscopy system is designed with the coherent light, in which the object can be magnified by microsphere and microscopy objective (MO) twice. The polystyrene (PS) microspheres with

the diameter of 50?m and 90?m are applied, and their refractive index is 1.59. The object is a transmission grating with a cycle of 1.2?m separated by a gap of 500nm. The results indicate that the grating can be clearly detected, and the magnification of the microsphere with diameter of 50?m and 90?m is 2.33 and 1.96 respectively. If the microsphere is absent, the resolution of this system is 870nm, which demonstrates that the microsphere can improve the observed resolution from 870nm to 500nm at least. The proposed microsphere microscopic imaging system with the coherent light eliminates the chromatic dispersion and has the potential application in some coherent phase-contrast imaging.

10022-58, Session Post

Generation of speckle vortices by Archimedes' spiral micro-holes

Haibin Sun, Shandong Normal Univ. (China) and Taishan Univ. (China); Tingting Liu, Taishan Univ. (China); Ping Sun, Shandong Normal Univ. (China)

Speckle plays an important role in optical field. Optical vortices which exist in random speckle fields usually contain useful phase information. The distribution of speckle field is determined by these optical vortices. In order to study speckle vortices quantitatively, we established a micro-hole array model based on the law of Archimedes spiral arrangement. Vortex beam can be generated by random diffuse reflection points (spiral micro-holes), and the interference between vortex beams can generate speckle vortices. In the experiment, the gray image of Archimedes' spiral micro-holes is displayed on the screen of spatial light modulator (SLM), and the output optical field is captured by a CCD camera. The numerical simulations and experimental results show that the model can be used to generate speckle vortices.

10022-59, Session Post

Design and numerical simulation of a silicon-based linear polarizer with multilayer metallic nano-gratings

Yu Lin, Jingpei Hu, Chinhua Wang, Soochow Univ. (China)

With the increasing demand for linearly polarized elements with high performance in many fields and applications, design and fabrication of sub-wavelength metallic linear polarizer have made tremendous progress in recent years. In this paper, we proposed a novel structure of a silicon-based linear polarizer working in the infrared (3-5?m) waveband with a multilayer metallic grating structure. A double-layer metallic grating with a transition layer of low refractive index is fabricated on a silicon substrate. In contrast to those conventional single layer metallic polarizing grating, the multilayer polarizing structure has the advantages of easy fabrication and high performance. Numerical simulation results show that an extinction ratio of linear polarization can be up to 60dB and the TM-polarized light transmission is greater than 90%. The behaviors and advantages of the proposed multilayer polarizer are compared with that of a traditional single-layer metallic grating in detail. The proposed silicon-based linear polarizer will have great potential applications in real-time polarization imaging with high extinction ratio and high transmission.

10022-60, Session Post

Asymmetric propagation of electromagnetic waves through nanoscale spirals

Jingpei Hu, Yu Lin, Xiaonan Zhao, Aijiao Zhu, Chinhua Wang, Soochow Univ. (China)

Polarization not only represents an intrinsic feature of optical waves but also offers an extra degree of freedom to manipulate light for various applications. In particular, circularly polarized light has its instant electric field vector directed along a helical trajectory and therefore possesses an inherently chiral nature. Recently, archimedes spiral designs have been utilized to be miniature circular polarization analyzer. S. Yang et al. studied Archimedes' spiral groove etched into a gold film can focuses the circular polarization with an opposite chirality into a solid spot in the center, while defocusing the circular polarization with the same chirality into a donut shape. In 2015, S. Grisha et al. designed and implementation of a metasurface-based spiral plasmonic lens that achieves both optimized SPP focusing and high-contrast, large-collection-area circularly dichroic focusing. However, the spiral structures can only distinguish the CPL in mode, not the transmission intensity. In this paper, we report that normal incidence transmission of different circularly polarized waves through the 2D Archimedes' nanoscale spirals is asymmetric. The structures consist of raised spiral line and two layers metal film covered on the substrate and the line. The device can distinguish the different circularly polarized wave across the transmission intensity compare with the commom Archimedes' nanoscale spirals which just exhibit the bright or dark modes in the light field. We confirmed that the device provide about 10% circular dichroism in 3.85um-6.0um broadband region. The circular dichroism in the wavelength 3.95 um can reach 13%. This ultracompact device could prove useful for remote sensing and advanced telecommunication applications.

10022-61, Session Post

High resolution digital holography based on the point source scanning

Minchao Wang, Dayong Wang, Lu Rong, Yunxin Wang, Fengpeng Wang, Qiaowen Lin, Beijing Univ. of Technology (China)

Digital holographic microscopy has been widely used for the imaging of micro-objects and biological samples. Lensless in-line digital holographic microscopy is capable of wide field-of-view imaging, however the spatial resolution of the reconstructed images is limited by the pixel size of the detector. The relative position shift between the sample and the detector can effectively improve the resolution in the traditional sub-pixel shifting method, but it requires a high precision of translation stage. Therefore to overcome this problem we propose a method based on the point source scanning to realize sub-pixel shifting, where by using the geometric relations between point source and detector, high precision sub-pixel shifting is achieved easily. Through moving the point source, multiple holograms with sub-pixel shifts are captured which are merged together to obtained a hologram by using the synthesizing algorithm, then a phase retrieval algorithm is used to reconstruct the phase and amplitude distributions of the object. Using 1951 USAF resolution test target as object, we effectively recover a much higher resolution as compared to traditional digital hologram, which is no longer limited by the pixel size of the detector. The feasibility of the proposed method is demonstrated by simulation and experiments. The proposed method has the advantages of simple recording setup and lower precision requirement of the

translation stage. It can obtain the wide field-of-view and high resolution imaging.

10022-62, Session Post

Experimental study of the method of recording color volume security holograms on different photosensitive materials on the base of the diffuser with a narrow indicatrix of laser radiation

Dmitry S. Lushnikov, Sergey B. Odinokov, Vladimir V. Markin, Alexander Y. Zherdev, Bauman Moscow State Technical Univ. (Russian Federation); Andrey V. Smirnov, Krypten (Russian Federation)

The objective of this paper was to obtain a new type of security holograms - multicolored holographic stereograms with different security elements on the photosensitive medium of large thickness. During work performance the following problems have been solved:

1. Reducing the production time of color holograms as holographic stereograms.

2. Improve the quality of images reconstructed from holographic stereograms.

The work has been divided into the following stages:

1. One-parallax and full-parallax holographic stereograms production by using one-step and two-step schemes with a diffuser with wide emission indicatrix in a subject branch. Quality analysis of the obtained holograms.

2. Full-parallax holographic stereograms production by using two-step schemes without a diffuser in a subject branch. Quality analysis of the obtained holograms.

3. Production of the holographic diffusor with narrow emission indicatrix.

4. Full-parallax holographic stereograms production by using two-step schemes with a diffuser with narrow emission indicatrix in a subject branch. Quality analysis of the obtained holograms.

All these schemes and holograms were obtained and analyzed.

The disadvantages of schemes without a diffuser are shown in this article. The scheme for recording of holographic stereograms using a holographic diffuser with a narrow indicatrix has been developed and described in the article. The high quality of images reconstructed from these holographic stereograms are shown. The time of recording such holographic stereograms was 3..5 hours.

10022-63, Session Post

Realization of Fourier and Fresnel computer-gengerated holography based on MATLAB

Guoqiang Lin, Xuechang Ren, Xiamen Univ. (China)

Computer-generated hologram(CGH) could be widely used. The image, which could be considered the original object of traditional optics, can be divided into two parts. A portion of it is encoded into Fourier CGH, while the remaining is coded into Fresnel computer generated hologram. Hence, in the processing of message transmission, the possibility of information being stolen can be greatly reduced. When the image is coded into the Fourier CGH and Fresnel CGH, and reached the receiving end, the original image could be obtained by the reconstruction of the two CGH. This paper presents three important points. Firstly, it provides the recording and reconstruction of the source program of Fresnel CGH and Fourier CGH in MATLAB. Secondly, it isolates the original image and the conjugate image in regeneration of Fourier CGH by using grater than image coding with matrix of all zero matrix. Even though the original image and the conjugate image can be separated, the two of them also prevent us to acquire the original message. For reserving the most valuable message, we could apply the window function to filter one of them. Finally, in the coding of Fourier and Fresnel CGH, this paper describes several functions to decrease the noise that the original image is encoded into program. The functions can be available in Fourier CGH and Fresnel CGH. The simulated result demonstrates the proposed method has high applicability. This method of coding have the potential for applications in encryption.

10022-64, Session Post

Improve the diffraction efficiency of the multilayer dielectric gratings

Bilali Muhutijiang, Xinjiang Normal Univ. (China); Keqiang Qiu, Univ. of Science and Technology of China (China); Taximaiti Yusufu, Xinjiang Normal Univ. (China)

The chirped-pulse amplification system plays a critical role in the process of achieving high-peak ultrashort pulses. Chirped-pulse amplification technology performance mainly depends on the pulse compression gratings. Diffraction efficiency is the critical parameter of the pulse compression gratings, and optimization of grating shape can achieve higher diffraction efficiency. If the photoresist grating mask bottom is not clean, the side walls would not be steep and duty cycle would be too big or too small, thus multi-layer dielectric grating diffraction efficiency would decrease. Solving these problems is the key to improve the diffraction efficiency. In this paper, ashing and oxygen etching methods are used to reduce the photoresist mask duty cycle, and PDMS pressing method is used to increase the duty cycle of photoresist mask, and aperture up to 100 mm?100 mm. Best photoresist grating mask parameter could be obtained by effectively combining the above two methods. Based on above techniques, a number of pulse compression gratings with line densities of 1740 lines?mm was achieved. The diffraction efficiency at the-1st order was greater than 99% for TE polarized light. A qualitative judgments for graphic transfer of ion beam etching is received through the picture before and after etching which is get from the SEM. These experimental results proved the accuracy, stability, and success rates of the technique.

10022-65, Session Post

Broadband Plasmonic Metasurface-enabled Quarter Waveplates with Fence-type Grating

Aijiao Zhu, Jingpei Hu, Chinhua Wang, Soochow Univ. (China)

Metasurface-enabled waveplates have attracted considerable attentions. Optical metamaterials consist of subwavelength plasmonic building blocks arranged in two-dimensional arrays. Compared to conventional bulky waveplates made of birefringent optical crystals, two-dimensional metasurfaces have comparable ability to enhance electromagnetic fields and control light polarization while in an ultrathin, planar platform, making them attractive for optical system miniaturization and integration. Metasurface-enabled waveplates typically utilized arrays of anisotropic resonant building blocks, such as crossed nanoslits, L-shaped or V-shaped nanoantennas, and so on, which often suffer from narrow bandwidth. Broadband and high-performance polarization conversion is in urgent need at this time. Recent years, rod-shaped, metallic nanoantennas

demonstrated to have strong, localized, plasmonic resonances are utilized to control polarization. A broadband optical meta-waveplate operating at the near-infrared regime in the transmission mode has been proposed using plasmonic nanorods with two orthogonally coupled nanodipole elements. Here we report a metasurface consisted of cross-shaped Ag nanorods to make a high-performance quarter waveplate with extreme bandwidths in the near-to-mid infrared. We tune the wavelength of plasmonic resonance and the magnitude together with the phase of polarization of the nanorods by engineering the geometric dimensions of them. The quarter waveplate is realized by optimizing the anisotropic response of the metasurface via changing the sizes of the arms of the crosses. Compared to previously reported metasurface-enabled waveplates, the phase retardation of the electric component of the transmitted wave is exactly equal to ?/2 across a broad wavelength range rather than merely near the resonant wavelength of the metasurface building blocks. Simulation results indicate that the polarization conversion can be realized in the near-to-mid infrared. In addition, a wavelength-dependent electric field polarization direction was required for the incident linearly polarized light in this structure.Our work gives intriguing possibilities for novel metasurface-enabled optical components with broad operational bandwidth for photonics devices.

10022-67, Session Post

Virtual viewpoint generation for three-dimensional display based on the compressive light field

Qiao Meng, Xinzhu Sang, Duo Chen, Nan Guo, Binbin Yan, Chongxiu Yu, Beijing Univ. of Posts and Telecommunications (China); Wenhua Dou, Liquan Xiao, National Univ. of Defense Technology (China)

Virtual view-point generation is one of the key technologies the three-dimensional (3D) display?which renders the new scene image perspective with the existing viewpoints. The three-dimensional scene information can be effectively recovered at different viewing angles to allow users to switch between different views. However, in the process of multiple viewpoints matching, when N free viewpoints are received, we need to match N viewpoints each other, namely matching CN2=(N(N-1))/2 times, and even in the process of matching different baselines errors can occur. To address the problem of great complexity of the traditional virtual view point generation process, a novel and rapid virtual view point generation algorithm is presented in this paper, and actual light field information is used rather than the geometric information. Moreover, for better making the data actual meaning, we mainly use nonnegative tensor factorization(NTF). A tensor representation is introduced for virtual multilayer displays. The light field emitted by an N-layer, M-frame display is represented by a sparse set of non-zero elements restricted to a plane within an Nth-order, rank-M tensor. The tensor representation allows for optimal decomposition of a light field into time-multiplexed, light-attenuating layers using NTF. Finally, the compressive light field of multilayer displays information synthesis is used to obtain virtual view-point by multiple multiplication. Experimental results show that the approach not only the original light field is restored with the high image quality, whose PSNR is 25.6772dB, but also the deficiency of traditional matching is made up and any viewpoint can obtained from N free viewpoints.

10022-68, Session Post

Software adaptation requirements identification based on space light modulate

Hua Liu, Science and Technology on Electro-optic Control Lab. (China)

The development of space-time adaptive system is based on the adaptation requirements identification and analysis. It clarifies what changes the software and hardware will face during operation and how it needs to deal with them. In space-time adaptive system requirements analysis and system modeling, the adaptive spatial light modulation control software is based on the needs of identification and the analysis of real applications,which will be considered a software of the control object. From the environmental awareness and sense of two kinds of feedback mechanism of demand, it will to identify and analyze the adaptability of software/hardware system requirements. Based on spatial light modulation theory, the core photoelectric information control system is explored to build in the complex environment, and to realize the space-time adaptive system framework which satisfy the requirements for construction and operation support. An example is used to demonstrate the feasibility of the proposed approach.

10022-69, Session Post

Characteristics of the autostereoscopic three-dimensional LED display based on diffractive optical elements sheet

Ping Su, Graduate School at Shenzhen, Tsinghua Univ. (China); Pengli An, Jianshe Ma, Shu An, Liangcai Cao, Tsinghua Univ. (China)

The autostereoscopic LED display (ALEDD) using diffractive optical elements sheet as light steering element has been proposed recently in order to obtain thinner display panel and achieve a better 3D perception. Research on the characteristic of the ALEDD using DOEs sheet is of prime importance to the widely application of the ALEDD.

In this paper, the effects caused by the assembling errors between the LED display and DOEs sheet are theoretically analyzed. The mathematical model of the relationship of the display parameters and the 3D display effect is built. Based on the model, the impact of errors of the parameters on the 3D display effect is analyzed. An adjusting device fixed onto the DOEs sheet with 6 degrees of freedom is implemented, and the impact of the deviations along every direction on the 3D display effect is studied experimentally. The results show that, the tolerance assembling errors are |?z|≤1mm, and |??x, ??y|≤1°, respectively. This conclusion will benefit a lot in instructing the installation of the autostereoscopic three-dimensional LED display system to reduce the crosstalk and improve the quality of 3D perception. The methodology of this paper also can be used in most kinds of autostereoscopic displays.

10022-70, Session Post

Experiments of diffractive optical elements obtained by ion plasma etching for aiming and display devices

Sergey B. Odinokov, Hike Sagatelyan, Artem Solomashenko, Yanina Grad, Polina Malinina, Bauman Moscow State Technical Univ. (Russian Federation)

Diffractive optical elements (DOEs) are used in the information, aiming and display systems, where the observed signs-symbolic information is superimposed on the real scene. The use of aiming and display devices in different climatic conditions requires the protection of the photosensitive layer. These elements may need to be physically protected or recorded directly into the glass. Method of their design and fabrication based on ion plasma etching are described. The optimal parameters of period and relief depth are defined and experimental results of DOEs are presented. These results show that the DOEs obtained by ion plasma etching can be applied in display systems used in difficult climatic conditions.

10022-71, Session Post

Tunable nanostructure generation using a surface plasmon resonant cavity

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With the developments of the nanoscale science and technology, the breakthrough of optical diffraction limit has become a significant issue in lithography. And the phenomena of surface plasmon polaritons (SPPs) provides another promising approach to achieve sub-diffraction limit nano-patterning.In this paper, we report a tunable two-dimensional (2D) dot array nanostructure generation using a metal-insulator-metal (MIM) surface plasmon resonant cavity formed by top silver layer, photoresist layer and bottom silver layer. Theoretical analysis and numerical simulation results show that the period of the 2D dot array can be tuned to generate ultra-deep subwavelength patterns by varying the cavity length with a fixed 2D diffraction-limited mask, and the exposure depth can be extended to the entire cavity. It may provide a flexible photolithography technique with capability of large area, tunable period and deep exposure depth.

10022-72, Session Post

Decoupling refractive index and geometric thickness based on dual-wavelength digital holography

Weining Chi, Dayong Wang, Lu Rong, Yunxin Wang, Fengpeng Wang, Beijing Univ. of Technology (China)

The information of phase distribution of an object is a key to calculate its geometric thickness and index of refraction. Digital holography has the advantages of three dimensional imaging, non-contact and flexible digital processing, it has been widely used in the fields of biomedicine, material sciences and so on. The phase information of the sample, which is proportional to the refractive index and thickness, can be obtained by digital holography. Quantitative phase imaging techniques (QPM) based on dual-wavelength digital holography has been presented, which in principle can accurately measure the refractive index and thickness information of the transparent sample at a given wavelength by using decoupling algorithm, without prior knowledge of their respective parameters. In this paper, the pre-magnified digital holographic microscopy setup based on Mach-Zehnder interferometer is used to recording two holograms with two different wavelengths respectively. Different wavelengths of light causes different optical-path-differences (OPD) when it passes through the transparent samples or the reference medium, as a result the reconstructed phase distribution of two holograms is different. The phase distribution of each wavelength is reconstructed by fast Fourier transform and spectrum filtering algorithm which is later use to calculate the refractive index and thickness of the samples by decoupling algorithm. The experimental system is greatly simplified by using the tunable laser which provides the opportunity to choose more than one wavelength in order to improve the accuracy of experimental results. Simulation and experimental results are presented to demonstrate the feasibility of suggested method with the decoupling algorithm.

10022-73, Session Post

The measurement of flow speed of on-chip micro-fluid by digital holography

Yutong Cui, Zhe Wang, Chan Sun, Zhuqing Jiang, Beijing Univ. of Technology (China)

In most of the measurement and analysis in liquid, flow speed of the fluid is one of the important parameters, especially in microfluidic chip imaging. Some published papers point out that the change of flow rate may be related to the change of phase information of the fluid. The behavior of micro-fluids on a microfluidic chip is different from common fluidic' behavior in that factors such as surface tension, energy dissipation, and fluidic resistance. The flow speed as a basic parameter may be detected via retrieval of phase information in the fluid. Digital holographic microscopy is an effective imaging technique that employs a CCD camera to record holograms and a numerical simulation diffraction process to achieve imaging reconstruction of one object. In this paper, a method to measure the flow speed based on microfluidic chip by digital holography in real-time is presented. The injection pressure of microfluidic device is changed to create different flow speed in microfluidic channels. On this basis, the phase distributions within the microfluidic channels can be reconstructed by using digital holographic microscopy, and then, the relationship between the fluidic phase and flow speed could be obtain by measuring the phase distributions of cross section. In the experiments, the several liquids of the different concentrations are used to demonstrate the fluidic speed measurement. In addition, the chip calibration is made to ensure the validity of the experimental results.

10022-74, Session Post

Real-time measurement of liquid concentration changing by digital holography

Chan Sun, Zhe Wang, Yutong Cui, Zhuqing Jiang, Beijing Univ. of Technology (China)

The microfluidic technology has been widely used in the field of biochemical analysis, disease diagnosis, minimally invasive surgery and environment monitoring. The measurement of solution concentration as one of important characteristics parameters is commonly required, particularly, in the case of the real time variation of the solution concentration in the microfluidic system. Digital holography is a high-resolution imaging technique that employs the CCD as a recording device and a numerical simulation diffraction process to achieve amplitude and phase imaging reconstruction of an object. The digital holographic imaging typically consists of the procedures of holographic recording and phase reconstruction from the recorded holograms. As we known, the change of refractive index of a liquid could be related to its phase distribution, and the change of solution concentration could result in the increase or decrease of refractive index. Thus, the variation and distribution of solution concentration can be described via its phase image reconstructed by digital holography. In this paper, a method of real-time measurement of liquid concentration changing in Y-type microfluidic chip by digital holography is presented. In the experiments, salt solutions of different concentrations are injected into the two channels of the Y-type microfluidic chip as a target object, and then the refractive index of the target can be yielded from the reconstructed phase image. The experiment

results show that the real-time changing of liquid concentration in microfluidic chip can be effectively measured by digital holographic microscopy.

10022-75, Session Post

A novel three-dimensional display system based on integral imaging using light-shaping diffusor

Xiaoyu Jiang, Zhiqiang Yan, Xingpeng Yan, Jian Su, Hui Gao, Academy of Armored Force Engineering (China)

Integral imaging is known as a promising 3D display method for its ability to reconstruct the light field of the scene. However, integral imaging suffers from low spatial resolution and narrow viewing angle due to the limited spatial bandwidth product of LCD, which prevents its commercial application. In conventional integral imaging display, spatial resolution and viewing angle are two conflicting factors, and previous research mainly focuses on the compromise of the two factors. A novel integral imaging 3D display system with large viewing angle (about 40°) and high spatial resolution for HVS is presented. The system is composed of a high definition 4K LCD, a macro lens array and a light shaping diffusor. One point of the system different from conventional integral imaging in which micro lens array is used, a macro lens array (with elemental lens diameter 1cm) is employed in our system to ensure a large viewing angle, however, this may result in low spatial resolution for HVS. And the other point is a light shaping diffusor is placed in front of the lens array with proper distance, and lifelike 3D reconstruction is obtained. The context is organized as follows: Firstly, the principle of the system is explained; Secondly, the configuration and design of the system are depicted, also the spatial resolution and viewing angle are analyzed; Finally, experimental results with full parallax, large viewing angle and high resolution 3D images are shown to verify the validity of the proposed system.

10022-76, Session Post

Generation and representation of vector vortex beams based on metasurfaces

Xunong Yi, Hubei Engineering Univ. (China)

Metasurfaces can be regarded as a class of metamaterials with a reduced dimensionality. In this work, we present a method for generating vector vortex beams with metasurfaces. The metasufaces are designed based on space-varying Pancharatnam-Berry geometric phase. A Jones calculation is employed to theoretically analyze the phase and polarization transformation from metasurfaces. The experimental results are shown to agree well with the theoretical expectation. Lastly, as a geometrical representation, the hybrid-order Poincaré sphere is proposed to describe the evolution of polarization states of light wave propagating in metasurfaces. Using the hybrid-order Poincaré sphere, we can conveniently obtain the polarization evolution in metasurfaces with special geometry. Similar to the previously proposed Poincaré sphere, the hybrid-order Poincaré sphere can intuitively demonstrate the Pancharatnam-Berry phase due to the change of polarization state. So the hybrid-order Poincaré sphere can also become an effective tool to provide help in designing metasurfaces. Our research deepens the understanding on the manipulation of polarization and phase based on Pancharatnam-Berry phase and offer an alternative method for generating vector vortex beams.

10022-77, Session Post

Analysis of performance of the direct search with random trajectory method applied to the task of minimization of kinoform synthesis error

Vitaly V. Krasnov, National Research Nuclear Univ. MEPhI (Russian Federation)

Synthesis of diffractive optical elements is one of the vital tasks of computer optics. Diffractive optical elements (DOE) are widely used in different areas of science and technology. Among different kinds of DOE, kinoforms are most effective for many applications. Kinoform is synthesized phase DOE which allows to reconstruct image by its illumination with plane wave similarly to hologram. Unlike hologram however, kinoform forms only one diffraction order containing reconstructed image. Thus, kinoform has maximum theoretical diffraction efficiency. Kinoforms are generally used as focusers, wavefront correctors, optical switches and transducers in image processing systems. There is no analytical solution to kinoform synthesis problem, therefore various iterative methods providing relatively small synthesis error are used. However, with restrictions on quantity of addressable phase levels this error becomes significant. Direct search with random trajectory (DSRT) method applied to the task of minimization of kinoform synthesis error is similar to direct binary search method for binary holograms synthesis. Main difference is that the used method is designed to process arrays with multiple phase levels. Synthesis procedure is described as follows. First, kinoform is generated with conventional method such as Gerchberg-Saxton. Then, elements of kinoform are sequentially switched to obtain lower synthesis error value. This process goes on until minimum error value is reached. Analysis of performance of the DSRT method depending on kinoform size and number of phase levels is conducted. Results of numerical experiments are presented.

10022-78, Session Post

Numerical comparison of scalar and vector methods of digital hologram compression

Pavel A. Cheremkhin, Ekaterina A. Kurbatova, National Research Nuclear Univ. MEPhI (Russian Federation)

Digital holography allows reconstruction of amplitude and phase 3D-scenes. For this interference pattern should be formed, registered by the digital camera and then processed. Currently images files sizes are equal to tens megabytes. For transfer of holographic video with movies standard frequency, channel with capacity of 2-4 Gbit/sec should be used. 10 minutes of holographic video is more than 1 terabyte. Thus large memory volumes are required to store holographic video. For speed up of holograms transmission and memory volumes reducing, it is possible to compress holograms. Compression of the holographic data is important in different tasks: security systems, registration of micro and macro objects, tomography, and etc. Standard methods of compression of digital images (for example, JPEG) can be used for holograms. However they are less applicable due to the various facts: intensity sharp changes in holograms images; holographic registration not only amplitude, but also phase of wave; and etc. Therefore other types of methods of holograms compression and quantization were analyzed: scalar and vector ones. In this paper 4 common scalar and vector methods of holograms compression are considered. Experiments of compression of digital holograms were numerically carried out. Two scalar methods were used: nonuniform logarithmic and uniform quantization. Two vector methods were investigated: k-means and k-medians clustering. Compression of hologram file was achieved primarily by decreasing of hologram quantization

levels quantity. Quality of objects reconstruction by mentioned methods, diffraction efficiency and computational resources were compared. Dependencies of these values on quantity of hologram quantization levels are plotted.

10022-79, Session Post

High linearly polarized white-light emission from LEDs with multilayer dielectric/metal wire-grid structure

Linghua Chen, Chinhua Wang, Soochow Univ. (China)

We proposed and experimentally demonstrated a linearly polarized white light from InGaN light-emitting diode with nano-gratings integrated fluorescent ceramics. By incorporating a dielectric layer of low refractive index between multilayer nano-gratings and a fluorescent ceramics of high refractive index, both high TM transmission (TMT) and high ER can be effectively achieved across the whole range of white light. An extinction ratio of higher than 20dB and TMT of 60% were obtained experimentally for a GaN/fluorescent ceramics integrated white LED (450nm-650nm) with a multilayer grating of 150nm period. The fluorescent ceramics integrated structure shows possibilities of implementing polarized white light LED in a fashion of compact, long-life and high performance.

10022-80, Session Post

Optimization design and laser damage threshold analysis of pulse compression gratings

Shuwei Fan, Liang Bai, Nana Chen, Xi'an Jiaotong Univ. (China)

As a milestone in the development of laser technique,chirp pulse amplification(CPA) technique is widely applid to produce ultra high power laser.Pulse compression gratings (PCG),one of CPA core components, is becoming hot topic. Multilayer dielectric gratings(MDG) and mixed metal dielectric grating(MMDG) ,with higher damage threshold(LDT) and higher diffraction efficiency(DE) compared with metal grating, are gradually used as compression gratings. Paper's main work about MDG and MMDG is as follows:

Firstl, thin-film structure with high reflectance, which would be applied to MDG and MMDG, was designed by combining characteristic matrix method and global optimization algorithm. The reflectance of the thin-film was closed to 100% after being optimized, and the bandwidth was over 200nm.

Second, grating optimization design software based on vector rigorous coupled-wave and generic algorithm was developed. The optimization design of MDG and MMDG was studied, which demonstrated that the highest diffraction efficiency was over 99% and bandwidth of MMDG was to over 200nm, 50nm wider than that of MDG.

Third, the study on laser damage threshold of thin-film structure was done by discussing the internal electric field distribution of the thin-film. With the help of Matlab, the simulation software of standing wave field distribution within MDG and MMDG was developed. The standing wave field of MMDG with three different reflective thin- film structure was calculated. And the key parameters which affected the electric field distribution were studied with the aid of the software.

10022-81, Session Post

A three-dimensional content remapping method for the auto-stereoscopic display

Can Cui, Xinzhu Sang, Peng Wang, Duo Chen, Nan Guo, Binbin Yan, Kuiru Wang, Beijing Univ. of Posts and Telecommunications (China); Liquan Xiao, National Univ. of Defense Technology (China)

Generally, there is a depth of field (DOF) constraint for each kind of auto-stereoscopic display owing to the limited angular resolution, which restricts the depth of display. Device-specific blurring will occur if the depth of object exceeds the DOF boundary. A novel depth-perception preserved three-dimensional (3D) content remapping method is presented to meet the DOF constraint of a target 3D display, by using a nonlinear global operation followed with local depth contrast recovery. Apparent depth is dominated by the distribution of depth contrast rather than an absolute depth value. The framework can be divided into two steps. Firstly, a nonlinear operation is adopted to remap the reference depth map of image to fit into the DOF limitation. Secondly, the depth contrast is recovered by decomposing the reference and remapped depth map into multi-frequency bands, calculating the difference for each band, and then the remapped depth map is used to add the scaled difference of depth map of top levels' frequency bands. A warping-based view synthesis method is adopted to retarget the light field according to the modified depth map. The experimental results show that the modified light field is sharp while the original perception of depth is maximally preserved.

10022-84, Session Post

Phase extracting and unwrapping algorithm of electrical speckle shearing phase-shifting pattern interferometry

Chao Jing, Ping Zhou, Beijing Institute of Environmental Features (China)

Electrical Speckle Shearing Phase-shifting Pattern Interferometry (ESSPPI) has been used in the fields of non destructive testing (NDT) and stress field analysis as a precise deformation measuring method. The general fixed-step phase extracting algorithms of ESSPPI, such as three-step algorithms, four-step algorithms, five-step algorithms, and their corresponding errors are analyzed. It is proved that the phase accuracy of ESSPPI with different algorithms are mainly affected by linear error of phase-shifting. Therefore the modified four-step phase-shifting extracting algorithm that isn't sensitive to linear error of phase-shifting is adopted in the paper. The filtering algorithm should be employed to reduce the influences of speckle noise and wrong data caused by errors during measurement. Then the least-squares phase-unwrapping algorithm based on fast discrete cosine transform (LPABFDCT) is adopted to search the least-squares solutions between phase difference value of adjacent pixels and unwrapping phase difference value of the pixel and the real phase distribution caused by object deformation is obtained. The Electrical Speckle Shearing Phase-shifting Pattern Interferometric images are captured with four-step phase-shifting method and the real phase distributing image is achieved with modified four-step phase-shifting extracting algorithm, denoising filter and the least-squares phase-unwrapping algorithm based on fast discrete cosine transform. It is proved with experiment results that the real phase distributing images are effective achieved by mean of combination of average filter and the least-squares phase-unwrapping algorithm based on fast discrete cosine transform.

10022-85, Session Post

Boundary perturbation solution of the circular hollow waveguide

Xue Qin, Yan Wang, Xiaoyan Wang, Xiaona Yan, Huifang Zhang, Lihua Bai, Shanghai Univ. (China)

A method based on the perturbation of the boundary conditions on the metallic walls of the waveguide is used for computing the propagation constant. This method is more direct, effective and quicker than obtaining the propagation constant from the characteristic equation. The expression of propagation constant includes both the real part and imaginary part. There is a good agreement between this expression and the result of numerical simulation from the COMSOL Multiphysics. The result shows that the HE11 is the perturbation of the TE11, we can obtain the expression of the HE11 propagation constant relies on the distribution of the TE11. Moreover, the propagation constant is studied for the single-mode transmission and the multi-mode we haven't considered.

10022-86, Session Post

Experimental study on degree of coherence for stochastic electromagnetic fields

Juan Zhao, Heriot-Watt Univ. (United Kingdom) and SuperD Co., Ltd. (China); Mitsuo Takeda, Utsunomiya Univ. (Japan); Wei Wang, Heriot-Watt Univ. (United Kingdom)

All optical fields undergo random fluctuation and the degree of coherence defined as the normalized correlation function of optical fields has played a fundamental role as an important manifestation of the underlying random fluctuations. For randomly varying electromagnetic waves, the usual treatment of polarization based on the well-known Stokes parameters or polarization matrices is not adequate and a unified theory of coherence and polarization of random electromagnetic beams has been proposed by Wolf to elucidate the changes of polarization and coherence as the beam propagate.

In this paper, a novel optical geometry is proposed based on the polar-interference law of electromagnetic beams with its unique capability to visualize the mutual coherence tensor directly. Note the fact that wave equations govern the propagation of mutual coherence tensor, which can be regarded as a tensor wave. After retrieval of the complex functions for all the elements of coherence tensor from the recorded interferograms, we obtain the magnitude and the unit direction tensor for the coherence tensor wave and demonstrate the degree of coherence for stochastic electromagnetic fields with partial polarization and partial coherence experimentally for the first time.

10022-88, Session Post

Bilayer metasurface for asymmetric polarization conversion for transmission and reflection

Joonsoo Kim, Hyeonsoo Park, Byoungho Lee, Seoul National Univ. (Korea, Republic of)

Metasurfaces refer to two-dimensional array of subwavelength-sized nano-antennas which can be designed to manipulate amplitude and phase of scattered light. Due to their abilities to control wavefronts, polarization distributions of optical fields and potential applicability to ultrathin, high numerical aperture optical components, metasurfaces have been attracting attention of many researchers. Particularly, there have been efforts to enhance functionality of individual metasurface cells by exploiting various degrees of freedom in the nano-antenna design. For instance, various schemes for polarization multiplexing and a metasurface for simultaneous control of phase and polarization have been reported. Actually, asymmetric transmission/reflection characteristics are closely related to multiplexing since multiplexing can be achieved by combining the asymmetric scattering behaviors. In the case of polarization multiplexing, asymmetry in the polarization conversion for two polarization inputs plays a central role. Similarly, asymmetry in transmittance and reflectance for cross-polarization can be exploited for two-side multiplexing of metasurfaces.

In this paper, we propose a bilayer metasurface structure with transmission/reflection asymmetry. We assume that the proposed metasurface is embedded in homogeneous dielectric medium to ensure that the reflection asymmetry is not originated from the substrate effect. Firstly, we design a two ultrathin metasurfaces one of which consists of polarization-sensitive nanoslit antennas and the other one consists of polarization-insensitive apertures in a way that maximizes the transmission. Then, we cascade the two surfaces with a thin dielectric gap and observe the transmittance/reflectance ratio for varying gap thicknesses and antenna dimensions. The proposed structure is expected to be used for development of transflective metasurfaces.

10022-89, Session Post

3D polarisation speckle as a demonstration of tensor version of the van Cittert-Zernike theorem for stochastic electromagnetic beams

Ning Ma, Juan Zhao, Heriot-Watt Univ. (United Kingdom); Steen Grüner Hanson, DTU Fotonik (Denmark); Mitsuo Takeda, Utsunomiya Univ. (Japan); Wei Wang, Heriot-Watt Univ. (United Kingdom)

Laser speckle has received extensive studies of its basic properties and associated applications. In the majority of research on speckle phenomena, these random optical fields have been treated as scalar optical fields, and the main interest has been in the statistical properties and applications of the intensity distribution of the speckle patterns. Recently, statistical properties of random electric vector fields referred to as Polarization Speckle have come to attract new interest because of their importance in a variety of areas for practical applications such as biomedical optics and optical metrology. Statistical phenomena of random electric vector fields have close relevance to the theories of speckles, polarization and coherence theory.

In this paper, we investigate the correlation tensor for stochastic electromagnetic fields modulated by a depolarizer consisting of a rough-surfaced retardation plate. Under the assumption that the microstructure of the scattering surface on the depolarizer is as fine as to be unresolvable in our observation region, we have derived a relationship between the polarization matrix/coherency matrix for the modulated electric fields behind the rough-surfaced retardation place and the coherence matrix for free space geometry. This relation may be regarded as entirely analogous to the van Cittert-Zernike theorem of classical coherence theory. Within the paraxial approximation as represented by ABCD-matrix theory, the three-dimensional polarization speckle has been investigated from the correlation tensor for the generated polarization speckle, indicating a typical spindle structure with a much longer axial dimension than the extent in its transverse dimension.

10022-90, Session Post

Space telescope using laser beam holography for interferometric image construction using telescopic apparatus for celestial objects, space, and also for construction and spatial mapping, remote sensing in other planets in base plate and other materials, and monitoring devices

Mohammad M. Anwar, Forever Living Products (Bangladesh)

The celestial objects can be visible using any telescope and we can take the object picture with a telescope and then illuminate that using laser beam and make a holographic image for that that can be seen on the holographic recording device or in any monitoring device .We may use the holographic apparatus in connection with any telescope for doing regular holographic image with the objective lens of the telescope to visualize any celestial object image like any planets , star, or any planetary surface or any object studying there , for mapping or remote sensing and also many other purposes for exploring space and celestial objects even for making 3D map for asteroid belts and its component .The basic instrument may have the same basic principle as that for producing holography like interference production from reference beam and scattered beam , but we can use more complicated things for phase matching and properly tuning the image very clear using computer software and also other technique in geometrical optics.

Introduction:

10022-91, Session Post

Autofocusing through cosine and modified cosine score in digital holography

Aga He, Wen Xiao, Feng Pan, Beihang University (China)

Digital holography possesses the ability of numerically refocusing a scene plane-by-plane from a hologram by selecting different reconstruction distance, and an automatic focus algorithm is necessary to quantify the focus degree of the reconstructed images and determine the focused plane. In this paper, an autofocusing method is proposed that utilizes the cosine score between the axial neighboring amplitude images. It is based on the fact that the images near the focus contain more regular features of object than in the defocused region, therefore, the neighboring reconstructed images are more similar to each other at the focus position than at defocused and a cosine score is employed to evaluate such similarity. However, the cosine scores between the axial adjacent amplitude images are so close that it is difficult to distinguish the extremum. Therefore, a modified cosine algorithm is presented to offset such problem on consideration of the correlation of the elements, by subtracting the inner product term from the denominator of the cosine algorithm. The cosine and modified cosine score based autofocusing method procedure is first introduced, and then it is utilized in simulation and real holographic data. In simulation, it precisely judges out the actual recording distance and the focus curve shows good focus function criteria, which verifies the method as an ideal circumstance. In real experiment, it can easily search out the focus distance from the focus curve, and it shows good focus judgement ability than most traditional focus metrics selected. Therefore, the feasibility and validation of the proposed autofocusing method are proved by simulation and experiment results.

10022-92, Session Post

Temperature sensor based on Fano and Lorentzian resonance lineshapes of a photonic crystal cavity

Chenyang Zhao, Xuetao Gan, Qingchen Yuan, Jianlin Zhao, Northwestern Polytechnical University (China)

So far, the well-developed optical temperature sensors are fiber-optic sensors due to the high sensitivity and easy fabrication. However, they can hardly be used in integrated chips, limiting their applications in the fields of micro-optoelectronics. Compared with optical fiber based temperature sensors, silicon photonic sensors can achieve much higher sensitivity due to the high thermo-optic coefficient and compatible with the complementary metal-oxide-semiconductor (COMS) fabrication process. Photonic crystal (PC) cavities, as one of the important chip-integrated photonic architectures, enable the control of light propagation and interaction with matter in wavelength-scale. Using the character of high quality (Q) factors and strong field confinement, PC cavity can be designed as a sensor to detect the local index changes in their environment.

We report an ultra-small temperature sensor based on silicon PC cavity, which employs two resonance line shapes of the cavity, i.e., high Q factor Lorentzian resonance line shape and sharp asymmetric Fano resonance line shape. To achieve the sensitivity with different temperature, the temperature variation is measured by monitoring the shift of the resonant wavelength and the variations of transmitted intensity in the PC cavity, which is induced by the thermo-optic effect and the thermal expansion effect. We have demonstrated that the Fano resonance of the cavity-based sensor has a similar sensitivity for the resonant wavelength shift, but a higher sensitivity for intensity variation, comparing with the Lorentzian resonance sensor. The demonstrated PC cavity-based sensor offers potential for a low-cost, high sensitivity homogeneous sensing in single on-chip integration devices.

10022-93, Session Post

Application of the Microlens Array in the projection of the Laser Scanning

Lulu Wang, Xi'an Jiaotong Univ. (China); Min Li, Suzhou Institute of Nano-Tech and Nano-Bionics (China); Hai Tan, Changzhou Micro Innovation Technology Co., Ltd. (China); Peng Zhou, Yu Bai, Wenjiang Shen, Dongmin Wu, Suzhou Institute of Nano-Tech and Nano-Bionics (China)

Retinal scanning display (RSD) technology, as a new type of helmet-mounted display (HMD) technology, has been used in virtual reality (VR) and augmented reality (AR) area, and it has gradually become a hot research topic. However, a small exit-pupil restricts the application of the RSD in the intelligent head-mount display (HMD). In this paper, we use the microlens array to solve this problem. We have designed a new process and prepared a circular-type microlens array with 70% fill factor in the form of a hexagonal close-packed arrangement by melting photoresist. The aperture size of the lens is 14?m and the period is 16?m. The gap is coated with a metal film to reflect off the beam which will not be modulated by the microlens. This can achieve a more uniform exit pupil expansion. An optical system for detecting pupil expansion performance was established in this paper. Simultaneously, we study the effect of different defects of the microlens array for the pupil expansion. We also demonstrate the function of the retinal scanning imaging with the microlens array. The result shows that the NA and expansion angle of the microlens array are greater than 0.28 and 33°. After the expansion, the beam uniformity is more uniform, which

meets requirements for the helmet-mounted display needs, and achieves the goal of near eye display.

10022-94, Session Post

Gravure printing for electrophoretic e-paper

Li Wang, Gui-Shi Liu, Yu-Wang Xu, Yu-Cheng Wang, Peng Chen, Bo-Ru Yang, Sun Yat-Sen Univ. (China)

Color microcapsules have been prepared by some corporations and they are better than the EPD with color filter in color performance. Theoretically, the color microcapsule EPD without color filter can be achieved if the color microcapsules could be patterned in the desired area, respectively. However, it is virtually difficult to make these color capsules to be patterned and aligned with corresponding TFT pixels. We propose an interesting technology with gravure process to achieve color EPD. The proposed gravure process is as follows: Firstly, a conventional photolithography was used to make the mother mold with photo-resist (SU8) to define the shape and spatial deployment of the capsules. Secondly, the Poly-Di-Methyl Siloxane (PDMS) was further poured onto the SU8 mold and cured as a stamp. Thirdly, the color capsules of EPD were coated with doctor blade. After dried out the solvent, the spatially patterned EPD capsule with specific colors are formed. Finally, the patterned EPD capsules were transferred onto another target substrate with the aid of certain adhesive agent. Different color capsules were nested together by repeating the above steps.

The reason for using SU8 is to make the high aspect ratio geometry of trench, as well as precisely control the depth of the trench to accommodate enough capsules to render well-defined optical performances. While PDMS has better chemical inertness and low surface energy which facilitate the transfer process.

10022-95, Session Post

Three-dimensional simulation and auto-stereoscopic 3D display of the battlefield environment based on the particle system algorithm

Jiwei Ning, Xinzhu Sang, Shujun Xing, Huilong Cui, Chongxiu Yu, Binbin Yan, Beijing Univ. of Posts and Telecommunications (China); Wenhua Dou, Liquan Xiao, National Univ. of Defense Technology (China)

In times of peace, the army's combat training is still very important, and the simulation of the real battlefield environment is of great significance. Two-dimensional information has been unable to meet the demand at present. With the development of virtual reality technology, three-dimensional (3D) simulation of the battlefield environment is possible. In the simulation of 3D battlefield environment,in addition to the terrain, combat personnel, combat tool, the simulation of explosions, fire, smoke and other effects is also very important, since these effects can enhance the sense of realism and immersion of the 3D scene. However, these special effects are irregular objects which makes it difficult to simulate with the general geometry. Therefore, the simulation of irregular objects is always a hot and difficult research topic in computer graphics. In the past decades, a variety of simulation algorithms have emerged, so far, the particle system algorithm for simulating irregular objects is considered to be the best algorithm and widely used for simulating irregular objects.Here, the particle system algorithm is used for simulating effects in the 3D battlefield environment.

In the paper, we researched and designed the simulation algorithm of the explosions, fire, smoke based on particle system and applied it to the battlefield 3D scene. Besides, the battlefield 3D scene simulation with the glasses-free 3D display is carried out with an algorithm based on GPU 4K super-multiview 3D video real-time transformation method. In this algorithm, the 3D scene is represented as the data format of "video + depth", and the 3D video is synthesized by super -multi virtual viewpoint which is generated by view graph and the corresponding depth map. At the same time, with the human-computer interaction function, we ultimately realized glasses-free 3D displays of the simulated more realistic and immersive 3D battlefield environment. The experimental results show that the algorithms designed and realized by us are effective and feasible, and will be widely used for simulation of complex objects and their 3D display.

10022-96, Session Post

Vertex shading of the three-dimensional model based on ray-tracing algorithm

Xiaoming Hu, Xinzhu Sang, Shujun Xing, Binbin Yan, Kuiru Wang, Beijing Univ. of Posts and Telecommunications (China); Wenhua Dou, Liquan Xiao, National Univ. of Defense Technology (China)

Ray tracing is a significant algorithm that can generate very high quality and extremely realistic images, which can simulate various physical phenomena like reflection, refraction, shadow etc. Although the image generated by ray tracing is very realistic, the rendering process is very time consuming without any accelerating algorithm. Moreover, the rendering time of the algorithm is influenced by the resolution of the generated image, the number of the light source, the number of objects and the distribution of the 3D scene. As a result, it is difficult to realize real-time ray tracing of any 3D scene. Here, the optimization of the entire ray tracing process is presented. With the open-source 3D engine library of OPENSCENEGRAPH, we wield the ray tracing algorithm to color vertices of a model directly, as well as a simple patch subdivision whenever needed. In this way, good lighting effects are achieved and a considerable part of the calculation of the time-consuming intersection is effectively avoided. In the case of high resolution, the efficiency of ray tracing rendering is improved. At the same time, the results can be directly saved as a 3D model with a global effect of light and shadow, which extends the application range of ray tracing. Due to the direct ray tracing operation in the 3D virtual scene, the running time of the presented method only depends on the number of triangular patches in the 3D scene (number of vertices), the scene distribution and the number of light sources. It is irrelevant to the screen resolution. In addition, once a 3D scene rendering is completed, the model's attitude can be observed or changed from different angles, which will bring a lot of convenience for interaction and dynamic processing of the 3D scene.

10022-97, Session Post

Real-time synchronized rendering of multi-view video for 8Kx2K three-dimensional display with spliced four liquid crystal panels

Huilong Cui, Xinzhu Sang, Shujun Xing, Jiwei Ning, Binbin Yan, Beijing Univ. of Posts and Telecommunications (China)

A high speed synchronized rendering of multi-view video for 8K?2K multi-LCD-spliced three-dimensional (3D) display system based on CUDA is demonstrated. Because the conventional image processing calculation method is no longer applicable

to this 3D display system, CUDA technology is used on 3D image processing to address the problem of low efficiency. The 8K?2K screen is composed of four LCD screens, and accurate segmentation of the scene is carried out to ensure the correct display of 3D contents and a set of controlling and host softwares are optimally implemented to make all of the connected processors render 3D videos simultaneously. The system which is based on master-slave synchronization communication mode and DIBR-CUDA accelerated algorithm is used to realize the high resolution, high frame rate, large size, and wide view angle video rendering for real-time 3D display. Experimental result shows a stable frame-rate at 30 frame-per-second and the friendly interactive interface can be achieved.

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10022-98, Session Post

Three-dimensional scene capturing for the virtual reality display

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A virtual reality shooting and display system based on multiple degrees of freedom camera is designed and demonstrated. Three-dimensional scene display and the wide angle display can be achieved easily and quickly through the construction with the proposed system. The range of the viewing scene can be broaden with the image stitching process, and the display in the demonstrated system can achieve the effect of wide angle for applications of image mosaic. In the meantime, the system can realize 3D scene display, which can effectively reduce the complexity of the 3D scene generation, and provide a foundation for adding interactive characteristics for the 3D scene in the future. The system includes an adjustable bracket, computer software, and a virtual reality device. Multiple degrees of freedom of the adjustable bracket are developed to obtain 3D scene source images and mosaic source images easily. 5 degrees of freedom are realized, including rotation, lifting, translation, convergence and pitching. To realize the generation and display of three-dimensional scenes, two cameras are adjusted into a parallel state. With the process of image distortion eliminating and calibration, the image is transferred to the virtual reality device for display. In order to realize wide angle display, the cameras are adjusted into “V” type. The preprocessing includes image matching and fusion to realize image stitching. The mosaic image is transferred for virtual reality display with its image reading and display functions. The wide angle 3D scene display is realized by adjusting different states.

10022-99, Session Post

Research situation and development trend of the binocular stereo vision system

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Since the 21st century, with the development of the computer and signal processing technology, a new comprehensive subject that called computer vision was generated. Computer vision covers a wide range of knowledge, which includes physics, mathematics, biology, computer technology and other arts subjects. It becomes more and more powerful, not only can realize the function of the human eye “see”, also can realize the human eyes cannot. In recent years, binocular stereo vision which is a main branch of the computer vision has become the focus of the research in the field of the computer vision. Binocular stereo vision is a kind of the computer vision technology that can simulate human eyes to deal with the surroundings directly, which uses two cameras to shoot the same scenes at the same time, the three-dimensional (3D) images are collected. The 3D coordinate information of the scene is obtained automatically by this technology without touch. In addition, binocular stereo vision also has such advantage as simple structure, flexibility, reliability, wide range of application and so on, so it has been applied to many aspects of social life, such as 3D reconstruction of image, robot navigation, industrial product testing and so on. In this paper, the binocular stereo vision system, the development of present situation and application at home and abroad are summarized. With the current problems of the binocular stereo vision system, his own opinions are given. Furthermore, a prospective view of the future application and development of this technology are prospected.

10022-100, Session Post

Interactive dynamic three-dimensional scene for the ground-based three-dimensional display

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Three-dimensional (3D) displays provides valuable tools for many fields, such as scientific experiment, education, information transmission, medical imaging and physical simulation. Ground based 3D display with dynamic and controllable scene can find some special applications, such as design and construction of buildings, aeronautics, military sand table and so on. It can be utilized to evaluate and visualize the dynamic scene of the battlefield, surgical operation and the 3D canvas of art. In order to achieve the ground based 3D display, the public focus plane should be parallel to the cameras’ imaging planes, and optical axes should be offset to the center of public focus plane in both vertical and horizontal directions. Virtual cameras are used to display 3D dynamic scene with Unity 3D engine. Parameters of virtual cameras for capturing scene are designed and analyzed, and locations of virtual cameras are determined by the observer’s eye positions in the observing space world. An interactive dynamic 3D scene for ground based 3D display is demonstrated?which provides high-immersion 3D visualization.

10022-101, Session Post

A-star algorithm based path planning for the glasses-free three-dimensional display system

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A-Star (A*) algorithm is a heuristic directed search algorithm to evaluate the cost of moving along a particular path in the search space, which can get the shortest path. Here, path planning between any two points on the map is carried out. The STAGE tool is used to manually add way points on the map and determine their spatial location. The adjacent waypoint with a waypoint ID is connected by the line segment to form the navigation graph. A* algorithm can search the navigation graph to find the shortest path from a starting point to the destination.

The A* algorithm can restart searching for path from a certain point, and the complex path can be divided in a plurality of frames. Since the navigation graph consists of the movable space, it is considered the obstacle formed by static objects in the scene, and collision detection between the character and static objects is not considered. A-star algorithm based path planning is experimentally demonstrated on a glasses-free three-dimensional display equipment, so that 3D effect of path finding can be perceived.

10022-102, Session Post

Electric breakdown of dielectric coatings for high-voltage display applications

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Smectic liquid crystal is the most promising material for smart glass application due to infinite bistability and low haze at clear state. To switch from scattering to transparent state up to 10x higher voltage is needed than twisted nematics LCDs and is likely for dielectric breakdown to occur. Thin film with high dielectric strength and high transparency is required between ITO and liquid crystal.

In this work we have compared electrical and optical properties of SiO2 thin films with thickness up to 500 nm coated by flexographic printing and reactive magnetron sputtering

Current-voltage characteristics and dielectric breakdown values show sputtered coatings to have higher dielectric strength. For sputtered coatings with thickness >240 nm also self-healing effect was observed. Self-healing mechanism will be discussed.

10022-103, Session Post

Visual discomfort caused by color asymmetry in 3D displays

Zaiqing Chen, Xiaoqiao Huang, Chao Zhang, Junsheng Shi, Lijun Yun, Yunnan Normal Univ. (China)

Color asymmetry is a common phenomenon in 3D displays, which can cause serious visual discomfort. To ensure safe and comfortable stereo viewing, the color difference between the left and right eyes should not exceed a threshold value, named as comfortable color difference limit. In this paper, we have experimentally measured the limit of (dis)comfort color difference by human observers viewing brief presentations of color asymmetry image pairs. Five sample color points are selected from the 1976 CIE u'v' chromaticity diagram to measure the comfortable color difference limits. As the presentations of color asymmetry image pairs, left and right circular patches are horizontally adjusted on image pixels with five disparity levels and six color directions. The experimental procedure was wholly controlled by the Software. First, one kind of color is randomly selected from five sample points to fill the circular patch on the right half of the screen. Then, the left stimulus on the left half of the screen is randomly filled with a neighboring point color of the sample point. And then a disparity level is randomly selected from five disparities to move the left and right circular patches horizontally on image pixels. The subject is asked to report whether he/she feels visual uncomfortable when the stimulus is presented. The experimental results showed that comfort limits for each sample point varied with the disparity and color direction. To analyze the results, we quantified the comfortable color difference by drawing ellipses in the chromaticity diagram. The semi-minor axis of the ellipses ranges from 0.0120 to 0.0301 in terms of the Euclidean distance in the u'v´ chromaticity diagram and the semi-major axis ranges from 0.0210 to 0.0520. The database collected in this study greatly helps 3D system design and 3D content creation.

10022-105, Session Post

The implementation of laser speckle reduction based on MEMS two-dimensional scanning mirror

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The laser display, a new display technology, involves optics, electronics and system design. Laser display has many advantages, such as wide color gamut, high brightness and long lifetime. So it has strong potential in the market and important research significance in recent years. When laser light was reflected from a screen surface, a high-contrast, fine-scale granular pattern would be seen by an observer looking at the scattering spot. This type of granularity is so-called laser speckle. This phenomenon is mainly due to the interference of the reflected light waves. Laser speckle, which decreases image resolution and masks the image information, needs to be suppressed.

With advantages such as miniaturization, mass production, superior performance at high resonant frequency actuation, MEMS micro-mirror becomes an ideal core component in many fields. Compared with other speckle reduction methods, using MEMS mirror is more efficient, lower cost, and simpler.

In this paper, we design and fabricate MEMS two-dimensional scanning mirrors. The MEMS mirror has a reflective surface with diameter of 15mm. This large reflective surface can handle high laser optical power for projecting images with big lumens. We design a system to reduce the laser speckle contrast based on this MEMS two-dimensional micro-mirror. The MEMS mirror is driven by electromagnetic force. The system will generate a large number of independent speckle patterns when the laser beam is reflected by the scanning MEMS mirror. The speckle contrast can be reduced to less than 4% through averaging these independent speckle patterns.

10022-23, Session 5

Analytical description of quasi normal modes in resonant metallic nano-grooves

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We report an analytical model of quasi normal mode (QNM) supported by metallic nano-grooves that form resonant plasmonic nano-cavities [1]. The QNM is a solution of source-free Maxwell's equations that satisfies the outgoing wave condition at infinity, and has shown great advantages in providing analytical descriptions of the frequency response of resonant nano-structures. However, the QNM itself is commonly obtained with numerical calculation which conceals its physical origin and blocks an efficient design. The model shows that the QNM originates from a resonance of the fundamental mode in each groove and their interaction via surface waves launched by each groove. Analytical expression for the complex eigenfrequency as

well as the field distribution of the QNM can be derived from the model. Under external illumination of a plane wave, the legitimacy for the expansion of scattered field with QNMs is justified with the complex pole expansion theorem of meromorphic function under a few assumptions on the scattered field. The expansion coefficients of QNMs are analytically expressed in the model with a finite set of elementary scattering coefficients, which avoids the calculation of the mode volume of QNMs that have a spatial divergence at infinity. The model also drastically reduces the computational load of QNMs especially for a large ensemble of grooves for which the brute-force numerical tools are not available. The validity of the proposed model is tested against full-wave numerical results.

[1] F. Yang, H. T. Liu, H. W. Jia and Y. Zhong, J. Opt. 18, 035003 (2016).

10022-24, Session 5

Hyperbranched-polymer dispersed nanocomposite volume gratings for holography and diffractive optics

Yasuo Tomita, Shinsuke Takeuchi, Satoko Oyaizu, Hiroshi Urano, Taka-aki Fukamizu, The Univ. of Electro-Communications (Japan); Naoya Nishimura, Keisuke Odoi, Nissan Chemical Industries, Ltd. (Japan)

We describe the volume holographic recording properties of photopolymerizable nanoparticle-polymer composites (NPCs) that incorporate hyperbranched polymer (HBP) acting as transporting organic nanoparticles. Synthesized HBPs are easy to disperse in monomer without any substantive aggregation, so that film samples with good optical quality are available. It is also possible to control the size and refractive index by chemical treatment. They would behave themselves like hard nano-spheres in monomer. It is also possible to control and add the optical properties and functionalities of HBPs by means of chemical treatment of functional end groups. Here we describe the performance of NPC volume gratings with various HBPs in photopolymer. These HBPs include hyperbranched poly(ethyl methacrylate), hyperbranched polystyrene and hyperbranched triazine/aromatic units whose refractive indices were 1.51, 1.61 and 1.82, respectively. Their heterogeneity indices showing the relative size distribution of polymers were estimated by the gel permeation chromatography to be 1.68, 4.86 and 4.40, respectively. Each HBP was dispersed in monomer whose refractive index was so chosen that a refractive index difference between HBP and the formed polymer was larger. Such syrup was further mixed with a green-sensitive photoinitiator titanocene for holographic recording measurements. We used a two-beam interference setup to write an unslanted transmission volume grating at grating spacing of 1 micron and at a wavelength of 532 nm. It is shown that volume NPC gratings with the refractive index modulation amplitudes as large as 0.008, 0.004 and 0.02 can be recorded at their optimum HBP concentration of 34, 34 and 25 vol.%, respectively. This result shows the usefulness of HBP-dispersed NPC gratings for various holographic applications.

10022-25, Session 5

A printable color filter based on the micro-cavity incorporating a nano-grating

Yan Ye, Soochow Univ. (China)

A printable color filter based on the micro-cavity incorporating a nanostructure is proposed, which consists of chromium (Cr) nano-grating, a dielectric layer and aluminium (Al) film. To figure out the influence on the reflection introduced by the nano-grating, the reflective characteristics of the micro-cavity with or without a nano-grating are analyzed by

The simulation results show that for the micro-cavity, the same resonant wavelength can be induced under different depths of dielectric layer. Therefore, by introducing different depths for the same resonant wavelength inside one period into a dielectric layer, a nano-grating is obtained on top surface of the dielectric layer. And its reflective spectrum shows that the bandwidth of its reflective spectrum decreases much more compared to the one of the spectrum for the micro-cavity. Furthermore, its reflective efficiency at resonance is more than one time larger than the one comparing to the reflection of the Cr nano-grating, which is caused by reflective capability of the Al layer by comparing their corresponding magnetic amplitude distribution at the resonant wavelength.

For the micro-cavity can be a byproduct in the fabrication of the proposed filter, they can be utilized together to realize a colorful display with different background for an anti-counterfeiting certificate.

10022-26, Session 5

A small deployable infrared diffractive membrane imaging system

Yue Zhang, Beijing Institute of Space Mechanics and Electricity (China)

Diffractive membrane imaging can be widely used in infrared due to its longer minimum linewidth than used in visible light and its loose requirement of RMS to fabricate easier and reduce processing cycle and development cost. A small deployable infrared diffractive membrane imaging system with 200mm imaging aperture (actual aperture is 500mm) and 6U dimensions was designed. The imaging system consists of deployable structure than supports the infrared membrane under tension. The imaging wavelength is >1?m, field of view is >1º, and diffractive efficiency can be >60%. The technology is particularly promising as a means to achieve extremely large optical primaries from compact and lightweight packages.

10022-27, Session 5

Design of soft x-ray varied-line-spacing grating based on electron-beam lithography near-field lithography

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Soft x-ray varied line spacing gratings (VLSGs), being vital optical elements for laser plasma diagnosis and spectrometry analysis are conventionally fabricated by holographic lithography or mechanical ruling. Although soft x-ray VLSGs by holographic lithography show lower stray light than those from mechanical ruling, the flexibility of density distribution from holographic lithography is still limited by critical requirement to obtain aspecific wavefront. In order to overcome these issues a method based on electron beam lithography-near field lithography (EBL-NFH) is proposed. This combination simultaneously benefits from EBL's flexibility and NFH's high throughput.

In this paper, we will show a newly designed soft x-ray VLSG with a central groove density of 3600 lines/mm, which is to be realized based on EBL-NFH. First, the optimization of the spatial distribution of line density and groove profile of the VLSG will be shown. As an important element in NFH, a fused silica mask plays a key role during NFH in order to obtain a required line density of VLSG. Therefore, secondly, the transfer relationship of spatial distribution of line densities between fused silica mask and resist grating will be investigated in different exposure modes during NFH. We will propose a formulation about the transfer of line density to design of the groove density distribution of a fused silica grating mask. Finally, the spatial distribution of line densities between the fused silica mask, which is to be fabrication by using EBL, will be demonstrated.

10022-28, Session 5

Antireflective subwavelength structures at a wavelength of 441.6 nm for phase masks of near-field lithography

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With the development of micro- & nanofabrication technology, micro- & nanostructures have been widely used in many fields, including spectroscopy, coding, sensor, subwavelength element, etc. With phase masks realized by a combination of electron beam lithography (EBL), near field lithography (NFH) has great potential to fabricate versatile nanostructures, because it combines the advantages of both lithographic methods.

Currently, subwavelength structures attract much attention due to their various functions, such as antireflection, polarization beam splitter and filter. In this presentation, aiming at reducing the interface reflection of a fused silica mask of NFH at a wavelength of 441.6 nm and incidence angles of either 0º or 32º. First, we will compare the difference of antireflection property of one-dimensional (1D) and two-dimensional (2D) subwavelength structures with line density of 3600 lines/mm by simulation. Then, the optimized 1D and 2D subwavelength structures with 3600 lines/mm will be fabricated by using EBL-NFH method. Finally, the antireflection property of these 1D and 2D subwavelength structures will be characterized at the wavelength of 441.6 nm.

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10022-29, Session 6

Fabrication of grating-Fresnel (G-Fresnel) lens by using PDMS based on soft lithography

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Fabrication of a type of hybrid plane optics, Grating-Fresnel (G-Fresnel) lens, is presented in this research. A polydimethylsiloxane (PDMS) based soft lithography technology is employed. PDMS is poured onto the surface of a Fresnel lens and a negative Fresnel mold is formed after its being cured for two hours at a temperature of 65?. The formed Fresnel lens mold is peeled off and an anti-adhesion treatment for the Fresnel surface is performed. Then the PDMS is sandwiched between the negative Fresnel mold and a grating. After curing the sandwiched PDMS at 65? for two hours, the Fresnel mold and the grating are removed and a transmission-type Grating-Fresnel lens is obtained. Optimization of the Grating-Fresnel lens is primarily conducted. Two different surface treatment methods have been proposed to solve the innate adhesion of PDMS layers during PDMS double casting (PDMS-DC) technique. A fabrication system is constructed and G-Fresnel with grating line spacing of 1.67 ?m (600g/mm) and Fresnel lens with a diameter of 25.4 mm and a focal length of 25 mm was successfully fabricated. Three-dimensional surface profilometry has been performed to examine the device quality. Measured results show that replicas remain high fidelity to its primary master mold. A miniature spectrometer system was constructed to evaluate the performances of this fabricated G-Fresnel lens. Experimental results verified the grating fabrication method is effective and it can provide comparable resolutions with the spectrometer using concave grating.

10022-30, Session 6

Electro-optically and all-optically addressed spatial light modulators based on organic-inorganic hybrid structures

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Two types of organic-inorganic hybrid structures: electro-optically controlled and all optically controlled, that can be used as optically addressed spatial light modulator devices, operating with fast temporal response, high spatial resolution and in wide spectral range are presented and their functionality demonstrated. Both devices are assembled by doped inorganic Bi12SiO20 (BSO) crystals (characterized with excellent photoconductivity and photorefractivity) and strong birefringence of organic liquid crystal (LC), optimized with selected nanoparticles addition.

The operation principle of electro-optically controlled device relays on electro-optical control of LC birefringence that allows spatial modulation of the amplitude or the phase of the incident beam. Supported by graphene –based electrodes, the proposed device operates at low driving voltages, high contrast ratio and response time of about 100 ms. By projecting a video image through the device a modulation of the pump light intensity is demonstrated with the frame rate of 4.5 frames/sec.

Operation principle of all optically controlled device is based on a surface activated photorefractive effect, photoinduced in an inorganic substrate, acting as a driving force for LC re-alignment and refractive index modulation. Such configuration is simple and easy to fabricate, without need of conductive layers, alignment layers and polarizers -all the processes are controlled by light. Moreover, all optically controlled device operates at Bragg matched regime of diffraction, where sub-micron spatial resolution can be achieved.

Image patterns, optically addressed on the proposed organic-inorganic hybrid structures reveal the spatial light modulation ability and open future potentials for 3D display applications and image processing.

10022-31, Session 6

Polarization holography written by elliptically-polarized wave at a large cross

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Conventional hologram records information by varying the amplitude and phase. While Polarization holography employs waves with two different polarization state. In this case, information of amplitude, phase and polarization state are recorded on the polarization-sensitive materials. Here, we apply the new tensor theory which expresses the response of a polarization hologram as the tensor product or dyadic product to present the process of polarization holography. It breaches the limit of small cross angle and can be applied to any arbitrary forms of waves.

In the research of the new tensor theory, we have found some phenomena. For example, when linearly polarized waves are used for recording and reconstruction, faithful reconstruction and orthogonal reconstruction can be realized by the illumination of the original and orthogonal reference wave. In the case of circularly polarized wave, we can also observe the phenomena of faithful reconstruction and orthogonal reconstruction. In this paper, we derive the elliptical polarization holography theoretically to illustrate that both linear and circular polarization holography are the particular cases of elliptical polarization holography. Elliptical polarization holography is a more general case that can be applied to various conditions.

10022-32, Session 6

Realization of arbitrary full Poincaré beams on the hybrid Poincaré sphere

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The full Poincaré beam is a kind of beam whose polarization distribution in its transverse plane covers all possible polarization states in the traditional Poincaré sphere. We propose that the full Poincaré beam with any polarization geometries can be pictorially described by a hybrid Poincaré sphere whose eigenstates are defined as a fundamental-mode Gaussian beam and a Laguerre-Gaussian beam. We further establish a robust and efficient experimental setup to generate any desired full Poincaré beam on the hybrid Poincaré sphere, via modulating the incident polarization state of light. Although the polarization geometry of the FPB will change upon propagation owing to its intrinsic Gouy phase, we can employ two cascaded half-wave plates to compensate the Gouy phase and obtain a desired full Poincaré beam in a given propagation distance. Our research provides an alternative way for describing and manipulating the full Poincaré beam and an effective method to control the polarization state of light and study the polarization singularities of light.

10022-33, Session 6

Analysis of complex modulation with layered spatial light modulators

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A holographic three-dimensional (3D) display in complex modulation is the ideal 3D display. When observing the hologram, 3D display makes a great 3D images and complex modulation shows clearly and accurately. Method that we used to configure the complex modulation is a multi-layered SLM(Spatial light modulator). One method using cascaded amplitude and phase only SLM and another way is multi-layered double phase SLM. This system has the advantage of improving the disadvantages of the conventional SLM. However, there are advantages and disadvantages with each method. Thus, in this paper, we will analyze the characteristics of the complex modulation and presents the expected effects of the respective methods.

10022-34, Session 7

Interference pattern period measurement at picometer level *(Invited Paper)*

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To produce large scale gratings by Scanning Beam Interference Lithography (SBIL), a light spot containing grating pattern is generated by two beams interfering, and a scanning stage is used to drive the substrate moving under the light spot. In order to locate the stage at the proper exposure positions, the period of the Interference pattern must be measured accurately.

We developed a set of process to obtain the period value of two interfering beams at picometer level. The process includes data acquisition and data analysis. The data is received from a photodiode and a laser interferometer with sub-nanometer resolution. Data analysis differs from conventional analyzing methods like counting wave peaks or using Fourier transform to get the signal period, after a preprocess of filtering and envelope removing, the mean square error is calculated between the received signal and ideal sinusoid waves to find the best-fit frequency, thus an accuracy period value is acquired, this method has a low sensitivity to amplitude noise and a high resolution of frequency.

With 405nm laser beams interfering, a pattern period value around 632nm is acquired by employing this process, fitting diagram of the result shows the accuracy of the period value reaches picometer level, which is much higher than the results of conventional methods.

10022-35, Session 7

Effect of optical surface flatness performance on spatial-light-modulator-based imaging system

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The spatial light modulator (SLM) plays more and more important roles in variety of imaging applications. SLM can be used for beam shape modification, aberration correction, image edge enhancement, three-dimension display and so on. However, when the SLM is used as an optical phase modulator in some of practical imaging applications such as fluorescence adaptive super-resolution microscopy, the imaging performance of the

system could be affected by the flatness of the optical surface of SLM. Large amount of optical aberrations will be introduced while the peak to valley (PV) value of the optical surface of SLM is more than, for example, 10 percent of the wavelength of the illumination light. Thus the point spread functions (PSF) of the imaging system will be degrade and further decrease the resolution and signal to noise ratio of the system. In this paper, we present a method for detecting and correcting the optical aberrations is introduced by the optical surface flatness of SLM. The aberrations are measured by capturing the hologram of the SLM surface using the modified Mach-Zehnder interferometer. The aberrations information is extracted directly from the phase of the reconstructed image of the hologram. Then the conjugated phase is displayed on the SLM to correct the aberration. The imaging results show the resolution and signal to noise ratio of the system have been improvement by using the proposed aberration detection and correction method. The effect of SLM optical surface flatness on imaging characteristics are evaluated quantitatively.

10022-36, Session 7

High-density grating pair for displacement measurement

Changcheng Xiang, Changhe Zhou, Shubin Li, Zhumei Sun, Shanghai Institute of Optics and Fine Mechanics (China)

A novel structure consisting of a high density grating pair for displacement measurement is proposed. When a laser beam is incident normal to the closely placed high density grating pair, efficiencies of transmission diffraction orders will change periodically along with the relative displacement of the two gratings in the grating period direction. The period of efficiency change is due to the grating period, thus measurement of displacement in the grating period direction can be accomplished by detecting the power of diffraction orders. Unrelated to interference of optical waves, this measurement is not sensitive to the environment fluctuation. Simplified modal method, describing the diffraction progress with the propagation of several grating modes, gives simple and clear expressions to predict diffraction efficiencies of the gratings. With simplified modal method, the grating pair has been designed to be suitable for application. Rigorous coupled wave analysis is also applied to calculate the periodic efficiency change of the designed grating pair structure to verify the design result obtained by simplified modal method.

10022-37, Session 7

Image grating metrology based on phase-stepping interferometry in scanning beam interference lithography

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Large-sized gratings are essential optical elements in laser fusion and space astronomy facilities. Scanning beam interference lithography is an effective method to fabricate large-sized gratings. To minimize the nonlinear phase written into the photoresist, the image grating must be measured to adjust the left and right beams to interfere in the waist. In this paper, we propose a new method to conduct wavefront metrology based on phase-stepping interferometry. Firstly, a transmission phase grating is used to combine the two beams to form an interferogram which is recorded by a charge coupled device(CCD). Phase steps are introduced by moving the grating with a linear stage monitored by a laser interferometer. A series of interferograms are recorded as the displacement is measured by the laser interferometer. Secondly, to eliminate the tilt and piston error during the phase stepping, the iterative least square phase shift method is implemented to obtain the wrapped phase. Thirdly, we use the discrete cosine transform least square method to unwrap the phase map. Experiment results indicate that the measured wavefront has a nonlinear phase around 0.05@404.7nm. Finally, as the image grating is acquired, we simulate the print-error written into the photoresist.

10022-38, Session 7

Research on a grating interferometer with high optical subdivision based on quasi-Littrow configuration

Jili Deng, Changhe Zhou, Shanghai Institute of Optics and Fine Mechanics (China) and Shanghai Univ. (China); Xiaona Yan, Shanghai Univ. (China); Chunlong Wei, Yancong Lu, Shanghai Institute of Optics and Fine Mechanics (China)

Grating interferometers are widely used in the nanometer displacement measurement. Compared with displacement laser interferometers, the grating interferometers are less sensitivity to the environment, including air turbulence, pressure, and humidity. Because their measuring scale is grating period, which is more stable than wavelength in practical measurement. However, the resolution of grating interferometers is usually lower than the laser interferometer. Therefore, in order to improve the resolution and accuracy of grating interferometer, further study is needed. As we known, the measuring resolution is determined by the electronic subdivision and optical subdivision. In this paper, in order to improve the optical subdivision, we present a grating interferometer based on the quasi-Littrow configuration. We mainly use the plane mirrors to make the measuring lights reflect and diffract between the mirror and grating scale for many times. According to the grating Doppler shift, the more times that measuring light diffracted by the grating scale, the higher optical subdivision can be obtained. In theory, this kind of grating interferometer allows to increase the subdivision infinitely. But it will be limited by the physical size and diffraction efficiency of the grating scale in reality. Fortunately, the use of quasi-Littrow configuration is very helpful to design and fabricate a grating scale with high diffraction efficiency. As an example, a grating interferometer with an optical subdivision factor of 1/16 is designed. And the influence of grating motion error is also analyzed. This work provides a technique to increase the resolution and accuracy of the grating interferometer, which should be interesting for high precision measurement.

10022-39, Session 7

Study of a grating interferometer with high optical subdivision techniques

Yancong Lu, Changhe Zhou, Shubin Li, Chunlong Wei, Minkang Li, Xiansong Xiang, Jili Deng, Changcheng Xiang, Wei Jia, Junjie Yu, Jin Wang, Chao Li, Shanghai Institute of Optics and Fine Mechanics (China) and Univ. of Chinese Academy of Sciences (China)

Displacement laser interferometers and grating interferometers are two main apparatus for the micron-nanometer displacement measurement over a long range. However, the laser interferometers, which are based on the wavelength, are

very sensitive to the environment. On the contrast, the grating interferometers change the measuring scale from wavelength to grating period, which is much stable for the measurement results. But the resolution of grating interferometer is usually lower than that of laser interferometer. Therefore, further investigation is needed to improve the performance of grating interferometer. As we known, the optical subdivision is a main factor that affects the measurement resolution. In this paper, a grating interferometer with high optical subdivision is presented based on the Littrow configuration. We mainly use right angle prisms accompanied with plane mirrors to make the measuring lights diffracted by the grating scale for many times. An optical subdivision factor of 1/32 can be obtained by this technique. A smaller optical subdivision factor can also be obtained, which is only limited by the size and the diffraction efficiency of the grating scale. Fortunately, the grating scale can be designed with very high efficiency due to the Littrow configuration, which is very helpful to increase the optical subdivision. Additionally, the influence on the measurement results that caused by motion errors of grating scale is also analyzed. Compared with traditional grating interferometers, this kind of grating interferometer can greatly increase the measuring resolution and accuracy, which could be widely used in nanometer-scale fabrications and measurements.

10022-40, Session 8

design and analysis of highly efficient reflective 1*3 splitting grating with triangular structure

Jin Wang, Changhe Zhou, Jianyong Ma, Yonghong Zong, Wei Jia, Yancong Lu, Shanghai Institute of Optics and Fine Mechanics (China)

A highly efficient reflective 1*3 splitting grating with triangular structure operating in 1.064?m wavelength under normal incidence for TE polarization is designed. These subwavelength gratings can be used as important optical elements in inertial confinement fusion (ICF). For applications in high power laser systems, an important requirement for the reflective gratings is high efficiency. The schematic of the grating with four layers: SiO2, Au, Cr and SiO2 substrate. The first layer with SiO2 is triangular structure. This highly efficient triangular grating is designed by the vector theory. Rigorous coupled wave analysis (RCWA) and Simulated Annealing (SA) algorithm are adopted to design and analyze the properties. The period and depth are 1320nm and 350nm respectively. The theoretical efficiency is nearly about 99%, which is much bigger than the efficiency of traditional Dammann grating. The deviation of profile could also influence the efficiency of the 1*3 splitting grating. The error tolerance is analyzed by rigorous coupled wave analysis, too. This structure has bigger tolerance, which is convenient for fabrication. These reflective gratings as splitters should be useful optical elements in the field of high-power laser as well as other reflective applications.

10022-41, Session 8

Imaging performance tests of diffractive optical system

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Diffractive optical imaging is a new method to realize high-resolution imaging from geostationary orbit(GEO). Technical advantages of diffractive optical imaging is analyzed in the field of space optics. For application of super large diameter space optical system, the system scheme and a new achromatic method is proposed. An imaging system is developed and tested, the result of optical system wavefront is 0.169?(RMS), optical system MTF is 0.85, and the imaging system MTF is 0.19. Test results show the new achromatic method is feasible. The above conclusions have reference significance for development of super large diameter diffractive optical imaging system.

10022-42, Session 8

High beam quality spectral beam combined diode laser array

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The 2.4 W spectral combined beam of a 19-element 940nm diode laser array has been demonstrated in our experiment, and the efficiency of beam combining was 87% from free running laser bar. The outputs have been combined into a single beam with a diffraction-limited beam quality in the fast axis and M2< 20 in the slow axis. For high power diode lasers, beam quality was required in a variety of the applications, such as material processing and pumping of fiber and solid-state lasers. Spectral beam combining (SBC) technology has been proved to be a solution to scale the output power while maintaining the beam quality of a single element. In the experiment, the laser bar consisted of 19 elements spaced at a 500 ?m pitch, each element was 100 ?m wide. The array was high-reflection coated on the back facet and anti-reflection coated on the front facet, with a front facet reflectivity of <0.5%. The beam combining was based on an external cavity structure formed between the back facet of the laser array and the output coupler. All the elements were focused on a transmission grating by a cylindrical transform lens, and the grating dispersed beams at a same direction, so all the elements were spatially overlapped at the output coupler. The grating was 1410 lines/mm with 80% efficiency in -1st order. Because of the oscillation in the external cavity, the combining efficiency could be higher than the grating efficiency, and even higher than 100%. Each emitter received its own feedback from the output coupler. This forced every element to lase at a different wavelength, while the intensity was enhanced with the spectral beams.

10022-43, Session 8

Facial skin color measurement based on camera colorimetric characterization

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Color plays an important part in our visual system, the same is true for Machine Vision system. When we observe human being, his or her face attracts most attention, especially the color of the facial skin. Much information can be obtained from the color appearance of human face, such as race, age, health and so forth. As human visual system is sensitive to small color changes, hence, a subtle change in facial skin structure will result in noticeable color difference to human. Therefore it is of great importance to make a relatively objective measurement of facial skin color as well as the color difference of the same face at different status.

In this paper, a simple but novel approach to measure the color of facial skin was proposed. A new Skin Tone Color Checker made of Pantone Skin Tone was designed to correct the color variance caused by the different spectral sensitivity of cameras. Then a standard color target taken in the same illumination environment as human face to characterize the camera so as to get a prior knowledge about how camera records color information. A facial

color measurement procedure was developed in consideration of several previous algorithms, which is specially designed considering the measurement purpose and experiment condition. Finally, we compared the results obtained by our procedure with these by spectrophotometer, and the validity as well as the accuracy of our algorithm was verified.

10022-45, Session 8

Recent progress in holographic wavefront sensing

Sergey B. Odinokov, Bauman Moscow State Technical Univ. (Russian Federation); Vladimir Y. Venediktov, Saint Petersburg Electrotechnical Univ. "LETI" (Russian Federation)

Many areas of optical science and technology require fast and accurate measurement of the radiation wavefront shape. Today there are known a lot of wavefront sensor (WFS) techniques, and their number is growing up. The last years have brought a growing interest in several schematics of WFS, employing the holography principles and holographic optical elements (HOE). Some of these devices are just the improved versions of the standard and most popular Shack-Hartman WFS, while other are based on the intrinsic features of HOE. These are, for instance the modal holographic WFS configurations and some others. The paper presents the review of such techniques and the drawbacks of the demonstrated holographic WFS. Our studies have shown that it reasonable and promising to shift the holographic WFS design methods from the use of traditional analogous holograms to the digital holography, employing the Fourier holography technique. In the paper we describe the reasons for such shift and demonstrate the results of numerical simulation and experimental verification of such an approach.

10022-46, Session 8

Support subspaces construction applied to object recognition using SAR images

Denis A. Zherdev, Samara Univ. (Russian Federation); Vladimir A. Fursov, Samara Univ. (Russian Federation) and Russian Academy of Sciences Image Processing Systems Institute (Russian Federation)

There are growing interest in using SAR images for object detection and recognition. It can be explained by the low sensitivity of observed data related to cloud cover, which restricts the use of visible, near-infrared and radar satellite data. For example, DARPA made a SAR images dataset (MSTAR) of ground targets for experiments in object recognition. It is formed by airborne radar in spotlight mode with a resolution of 0.3 m ? 0.3 m with HH polarisation.

The main problem in SAR image recognition consists of depending on change of obtained object pose, an object shape, electromagnetic ground plane properties and etc. Therefore, a central problem is in developing a method and an algorithm with less sensitivity to the changing pose of an obtained object. In this work, we suggest and examine an automatic algorithm for image preparation and object recognition method based on using of conjugation indices. The proposed recognition method also can be applied to recognition of different kind of data.

The development of ideas presented in [1,2] is continued in this study. In the study, we extend our support plane method to case of support subspaces, which have sizes higher than two vectors.

[1] Denis A. Zherdev, Vladimir A. Fursov, "Pattern recognition of electromagnetic field scattering from anthropogenic objects on underlying surface" Proc. SPIE 9216, Optics and Photonics for Information Processing VIII, 92160Z, 2014; doi:10.1117/12.2061354.

[2] Denis A. Zherdev, Vladimir A. Fursov, "Support plane method applied to ground objects recognition using modelled SAR images" Proc. SPIE 9599, Applications of Digital Image Processing XXXVIII, 95992J, 2015; doi: 10.1117/12.2188531.

10022-48, Session 9

Phase problems in optical imaging and laser display *(Invited Paper)*

Guohai Situ, Wei Wang, Shanghai Institute of Optics and Fine Mechanics (China)

It is well known that the phase contains more important information about the field in comparison with the amplitude. Therefore the imaging of phase is encountered in many branches of modern science and engineering. Direct measurement of the phase is difficult in the short regime such as the visible light due to the limited bandwidth of imaging sensors. One must employ computational techniques to extract the phase from the captured intensity. In this talk, we will discuss the phase problems encountered mainly in optical imaging and laser display. In particular, we will talk about our previous works on iterative phase retrieval techniques, and how they can be used to improve imaging performance such as resolution and signal-to-noise ratio.

10022-49, Session 9

Zoomable three-dimensional computer-generated holographic display based on shifted Fresnel diffraction

Hao Zhang, Liangcai Cao, Guofan Jin, Tsinghua Univ. (China)

Holographic three-dimensional (3-D) display has the potential to provide all the depth cues that human eyes can perceive since it can reconstruct the whole optical wavefront of the 3-D scene. With the developments of spatial light modulators (SLMs) and computer-generated holograms (CGHs), both real and virtual 3-D scenes can be reconstructed dynamically without the complicated interference recording systems. Layer-based approaches can accelerate the CGH computing speed by slicing the 3-D scene into a group of parallel layers according to its depth map while maintaining the depth information. Fast Fourier transform (FFT) can be implemented in the wave propagation simulation between the parallel planes. However, the current layer-based 3-D CGH algorithms suffer from the sampling restrictions in the wave propagation simulations between the sliced layers and the hologram plane. In this study, we use layer-based shifted Fresnel diffraction to simulate the wave propagation from the sliced layers to the hologram plane with adjustable sampling rates. Shifted Fresnel diffraction can simulate wave propagation between parallel planes with flexible sampling rule. By introducing shifted Fresnel diffraction into layer-based 3-D CGH calculation, the holographic display system can zoom the 3-D images without the optical zoom module. The resolutions of reconstructed 3-D images can be adjusted accordingly. Optical experiments are performed with the help of a phase-only SLM based holographic display system. The reconstruction results demonstrate the effectiveness of our proposed method.

10022-50, Session 9

Wave optic modeling of moire patterns on curved surfaces and line-defect removal in the fast-Fourier transform

Jeon Youngjin, Hwi Kim, Korea Univ. (Korea, Republic of)

When display products manufactured, several functional display panels are integrated. These combination of panels cause unexpected optical problems. Moiré phenomenon is one of representative issues in the display manufacturing. In this presentation, we simulate the moiré pattern through mathematical model based on computational wave optic theory. Two curved surfaces those have different pattern are integrated and consist of synthesis of polygons. We observe these panels by changing the location of the observation. This simulation can calculate the light field distribution of the deformed polygons. Also, it is found that line-defects appear when we calculate the polygon computer-generated hologram(CGH) by the fast Fourier transform. When we calculate the angular spectrum CGH of polygon by the analytic method that based on formula, the exact angular spectrum of polygon facets can be obtained. However, when we use numerical method that based on fast Fourier transform, the discrete approximation of the continuous angular spectrum integral induces some numerical errors. Therefore, to solve this problem, we propose a partial filtering method of the phase-mismatched angular spectrum components of the polygon object, where the phase-mismatched partial angular spectrum components of the borders of the two adjacent triangular facets is selectively filtered that should be removed when the two adjacent triangular is connected.

10022-51, Session 9

Design of computer-generated hologram apertures with the Abbe transform

Yunlong Sheng, Jing Wang, Univ. Laval (Canada)

The computer generated hologram (CGH) contains a very large number of pixels, thanks to the modern fabrication technology such as the e-beam lithography. According to the Abbe transform, the basic diffraction elements in a binary phase CGH are the edges in the apertures, which act as an infinitely narrow slit, sending a light fan in the direction perpendicular to the edge with the fan width inversely proportional to the edge length. The diffraction pattern of the CGH is then a coherent summation of all the light fans from all the edges of different orientations and lengths in the arbitrary-shaped apertures of the binary phase CGH. For the arbitrary-shaped polygonal apertures with straight edges, the diffraction pattern is computed by analytical formula of the Abbe transform whose computation time is independent of the size of the apertures. We propose to directly design the arbitrary-shaped polygonal apertures in the CGH with arbitrary shaped triangular and quadrilateral apertures, and perform a global optimization of the CGH using the Genetic Algorithm with local search, followed by an optimization of floating co-vertices of the elementary apertures. The experiments result in high performance holograms with very low reconstruction error of 2 % for a grayscale image.

10022-52, Session 9

Recent progress on fully analytic mesh based computer-generated holography *(Invited Paper)*

Jae-Hyeung Park, Inha Univ (Korea, Republic of)

Computer generated holography plays a main role in the contents generation for holographic displays and digital archiving of three-dimensional objects. The fully analytic mesh based computer generated holography finds exact complex optical field for each triangular mesh of the three-dimensional objects for given sampling interval in the hologram plane without any approximation, enhancing the quality of the reconstruction. The mesh based processing rather than conventional point based one makes it compatible with most computer graphics techniques and efficient especially for large objects. In this talk, we present a few recent progress on fully analytic mesh based computer generated holography techniques.

The first topic covered in the talk is efficient implementation of the angular reflectance distribution of the object surface. The angular reflectance distribution is important as it reveals surface property of the object. In conventional methods, it has been realized by finding phase distribution on each mesh surface. However, the phase distribution is obtained in discrete form in the local plane of the mesh, and thus the fully analytic nature is deteriorated, lowering the reconstruction quality. In this talk, we present a method that uses convolution in the hologram plane, which is efficient in calculation and maintains the advantages of the fully analytic process.

The second topic is the efficient implementation of the texture map to the object surface. The texture map is the amplitude distribution over the object surface which is frequently used in computer graphics for realistic representation. We present an adaptive mesh division method to apply the texture map to the computer generated holography without significant increase of the computational load.

10022-106, Session 9

Review on holographic display and future research trade *(Invited Paper)*

Juan Liu, Beijing Institute of Technology (China)

Providing all depth cues for human eyes without eyewear devices, holographic display becomes one of the most promising display technologies and is widely studied. However, there are still many bottlenecks limiting the applications of holographic display. Here, we review our mainly investigation on the fast calculation of computer generated holograms (CGHs), the improvement of display image quality and other aspects.

To realize dynamic and real-time interactive holographic display, the CGHs should be acquired with high speed; while, the huge amount of data in three dimensional (3D) scene slows down the calculation. The improved look-up table methods are employing to improve the calculating speed for the point source method, where the tables size are compressed. Polygon-based methods with affine transformation are proposed. Furthermore, the development of parallel calculation platforms can realize the acceleration effectively. Moreover, the CGH data storage is also optimized to achieve effective CGHs calculation and transmission.

There are many ways to improve the display image quality, and several algorithms are presented to render the color 3D scene, where the spatial light modulators (SLMs) are the most common optoelectronic devices, especially the phase-only liquid crystal (LC) devices. However, the pixelated SLMs have caused many disadvantages. For overcoming the limitation of LC SLM, the assistant optical systems and devices are introduced to eliminate the noise, widen the viewing angle, and enlarge the image size. Different kinds of modulator are studied as well, including photo-reduced graphene oxides elements, meta-surface, and quantum dots material device to improve the display properties.

In summary, it is not only the algorithms, but also the systems to be improved for the holographic display. The calculation speed is accelerated, the CGH data storage amount is reduced, the display effect is improved such as scene rendering, noise elimination, color display, viewing angle, image size, as well as the

novel micro-/nano- modulators etc. Though there are still issues stunting the development, with the further study on optics and other fields, it is believed that the real-time full-color holographic display with high image quality and excellent visual experience will be realized and applied in daily life in the near future.

10022-53, Session 10

New explanation for the Talbot effect: simplified modal method

Shubin Li, Changhe Zhou, Yancong Lu, Shanghai Institute of Optics and Fine Mechanics (China)

Talbot effect, a classical optical phenomenon, was firstly found in 1831. Talbot effect has wide applications in modern optical systems, especially the Talbot effect of a grating. When the grating period is larger than the wavelength, the Talbot effect is polarization-independent and we can use the scalar optics theory to simulate the Talbot effect. When the grating period is close to the wavelength, the Talbot effect is polarization dependent generally. However, the polarization-independent Talbot effect is also existing when the diffraction efficiencies and phase meet some conditions for a high-density grating. We can use the simplified modal method to illustrate the Talbot effect of a high-density grating, which is a physical method and can offer us much physical insight about the diffraction process. Based on this simple method, we will give a new explanation of the Talbot effect. We hope this theoretical work can boost the practical applications of Talbot effect.

10022-54, Session 10

Design and analysis of broadband diffractive optical element for chromatic aberration correction

ShaoQing Wang, Changhe Zhou, Shanghai Institute of Optics and Fine Mechanics (China)

A modified direct binary search (MDBS) algorithm is proposed to design the broadband diffractive optical element (DOE) for chromatic aberration correction. To speed up the diffracted field computation, the search tragedy of DOE's groove heights is special optimized. To analyze the DOE's broadband focusing ability, these focuses of FdC wavelengths are simulated by using field tracing method, and the achromaticity of the DOE is also quantified by comparing each wavelength's PSF to the reference wavelength's PSF. Moreover, the DOE's profile is also exported to user-defined surface to analyze the geometric and RMS focus in commercial optical design software. As we all known, DOE's fabrication errors play an important role on SNR and diffractive efficiency, the tolerances of fabrication errors of DOE are numerically studied by adding random errors and usual fabrication errors. In real application, low SNR means that too much noise light are diffracted, which may form disastrous ghost spot or ghost line. In order to improve the DOE's SNR, the whole DOE is divided to several sub-apertures, and each sub-aperture's micro-structure is designed by MDBS separately. Numerical results show that by this mean the SNR can be increased, because statistically it's low probability that all sub-aperture's noise light emitted to the same target zone that results unexpected ghost spot or ghost line. The impact of oblique light is also simulated and chromatic aberration degrades significantly. Summarily, besides small focus size, results also show that the design offers polarization insensitive, error tolerant, high SNR, and great design flexibility.

10022-55, Session 10

Multi-modal computational microscopy with programmable illumination and coded aperture *(Invited Paper)*

Chao Zuo, Nanjing Univ. of Science and Technology (China)

Computational microscopy is an emerging technology which extends the capabilities of optical microscopy with the combination of optical coding and computational decoding. It provides us with novel imaging functionalities or improved imaging performance which are diffcult or impossible to achieve using a conventional microscopic system. Recent advance in LED lighting and digital display technology provide new opportunities for active digital illumination and imaging control for advancing microscopy. In this paper, we report our most recent developments of computational microscopy with programmable illumination and coded aperture. We describe several new approaches for achieving multi-modal computational imaging, including contrast-enhancement imaging, quantitative phase imaging, light field imaging, and lens-less tomographic imaging, with use of a programmable LED array or a programmable LCD panel.

10022-56, Session 10

Photorefractive and computational holography in the experimental generation of single arrays and superposition of nondiffracting beams

Marcos R. R. Gesualdi, Rafael A. B. Suarez, Indira S. V. Yepes, Tárcio de Almeida Vieira, UFABC (Brazil); Michel Zamboni-Rached, Univ. Estadual de Campinas (Brazil)

This work presents the optical generation of nondiffracting beams via computational holography and, for the first time, via photorefractive holography. Optical generation of nondiffracting beams using conventional optics components is difficult and, in some instances, unfeasible, as it is wave fields given by superposition of nondiffracting beams. It is known that computational holography and computer generated holograms implemented in spatial light modulators (SLMs) successfully generate such beams. With photorefractive holography technique, the hologram of a nondiffracting beam is constructed (recorded) and reconstructed (reading) optically in a nonlinear photorefractive medium. The experimental realization of nondiffracting beam was made in a photorefractive holography setup using a photorefractive silenite crystal (BSO/BTO) as holographic recording medium, where the nondiffracting beams (Bessel, Airy, Mathieu and Parabolic), the nondiffracting beam arrays and superposition of co-propagating nondiffracting beams were obtained experimentally. The experimental results are in agreement with the theoretically predicted presenting excellent prospects for implementation of this technique for dynamical systems at applications in optics and photonics.

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10023-1, Session 1

Precision measurement technology based on femtosecond frequency comb *(Invited Paper)*

Weihu Zhou, Academy of Opto-Electronics, CAS (China)

In the past decade, remarkable advance associated with measurement technology of frequency comb have been acquired owing to rapid development of femtosecond frequency comb. The frequency comb can produce millions of sharp laser lines in a precise evenly spaced grid spanning much of the visible and near infrared spectrum. It has been widely used in optical metrology, such as absolute distance measurement, frequency or wavelength metrology and surface measurement. It also can be used for spectrograph measurement, frequency synthesis and attosecond pulse generation because of its excellent characteristic in time and frequency domain. This paper will focus on absolute distance measurement technology based on optical frequency comb. Several kinds of absolute distance measurement methods with femtosecond frequency comb will be discussed. Meanwhile, applications of optical frequency comb in time and frequency transfer, surface tomography measurement will be introduced.

10023-3, Session 1

Software system design for the non-null digital Moiré interferometer

Meng Chen, Qun Hao, Yao Hu, Shaopu Wang, Tengfei Li, Lin Li, Beijing Institute of Technology (China)

Aspheric optical components are an indispensable part of modern optics systems. With the constant development of aspheric optical fabrication technique, high-precision figure error testing method of the aspheric surfaces is a quite urgent issue now. We proposed a digital Moiré interferometer technique (DMIT) based on partial compensation principle for aspheric and freeform measurement. Different from traditional interferometer, DMIT consists of a real and a virtual interferometer. The virtual interferometer is simulated with Zemax software to perform phase-shifting and alignment. We can get the results by a series of calculation with the real interferogram and virtual interferograms generated by computer. DMIT requires a specific, reliable software system to ensure its normal work. Image acquisition and data processing are two important parts in this system. And it is also a challenge to realize the connection between the real and virtual interferometer. In this paper, we present a software system design for DMIT with friendly user interface and robust data processing features, enabling us to acquire the figure error of the measured asphere. We choose Visual C++ as the software development platform and control the ideal interferometer by using hybrid programming with ZEMAX. After image acquisition and data transmission, the system calls image processing algorithms written with MATLAB to calculate the figure error of the measured asphere. Finally, we test the software system experimentally. In the experiment, we realize the measurement of an aspheric surface and prove the feasibility of the software system.

10023-4, Session 1

FPGA-based real-time phase measuring profilometry algorithm design and implementation

Guomin Zhan, Hongwei Tang, Zhongwei Li, Kai Zhong, Huazhong Univ. of Science and Technology (China)

Phase measuring profilometry (PMP) has been widely used in many fields. However, the instruction time delay in the computer caused by numerous repetitive operations greatly limit the efficiency of data processing. To solve this problem, we have proposed a method of PMP system based on FPGA with the advantages of pipeline architecture and parallel execution. In this paper, we design a fully pipelined hardware architecture for PMP. The entire hardware system on the basis of multi-frequency heterodyne principle includes rectification, phase calculation, phase shifting, stereo matching and triangulation. Finally, we analysis experiment results and the factors which may influence results. The results show that the measurement speed and accuracy can meet the desired requirements.

10023-5, Session 1

Elongation measurement using one-dimensional image correlation method

Phachara Phongwisit, Prathan Buranasiri, King Mongkut's Institute of Technology Ladkrabang (Thailand)

Aim of this paper was to study, setup, and calibrate an elongation measurement by using 1- Dimensional Image Correlation method (1-DIC). To confirm our method and setup correctness, calibration with other method is required. In this paper, we used a small spring as a sample to find a result in terms of spring constant. With a fundamental of Image Correlation method, an image of formed and deformed sample were compared to understand the difference between deformed process. By comparing the location of reference point on both image's pixel and calculate result in term of elongation. After that, elongate and force on samples were compared to find a spring constant in the same way as Hook's law. The results from 1-Dimensional Image Correlation and Hook's law were different by 5 percent. This method can be applied to measure the elongation of a small fiber samples more variously.

10023-6, Session 1

A vision weight method of billet based on linear structure laser

Fengshan Huang, Yusong Ren, Li Chen, Hebei Univ. of Science and Technology (China)

In order to upgrade the cut-by-length technology of billet to cut-by-weight, a real-time accumulation vision weight method of billet based on linear structured laser was proposed, and its principle, measurement model and weighing process were studied. According to the vision measurement principle of linear structure laser, the current cross section area of billet was measured and calculated by two vision sensors. Meanwhile, the distance between the current cross section and the previous one was acquired by another vision sensor, and the billet weight between two adjacent cross sections was calculated and accumulated. Thus, the billet weight passing the measuring

position was monitored real-timely, and the real-time weight-cut control of billet was realized. The experimental system was set up and the weight experiment was carried out with rectangular solid steel. Experimental results show that the relative error of weight is1‰, which is far less than 8‰ used in present production enterprises. This research provides a theoretical reference for the realization of billet cut-by-weight technology.

10023-7, Session 1

Spindle error motion measurement using concentric circle grating and sinusoidal frequency-modulated semiconductor lasers

Masato Higuchi, Masato Aketagawa, Thanh Vu, Nagaoka Univ. of Technology (Japan)

The conventional method of measuring the radial, axial and angular spindle motion is complicated and needs large spaces. Smaller instrument is better in terms of accurate and practical measurement. A method of measuring spindle error motion using a sinusoidal phase modulation and a concentric circle grating was described in the past. In the method, the concentric circle grating with fine pitch is attached to the spindle. Three optical sensors are fixed under grating and observe appropriate position of grating. The each optical sensor consists of a sinusoidal frequency modulated semiconductor laser as the light source, and two interferometers. One interferometer measures an axial spindle motion by detecting the interference fringe between reflected beam from fixed mirror and 0th-order diffracted beam. Another interferometer measures a radial spindle motion by detecting the interference fringe between ±2nd-order diffracted beams. With these optical sensors, 3 axial and 3 radial displacement of grating can be measured. From these measured displacements, axial, radial and angular spindle motions are calculated concurrently. In the previous experiment, concurrent measurement of 5 axis (1 axial, 2 radial and 2 angular) spindle motion at 4rpm was described. In this paper, concurrent measurement of the 5 axis spindle motion at 4000rpm would be described.

10023-8, Session 2

Phase-shifting interferometry and its applications *(Invited Paper)*

Shouhong Tang, Suzhou H&L Instruments LLC (China)

Phase shifting interferometry (PSI) is a highly effective method for measuring the optical path difference (OPD) between two reflective surfaces. It has been widely used in applications such as optical testing and surface profiling due to its outstanding nanometer accuracy and precision. As technologies, especially the digital hardware and software, have rapidly developed in recent years, the method has found its fresh applications that are hard to imagine before. For example, it is well accepted to measure the flatness, nanotopography, and thickness variation of wafers. This is because PSI is able to meet the measurement needs as the semiconductor industry progressing down the roadmap to smaller device geometries. The method has many significant advantages including rapid data acquisition, improving the measurement sensitivity, and increasing the measurement accuracy and precision. In this presentation we will give details about the principle of PSI, illustrate how to use it, and demonstrate its advantages with measurement results from our tools. We will also show the outcome of its applications in semiconductor industry.

10023-11, Session 2

Concentricity calibration of photogrammetry retro-reflector target

Hengzheng Wei, Wei Nong Wang, Limei Pei, Guoying Ren, National Institute of Metrology (China)

Digital Photogrammetry System is widely used in recent years due to its fully functional, accurate measurement, and non-contact portable feature. Especially it is suitable for large objects measurement. The measurement is usually carried out with a mobile retro-reflector target, which is consists of hemispheres and reflective signs fixed in the center of the hemisphere. When the center of the sphere and the center point of the reflectors do not overlap, it will introduce measurement error. Therefore, the concentricity of target is an important measurement parameter for the measurement result.

To achieve the concentricity of the target a multisensor coordinate measurement machine with imaging probe and contact probe is used. In this combined measurement system the contact probe measure the sphere center of the target, and image probing measure the center of reflective sign. An artifact is designed to evaluate the performance of combined system. This artifact is defined a sharp edged hole in a metal plate. It is suitable to measure with touch probe as well as imaging probe. First the touch probe measures 25 points on the hole and then with the imaging probe. With all the points measured by two kinds of probe the evaluation parameters including combination size error, form error and location error are calculated. These parameters are consistent with the ISO standard 10360-8. The results indicate that there is a big systematic offset between the two sensors. To make an improvement a data fusion method based on a transform with coordinates of hole centers is applied. It indicates that measurement uncertainty combined system is 5 microns which can meet the target calibration requirements.

10023-12, Session 2

Three-dimensional endoscopic measurement by uni-axis grating projection

Geliztle A. Parra Escamilla, Fumio Kobayashi, Yukitoshi Otani, Utsunomiya Univ. (Japan)

Three-dimensional endoscopic measurement can be archieved by an Uni-axis image guide fiber system to reconstruct the surface. The surface variation of the samples is retrieved by using fringe contrast modulation and the technique takes into account the defocus change and the encoding information on the fringe contrast of the projected structured light pattern. In the second part we implement a 2D Fourier Transform filter for remove the baseline information for increasing the fringes contrast and also we improved the fitting function for better results in the 3D reconstruction. Experimental results will be presented.

10023-13, Session 2

A field calibration method to eliminate the error caused by relative tilt on roll angle measurement

Jingya Qi, Xian Jiaotong Univ. (China); Zhao Wang, Junhui Huang, Xi'an Jiaotong Univ. (China); Bao Yu, Xi'an Jiaotong Univ. (China); Jianmin Gao, State Key Lab. for Manufacturing Systems Engineering (China)

The roll angle measurement method based on a heterodyne

interferometer is an efficient technique for its high precision and environmental noise immunity. The optical layout bases on a polarization-assisted conversion of the roll angle into an optical phase shift, read by a beam passing through the objective plate actuated by the roll rotation. The measurement sensitivity or the gain coefficient G is calibrated before. However, a relative tilt between the laser and objective plate always exist due to the tilt of the laser and the roll of the guide in the field long rail measurement. The relative tilt affect the value of G, thus result in the roll angle measurement error. In this paper, a method for field calibration of G is presented to eliminate the measurement error above. The field calibration layout turns the roll angle into an optical path difference (OPD) by a rotary table. Thus, the roll angle can be obtained from the OPD read by a conventional two-frequency interferometer. Together with the phase shift, an accurate G in field measurement can be obtained and the measurement error can be corrected. Besides that, we can also enhance the measurement sensitivity by optimizing the tilt of the objective plate based on the value of the measurement G. The optical system of the field calibration method is set up and the experiment results are given. Contrasted with the Renishaw XL-80 for calibration, the proposed field calibration method can obtain the accurate G in the field rail roll angle measurement.

10023-14, Session 2

The study of fast measurement hexahedron verticality error by wavefront interferometer

Peng Shijun, Songtao Gao, Wu Dongcheng, Erlong Miao, Changchun Institute of Optics, Fine Mechanics and Physics (China)

We present a method for measuring hexahedral adjacent sides of the vertical error by wavefront interferometer. The vertical error of hexahedral adjacent faces is obtained from comparing the hexahedral prism, which is placed on a stable three-point support tooling, with wavefront interferometer reference surface and using the least squares method. Firstly, the measurement system and measurement experimental procedure is introduced. Second, the method of least squares vertical evaluation method is described in detail and a lot of repeatability measurement experiments have done. Finally, the hexahedral adjacent sides of the vertical error are measured both by coordinate measurement machine and wavefront interferometer. The measurement results are basically the same, which proved the method of measuring the results credible. It is found that the measurement accuracy of the method is better than 0.5sec through analysis of measurement data. This method not only has high accuracy but also both sides of the adjacent vertical error distribution data can be obtained directly. And the vertical error distribution data can be used to guide hexahedral bit error in high precision machining modification.

10023-80, Session 2

Performance analysis of three-dimensional surface profilometry using a MEMS mirror

Yuxin Cheng, Sining Li, Guohang Shan, Harbin Institute of Technology (China)

Accurate 3D shape measurement has played an increasingly important role in various diverse industrial applications, such as manufacturing, robot vision etc. To achieve a low cost, compact 3D profiling system, a phase shifting scheme with a single MEMS scanner has been proposed and studied by some international colleagues. In this paper, we established a mathematical model for the 3D profiling system to reconstruct surface contour of the object. A data processing flow chart is designed, and the algorithm is developed correspondingly, in which some means to improve accuracy are also taken into consideration. Then, numerical simulation for the whole working processing of the profiling system is performed according to the theoretical model. The simulation results are analyzed in detail to get the optimal parameters. In order to verify the feasibility of the scheme, we build an experimental setup and carry out a series of experiments. The results show that the RMSE is about 6% and the range resolution is about a few millimeters.

10023-81, Session 2

Quadrant-division technique for differential sensitivity optical beam measurement

King Ung Hii, Swinburne Univ. of Technology, Sarawak (Malaysia)

Optical beams with high collimation degree are required in numerous optical applications such as metrology. The conventional approaches of adapting the double-pass and quadruple-pass configurations into a lateral shearing interferometer for the improvement of collimation testing sensitivity have shown limitation to increase further the number of passes of the test beam in the system due to their configurational constraint. Intrinsically, it is necessary to increase the number of passes in order to improve the sensitivity of the system further.

In this work, we present a technique where the collimating lens is utilized in a way of four different quadrants in order to allow further increment on the number of passes of the test beam to eight times. Generally, the quadrant-division approach make use of a collimating lens in four parts of quadrants, namely quadrants I, II, III, and IV. Instead of aligning the test beam onto the center of the collimating lens, the beam is directed onto the first quadrant and configured to pass the subsequent quadrants. This creates the first four-pass. Subsequently, a total number of eight passes can be achieved by reversing the test beam after the first four-pass. Hence, for a defocus introduced, the collimation state of the test beam can be evaluated at the amplification of eight. In the simulation experiment, for a beam size of 4 mm in diameter, the minimum detectable divergence angle of [theta]div.=1.1?10-3 degrees is achieved. The corresponding minimum detectable wavefront height is found to be (Wo)min = 0.015[lambda].

10023-15, Session 3

Requirements of precision and innovative manufacturing for ultrahigh precision laser interferometry of gravitational-wave astronomy *(Invited Paper)*

Wei-Tou Ni, Sen Han, Tao Jin, Univ. of Shanghai for Science and Technology (China)

With the LIGO announcement of the first direct detection of gravitational waves, the Gravitational-Wave Astronomy was formally ushered into our age. After one-hundred years of theoretical investigation and fifty years of experimental endeavor, this is a historical landmark not just for physics and astronomy, but also for industry and manufacturing. The challenge and opportunity for industry is precision and innovative manufacturing in large size – production of large and homogeneous optical components, optical diagnosis of large components, high reflecting dielectric coating on large mirrors, manufacturing of components for ultra-high vacuum of large volume, manufacturing of high attenuating vibration isolation

system, production of high-power high-stability single-frequency lasers, production of high resolution positioning systems etc. In this talk, we address and review the requirements and methods to satisfy these requirements.

Large Optical diagnosis of large optical components requires large phase-shifting interferometer; the 1.06 ?m Phase Shifting Interferometer for testing LIGO optics and the recently built 24" phase-shifting interferometer in Chengdu, China is an extension of it. High quality mirrors are crucial for laser interferometric GW detection, so as for ring laser gyroscope, high precision laser stabilization via optical cavities, quantum-optomechanics, cavity quantum electrodynamics and vacuum birefringence measurement. There are stringent requirements on the substrate materials and coating methods. For cryogenic GW interferometer, appropriate coating on sapphire or silicon are require for thermal and homogeneity property. Large ultrahigh vacuum components and high attenuating vibration system together with an efficient metrology system are required and will be addressed.

10023-16, Session 3

Illumination fluctuation elimination in phase-shifting technique by use of a gray-level transformation based on fringe histograms

Ruihua Zhang, Hongwei Guo, Shanghai Univ. (China)

Phase-shifting technique has been extensively employed in optical metrology by taking advantage of high resolution. Most phase-shifting algorithms assume the background intensity and modulation at each point of the captured fringe patterns to be constant during phase shifting, so that these two values together with the phase, as three unknowns, can be calculated from at least three phase-shifting intensities. In measurement practice, however, the background intensities and modulations of captured fringe patterns do not always keep constant under the influence of the voltage fluctuations and the unsteadiness of the ambient light, so the illumination fluctuation may lead to errors in the calculated phase, and thereby decrease the measurement accuracies with phase-shifting technique. To solve this problem, this paper presents an intensity correction method by use of a gray-level transformation based on the histograms of fringe patterns. A fringe pattern containing bright and dark fringes can be recognized as an image having two classes of pixels following a bimodal histogram. We segment each fringe pattern by using the optimal threshold based on maximumizing the inter-class variances. Noting that the means of the semented classes are inesnsitive to the phase shifts, but change with the illimination fluctuations, we establish a linear gray-level transformation function, by which the fluctuations of this fringe pattern in background intensities and modulations can be corrected. Numerical simulation and experimental results demonstrate the proposed method to be efficient and effective in improving the phase measuring accuracies with phase-shifting technique.

10023-17, Session 3

Development of an optical technique for measurement of centering error of glass molds for production of ophthalmic lenses

Boonsong Sutapun, Saharat Kaew-aram, Suranaree Univ. of Technology (Thailand); Armote Somboonkaew, Ratthasart Amarit, National Electronics and Computer Technology Ctr. (Thailand)

Manufacturing of plastic ophthalmic lenses requires glass molds for the casting process. The two molds are held together by a sealing gasket ensuring that a defined distance between the two molds is maintained. The liquid monomer is filled into the molds and hardens to form a plastic lens when exposed to a thermal process for many hours. During the production process, the geometric center of both molds may be displaced from each other. The cast plastic lenses from such molds will have the geometric center decentered from the optical center; as a result, the lens' prism diopter could be out of the preset range. Therefore, to improve the production yield, it is important to inspect the centering error of the assembled molds prior the monomer filling step. In this work, we have been developing an optical apparatus for measurement of centering error of the assembled glass molds for the production of the ophthalmic lenses. The working principle of the instrument is based on a reflection-mode autocollimator with an addition objective lens to focus at the center of curvature of both inner surfaces of the glass molds. The image reflected from the glass mold surface is observed by a camera. When a centering error occurs, the observed image depicts as a circle while the molds are rotated around a reference axis. In this talk, we will present the instrument design challenges as well as preliminary results.

10023-18, Session 3

An automatic large-scale 3D coordinate measurement system based on vision guidance

Zili Zhang, Academy of Opto-Electronics, CAS (China); Guanghua Wu, Hefei Univ. of Technology (China); Qiyue Wang, BeiHang Univ. (China); Yan Zhang, Beijing Information Science & Technology Univ. (China); Weihu Zhou, Academy of Opto-Electronics, CAS (China)

An automatic large-scale 3D coordinate measurement system based on vision guidance is presented. With a high-accuracy total station accomplishing the basic coordinate measurement, a camera mounted on the total station is used to guide it to aim at the target in the measuring field. The optical axis of the camera is set to coincide with the collimation axis of the total station so that the position of the principle point coincide with the position of the telescope reticle of the total station in the image obtained by the camera. Calibration is performed to calculate the relationship between the angular deviation of the collimation axis from the target and the pixel deviation of the target from the reticle. When the target is in the viewing field of the camera, the image processing system can identify it automatically and then angles for the total station to move horizontally and vertically to aim at it can be calculated according to the pixel difference between the target and the principle point. Then the total station will automatically aim at the target and accomplish the measurement automatically. Thus high-accuracy non-contact measurement can be accomplished without additional effort for targeting. The results show that the measurement system can realize automatic large-scale measurement precisely and efficiently which provides an efficient approach for solving automatic large-scale measurement problems.

10023-19, Session 3

Spatial intensity correlation properties of scattered optical vortices

Salla G. Reddy, The Univ. of Electro-Communications (Japan); Ravindra Pratap Singh, Physical Research Lab. (India)

The intensity correlation length of an optical field is now playing an important role in enhancing the resolution. Here, we control the spatial coherence properties of a scattered field by changing

the mode of the input beam, the area of illumination as well as the propagation distance. We generate the higher order optical vortices and scatter them through a ground glass plate. We focus the input beam on the ground glass using a lens in order to control the size of the illuminated beam. Then, we analyze the spatial intensity correlation properties of the recorded speckle patterns. The correlation studies are performed using Matlab. We find that the intensity correlation length decays faster with the increase in the order of the vortex. We also determine the change in intensity correlation length as a function of propagation distance, area of illumination and the order of an optical vortex. We present the corresponding experimental as well as the supported numerical results.

10023-20, Session 3

Fast in-situ tool inspection based on inverse fringe projection and compact sensor heads

Steffen Matthias, Markus Kästner, Yinan Li, Eduard Reithmeier, Leibniz Univ. Hannover (Germany)

Inspection of machine elements is an important task in production processes in order to ensure the quality of produced parts and to gather feedback for the continuous improvement process. A new measuring system is presented, which is capable of performing the inspection of critical tool geometries, such as gearing elements, inside the forming machine. To meet the constraints on sensor head size and inspection time imposed by the limited space inside the machine and the cycle time of the process, the measuring device employs a combination of endoscopy techniques with the fringe projection principle. Compact gradient index lenses enable a compact design of the sensor head, which is connected to a CMOS camera and a flexible micro-mirror based projector via flexible fiber bundles. Using common fringe projection patterns, the system achieves measuring times of less than five seconds. To further reduce the time required for inspection, the generation of inverse fringe projection patterns has been implemented for the system. Inverse fringe projection speeds up the inspection process by employing object-adapted patterns, which enable the detection of geometry deviations in a single image. Two different approaches to generate object adapted patterns are presented. The first approach is based on a virtual master geometry in the form of a CAD file with tolerance specifications and a ray-tracing model of the measuring system. The second approach uses a reference measurement of a manufactured tool master to generate the inverse pattern. Following the description of the pattern generation process, the image processing steps required for inspection are demonstrated on captures of gearing geometries.

10023-21, Session 3

Numerical simulation research and applications on scatter imaging of surface defects on optical components

Huiting Chai, Yongying Yang, Zhejiang Univ. (China); Pin Cao, Hangzhou Zernike Optical Technology Co., Ltd. (China); Chen Li, Fan Wu, Yihui Zhang, Haoliang Xiong, Zhou Lin, Kai Yan, Wenlin Xu, Dong Liu, Jian Bai, Yibing Shen, Zhejiang Univ. (China)

The principle of microscopic scattering dark-field imaging (MS-DFI) is adopted in surface defects evaluation system (SDES) for large fine optics. However, since defects are of micron or submicron scale, scattering imaging cannot be described simply by geometrical imaging. In this paper, the electromagnetic simulation model for microscopic scattering imaging, established on the basis of vector diffraction theory and Finite-Difference Time-Domain (FDTD) method, is used to study the scatter light intensity distribution of rectangular and triangular defects with different sizes in simulations. Standard defects on the criterion board are evaluated by SDES to study their grayscale distribution in experiments. Both the simulation and experiment results are in good agreement. Because of the existence of diffraction limit, scatter light intensity distributions of micron-scale defects broaden to different degrees and also have difference in curve shape. Scatter light intensity distributions of rectangular defects are might in Gaussian or double-Gaussian shape while those of triangular defects are might in Gaussian or epsilon-type shape. Different width extraction methods are adopted in terms of different curve shapes. Double-Gaussian fitting is applied to double-Gaussian shape and threshold segmentation is applied to Gaussian and epsilon-type shape. In terms of scatter light intensity distributions of Gaussian shape, severe broadening might lead to confusion and misjudgment, so multiple parameters besides threshold segmentation should be introduced to extract actual width. The research findings presented in this paper provide significant theory references for defect calibration in optical manufacturing and inspection.

10023-22, Session 4

Plane stitching optical testing in manufacturing workshop *(Invited Paper)*

Yingjie Yu, Shanghai Univ. (China); Xin Wu, Shanghai Univ (China)

Subaperture stitching is an effective technology to overcome the limitation of conventional large aperture interferometers. The combination of stitching and in-situ measurement in manufacturing workshop will be an efficient testing method for fabrication of large optical flat, but still difficult and challengeable. The environmental disturbance is the most troublesome. Commonly commercial phase-shifting interferometers are not suitable for the vibrating environment. An in-situ stitching measurement system has been built to supporting the use of grinding machine, which contain dynamic interferometer, marble gantry, precision guide and software system. The dynamic interferometer is mounted in a down-looking configuration on the gantry, which could close to grinding position during measurement and away from it when processing. The software system could scheme the number and position of the subapertures and control the interferometer to scan them automatically. Meanwhile the data could be stitched together and reconstruct the full surface of tested flat. In this processing, the systemic error from interferometer, the random noise from the vibrating environment and the alignment error from the mechanical guide have been analysed and corresponding restrained methods have been proposed by some simulation and experiment. It has been verified that the testing range of this in-situ stitching measurement system could up to 1200mm?450mm, and flatness accuracy is better than 0.7?m.

10023-23, Session 4

Spin Hall effect of light applied in optical linear scale

Yasuhiro Mizutani, Kazunori Ueda, Yasuhiro Takaya, Osaka Univ. (Japan)

We propose a new concept of a linear scale to detect scale displacement by using the spin Hall effect of light (SHEL). The SHEL is a phenomena about a correlation between a spin angular momentum and an orbital angular momentum of light. When the linear polarized light reflects on a surface of a dielectric media, the SHEL divides the light into a right and a left circular polarized

light and gives a slightly position changing of the reflected light about sub-10-nm scale which can be detected by a technique as the weak measurement. On the other hand, it is necessary to prepare a main scale of a linear scale. We attempt to apply carbon nano tube (CNT) for the scale. It was shown that the CNT exhibited giant circular dichroism. By reflection on a dielectric surface aligned the CNT as a scale, a left circular light of the reflected light generated by the SHEL is absorbed and amount of an optical absorption depends on a position of the CNT. In this paper, as a first attempt, we have measured the SHEL of a BK-7 glass plate by detecting a distance of two spitted lights via the weak measurement. As a results, distance of two beams generated by the SHEL was about 80nm and further results on the displacement dependency are presented and discussed.

10023-24, Session 4

Accurate reconstruction in measurement of microstructures using digital holographic microscopy

Xiaolei Zhang, Xiangchao Zhang, Min Xu, Fudan Univ. (China)

Micro-structured components with salient geometrical features designed to provide a specular function are widely used in the field of precision engineering. The measurement of their surface topographies has become an important issue. Due to the limited ability of conventional laser interferometry, digital holographic microscopy has attracted intensive attention for its capability of measuring complex surfaces. However, speckles are inevitable in the recorded interferometric patterns, thereby polluting the reconstructed surface topographies. Thus speckle reduction comes to be critical for improving the measurement accuracy. In this paper, a phase-shifting Mach-Zehnder interferometer is built to realize the in-axis digital holographic microscopy. The anti-aliasing shift-invariant contourlet transform (ASCT) is used for reconstructing the measured surfaces. By avoiding subsampling in the scale and directional filtering schemes, the frequency aliasing and phase distortion can be effectively solved, consequently overcoming severe degradation of the measurement quality.

Experimental results of the ASCT reconstruction are compared to the results of Fresnel integration and Fresnelet on the aspects of feature preserving and speckle removal. The experiments show that the Fresnel reconstruction leaves conspicuous speckles and causes image artifacts. Fresnel-wavelets would destruct curved features. On the contrast, as contours between piecewise continuous sections have sparse representations in the transform domain of ASCT, then speckles can be recognized and removed straightforwardly. Therefore the proposed method has excellent performance in reconstructing structured surfaces.

10023-25, Session 4

Tip/tilt-compensated through-focus scanning optical microscopy

Jun Ho Lee, Jun Hyung Park, Kongju National Univ. (Korea, Republic of)

Through-Focus Optical Microscopy (TSOM), proposed and mostly developed by Dr. Ravikiran Attota and his group at NIST, has been demonstrated to be utilized for 3D inspection and metrology with nanometer scale lateral and vertical sensitivity matching a scanning electron microscopy. However, there have been sensitivity and instability issues in acquiring through-focus images since TSOM 3D information is indirectly extracted from differentiating a target TSOM image from reference TSOM images. Ryabko proposed motion-free TSOM scanning using the chromatic aberration in an imaging optical system and a tunable light source and taking consideration of optical aberrations of the measurement setup into the TSOM reference library buildup. However, we found that both the previous methods still are vulnerable to mechanical or optical instability during z-axis through-focus scanning process. We are currently forming a research consortium consisting of four universities (Kongju National Univ., Seoul Univ., Korea Univ., Incheon National Univ.) for studying co-technologies for developing develop in-line TSOM inspection & metrology tools. This paper presents herein two tip/tilt compensated TSOM optical acquisition methods applied with adaptive optics, which are currently under construction. The first method simply adopts a tip/tilt mirror with a quad cell in a simple closed loop while the second method adopts a high-order deformable mirror with a Shack-Hartmann sensor. The second version is able to correct high-order residual aberrations as well as performing through-focus scanning without z-axis movement. Currently we are building a prototype of the first model and the first measurement results will be presented.

10023-26, Session 4

The total spectral radiant flux calibration using a spherical spectrometer at National Institute of Metrology China

Weiqiang Zhao, Hui Liu, Jian Liu, National Institute of Metrology (China)

At present day, in the field of lighting the incandescent lamps are phasing out. The solid state lighting products, i.e. LED, and the related market are developing very fast in China for its promising application, due to the energy-saving and the colorful features. For the quality control and the commercial trade purpose, it is highly necessary to measure the optical parameters of LED light sources with a fast, easy and affordable facility. Therefore, more test labs use the spherical spectrometer to measure LED. The quasi- monochrome of LED and the V(lambda) of silicon photodetector mismatch problem is reduced or avoided, because the spectral total radiant flux (STRF) is measured, and all the optical parameters are calculate from the STRF. In such a way, the spherical spectrometer calibration requires STRF standard lamps instead of the traditional total flux standard lamps. National Institute of Metrology China (NIM) has studied and developed the facilities for STRF measurement and provides related calibration services.

This paper shows the STRF standard lamp calibration procedure using a spherical spectrometer in every-day calibration and its traceable link to the primary SI unit at NIM. The sphere is of 1.5 m diameter, and installed with a spectrometer and a silicon photodetector. It also shows the detail of data process, such as the spectral absorption correction method and the calculation of the result derived from the spectral readings. The STRF calibration covers the spectra range of 350 nm to 1050 nm, with a measurement uncertainty of 1.8% ~ 3.6% (k=2).

10023-9, Session Post

Error analysis of a self mixing interferometry operated near relaxation oscillation region

Yuanlong Fan, Yanguang Yu, Jiangtao Xi, Qinghua Guo, Roger A. Lewis, Univ. of Wollongong (Australia)

Self-Mixing Interferometry (SMI) is an emerging non-contact sensing technique for the measurement of various metrological quantities. An SMI system is composed of a laser diode (LD) with a photodiode (PD) packaged at the rear of the LD, a lens and an external target. When the external target moves, a small portion

of light reflected re-enters the internal cavity of the LD, leading to the modulation of the LD output power. The modulated power is detected by the PD as an SMI signal, which can be used for extracting useful information and its accuracy strongly depends on the shape of the SMI signal. It is usually desired that an SMI system operates in a stable mode, in which case the SMI signal contains sinusoidal-like fringes or sawtooth-like fringes. However, in some cases, it is inevitably that the system will become unstable and the SMI signal becomes distorted which could induce significant measurement errors. This is due to the limit of the bandwidth of the PD, and the SMI signal detected is actually a distorted version of a waveform containing a very high frequency (usually 2-4GHz). In this paper, in order to achieve a reliable SMI system in the unstable region, the measurement error is analyzed by investigating the influence of the bandwidth of the PD on the shape of SMI signals via numerical simulations on the well known Lang and Kobayashi (LK) equations. The results presented in this paper are helpful for designing an accurate SMI system operated in the unstable region.

10023-10, Session Post

FBG-based fiber self-mixing sensor for acoustic emission measurement

Bin Liu, Ginu Rajan, Yanguang Yu, Jiangtao Xi, Qinghua Guo, Jun Tong, Univ. of Wollongong (Australia)

Fiber Bragg grating (FBG) based sensors can be utilized in various applications ranging from strain to temperature to vibration measurements. Acoustic emission (AE) is a well-known technique in detecting stress/strain waves generated by structural defects, allowing continuous structural monitoring during the service life of an infrastructure. However, measuring AE signals using FBGs is always a challenge as the strain induced by the high frequency dynamic signal will be in the nano or pico strain levels. On the other hand, as a non-contact sensing technique, self-mixing interferometry (SMI) has been exploited intensively for the measurement of various metrological quantities because of the compact structure and quasi-interferometric resolution. This paper combines the techniques above and devises a fiber optic strain sensor based on SMI and FBG for AE measurement. Compared to typical SMI systems, what makes it different in an FBG-SMI system is that, the strength of the reflected signal will vary as the FBG vibrates, which makes the feedback strength variable. In this work, firstly, the mathematical model of SMI has been modified by considering the variable feedback strength, and simulations have been conducted based on the modified model. From this model, SMI signals carrying features of strain applied to the FBG are observed and the estimated dynamic strain sensitivity is about 0.1μ? which is suitable for micro-crack monitoring in structures. Then, an experimental system for AE measurement has been established to verify the simulation results. The FBG-SMI sensor presented in this paper combines the advantages of fiber FGB and SMI, contributing to a novel system which can be used to measure crack-induced AE signals to enable the early detection of failure of structures.

10023-52, Session Post

Remote sensing multiple hazardous and toxic gases by passive open-path FTIR

Zhan Lu, Univ. of Chinese Academy of Sciences (China); Xiao Zuo Dai, Univ. of Chinese Academy of Science (China); Bei Ma, Univ. of Chinese Academy of Sciences (China)

In recent years open-path FTIR systems (active and passive) have demonstrated great potential and success for environment gas pollution remote detection as its higher spectrum resolution, a large range of spectrum and high spectral flux. However, there are few reports about FTIR used to detect hazardous and toxic gases in the case of terrorist acts and chemical accidents in those places for surveillance, such as public stadium and subway or train station and highway or chemical plants. In those places, passive infrared is an emerging method for remote sensing of hazardous and toxic gases and FTIR is an ideal instrument to give an early warning and situation assessment, which is helpful for emergency response personnel at site to take appropriate measures to protect passengers, works and residents. Passive open-path FTIR remote sense the target gases spectrum due to the temperature difference with backgrounds. Retrieving the measured spectrum we can get the gas column concentration and species by contrast to the standard gas library.

10023-53, Session Post

Dimensional measurement of micro parts with high aspect ratio in HIT-UOI

Hong Dang, Jiwen Cui, Kunpeng Feng, Junying Li, ShiYuan Zhao, Haoran Zhang, JiuBin Tan, Harbin Institute of Technology (China)

Micro parts with high aspect ratio have been widely used in different fields including aerospace and defense industries, while the dimensional measurement of these micro parts becomes a challenge in the field of precision measurement and instrument. To deal with this contradiction, several probes for the micro parts precision measurement have been proposed by researchers in Center of Ultra-precision Optoelectronic Instrument (UOI), Harbin Institute of Technology (HIT). In this paper, optical fiber probes with structures of spherical coupling(SC) with double optical fibers, micro focal-length collimation (MFL-collimation) and fiber Bragg grating (FBG) are described in detail. After introducing the sensing principles, both advantages and disadvantages of these probes are analyzed respectively. In order to improve the performances of these probes, several approaches are proposed. A two-dimensional orthogonal path arrangement is propounded to enhance the dimensional measurement ability of MFL-collimation probes, while a high resolution and response speed interrogation method based on differential method is used to improve the accuracy and dynamic characteristics of the FBG probes. The experiments for these special structural fiber probes are given with a focus on the characteristics of these probes, and engineering applications will also be presented to prove the availability of them. In order to improve the accuracy and the instantaneity of the engineering applications, several techniques are used in probes integration. The effectiveness of these fiber probes were therefore verified through both the analysis and experiments.

10023-54, Session Post

Simulation of out-of-plane displacement measurement using vortex beam: on the base of liquid crystal spatial light modulator

Haibin Sun, Shandong Normal Univ. (China) and Taishan Univ. (China); Ping Sun, Shandong Normal Univ. (China)

Electronic speckle pattern interferometry (ESPI) is a useful optical technique for deformation measurements. In ESPI experiment, object beam and reference beam are always plane light. With the development of optical vortices research, the plane light which usually used as object light or reference light can be replaced by vortex beam. Vortex beam can be generated by a reflective liquid crystal spatial light modulator (LC-SLM)

which added in the optical path. The gray image of fork hologram is displayed on the screen of LC-SLM, and the generated vortex beam is used as object light or reference light in out-of-plane displacement measurement. The interference intensity of the out-of-plane displacement is calculated and analyzed, and the interference fringe patterns are simulated before and after the object deformation. By phase shifting method and unwrapping, the three-dimensional distribution of phase difference is obtained. The simulation results demonstrate the efficacy of the proposed method for the out-of-plane displacement measurements. Vortex beam can become a powerful method in micro-measurements.

10023-55, Session Post

Super-resolution confocal microscopy based on radially-polarized beams and pupil filtering

Zhehai Zhou, Beijing Information Science and Technology Univ. (China); Jiaxing Liu, Lianqing Zhu, Beijing Information Science & Technology Univ. (China)

High spatial resolution optical measurement methods and techniques have become a major research topic in modern measurement areas. Some super-resolution imaging methods have been proposed to meet the urgent need of high resolution optical measurement, including 4Pi confocal microscopy, structured illumination microscopy (SIM), stimulated emission depletion (STED), Stochastic optical reconstruction microscopy (STORM), photo activated localization microscopy (PALM) and fluorescence photo-activation localization microscopy (FPALM). However, to some extent, these methods are complicated, expensive or cumbersome. So we propose a super-resolution imaging scheme based on a standard confocal microscopy, and radially polarized beams and pupil filtering are used in the scheme by use of the unique focusing properties of radially polarized beams and optical shaping technology. The 3D optical transfer function (OTF) and point spread function (PSD) are derived based on vector diffraction theory, and some simulation results are presented to verify the feasibility of super-resolution imaging. Meanwhile, the effects of system structure parameters, such as the size of detector, size of pin-hole, and their position deviations on imaging performances are analyzed.

10023-56, Session Post

Experimental investigation of correlation between surface amplitude parameters of frosted glass diffuser and size of polishing grit

Dong Wei, Masato Aketagawa, Tomoya Katagiri, Nagaoka Univ. of Technology (Japan)

Frosted glass (FG) diffusers are used for various purposes in optical experiments and are qualitatively classified based on the particle size of the grit used to polish them. Moreover, their surface topographies are known to affect their optical ability. However, a quantitative relationship between the surface topography (especially the surface amplitude parameters) and the polishing grit size is yet to be established. In the present study, a contact-type surface roughness measurement instrument was used to measure the surface amplitude parameters of a variety of commercial FG diffusers. The determined parameters, which are defined in ISO 4287-1997, were then compared with the root mean square of the grit size and the quantitative relationships were investigated. The parameters that were most strongly correlated with the root mean square of the grit size were identified. The established relationships, which statistically reflect the optical properties of an FG diffuser, may be used to optimally select a diffuser for a particular optical experiment or numerical calculation.

10023-57, Session Post

A colorful codification method for structured light measurement based on the hue of single image

Wei Yin, Haihua Cui, Nanjing Univ. of Aeronautics and Astronautics (China); Chenbo Zhang, Nanjing University of Aeronautics and Astronautics (China); Xiaosheng Cheng, Dawei Li, Nanjing Univ. of Aeronautics and Astronautics (China)

This paper presents an effective optical metrology by employing the HSI color space (hue, saturation and intensity) to form the color pattern for reconstructing an object with one-shot image. The color pattern consisting of three sinusoidal fringes with different phase steps encoded in RGB channels is projected by a digital video projector then the deformed pattern is recorded by a color CCD camera. The captured color fringe is transformed to HSI color space and separated into hue, saturation and intensity components. As the hue component of the deformed fringe pattern changes in a linear trend, it is regarded as phase quantity to reconstruct 3D profile with triangulation principle efficiently and accurately. For some complex surface, the discontinuities parts mainly caused by spatially isolated surfaces, height steps or shadow will induce various error points in the 3D profile of testing object. It is considered as one of the remaining challenges faced by phase shifting methods. As these invalid parts do not contain the pure color information, intensity and saturation components are applied to establishing a binary map to segment these invalid parts before reconstruction procedure. Besides, as some factors will affect the linearity of hue, such as gamma error and color crosstalk, an effective and simple compensating procedure is proposed to correct the hue error. Experiments are conducted to verify the feasibility of the developed methodology. In conclusion, this method, this method is proposed to measure 3D shape with one snapshot color fringe pattern which can avoid phase discontinuities.

10023-58, Session Post

Corner detection and sorting method based on improved Harris algorithm in camera calibration

Ying Xiao, Yonghong Wang, Xizuo Dan, Anqi Huang, Yue Hu, Hefei Univ. of Technology (China); Lianxiang Yang, Hefei Univ of Technology (China) and Oakland Univ. (United States)

In traditional Harris corner detection algorithm, the appropriate threshold which is used to eliminate false corners is selected manually. In order to detect corners automatically, an improved algorithm which combines Harris and circular boundary theory of corners is proposed in this paper. Firstly, a small threshold is set in order to make sure all the correct corners will not be missed. Secondly, traditional Harris algorithm is used to detect integer corner coordinates and the Forstner algorithm is used to revise the results and obtain accurate sub-pixel corner coordinates. Thirdly, by using the circular boundary theory of corners, false corners within the chessboard pattern of the calibration plate can be eliminated automatically. Moreover, a corner sorting method based on an improved calibration plate is proposed. The plate is designed by adding three circles into the black and white chessboard pattern. Using the centers of three circles, a

new coordinate system is established. According to the distance between corners and the new origin point, background corners are eliminated and all the remaining corners are sorted in order. As the location of corners in new system doesn't change with the rotation of plate, sorting result can adapt to complex background and free rotation of the calibration plate. The final corner coordinates can be used in calibration calculation and all the intrinsic and extrinsic parameters can be obtained. Experiment results show that the proposed algorithms can eliminate all false corners and sort remaining corners correctly and automatically.

10023-59, Session Post

An onsite non-contact dynamic angle metrology system based on stereo vision

Jiping Guo, Shenzhen Univ. (China) and Shenzhen Academy of Metrology and Quality Inspection (China); Jiping Yu, Shenzhen Academy of Metrology and Quality Inspection (China); Xiang Peng, Shenzhen Univ. (China); Ameng Li, Shenzhen Academy of Metrology and Quality Inspection (China); Xiaoli Liu, Shenzhen Univ. (China)

Angle metrology is an important content in the field of industrial measurement. And the non-contact metrology method for on-site dynamic angle measurement is becoming more and more demanded recently. Here we present a dynamical large swing angle and attitude angle metrology method base on stereo vision. Firstly, image sequences of the object attached with point markers are captured synchronously by a calibrated dual camera stereo system in real time. Secondly, the 3D coordinates of the markers recorded during the moving cycle are reconstructed. Finally, the fitted motion curve of the object can be obtained with aid of 3D coordinates of the markers, and then the angle variation is calculated out by a specific algorithm. In this method, the off-plane error of the swing arm (or rotation plate) can also be obtained. A set of measurement experiments have been implemented, and the results show that the presented method is rather suitable for measuring the dynamic angle on-site with advantage of on-contact . And the measurement error of the system can reach to ±0.02°for swing angle measurement and± 0.12 °for attitude angle measurement, which can satisfy the dynamic angle metrology requirement in many cases.

10023-60, Session Post

3D measurement and camera attitude estimation method based on trifocal tensor

Shengyi Chen, Haibo Liu, Linshen Yao, Qifeng Yu, National Univ. of Defense Technology (China)

An efficient and robust 3D measurement method based on trifocal tensor is proposed in this paper, which only employs the intrinsic parameters and positions of three cameras to perform 3D measurement and camera attitude estimation simultaneously. The initial trifocal tensor among the three views is obtained by using heteroscedastic errors-in-variables (HEIV) estimator and the initial relative poses of the three cameras is acquired by decomposing the tensor. Further the initial attitude of the cameras is obtained with knowledge of the three cameras' positions. Then the camera attitude and the interested points' image positions are optimized according to the constraint of trifocal tensor with the HEIV method. Finally the spatial positions of the points are obtained by using intersection measurement method. Compared with the traditional method based on Bundle Adjustment (BA), we inspected the performance of our proposal method. We took advantage of several sets of simulation data to investigate the location accuracy and computing time of the different methods. Experimental results suggested that our method achieve the same precision of the BA method but be more efficient. Respect to the methods that traditionally take Direct Linear Transformation (DLT) to get initial solution, our method is more robust and under the condition of poor camera position configuration it is still able to converge and calculate positions of the interested points. We also conducted real image experiment and obtained satisfactory measurement result.

10023-61, Session Post

Influence of irradiance non-uniformity on IV performance test of photovoltaic modules

Junchao Zhang, Limin Xiong, Haifeng Meng, Yingwei He, Bifeng Zhang, National Institute of Metrology (China); Chuan Cai, Kejia Zhang, Beijing Institute of Technology (China)

The effect of irradiance non-uniformity on IV performance of photovoltaic (PV) module is analyzed. The theoretical calculation results and the experimental results are in good agreement. The irradiance, irradiance uniformity and irradiance stability testing device is established. The accurate measurement of irradiance characteristics of solar simulator is realized. Through the actual test of solar simulator irradiance distribution and the theoretical calculation of the measurement results, the irradiance distribution and the monitor cell position effect on IV performance testing of PV modules is analyzed. The analysis result is beneficial to evaluating the performance of the solar simulator.

10023-62, Session Post

Virtual-stereo fringe reflection technique for specular freeform surface testing

Suodong Ma, Soochow Univ. (China); Bo Li, Nanjing Institute of Astronomical Optics & Technology (China)

Due to their excellent ability to improve the performance of optical systems, free-form optics have attracted extensive interest in many fields, e.g. optical design of astronomical telescopes, laser beam expanders, spectral imagers, etc. However, compared with traditional simple ones, testing for such kind of optics is usually more complex and difficult which has been being a big barrier for the manufacture and the application of these optics. Fortunately, owing to the rapid development of electronic devices and computer vision technology, fringe reflection technique (FRT) with advantages of simple system structure, high measurement accuracy and large dynamic range is becoming a powerful tool for specular free-form surface testing. In order to obtain absolute surface shape distributions of test objects, two or more cameras are often required in the conventional FRT which makes the system structure more complex and the measurement cost much higher. Furthermore, high precision synchronization between each camera is also a troublesome issues. To overcome the aforementioned drawback, a virtual-stereo FRT for specular free-form surface testing is put forward in this paper. It is able to achieve absolute profiles with the help of only one single biprism and a camera meanwhile avoiding the problems of stereo FRT based on binocular or multi-ocular cameras. Preliminary experimental results demonstrate the effectiveness of the proposed technique.

10023-63, Session Post

Digitization and visualization of virtual cultural heritage

Ameng Li, Jiping Guo, Jiping Yu, Shenzhen Academy of Metrology and Quality Inspection (China); Yong Yao, Harbin Institute of Technology Shenzhen Graduate School (China)

In recent years, virtual cultural heritage generated by optics and computer graphics methods has become an active research subject that has drawn much attention and interest from communities of optical engineering, computer science and cultural heritage around the world. In this talk, we are going to briefly introduce some of typical research projects regarding virtual heritage undertaken and ongoing in the North America, European Community (EC), Japan and China, from which we can see that the technology of 3D scanning and interaction with high quality graphics plays a central role in virtual heritage. Thereafter we present a new optics-graphics platform for automatically digitizing and presenting the virtual cultural heritage. This platform is designed with a strategy of using an optical scanning network arranged as one-dimensional array consisted of a set of 3D node-sensors. The 3D sensor array works in conjunction with a motorized controlled turntable in our proposed platform architecture. With this dedicated design, we are able to digitize complete 3D virtual heritage with complex geometry and topology while the 3D scanning pipeline, including the acquisition and registration of multiple range images can be implemented in a fully automatic fashion. Furthermore, the texture mapping and blending are also applied for generating photorealistic 3D graphic models of virtual cultural heritages. The architecture design of instrument prototype for scanning hardware and the framework for reconstruction and interaction software are described in this presentation. Furthermore, some of experiment results for digitization and visualization of virtual cultural heritage are shown to demonstrate the effectiveness of proposed platform.

10023-64, Session Post

A simple phase-shift ESPI for 3D deformation measurement

Ping Sun, Xinghai Wang, Shandong Normal Univ. (China); Haibin Sun, Shandong Normal Univ. (China) and Taishan Univ. (China)

Electronic speckle pattern interferometry (ESPI) is a widely employed technique for static and dynamic deformation measurements. There have been many techniques reported to measure the three dimensional displacement of an object. The complicated optical arrangement affects the measurement precision. Give attention to the sensitivity of the displacement components and the simplicity of the optical setup, a simple setup for 3-D deformation measurement is offered. In the scheme a novel Cube Beam-Splitter, called Non-Cube Beam-Splitter (NCBS), is used for 3-D phase-shift ESPI. By using the NCBS lights from a tested object and lights from a reference surface can be combined and then interfere each other on a CCD camera when a laser beam illuminate the test object and the reference surface simultaneously. When three laser beams illuminate the test object at different incident angles respectively before and after deformation, three interference fringe patterns are formed. Then three phase maps corresponding to three lasers can be calculated by using phase-shift, by which three displacement components are completed. The principle of the method is presented and proved by a typical three-point bending experiment. Using the NCBS presented and the 3-D optical setup with phase shifts, three phase components can be determined effectively. The new setup is simple, less sensitive to surroundings.

10023-65, Session Post

Evaluation of 3D displacement components by combining DSCM with ESPI

Ping Sun, Kai Shi, Shandong Normal Univ. (China); Mingyong Sun, Shandong Xiehe Univ. (China); Haibin Sun, Shandong Normal Univ. (China) and Taishan Univ. (China)

Three dimensional (3-D) deformation measurement of an object has always been required in the evaluation of material properties. By comparing the changes of the gray intensity of an object surface before and after deformation Digital Speckle Correlation Method (DSCM) obtains in-plane deformation. But strict limitations are taken in measurement such as those the test object surface must be flat, the speckle patterns have to be fully developed, the modulation transfer function of the camera must be taken into consideration, and carefully adjusted focus is needed. In order to increase the sensitivity of the in-plane displacement components, the in-plane and out-of plane ESPI interferometers are combined for 3-D evaluation of deformations. The combination can obtain three components of displacement directly without computation. But it is too complicated in optical arrangement, which affects the measurement precision. A method for 3-D deformation measurement is presented by combining DSCM with Electronic Speckle Pattern Interferometry (ESPI). The combination is completed based on a typical ESPI system, in which the reference light is controlled to turn on or shut down. The in-plane displacement components are obtained by using DSCM when the reference light is shut. A phase shifting ESPI is formed when the reference light is used, which can be used for the measurement of the out-plane displacement component. A typical three-point-bending experiment is completed. Experiment results show that the three displacement components can be obtained by the combination effectively.

10023-66, Session Post

The calibration of specular gloss meters and gloss plates

Tiecheng Li, Lei Lai, Leibing Shi, Dejin Yin, Fangsheng Lin, Ming Xia, Biyong Huang, Shanghai Institute of Measurement and Testing Technology (China)

Specular gloss is the perception by an observer of the mirror-like appearance of a surface. The definition of specular gloss is the ratio of luminous flux reflected from an object to that reflected from a gloss reference standard in the specular direction for a specified reflection angle and specified aperture angles of source and receptor. Specular gloss is usually measured by a gloss meter, which can be calibrated by a group of gloss plates ranging from high to matt gloss values according to ISO 2813:2014 (Paints and varnishes – Determination of gloss value at 20°, 60° and 85°) and JJG 696-2002 (verification regulation of specular gloss meters and gloss plates). The characteristics of a gloss meter include measuring range, resolution, stability, zero error, error of indication, uniformity of illumination, match between light source and photo detector. The characteristics of a gloss plate include gloss value, roughness and spectral transmissivity of a high gloss plate, spectral reflectivity of a ceramic gloss plate, annual variation. Experiments have been performed on different kinds of gloss meters and gloss plates. The results indicate that stability of indication may exhibit significant differences among various gloss meters, which will seriously affect the verification result. Similar to gloss meters, verification procedure of gloss plates unavoidably is influenced by roughness and spectral transmissivity of a high gloss plate, spectral reflectivity of a ceramic gloss plate. Therefore, calibration of both gloss meters

and gloss plates should be carefully performed according to the verification regulation in order to reduce the measurement error.

10023-67, Session Post

Numerical calibration of laser line scanning system with multiple sensors for inspecting cross-section profiles

Jingbo Zhou, Yuehua Li, Fengshan Huang, Lijian Liu, Hebei Univ. of Science and Technology (China)

Laser line scanners (LLSs) have gained more and more applications in industry. An interested profile can be easily obtained through the analyses of laser-object intersection stripe. But one sensor is inadequate to get a closed cross-section profile due to the obstacle of the laser light. Thus, multiple LLSs are integrated as a whole for profile inspection and a numerical calibration method was also proposed. Firstly, the laser planes from all the projectors were adjusted to coincide with the target plane with the aid of a marked rectangular block. After that the origin of the world coordinate frame was fixed at the center of the up-corner calibration dot with its X and Y axis coincide with the target plane. Each sensor camera captured an image of the same target. The relationship between the pixel and the world coordinates was established using an interpolation method via the world coordinates of target dot centers and their corresponding pixel coordinates. Such that the measured point from all of the sensor cameras have a same world coordinate frame and a closed cross-section profile can be achieved. This proposed method neither need to establish the intrinsic, the extrinsic and the distortion models of the camera, nor need to solve the complex optimization equations to determine the model coefficients. The factors affecting the measuring accuracy were also analyzed. Finally, a cylinder and a rectangular block were inspected and their cross-section profiles were successfully obtained. The comparison with the measuring results from the coordinate measuring machine further validates the high accuracy of the proposed method.

10023-68, Session Post

Uncertainty evaluation of ellipsometer: from instrumentation to material and application in Avogadro's project

Wende Liu, Chi Chen, Qiming Fan, Chu Chu, National Institute of Metrology (China)

As a flexible tool for characterizing optical and structural parameters of thin film, ellipsometers have been widely employed in various fields including new-type thin film material such as solar cells, OLED, and in-situ parameter control applications. On the other hand, ultra sensitivity enables ellipsometry to be used in avant-garde metrological problem of precise counting of silicon atoms in a macro sphere made of monocrystalline silicon, which is one of the candidates for redefining Kg unit in the near future. Sub-atom accuracy (about 0.1nm) is generally required for measuring the several-nanometer-thick overlayer on the surface of a highly polished Si sphere. The paper reviews the effort for setting up a traceable ellipsometer with the uncertainty outlined to include both instrumentation and material contributions. For special consideration of the application in Avogadro's project, some new uncertainties are considered.

It is for a long time, NIST's standard reference material series are used by users from all over the world. The ellipsometer set up by NIST consists of only rotating polarizers, without phase retarding elements, therefore eliminating possible error from the uncertainty of the phase retardance. The AOI is determined with high precision by high-resolution encoders. Therefore, the various angles that determine the (Psi, Delta) uniquely are all calibrated in a traceable manner, which further ensures the traceability of (Psi, Delta).

The idea is applied to the Avogadro's project, in which the crystalline silicon atoms in a macro silicon sphere are counted to give Avogadro's constant, which is in turn used to define the SI unit Kg with a desired relative uncertainty of 2E-8. The paper investigates the use of ellipsometer to measure the outermost silicon oxide layer, which contributes to both diameter and mass measurement results of the sphere, therefore resulting in a relatively large contribution to the final uncertainty of Avogadro's constant. An uncertainty is outlined according to the instrumentation analysis here, and future works are envisaged.

10023-69, Session Post

Dynamic 3D shape measurement based on digital speckle projection and temporal sequence correlation

Ren Chao Xu, Sichuan Univ (China); Fangyan Zhou, Qican Zhang, Sichuan Univ. (China)

Digital speckle correlation method, as one of optical measurement methods, has been developing from 1980s. The distributions of the speckle field on objects' surface before and after objects' displacement or deformation are analyzed, and then the values of displacement or deformation are obtained by the statistical correlation method. Taking its advantage of no-contact, wide measuring range and simple optical setup, digital image correlation method has been widely used in many fields such as mechanics, biomedicine and so on.

Because of the non-periodicity and discrete nature, unnecessary of phase unwrapping process, the digital image correlation method shows significant advantages in 3D shape measurement. Based on digital speckle temporal sequence correlation and speckle projection, an experimental platform was built to measure the dynamic 3D shape measurement in this paper. The frame rate of high-speed camera was set to acquire modulated speckle patterns during quartz clock's pointers' walking. Programming was written to implement the algorithm to reconstruct every motion of the clock's pointers. Beyond that, a simple Newton's cradle was established, and the collision course between three steel balls was reconstructed. These experimental results show that the method can be used for dynamic 3D shape measurement, which has a better effect on the reconstruction of objects with characteristics of steep variation, isolation and small details.

10023-70, Session Post

A flexible new method for 3D measurement based on multi-view image sequences

Haihua Cui, Nanjing Univ. of Aeronautics and Astronautics (China)

Three-dimensional optical measurement is a flexible method to acquire the data of objects. It has been widely applied in various industries, aerospace, biomedical engineering, and so on. The paper developed a new flexible and fast optical measurement method based on multi-view geometry theory. At first, feature points are detected and matched with improved SIFT algorithm. The Hellinger Kernel is used to estimate the histogram distance instead of traditional Euclidean distance, which is immunity to the weak texture image; then a new filter three-principle for filtering the calculation of essential matrix is designed, the essential matrix is calculated using the improved a Contrario Ransac filter method. The position of the camera and 3D points are

considered, Instead of choosing the reprojection error, the first order geometrical error is used to estimate the 3D measurement error. Then, the essential matrix is calculated with the optimized RANSAC algorithm. The RANSAC algorithm based on the A Contrario thought is better to measure the reliability of the model than the traditional method. One view point cloud is constructed accurately with two view images; after this, the overlapped features are used to eliminate the accumulated errors caused by added view images, which improved the camera's position precision, then the different view point cloud are transformed to the same coordinate with different scale factor. At last, the method is verified with the application of dental restoration CAD/CAM, experiment results show that the proposed method is fast, accurate and flexible for tooth 3D measurement.

10023-71, Session Post

A robust real-time laser measurement method based on noncoding parallel multi-line

Chenbo Zhang, Nanjing Univ of Aeronautics and Astronautics (China); Haihua Cui, Wei Yin, Liu Yang, Nanjing Univ. of Aeronautics and Astronautics (China)

Single line 3D measurement is the main method in traditional 3D hand-held laser measurement, whose reconstruction speed is very slow and cumulative error is very large. Therefore, we propose a rapid real-time 3D measurement method based on parallel multi-line. Two cameras and a laser that project multiple laser lines are needed in this method. Firstly, we calibrate the system of the two cameras and the laser, obtaining intrinsic parameters and spatial relations between the two cameras and 3D laser plane equations. Secondly, we process the two images that contain multi-line laser stripes shot by the the two cameras. In order to match the multi-line laser stripes conveniently, we need to refine them and then extract their centers accurately. With the previous calibration results, we transform one points on the left image laser stripe centers to the right image with triangulation principle, and get a series of corresponding points calling An. Then we find the polar lines of An on the right image, a series of intersection points calling Bn can be acquired by the polar lines and laser stripes on the right image.Finally, we compare the distance of An and Bn to get the correct match point within the threshold value range we set. Through the above measurement,we can find match points of other laser stripe centers on the left image in turn. Experiments of this paper prove that this method is feasible, not only improve the scanning speed greatly, but also increase the scanning area greatly, which can meet the demand of more industrial measurement.

10023-72, Session Post

Experiments and error analysis of laser ranging based on frequency-sweep polarization modulation

Shuyuan Gao, Hefei Univ. of Technology (China); Rongyi Ji, Weihu Zhou, Academy of Opto-Electronics, CAS (China)

Frequency-sweep polarization modulation ranging method uses a polarization-modulated laser beam to determine the distance to the target, the modulation frequency is swept and frequency values are measured when transmitted and received signals are in phase, thus the distance can be calculated through these values. This method gets a much higher theoretical measuring accuracy than phase difference method for the prevention of phase measurement. However, actual accuracy of the system is limited because additional phase retardation occurs in the measuring optical path when optical elements are imperfectly processed and installed. In this paper, working principle of frequency sweep polarization modulation ranging method is analyzed and transmission model of polarization state in light path is built based on the theory of Jones Matrix, additional phase retardation of ?/4 wave plate, PBS, and retro-reflector and their impact on measuring performance is analyzed. Theoretical results show that wave plate's retardation error dominates the limitation of ranging accuracy, while azimuth deviation of wave plate and PBS has little influence on that, though retro-reflector can profoundly affect the polarization state of the output beam, symmetry of such effect to the beam can diminish the ranging error, so it is crucial to ensure the light points to center of the reflector. According to the system design index, element tolerance and error correcting method of system is proposed, ranging system is built and ranging experiment is performed. Experiential results show that with proposed tolerance and error correcting method, the system can satisfy the accuracy requirement. The present work has a guide value for further research about system design and error distribution.

10023-73, Session Post

High-speed image acquisition technology in quality detection of workpiece surface

Kaihua Wu, Wenjie Wang, Xuechao Sun, Hangzhou Dianzi Univ. (China)

High-speed image acquisition technology has a great significance to improve the effciency of the workpiece surface quality detection, image quality directly affects the final test results. Aiming at the high-speed image acquisition of workpiece surface quality online detection, a workpiece image high-speed online acquisition method was produced. A high-speed online image acquisition sequence was designed. The quantitative relationship between the positioning accuracy in the high speed online image acquisition, motion blur, exposure time and the speed of workpiece was analyzed. The effect between the vibration between transfer mechanism and workpiece was analyzed. Fast trigger was implemented by photoelectric sensor. The accurate positioning was implemented by using the high accuracy time delay module. The motion blur was controlled by reducing the exposure time. A high-speed image acquisition system was designed based on the high-speed image acquisition method. The positioning accuracy was less than 0.1 mm, and the motion blur was less than 1 pixel.

10023-74, Session Post

Research of dimension and density measurement system for minor artifacts

Yu Gao, Chao Gao, Chongqing Univ. (China)

The measuring object is cylindrical pellets, the system detects pellets' diameter and height with non-contacting mode, getting quality through high precision electromagnetic balance, and then the density can be calculated.The hardware part of the measuring system consists of size and quality measurement module. The size measuring module is made of CMOS image sensor, GaNgreen LED,embedded image processing system and power source. The system can get pellet's 2-dimentionnal image by light projection principle, then CMOS sensor convert the image signal to electrical signal, so the pellet diameter and height values can be obtained after analyzing and calculating.Monte Carlo simulation methoddemonstrate that, the use of two sets of each other into 90 ° measuring device can obtain more accurate size values.Quality measurement module is mainly composed of high precision electromagnetic balance.The geometric densities

can be obtained by sing corresponding calculation formula after software receive these data.

10023-75, Session Post

The research of weld defect detection based on high precision displacement sensor

Kelin Hu, Chao Gao, Chongqing Univ. (China)

Welding is one of the very common process in industrial production. It is a kind of manufacturing process and technology which joint mental or other thermoplastic materials by heating, high temperature or high pressure. Welding quality will directly affect the final quality of workpiece. So during the welding process, each links have strict standards and welding quality evaluation has different indicators. Therefore, how to make a rapid detection for weld defect has become a valuable research. This topic is aimed at weld defect detection of small workpiece. The study contains the selection of sensor, design of detection system, hardware platform, software design, user interface design, etc. In the end, a set of high accuracy detector of weld defect will be designed.

10023-76, Session Post

Research of non-contact measurement method for outline dimensions of some special workpiece

Qiaoling Feng, Chongqing Univ. (China)

In industrial production, machine vision is widely used in a variety of automated testing industry, because of its characteristics of non-contact, high precision, fast detection time, etc. This paper introduces a nondestructive detection system for the outline dimensions of a kind of special workpiece. For the purpose of controlling the quality of image—an ultra-high-resolution monochrome CCD image sensor is adopted to capture source image. Then it's the image preprocessing, including image cropping processing, grey scale processing, image denoising processing, etc. Then it is the progress of edge extraction, using gradient operator to get its contour edge. And then piecewise fitting methods are used to get the dimensions. This method achieves once measuring multiple outline dimensions without moving the workpiece. It has been used in industrial production. The result sees its practical value for meeting the production needs, with the advantages of high accuracy, fast speed and high stability of the measurement system through experiments.

10023-77, Session Post

GPU-accelerated phase extraction algorithm for interferograms: a real-time application

Xiaoqiang Zhu, Yongqian Wu, Institute of Optics and Electronics (China)

Optical testing, having the merits of non-destruction and high sensitivity, provides a vital guideline for optical manufacturing. But the testing process is often computationally intensive and expensive, usually up to a few seconds, which is sufferable for dynamic testing. In this paper, a GPU-accelerated phase extraction algorithm is proposed, which is based on the advanced iterative algorithm. The accelerated algorithm can extract the right phase-distribution from thirteen 1024x1024 fringe patterns with arbitrary phase shifts in 233 milliseconds on average using NVIDIA Quadro 4000 graphic card, which achieved a 12.7x speedup ratio than the same algorithm executed on CPU and 6.6x speedup ratio than that on Matlab using DWANING W5801 workstation. The performance improvement can fulfill the demand of computational accuracy and real-time application.

10023-78, Session Post

Study of angle measuring error mechanism caused by rotor run-outs

Dabao Lao, Weihu Zhou, Wenying Zhang, Academy of Opto-Electronics, CAS (China)

In a rotating Angle measuring system, Errors of grating sensor, installation and rotor run-outs will affect angle measuring error. The error caused by rotor run-outs is usually the biggest and the hardest to eliminate of them. To improve the accuracy, the table should be fabricated precisely, thus, the table system will be complicated and expensive. This paper provides a method to solve the challenge by using two gratings in the same table, whose gratings respectively grooved on end face and side face. The error mechanism of end face and side face caused by axial and radial rotor run-outs by were deduced, which were tested by a set of experiments. It can be concluded from the results showed that end face grating is sensitive when radial rotor run-outs happens, side face grating is sensitive when axial rotor run-outs happens. Due to the conclusion, combined type gratings with one end face grating and one side face grating can be used to restrain the error caused by Rotor Run-outs of table.

10023-79, Session Post

Truncated pyramid artifact for performance evaluation experiments on laser line scanner

Sen Zhou, Chongqing Academy of Metrology and Quality Inspection (China) and Chongqing Univ. (China); Jian Xu, Tao Lei, Chongqing Academy of Metrology and Quality Inspection (China)

Non-contact measurement techniques using 3D laser scanning have the power to deliver tremendous benefits to most notably manufacturing, and have the advantage of high speed and high detail output. However, procedures for evaluation and verification of non-contact laser line scanner have not been well-established because of many influencing factors like scan depth, incident angle, probe head orientation and surface properties. A truncated pyramid artifact representation of five- planar with different included angles was designed and used to straightforwardly identify the influence of in-plane and out-of-plane angle, as well as scan depth on dimensional measurement accuracy of the laser scanner. Then, a series of easy, fast and representative experiments, based on this simple artifact, were performed on a commercial laser line scanner, and found that the output of this scanner can be improved for metrology applications after calibration.

10023-27, Session 5

Development of a high-sensitive optical probe for inner profile measurement of pipes and holes *(Invited Paper)*

Toru Yoshizawa, Non-Profit Organization 3D Associates (Japan); Toshitaka Wakayama, Saitama Medical Univ. (Japan)

The requirements of inner profile measurement of pipes and tubes become recently larger and larger, and applications of inner profile measurement have rapidly expanded to various industrial fields such as mechanical, automobile and heavy industries. We have proposed measurement method by incorporating a ring beam device that produces a circular beam and have developed various probe cameras for different inner profile measurement. To meet request for applying to smaller diameter pipes, we tried to improve the ring beam light source using a conical mirror and a laser diode. At the same time, we are trying to realize high-sensitive probe on the basis of selective compliance applied method (SCAM). Some applications are shown for industrial purposes.

10023-28, Session 5

Binocular stereo vision system based on phase matching

Huixian Liu, Hebei Univ. of Technology (China); Shujun Huang, Hebei University of Technology (China); Nan Gao, Zonghua Zhang, Hebei Univ. of Technology (China)

The binocular stereo vision is an efficient way for three dimensional (3D) profile measurement and has broad applications. Binocular stereo vision directly simulates the physical structure of human eyes,and has choiceness characteristics such as small in size, low cost, little power consumption and high efficiency. Image acquisition, camera calibration, stereo matching, and 3D reconstruction are four main steps. Among them, stereo matching is the most important step that has a significant impact on the final result. In this paper, a new stereo matching technique is proposed to combine the absolute fringe order and the unwrapped phase of every pixel. Different from traditional phase matching method, sinusoidal fringe in two perpendicular directions are projected. It can be realized through the following three steps. Firstly, colored sinusoidal fringe in both horizontal (red fringe) and vertical (blue fringe) are projected on the object to be measured, and captured by two CCD cameras synchronously. The absolute fringe order and the unwrapped phase of every pixel along the two directions are calculated based on the optimum three-fringe numbers selection method. Then, based on the absolute fringe order of the left and right phase maps, stereo matching method is presented. In this process, the same absolute fringe orders in both horizontal and vertical directions are searched to find the corresponding points. Based on this technique, as many as possible pairs of corresponding points between two cameras are found to improve the precision of the measurement result. Finally, through 3D reconstruction of a certain measuring system, this paper analyses the reconstruction results. The experimental results show that the proposed method can meet the requirements of high precision for industrial measurements.

10023-29, Session 5

Algorithms and applications of distortion correction and American standard-based digital evaluation in surface defects evaluating system

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The inspection of surface defects is one of significant sections of optical surface quality evaluation. Based on microscopic scattering dark-field imaging, sub-aperture scanning and stitching, the Surface Defects Evaluating System (SDES) can acquire full-aperture image of defects on optical elements surface and then extract geometric size and location information of defects with image processing such as feature recognization. However, optical distortion existing in SDES badly affects the inspection precision of surface defects. In this paper, a distortion correction algorithm based on standard lattice pattern is proposed. Feature extraction, polynomial fitting and bilinear interpolation techniques in combination with adjacent sub-aperture stitching are employed to correct the optical distortion of SDES automatically with high accuracy. Subsequently, in order to digitally evaluate surface defects with American standard by using American military standards MIL-PRF-13830B to judge the surface defects information obtained from SDES, an American standard-based digital evaluation algorithm is proposed, which includes judgment algorithm of surface defects size and judgment algorithm of surface defects concentration. Among them, the judgment algorithm of surface defects concentration establishes weight region for each defect and adopts the method of overlap of weight region to calculate defects concentration. This algorithm takes full advantage of convenience of matrix operations and has merits of low complexity and fast in running, which makes itself suitable very well for high-efficiency inspection of surface defects. Finally, various experiments are conducted and the correctness of these algorithms are verified. At present, these algorithms have been used in SDES.

10023-30, Session 5

Global optimization to improve system resolution

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To improve the system resolution is an important aspect of the development of a complicated sensor . In order to improve the resolution of the imaging system, and achieve the theoretical limit, we introduced the technology principle of super resolution restructure from the point of view on theory and engineering. Several methods to realize high resolution restructure configurations are introduced based on theoretical analysis and engineering practice. Then, three kinds of restructure technologies, that prototype, micro scanning and sub pixel are described, and how to decrease their shortcomings are discussed in detail. Furthermore, to improve the band width by reconstruction without the spectral alias in super resolution technologies, a new coding technology combining a optical encoding and the sub pixel is proposed. With the global method, the bandwidth has been amplified by ten times as compared with that of traditional ones. Simulation results show that the system can meet the application requirements in MTF, REA, RMS and other related criteria. Compared with the conventional design, the system has reduced in volume and weight significantly. Therefore, the determining factors are the prototype selection and the system configuration combined optical, electronic and signal processing technologies, and as an important developing trend.

10023-31, Session 5

Signal processing in white-light scanning interferometry by Fourier transform and its application to surface profile measurements

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When some dispersion effects are contained in an interference signal of white-light scanning interferometer (WSI), it is impossible to measure a reflecting surface position with an accuracy of a few nanometers. In this situation it becomes important to process the interference signal both in position and wavenumber domains by using Fourier transform. Although the interference signal detected with a WSI is a real-valued function, its complex-valued function is easily obtained by using Fourier transform. This complex-valued interference signal (CVIS) of WSI is very effective for the accurate position measurement. In this paper a general equation of the interference signal of WSI with a light source of an arbitrary spectrum and Fourier transform of the interference signal are derived. Based on these equations, a method for eliminating the dispersion effect in WSI is proposed. The phase and amplitude distributions of the CVIS of WSI without the dispersion effect are utilized to determine accurately the position of the reflecting surface. A position of zero phase nearest to the position of maximum amplitude in the two distributions is the position of the reflecting surface.

10023-32, Session 5

Calibration of angle-measurement system for direction measurements

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Tasks of space orientation very often should be solved by means of the non-contact optical measurements of angles between some directions set in space by mirrors. Such measurements usually are conducted with the use of theodolites or tacheometers. Usually the accuracy of these devices is limited by one arc second or a little bit better. In some tasks the accuracy should be on the level of one tenth of arc second. The way of solving the considered problem is the use of dynamic method of angle measurements. In this method the high-precision optical encoder continuously rotates around vertical axes together with the optical null-indicator (NI). The NI generates pulses at those moments of time when the optical beam falls normally on the mirrors. The intervals between these pulses defines the angles between mirrors. To measure these angles one has to count the number of the optical encoder output pulses falling in the intervals. The reference direction in the system is formed by the normal to the reference mirror, which is fixed on the rotating platform.

The suggested method together with the resolution and accuracy of the optical encoder on the level of 0,1 arc-sec makes it possible to provide the required quality of considered kind of measurements.

Important part of the problem is the calibration of the measurement system. The report describes the various procedures of calibration and results of experimental research of system calibration.

10023-33, Session 6

Full-field 3D shape measurement of specular surfaces by direct phase to depth relationship *(Invited Paper)*

Zonghua Zhang, Yue Liu, Shujun Huang, Zhenqi Niu, Jiao Guo, Nan Gao, Hebei Univ. of Technology (China)

With the development of Three-Dimensional (3D) optical shape measurement technique, it has been widely applied in the fields of reverse engineering, biological recognition and digitalization of cultural relics, etc, because of the advantages of high speed, non-contact, and high measurement precision. However, most of the existing techniques are applied to measure objects with diffused surface. There are a large number of transparent, black, and reflective objects in industrial applications. The research of shape measurement for these objects is still in the early stage. The main methods in industry are using coordinate measuring machine or changing the surface characteristics by spraying paint. Therefore, it is vital to study a direct optical shape measurement method for specular objects.

Phase Measuring Deflectometry (PMD) has been developed to test specular free-form surfaces,. This kind of technique needs to display straight sinusoidal fringe patterns on a screen or to project the structured pattern onto a ground glass. From another viewpoint, the reflected fringe patterns via the tested surface appear deformed with regard to the slope variation of the surface and the modulated fringe patterns are recorded by an imaging (CCD) camera. Phase information in the deformed fringe patterns are demodulated to obtain the slope of the measured specular surface and then 3D shape of the tested surface can be reconstructed by integrating the gradients. All the existing PMD methods just measure the local slope of smooth surfaces, instead of the actual 3D shape, and then a two-dimensional (2D) integration procedure is necessary to reconstruct the shape from the measured derivatives, which is incapable of measuring multiple discontinuous surfaces.

This paper presents a new PMD method to measure specular surface. A mathematical model is established to directly relate phase and depth, instead of phase and gradient. Based on the model, a hardware measuring system has been set up, which consists of a beam splitter to change the optical path, and two LCD screens to display the same sinusoidal fringe patterns. By using model-based and machine vision method, system 3D calibration is accomplished to provide the required parameters and conditions. The verification tests are given to evaluate the accuracy of the developed system and to analyze the error source. The 3D shape of a specular step and a reflective mirror has been measured. Experimental results show that the proposed measurement method can obtain 3D shape of specular objects with discontinuous surface effectively and accurately.

10023-34, Session 6

Three-dimensional surface inspection for semiconductor components with fringe projection profilometry

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With the increasing integration level of components in modern electronic devices, three-dimensional automated optical inspection has been widely used in the manufacturing process of electronic and communication industries to improve the product quality. Three dimensional inspection provides complete information for high-precision metrology and solution for quality control and automatic assembly. In this paper, we develop a three dimensional inspection and metrology system for semiconductor components with fringe projection profilometry, which is composed of industry camera, telecentric lens and projection module. This system is used to measure the height, flatness, volume, shape, coplanarity and quality checking. The system calibration includes the camera calibration and projector calibration, the details are explained in the paper. To detect the discontinuous parts and sharp changes in the internal surface of semiconductor components, we employ the fringes with multiple spatial frequencies to avoid the measurement ambiguity. To increase the efficiency of using multiple spatial frequencies, the fringes on two different spatial frequencies are selected based on the number theories which are developed in our previous papers. The complete three dimensional information of semiconductor

component is obtained by fusing the measurement results from different views. The inspection specifications such as flatness, height, cross-sectional profile, volume and shape are obtained to evaluate the quality of semiconductor component, the depth resolution of our system reaches 5 micrometers. This system can be further embedded for the online inspection of various electronic and communication products.

10023-35, Session 6

Measurement uncertainty evaluation of the six-degree of freedom surface encoder

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A six-DOF surface encoder can be used to measure the six degree of freedom (DOF) displacement of the grating. Indeed, any measurement result is in general just a point estimate of measured quantity, the “true” value of which remains unknown. For this reason, one should appraise the dispersion of the values about the estimate that could as well be attributed to the measurand. In metrology, this parameter is called the measurement uncertainty. In this paper, a measurement uncertainty of the developed six-DOF surface encoder was systematically investigated to confirm its feasibility on the precision positioning of planar motion stage. An expanded uncertainty of 124.4 nm has been calculated in the measurement results of testing three-axis translational motions over a range of 2.5 um. Among those error sources, cross-talk errors caused by misalignment existing in experimental setup were identified to be the largest error source. A method that is able to identify the misalignment factors was proposed for reduction of the cross-talk errors and correspondingly for improvement of measurement accuracy. An expanded uncertainty of 3.8 arcseconds has been calculated in the measurement results of testing three-axis angular error motions at a motion range of ±30 arcsecond. Periodic cross-talk error components have been observed in the angular outputs, which were caused by the polarization leakage in the optical paths of the diffraction beams. The cross-talk errors of the surface encoder outputs were identified to be the largest uncertainty source for the surface encoder. Optimization of the optical design of the surface encoder has then been proposed to eliminate the cross-talk errors.

10023-36, Session 6

Optimum camera setting on fringe edge detection

Rima Zuriah Amdani, Eka Pratiwi, Ardi Rahman, Purwo Wibowo, Ctr. for Metrology LIPI (Indonesia)

Optical has widely used in industry and metrology areas. Research Center for Metrology (RCM) LIPI as a National Metrology Institute in Indonesia has important role in traceability of the national standard. The application of dissemination provided with calibration service to industry. Percentages of the optical calibration order in Length Laboratory RCM LIPI for three years are over than 10% of the total amount order. The large requirement of calibration service needs a reliable calibration system. Otherwise, the calibration system in Length laboratory has large human error factor. Measurement system of the optical are using contact method between optical test and standard with monochromatic lamp. Improvement to the system carried out with a calibration system using image processing. Fringe image that observed using eyes are replaced with camera that automatically controlled in computer. This research is concerned to find the optimum setting on camera to get a good result on detecting fringe edge images. Measurements are set on the fix distance with variation of focus on the camera. The variation also set using parameter ISO, aperture and shutter time on the camera. Detection of fringe image are programmed using octave. fringe edge images result are analyzed visually. It is obtained that on focus 0.7 m, ISO 100, aperture f/2.5 and shutter time 5s give a better result on detecting fringe edge images.

10023-37, Session 6

Monitoring the VOCs in chemical plants with SOF-FTIR

Xin Han, Anhui Institute of Optics and Fine Mechanics (China)

Chemical plant area emit large quantities of VOCs, carbon oxides and other serious impact on the atmospheric environment and human health, in recent years, widespread attention. In this paper, recent development of SOF-FTIR technique of a chemical plant in Tangshan area for a period of five days of monitoring measurement experiment in the monitoring process, select a closed path monitoring, audience 6.5KM, analyzed between selected xylene (C8H10_1), p-xylene (C8H10_3), p-cresol (C7H8O) as the target component, and nonlinear least squares inversion gas concentrations and fluxes. Experimental results show that, SOF-FTIR technology has broad application prospects in terms of chemical emissions monitoring area, the development of relevant policy guidelines for government departments providing effective help.

10023-38, Session 6

An accurate approach for calibrating rotational angle of camera

Zhenqi Niu, Kuo Liu, Zonghua Zhang, Hebei Univ. of Technology (China)

With the advent of the information technology, the color digital camera and the depth camera are more and more widely used to obtain color and 3D scene information in various fields. However, such cameras can only obtain data in one direction. In order to obtain the scene information of a larger or 360 degree field of view, the camera needs to move or rotate to collect a series of 2D or 3D data . Especially in a room, the data of the large field of view can be obtained by the camera rotated around a rotation axis. In order to obtain the scene information of a larger or 360 degree field of view, it is necessary to accurately know the angle of the camera rotating around a fixed axis that directly affects the quality of the registration result .

This paper presents a novel method to calibrate the rotated angle of a camera around a fixed axis by using a large scene camera and two high precise checkerboards. The large scene camera is fixed and has the same imaging direction as the calibrated camera. One checkerboard is placed in front of the two cameras to determine their relative positions. The other checkerboard is rotated to several positions along the camera. At each position, the big scene camera captures the checkerboard to calibrate the angle of the rotation axis. Experimental results show that the proposed calibration method can accurately obtain the rotational angle of a camera around a fixed axis.

10023-39, Session 7

Temporal phase unwrapping algorithms for fringe projection profilometry: a comparative assessment based on a stochastic noise model *(Invited Paper)*

Chao Zuo, Nanjing Univ. of Science and Technology (China)

In fringe projection profilometry (FPP), temporal phase unwrapping is an essential procedure to recover an unambiguous absolute phase even in the presence of large discontinuities or spatially isolated surfaces. So far, there are typically three groups of temporal phase unwrapping algorithms proposed in the literature: multi-frequency (hierarchical) approach, multi-wavelength (heterodyne) approach, and number-theoretical approach. In this talk, the three methods are compared in details by analytical, numerical, and experimental means. The basic principles and recent developments of the three kind of algorithms are briefly recalled. Then, the reliability of different phase unwrapping algorithms is compared based on a rigorous stochastic noise model developed. Furthermore, this noise model is used to predict the optimum fringe period for each unwrapping approach, which is a key factor governing the phase measurement accuracy in FPP. Simulations and experimental results verified the correctness and validity of the proposed noise model as well as the prediction scheme. We will show that the multi-frequency temporal phase unwrapping provides the best unwrapping reliability, while the multi-wavelength approach is the most susceptible to noise-induced unwrapping errors.

10023-40, Session 7

Embedded 3D shape measurement system based on a novel spatio-temporal encoding

Li Dong, Haoming Guo, Guiwen Lin, Yong Tian, Jindong Tian, Shenzhen Univ. (China)

Structured light 3D shape measurement has been wildly used in industrial component detection, reverse engineering, 3D molding, robot navigation, medical and many other fields. In this paper, a novel structured light based on spatio-temporal encoding is proposed. The new designed patterns consist of grey coding and binary coding in space, which are projected to the measurement object in sequence to form a unique gray vector temporally for every pixel. And a decoding algorithm is presented to convert the unique gray vector to a code value which could be used as characteristic information for binocular matching. Compared with the temporal phase shift method, fewer patterns are needed and the time-consuming phase unwrapping and trigonometric functions calculation are avoided in this method. An Embedded system based on DM3730 is set up for to perform the proposed method, which is a SOC consist of a DSP core and an ARM core. We packaged the gray vector modulating method into xDM complaint algorithm which is appropriate for dual core communication. The ARM side application realized the control of the projector and the camera. The DSP algorithm for data process is then called by the application. 3D object measurement experimental results show the feasibility of the system.

10023-41, Session 7

Imaging ellipsometer with large field-of-view

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With non-contact, non-destructive and high precision measurement, the ellipsometer is widely used to detect the thickness, refractive index and extinction coefficient of the thin film. The traditional ellipsometer can only adapt to single-point measurement. To overcome this disadvantage, the imaging ellipsometer with microscopy has been developed. The current commercial imaging ellipsometer can realize 10?m lateral resolution and 2mm?2mm field of views.

In this paper, we present an imaging ellipsometer which has 13?m lateral resolution and 13mm?13mm field of views. In the imaging ellipsometer, the polarizer-compensator-sample-analyzer (PCSA) structure is used. The sample is imaged on a CCD by a telecentric imaging system. The CCD is tilted to satisfy the Scheimpflug condition. The rotation accuracy of all polarizing optical components which are controlled by servo motors is smaller than 0.01?. The accuracy of the incidence and reflection angles can reach 0.001° with the stepping motor and the grating ruler. In its measurement, the light extinction measurement method can be utilized to eliminate the influence of light intensity fluctuation.

In the experiments, a thin film with non-uniform thickness is measured. The experimental result agrees with the measurement result of the AFM. The usefulness of the imaging ellipsometer is verified.

10023-42, Session 7

Hybrid probing technique for coordinate measurement using an optically-trapped microsphere

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Engineered surfaces have been fabricated to provide enhanced properties such as low friction, anti-adhesive behavior, or low reflection of light. At micro-scales, surface force highly affects the functionality of mechanical parts. So as to reduce surface force such as friction, micro mechanical parts that have engineered surfaces are demanded. In order to investigate the functionality of the textured micro parts, it is necessary to evaluate both the three-dimensional shape and the surface topography along with its geometry. Then we propose hybrid probing technique using an optically trapped micro sphere. Tightly focused laser beam makes it possible for a dielectric micro sphere to sustain near the focal point in the air. The dynamic behaviour of the micro sphere changes as the result of the interaction of the surface. Therefore, the surface is detected by monitoring the micro sphere. This enables the three-dimensional shape measurement of the substrate. On the other hand, Surface topography is imaged with the lensing effect of the trapped micro sphere. Therefore, this trapped sphere is used as both a probe for coordinate metrology and a micro-lens in optical microscopy in this study. This present investigation deals with the development and fundamental validation of the hybrid measurement system with the optically trapped micro sphere. The measurement result with high performance was demonstrated using the diffraction grating.

10023-43, Session 7

Research on application of photoelectric rotary encoder in space optical remote sensor

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In space optical remote sensor, especially for wide swath detecting, focusing control system for the focal plane, which is the real-time control and dynamic measurement system, need to be designed to ensure the best image quality.

The measuring instrument called a potentiometer, which is used as position feedback devices in order to create “closed loop” control, is the simplest and important method of motion control used in this system. But both electro-mechanical and digital potentiometers generally have some limitations, such as poor tolerances, poor temperature coefficients and a stop resistance.

To resolve these issues as above, this article presents a new measuring method with photoelectric rotary encoder, consisting of the photoelectric conversion system and the signal process system. For using in the aerospace areas, three aspects of design should be considered seriously, including reliability, flexibility and simplicity, without making it complex.

In this focusing control system, the photoelectric conversion system is fixed with motor axis, which could real-time transform the angle information into a certain analog code signal. With the signal process system, after analog - to - digital converting and data format processing of the certain analog code signal, the focusing control system can receive the digital precision angle code which can reflect the current moving position of focal plane by conversion of angle-to-line.

As mentioned above, because of characters such as high resolution, high accuracy, long service life, and easy to maintain, this photoelectronic and precision angle measurement device is a good match for the focusing control system.

10023-44, Session 7

Application of grey relational analysis on lens distortion correction

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High-precision correction for lens distortion is the core technology in vision based measurements. The current linear regression method (LRM) which is based on statistical theory needs a mass of collinear points to estimate the lens distortion. However, since the size of image is constant in a certain camera. The more points mean greater measuring distance and lower measurement accuracy. In this paper, according to the principle of straight line projection invariance, a lens distortion correction method based grey relational analysis (GRA) is proposed. The proposed method utilizes particular grey relational degree of image feature points to estimate the distortion coefficients of lens. The GRA needs less feature points and owns higher computational precision compared with the LRM. In order to validate the validity of proposed method. Computer simulation and real experiment are conduct. The simulation results indicate that the proposed method is manifest well in different number of features points. In addition, the proposed method also compared with other LSM in a real experiment. The rectified images are used to calibrate the camera. The mean reprojection error using rectified images corrected by our proposed method is 0.127 pixels, which is one third less than 0.368 pixels by LSM. The results indicate that the measurement precision using proposed method is superior than LSM. At the meantime, the calibrated camera is used to construct vision measurement. The mean measurement error calculated by LSM is 0.173mm nearly two times than 0.095mm by GRA. Therefore, the proposed GRA is superior to LSM under the given experimental condition.

10023-45, Session 7

Detection algorithm of circular-coded point in vision measurement

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Distributing coded points on the measured object is a reliable and common method for achieving optimum target location and accurate matching of corresponding points among multi-view images?However, it is difficult to decode the coded point while the image noise and the projection angle is large. Aiming at solve this problem, an accurate and stable detection algorithm was proposed. Firstly, an accurate ellipse detection which can get sub-pixel locations was adopted to extract targets, and several rules according to the target’s shape and size were used to remove the non-target points. Then, gray scale gradient in the circular was calculated to find the point whose gray scale is changing, and the central angle of coded arc will be calculated to decode the target. Experiments show that the algorithm can identify and locate coded points accurately, and it is robust to the change of projection angle and noise.

10023-46, Session 8

An underwater ranging system by using photoacoustic effect on solid surface

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In this paper, an underwater ranging system based on photoacoustic effect on solid surface is proposed. Differing from the traditional photoacoustic detection system, in this proposal, a high power blue-green laser beam raying from a laser source that is located underwater, is directly incident on the target surface, where the photoacoustic effect on solid surface occurs and a sound source region is formed. The acoustic signal spreads outward from the sound source, later it is received by an ultrasonic receiver. According to the time delay between transmitting laser and receiving photoacoustic signal, and the speeds of light and sound under the water, the distance between the target and the detection system can be calculated. Since efficiency of the photoacoustic conversion on solid surface is higher than that of sea water under the same conditions, this system can ensure a large measurement range and at the same time a high spatial resolution. Based on this principle and preliminary calculation, a resolution of mm when a target is located at a distance of up to 200 m can be effectively achieved. Experimental system is constructed to verify the feasibility of this technology.

10023-47, Session 8

Rail profile control using laser triangulation scanners

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Railway state monitoring is needed to ensure the rail transportation safety. A wide range of parameters is a subject of monitoring: rail condition characteristics (defects inside rail and on the running surface) and the geometric parameters of track. The first ones are traditionally controlled using flaw detecting and

magnetometric systems. The latter are measured by determining the displacement of each rail section. It is traditionally carried out by the contact method that has obvious disadvantages. Therefore, non-contact (optical) methods are used in modern track condition monitoring systems.

Measurement of track gauge, cross level, longitudinal level and alignment requires knowledge of rails head location in each section. Displacement in transverse plane of rail head point located at a distance of 14 mm below the running surface must be controlled. It is carried out by detecting of each rail profile using triangulation laser scanners.

Optical image recognition is carried out successfully in the laboratory, approaches used for this purpose are widely known. However, laser scanners operation has several features on railways leading to necessity of traditional approaches adaptation for solving these particular problems. The most significant problem is images noisiness due to the solar flashes and the effect of "Moon path" on the smooth rail surface. Using of optical filters gives inadequate result, because scanner laser diodes radiation frequency varies with temperature changes that forbid the use of narrow-band filters. Consideration of these features requires additional constructive and algorithmic solutions, including involvement of information from other sensors of the system. The specific usage of optical scanners for rail profiles control is the subject of the paper.

10023-48, Session 8

Non-uniform sampling knife-edge method for camera modulation transfer function measurement

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Traditional slanted knife-edge method experiences large errors in the camera modulation transfer function (MTF) due to tilt angle error in the knife-edge resulting in non-uniform sampling of the edge spread function. In order to resolve this problem, a non –uniform sampling knife-edge method for camera MTF measurement is proposed. By applying a simple direct calculation of the Fourier transform of the derivative for the non-uniform sampling data, the camera super-sampled MTF results are obtained. Theoretical simulations for images with and without noise under different tilt angle errors are run using the proposed method. It is demonstrated that the MTF results are insensitive to tilt angle errors. To verify the accuracy of the proposed method, an experimental setup for camera MTF measurement is established. Measurement results show that the proposed method is superior to traditional methods, and improves the universality of the slanted knife-edge method for camera MTF measurement.

10023-49, Session 8

A precise reference position detection method for linear encoders by using a coherence function algorithm

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This paper proposed a new method for reference position detection with high precision for linear encoders by using a home designed scale grating and a coherence function algorithm. Differing from the traditional methods, in which the reference position alignment and calibration of reference position was achieved by detecting the peak of the signal with a negative pulse at the reference position, the method in this paper no longer detects the single peak of the signal, but matching and aligning the integral shape of reference position signal through the algorithm based on the coherence function. The proposed method does not require a complex design and precision manufacturing of reference position. Due to the coherence function algorithm, a multi-pulse reference position signals design is available, which not only reduces the difficulty of reference position design and manufacturing, but also shortens the length of reference position area so that the negative effect on the grating diffraction efficiency is limited. What is more, robustness of the reference detection method introduced here is greatly enhanced. Experimental results show that the accuracy of reference detection can still achieve 2 times of resolution even under the low signal to noise ratio (SNR) of 2dB.

10023-50, Session 8

Development of an edge sensor based on polyview optics and laser triangulation principle

Yinan Li, Hagen Bossmeyer, Markus Kästner, Eduard Reithmeier, Leibniz Univ. Hannover (Germany)

Laser line triangulation sensors as non-contact measurement devices are very desirable in many inspection and measurement situations. Compared to common sensors like capacitive, inductive or ultrasonic devices, laser line triangulation sensors are available with longer working distances, higher resolutions and accuracy specifications. In different applications and diverse industry sectors, the sensors are available with a wide variety of configurations and specifications which replace and outperform older types of contact measurement sensors. However, the common laser line triangulation sensors have a geometrical optics limit for the measurement range and direction. The measurement range of a single sensor is limited by the rotation angle between the imaging detector and the projected structured laser light. The measurement direction is limited by the 180° field of view (FOV) of the imaging lens and the 2D detector, which have flat light sensitive elements like CCDs or CMOS. For this reason, to scan samples with great curved surfaces like edges, a single laser line triangulation sensor is not capable of measuring the entire form of the object. In this case, an entire 3D edge measurement requires either multiple measurements of one single sensor from different directions or a multi sensor system. The purpose of this paper is to explain the development of an edge sensor based on in-house designed polyview optics and the well-known laser triangulation principle. The configuration, the calibration process and the measurement results of this edge sensor will be discussed.

10023-51, Session 8

Arbitrary optical frequency synthesis traced to an optical frequency comb

Zihang Cai, Honglei Yang, Yan Li, Haoyun Wei, Tsinghua Univ. (China)

An arbitrary optical frequency synthesizer with a broad tuning range and high frequency accuracy is presented. The system includes an external cavity diode laser (ECDL) as the output laser, an Erbium-doped optical frequency comb being a frequency reference, and a control module. The optical frequency from the synthesizer can be continuously tuned by the large-scale trans-tooth switch and the fine intra-tooth adjustment. Robust feedback control by regulating the current and PZT voltage enables the ECDL to phase-lock to the Erbium-doped optical frequency comb, therefore to keep stable frequency output. In the meanwhile, the absolute frequency of the synthesizer is determined by the repetition rate, the offset frequency and the beat frequency. All the phase lock loops in the system are traced back to a Rubidium clock. A powerful and friendly software is developed to make the operation convenient by integrating the functions of frequency setting, tuning, tracing, locking and measuring into a LabVIEW interface. The output frequency tuning span and the uncertainty of the system are evaluated as >4 THz and <3 kHz, respectively. The arbitrary optical frequency synthesizer will be a versatile tool in diverse applications, such as synthetic wavelength based absolute distance measurement and frequency-stabilized Cavity Ring-Down Spectroscopy.

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10024-1, Session 1

Self-assembled photonic crystals for bioassay *(Invited Paper)*

Zhongze Gu, Southeast Univ. (China)

Photonic crystal (PC) is composed of two and more mediums with periodic nanostructure. The unique optical property and characteristic nanostructure of the PC provide effective means for biological and chemical analyses. In our group, we developed a series of analytical methods by using self-assembled PC.

1) Label-free detection of biomolecule. By utilizing the volume and refractive index change of biomolecules in PC,we realized label-free detection and visual detection of biomolecules.

2) Analysis of gas. Mesoporous PC with high specific surface are developed. By using this kind of material, we realized the analysis of gas molecules with PC.

3) Multiplex detection. One of the key techniques of multiple biological analysis is to identify different biological events simultaneously. Biomolecule encoding is the core technique for them ultiplex detection. By taking advantage of the spectrum-encoding ability of the PC, we fabricated the encoding carriers for biomolecules with low fluorescence background and high-stability.

4) PC paper-based chips. We realized the separation of biomolecules by taking advantage of the periodic nanostructure of PC. Meanwhile, the fluorescent signal for detection was enhanced due to the stop-band of the PC.

5) Organ chip analysis. We fabricated 3D cells caffolds on microfluidic chips to simulatethe in vivo environment for cell growth.On-line analysis was also realized with the PC microcarriers.

10024-2, Session 1

Angular compounded optical coherence tomography angiography for flow contrast enhancement

Pei Li, Liping Zhou, Zhejiang Univ. (China); Yuxuan Cheng, Zhejiang Univ (China); Zhihua Ding, Peng Li, Zhejiang Univ. (China)

Optical coherence tomography angiography (Angio-OCT) is a promising imaging modality that is capable of providing a label-free, high-resolution and high-contrast image of biological tissue microvasculature. Typically, the blood flow contrast is implemented by mathematically analyzing the temporal dynamics of light scattering, and setting a threshold to distinguish the dynamic blood flow from the static tissue bed. However, high flow contrast is degraded by the residual overlap that results in misclassification errors between dynamic and static signals in statistical analysis. We have demonstrated that flow contrast can be enhanced using a novel angular compounded Angio-OCT to facilitate the interpretation of angiograms. Because a continuous modulation is induced by the offset that the probing light is away from the beam center in the typical OCT sample arm, different incidence angles in the probing beam can be encoded in B-scan modulation frequencies. The complex-valued spectral interferogram is reconstructed by removing the conjugate terms in the depth space and its Fourier transform along the transversal fast-scan direction generates a wide conjugate-free B-scan modulation spectrum in the full space of the spatial domain. By splitting the modulation spectrum, angle-resolved independent sub-angiograms are generated and then compounded to enhance the flow contrast. Both flow phantom and in vivo animal studies on cerebral vascular imaging demonstrated that the proposed angular compounded Angio-OCT can offer a ~50% decrease of misclassification errors and an improved flow contrast and vessel connectivity. This method is beneficial to facilitating the interpretation of OCT angiograms in clinical applications.

10024-3, Session 1

Optical Image-guided cancer surgery

Xiao Feng Yang, First Hospital of Shanxi Medical Univ. (China)

Design visible and near-infrared LED ring light, multi-channel band-pass filter, multi-spectral 2 CCD cameras, image fusion software, we have developed the surgical navigation system with beam split and fusion the visible and near-infrared fluorescence by technology integration research, and established the production process and testing system.

Image-guided cancer surgery has the potential to be a powerful tool in guiding future surgical care. Photoimmunotherapy is a theranostic concept (simultaneous diagnosis and treatment) on the verge of clinical translation, and is highlighted as an effective combination of image-guided surgery and intraoperative treatment of residual disease. Multispectral optoacoustic tomography, a technique complementary to optical image-guided surgery, is currently being tested in humans and is anticipated to have great potential for perioperative and postoperative application in surgery.

Phage display and the human non-muscle-invasive bladder cancer cell line BIU-87 were used to identify a peptide. The isolated phage display peptide (CSSPIGRHC, named NYZL1) was tested in vitro for its binding specificity and affinity. Accumulation into xenograft tumors in a nude mouse model was analyzed with FITC-labeled NYZL1. NYZL1, with strong tumor homing ability, was identified by in vivophage library selection in the bladder cancer model. The NYZL1 phage and synthetic FITC-labeled NYZL1 peptides bound to tumor tissues and cells, but were hardly detected in normal control organs. Notably, accumulation of FITC-NYZL1 in bladder tumor cells was time-dependent. Biodistribution studies of xenografts of BIU-87 cells showed accumulation of injected FITC-NYZL1 in the tumors, and the bound peptide could not be removed by perfusion after 24 h.

10024-4, Session 1

The development of intravascular photoacoustic/ultrasonic/OCT tri-modality imaging technology for vulnerable plaque identification

Xiaojing Gong, Ji Leng, Riqiang Lin, Liang Song, Shenzhen Institute of Advanced Technology (China)

The rupture of vulnerable plaques is the major cause of acute heart attacks and strokes. The accurate diagnosis of vulnerable plaque is of vital important for the treatment, which depends on the identification of some key morphological and functional features, including thin fibrous caps, large lipid-rich cores, increased inflammation, and vasa vasorum. Current clinical intravascular imaging modalities, such as intravascular ultrasound (IVUS) and intravascular optical coherence tomography (IVOCT), are mainly capable of detecting plaque morphological features such as the overall plaque burden and thin fibrous caps. However, the detecting of lipid pool and inflammation remains challenging

for them. Intravascular photoacoustic (IVPA) imaging is capable of imaging the plaque composition and inflammation, benefiting from its high sensitivity to optical absorption. Consequently, the integration of IVPA, IVUS and IVOCT will provide the ability of acquiring both morphological and physiological information simultaneously.

In this study, for the first time to our knowledge, a tri-modality intravascular imaging system is developed, which is capable of photoacoustic, ultrasonic, and OCT imaging with a single catheter of ~0.9 mm in diameter. As a feasibility study, we validated the system by photoacoustic spectroscopic imaging of peri-adventitial adipose tissue excised from a porcine heart and tri-modality imaging of a stent deployed within a healthy rabbit aorta segment. These improvements potentially enable the acquisition of comprehensive macroscopic and microscopic structural information as well as the functional information, such as plaque composition and inflammation, leading to more accurate identification of vulnerable plaques.

10024-5, Session 1

Malignant melanoma and basal cell carcinoma control with Raman and autofluorescence spectroscopy

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Problem of increased incidence of cancer is known worldwide. For instance yearly in Russia more than half a million cases of cancers are registered and the largest amounts of deaths are caused by melanomas. In this regard optical methods may be very useful for tissues analysis. They allow one to find chemical composition of tested tissues in vivo and in real time mode.

In this study we present a method of skin neoplasms analysis based on Raman and autofluorescence effects. Raman signal was stimulated by 785 nm laser and autofluorescence was stimulated in visible and NIR regions by two lasers 457nm and 785 nm. Experiments were approved by the ethical committee of Samara State Medical University. More than 100 tissue samples were tested. Raman and autofluorescence spectrums were registered for neoplasms and surrounding normal tissues to design an optical method of malignant tissues detection. For melanomas and basal cell carcinomas detection proposed method demonstrated accuracy of 91% and 89% for Raman spectra and autofluorescence analysis correspondently. Combination of Raman and autofluorescence spectra analysis leads to the increase of precise malignancy detection up to 96%.

Proposed method of skin neoplasms optical analysis demonstrate high potential for malignant melanomas detection Analysis of autofluorescence spectra is simple and may be used in mass screening applications, as fluorescecne registration is possible within a few seconds. Raman spectra registration helps to increase accuracy of oncological pathologies diagnosis, but requires more time for spectra collection.

10024-6, Session 1

Quantitative detection of tissue fluorescence

Jian Zou, Wei Gong, Weijun W. J. Li, Fujian Normal Univ. (China); Qing Ye, Provincial Clinical Medical College of Fuzhou Medical Univ. (China); Zheng Huang, Fujian Normal Univ. (China) and Univ. of Colorado Denver (United States)

Fluorescence is the emission of light from a fluorescence substance that absorbs light or other electromagnetic radiation, in which the wavelength of emission is the same or different from the excitation radiation in the de-excitation. Tissue fluorescence is divided into intrinsic and extrinsic origins. The method of signal collection and data processing of tissue fluorescence might be divided into two categories: fluorescence imaging and fluorescence spectroscopy. The quantitative detection of tissue fluorescence is still challenging. In this study, we designed, built and validated an in vivo tissue fluorescence detection system based on the absorption and emission spectra of the target fluorescent substance. In ex vivo experiment, we utilized a tissue model by controlling the absorption and scattering coefficients. We optimized excitation and examined the irradiance with standard light source. In in vivo experiment, by processing the acquired fluorescence emission spectra of the fluorescent substance, tissue optical properties (e.g. ?a and ?s), and the calibrated absorption of excitation and emission light, we could quantitatively calculate the fluorescence intensity. Further by extracting the fluorescent substance from tissue we verified the accuracy and reliability of fluorescence detection system. Experimental results show that this approach might provide a noninvasive real-time and sensitive method for tissue fluorescence quantitative detection.

10024-7, Session 2

Nanoprobes for optical bioimaging and light-enacted therapy *(Invited Paper)*

Tymish Y. Ohulchanskyy, Shenzhen Univ. (China) and Univ. at Buffalo (United States); Junle Qu, Shenzhen Univ. (China)

The ability of light to penetrate a tissue is a key to diagnostic (e.g., optical bioimaging) and therapeutic (e.g., light induced therapy) applications of biophotonics, which is among the most promising and actively developing multidisciplinary approaches that are expected to make a major impact on health care. This presentation will provide results of our work on multifunctional nanostructures comprising inorganic and organic materials to tailor the nanoformulations for optical bioimaging and light induced therapy. The photoactive nanoplatforms, which will be presented, include organic polymer and silica-based nanoparticles, rare-ion doped nanophosphors, magnetic and plasmonic nanoparticles, as well as their hybrids. While providing optical contrast, the developed nanoplatforms can be also garnished with other imaging modalities, enabling the integration of cellular, tissue and whole body imaging and allowing us to employ a single formulation within multiple imaging techniques. Coupled with a therapeutic payload and conjugated with specific targeting agents, these imaging nanoplatforms turn into theranostics agents which act in the treatment of a disease and provide for real-time monitoring of the treatment efficacy. As a result, theranostics nanoparticles, which combine therapeutics and medical imaging modalities, allow for the “see and treat” and “see-treat-and see” approaches. The talk will demonstrate examples of applications of nanoparticles as optically traceable agents for detection and treatment of cancer and conclude with a discussion on the challenges and opportunities in the field of optical bioimaging and light induced therapy using photoactive nanoformulations.

10024-8, Session 2

A novel handheld linear-array photoacoustic probe towards clinical translation for sentinel lymph node mapping

Chengbo Liu, Mucong Li, Liang Song, Shenzhen Institute of Advanced Technology (China)

Breast cancer is the leading cause of death to women around the world. Sentinel lymph node (SLN) biopsy is currently the standard of care for staging of this disease. To conduct SLN biopsy, radioactive tracers and dyes are injected followed by an open surgery to identify SLN, causing major complication risks. Photoacoustic (PA) imaging is gaining widespread attention due to excellent imaging contrast and high resolution for deep imaging, which has also been demonstrated to be able to identify SLN after localized administration of PA contrast agents, and therefore potentially eliminate the usage of radioactive tracers and invasive open surgery. To perform SLN imaging in clinics, several research groups tried integrating PA imaging into clinical ultrasound imaging system by applying laser excitation from the side of the handheld linear array ultrasound probe. Simple as it is, this design suffers from low laser energy utilization efficiency and inconvenient handling of the probe due to the oversize issue.

In this study, we developed a compact handheld linear array PA imaging probe based on a novel optical-acoustic co-axial design. Compared with previously reported probes, our probe is more clinically friendly and the excitation laser energy is more efficiently utilized, enabling higher signal-to-noise ratio (SNR) as well as deeper imaging capability. The performance of the probe was validated by imaging a rat SLN embedded 2 centimeters below tissue surface in vivo.

The improved SNR together with reduced probe size suggests the handheld probe is of great potential to be further translated for clinical applications.

10024-9, Session 2

Boronate affinity structural colored contact lens for tear glucose monitor

Panmiao Liu, Zhuoying Xie, Zhongze Gu, Southeast Univ. (China)

Rapid increasing of diabetes mellitus is now global problem and development of a safe and convenient blood sugar level monitoring technology is strongly required. While “finger pricking” is a relatively painless and commonly used method for blood glucose monitoring today, there are several points to be improved.

Colloidal crystals, three-dimensional periodic microstructural materials, have successfully been applied in some chemical and biological moleculars sensing. In particular, the colloidal crystal hydrogels with three dimensional network structures exhibt reversible physical dimension changes, such as expansion and contraction, with the variation of external environment. The change will alter the spacing of periodic structure of colloidal crystal, leading to the variation of diffraction wavelength.

In this research, we present a novel strategy for the glucose monitor by boronate affinity structural colored contact lens. Structural colored contact lenses are fabricated by a typical commercial contact lenses hydrogel colored by colloidal crystals paints. Colloidal crystals paints are the close-packed inverse opal void nanostructure, and also the non-close-packed colloid particles ordered nanostructure. With the boronate a?nity as the functional elements for pre-hydrogel of contact lens, contact lens hydrogel reversibly appeals alternatives to glucose molecules. As a resualt, when the glucose molecules combine with boronate reactive sites, hydrogel network structure expands, increasing the spacing of periodic structure of the colloidal crystal and leading to the red-shift of the diffraction wavelength, which can be monitored by fiber optic spectrometer.

10024-11, Session 2

Detection and classification of ebola on microfluidic chips

Xue Lin, Tsinghua Univ. (China); Qin Huang, Yue Kou, National Engineering Research Ctr. for Beijing Biochip Technology (China)

Point-of-care testing (POCT) for an infectious diseases is the prerequisite to control of the disease and limitation of its spread. A microfluidic chip for detection and classification of four strains of Ebola virus was developed and evaluated. This assay was based on reverse transcription loop-mediated isothermal amplification (RT-LAMP) and specific primers for Ebola Zaire virus, Ebola Sudan virus, Ebola Tai Forest virus and Ebola Bundibugyo virus were designed. The sensitivity of the microfluidic chip was under 1000 copies per milliliter, as determined by ten repeated tests. This assay is unique in its ability to enable diagnosis of the Ebola infections and simultaneous typing of Ebola virus on a single chip. It offers fast reaction time, ease of use and high specificity. These features should enable POCT in remote area during outbreaks of Ebola virus.

10024-12, Session 2

A noninvasive optical technique for stenosis surveillance of a hemodialysis vascular graft

Boonsong Sutapun, Lawan Sampanporn, Suranaree Univ. of Technology (Thailand); Armote Somboonkaew, National Electronics and Computer Technology Ctr. (Thailand)

Prosthetic grafts have been used as a bypass conduit for a hemodialysis in renal failure. The grafts may develop stenosis and leading to subsequent thrombosis. Frequent monitoring and surveillance of vascular access are important to the care of hemodialysis patients. Early stenosis identification could enable intervention prior to thrombosis. For surveillance of the grafts, blood flow and pressure are measured with color-flow duplex ultrasound and dynamic venous pressure techniques. These techniques take considerable amount of time and cost and require expensive equipment. In this work, we report the feasibility study of using a near-infrared (NIR) imaging for noninvasive stenosis surveillance. Optical properties of human skin and tissues allow NIR light to penetrate deep enough to visualize the blood vessels. Vascular grafts are made from plastic that has a large different optical absorption in the NIR from that of the surrounding tissues. As a result, the graft luminal diameter and shape detection should be possible using the NIR imaging. In this study, we have developed a phantom with an embedded polytetrafluoroethylene (PTFE) tubing mimicking human tissue and a hemodialysis graft, respectively, to evaluate the possibility of the proposed technique. We found that NIR image can be used to visualize and differentiate the PTFE tubes with a diameter of 4-8 mm at the depth up to 6 mm. Future work on an in vivo vascular graft imaging experiment to explore the clinical possibility of the NIR imaging technique will be discussed.

10024-13, Session 3

Cell counting for in vivo flow cytometry with unstable background signals *(Invited Paper)*

Xunbin Wei, Shanghai Jiao Tong Univ. (China)

The in vivo flow cytometry (IVFC) is a useful technology to detect circulating cells dynamically in living animals, especially in the study of cell tracking, cancer metastasis. In practice, unstable background signals exist in IVFC data due to animals' respiratory movement, limb movement and photo-bleaching of tissue auto-fluorescence. Here we developed a processing method that could remove baseline drift using interpolation fitting, automatic segmentation and wavelet denoising. Compared with previous non-correction methods, i.e. the "line-gating" method or threshold method, this method showed higher sensitivity and specificity, as well as better Pearson's correlation coefficient and mean-squared error (MSE).

10024-14, Session 3

Microwave-induced thermoacoustic imaging system based on flexible transducer

Zhong Ji, Sihua Yang, Da Xing, South China Normal Univ. (China)

Microwave-induced thermoacoustic (TA) imaging combines the advantages of high imaging contrast due to electromagnetic absorption and high resolution of the ultrasound technology, and it is a potential alternative imaging technique for biomedical applications, particularly for breast tumor detection. The traditional TA system uses circular-scanning (CS) to obtain complete information to reconstruct a two-dimensional image, however, it needs a large operating space for rotation of the transducers and bulk of coupling medium limiting its medical applications. The linear-scanning (LS) system can overcome these problems partially but usually lose some information and cause image distortion. In this paper, in order to overcome above limitations, a TA imaging system with Sample-Cling-Scanning (SCS) model based on a flexible multi-element transducer is presented. It combines the advantages of both CS and LS modes, and overcome their limitations. Meanwhile, an adaptive back projection algorithm is presented to implement this scanning model. The experimental results show that the proposed system combines advantages including shape adaptation, information integrity, and efficient transmission. These advantages make it a preferred system for TA applications, especially in breast tumor detection.

10024-15, Session 3

Evaluation of the resolution of a commercial swept source OCT using point spread function phantom

Wei Gong, Weijun W. J. Li, Kui Dong, Shusen Xie, Zheng Huang, Fujian Normal Univ. (China)

Optical coherence tomography (OCT) is a useful tool in biomedical imaging. For structural imaging it is equally important to improve the resolution of OCT system and to accurately assess the sizes of structural components of inhomogeneous biological tissues from OCT images. Recently, point spread function (PSF) phantoms with randomly distributed nanoparticles in a transparent matrix have been used for evaluating the resolution and image quality of OCT. In this study, iron oxide particles embedded in polyurethane was used as the PSF phantom for objectively evaluating the resolution of a commercial model of swept source OCT. The density of iron oxide particles was approximately 7500 per mm3. For assessing and comparing the performance of the OCT system, OCT images of the PSF phantom were obtained, 3D spatial variations in PSF intensity, and FWHM in the axial and lateral directions in combination with volumetric representations of individual PSF were analyzed. Test results suggest that the PSF phantom is a reliable means for the intercomparison of OCT resolution and assessment of the sizes of some biological samples.

10024-16, Session 3

Second-generation photoacoustic and optical coherence tomography probe for in vivo human vasculature visualization

Mengyang Liu, Christoph Sinz, Zhe Chen, Behrooz Zabihian, Harald Kittler, Wolfgang Drexler, Medizinische Univ. Wien (Austria)

Both photoacoustic tomography (PAT) and optical coherence tomography (OCT) are comparatively novel optical imaging modalities for biophotonics. The combination of a swept source OCT (SS-OCT) system with an all optical detection PAT system has been developed and demonstrated from ex vivo embryonic imaging to in vivo human imaging. While morphological volumes provided by OCT in the optical mean free path has complemented the PAT volumes which show the major blood vessels, PAT's low spatial resolution makes it not capable of visualizing the microvasculature in the first mm in tissue. OCT angiography, therefore, has been explored in the combined PAT/OCT system to visualize capillaries. The first generation system uses a probe mounted on a modified microscope boom stand and has been shown to be able to apply to different parts of human body. However, the articulated arm and the probe with recessed sensor holder limits its application in clinics. It requires high level of patient compliance and the location to be imaged is restricted. In our second generation design, a homemade rack with a medical bed has been manufactured along with limb fastening vacuum pad for human extremity fixation. The probe can be adjusted in multiple dimensions with accuracy. The protruding sensor holder design also permits imaging in flattened regions of skin. With the options to either seat or lay the patient, our second generation PAT/OCT system gives unprecedented versatility in clinical applications. Both healthy subjects and patients with skin diseases are imaged using our second generation PAT/OCT system to demonstrate its clinical significance.

10024-17, Session 3

All-optically integrated multimodality imaging system: combined photoacoustic microscopy, optical coherence tomography, and fluorescence imaging

Zhongjiang Chen, Sihua Yang, Da Xing, South China Normal Univ. (China)

We have developed a multimodality imaging system by optically integrating all-optical photoacoustic microscopy (AOPAM), optical coherence tomography (OCT) and fluorescence microscopy (FLM) to provide complementary information including optical absorption, optical back-scattering and fluorescence contrast of biological tissue. By sharing the same low-coherence Michelson interferometer, AOPAM and OCT could be organically optically combined to obtain the absorption and scattering information of the biological tissues. Also, owing

to using the same laser source and objective lens, intrinsically registered photoacoustic and fluorescence signals are obtained to present the radiative and nonradiative transition process of absorption. Simultaneously photoacoustic angiography, tissue structure and fluorescence molecular in vivo images of mouse ear were acquired to demonstrate the capabilities of the optically integrated trimodality imaging system, which can present more information to study tumor angiogenesis, vasculature, anatomical structure and microenvironments in vivo.

10024-18, Session 3

Extinction measurement of dense media by an optical coherence tomography technique

Toshiaki Iwai, Tomoki Ago, Ryoko Yokota, Tokyo Univ. of Agriculture and Technology (Japan)

Absorption-scattering imaging by an optical-coherence tomography (OCT) technique has been investigated for biological tissues. The Beer-Lambert law as a function of path-length of the light propagated in a dense medium is applied to estimate amount of extinction. Since multiple scattering becomes dominant in the biological tissue, the path-length of the light scattered in the tissue cannot be obtained uniquely and deterministically. Therefore, a total path-length estimated in advance by the Mote Carlo simulation is applied to the modified Beer-Lambert law. On the other hand, the OCT image of the biological tissue can be reconstructed by using only the light propagated rectilinearly and retro-reflected from scatters which preserves its coherence. Therefore, the OCT technique will be available to measure absorption and scattering coefficients even for the dense medium directly by using the Beer-Lambert law. It, however, has not yet been experimentally confirmed that the BL-law is effective for diffusing light by multiple scattering as long as we know. The quantitative verification of BL-law in the OCT imaging is experimentally conducted in in this study. As a result, it is shown that the scattering and absorption coefficients can be successfully estimated for phantoms composed of silica particles with a given size as a scatterer and ink as an absorber.

10024-19, Session 4

A microflow cytometer with integrated on-chip optical components for blood cell analysis *(Invited Paper)*

Yingying Zhao, Qin Li, Xiaoming Hu, Beijing Institute of Technology (China)

In recent years, microfluidic technologies have shown the great potential in developing portable, point-of-care testing (POCT) blood cell analysis devices. It is challenging to integrate all free-space detecting components in a single microfluidic platform. In this paper, a microflow cytometer with integrated on-chip optical components was demonstrated. To facilitate on-chip detection, the device integrated optical fibers and on-chip microlens with microfluidic channels on one polydimethylsiloxane (PDMS) layer by standard soft photolithography. This compact design increased the sensitivity of the device and also eliminated time-consuming free-space optical alignments. Polystyrene particles of 4?m, 6?m, 10?m diameter, together with erythrocytes and platelets, were measured in the microflow cytometer by small angle forward scatter light. Experimental results indicated that the performance of the microflow device was comparable to a conventional cytometer, and also demonstrated its ability to detect on-chip optical signals in a highly compact, simple, truly portable and low cost format which was perfect suitable for POCT clinical haematology diagnostics.

10024-20, Session 4

A weighted optimization method for irradiance distribution planning of port wine stains with photodynamic therapy

Linhuan He, Xiaoming Hu, Ya Zhou, Beijing Institute of Technology (China)

Planning of irradiance distribution (PID) is one of the foremost factors for on-demand treatment of port wine stains (PWS) with photodynamic therapy (PDT). A weighted optimization method for PID was proposed according to the grading of PWS with the help of a three dimensional digital illumination instrument, which would improve the treatment efficacy in each session of PDT. First, the point clouds for three dimensional reconstruction were filtered to remove the error points and redundant points, the triangulation was carried out and the lesions was divided into many small triangular patches. The parameters for optimization of each triangular patch such as area, normal vector and orthocenter were calculated from the triangulation results. The weight coefficients were determined by the erythema indexes and areas of patches. Then, the initial point was calculated based on the normal vectors and orthocenters to optimize the light direction. The irradiation can be optimized according to cosine values of irradiance angles and weight coefficients. Comparing the irradiance distribution before and after optimization, the proposed weighted optimization method can make the irradiance distribution match better with the characteristics of lesions, and has the potential to improve the therapeutic efficacy.

10024-21, Session 4

Macroscopic singlet oxygen modeling for in vivo Photofrin-mediated photodynamic therapy dosimetry study

Haixia Qiu, Chinese PLA General Hospital (China) and Univ. of Pennsylvania (United States); Michele M. Kim, Univ. of Pennsylvania (United States); Rozhin Penjweini, Timothy C. Zhu, The Univ. of Pennsylvania Health System (United States)

Although photodynamic therapy (PDT) is an established modality for the cancer treatment, the ideal dosimetric predictor for PDT outcome is still unavailable. As the primary cytotoxic factor responsible for tumor destruction in the type II reaction, singlet oxygen (1O2) dosimetry deserves more consideration. In this in vivo study, a macroscopic singlet oxygen model was adopted to evaluate the ability of the calculated reactive singlet oxygen ([1O2]rx) as a dosimetric predictor for the outcome of Photofrin-mediated PDT. Mice with radiation-induced fibrosarcoma (RIF) tumor were subjected to PDT of different fluence (50, 135, 200 and 250 J/cm2) under different fluence rate (50, 75 and 150 mW/cm2). Tumor regrowth rate (k) was calculated by fitting the measured tumor volume to an exponential growth equation. By incorporating Photofrin concentration and the tissue optical properties as well as light dose (fluent rate and fluence) into the macorscopic singlet oxygen model, [1O2]rx was calculated. Then, the tumor cure index was correlated to the calculated [1O2]rx, the light fluence and PDT dose, respectively. The result showed among these three metrics, [1O2]rx had the best correlation with the tumor cure index with the R2=0.93. These preliminary results suggest that [1O2]rx could serve as a better dosimetric predictor for predicting PDT outcome.

10024-22, Session 4

Stage scoring of liver fibrosis using Mueller matrix microscope

Jialing Zhou, Tsinghua Univ. (China); Honghui He, Ye Wang, Hui Ma, Graduate School at Shenzhen, Tsinghua Univ. (China)

Liver fibrosis is a common pathological process of varied chronic liver diseases including alcoholic hepatitis, virus hepatitis, and so on. Accurate evaluation of liver fibrosis is necessary for effective therapy and a five-stage grading system (F0-F4) was developed. Currently, experienced pathologists use stained liver biopsies to assess the degree of liver fibrosis. However, it is difficult to obtain highly reproducible results because of discrepancy among different observers. Polarization imaging technique has the potential of scoring liver fibrosis since it is capable of probing the structural properties of samples. Considering that the Mueller matrix measurement can provide comprehensive microstructural information of the tissues, in this paper, we apply the Mueller matrix microscope to human liver fibrosis slices in different fibrosis stages. We adopt the Mueller matrix polar decomposition (MMPD) and Mueller matrix transformation (MMT) parameters for quantitative analysis. We also use the Monte Carlo simulation to study the method to remove orientation dependence of the Mueller matrix, and analyze the relationship between the microscopic Mueller matrix parameters and structural changes during the fibrosis process. The experimental and Monte Carlo simulated results show good consistency. The parameters corresponding to retardation increase and the distribution of the fast axis angle becomes more concentrated as the liver fibrosis getting more serious. The results presented in this paper indicate that the Mueller matrix microscope and the orientation independent Mueller matrix parameters can provide additional information for the detections and fibrosis scorings of liver tissues. Thus, it has a good application prospect in liver fibrosis diagnosis.

10024-23, Session 4

3D printing of tissue-simulating phantoms for calibration of biomedical optical devices

Zu Hua Zhao, Ximing Zhou, Shu W. Shen, Guang Li Liu, Li Yuan, Yu Q. Meng, Xiang Lv, Peng Fei Shao, Erbao Dong, Univ. of Science and Technology of China (China); Ronald X. Xu, The Ohio State Univ. (United States)

Clinical utility of many biomedical optical devices is limited by the lack of effective and traceable calibration methods. This limitation induces the pressing need for a phantom standard to calibrate medical optical devices. Optical phantoms that simulate biological tissues have been explored for optical device calibration in clinical settings. Various optical phantoms are fabricated by the methods such as mold casting, spin coating and 3D printing. However, these phantoms can hardly simulate both structural and optical properties of multi-layered biological tissue. To address this limitation, we develop a 3D printing production line that integrates different rapid manufacturing processes for freeform fabrication of optical phantoms with mechanical and optical heterogeneities. The production line consists of a three-dimensional mobile platform and different modules for spin coating, light-cured 3D printing and Fused Deposition Modeling (FDM) respectively. With the Polydimethylsiloxane (PDMS), colorless light-curable ink?and gel wax as matrix materials, titanium dioxide (TiO2) powder as the scattering ingredient, graphite powder and black carbon as the absorption ingredient, a multilayer phantom with high-precision is fabricated. The absorption and scattering coefficients of each layer are measured by a double integrating sphere system. The results demonstrate that the system has the potential to fabricate reliable tissue-simulating phantoms to calibrate optical imaging devices.

10024-24, Session 4

Effect of surface topographic features on the optical properties of skin: a phantom study

Guang Li Liu, Jian Feng Chen, Yilin Han, Zu H. Zhao, Gang Zhao, Erbao Dong, Univ. of Science and Technology of China (China); Ronald X. Xu, The Ohio State Univ. (United States)

Tissue-simulating phantoms are used to validate and calibrate optical imaging systems and to understand light transport in biological tissue .Light propagation in a strongly turbid medium such as skin tissue experiences multiple scattering and diffuse reflection from the surface. Surface texture and roughness have considerable influence on the optical characteristics of skin. Surface roughness introduces phase shifts and optical path length differences for light scattered within the skin tissue and that reflected from the surface. In this paper, we study the effect of mismatched surface roughness on optical measurement and subsequent determination of optical properties of skin tissue. A series of phantoms with controlled surface features and optical properties corresponding to normal human skin are fabricated. The fabrication of polydimethylsiloxane (PDMS) phantoms with known surface roughness follows a standard soft lithography process. Surface roughness of skin-simulating phantoms are measured with optical stylus profiler. To obtain single layer equivalent skin tissue ,the thickness (between 9 and 370 ?m) is controlled using a spin coater. The diffuse reflectance of the phantom is validated by a UV/VIS spectrophotometer .The results show that surface roughness plays an important role in the determination of optical properties of phantoms .This study suggests that surface roughness should be considered as an important contributing factor for the determination of tissue optical properties.

10024-25, Session 4

Structured light imaging system for characterization of tissue-simulating phantoms

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The pressing need for a phantom standard to calibrate medical optical devices has made 3D printing of tissue-simulating phantoms one of the hotspots and difficulties in 3D printing field. Its difficulties include not only how to print the tissue-simulating phantoms but also how to characterize them. Measurement tools such as computed tomography (CT), optical coherence tomography (OCT), magnetic resonance imaging (MRI), and step profiler has been used to characterize the phantoms' internal structure or external profile; double-integrating sphere system, frequency domain photon migration technique (FDPM) has been used to characterize the phantoms' optical properties. But none of them can characterize both 3D profile and optical properties at the same time. To overcome this limitation, we develop a structured light imaging system which can characterize both 3D profile and optical properties at the same time with the same set of equipment. The system consists of a hyperspectral light source, digital light projector (DLP), CCD/CMOS camera,

rotational platform, and two polarizers. We choose double-integrating sphere system to characterize our system's ability in reconstruction of optical properties. The results show that the system can get a pixel-level optical properties with an error of within 10%. At the same time, an accuracy of submillimeter of 3D profile can be retrieved from this system. All of this demonstrate that our system has the potential to characterize homogeneous and even heterogeneous tissue-simulating phantoms.

10024-26, Session 4

1040nm femtosecond fiber laser system for the regain accommodation of the crystalline lens

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Presbyopia is the diminished ability of eyes to focus on near objects, which happens to every human with growing age. The origin of the presbyopia is the loss elasticity of the lens due to the increasing sclerosis. Femtoseocnd laser which has achieved great success in the refractive surgery, is applied in the crystalline lens to regain the accommodation of the lens tissues. We have build an femtosecond fiber laser based on the chirped pulse amplification technology. An femtosecond fiber oscillator delivers 1040 nm laser pulses with compressed pulse duration of 150 fs. After three stages of amplification, and compressed by a two-pass configuration grating, femtosecond laser pulses with pulse energy of 3 ?J, pulse duration of 400 fs at 200 kHz are achieved. In order to create structure in the crystalline lens, a three dimensional scan system is constructed, which consists of a telescope, an aspherical lens, a galvanometric scanner and a translation stage. Since the diameter of the femtosecond is 3 mm, the telescope and the an aspherical lens are employed to improve the focus quality. While the galvanometric scanner is used to generate a two dimensional scan in the crystalline lens, and the translation stage where the crystalline lens is mounted adds another movement direction. The integrated system can perform the three dimensional cut in the crsytalline lens with a foucs of 25 ?m diameter. The whole system is easy to start, insensitive to outside distortions and can be improved for clinical use.

10024-27, Session 4

Simulation study of haze weather based on particle system

Jiwei Ning, Beijing Univ. of Posts and Telecommunications (China)

Since 2013, the haze weather was more and more serious. Haze weather has produced great harm on human health and traffic safety. Effectively to predict the interval of the haze weather pollution, pollution degree, realize the real-time simulation of haze weather, for the environment protection, human health, preventing traffic accidents, improving labor productivity and so on all is of great significance. Based on the analysis of the characteristics and causes of haze weather, using the particle system and texture mapping and optical principle , I established the mathematical model for describing the haze weather. Using OSG (OpenSceneGraph), I has realized the real-time simulation and analysis of haze weather.

10024-28, Session 5

Challenges of large-scale data processing for visible brain-wide networks *(Invited Paper)*

Qingming Luo, Huazhong Univ. of Science and Technology (China)

The brain is the most complex and significant organ, but little is known about the mechanisms of brain function yet. Brain functions rely primarily on neuronal networks rather than on individual neurons, thus we promote the Visible Brain-wide Networks (VBN) project covering neuron morphology, neuronal circuits, cyto-architecture and vascular networks, which is the basis of understanding the brain function.

We obtained the dataset of whole mouse brain with Micro-Optical Sectioning Tomography (MOST) system at single-neuron resolution which directly demonstrates the whole-brain structural connectivity. After data collection, we developed a pipeline to reconstruct the complete morphology and long-range projection of neuron. Meanwhile, from the Nissl-stained dataset, we can also get the division of brain regions and nuclei based on cyto-architecture and the blood vessel. Based on the accumulated dataset, we can perform analysis and simulation, even it is beneficial to artificial intelligence.

However, we also met many challenges. The big data problem is the most troublesome one. We need to develop new method for data compression and high performance computing. Another challenge is about the highly complex structure, there are large number of numerous types of neurons, the morphology of some neurons is so intricate. Therefore, we also need to fully optimize and accelerate the reconstruction algorithm.

The VBN project is aimed at providing a research platform, after that, we can perform analysis and simulation the complex brain function from bottom to top, by the method of reductionism.

10024-29, Session 5

Recent advances in fluorescence lifetime imaging: superresolution, single particle tracking, and some novel applications *(Invited Paper)*

Wei Yan, Qianqian Wu, Jing Qi, Shuyi Yuan, Teng Luo, Shaozhuang Yang, Xiao Peng, Danying Lin, Junle Qu, Shenzhen Univ. (China)

Fluorescence microscopy is a widely used tool in biomedicine. Unlike fluorescence intensity, fluorescence lifetime depends on the micro-environment of fluorophores. There are a number of parameters that can influence fluorescence lifetime, such as local viscosity, pH, refractive index, oxygen saturation and protein binding. Fluorescence lifetime imaging (FLIM) offers the ability to discriminate between tissue fluorophores on the basis of their characteristic emission lifetimes. As an established imaging method, FLIM analysis can provide clues to diseased intracellular activity at subcellular resolution, further improving diagnostic accuracy. Recently, FLIM techniques have been broadly applied to imaging and characterization of biological tissues.

This presentation will introduce the principles of FLIM and present our recent work in FLIM, including superresulution FLIM through stimulated emission by depletion (STED), the combination of lifetime measurement with single particle tracking, and some applications of FLIM in tissue discrimination.

10024-30, Session 5

Spectral Domain Optical Coherence Tomography with Extended Depth-of-focus by Aperture Synthesis

En Bo, Linbo Liu, Nanyang Technological Univ. (Singapore)

We developed a novel depth-encoded FD-OCT system with an extended depth-of-focus (DOF) using multiple aperture synthesis. Multiple aperture synthesis can achieve equivalent lateral resolution along an extended DOF by correcting the defocus-induced wavefront curvature. For a designated Gaussian-shape light source, the lateral resolution is determined by the numerical aperture (NA) of the objective lens and can be approximately maintained over the confocal parameter, which is defined as twice the Rayleigh range. However, the DOF is proportional to the square of the lateral resolution. Consequently, a trade-off exists between the DOF and lateral resolution, and researchers have to weigh and judge which is more important for their research reasonably. In this paper, we reported a novel multiple aperture synthesis method for DOF extension. In this study, multiple distinct optical apertures can be achieved by imbedding an aperture synthesis element (ASE) in the sample arm. Due to the optical path difference between multiple distinct apertures caused by ASE, multiple images will be aligned along z-axis vertically. By correct the OPD and defocus-induced wavefront curvature, multiple images with distinct depths will be coherently summed together. By correcting the optical path difference and defocus-induced wavefront curvature, images with distinct aperture were coherently summed together. This system digitally refocused the sample and obtained a brand new image with nearly the same lateral resolution over an extended DOF, which was multiple times more than the confocal parameter when imaging the polystyrene calibration particles.

10024-31, Session 5

Optimization of wide-field large-volume tomography to accelerate whole-brain imaging

Qiuyuan Zhong, Xiaoyu Zhang, Zhangheng Ding, Sile An, Jing Yuan, Hui Gong, Qingming Luo, Britton Chance Ctr. for Biomedical Photonics (China)

Fast imaging a mammalian brain in 3D at single-axon resolution is crucial to reconstruct and analyze neural morphology and connectivity. However, even the latest wide-field large-volume tomography (WVT) takes more than 3 days to acquire a 3D dataset of whole mouse brain at a voxel size of 0.32 ? 0.32 ? 2.0 ?m. So long data acquisition time of whole-brain imaging limits potential applications of the technology. Here, we optimize the data acquisition and uploading strategies of the WVT technology, respectively, to accelerate imaging a whole brain. We optimize acquisition flow and adjust time distribution in single imaging-sectioning circle to decrease total time consume. Automated exposure adjustment is employed to reduce exposure time according to signal intensity layer by layer. Different image compression formats are compared to choose the fit to shorten image saving time and image size. We also introduce automated contour identification to define minimized imaging range according to brain contour in real time, avoiding redundant data acquisition and saving. All of these efforts totally improve 20% of the data acquisition time of WVT, from 77 hours to 62 hours. In addition, we employ real-time data packing to accelerate data uploading after data acquisition. The data uploading time is shortened from 12 hours to 5 hours. The optimized WVT potentially becomes a routine tool of neural connectome and projectome.

10024-32, Session 5

Lensless quantitative phase imaging based on ptychographic iterative engine with partially-coherent illumination

Wei Yu, Xiaolin Tian, Xiaoliang He, Shouyu Wang, Cheng Liu, Jiangnan Univ. (China)

As an ideal phase microscopic method for imaging with short wavelength including x-ray and electron beam, Ptychographic Iterative Engine (PIE) is widely applied due to its advantages. However, the traditional PIE algorithm requires a purely coherent illumination. Since the coherency of x-ray and electron beam is always much lower than that of the laser, it is high of importance to develop a new algorithm for PIE to enhance its capability in handling the partially coherence. In this paper, an improved polyPIE algorithm is developed to realize the high resolution phase imaging under partially coherent illumination by taking the shape of the illuminating pinhole and the spectral distribution of the light source into the iterative computation. During reconstructing the amplitude and phase of the sample, the shape of the pinhole forming the illumination is used as the same spatial constraint for all the reconstructed probes on the pinhole plane. With this method, a much high convergence speed and reconstruction accuracy can be achieved as well as a wide view field. The influence of the spectral width to the reconstruction accuracy is also analyzed in this paper. When the width of the incoherent illuminating source is smaller than 10% of the central wavelength, the polyPIE algorithm can accurately reconstruct the phase and modulus images of the object, otherwise, the convergence speed and reconstruction accuracy will become remarkably lower. This method also can be widely used in other CDI field with partially coherent illumination.

10024-33, Session 5

Determination of the real focal plane with transport intensity equation and wavefront propagation method

Xin Meng, Xiaolin Tian, Wei Yu, Jiangnan Univ. (China); Liang Xue, Shanghai Univ. of Electric Power (China); Cheng Liu, Shouyu Wang, Jiangnan Univ. (China)

Microscopy combining with transport intensity equation is an effective method which only needs in-focus and defocus images to retrieve both the phase and the intensity of a sample. However, in practical TIE measurements, errors are induced since the position of the in-focus image is chosen artificially. Halos and blurs decrease the imaging quality as well as the accuracy in phase measurement. In order to obtain in-focus quantitative intensity and phase distributions of samples, numerical wavefront propagation is proposed combining with focal determination criteria. In our method, three images are captured, then amplitude and phase distributions at center plane are retrieved with transport intensity equation. Using algorithm based on wavefront propagation, both intensity and phase distributions at different positions with adjacent interval of 0.1 mm near the chosen center plane can be obtained. To seek the in-focus position from a series of numerical obtained wavefront, focal determination criteria based on the cellular duty ratio is designed and adopted. In experiment, the real focal plane can be accurately determined within an wide range from -40 mm to 40 mm. Additionally, the correlation coefficients between the intensities of real and numerical retrieved are higher than 0.95 indicating the proposed method not only can catch the real focal plane, but also provide clear images without any hardware alterations. It is believed that the proposed method reduces the dependence of accurate focal plane choosing in

TIE measurements and owns the potentiality in automatic focal determination in microscopic imaging.

10024-34, Session 6

Tissue optical clearing for enhancement of in vivo blood flow imaging *(Invited Paper)*

Dan Zhu, Huazhong Univ. of Science and Technology (China)

The tissue optical clearing (TOC) technique could significantly improve the biomedical optical imaging depth, but most current investigations are limited to in vitro studies. For in vivo applications, the TOC method must provide a rapid treatment process, sufficient transparency, and safety for animals, which makes it more difficult. Recently developed innovative optical clearing methods for in vivo use show great potential for enhancing the contrast and resolution of blood flow imaging. This paper gives an overview of recent progress in the use of TOC for vascular visualization. First, this presentation introduces transparent windows, including various skin windows and a cranial window, that permit Laser speckle imaging to monitor dermal or cortical blood flow, respectively, with high resolution and contrast. We demonstrate the capability of the combination method of LSCI and skin optical clearing to describe in detail the dynamic response of cutaneous vasculature to vasoactive noradrenaline injection. Moreover, the superior resolution, contrast and sensitivity make it possible to rebuild arteries-veins separation and quantitatively assess the blood flow dynamical changes in terms of flow velocity and vascular diameter at single artery or vein level.

10024-35, Session 6

High-speed phase-based auto-focusing method with transport of intensity equation and numerical wavefront propagation

Xiaolin Tian, Xin Meng, Wei Yu, Jiangnan Univ. (China); Liang Xue, Shanghai Univ. of Electric Power (China); Cheng Liu, Shouyu Wang, Jiangnan Univ. (China)

As a non-interferometric technique, the transport of intensity equation (TIE) phase imaging shows great potentials in various fields. Traditionally, phase retrieval from TIE can be realized only by capturing single in-focus image and two defocused ones symmetrically. However, during experimental measurements, the focal plane is often chosen artificially, which may induce errors and blurs in retrieved phase and intensity. Though combining with numerical wavefront propagation and focal determination criteria, both in-focus position and intensity can be acquired, unfortunately, considering the high-frequency loss in angular spectrum algorithm, details in the samples are lost which severely decrease the imaging quality, as well as the retrieved information. Moreover, with numerical calculations based imaging plane scanning, a great deal of calculation is needed indicating long time consuming and low calculation efficiency. In order to acquire the high-accurate in-focus information, as well as realize fast focal plane seeking, in this paper, dichotomy method is introduced which can greatly reduce computing time of focal determination. Moreover, after obtaining the focal plane, the imaging recorder is translated to that plane to capture the real intensity distribution physically. Proved by practical measurements, even the bias imaging plane is 30 mm away from the real focal plane, the focal plane can be obtained with the error less than 0.05 mm. Additionally, the focal seeking efficiency is raised by 50 times because of the application of the dichotomy method. It is believed with this phase based auto-focusing method, both the in-focus location and information can be obtained with high accuracy and fast speed.

10024-36, Session 6

Contrast improvement for swept source optical coherence tomography image of sub-surface tissue

Xinyu Li, Shanshan Liang, Jun Zhang, Sun Yat-Sen Univ. (China)

Swept source optical coherence tomography (SSOCT) is an attractive biological imaging technology due to its advantages of simple setup and high imaging speed. As the light intensity attenuated rapidly in high scattering biological tissues, the contrast of OCT image will drop with depth. In this paper a new method was introduced to compensate the attenuation of imaging contrast in SSOCT. The interference signal was divided into two channels of analog to digital converter (ADC) with a splitting ratio of 1:5. The stronger signal was used to reconstruct deep structure of tissue and the weaker signal was used to reconstruct surface structure of tissue. The low frequencies in the stronger channel were filtered to make full use of the measurement range of ADC, the combined OCT image will obtain a higher signal intensity in the imaging range and the contrast of system will be improved. A tape, human nail and porcine windpipe were used to test capacity of our method. OCT images obtained by a SSOCT system were reconstructed with two channels method. Results show the contrast of structures in OCT images has been improved, especially in deep region.

10024-37, Session 6

Large virtual histology using confocal microscopy

JueHyung Kang, Hanyang Univ. (Korea, Republic of); HongRae Kim, National Cancer Ctr. (Korea, Republic of); Incheon Song, NanoScope Systems, Inc. (Korea, Republic of); Hyeong Soo Nam, Hanyang Univ. (Korea, Republic of); Hyunjin Kim, S. H. Lee, National Cancer Ctr. (Korea, Republic of); Young Jae Won, Osong Medical Innovation Foundation (Korea, Republic of); Yongdoo Choi, Hee Jin Chang, Kwang-Gi Kim, Dae Kyung Sohn, National Cancer Ctr. (Korea, Republic of); Hongki Yoo, Hanyang Univ. (Korea, Republic of)

Confocal microscopy was used due to its ability to optically section fresh tissue. Confocal images were acquired using a multichannel confocal microscope setup. The system uses a 20x objective and a confocal imaging chamber for imaging. Raster scanning was done using Galvano mirrors for x and y scan. Hoechst 33342 (Ex.300-410nm/Em.390-620 nm) and Eosin (Ex.300-560nm/Em.510-700nm) were used as fluorescent dyes to stain nuclei and cytoplasm respectively. 405 nm and 488 nm lasers were used as excitation light source for each fluorescent dyes. Normal tissues and tumor tissues were collected from a mouse. Normal liver, stomach, lung and kidney tissues were acquired. Tumor tissues were acquired by grafting SSC7 cell lines under the skin of the mouse. The acquire tissues were cut into sizes of around 5x5 mm. Images were acquired simultaneously and serially to observe any crosstalk between channels. Image mosaics were created using a mechanical stage. Acquired images were then stitched together using a stitching algorithm provided by the National Institutes of Health. It took around 5 minutes to acquire a 9x9 mosaic image which equals to size of around 4x4 mm2. H&E colormap was created from the RGB values of a frozen histology image. Using the H&E colormap, grayscale confocal

images were converted to resemble frozen histology. Acquired confocal images were validated with matching frozen histology. Using the technique, physicians can examine potentially malignant lesions much quickly than the conventional H&E staining and decide a treatment plan within the surgical room.

10024-38, Session 6

A frequency domain 4-frame SIM reconstruction algorithm

Amit Lal, Xiaoshuai Huang, Peng Xi, Peking Univ. (China)

Conventionally, super resolution image reconstruction from Structured Illumination Microscopy (SIM) is carried out using nine raw images (Heintzmann and Cremer, 1999; Rego et al., 2012; Shroff et al.,2010; Wicker et al., 2013). Recently, in order to increase the frame rate, attempts are made to carry out SIM reconstruction by using reduced number of raw images. Successful reconstructions of SIM images are demonstrated by utilizing as low as 4 raw images (Orieux et al., 2012; Dong et al., 2015). The reconstruction method employed while utilizing 4 raw images differs from that employed in conventional SIM in two key aspects: (1) The reconstruction is carried out in spatial domain. In contrast, conventional 9-frame SIM reconstruction is carried out in Fourier domain. (2) An iterative algorithm is used to arrive at the reconstructed image. Conventional 9-frame SIM reconstruction provides a single-step (closed-form) solution!

These differences raise curious questions, for instance: Is it not possible to carry out 4 frame SIM reconstruction using conventional approach in Fourier domain? Or is it that the reconstruction methodology in Fourier domain suffers severe inherent disadvantages, which justifies preference for spatial domain reconstruction in published literature? The present work is motivated by these curious questions.

In this manuscript, we describe a SIM reconstruction algorithm which utilizes 4 raw images (1 wide-field and 3 SIM images) and carries out the reconstruction process in Fourier domain. The reconstruction provides a single-step (closed-form) solution, just as the case with conventional 9-frame SIM reconstruction. Subsequently, the operation of devised 4-frame SIM reconstruction algorithm is tested on simulated raw data for varied noise levels. Results obtained suggests that for low noise level (<10%) 4-frame SIM reconstruction algorithm produces images comparable to that obtained by conventional 9-frame SIM reconstruction algorithm; however, the results begin to deteriorate at higher noise levels.

10024-60, Session Post

Hemoglobin concentration determination based on near-infrared spatially-resolved transmission spectra

Linna Zhang, Ling Lin, Gang Li, Tianjin Univ. (China)

Spatially resolved diffuse reflectance spectroscopy method has been proved to be more effective than single point spectroscopy method in the experiment to predict the concentration of the Intralipid diluted solutions. However, Intralipid diluted solution is simple, cannot be the representative of turbid liquids. Blood is a natural and meaningful turbid liquid, more complicate. Hemoglobin is the major constituent of the whole blood. And hemoglobin concentration is commonly used in clinical medicine to diagnose many diseases. In this paper, near infrared spatially resolved transmission spectra (NIRSRTS) and Partial Least Square Regression (PLSR) were used to predict the hemoglobin concentration of human blood. The results showed the prediction ability for hemoglobin concentration of the proposed method is better than single point transmission spectroscopy method. This paper demonstrated the feasibility of the spatially resolved diffuse reflectance spectroscopy method for practical liquid composition analysis. This research provided a new thinking of practical turbid liquid composition analysis.

10024-61, Session Post

Research of transmissive near-infrared spectroscopy for non-invasive blood glucose measurement

Wen-Ming Yang, Ningfang Liao, Yasheng Li, Liwei Shao, Dehuang Huang, Beijing Institute of Technology (China)

Near infrared (NIR) spectrum can be used to analysis the optical properties of human blood components. Non-invasive blood glucose measurement using NIR transmittance or reflectance is feasible for diabetic patients to know the level of blood glucose tightly. However, the spectrum changing level caused by unique glucose absorption is hard to identify due to other blood components and low signal-to-noise (SNR). In this work, we delivered a non-invasive glucose detection system with Fourier transform spectrometer which will work in fingertips or other human body tissues. The measurement system mainly consists of a Sagnac interferometer, a refrigerated InGaAs detector, a NIR LED light source and a Fourier transform spectrum analyzing system. The InGaAs detector with high quantum efficiency performing well in the range of 1.0-1.7?m wavelength is used to acquire transmissive radiation. We have focused on the explorations on the NIR spectral bands known to be dominated by the glucose absorption information. Preliminary experiment investigations were set up to test glucose levels of fingertips and aqueous solutions with different concentrations. SNR of spectral information recorded in the interference fringes is improved by using refrigerated InGaAs detector. The analytical modeling of the interference pattern is based on arithmetic Fourier transform and supported by the curvilineal characterization. Experimental results show the variation of light intensity among different glucose concentrations and emphasize the obvious absorption of glucose in NIR wave-range. This study confirms the suitability that NIR can be developed in non-invasive glucose measurement.

10024-62, Session Post

Amplitude enhancement by a gold dimer

Xin Hong, Jingxin Wang, Zheng Jin, Dalian Univ. of Technology (China)

The unique optical properties such as brightness, non-bleaching, good bio-compatibility make gold particles ideal label candidates for molecular probes. Due to the strongly enhanced field, aggregation of gold nanoparticles finds themselves plenty of applications in bio-imaging. But limited by its small cross-section associated with nanometer sized particle, it is a big challenge to employ it in a single molecular detection. The field enhancement results from the effect of plasmonic coupling between two closely attached gold nanoparticle under the right excitation condition. With the aim to apply the gold dimer probe to find the molecules in our recently established optical detection method, we compared of the amplitude enhancement by the dimer relative to a single particle. The amplitude distribution under a highly focused illumination objective was calculated, whose results suggest that at the optimized excitation condition, the local field can be enhanced ~190 fold relative a single plasmonic particle. In consequence, experimental detection was carried out. Gold dimers were linked together by the hybridization of two single chain DNAs. Dimer and single particle probes were mixed together in one detection. Overwhelming contrast between these two kinds of probes were clearly exhibited in the experimental detection image. This method can provide a way to a high specific detection in early diagnosis.

10024-63, Session Post

Wavelength selection based on two-dimensional correlation spectroscopy: application to noninvasive hemoglobin measurement by dynamic spectrum

Shengzhao Zhang, Zhe Li, Gang Li, Ling Lin, Tianjin Univ. (China)

Dynamic spectrum (DS) method is one of the noninvasive approaches to measure the concentration of components in human blood based on the application of photoplethysmogram (PPG). One of the targets of the DS method is to predict the hemoglobin concentration in human blood noninvasively. In previous works, the usually used wavelength in the spectrum is 600-1100 nm which is regarded as the analysis “window” in human tissues. Optimum wavelengths for measurements of hemoglobin concentration have not been investigated yet. In order to improve the precision and reliability of hemoglobin measurements, a method for wavelength selection based on two-dimension (2D) correlation spectroscopy has been studied in this paper. By analyzing the 2D correlation spectroscopy which is generated by the DS data from subject with different blood hemoglobin concentrations, the wavelength bands which are sensible to hemoglobin concentrations in DS can be found. We developed calibration models between the DS data and hemoglobin concentration based on data from 57 subjects. The correlation coefficient is 0.76 in the test set of the model using the whole wavelength band (600-1100nm), while in the test set of the model using the selected wavelength band (850-950nm) the correlation coefficient is 0.92. Results show the feasibility of wavelength selection utilizing 2Dcorrelation spectroscopy.

10024-64, Session Post

Adaptive photoacoustic imaging quality optimization with EMD and reconstruction

Chen Zhu, Jianbo Guo, Jie Yuan, Nanjing Univ. (China); Guan Xu, Univ. of Michigan Medical School (United States); Xueding Wang, Univ. of Michigan (United States); Paul L Carson, University of Michigan (United States)

Biomedical photoacoustic (PA) signal is characterized with extremely low signal to noise ratio which will yield significant artefacts in photoacoustic tomography (PAT) images. Since PA signals acquired through ultrasound transducers are non-linear and non-stationary, traditional data analysis methods like Fourier analysis and wavelet analysis cannot give useful information for further research. In this paper, we introduce an adaptive method to improve the quality of PAT images based on empirical mode decomposition and reconstruction. PA signals are adaptively decomposed into several intrinsic mode functions (IMFs) after a time shifting pre-process. Since noise is randomly distributed in different IMFs, depressing IMFs with more noise while enhancing IMFs with less noise can effectively enhance the quality of reconstructed PAT images. However, searching optimal parameters by means of brute force searching algorithms will cost too much time, which prevent this method from clinical application. To find parameters within reasonable time, Heuristic algorithms, which are designed for finding good solutions more efficiently, are adopted in our proposed method. Two of the Heuristic algorithms, Simulated Annealing Algorithm, a probabilistic method to yield global optimal solution, and Artificial Bee Colony Algorithm, an optimization method inspired by the foraging behavior of bee swarm, are selected to search optimal parameters of IMFs in this paper. The effectiveness of our proposed method is proved both on simulated data and PA signals from real biomedical tissue, which might be beneficial for future clinical PA imaging de-noising.

10024-65, Session Post

In situ hyperspectral microscopy with acousto-optic tunable filter

Lv Yanlu, Jing Bai, Jianwen Luo, Tsinghua Univ. School of Medicine (China)

Multispectral imaging systems are effective to acquire spatial and spectral features of biological tissues. There is a great interest in developing multispectral imaging systems with the capability of performing in situ tissue diagnosis without the need for sample excision and processing. To satisfy the need of monitoring dynamic phenomenon and observing multiple structures of the specimen simultaneously, we develop a multispectral microscopic imaging system with an acousto-optic tunable filter (AOTF). AOTFs are solid state wavelength tunable optical filters and can achieve spectral scanning at very high rates (milliseconds timescale) without the possibility of error due to gear backslash or other mechanical problems. The system can achieve a spatial resolution of 100 lines per mm with an effective aperture of 10 mm. With the AOTF, the system can work within a wavelength range from 450 nm to 720 nm in both reflection and fluorescence modes. And this multispectral imaging system allows fast acquisition of spectral and spatial information of biological tissues in the wide field mode (2?2 mm, 10? objective lens). Biomedical imaging experiments on the taste-goblet and the skin tissue of a nude mouse are conducted to test the performance of the system. The results demonstrate that the system can provide high spatial resolution multispectral images of biological tissues.

10024-66, Session Post

Spatially-variant regularization algorithm based on cluster analysis for reconstruction of fluorescence molecular tomography

Jiulou Zhang, Yanlu Lv, Jianwen Luo, Tsinghua Univ. School of Medicine (China)

In fluorescence molecular tomography, the detector sensitivity is degraded non-linearly with the increase of distance between the fluorescent targets and detector, because of the absorbing and scattering characteristics of photons transport in heterogeneous biological tissues. Thus, the relative-quantitation accuracy of the reconstruction results is reduced when multiple fluorescent targets with different depths and/or volumes appear randomly in the tissues. A spatially variant regularization algorithm based on cluster analysis is proposed to improve the reconstruction quality. The intermediate result is obtained by Tikhonov regularization algorithm, in which different fluorescent targets and background noise can be roughly distinguished using the cluster analysis. Then, small regularization parameter is set to deeper or smaller fluorescent target and large parameters are allocated to other targets and background noise. Numerical simulation and physical phantom experiments are conducted to test the performance of the proposed algorithm. The relative-quantitation coefficients of the reconstruction results are reduced from 0.3846 to 0.0265 and 0.3353 to 0.0211 for numerical simulation and physical phantom experiments, respectively. Furthermore, the corresponding signal-to-noise ratios are increased from -8.11 to 20.60 and 1.40 to 2.34.

10024-67, Session Post

Influence of incident light offset on diffuse reflectance measurement for curved object: a Monte Carlo-based study

Chizhu Ding, Huazhong Agricultural Univ. (China)

Diffuse reflectance spectroscopy in the near-infrared (NIR) spectral ranges is a widely used technique for non-destructive inspection of biological tissues. The optical properties, such as absorption and scattering coefficients, can be inversely deduced from the measured quantities and then be used to speculate on some related chemical and physical properties of the tissue. Most studies consider biological tissues as homogeneous semi-infinite turbid media or infinitely-wide planar layered turbid media. However, the biological tissues have various geometries, and nearly all of them have curved surfaces. The position and direction of the incident light relative to the tissue surface affect the diffuse reflectance. In this work, we study the influence of incident light offset on the measured diffuse reflectance signals based on the Monte Carlo (MC) simulation. The MC method are regarded as golden standard for light propagation in turbid media and can be used without the limitations of complex tissue geometries. A model for diffuse reflectance spectroscopy measurement using optic fiber probe is built. The incident light is assumed to be an infinitely narrow photon beam. The tissue under detection is assumed to be spherical described by its curvature radius. A series of Monte Carlo simulation are carried out with varying incident positions. Simulation results are analyzed and discussed to assess the influence on the measurements for tissues with different curvature radii. This study may aid in achieving more accurate and effective measurement without extensive experiments.

10024-68, Session Post

Repetition doubling in a soliton self-frequency shift system for multiphoton microscopy

Ke Wang, Jiexing He, Shenzhen Univ. (China)

Multiphoton microscopy (MPM) has benefitted tremendously from the development of fiber-based laser technology, such as soliton self-frequency shift (SSFS). SSFS enables femtosecond laser pulse generation with broadband wavelength tunability that spans hundreds of nanometers and excellent beam quality. In MPM, signal level is linearly proportional to the repetition rate of the laser system. As a result, below damage threshold, increasing the repetition rate of the laser system is an efficient means of achieving higher signal levels, which in turn could reduce exposure time. Here we demonstrate a repetition doubling technique that is well suited in doubling the repetition rate of the SSFS system. Through polarization separation before and multiplexing in a photonic-crystal (PC) rod, we could double the repetition rate of the optical solitons generated through SSFS. The orthogonally polarized solitons have identical spectrum and pulse energy, which could find potential applications in boosting signal levles in MPM.

10024-69, Session Post

Pigmented skin lesion detection using random forest and wavelet-based texture

Ping Hu, Tie-Jun Yang, Guilin Univ. of Technology (China)

The incidence of cutaneous malignant melanoma, a disease of worldwide distribution and is the deadliest form of skin cancer, has been rapidly increasing over the last few decades. Because advanced cutaneous melanoma is still incurable, early detection is an important step toward a reduction in mortality. Dermoscopy photographs are commonly used in melanoma diagnosis and can capture detailed features of a lesion. A great variability exists in the visual appearance of pigmented skin lesions. Therefore, in order to minimize the diagnostic errors that result from the difficulty and subjectivity of visual interpretation, an automatic detection approach is required. The objectives of this paper were to propose a hybrid method using random forest and Gabor wavelet transform to accurately differentiate which part belongs to lesion area while the other does not belong to in a dermoscopy photograph, and analyze segmentation accuracy. Gabor wavelet transform are the mathematical model of visual cortical cells of mammalian brain and an image can be decomposed into multiple scales and multiple orientations by using it. The Gabor function has been recognized as a very useful tool in texture analysis, due to its optimal localization properties in both spatial and frequency domain. Texture features based on Gabor wavelet transform are extracted in different scales and orientations. Then, a random forest classifier consisting of a set of decision trees is used for classification. Experiment results indicate the following: (1) the proposed algorithm based on random forest outperforms the state-of-the-art in pigmented skin lesions detection (2) and the inclusion of Gabor wavelet based texture features can improve segmentation accuracy.

10024-70, Session Post

Wavelength-swept fiber laser based on acousto-optic tuning method

Minghui Chen, Fan Yunping, Zhang Hao, Tao Jianfeng, Gang Zheng, Univ. of Shanghai for Science and Technology (China)

In this study, we have demonstrated a wavelength-swept fiber laser based on an acousto-optic tunable filter(AOTF) as a selective element and a semiconductor optical amplifier(SOA) as a gain medium in an internal fiber ring cavity. The light deriving from one port of the SOA goes through an optical isolator, the AOTF, a fiber coupler and a polarized controller successively, then it goes back to the other port of the SOA to form a ring cavity. The laser output is from another port of the fiber coupler. The laser made by this method is mainly used for swept-source optical coherence tomography(SS-OCT). The application of the SOA provides a sufficiently broad range of tunability and can ensure an increased axial resolution of SS-OCT. AOTF offeres a wide tuning range, high switching speed and stable operation against vibration for the non-mechanical structure. The proposed wavelength-swept fiber laser ensures a high axial resolution of tomographic images and has a stable laser ouput. We have discussed the influence of the SOA injection current to the tuning range of the laser. In the SOA injection current of 280 mA, a continuous wavelength tuning range from 1295 to 1370 nm centered at a wavelength of 1325 nm is obtained at the sweep rate of 1.06 kHz. In addition, for quantitative characterization of the wavelength-swept performance with a AOTF, we have theoretically and experimentally analyzed the influence of the fllowing controllable parameters: injection current, output power and sweeping frequency.

10024-71, Session Post

Multiphoton microscopy for detecting the depth of tumor infiltration in the esophageal squamous cell carcinoma

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Esophageal squamous cell carcinoma (ESCC) is one of the most common malignancies of the gastrointestinal cancers and carries poorer prognosis than other gastrointestinal cancers. Patients with early esophageal neoplasia limited to the mucosal layer can be cured with endoscopic treatment, whereas patient with more advanced carcinomas may achieve higher long-term survival rates with appropriate treatment which is established by primary tumor stage. However, the malignant degree of ESCC in the esophageal wall is mainly determined by the depth of tumor infiltration. Our aim was to evaluate whether multiphoton microscopy (MPM) can be used to detect the depth of tumor infiltration in the esophageal wall. MPM is well-suited for real-time detecting morphologic and cellular changes in fresh tissues since many endogenous fluorophores of fresh tissues are excited through two-photon excited fluorescence (TPEF) and second harmonic generation (SHG). In this work, spectral information and morphological features of epithelial cells, collagen fibers and muscular tissues were first studied. Then, the morphological differences between normal epithelial cells and tumor cells were described. At last, tumor invasion of the mucosa, submucosa, muscularis propria and adventitia were presented respectively. These results show that MPM has the ability to detect the depth of tumor infiltration in the esophageal wall of ESCC. In the future, MPM may be a promising imaging technique for preoperative diagnosis of the depth of tumor infiltration in the esophageal wall of ESCC.

10024-72, Session Post

Identification of calcifications in intracranial neoplasms using two-photon excitation fluorescence microscopy

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Calcifications within brain tumors may be an indicator of a relatively long survival because a long time is required for the formation of calcium deposits, and may present a novel biomarker associated with response and improved outcome of therapy. In this paper, we describe the use of two-photon excitation fluorescent (TPEF) microscopy combined second harmonic generation (SHG) microscopy for high-resolution imaging that can be applied in identification of intratumoral calcification. Our results demonstrate that the calcification has stronger TPEF signal than the area around it and the emission spectra shows the difference between the two areas clearly. The TPEF image of calcified region corresponds well with the corresponding H&E stained image. In this work, we present that the label-free imaging technique is able to distinguish the calcified mass lesions in intracranial neoplasms reliably.

10024-73, Session Post

Smart AQ4N-Cu(II)-DNA@GNPs nano complex for tumor-microenvironment stimuli-responsive synergetic photodynamic/aggregation-induced photothermal therapyemotherapy of hepatocellular carcinoma

Da Zhang, Ming Wu, Xiaolong Liu, Fujian Medical Univ. (China)

In this work, multi stimuli-responsive coordination nansystem based on di-N-oxide of 1, 4-bis [2-(dimethyl aminoethyl-amino] 5, 8-dihydroxyanthracene-9, 10-dione (AQ4N) prodrug and Cu(II)-DNA(TLS11a aptamer)-gold nanoparticle were designed. Cu(II)-DNA complexes are employed as a binders to guest AQ4N via C-O and C=O bonds, formed a “host-metal-guest” architecture. In aerobic cancer cells, the intracellular of GSH dissociate chlorin e6 labelled-aptamer from GNPs and triggered an activated fluorescence signal for real-time image and controlled photodynamic therapy (PDT). AQ4N release was mainly governed by acid-cleavage of the “guanine-Cu(II)” and “Cu(II)-AQ4N”coordination bond, and this is accompanied by a release of Cu(II). The latter is immediately induced the electrostatic aggregates of GNPs and shifted absorption peak to near-infrared, which could be able to use as NIR-absorbing agents for photothermal ablation (PTA). Furthermore, the “on” state PDT not only leads to serious cell damage but activate AQ4N converted to cytotoxin (AQ4) in PDT-induced hypoxic micro-environment, achieving synergistic PDT / PTT-chemotherapy under single laser irradiation in HCC. In summary, Tumor-microenvironment triggered multiple therapeutic stragtegies may be open up new avenues for programmed and cost-effective precision medicine in cancer therapy.

10024-74, Session Post

Identification of the boundary between normal brain tissue and ischemia region using two-photon excitation fluorescence microscopy

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Ischemic stroke is one of the common neurological diseases, and it is becoming the leading causes of death and permanent disability around the world. Early and accurate identification of the potentially salvageable boundary region of ischemia brain tissues may enable selection of the most appropriate candidates for early stroke therapies. Our aim was to evaluate whether two-photon excitation fluorescent (TPEF) microscopy can be used to identify the boundary between normal brain tissue and ischemia region. TPEF microscopy has the ability to noninvasively visualize the architectures of unstained biological tissues at the cellular level relied on intracellular intrinsic sources. In this work, TPEF microscopy was used to image the microstructures of normal brain tissues, ischemia regions and the boundary region between normal and ischemia brain tissues. The ischemia brain tissues from Sprague–Dawley (SD) rats were subjected to 6 hours of middle cerebral artery occlusion (MCAO). Our study demonstrates that TPEF microscopy has the ability to not only reveal the morphological changes of the neurons but also identify the boundary between normal brain tissue and ischemia region, which correspond well to the hematoxylin and eosin (H&E) stained images. With the development of miniaturized TPEF

microscope imaging devices, TPEF microscopy can be developed into an effectively diagnostic and monitoring tool for cerebral ischemia.

10024-75, Session Post

Research on hyperspectral imaging for tobacco early diseases

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There are many kinds of tobacco diseases which seriously affect the quality and yield of tobacco. To identify diseases of tobacco in early stage is essential to the effective prevention and treatment of them. Traditional methods such as visible light image comparison and biochemical analysis are time-consuming and arduous, which makes it difficult to realize the detection and prevention of early-stage diseases of tobacco. Meanwhile, the hyperspectral imaging technology combining image and spectral information has the advantage to detect a sample in a non-destructive and fast way, which offers promise for its application in the non-destructive detection of early-stage diseases of tobacco. In the reasearch of this paper, the hyperspectral imaging technology was used to detect early-stage diseases of tobacco. By inoculating tobacco mosaic virus on Nicotiana tabacum and Nicotiana glutinosa, hyperspectral images from different time points before and after the inoculation were dynamically sampled. The images were preliminarily processed to find the sensitive bands and suspected infected areas of early-stage diseases of tobacco, and then, by identifying the relevant characteristic parameters and combining the time-depending images, a model of early-stage tobacco disease dection method using hyperspectral imaging technology was established.

10024-77, Session Post

Quantification of collagen distributions in rat hyaline and fibro cartilages based on second harmonic generation imaging

Xiaoqin Zhu, Chenxi Liao, Fujian Normal Univ. (China); Zhenyu Wang, Fujian Medical Univ. (China); Shuangmu Zhuo, Fujian Normal Univ. (China); Wenge Liu, Fujian Medical Univ. (China); Jianxin Chen, Fujian Normal Univ. (China)

Hyaline cartilage is a semitransparent tissue composed of proteoglycan and thicker type II collagen fibers, while fibro cartilage large bundles of type I collagen besides other territorial matrix and chondrocytes. It is reported that the meniscus (fibro cartilage) has a greater capacity to regenerate and close a wound compared to articular cartilage (hyaline cartilage). And fibro cartilage often replaces the type II collagen-rich hyaline following trauma, leading to scar tissue that is composed of rigid type I collagen. The visualization and quantification of the collagen fibrillar meshwork is important for understanding the role of fibril reorganization during the healing process and how different types of cartilage contribute to wound closure. In this study, second harmonic generation (SHG) microscope was applied to image the articular and meniscus cartilage, and Fourier analysis were developed to quantify the collagen distribution. High-resolution images were achieved based on the SHG signal from collagen within fresh specimens, and detailed observations of tissue morphology and microstructural distribution were obtained without shrinkage or distortion. Fourier analysis of SHG images was performed to confirm that collagen in fibrocartilage showed significantly greater organization and directionality compared to collagen in hyaline cartilage ($p < 0.01$). Our results show that each type of cartilage has different structural features, which may significantly contribute to pathology when damaged. Our findings demonstrate that SHG microscopy holds potential as a clinically relevant diagnostic tool for imaging degenerative tissues or assessing wound repair following cartilage injury.

10024-78, Session Post

Label-free imaging of rat spinal cords based on multiphoton microscopy

Chenxi Liao, Fujian Normal Univ. (China); Zhenyu Wang, Linquan Zhou, Fujian Medical Univ. (China); Xiaoqin Zhu, Fujian Normal Univ. (China); Wenge Liu, Fujian Medical Univ. (China); Jianxin Chen, Fujian Normal Univ. (China)

As an integral part of the central nervous system, the spinal cord is a communication cable between the body and the brain. It mainly contains neurons, glial cells, nerve fibers and fiber tracts. The recent development of the optical imaging technique allows high-resolution imaging of biological tissues with the great potential for non-invasively looking inside the body. In this work, we evaluate the imaging capacity of multiphoton microscopy (MPM) based on second harmonic generation (SHG) and two-photon excited fluorescence (TPEF) for the cells and extracellular matrix in the spinal cord at molecular level. Rat spinal cord tissues were sectioned and imaged by MPM to demonstrate that MPM is able to show the microstructure including white matter, gray matter, ventral horns, dorsal horns, and axons based on the distinct intrinsic sources in each region of spinal cord. In the high-resolution and high-contrast MPM images, the cell profile can be clearly identified as dark shadows caused by nuclei and encircled by cytoplasm. The nerve fibers in white matter region emitted both SHG and TPEF signals. The multiphoton microscopic imaging technique proves to be a fast and effective tool for label-free imaging spinal cord tissues, based on endogenous signals in biological tissue. It has the potential to extend this optical technique to clinical study, where the rapid and damage-free imaging is needed.

10024-79, Session Post

A method based on coffee-ring deposition confocal Raman spectroscopy for analysis of melamine in milk

Zong Tan, Da Chen, Tianjin Univ. (China)

The safety of dairy products was a hot topic in the field of food safety and public health. In this work, melamine, which had caused severe infant kidney damage for the illegal adding into dairy products for its high nitrogen level, was chosen as the target analyte, and a method based on coffeeing effect micro Raman spectroscopy for detection of melamine in milk was developed. In this method, the separation and enrichment effect of coffee-ring phenomenon was combined with the micro-region analysis of micro Raman spectroscopy, in addition, assisted with chemometric algorithmthe of discrete wavelet transform (DWT) to extract characteristic signal of target analyte from complex and fluctuant noise and background interferences. Consequently, a desired result was obtained that the LOD of melamine in this method was as low as 1 ppm, which was excellent with a sensitivity improvement of 103 - 104 times better than conventional Raman method. Furthermore, the sample pretreatment was easy and convenient, and there was almost no chemical reagents consumption during the whole process, as well as the detection process could proceeded in an easily available condition and the chosen substrates for the formation of coffee-ring were reusable. Thus, an economical, high efficient and envorinmental friendly method was established and

demonstrated a great potential application in safety inspection of dairy products especially in less developed regions.

10024-80, Session Post

Monitoring the elasticity changes of hela cells during mitosis by atomic force microscopy

Ningcheng Jiang, Yuhua Wang, Fujian Normal Univ. (China); Jinshu Zeng, Fujian Medical Univ. (China); Shusen Xie, Hongqin Yang, Fujian Normal Univ. (China)

Cell mitosis plays a crucial role in cell life activity, which is one of the important phases in cell division cycle. During the mitosis, the cytoskeleton micro-structure of the cell changed and the biomechanical properties of the cell may vary depending upon different mitosis stages. In this study, the elasticity properties of HeLa cells during mitosis were monitored by atomic force microscopy. The distribution of actin filaments in different mitosis stages of the cells was also observed by confocal imaging. Our results show that the cell in anaphase is stiffer than that in metaphase and in telophase. Furthermore, lots of actin filaments gathered in cells center area in anaphase, which contributes to the rigidity of the cell in this phase. Our findings demonstrate that the nano-biomechanics of the living cells could provide a new index for characterizing cell physiological states.

10024-81, Session Post

Determination of acceptor-to-donor cross section ratio for two-photon excitation in living cells

Zexian Hou, Yuhua Wang, Liqin Zheng, Fujian Normal Univ. (China); Tongsheng Chen, South China Normal Univ. (China); Hongqin Yang, Shusen Xie, Fujian Normal Univ. (China)

The cross section is a significant parameter for fluorescence protein and the determination of acceptor-to-donor cross section ratio for two-photon excitation in living cells is the vital issue for two-photon excitation FRET quantification. In this study, Hela cells were labeled with FPs that acceptor-to-donor concentration ratio is 1 to 1 and acceptor-to-donor cross section ratio ranged from 700nm to 950nm was obtained by emission spectral unmixing with independent excitation crosstalk correction. The results show that acceptor-to-donor cross section ratio declines with the excitation wavelength from 700nm to 790nm and then increases inversely from 790nm to 950nm, which is consistent with 2-channel FRET quantification method. This method can quickly determine the cross section without any additional references and could provide a powerful and convenient tool for measuring acceptor-to-donor cross section ratio by two-photon excitation in living cells.

10024-82, Session Post

Detection of mast cell secretion by using surface-enhanced Raman scattering

Juan Li, Ren Li, Liqin Zheng, Yuhua Wang, Shusen Xie, Juqiang Lin, Fujian Normal Univ. (China)

Acupuncture can cause a remarkable increase in degranulation of the mast cells, which has attracted the interest of researchers since the 1980s. Surface-enhanced Raman scattering (SERS) could obtain biochemical information with high sensitivity and specificity. In this study, SERS was used to detect the degree of degranulation of mast cells according to different incubate time. Mast cells was incubated with culture medium for 0 h, 12 h and 24 h, then centrifuge the culture medium, decant the supernatant, and discard the mast cell. SERS was performed to obtain the biochemical fingerprinting signatures of the centrifuged medium. The spectra data are then analyzed by spectral peaks attribution and the principal component analysis (PCA). The measured Raman spectra of the two groups were separated well by PCA. It indicated that mast cells had secreted some substances into cultured medium though degranulation did not happen.

10024-83, Session Post

Polymer dots with broadband optical absorption (500 nm - 700 nm) and high-efficiency photoacoustic conversion for in vivo multispectral photoacoustic imaging

Jian Zhang, zhen Yuan, Univ. of Macau (Macao, China)

Multi-spectral photoacoustic (MSPA) imaging can extract quantitative information of interesting component from morphological photoacoustic image of targets. A probe with an optimal optical absorption can be detected by MSPA imaging with higher sensitivity and specificity. Here we developed a Nano polymers dots (P-dots) for MSPA imaging that has a high photoacoustic conversion efficiency in a broad optical absorbing band (500 nm - 700 nm). Both ex vivo photoacoustic imaging of phantom and in vivo photoacoustic imaging experiment demonstrated P-dots has better performance than gold nanoparticles and gold nanorods. In vivo MSPA imaging experiment was successfully performed in mouse model. The relative concentration map of P-dots was exactly obtained from the background of tissues, which demonstrated the potential use of P-dots in the bio-imaging field based on MSPA imaging.

10024-84, Session Post

Effect of 17[beta]-estradiol on the elasticity of MCF-7 cells by atomic force microscopy

Yuhua Wang, Liqin Zheng, Hongqin Yang, Shusen Xie, Fujian Normal Univ. (China)

Estrogen plays an important role in the development and progression of breast cancer, and it promotes proliferation, invasion and metastasis of the breast cancer cells. In this paper, we investigated the effect of estrogen on the elasticity of breast cancer cells. 17?-estradiol, one of the most active estrogen in the human body was applied to MCF-7 living cells and the elasticity of the cells were measured by atomic force microscopy. The force spectroscopy was performed on the center of the cell and the Hertz model was used to calculate the elasticity. Furthermore, the confocal fluorescence imaging was taken to observe the effect of 17?-estradiol on the actin distribution in the cells. The results show that the elasticity of the cells is 218.1±54.6 Pa. After the addition of 17?-estradiol, the value declines to 181.7±42.7 Pa. The elasticity of the cells decreases rapidly, which indicates that the cells appear softer responding to 17?-estradiol. In addition, from the confocal imaging, it can be observed that the actin appears less in the center of the cell and assembles toward the cell edge for 17?-estradiol's treatment, which may contribute to the alteration of the cell elasticity. Our findings may deepen our understanding on the rapid effect of 17?-estradiol to MCF-7 cells.

10024-85, Session Post

Numerical simulation and analysis of accurate blood oxygenation measurement by using optical resolution photoacoustic microscopy

Tianhao Yu, Qian Li, Lin Li, Xinyu Chai, Chuanqing Zhou, Shanghai Jiao Tong Univ. (China)

Accuracy of photoacoustic signal is the crux on measurement of blood oxygen saturation in photoacoustic imaging, which is influenced by factors such as out-of-focus laser, edge of great vessels, saturation nonlinear effect of optical absorption in biological tissues. We apply Monte Carlo modeling to stimulate energy deposition and predict acoustic signals reaching a given focused surface detector. The stimulation models blood vessels positioned under particular depth of dermis with different optical absorption coefficients and focus positions. The spatial distribution of energy deposition is calculated and imaged, then turned to stress wave based on the velocity potential. The results show that acoustic signal attenuation will occur on edge of blood vessel, which will obviously effect calculation of oxygen saturation in universal voxel-based method. As for out-of-focus factor, results show that for great blood vessel, excursion of 100 microns on z direction can bring about error of 5%, which may influence accuracy of quantitative photoacoustic imaging in particular with uneven tissue surface. In follow-up phantom tests, a transparent tube and diluted double-ink mixtures are used to simulate circumstance of blood vessel. We adjust B-scan signals on edge of tube based on specific A-line depth, in which inverse calculation of ink ratio is more accurate. We also apply the compensation on photoacoustic signals of in vivo cerebral blood vessels, in which signals from edge of vessels on different depths are corrected according to their particular positions. And this process obviously improve the accuracy of oxygen saturation calculation. As for optical absorption, photoacoustic signal amplitude is found to be linearly proportional to the given coefficient of blood vessel and ink on both stimulation and phantom tests, which can be regarded negligible in OR-PAM system.

10024-86, Session Post

In vivo noninvasive measurement of preprandial and postprandial blood glucose using optical coherence tomography

Ying Zhang, Xiyang Zhang, Zhifang Li, Hui Li, Fujian Normal Univ. (China)

Blood glucose concentration measurement is essential for the diagnosis and treatment of diabetes. However, conventional glucose measurement methods are invasive and not suitable for real-time monitoring. This study demonstrated a noninvasive blood glucose measurement method using optical coherence tomography to image human lip in vivo. Optical coherence tomography (OCT) is a noninvasive and depth-resolved technique capable of acquiring tissue structure images in real time. Human lip has very thin skin and is full of blood vessels, which is appropriate for noninvasive glucose measurement. To verify the feasibility of OCT for glucose concentration monitoring, two groups of OCT imaging data were obtained from human lips of normal people. In one group, OCT images of lip were acquired from people on an empty stomach. In the other group, the same sites of lip were observed by OCT 2 hours after breakfast. Evident differences were found from two groups of OCT images that correspond to preprandial glucose and 2-hours postprandial glucose, respectively. The relationship between OCT image and blood glucose concentration was investigated. The result indicates that OCT possesses considerable prospects in terms of noninvasive blood glucose measurement.

10024-87, Session Post

Measuring blood oxygenation of pulsatile arteries using photoacoustic microscopy

Qian Li, Tianhao Yu, Lin Li, Xinyu Chai, Chuanqing Zhou, Shanghai Jiao Tong Univ. (China)

Heart pumps blood through the blood vessels to provide body with oxygen and nutrients. As the result, the blood flow, volume and oxygenation in arteries has a pulsatile nature. Measuring these pulsatile parameters enables more precise monitoring of oxygen metabolic rate and is thus valuable for researches and clinical applications. Photoacoustic microscopy (PAM) is a proven label-free method for in vivo measuring blood oxygenation at single blood vessel level. However, studies using PAM to observe the pulsatile nature of arteries is lacking. In this paper, we use optical-resolution PAM (OR-PAM) technology to study the blood oxygenation dynamics of pulsatile arteries. First, the ability of our OR-PAM system to accurately reflect the change of optical absorption in imaged objects is demonstrated in a phantom study. Then the system is used to image exposed cortical blood vessels of cat. The pulsatile nature of blood volume and oxygenation in arteries is clearly reflected in photoacoustic (PA) signals, whereas it's not observable in veins. By using multi-wavelength laser light, the blood oxygenation of pulsatile arteries can be measured, based on the spectroscopic method.

10024-88, Session Post

Self-assembled dye-doped polymer microspheres as whispering gallery mode lasers

Xiaogang Chen, Fujian Normal Univ. (China); Hongyi Sun, Fudan Univ. (China); Hongqin Yang, Fujian Normal Univ. (China); Xiang Wu, Fudan Univ. (China); Shusen Xie, Fujian Normal Univ. (China)

Microlasers based on high-Q whispering-gallery-mode (WGM) resonances are promising low-threshold laser sources for bio-sensing and imaging applications. In this talk, we demonstrate a cost effective approach to obtain size-controllable polymer microspheres, which can be served as good WGM microcavities. By injecting SU-8 solution into low-refractive-index UV polymer, self-assembled spherical droplet with smooth surface can be created inside the elastic medium and then solidified by UV exposure. The size of the microspheres can be tuned from several to hundreds of microns. WGM Lasing has been achieved by optically pumping the dye-doped microspheres with ns lasers. Experimental results show that the microsphere lasers have high quality factors and low lasing thresholds. The self-assembled dye-doped polymer microspheres would provide an excellent platform for the micro-laser sources in on-chip biosensing and imaging systems.

10024-89, Session Post

A method to improve the measurement stability of scattering coefficients in lip and tongue with optical coherence tomography

Xiyang Zhang, Ying Zhang, Zhifang Li, Hui Li, Fujian Normal Univ. (China)

Optical coherence tomography (OCT) is a non-invasive imaging technique that provides real-time two- and three-dimensional images of scattering tissues with micrometer resolution. Scattering coefficient is estimated based on the slope of OCT dependent of depth. However, stability of the OCT signal slope is dependent on tissue heterogeneity . Our work is to provide a method of combining post-processing Fourier filtration with automatic identification of fitting range to reduce the effect of tissue heterogeneity on scattering coefficient, and used for noninvasive monitoring of glucose concentration in lip and tongue respectively. Axial and lateral resolutions of OCT are 20 μm and 15 μm respectively. OCT images were obtained from lip and tongue before and after breakfast respectively. Results demonstrate that the method improve the stability and the precision of measurement of scattering coefficient of lip and tongue. There are obviously different in scattering coefficient of tissue between preprandial glucose and 2-hours postprandial glucose. These pilot studies show that OCT scattering coefficient extraction of lip and tongue may be considered as a significant diagnostic marker. OCT has potential to monitor glucose-induced changes in lip and tongue in vivo.

10024-90, Session Post

The optimum measurement precision evaluation for blood components using near-infrared spectra on 1000-2500 nm

Ziyang Zhang, Di Sun, TongShuai Han, Chao Guo, Jin Liu, Tianjin Univ. (China)

In the non-invasive blood components measurement using near infrared spectroscopy, the useful signals caused by the concentration variation in the interested components, such as glucose, hemoglobin, albumin etc., are relative weak. Then the signals may be greatly disturbed by a lot of noises in various ways. We improved the signals by using the optimum path-length for the used wavelength to get a maximum variation of transmitted light intensity when the concentration of a component varies. And after the path-length optimization for every wavelength in 1000-2500 nm, we present the detection limits for the components, including glucose, hemoglobin and albumin, when measuring them in a tissue phantom. The evaluated detection limits could be the best reachable precision level since it assumed the measurement uses a high signal-to-noise ratio (SNR) signal and the optimum path-length. From the results, available wavelengths in 1000-2500 nm for the three component measurements can be screened by comparing their detection limit values with their measurement limit requirements. For other blood components measurement, the evaluation on their detection limits could also be designed using the method proposed in this paper. Moreover, we use an equation to estimate the absorbance at the optimum path-length for every wavelength in 1000-2500 nm caused by the three components. It could be an easy way to realize the evaluation because adjusting the sample cell's size to the precise path-length value for every wavelength is not necessary. This equation could also be referred to other blood components measurement using the optimum path-length for every used wavelength.

10024-91, Session Post

Quantitative optical biomarkers of lung cancer based intrinsic two-photon excited fluorescence signal

Jingwen Li, Zhenlin Zhan, Hongxin Lin, Xiaoqin Zhu, Jianxin Chen, Shuangmu Zhuo, Fujian Normal Univ. (China)

Alterations in the elastic fibers have been implicated in lung cancer. However, the label-free, microscopic imaging of elastic fibers in situ remains a major challenge. Here, we present the use of intrinsic two-photon excited fluorescence (TPEF) signal as a novel means for quantification of the elastic fibers in intact fresh human lung tissues. We obtained the TPEF images of elastic fibers from ex vivo the human lung tissues. We found that three features, including the elastic fibers area, the elastic fibers orientation, the elastic fibers structure, provide the quantitative identification of lung cancer and the direct visual cues for cancer versus non-cancer areas. We described that the combination of all three features by using a support vector machine classification algorithm can provide a more accurate prediction than each feature alone in lung diagnosis. These results suggest that the TPEF signal can be used as the label-free optical biomarkers for rapid clinical lung diagnosis and instant image-guided surgery.

10024-92, Session Post

Performance evaluation of akinetic swept sources for both intensity and phase-based OCT angiography

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As the most successful functional extension of optical coherence tomography (OCT) nowadays, OCT based angiography (OCTA) gradually becomes a standard add-on feature for OCT systems. It is easily implementable in most spectral domain systems and can yield clinically relevant volumes at the same time when morphological volumes are acquired. For OCTA, both intensity based and phase based algorithms are developed to visualize vasculature, but phase based OCTA normally does not use swept source OCT (SS-OCT) due to the consideration of phase stability issues and trigger jitter problems in most swept sources. In our work, we present an OCTA system employing an akinetic swept source which provides high wavelength stability with a phase repeatability <2 mrad (measured in terms of standard deviation). To fully evaluate the akinetic swept sources' potential for OCTA, we tested the system using two wavelength ranges, one at 1340 nm with 30 nm bandwidth and the other at 1550 nm with 40 nm bandwidth. Another akinetic source with 100 nm bandwidth was tested to compare bandwidth's effects on OCTA. It is proved by our results that this akinetic source enables SS-OCTA without the need for hardware phase stability control or excessive post-processing. The impact of higher phase stability of the sources used on the number of tomograms needed for motion contrast compensation is also discussed. We also compared the differences of intensity based and phase based OCTA using akinetic swept sources. In in vivo applications, we demonstrated that phase based OCTA has better resolvability for human vasculature in deeper depth range.

10024-93, Session Post

Effects of large blood vessel on temperature distribution based on photothermal coupling interaction model

Zhifang Li, Fujian Normal Univ. (China); Xiyang Zhang, Zuoran Li, Fujian Normal Univ (China); Hui Li, Fujian Normal Univ. (China)

In the study, the distribution of light and temperature in biological tissue over time was studied in some cases of optical properties dynamically-changed with temperature using the finite element method to couple the physical field of biological tissue optical transmission with the physical field of biological tissue heat transfer. The results demonstrated that the piecewise dependence of optical properties on temperature for dynamic photothermal coupling interaction model is consistent with the experimental results. It could be potential applications for laser intersititial thermotheraphy and laser immunotherapy.

10024-94, Session Post

The effect of hematoxylin-and-eosin staining on the result of multiphoton microscopy imaging

Yaping Zeng, Jian Xu, Fujian Normal Univ. (China); Deyong Kang, Jiangbo Lin, Fujian Medical Univ. (China); Jianxin Chen, Fujian Normal Univ. (China)

Multiphoton microscopy (MPM) based on two-photon excited fluorescence (TPEF) and second harmonic generation (SHG) imaging, has become a powerful, important tool for tissue imaging at the molecular level. Recently, MPM is also used to image hematoxylin and eosin (H&E)-stained sections in cancer diagnostics. However, several studies have showed that the results of H&E-stained sections are very different from unstained tissue sections. The unstained tissue could reveal TPEF and SHG image. But the H&E-stained tissue can only reveal a TPEF image. Our aim was to evaluate how the dyes affect the results of imaging by using MPM. In this paper, MPM was used to image histological sections of esophageal invasive carcinoma tissues stained with H, E, and H&E. For comparison, the unstained esophageal invasive carcinoma tissues were also investigated. To elucidate the origins of multiphoton signals in histological sections, the emission spectroscopic of H, E, H&E, and unstained tissue were obtained. Our results showed that the tissue stained with H, E, H&E could show and enhanced the TPEF signal, even low power laser could excite it. But only the H stained and unstained tissue reveal the TPEF and SHG signals. The absent SHG of collagen showed the H&E staining procedure destroyed the noncentrosymmetric molecular structure of collagen. Besides, there is leakage of TPEF signal into the SHG channel. Thus, in the H&E-stained tissue where the SHG signal hardly be observed. In this work, we reveal the effect of H&E stained on multiphoton signals. These findings will be useful for choosing suitable staining method so to improve the quality of cancer imaging and diagnosis in the future.

10024-95, Session Post

The novel drug delivery to vascular wall using laser driven thermal balloon: basic study ex vivo

Kao Suganuma, Rie Homma, Natsumi Shimazaki, Emiyu Ogawa, Tsunenori Arai, Keio Univ. (Japan)

To enhance drug delivery performance of popular drug eluting balloon(DEB) against re-stenosis after angioplasty, we have an idea of adjacent use of our unique laser driven thermal balloon of which realize short term and uniform temperature

to modify delivery characteristics. We have already reported an enhancement effect using this idea, however, detailed characteristics is unknown. Therefore, we studied balloon dilatation on the heating drug delivery performance in terms of vascular circumferential tension using porcine carotid artery wall ex vivo.

The extracted carotid wall was used and circumferential tension of 0-30 mN/mm^2 was added.

Heating drug delivery was performed on this carotid wall with the heated solution of hydrophobic fluorescent Rhodamine B with 3 ?g/ml in concentration and 60, 70, and 37?. We measured a defined drug delivery quantity as well as delivery depth by a microscopic fluorescence measurement on the cross section of the drug delivered vessel.

In the case of 60, 70?, we found the drug penetration increase against 37? case.

We predict that the collagen thermal denaturation of the vessel wall may play important role to this penetration.

In the case of 37?, we found the intima surface drug concentration with 7 mN/mm^2 at 37? was increased as 10-30 times as other tension values. We found surface grooves in this case using an electron micrography. Therefore, we think that the drug delivery enhancement might be related to the groove formations of the vessel wall.

10024-96, Session Post

Optimization on source detector distance for the glucose sensing in a tissue phantom using near-infrared diffuse spectra

Chao Guo, Ziyang Zhang, Tongshuai Han, Di Sun, Jin Liu, Tianjin Univ. (China)

In the non-invasive blood glucose concentration (BGC) sensing, the measurement based on near infrared spectroscopy has been a promising technology since it had acquired dozens of satisfactory results in short-term glucose monitoring tests. However, it's still necessary to improve the measurement precision because it has challenges of the reduced precision in a long-term test when a lot of variables in the test would exist. Considering the requirement of multivariable analysis, the signals of diffuse reflectance spectra should include enough absorption information from glucose. However, the sensitivity of diffuse light intensity to the absorption variation at different source detector separations (SDSs) could be different. We present an analysis method using Monte-Carlo (MC) simulation and the diffuse equation for reasonably selecting proper SDS to get a satisfactory glucose measurement precision when there are multivariable disturbances. In the case of measuring glucose in a tissue phantom using the waveband of 1000-1340nm, we show the SDS optimization result by using this analysis method. The experiment was designed to measure the diffuse reflectance spectra at 0.1-3 mm with the step of 0.1 mm, and the phantom solutions with different glucose concentrations and hemoglobin concentrations are tested. The glucose prediction precision was evaluated using the root mean squared error of prediction (RMSEP) for the all SDSs of 0.1-3mm, and the SDSs with the lower RMSEP were selected for use. Moreover, the selected SDSs in the experiment shows a similar conclusion from the MC simulation. This work could be referenced to the in vivo BGC measurement.

10024-97, Session Post

Assessment of spatial information for hyperspectral imaging of lesion

Xue Yang, Gang Li, Ling Lin, Tianjin Univ. (China)

Multiple diseases such as breast tumor poses a great threat to women's health and life, while the traditional detection method is complex, costly and unsuitable for frequently self-examination, therefore, an inexpensive, convenient and efficient method for tumor self-inspection is needed urgently, and lesion localization is an important step. This paper proposes an self-examination method for positioning of a lesion.

The method adopts transillumination to acquire the hyperspectral images and to assess the spatial information of lesion. Firstly, multi-wavelength sources are modulated with frequency division, which advantageous to separate images of different wavelength, meanwhile, the source serves as fill light to each other to improve the sensitivity in the low-light-level imaging. Secondly, the signal-to-noise ratio of transmitted images after demodulation are improved by frame accumulation technology. Next, gray distributions of transmitted images are analyzed through gray-level ratio images. The gray-level ratio images is constituted by the ratio of actual transmitted images and fitting transmitted images of tissue without lesion, which is to rule out individual differences. Due to scattering effect, there will be transition zones between tissue and lesion, and the zone changes with wavelength change, which will help to identify the structure details of lesion. Finally, image segmentation is adopted to extract the lesion and the transition zones, and the spatial features of lesion are confirmed according to the transition zones and the differences in the ratio images. Experiment using flat-shaped tissue as an example shows that the proposed method can extract the space information of lesion.

10024-98, Session Post

Phase measurements and analysis on erythrocytes affected by lithium and lead ions with quantitative interferometric microscopy

Qi Wei, Jiangnan Univ. (China); Keding Yan, Xi'an Technological Univ. (China); Xiaojun Song, Liang Xue, Shanghai Univ. of Electric Power (China); Cheng Liu, Shouyu Wang, Jiangnan Univ. (China)

Compared to traditional intensity and fluorescent based imaging, phase imaging techniques are able to obtain high contrast sample information often without labeling, thus they can be widely applied for live cell observations and measurements. Among these phase imaging techniques, interference based methods not only can retrieve quantitative phase distributions compared to those qualitative approaches including phase contrast and differential interference contrast, but also owns real time capability and compact system, thus it acts as important tool in biological and medical imaging. Taking the advantages of the quantitative interferometric microscopy, in this paper, the morphology of erythrocytes affected by metal ions are measured and analyzed in details. Quantitative phase distributions of live erythrocytes cultured in 0.9% NaCl solution with lithium carbonate at Li ion density of 0.1 mM and 0.9% NaCl solution with lead nitrate at Pb ion density of 0.1 ?M, respectively, were obtained via interferograms capturing by quantitative interferometric microscopy and phase retrieval according to fast Fourier transform based algorithm. According to multiple sample measuring and statistical analysis, it indicates that when erythrocytes were affected by Li ion, phase volume decreased as phase distributions of erythrocytes reduced, while cellular area did not change obviously. However, both cellular area and phase volume decreased severely with time when erythrocytes were in Pb ion solution. The quantitative measurement can provide reference for erythrocyte testing and study, additionally, it also proves that quantitative interferometric microscopy is an effective tool in cellular observations and measurements.

10024-99, Session Post

Endoscopic optical coherence tomography using compressive sensing

Jie Wang, Yang Hu, Jigang Wu, Shanghai Jiao Tong Univ. (China)

Optical Coherence Tomography (OCT) is a widely used biomedical imaging modality in clinical diagnosis because of its advantage of high resolution and being non-invasive. And endoscopic OCT aims to examine the interior of hollow organs and structures such as respiratory tract and blood vessels. Conventionally OCT images are reconstructed by uniform sampling in both axial and transverse direction of the image. And the sampling distance must satisfy the Nyquist sampling criteria to match the image resolution. To shorten the scanning time and reduce the acquisition data, we propose to sparsely sample the axial scans and use compressive sensing (CS) reconstruction in endoscopic OCT imaging. Since being proposed in 2006, CS have been proved to be efficient to reconstruct the full image with random part of original information under specific conditions. Similarly, we can reconstruct the full endoscopic OCT image with randomly chosen axial scans that are much less than conventional Nyquist criteria requirement. We have designed and made a prototype side-imaging endoscopic OCT imaging system to demonstrate our idea. Our endoscopic OCT probe can achieve circumferential scanning by rotating a reflecting micro-prism for 360 degrees. Unlike compressive sensing reconstruction in sparsely sampled rectilinear images, the sampling distances in the circumferential images are different for different imaging depths and require additional considerations. And we study the ratio of sparse sampling numerically and experimentally that are required to reconstruct acceptable OCT images. We have demonstrate that the OCT image acquisition time can be significantly reduced because of much less acquired data.

10024-100, Session Post

Temperature insensitive prediction of glucose concentration in turbid medium using multivariable calibration based on external parameter orthogonalization

TongShuai Han, Ziyang Zhang, Chao Guo, Di Sun, Jin Liu, Tianjin Univ. (China)

The measurement accuracy of non-invasive blood glucose concentration (BGC) sensing with near-infrared spectroscopy is easily affected by the temperature variation in tissue because it would induce an unacceptable spectrum variation and the consequent prediction deviation. We use a multivariable correction method based on external parameter orthogonalization (EPO) to calibrate the spectral data recorded at different temperature values to reduce the spectral variation. The tested medium is a kind of tissue phantom, the Intralipid aqueous solution. The calibration uses a projection matrix to get the orthogonal spectral space to the variable of external parameter, i.e. temperature, and then the useful spectral information relative to glucose concentration has been reserved. Even more, training the projection matrix can be separated to building the calibration matrix for the prediction of glucose concentration as it only uses the typical samples' data with temperature variation. The method presents a lower complexity

than modeling a robust prediction matrix, which can be built from comprehensive spectral data involved the all variables both of BGC and temperature. In our test, the calibrated spectra with the same glucose concentration but different temperature values show a significantly improved repeatability. And then the glucose concentration prediction results show a lower root mean squared error of prediction (RMSEP) than that using the robust calibration model, which has considered the two variables. We also discuss the selection of the used typical samples to get a better calibration. This research may be referenced to the temperature calibration for in vivo BGC sensing.

10024-101, Session Post

Determination of the reference position in the near-infrared non-invasive blood glucose measurement in vivo

Guang Han, Jin Liu, Rong Liu, Kexin Xu, Tianjin Univ. (China)

Position-based reference measurement method is taken as one of the most promising method in non-invasive measurement of blood glucose based on spectroscopic methodology. Selecting an appropriate source-detector separation as the reference position is important for deducting the influence of background change and reducing the loss of useful signals. Our group proposed a special source-detector separation named floating-reference position where the signal contains only background change, that is to say, the signal at this source-detector separation is uncorrelated with glucose concentration. The existence of floating-reference position has been verified in a three layer skin by Monte Carlo simulation and in the in vitro experiment. But it is difficult to verify the existence of floating-reference position on the human body because the interference is more complex during in vivo experiment. Aiming at this situation, this paper studies the determination of the best reference position on human body by collecting signals at several source-detector separations on the palm and measuring the true blood glucose levels during oral glucose tolerance test (OGTT) experiments of 5 subjects. Partial least square (PLS) calibration model is established between the signals at every source-detector separation and its corresponding blood glucose levels. The results shows that the correlation coefficient around 2mm is lowest and it can be used as reference for background correction. The signal of this special position is important for improving the accuracy of near-infrared non-invasive blood glucose measurement.

10024-102, Session Post

Rotary-scanning optical resolution photoacoustic microscopy

Weizhi Qi, Lei Xi, Univ. of Electronic Science and Technology of China (China)

Optical resolution photoacoustic microscopy (ORPAM), one of the fastest developing photoacoustic imaging modalities, owns comparable spatial resolution but deeper penetration depth compared with pure optical microscopic techniques such as fluorescence confocal microscopy, two-photon microscopy and optical coherence microscopy. In this letter, we developed a new ORPAM system without raster scanning of imaging interfaces or objects. We utilized a two-dimensional (2D) galvanometer scanner together with a scanning lens to realize 2D scanning of the laser beam. A 10 MHz cylindrically focused ultrasound transducer was mounted on a motorized rotation stage to synchronized move with the laser beam. To minimize the loss in signal to noise ratio (SNR), the position of acoustic focus was optimized to achieve confocal with optical focus. Carbon fibers embedded inside a tissue mimicking phantom was imaged to evaluate the lateral resolution of the system. We have achieved resolutions of 10 ?m in lateral and 70 ?m in axial. Additionally, we successfully accomplished in vivo imaging of vasculature network inside mouse ears by using this system. This study suggests that this new ORPAM system has the potential to be used in applications where raster scanning of imaging interfaces or objects is not suitable.

10024-103, Session Post

Fast acquisition of Golgi-stained neuronal morphology and distribution with anatomical annotation at single-cell resolution in whole brain

Xiao Chen, Xiaoyu Zhang, Qiuyuan Zhong, Jing Yuan, Hui Gong, Qingming Luo, Huazhong Univ. of Science and Technology (China)

Precisely annotating and accurately reconstructing dendritic morphology of Golgi-stained neurons are prerequisite to cell type study. However there is no research tool to orientate Golgi-stained neurons at single cell resolution due to the lack of anatomic reference in existing whole-brain imaging datasets. Here, we develop a dual-mode micro-optical sectioning tomography (dMOST) for dissecting and locating brain-wide Golgi-stained neurons with cytoarchitectonic landmarks at single-cell resolution. We introduce a whole-brain real-time counterstain protocol for staining cytoarchitectonic landmarks simultaneously during the imaging process. The method employs a three-working window dichroic mirror to achieve simultaneous detection of both reflective (for Golgi staining) and fluorescent (for cytoarchitecture staining) signals. Structural illumination helps the method to improve imaging throughput and accelerate whole-brain imaging at single-neuron resolution. By this system, we acquire a full-volume, dual-color mouse brain datasets of Golgi-stained neurons with single-cell location reference at a voxel size of 0.32 ? 0.32 ? 1.0 ?m in 88 hours. For this dataset, we also define different brain regions according to the cytoarchitecture images, and then analyze the cell densities of Golgi-stained neurons in different brain regions. These results show that dMOST can be used as an essential tool for brain-widely anatomizing dendritic morphology at precise anatomical annotation.

10024-104, Session Post

Unwrapping and aberration compensation free-phase retrieval method for quantitative interferometric microscopy

Keding Yan, Xiaoning Yu, Xi'an Univ. of Technology (China); Xiaojun Song, Liang Xue, Shanghai Univ. of Electric Power (China); Shouyu Wang, Jiangnan Univ. (China)

As quantitative interferometric microscopy can provide phase distributions of biological samples, it is becoming important detecting tool in cellular observations and measurements in both biological and medical fields. However, traditional quantitative interferometric microscopy suffers from the complex phase unwrapping procedure, which needs long time consuming and heavy calculation load and limits its applications in dynamic and high speed measurements. Though several methods as dual-wavelength algorithm are proposed to accelerate the phase unwrapping speed, they often need more additional devices and complicated systems. In order to increase the calculation efficiency of phase retrieval as well as simplify its procedures, here, a high speed moire based phase retrieval method is

proposed which is capable of recovering quantitative phase distributions in fringe analysis without phase unwrapping or aberration compensation. Both numerical simulations and experiments are provided proving that the method not only can retrieve the high-accurate quantitative phase distributions of cells, but also raise the calculation efficiency for nearly 100 times compared to traditional phase retrieval since both phase unwrapping and aberration compensation are not necessary in the phase retrieval process. It is believed that the proposed method would be useful in real time phase observations and measurements.

10024-105, Session Post

Evaluation on the detection limit of blood hemoglobin using photolepthysmography based on path-length optimization

Di Sun, Chao Guo, Ziyang Zhang, Tongshuai Han, Jin Liu, Tianjin Univ. (China)

The blood hemoglobin concentration's (BHC) measurement using Photoplethysmography (PPG), which gets blood absorption to near infrared light from the instantaneous pulse of transmitted light intensity, has not been applied to the clinical use due to the non-enough precision. The main challenge might be caused of the non-enough stable pulse signal when it's very weak and it often varies in different human bodies or in the same body with different physiological states. We evaluated the detection limit of BHC using PPG as the measurement precision level, which can be considered as a best precision result because we got the relative stable subject's pulse signals recorded by using a spectrometer with high signal-to-noise ratio (SNR) level, which is about 30000:1 in short term. Moreover, we optimized the used path-length using the theory based on optimum path-length to get a better sensitivity to the absorption variation in blood. The best detection limit was evaluated as about 1 g/L for BHC, and the best SNR of pulse for in vivo measurement was about 2000:1 at 1130 and 1250 nm. Meanwhile, we conclude that the SNR of pulse signal should be better than 400:1 when the required detection limit is set to 5 g/L. Our result would be a good reference to the BHC measurement to get a desired BHC measurement precision of real application.

10024-106, Session Post

Evaluation and recognition of aging skin images with aging by support vector machine

Liangjun Hu, Shulian Wu, Fujian Normal Univ. (China)

Aging is a very important issue not only in dermatology, but also cosmetic science. Cutaneous aging involves both chronolgical and photoaging aging process. The evaluation and classification of aging is an important issue with the medical cosmetology workers nowadays. The purpose of this study is to assess chronological-age-related and photo-age-related of human skin. The texture features of skin surface skin, such as orientation index, coarse, were analyzed by Fourier transform and Tamura. And the aim of it is to detect the object hidden in the skin texture in difference aging skin. Then, Support vector machine was applied to train the texture feature. The different age's states were distinguished by the Support vector machine model. The results help us to further understand the mechanism of different aging skin from texture feature and help us to distinguish the different aging states.

10024-107, Session Post

An experimental research on highly-sensitive pharmacokinetic diffuse fluorescence tomography of CT scanning mode

Yanqi Zhang, Xin Wang, Limin Zhang, Huijuan Zhao, Feng Gao, Tianjin Univ. (China)

In vivo tomographic imaging of the fluorescence pharmacokinetic parameters in tissues can provide additional specific and quantitative physiological and pathological information to that of fluorescence concentration. This modality normally requires a highly-sensitive diffuse fluorescence tomography (DFT) working in dynamic way to finally extracts the pharmacokinetic parameters from the measured pharmacokinetics-associated temporally-varying boundary intensity. This paper is devoted to experimental validation of our proposed direct reconstruction scheme of instantaneous sampling based pharmacokinetic-DFT: A highly-sensitive DFT system of CT-scanning mode working with parallel four photomultiplier-tube photon-counting channels is developed to generate an instantaneous sampling dataset; A direct reconstruction scheme then extracts images of the pharmacokinetic parameters using the adaptive-EKF strategy. We firstly investigate the principle validity of the experiment system and reconstruction algorithm by designing a dynamic phantom that can simulate the agent metabolism in living tissues, and then the application feasibility of the propose methodology in revealing metabolic rates of the fluorescence agent by imaging healthy and tumor-bearing mice.

10024-108, Session Post

Accelerating data acquisition of large-sized sample by propidium iodide-stained contour extraction in real time

Xiaoyu Zhang, Qiuyuan Zhong, Jing Yuan, Hui Gong, Qingming Luo, Huazhong Univ. of Science and Technology (China)

Imaging large tissue and organs in 3D is critical to understand biological process. Due to the contour irregularity of the large-sized sample, a cuboid bigger than the sample in size would be usually defined as imaging range to guarantee the integrity of imaging results. However, this approach has to acquire a lot of redundant data and sacrifice data acquisition time. Here, we propose to a real-time contour extraction of propidium iodide (PI)-stained sample to define minimized imaging range for large-sized sample to shorten data acquisition time. Immersing the sample in PI solution in several minutes before imaging could stain the sample contour without polluting potential internal fluorescent labels. Strong contrast of PI-stained contour enables to extract the sample contour and then define minimized imaging region in real time. To validate the efficiency of this method, we apply this method to wide-field large-volume tomography (WVT) imaging. Benefit from this method, we achieve a data acquisition of a 4-month-old SOM-cre mouse brain at the voxel size of 0.32 ? 0.32 ? 2 ?m in 2.1 days, improving 38% from the one without imaging range adjustment. The imaging mosaics of the dataset is 0.65M, reducing 48% from the one without imaging range adjustment. Our method can be generalized to other large-sized tissue and organs to accelerate large-scale 3D imaging in biological research.

10024-109, Session Post

Differentiation of highly-metastatic nasopharyngeal carcinoma cells using multiphoton microscopy

Zhenlin Zhan, Fujian Normal Univ. (China)

Nasopharyngeal carcinoma (NPC) is one of the most common tumors in Southeast Asia and Southern China. It is often associated with advanced clinical stage with higher incidence of invasion and metastasis at the time of diagnosis. Hence, the 5-year survival rate of patients with metastatic diseases is less than 60%. It is of great clinical value to further understand the metastatic status of cancerous cells and find valuable early diagnostic markers as well as novel therapeutic strategies. The primary hypothesis tested in the study was that NPC cells at different stage of invasion and metastasis can be differentiated using multiphoton microscopy (MPM). Based on the development of the field of non-linear optics and femtosecond lasers, MPM can provide real-time detailed information about cell morphology. In this study, CNE1 and CNE2Z cells were cultured and used for subsequent experiments. The activity of cell migration and invasion was measured using Transwell migration and Transwell invasion assays. At the same time, the morphologic features were quantified from the multiphoton images. The results of Transwell migration and invasion measurements showed that the invasion and migration of CNE2Z cells were significantly enhanced when compared with that of CNE1 cells. Also, statistically significant differences in the morphologic features were found between two kinds of cancer cells. In conclusion, it is feasible to use MPM to differentiate cancer cells with different stage of invasion and metastasis.

10024-110, Session Post

Measuring the biomechanical properties of actin in single breast cancer cell

Minghai You, Yuhua Wang, Ningcheng Jiang, Shusen Xie, Hongqin Yang, Fujian Normal Univ. (China)

Biomechanics of cells play an important role in the behavior and development of diseases. Such forces could have a profound influence on the health, structural integrity, and function of cells. In this study, we proposed a method to assess the actin biomechanical properties in single breast cancer cell by combining structured illumination microscopy (SIM) with atomic force microscopy (AFM). High resolution optical image of actin area in MCF-7 cell and its elastography were given. The result shows that the optical image of actin via SIM could improve about 40% in resolution than conventional wide field fluorescence microscopy, which could give a precise local site for AFM measurement. The elasticity of actin is about in the range of 10~100 kPa. It indicates that optical elastography and biomechanics methods will aid in the understanding and clinical diagnosis of diseases at single cell level.

10024-111, Session Post

Childhood lymphoblastic leukemia adverse drug reactions: study of risk factors and therapy prognosis by optical methods

Andrey Zyubin, Anastasiya Lavrova, Svetlana Babak, Vladimir Malaschenko, Anastasiya Borisova, Nikita Opryishko, Immanuel Kant Baltic Federal Univ. (Russian Federation)

We describe the study of children lymphoblastic leukemia adverse drug reactions. We use a concentration of adenosine triphosphate (ATP) as a marker to estimate processes of hepatotoxic effects and drug resistance, during the therapy, and show the applicability of confocal microscopy method for revealing and working with cellar and mitohondrial concentration of ATP. ATP is involved in the transport of the drug across the cell membrane into the cell. Drug transport osmotically sensitive and depends on the concentration of ATP. For example, daunorubicinum, etoposide and vincristine transports into the cell at the concentration of cellular ATP 0.3 mg/l, 0.29 mg/l and 0.28 mg/l, respectively. Experimental data from blood cells and its mitohondria was taken with a confocal microscope LSM 700 (Carl Zeiss, Germany) using ZEN black Microscope and Imaging Software Software (CarlZeiss, Germany). The luminescence intensity value had been recorded.Detection was carried out in the emission spectrum of lucefireine in the visible range of ~ 500-700 nm, with an expected maximum of about 536 nm. All gained data of quantitative values for cellular and mitochondrial ATP concentration had been calculated and allow us to mark the supposed correlation between the degrees of adverse drug reactions and ATP concentration value. The model describes correlation between hepatotoxic effects, drug resistance and ATP cellar and mitohondrial concentration had been created.

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10024-112, Session Post

Parameter estimation and analysis model selections in fluorescence correlation spectroscopy

Shiqing Dong, Jie Zhou, Yuhua Wang, Shusen Xie, Hongqin Yang, Fujian Normal Univ. (China)

Fluorescence correlation spectroscopy (FCS) is a powerful technique that could provide high spatiotemporal resolution and detection for the diffusions of biomolecules at extremely low concentrations. The accuracy of this approach depends on experimental condition requirements and the data analysis model. We set up a laser confocal-based FCS system, and used a Rhodamine6G solution to calibrate the system and get the related parameters. Then, we carried out an experimental measurement in one component solution to evaluate the relationship between a certain number of molecules and concentrations. The results showed FCS system was stable and valid. Finally, a two-component solution experiment was done to show the importance of analysis model selection. It is valuable for single molecular diffusion study in living cells using FCS.

10024-113, Session Post

Estimation of mouse optical structures in vivo with the aid of image registration

Wenbo Wan, Feng Gao, Tianjin Univ. (China)

The reconstruction quality in the model-based optical tomography modalities can greatly benefit from a priori information of accurate tissue optical-structures. Optical structures of tissue highly relies on its anatomical structures, which can be obtained from anatomical imaging system such as X-ray computed tomography (XCT). However, since X-ray offers low soft-tissue contrast, segmentation of the abdominal organs from XCT images can be problematic. In order to overcome the challenges, the anatomical-structures of a target mouse are approximately obtained through registering a standard mouse anatomical atlas, i.e., the Digimouse, to its XCT volume with non-rigid image registration, and the optical-structures of the target

mouse is approximately estimated when literature published optical parameters are assigned to the registered anatomical structures. Results of numerical simulations reveals that the Digimouse can be effectively registered to the XCT volumes of the target mouse, and the registered atlas shows well similarity with the theoretical anatomical structures of the target mouse. Result of mouse experiment have further demonstrated that the proposed method is feasible to estimate optical structures of the target mouse in vivo, which shows possibility for enhancing the reconstruction of model-based optical tomography such as fluorescence molecular tomography.

10024-114, Session Post

Novel shadowless imaging for eyes-like diagnosis in vivo

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Eyes-like diagnosis was a traditional Chinese medicine method for many diseases, such as chronic gastritis, diabetes, hypertension, etc. There was a close relationship between viscera and eyes-like. White-Eye was divided into fourteen sections, which corresponded to different viscera, so eyes-like was the reflection of status of viscera, in another words, it was an epitome of viscera health condition.

In this paper, we developed a novel shadowless imaging technology and system for Eyes-Like diagnosis in Vivo, which consisted of an optical shadowless imaging device for capturing and saving images of patients' eyes-like, and a computer linked to the device for image processing. A character matching algorithm was developed to extract the character of white-eye in corresponding sections of eyes-like images taken by the optical shadowless imaging device, according to the character of eyes-like, whether there were viscera diseases could be learned. A series of assays were carried out, and the results verified the feasibility of eyes-like diagnosis technique.

10024-115, Session Post

Interstitial optical parameter quantification of turbid medium based on CW radiance measurements

Lingling Liu, Limin Zhang, Feng Gao, Huijuan Zhao, Tianjin Univ. (China)

CW radiance measurements examine the light intensity at fixed source-detector location from multiple detection directions which thus is benefit for the noninvasive interstitial optical parameter quantification. The CW radiance measurements are generally needed to meet the requirement of small source detector separation (SDS) and sample as few source-detector locations as possible. Howerver, the diffuse approximation normally utilized as a forward model for the recovery of optical parameters has a limitation at small SDS and in media with low albedo, in addition, at least two source-detector locations are needed to sample. In this paper, Monte Carlo (MC) simulations aimed at angular radiance are used to simulate experimental measurements and the Pn approximation is used as the forward model for fitting to recover optical parameters at just one source-detector location. Over a wide range of reduced albedo of medium between 0.69 and 0.99, the recovery errors of absorption coefficient and reduced scattering coefficient are less than 13.88%, 2.91% respectively at 2mm SDS. The effects of the maximum angle used for fitting and noise on optical parameter recovery have been further studied respectively in this paper. The results show that the recovery errors of absorption coefficient and reduced scattering coefficient are less than 7.43%, 2.58% respctively when the maximum angle is 140 degree with minimum error and the recovery errors of absorption coefficient and reduced scattering coefficient less than 8.02%, 2.58% in 40 dB Gaussian noisy. Experiments on a liquid phantom with a CW radiance measurement system are conducted and the results show that the optical parameters can be effectively recovered at just one source-detector location.

10024-116, Session Post

The phase characteristics and sub-structure shape analysis of a neuron based on electrical-optical modeling

Ying Ji, Tingting Hua, Wenbo Tang, Yuanyuan Xu, Yawei Wang, Jiangsu Univ. (China)

The research on electrical activity of a neuron has a very significant application in many fields, such as bioscience, clinical medicine and so on. It is very important to take images of the sub-structure of a neuron due to that the morphology of which is closely related to its function and the associated firing status as well. Quantitative phase imaging is a technology which could get the morphology information of an object non-invasively and non-destructively in full field at real time. Based on this technology and optical simulation, a practical simplified model of a neuron including cell body, axon and dendrite is established in this paper with considering the relationship of the distribution of ions and the refractive index of the cell. The related phase images are gotten by the simulation as well. The optical phase characteristic analysis of this model is given based on these phase images, that is, the gradient calculation of the phase distributions and shape analysis of the phase diagrams are presented respectively. Then the sub-structure boundaries of the sample and the variation characteristics of refractive index of the object are obtained. From which, the information of the distribution of ions as well as the associated firing status of the neuron can be indicated intuitively to some extent. This work could provide a new method for the research on firing behavior analysis of neurons or other biological cells.

10024-117, Session Post

Dorsal hand vein recognition based on Gabor multi-orientation fusion and multi-scale HOG features

Tuo Han, Zhiyong Wang, Xiaoping Yang, Tianjin Univ. of Technology (China)

Kinds of factors such as illumination and hand gestures would reduce the accuracy of dorsal hand vein recognition.Aiming at single hand vein image with low contrast and simple structure,an algorithm combining Gabor multi-orientation features fusion with Multi-scale Histogram of Oriented Gradient (MS-HOG) is proposed in this paper.With this method,more features will be extracted to improve the recognition accuracy.Firstly,diagrams of multi-scale and multi-orientation are acquired using Gabor transformation,then the Gabor features of the same scale and multi-orientation will be fused,and the features of the correspondent fusion diagrams will be extracted with a HOG operator of a certain scale.Finally the multi-scale cascaded histograms will be obtained for hand vein recognition.The experimental results show that our method not only improve the recognition accuracy but has good robustness in dorsal hand vein recognition.

10024-118, Session Post

Discrimination of liver cancer in cellular level based on backscatter micro-spectrum with PCA algorithm and BP neural network

Jing Yang, Univ. of Shanghai for Science and Technology (China)

The incidence and mortality rate of the primary liver cancer are very high and its postoperative metastasis and recurrence have become important factors to the prognosis of patients. Circulating tumor cells (CTC), as a new tumor marker, play important roles in the early diagnosis and individualized treatment and CTC also have induced the interest of researchers. This paper presents an effective method to distinguish liver cancer based on the cellular scattering spectrum, which is a non-fluorescence technique based on the fiber confocal microscopic spectrometer. The principal component analysis (PCA) and back propagation (BP) neural network was utilized to establish an automatic recognition model for backscatter spectrum of the liver cancer cells. Principal component analysis was applied to reduce the dimension of the cell spectral data which obtained by the fiber confocal microscopic spectrometer. We established a neural network pattern recognition model with 2 input layer nodes, 11 hidden layer nodes, 3 output nodes. We trained the network with 66 samples and also tested it. Results showed that the recognition rate of the three types of cells is more than 90%, the relative standard deviation is only 2.36%. The experimental results showed that the fiber confocal microscopic spectrometer combining with the algorithm of PCA and BP neural network can automatically identify the liver cancer cell from the blood cells. This will provide a better tool for investigating the metastasis of liver cancers in vivo, the biology metabolic characteristics of liver cancers and drug transportation. Additionally, it is obviously referential in practical application.

10024-119, Session Post

Analysis of human hairs by femtosecond laser-induced breakdown spectroscopy

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The time-resolved femtosecond laser-induced breakdown spectroscopy (LIBS) was used to analyze human hairs. Spitfire Ti:sapphire amplifier system (Spectra-Physics) was used as a source of femtosecond laser pulses (<45 fs, pulse energy up to 5 mJ) and ICCD cameras (PicoStar HR, LaVision and PI-MAX3, Princeton Instruments) coupled with 2500i or 2300 Acton SpectraPro spectrographs were used as a detectors. Plasma was generated by focusing laser radiation directly on the glued strand of hairs. Gate delays were varied from 0 to 200 ns and kinetic of luminescence of emission lines and background spectra were obtained in spectral range of 200-750 nm. Measurements of different social classes were carried out. Correlation between concentrations of elements (Na, Ca, K, Mg) in hairs was obtained. It is shown that femtosecond LIBS can be a promising technique for the analysis of essential and toxic elements in hair and allows to diagnose disorders of mineral metabolism in the human body.

10024-120, Session Post

Compact hybrid real-time hyperspectral imaging system with high effective spatial, spectral, and temporal resolution

Filip Roth, Masaryk Univ. (Czech Republic) and IBSmm Engineering, spol. s r. o. (Czech Republic); Ahmad Abbadi, Masaryk Univ. (Czech Republic)

Medical endoscopes for image-guided surgery commonly use standard color image sensors, discarding any more detailed spectral information. Medical spectroscopy devices with various spectral working ranges are specialized to specific medical procedures and in general are not usable for image-guided surgery due to limitations in spatial or temporal resolution.

In this paper, we present an initial demonstrator of hyperspectral endoscope, composed of two image sensors with complementing parameters. Using this hybrid approach, combining sensors with different spatial and spectral resolutions and spectral ranges, we obtain improved coverage of all the respective parameters. After digitally processing and merging the video streams, while maintaining the better features of both, we obtain an imaging system providing high effective spatial, spectral and temporal resolution.

The system is based on field programmable gate arrays and provides real-time video output (60 Hz), which is usable for navigation during image-guided surgery. The flexible system architecture allows for an easy extension of the processing algorithms and enables minimal video signal latency.

Physical dimensions and portability of the system are comparable to standard off-the-shelf medical endoscope cameras. The device can output both processed video and standard visible light video signals on one or more video outputs of the system. The resulting processed video signal obtained from the combined image sensor data greatly increases the amount of useful information available to the end user.

10024-121, Session Post

Interferometer immunosensor based on porous silicon for determining alpha-fetoprotein

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Alpha-fetoprotein (AFP) is a kind of plasma glycoprotein synthesized by human liver in the early stage. An increased level of AFP in the blood may be a sign of liver cancer. Normal human AFP protein content is very low, less than 20ng/L.According to the survey found that in the serum of about 80% patients with hepatocellular carcinoma, the AFP will increase, generally in the 8 months before the onset of symptoms of liver cancer has increased.In this paper,porous silicon based optical Fabry-Perot cavity structure is prepared as a label-free immunosensor platform for detecting AFP. After the antigen-antibody reaction, it is monitored that the red shift of the reflection spectrum of the immunosensor increases with the antigen concentration.This research also plays a potential role for the extensive applications in immunoassay.

10024-122, Session Post

Label-free and high-sensitive detection for genetic point mutation based on hyperspectral interferometry

Rongxin Fu, Qi Li, Junqi Zhang, Ruliang Wang, Xue

Lin, Ning Xue, Ya Su, Kai Jiang, Tsinghua Univ. (China); Guoliang Huang, Tsinghua Univ. School of Medicine (China)

Label free point mutation detection is particularly momentous in the area of biomedical research and clinical diagnosis since gene mutations naturally occur and bring about highly fatal diseases. In this paper, a label free and high sensitive approach is proposed for point mutation detection based on hyperspectral interferometry. A hybridization strategy is designed to discriminate a single-base substitution with sequence-specific DNA ligase. Double-strand structures will take place only if added oligonucleotides are perfectly paired to the probe sequence. The proposed approach takes full use of the inherent conformation of double-strand DNA molecules on the substrate and a spectrum analysis method is established to point out the sub-nanoscale thickness variation, which benefits to high sensitive mutation detection. The limit of detection reaches 4pg/mm2 according to the experimental result. A lung cancer gene point mutation was demonstrated, proving the high selectivity and multiplex analysis capability of the proposed biosensor.

10024-123, Session Post

Application of CRDS laser breath acetone analyzer in fat burning

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Breath acetone is the production in the process of fat metabolism. Through measuring the breath acetone concentration, we can track the fat metabolism in healthy individuals. The method is suitable for the person being reduced fat, which can eliminate the interference of water and inspire the power of fat burning. At the same time, it can prevent the risk of personal injury due to the high ketone body. In order to show the advantage of breath acetone monitoring in fat burning, we recruit 14 healthy volunteers who are in the process of fat loss. The breath acetone, urine ketone, weight, BMI and body fat rate in the fasting state for 21 days are recorded, while the dietary intake calories and the sport consumption calories are recorded too. The breath acetone is measured by the CRDS laser breath acetone analyzer.

The experiment results show that the average breath acetone of volunteers who loss more weight is higher than those loss less weight in 21 days. The fasting breath acetone concentration has the same change trend with weight and body fat rate generally. While the urine ketone show ++ and +++, the acetone breath acetone increases dramatically, which has significant statistical differences. The experiment also shows that the fat is consumed slowly under the common action of reduced diet and increased sports. When the net calories of volunteers keep in a low level for days, the weight and body fat rate would drop slowly, and the breath acetone increase gradually. However in the process of fat burning, when the dietary intake of calories increases suddenly, breath acetone will decrease rapidly in one day, the weight and body fat rate will rise slowly. So we can fast know the quantitative and accurate fat burning state by monitoring the fasting breath acetone, which can help us to adjust the fat loss plan timely, avoid the injury due to the high ketone body, achieve the purpose to lose fat in healthy method.

10024-124, Session Post

Application study of transport intensity equation in quantitative phase reconstruction

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In order to improve detection speed and accuracy of biological cells, a quantitative non-interference optical phase field method is proposed in commercial microscope, taking the red blood cells as the classical phase research objects. This method not only gives quantitative phase distribution of cells quickly, but also measure a large number of cells at the same time. Three bright field micrographs were collected in the experiment. Utilizing the transport intensity equation, the quantitative phase distributions of red blood cell are gained and agree well with the previous optical phase models. Analysis shows that the resolution of introduced system reaches sub-micron dimension. This method is potential in the use of real-time observing and quantitative analyzing of cells in vivo.

10024-125, Session Post

Photophysical property of the pyridyl and pyrimidinyloxy silicon (IV) phthalocyanines and their morphology of polymeric nanoparticles

Yiru Peng, Sujuan Pan, Ting Lin, Shijun Wu, Yufeng Jiang, Di Zeng, Hongqin Yang, Yide Huang, Fujian Normal Univ. (China)

Phthalocyanines (Pcs) are extensively studied by many scientists because of their interesting optical, electrical properties and good thermal stability. The unsubstituted Pcs can present solubility and aggregation behaviour problems for limiting their applications. In our study two pyridyl and pyrimidinyloxy silicon (IV) phthalocyanines were synthesized. Their photophysical properties were examined by UV-Vis, steady-state and time-resolved fluorescence spectroscopic methods. The positions of Q band were observed at 670 nm for two phthalocyanines. Compared with silicon phthalocyanine dichloride (SiPcCl2), the fluorescence intensities and lifetimes of two pyridyl and pyrimidinyloxy silicon (IV) phthalocyanines increased. In order to improve biocompatibility and tumor-targeted delivery, the hydrophobic dendritic phthalocyanine were encapsulated by diblock amphiphilic copolymer poly (N'-benzyl oxygen carbonyl lysine)-poly (ethylene glycol)-poly (N'-benzyl oxygen carbonyl lysine) (PLL(Z)-PEG-PLL(Z)) to form the polymeric nanoparticles. The morphology of two nanoparticles were investigated by using atomic force microscope. The polymeric nanoparticle is spherical with a diameter at about 35 nm. The polymeric nanoparticles would be the promising third-generation photosensitizer (PS) for PDT.

10024-126, Session Post

Dual-modal in-vivo imaging system for small animal using individual novel detector OptX

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Rongxin Fu, Ning Xue, Tsinghua Univ. School of Medicine (China); Xue Lin, Ya Su, Tsinghua Univ. (China); Kai Jiang, Tsinghua Univ. School of Medicine (China)

Multimodal imaging system which always combines imaging modalities providing structural information with modalities providing functional information plays an important role in animal research. A lot of multi-modal imaging system has been reported and used in different area of biomedical research. While most reported multi-modal imaging systems employ separated detector for each modality and always have difficulties in merging multi-modal information.

Herein, we present a novel detector – OptX capable of detecting both high-energy X-ray and optical wavelength photons. The design concept of this detector is discussed and a prototype detector is demonstrated. A dual-modal imaging system based on this detector is designed and established, which realized optical molecular imaging and X-ray based imaging. No extra marker or algorithm is needed for registration and merging two modalities. Dual-modal imaging is successfully performed with this imaging system. The performance (resolution and field of view) of this imaging system is evaluated. The results indicate that the construction of this OptX detector and a dual-modal imaging system based on it is feasible.

10024-127, Session Post

2D light scattering label-free cytometry using light-sheet illumination

Meiai Lin, Xuantao Su, Shandong Univ. (China)

Flow cytometry that measures optical signals from biological cells has wide application in many fields such as biomedicine. Conventionally the cells are labeled with fluorescent dyes to obtain detailed cellular information, which is complex and may interrupt the cell function. Compared with fluorescent labeling, two-dimensional (2D) light scattering cytometry is an effective label-free technology for cell analysis.

Light-sheet technique has been introduced into fluorescence microscopy in recent years. Here we adopt the light-sheet illumination in 2D light scattering static cytometry. The light-sheet restricts the excitation volume near the scatter, thus reduces background noise. In our cytometer, a cylindrical lens is used to form light-sheet and a sample chamber is fabricated for better excitation of the cells under an inverted microscope. Two-dimensional light scattering patterns are obtained by a complementary metal oxide semiconductor (CMOS) detector via a low numerical aperture (NA 0.4) objective lens.

The thickness of the light-sheet measured in fluorescent solution is about 10 ?m. Two-dimensional light scattering patterns of single polystyrene microspheres with 3.87 ?m in diameter are obtained. The experimental patterns characterized with fringe structure agree well with the Mie theory simulated ones. We further demonstrate that the technique developed here can be used for yeast cell size determination. Our results suggest that the light-sheet illumination is an effective excitation method for label-free cytometry and light-sheet-based 2D light scattering static cytometry has the potential for cell diagnostics.

10024-128, Session Post

The effect of metal ions on the photophysical and photochemical properties of bromo dendrimer metal phthalocyanines

Yiru Peng, Sujuan Pan, Dongdong Ma, Tiantian Zhang, Kuizhi Chen, Shusen Xie, Hongqin Yang, Fujian Normal Univ. (China)

Phthalocyanines (Pcs) have attracted great attention because of their applications in material science including electro-optical devices, electrochromic display, and photodynamic therapy (PDT) of cancer. The photophysical and photochemical properties of Pcs can be modulated by either peripheral substituents or metal ions co-ordination to central cavity of highly conjugated tetrapyrrolic macrocycles. However, because of the hydrophobic nature of the Pcs ring, Pcs have strong tendency to aggregate in solution, which limited their applications. To overcome this problem, the introduction of dendritic wedge to peripheral positions of phthalocyanines can prevent the formation of aggregation to some extent. The photophysical and photochemical properties of metal dendritic phthalocyanines were studied by UV/Vis and fluorescence spectroscopic methods. The result indicated that the photophysical properties of dendrimer zinc (II) phthalocyanine exhibited metal ions dependence. Compared with the magnesium (II) phthalocyanine, the intensity of Q band of zinc (II) phthalocyanine was increased but no obviously position change was observed. Meanwhile, the fluorescence intensity of zinc (II) phthalocyanine exhibited relatively higher than the magnesium (II) phthalocyanine. Whereas the fluorescence quantum yield and lifetimes of magnesium (II) phthalocyanine was clearly longer than that of zinc (II) phthalocyanine. The singlet oxygen quantum yield of zinc (II) phthalocyanine was higher than the magnesium (II) phthalocyanine. This results indicated that the zinc (II) phthalocyanine is a better candidate for photodynamic therapy of cancer.

10024-129, Session Post

Monitoring the changes of mitochondrial morphology and its metabolism of breast cancer cells with the treatment of HSP70 inhibitor after heat shock by fluorescence imaging

Biying Yu, Hongqin Yang, Hui Li, Fujian Normal Univ. (China)

Heat shock (HS) is one of the best-studied exogenous cellular stresses, and all cellular compartments and metabolic processes are involved in HS response. The heat shock protein (HSP) expression enhanced during HS mainly localized in subcellular compartments, such as cytosol, endoplasmic reticulum and mitochandria. The major inducible heat shock protein 70 (HSP70) modulate cellular homeostasis and promote cellular survival by blocking a caspase independent cell death through its association with apoptosis inducing factor. Mitochondria as the critical elements of HS response that participate in key metabolic reactions, and the changes in mitochonrial morphology may impact on mitochondrial metabolism. In this paper, the changes of mitorchondrial morphology in breast cancer cell have been monitored in real time after heat shock (43?) by the fluorescence imaging, and the influence of HSP70 inhibitor on mitochandrial structures have also been investigated. Then the information of mitochondrial metabolism which can be characterised by the level of the mitochondrial membrane potential has also been obtained wihout/with the treatment of HSP70 inhibitor. Our data indicated that the mitochandrial morphology were related with the mitochandrial membrane potential, and the mitochandrial membrane potential was influenced significantly with the treatment of HSP70 inhibitor after HS.

10024-130, Session Post

Vigilance task-related functional connectivity revealed by wavelet-based coherence analysis of near-infrared spectroscopy signals

Wei Wang, Lingguo Bu, Liwei Xu, Shandong Univ. (China); Zengyong Li, National Research Ctr. for Rehabilitation Technical Aids (China)

During a cognitively demanding task such as driving, attention cannot always be maintained at a high level, as time elapses, the level of attention progressively diminishes, which impacts task performance negatively. This study assesses the vigilance task-related functional connectivity in healthy adults using the wavelet-based coherence analysis of near-infrared spectroscopy signals (NIRS). NIRS is a non-invasive method that continuously monitors brain activity by measuring the absorption of near-infrared light through the intact skull. A vigilance task was designed to simulate driver mental load in real-car driving. Three numbers changed randomly every second on the screen, the subjects need to immediately step on the brake pedal (i.e., within 1.3 s) when the three numbers are different odd numbers. Continuous recordings of NIRS signals were obtained from the prefrontal cortex (PFC) and sensorimotor cortical areas of 20 young healthy adults (24.9±3.3 years) during 10-min resting state and 10-min vigilance task state. Wavelet phase coherence (WPCO) was obtained as the NIRS signals were analyzed by wavelet transform, which reveal possible relationship by evaluating the match between the instantaneous phases of two signals. WPCO of six channel pairs were calculated in five frequency intervals: 0.6–2 Hz (I), 0.145–0.6 Hz (II), 0.052–0.145 Hz, (III) 0.021–0.052 Hz (IV), and 0.0095–0.021 Hz (V). The results show significant GC (global connectivity) levels in interval I and FC (functional connectivity) levels in interval III were significantly lower in the task group than in the rest group, particularly between the left PFC and bilateral sensorimotor regions.

10024-131, Session Post

Age-related changes in brain functional connectivity in response to posture change as assessed by wavelet phase coherence of NIRS signals

Bitian Wang, Shandong Univ. (China); Zengyong Li, Shandong Univ. (China) and National Research Ctr. for Rehabilitation Technical Aids (China)

Postural instability (PI) and falls is commonly seen due to aging and motor disabilities. Functional connectivity (FC) is broadly used to evaluate the correlation level between different regions or within local regions of the human brain. Wavelet phase coherence (WPCO) can discover possible correlations between two signals by evaluating how well the two instantaneous phases from the signals are matched. This study aims to assess the difference in brain functional connectivity in response to posture change between elderly subjects and young subjects by the WPCO values of ?[HbO2] signals measured with NIRS method.

The NIRS signals were continuously recorded from the prefrontal cortex and sensorimotor cortical areas in 17 healthy elderly subjects and 20 young healthy subjects during 10 min resting state and 10 min standing state. The WPCO were calculated in five frequency intervals in each channel pair. Two-Way ANOVA was used to check whether there were significant interactions between age and posture factors.

In summary, the present study showed that a sit-to-stand posture change task had significant effect on the FC and the global connectivity (GC) in the elderly subjects. The present results suggests different brain activity mode in response to posture change in the elderly subjects compared to young subjects and this may be useful in assessing the risk of postural instability in aged persons.

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10024-132, Session Post

Development of wide-angle 2D light scattering static cytometry

Linyan Xie, Qiaoxi Liu, Changshun Shao, Xuantao Su, Shandong Univ. (China)

We have recently developed a 2D light scattering static cytometer for cellular analysis in a label-free manner, which measures side scatter (SSC) light in the polar angle range from 79 to 101 degrees. Compared with conventional flow cytometry, our cytometric technique requires no fluorescent labeling of the cells, and static cytometry measurements can be performed without flow control. In this paper we present an improved label-free static cytometer that can obtain 2D light scattering patterns in a wider angular range.

By illuminating the static microspheres on chip with a scanning optical fiber, wide-angle 2D light scattering patterns from single standard microspheres with a mean diameter of 3.87 ?m are obtained. The 2D patterns of 3.87 ?m microspheres contain both large angle forward scatter (FSC) and SSC in the polar angle range from 40 to 100 degrees. Fourier analysis of experimentally obtained 2D patterns from 3.87 ?m microspheres are in good agreement with Mie theory simulated ones. The wide-angle 2D light scattering measurements may provide a better resolution for particle analysis as compared with the SSC measurements.

Two-dimensional light scattering patterns from HL-60 human acute leukemia cells are obtained by using our static cytometer. Compared with SSC 2D light scattering patterns, wide-angle 2D patterns contain richer information of the HL-60 cells. The obtaining of 2D light scattering patterns in a wide angular range could help to enhance the capabilities of our label-free static cytometry for cell analysis.

10024-133, Session Post

Diffuse reflectance spectroscopy study of in vitro tissue for nasopharyngeal carcinoma diagnosis

Zhihong Xu, Xiaosong Ge, Xueliang Lin, Duo Lin, Wei Huang, Fujian Normal Univ. (China)

Diffuse reflectance spectroscopy is a non-contact, non-invasive, and low-cost optical technique that provides real-time feedback about the absorptive characteristics and the microstructure properties of biological tissue. This optical technique shows the potential for monitoring metabolic status associated with malignancy transformation. Nasopharyngeal carcinoma is the third most frequently diagnosed cancer associated with virus and is the most common male malignancy with a characteristic regional and racial distribution worldwide. This paper provides an overview on the applications of diffuse reflectance spectroscopy in the cancer detection and also investigates the current screening state of nasopharyngeal malignancies. Futhermore, the latest research relevant to the diagnosis of nasopharyngeal cancer in vitro tissue using diffuse reflectance spectroscopy is introduced. The results of diffuse reflectance spectroscopy are summarized, showing a significant experimental and clinical value for further nasopharyngeal carcinoma detection in vivo in the future.

10024-134, Session Post

Photophysical properties of catechol axially-substituted tetra-[alpha]-(pentyloxy) titanium (IV) phthalocyanine

Yiru Peng, Xinxin Yu, Huafei Lv, Sujuan Pan, Shijun Wu, Di Zeng, Yufeng Jiang, Hongqin Yang, Shusen Xie, Fujian Normal Univ. (China)

Metal phthalocyanines (MPcs) have been found to be a promising photosensitizers for photodynamic therapy (PDT) of cancers and non-cancer diseases. Nevertheless, phthalocyanines are substantially limited in clinical applications owing to their poor solubility, aggregation and insufficient selectivity for cancer cells. Catechol is an important pharmaceutical intermediate, important in vivo biological activity. It plays an important role in medicine. Using catechol?pyrocatechin?as axial ligands, utilizing of the pharmaceutical effect of catechins, could improve the bioavailability, and achieve synergistic therapeutic effect in PDT. To address these issues, a novel catechol axially substituted tetra-?-(pentyloxy) titanium(IV) (TiPc(OC5H11)4-Catechol) was synthesized. The structure TiPc(OC5H11)4-Catechol was characterized by elemental analysis, IR, 1HNMR, MS methods. The photophysical properties of TiPc(OC5H11)4 and TiPc(OC5H11)4-Catechol have been studied by UV/Vis and steady-state fluorescence spectra. After being axially substituted with catechin groups, no obviously intensity and position of maximum wavelength in Q-band of TiPc(OC5H11)4 and TiPc(OC5H11)4-Catechol was observed. The fluorescence intensity of TiPc(OC5H11)4 is stronger than that of TiPc(OC5H11)4-Catechol, but the fluorescence lifetime of TiPc(OC5H11)4-Catechol is a longer than that of TiPc(OC5H11)4. TiPc(OC5H11)4-Catechol may be considered as a promising photosensitizer for PDT.

10024-135, Session Post

Functional connectivity analysis using fNIRS in healthy subjects during prolonged simulated driving

Liwei Xu, Bitian Wang, Wei Wang, Zhian Liu, Shandong Univ. (China); Zengyong Li, National Research Ctr. for Rehabilitation Technical Aids (China)

The present research proposed the assessment of cerebral functional connectivity (FC) during drawn-out simulated driving. Synergistic mechanisms in relevant brain regions were monitored by a driving simulator combined with fNIRS technology. 14 subjects were recruited to complete a primary driving tasks accompanied by a secondary mental task. Wavelet coherence (WCO) and wavelet phase coherence (WPCO) were calculated in frequency intervals: I, 0.6–2 Hz; II, 0.145–0.6 Hz; III, 0.052–0.145 Hz; IV, 0.021–0.052 Hz; V, 0.0095–0.021 Hz; and VI, 0.005–0.0095 Hz. The connectivity (WCO and WPCO) in intervals I and II was defined as global connectivity (GC), and that in intervals III–V was FC. Significantly lower connectivity levels (WCO and WPCO) were found in intervals I and III in prefrontal cortex (PFC), and significantly lower connectivity levels (WCO and WPCO) in interval IV in motor cortical areas by the end of the driving task. The results show that the lower GC in interval I in the PFC and the lower FC in intervals III and IV in the PFC and motor cortical areas are closely related to driving fatigue. A decreased connectivity indicates decreased cognitive functions in the PFC and reduced coordination among the PFC and motor cortical areas.

Acknowledgements

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10024-136, Session Post

Absolute flow velocity measurement by depth-encoded dual-beam phase-resolved Doppler optical coherence tomography

Jie Qian, Wei Cheng, Zhaoyuan Cao, Xinjian Chen, Jianhua Mo, Soochow Univ. (China)

Phase-resolved Doppler optical coherence tomography (PR-D-OCT) is a functional OCT imaging technique that can provide fast and high-resolution depth-resolved measurement on flow in biological materials. However, a common problem with conventional PR-D-OCT is that this technique often measures the flow motion projected onto the OCT beam path. Without knowing the projection angle ? between vessel orientation and the OCT beam path, it is hard to obtain the absolute flow velocity. Moreover, the projection angle is usually missing for in vivo measurement on human blood vessel, which obscures quantitative study on human blood flow. In this paper, we proposed a novel dual-beam PR-D-OCT method to measure absolute flow velocity, which does not require knowing the projection angle. The sampling beam is divided into two equal beams and separated laterally before being focused into samples, which leads to two different incident angles. The images by the two beams are encoded to different depths in individual B-scan. Thus, upon single B-scan, with the Doppler signals measured by the two beams and the difference between the incident angles of the two beams, we can calculate the absolute flow velocity. We validated our approach in vitro on an artificial flow phantom on our home-built 1060 nm swept source OCT. The flow phantom is a capillary with 400-?m diameter perfused with milk at constant speed by a syringe pump. Experimental results demonstrated that our method can provide an accurate measurement of absolute flow velocity without the projection angle.

10024-137, Session Post

Integrated acoustic-resolution and optical-resolution photoacoustic microscopy using a single multifunctional acoustic lens

Heng Guo, Lei Xi, Univ. of Electronic Science and Technology of China (China)

With the rapid development of photoacoustic imaging, it has been widely used in various research fields such as biology, medicine and nanotechnology. Due to the huge difference among photoacoustic imaging systems, it is hard to integrate them in one platform. To solve this problem, we propose to develop a new universal photoacoustic imaging platform that integrates acoustic-resolution photoacoustic microscopy and optical-resolution photoacoustic microscopy through a multifunctional liquid lens. This lens takes advantage of an inherently low acoustic impedance and a tunable focal length that was characterized by the infusion volume of the liquid. In this paper, the liquid lens was used to realize confocal of laser illumination and acoustic detection for both acoustic-resolution and optical-resolution photoacoustic microscopy. The home-made polyvinylidene fluoride (PVDF) acoustic transducer had a center frequency of 10MHz and -6dB frequency spectrum from 4MHz to 15MHz which yielded to an axial resolution of 70 ?m. The lateral resolutions of acoustic- and optical-resolution photoacoustic microscopy were evaluated to be 180 ?m and 4.8 ?m, respectively. The vasculature of rabbit and rat ears were carried out respectively to evaluate the performance of acoustic- and optical-resolution photoacoustic microscopy.

10024-138, Session Post

En-face sectional imaging using single-shot full-field optical coherence tomography (SS-FF-OCT) based on white-light-emitting diode (WLED)

Tulsi Anna, National Yang-Ming Univ. (Taiwan); Ting-Wie Chang, Industrial Technology Research Institute (Taiwan); Chih-Ming Lai, Ming Chuan Univ. (Taiwan); Wen-Chuan Kuo, National Yang-Ming Univ. (Taiwan)

Full-field optical coherence tomography (FF-OCT) is an interferometric technique that utilizes spatially incoherent broad-band illumination, using thermal, halogen and xenon arc lamp, to provide high-resolution en-face sectional images of biological and engineering materials1. However, white light emitting diodes (WLED)2 also have potential to be used in FF-OCT systems due to its higher energy efficiency, longer life time, compact, and also capable to provide high axial resolution that still to be explored to its potential in tomographic imaging. This work presents a cost-effective Linnik type single shot FF-OCT (SS-FF-OCT) system comprising a single WLED light source (wavelength range 470-850nm, central wavelength 650nm) and a CMOS device. The measured axial resolution is 0.9?m. For broader applications, low NA ≈ 0.1 objectives are used in the present system. The measured imaging area and lateral resolution are 1.0 x 1.0mm2 and ≈ 4.2?m, respectively.

The en-face sectional imaging is useful to obtain temporal information within the en-face plane. In this work, to achieve faster en-face imaging, a single shot Riesz transform (RT)3 demodulation scheme with background subtraction, that improves the time resolution limited by conventional phase shifting methods, has been utilized. The detail performance of present SS-FF-OCT system is demonstrated by imaging of fish skin and plant leaves. The present SS-FF-OCT is cost-effective due to low cost WLED and no phase shifting device, compact, fast (RT based scheme) and also significantly stable for the phase measurement. This system has the potential to be applied in dynamical phenomena such as in vivo biological samples.

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10024-139, Session Post

Whole-body and multispectral photoacoustic imaging of adult zebrafish

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Zebrafish is a top vertebrate model to study developmental biology and genetics, and it is becoming increasingly popular for studying human diseases due to its high genome similarity to that of humans and the optical transparency in embryonic stages. However, it becomes difficult for pure optical imaging techniques to volumetric visualize the internal organs and structures of wild-type zebrafish in juvenile and adult stages with excellent resolution and penetration depth. Even with the establishment of mutant lines which remain transparent over the life cycle, it is still a challenge for pure optical imaging modalities to image the whole body of adult zebrafish with micro-scale resolution. However, the method called photoacoustic imaging that combines all the advantages of the optical imaging and ultrasonic imaging provides a new way to image the whole body of the zebrafish. In this work, we developed a non-invasive photoacoustic imaging system with optimized near-infrared illumination and cylindrical scanning to image the zebrafish. The lateral and axial resolution yield to 80 ?m and 600 ?m, respectively. Multispectral strategy with wavelengths from 690 nm to 930 nm was employed to image various organs inside the zebrafish. From the reconstructed images, most major organs and structures inside the body can be precisely imaged. Quantitative and statistical analysis of absorption for organs under illumination with different wavelengths were carried out.

10024-140, Session Post

Revealing the cellular metabolism and microstructural changes in vivo in senescing Acer saccharum leaves using two-photon FLIM and full-field OCM

Sandeep Chakraborty, Tulsi Anna, Wen-Chuan Kuo, Arthur E. Chiou, National Yang-Ming Univ. (Taiwan)

Seasonal as well as climate changes have immense effect on bud burst, leaf color and leaf abscission. Autumn phenology of leaves is clearly distinguishable in deciduous plant leaves where changes of leaf color occur from green to red (leaf senescence).1 In this work, two-photon fluorescence lifetime imaging microscopy (2P-FLIM)2 and full-field optical coherence microscopy (FF-OCM)3 were applied to study mitochondrial activity as well as internal morphological microstructure in senescence of Acer saccharum (Sugar maple) leaves, respectively. Fluorescence lifetime of reduced nicotinamide adenine dinucleotide [NAD(P)H] was recorded using 2P-FLIM to quantify the cellular mitochondrial metabolic changes. Compared to the green leaves, the red leaves showed a 19% increase ($p < 0.05$) in the average fluorescence lifetime of NAD(P)H, and a 34% decrease ($p < 0.005$) in the free to protein-bound NAD(P)H ratio. This infers a significant change in mitochondrial metabolic regulation in red leaves in contrast to green leaves. Additionally, en-face sectional images at 0.8 μm axial resolution of the green and red color Acer saccharum leaves via FF-OCM using white LED showed a well-defined morphological microstructure in cuticle and upper epidermis in red leaves as compared to green leaves where more diffuse internal microstructure was observed. In contrast, surface scattering was much higher in green leaves than red leaves. Our approach can potentially be used to correlate mitochondrial activity with internal microstructural changes in other biological systems.

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10024-141, Session Post

Development of an automatic 3D foot scanner for customer shoe

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Shoes are used by everyone, a pair of shoes is very important. However, due to the existing shoe manufacturers are basically limited number of preset shoe size and type, so it is not suitable for everyone. To solve the above problem, we propose an automatic foot three-dimensional digital scanner measurement system. We use the stereoscopic digital cameras with digital speckle projection, which can quickly obtain single 3d data. We use a multi-node scanners setup, which can get the complete three-dimensional data of the foot. We use post-processing algorithm, which characteristic parameters of the foot for custom shoes. Our system parameters are: scanning time 30s, scanning accuracy 0.1mm and automated without user interaction. Our equipment dimensions: 1200mm X 500mm X 300mm, can be easily installed in the store. Our system has been widely installed and used.

10024-142, Session Post

Temporal evolution of liquid-assisted hard bio-tissue ablation with infrared pulsed lasers under a liquid environment

Faner Chen, Xianzeng Zhang, Fujian Normal Univ. (China)

Liquid-assisted hard bio-tissue ablation with the application of infrared pulsed laser takes advantage in precision and compatibility than others in traditional surgery. The objective of this study was to monitor the dynamic process of the cavitation bubble induced by Ho:YAG laser under water environments and identify the opening time of channel formation between the fiber tip to the target tissue surface. A free-running Ho:YAG laser was used in the experiment. The wavelength was 2.1 ?m with a pulse duration of 350us and pulse energy varied from 500mJ to 3000mJ. The high-speed camera(PCO.dimax, Germany, PCO) applied to monitor the whole ablation process was setting at a frame rate of 60000 frames/s. The results showed that the cavitation bubble induced by laser energy experienced a oscillation process including occurrence, expansion, contraction and subsequent collapse. A channel connected the fiber tip and target tissue surface was formed during the dynamic process and allowed the pulse energy transmitted through the channel with a relative low absorption and directly interacted with the target tissue. The beginning time of channel formation, as well as the duration of channel opening, as a function of incident laser energy and water layer thickness were also presented. A micro-explosion was observed near the tissue surface during the bubble collapse, which may help to produce a clean cut , reduce the thermal injury and improve the morphology of ablation crater. The results in the study will contribute to the interpretation of liquid-assisted hard tissue ablation.

10024-143, Session Post

A comparative study of metabolic state of stem cells during osteogenic and adipogenic differentiations via fluorescence lifetime imaging microscopy

Sandeep Chakraborty, Meng-Hsin Ou, Jean-Cheng Kuo, Arthur E. Chiou, National Yang-Ming Univ. (Taiwan)

Cellular metabolic state can serve as a biomarker to indicate the proliferation efficiency, and differentiation potential of stem cells into other specialized cell lineages. In this study, two-photon fluorescence lifetime imaging microscopy (2P-FLIM)1 was applied to determine the fluorescence lifetime and the amounts of the auto-fluorescent metabolic co-factor reduced nicotinamide adenine dinucleotide (NADH) to elucidate the cellular metabolism of human mesenchymal stem cells (hMSCs) in adipogenic and osteogenic differentiation processes. 2P-FLIM provides the free to protein-bound NADH ratio which can serve as the indicator of cellular metabolic state.2 We measured NADH fluorescence lifetime at 0, 7, and 14 days after hMSCs were induced for both adipogenesis and osteogenesis. The average fluorescence lifetime increased significantly at 14 day ($p < 0.05$) in adipogenic differentiation while no such increase was observed in osteogenic differentiations. However, the ratio of free to protein-bound NADH ratio decreased significantly in 7-days ($p < 0.05$) and 14-days ($p < 0.005$) in osteogenic differentiations. In contrast, in the case of adipogenic differentiations, the free to protein bound NADH ratio did not vary in 7 days, but showed variance comparable to osteogenic differentiations in 14 days. Thus, our preliminary results indicated a higher metabolic rate in both osteogenic and adipogenic differentiation processes, but a faster metabolic change in osteogenesis as compared to adipogenesis. This approach may be further utilized to study proliferation efficiency and differentiation potential of stem cells into other specialized cell lineages.

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10024-144, Session Post

Effect of femtosecond laser ablation on Ca2+ release in the dorsal root ganglion neurons

Liqin Zheng, Fujian Normal Univ. (China)

The Ca2+ is a ubiquitous second messenger that is responsible for regulating a wide range of cellular and biological processes, including cell proliferation and cell death, gene expression, muscle contraction and neurotransmission. The concentration of free intracellular Ca2+ is modulated by the balance between the cytosol and intracellular Ca2+ stores (such as the endoplasmic reticulum and mitochondria), and the extracellular fluid. The objective of this study was to assess if femtosecond laser ablation could affect the intracellular Ca2+ release in dorsal root ganglion neurons in vitro using confocal microscopy combined with special fluorescence probe Fluo-4/AM. The results showed that relative fluorescence intensity increased significantly after the axons of DRG neurons was performed with femtosecond laser ablation. It demonstrated that femtosecond laser ablation could enhance the intracellular Ca2+ release in the sensory neurons and might be used to treat pain by modulating intracellular Ca2+ release in DRG neurons.

10024-145, Session Post

Saliva surface-enhanced Raman spectroscopy for noninvasive optical detection of nasopharyngeal cancer

Xueliang Lin, Duo Lin, Zhihong Xu, Xiaosong Ge, Wei Huang, Fujian Normal Univ. (China)

The early cancer detection is of great significance to increase the patient’s survival rate and reduce the risk of cancer development. Surface enhanced Raman spectroscopy (SERS) technique is a rapid, convenient, non-destructive optical detection method, it can provide a characteristic “ fingerprint ” information of target substances, and even achieve single molecule detection. Its

ultra-high detection sensitivity has made it become one of the most potential biochemical detection methods. Saliva, a multi-constituent oral fluid, contains the bio-markers which is capable of reflecting the systemic health condition of human, showing promising potential as a effect medium for disease monitoring. Compared with the serum samples, the collection and processing of saliva is safer, more convenient and noninvasive. Thus, saliva test is becoming the hotspot issues of the noninvasive cancer research field. This review highlights and discusses current application progress within the field of SERS saliva test in cancer detection. Meanwhile, our guoup's primary research on noninvasive differentiation of nasopharyngeal cancer, normal and rhinitis groups using saliva-SERS method is introduced.

10024-146, Session Post

The effect of axial ligands on the quantum yield of singlet oxygen of new silicon phthalocyanine

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Phthalocyanines (Pcs) are regarded as one of the important organic materials. Pcs have attracted considerable attention over the last decades for their applications in material science. They have been used in electro-optical devices, solar cells, liquid crystals, optical data storage, electrochromic display, and photodynamic therapy (PDT). However, many applications are restrained by their limited solubility in common organic solvents and water. Moreover, because of the ϖ–ϖ interaction between planar aromatic structures, Pcs have a strong tendency to form insoluble aggregates. Aggregation is an unfavorable property of Pcs since it can reduce the possibility of generation singlet oxygen quantum yield, leading to lower their PDT effecicy.
In this paper, we designed and synthesized a novel series of axially di-substituents silicon phthalocyanines with different electron-donating or electron withdrawing properties. The effect of axially substituent groups on the quantum yield of singlet oxygen of the phthalocyanine were using the chemical capture method, the ability to take the measurement of absorbance at 412 nm DPBF change in intensity is measured to generate singlet oxygen. These complexes singlet oxygen quantum yields are high, sodium dodecylbenzenesulfonate axially substituted silicon phthalocyanine singlet oxygen quantum yield higher than other compounds.

10024-147, Session Post

Motion compensation of full-field swept-source optical coherence tomography integrated with surgical microscope

Chang-Soo Kim, Hyeong Soo Nam, Hanyang Univ. (Korea, Republic of); Hyunki Lee, Hong Ki Kim, Koh Young Technology, Inc. (Korea, Republic of); Hongki Yoo, Hanyang Univ. (Korea, Republic of)

Optical Coherence Tomography (OCT) is a non-invasive optical imaging method that shows cross-sectional images of biological tissue. On the other hand, surgeons examine the surgical site in detail using the surgical microscopes during surgery. Combination of these two technologies would enable to image the microscopic surface and the tomographic structures of surgical site at the same time. Full-field swept-source OCT (FF-SS-OCT) can achieve high-speed three-dimensional volumetric imaging because it does not need a beam scanner that is required in a point scanning OCT. However, acquisition time for A-line is much longer than the point scanning OCT for single point. In FF-SS-OCT, the motion of the sample during the acquisition can degrade the image quality significantly compared to the point scanning OCT. The motion distorts the interference fringe pattern. Even a small motion can be amplified significantly, which is affected by the A-line acquisition rate and the frequency of the motion in FF-SS-OCT acquisition. The motion leads to phase changes on interference pattern while sweeping the wavelengths, thus the motion can be measured by applying time-frequency analysis on the A-line data. We compensated the image degradations by correcting the motion-induced phase shift. Here, we present a system integration of FF-SS-OCT with surgical microscope. Also, we present an algorithm to measure and compensate the sample motion.

10024-148, Session Post

High-resolution three-dimensional integral imaging using Fourier ptychography

Leilei zhang, Juan Zhang, Muyang Zhang, Xing Zhao, Yanmei Liang, Nankai Univ. (China)

Integral imaging is a promising technology for three dimensional (3D) imaging in which depth information was recorded in image arrays. For some applications, such as guided surgery, micro-3D biological imaging, reconstructed images with high resolution were demanded. The quality of reconstructed images significantly depended on the resolution of the multi-view elemental images ?EIs?. Low-resolution EIs lead to the mismatch of the corresponding imaging points (CIPs) and decrease the precision of reconstructed images.

Fourier ptychography (FP) is a recently developed super-resolution technique which shares its roots with ptychography. FP is the improvement of the aperture synthesis technique and the phase retrieval technique, which acquires image arrays by multi-angle illumination and reconstructs a high resolution image in the frequency domain.

In this paper, we report an integral imaging scheme by exploring a LED array to provide multi-angle illumination and by using a lens array to generate the image array. FP procedure was firstly carried out to recover a super-resolution integral image, then phase matching method was used to gain CIPs, and finally triangulation was used to analyze all CIPs in the integral image and reconstruct the 3D scene. Simulated experiments were done for 3D objects, where a 5*5 lens array and a 15*15 LED array were adopted. The reconstructed results proved this method could obtain high-resolution and more precise 3D images.

10024-150, Session Post

Photo-induced electron transfer between benzyloxy dendrimer phthalocyanine and benzoquinone

Yiru Peng, Tiantian Zhang, Dongdong Ma, Sujuan Pan, Shijun Wu, Yufeng Jiang, Di Zeng, Hongqing Yang, Fujian Normal Univ. (China)

Photo-induced electron transfer (PET) is an important and fundamental process in natural photo-synthesis. To mimic such interesting PET process, a suitable donor and acceptor couple were properly chosen. Dendrimer phthalocyanines and their derivatives have emerged as promising materials for artificial photosynthesis systems. In this paper, the electron transfer between the light harvest dendrimer phthalocyanine (donor) and the 1,4-benzoquinone (acceptor) was studied by UV/Vis and fluorescence spectroscopic methods. It was found that phthalocyanine fluorescence quenching by BQ is via excited state electron transfer, from the phthalocyanine to the BQ. The results show that the fluorescence emission of these

dendritic phthalocyanines could be greatly quenched by BQ upon excitation at 610 nm. The Stern–Volmer constant (KSV) of electron transfer is calculated. Our study suggests that these dendritic phthalocyanines are an effective new electron donor and transmission complex and could be used as a potential artificial photosynthesis system.

10024-151, Session Post

Design and fabrication of common path OCT probe with extended depth-of-focus

Jingchao Xing, JunYoung Kim, Hongki Yoo, Hanyang Univ. (Korea, Republic of)

Optical coherence tomography (OCT) acquires three-dimensional microstructure of biological samples. Using fiber optic probe, minimally invasive imaging for hollow organs or deep tissues is possible. However, using optical fibers in OCT is associated with several challenges. First, the path length of a reference arm and a sample arm should be matched exactly. Any mismatch on optical fiber length between two arms may lead to a dispersion, which can reduce sensitivity and axial resolution. Second, the polarization states of the signal within the fibers need to be controlled in order to avoid polarization mismatch, which also degrades sensitivity. In order to avoid these problems, common path OCT probes which embeds reference arm in the sample arm, have been proposed. Here, we present a common path OCT probe by utilizing a custom designed prism. This prism has a beam split coating on one side, and the other side is coated with an internal reflecting aluminum to generate the reference signal. To fabricate a common path probe, we aligned this prism at the distal end of an endoscopic imaging probe. Additionally, to improve the depth of focus (DOF) and lateral resolution of this common path probe, we applied a binary phase spatial filter (BPSF) in this probe. The simulation analysis shows that the probe with the BPSF extended the DOF by a factor of 2.67 from 72 ?m to 192.2 ?m. We tested the performance of this common path probe by imaging 3M tape and micro-beads phantom. We anticipate that the common path probe with extended DOF might be used in various in vivo studies, such as cardiovascular disease and esophageal disease.

10024-152, Session Post

Study on nasopharyngeal cancer tissue using surface-enhanced Raman spectroscopy

Xiaosong Ge, Zhihong Xu, Xueliang Lin, Wei Huang, Duo Lin, Fujian Normal Univ. (China)

Surface-enhanced Raman spectroscopy (SERS) can provide detailed molecular structure and composition information, and has demonstrated great potential in biomedical filed. This spectroscopy technology has become one of the most important optical techniques in the early diagnosis of cancer. Nasopharyngeal cancer (NPC) is a malignant neoplasm arising in the nasopharyngeal epithelial lining, which has relatively high incidence and death rate in Southeast Asia and southern China. This paper reviews the current progress of SERS in the field of cancer diagnostics, including gastric cancer, colorectal cancer, cervical cancer and nasopharyngeal cancer. In addition to above researches, we recently develop an novel NPC detection method based on tissue section using SERS, and obtain primary results. The proposed method has promising potential for the detection of nasopharyngeal carcinoma.

10024-154, Session Post

Analysis of human biofluids with different concentrations by Raman spectroscopy method

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Changes in the biofluids (blood plasma, whole blood, protein fractions) concentration and is among the most important criteria for early diagnosis and assessment of the oncohematological diseases progression. There is a significant interest in optical measurement that would permit simultaneous analysis of multiple components in whole blood without the need for conventional sample processing, such as centrifuging and reagents adding. The major challenge in an analysis of whole blood samples lies in the presence of numerous low-concentration components. This work is devoted to study the possibility of plasma proteins (human serum albumin, globulin) concentration control using Raman spectroscopy (RS) setup. The blood proteins and whole blood were studied in this research.

Raman spectra were measured by integrated Raman setup. The setup comprises of thermally stabilized diode laser LML-785.0RB-04 (785 nm, 200 mW), commercial Raman probe and spectrograph Shamrock SR-500i-D1-R with deep cooling digital camera Andor iDus DU416A-LDC-DD with 0.05 nm resolution. Digital camera was air-cooled up to -70ºC. The acquisition time was 60 seconds for signal registration from biofluids. Biofluid samples were located in the aluminium cuvette with different reflector shape. Pure Raman spectrum was achieved by autofluorescence removal from raw data signal using polynomial approximation method.

Current research was associated with the determination of abnormal protein concentrations values in whole blood and blood plasma by Raman spectroscopy. For data processing PLS regression and PCA were utilized. The root mean squared error (RMSE) and squared correlation coefficient (R2) were calculated for blood compounds concentrations study.

10024-155, Session Post

Quantitative analysis on texture of skin damaged by excessive ultraviolet radiation

Shulian Wu, Liangjun Hu, Hui Li, Fujian Normal Univ. (China)

Texture feature is significant internal visual features of images. It includes the arrangement of surface structure and the order of the organization internal. The texture feature reflects the quality of images with phenomenon recurring visual characteristics. In our study, the images during the process of skin damage irradiated by excessive ultraviolet radiation in the mouse were monitored by multiphoton microscopy in vivo. A box-counting algorithm and gray lever co-occurrence matrix were applied to determine the collagen texture feature in order to evaluate the skin damage in different irradiated doses. Then, the neural network tool was applied to training the texture feature in different statues obtaining from skin imaging. The damage states were distinguished by the NNtool model. The results will help us to further understand the characters of skin damage from texture feature, and then the results will demonstrated that the distinguish of skin damage from texture with an objective method.

10024-156, Session Post

Monitoring oxygen saturation and blood perfusion changes in port wine stains during vascular targeted photodynamic therapy

Defu Chen, Beijing Institute of Technology (China); Ying Wang, Ying Gu, Chinese PLA General Hospital (China)

Vascular targeted photodynamic therapy (V-PDT) is believed to be an effective treatment modality for port wine stains (PWS). V-PDT uses the light source to activate the photosensitizer which reacts with molecular oxygen to generate the reactive oxygen species that can selectively damage the dilated and malformed blood vessels in PWS. The V-PDT efficacy is largely dependent on the blood oxygen and photosensitizer concentration levels, which can be affected by blood perfusion especially for systematic administration of photosensitizers. The objective of this study was to investigate the changes in oxygen saturation (StO2) and blood perfusion of PWS during V-PDT. In this study, the StO2 and blood perfusion in PWS immediately before and at 3, 5, 7, 10, 15, 20 min during V-PDT were non-invasively monitored by diffuse reflectance spectroscopy (DRS) and laser Doppler imaging (LDI), respectively. Our results showed that there were high inter- and intra-patient heterogeneity in StO2 and blood perfusion of PWS. Before V-PDT, blood perfusion in PWS could be larger than, or occasionally equivalent to, that of contralateral healthy skin, but there was no significant difference in StO2 between them. During V-PDT, the blood perfusion in PWS first increased, then reached a peak, followed by a slowly decrease to a relatively lower level. There was no obvious pattern observed for the changes of StO2 in PWS during V-PDT, and no significant reductions in StO2 were observed. In conclusion, the LDI and DRS are capable of assessing microvascular response to V-PDT.

10024-158, Session Post

In vitro photodynamic antimicrobial activity of cationic benzylidene cyclopentanone Photosensitizer (P2) against Helicobacter pylori

Ying Wang, Ying Gu M.D., Leili Wang, Zulin Ye, Chinese PLA General Hospital (China)

Background: Antibiotics combination therapies are the recoginized key approach to prevent H. pylori infection related diseases, such as peptic ulcer, gastric cancer, et al. With the widespread prolonged use of broad-spectrum antibiotics, antibiotic resistance rate of H. pylori increased and its eradication rates decreased notablely. Alternative monotherapy drug or method to kill H. pylori are needed to be explored. Photodynamic therapy (PDT) is a new anti-tumor and antibacterial technology. It has the potential to be a new strategy for the treatment of H. pylori infection in people at high risk of gastric cancer. In this study, the antimicrobial activity of a cationic benzylidene cyclopentanone photosensitizer (P2) against H. pylori was evaluated.

Methods: Suspensions Helicobacter pylori were incubated with P2 concentrations (2.5, 5, 10 and 25 ?M) for 30 min followed by 532-nm laser irradiation. Immediately after PDT, the viability of H. pylori was assayed by CFU counting. All the process was carried out at 37 °C in a standard microaerobic atmosphere within a microaerobic bag. The ultrastructure change of H. pylori induced by PDT was observed under scanning electron microscope (SEM).

Results: The bactericidal effect of PDT increased with the concentration of P2 increasing. The CFU count of H. pylori drcreased 2 log, 4 log, 5 log and 5 log at different concentration of P2(2.5, 5, 10 and 25?M respectively). Loss of structural integrity and evidence of extensive cell disruption and lysis was found under SEM.

Conclusions: The results demonstrated that benzylidene cyclopentanone photosensitizer?P2?is a potential photosensitizer to kill H. pylori.

10024-159, Session Post

Solutions to improve multiple configuration system resolution in imaging sensors

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To break the optical diffraction limit, to achieve an improved resolution, based on studies of single molecule microscopy in the field of traditional and the modern domain, we develop the method of continuous zoom multiple configuration, and the establishment of a micro lens array and core optics as the main component in a system to attempt to establish model by novel principle on resonance energy transfer and high accuracy localization by which between the principle and application of molecular resonance, as well as single molecule positioning technology, the system resolution can be improved with a level of a few nanometers. A comparative study on traditional design methods and their advantages and disadvantages of the implementation mechanisms can demonstrate that the dialectical relationship and their balance is important, among Merit function, Optimization algorithms and Model parameterization. The effect of system evaluated criterion that Modulation Transfer Function (Modulation Transfer Function, the MTF), Energy concentration (Radial Energy Analysis, REA), diffusion (Spot Diagram, RMS) and other aspects and other qualitative criteria can support our arguments. And the results can be used as basis for the development of new products.

10024-160, Session Post

Precision-enhanced fluorescence lifetime imaging method

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Tissue auto-fluorescence can be used for imaging specific components in biological sample. However, fluorescence intensity is prone to be distorted because of the difficulty to measure absolute value. Accordingly, fluorescence lifetime can be an alternative strategy and it has been widely used due to its benefit of insensitivity to the intensity. In approaches for measurements of lifetime using pulse sampling, fluorescent decay signals are recovered by the deconvolution process of instrumental response function (IRF). Unfortunately, in these approaches to estimate the IRF prior to measurement of a substance, jitter noise of the pulsed laser and the digitizer may degrade the precision. Averaging can be helpful for the problem, but it lowers acquisition speed. In this context, we present a method for precision enhancement for high speed application of fluorescence lifetime imaging system based on simultaneous acquisition of IRF. It was accomplished by multiple detection fibers with different lengths to measure signals of IRF and fluorescences of each channel, respectively. This simultaneous acquisition is insensitive to the jitter noise, thus it can improve precision of measurement of lifetime. It was validated by tissue phantoms and ex vivo rabbit atherosclerotic tissue, showing an enhanced precision under 50 picosecond without averaging

and correspondence between spectrally-resolved lifetimes and histopathological sections of tissues, respectively. This strategy may enable to acquire a molecular information of a biological sample in vivo in virtue of its advantage to the availability for high speed.

10024-162, Session Post

Automatic density artefact removal method for structured illumination microscopy data

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The reconstruction of exquisite neural network from microscopic image set is the base of understanding the mechanism of brain. Structured illumination microscopy (SIM) is one of the imaging instruments to obtain 3-D image set from a large sample, e.g. mouse brain. However, to perform high speed for data acquisition, the RAW tile images from SIM have non-uniform intensity and contrast, therefore we have to correct the tile images before structure analysis and visualization of brain.

The correction can be mainly splat into two steps, eliminating the grid stripes within one coronal layer and uniforming the brightness values in coronal sequence along the axial direction. In the first step, polynomials is used to fitting the mean value of one coronal layer along transverse and longitudinal respectively, and the correction factors got from fitting result are used to remove the grid dark lines. In the second step, The background's mean value within mouse brain is extracted with threshold and morphology method, then combined with a preset brightness value parameter, the correction parameter for every layer's brightness is obtained. The automatic method has been implemented on both single workstation and cluster which provides a high quality and efficiency data correction approach.

10024-163, Session Post

Tuning the red emission of NaYF4:Yb/Er through core-shell nanostructure

Yihua Zhao, Xiao Peng, Shuyi Yuan, Shaozhuang Yang, Wei Yan, Ming Zhu, Jun Song, Junle Qu, Shenzhen Univ. (China)

Lanthanide doped upconversion nanoparticles (UCNPs) have received much attention due to their potential application in optical devices, sensing, and therapeutics. Compared with conventional organic dyes and quantum dots, the UCNPs possess following advantages: near-infrared (NIR) excitation, low cytotoxicity, weak autofluorescence, high chemical stability, and low photo-bleaching. However, the commonly studied lanthnide activators such as Er3+ and Tm3+ contain abundant metastable excited states, and the dominant emission usually does not lies within the "tissue optical window" (spanning approximately from 650 to 1200 nm). Here, we present a core-shell-shell approach to tune the color emission of typical NaYF4:Yb/Er system. By embeding NaYF4: Yb/Er between NaYF4 layers, the energy migration induced energy loss to the crystal lattice in NaYF4:Yb/Er can be effectively suppressed. Moreover, the cross relaxation effect can be adopted to induce red color emission, without "concentration quenching effect. The resulting UCNPs show low cytotoxicity, according to HeLa cell-based MTT assay. In conclution, we show a novel core-shell-shell approach to boost both the red color emission and the of luminescence efficiency of typical NaYF4:Yb/Er system.

10024-164, Session Post

Immunomodulatory effects of NaYbF4:Er-based core-shell-shell upconversion nanoparticles on RAW264.7 cells

Xiao Peng, Yihua Zhao, Shuyi Yuan, Shaozhuang Yang, Wei Yan, Ming Zhu, Jun Song, Junle Qu, Shenzhen Univ. (China)

Recently, upconversion nanoparticles (UCNPs) have been proved to contain excellent optical properties. They have played more and more important role in biological and medical applications, including imaging and photo-therapy. Therefore, it is essential to reveal a comprehensive understanding of the cytotoxicity and biocompatibility of the UCNPs, especially their immunomodulatory effects [1-3]. In this study, a series of ~30 nm NaYbF4:Er-based core-shell-shell UCNPs, in which size effect could be harnessed to enhance 654 nm emission, were synthesized using Ostwald-Ripening strategy. Moreover, the surfaces of resulting UCNPs were modified with polyacrylic acid (PAA). In the following, both the bare UCNPs and the PAA-modified NCNPs were applied onto the mouse macrophage Raw264.7 cells for several biological tests to figure out their potential cytotoxicity, including cell viability assay and apoptosis test. Furthermore, the secretion of TNF-? and IL-6 by Raw264.7 cells with the addition of the UCNPs were tested to analyze their immunomodulatory effects. In conclusion, both the bare and the PAA-modified UCNPs contain low cytotoxicity and stimulatory effects on immune cells, suggesting promising biological applications.

10024-165, Session Post

Hyperspectral imaging in the visible range for in vivo skin cancer differentiation

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Study results of hyperspectral imaging (HSI) for in vivo visualization of skin neoplasms are presented. 53 patients of oncological center are diagnosed for determining a type of skin pathology by HSI method. Hyperspectral results are compared with the histological analysis of a patient samples. The in vivo tissues diagnostics are approved by the ethical committee of Samara State Medical University.

The following types of skin neoplasms are investigated: melanoma, basal cell carcinoma, pigmented nevi and benign with different stages of neoplasm growth (I - IV types). The system of HSI can display the images with spectral resolution of up to 2.1 nm in the range of 450-750 nm and provides the capability to obtain images at a rate of 3 frames per second with a resolution of 1360x1024 pxl (maximum increase in scanning area is 7x7 cm). Frame at each wavelength is stabilized in a time interval of scanning relative to a selected stationary frame due to a displacement of the scanning area related with a spontaneous macro-movements of the patient. The obtained data has been processed in MATLAB R2014a. Backscattering spectra are stimulated by white LED source. Background illumination has been calculated from approximated spectral images of the sample as a distribution function of the source field.

As a result, the index of optical densities amounts in maximum of hemoglobin and melanin absorption ranges (530-600 and 600-670 nm respectively) and the distribution of index values in the entire neoplasm area allows to differentiate the type of pathological tissues.

10024-166, Session Post

Classification for skin cancer using the intensity-based texture-based and fractal-based features with optical coherence tomography

Wei Gao, Ningbo Univ. of Technology (China); Oleg O. Myakinin, Ivan A. Bratchenko, Dmitry V. Kornilin, Valery P. Zakharov, Samara State Aerospace Univ. (Russian Federation)

Optical coherence tomography (OCT) is employed in the diagnosis of skin cancer. Particularly, quantitative image features extracted from OCT images might be used as indicators to classify the skin tumors. In the present paper, we investigated intensity-based, texture-based and fractal-based features for automatically classifying the melanomas, basal cell carcinomas and pigment nevi. Our results suggest that the selected quantitative image features of OCT images could provide useful information to differentiate basal cell carcinomas and pigment nevi from the melanomas. Further research is warranted to determine how this approach may be used to improve the classification of skin tumors.

10024-167, Session Post

Skin cancer texture analysis of OCT images based on Haralick, fractal dimension, Markov random field features, and the complex directional field features

Dmitry S. Raupov, Oleg O. Myakinin, Ivan A. Bratchenko, Valery P. Zakharov, Samara State Aerospace Univ. (Russian Federation); Alexander G. Khramov, Samara Aerospace Univ. (Russian Federation)

In this paper, we propose a report about our examining of the validity of OCT in identifying changes using a skin cancer texture analysis compiled from Haralick texture features, fractal dimension, Markov random field method and the complex directional features from different tissues. Described features have been used to detect specific spatial characteristics, which can differentiate healthy tissue from diverse skin cancers in cross-section OCT images (B- and/or C-scans). In this work, we used an interval type-II fuzzy anisotropic diffusion algorithm for speckle noise reduction in OCT images. The Haralick texture features as contrast, correlation, energy, and homogeneity have been calculated in various directions. A box-counting method is performed to evaluate fractal dimension of skin probes. Markov random field have been used for the quality enhancing of the classifying. Additionally, we used the complex directional field calculated by the local gradient methodology to increase of the assessment quality of the diagnosis method. Our results demonstrate that these texture features may present helpful information to discriminate tumor from healthy tissue. The experimental data set contains 166 OCT-images with normal skin and tumors as Basal Cell Carcinoma (BCC), Malignant Melanoma (MM) and Nevus. All images were acquired from our laboratory SD-OCT setup based on broadband light source, delivering an output power of 20 mW at the central wavelength of 840 nm with a bandwidth of 25 nm. We obtained sensitivity about 96% and specificity about 99% for a task of discrimination between MM and Nevus.

10024-168, Session Post

Facile synthesis of Gd-Cu-In-S/ZnS bimodal quantum dots with optimized properties for tumor targeted fluorescence/MR in vivo imaging

Bingbo Zhang, Weitao Yang, Tongji Univ. (China)

Dual-modal imaging techniques have gained intense attentions for their potential role in the dawning era of tumor early accurate diagnosis. Chelate-free robust dual-modal imaging nanoprobes with high efficiency and low toxicity are of essential importance for tumor targeted dual-modal in vivo imaging. It's still a crucial issue to endow Cd-free dual-modal nanoprobes with bright fluorescence as well as high relaxivity. Herein, a facile synthetic strategy was developed to prepare Gd-doped CuInS/ZnS bimodal quantum dots (GCIS/ZnS, BQDs) with optimized properties. The fluorescent properties of the GCIS/ZnS BQDs can be thoroughly optimized by varying reaction temperature, aging time and ZnS coating. The amount of Gd precursor can be well controlled to realize the optimized balance between the MR relaxivity and optical properties. The obtained hydrophobic GCIS/ZnS BQDs were surface engineered into aqueous phase with PEGylated dextran-stearyl acid polymeric lipid vesicles (PEG-DS PLVs). Upon the phase transfer, the hydrophilic GCIS/ZnS@PLVs exhibited pronounced near infrared fluorescence as well as high longitudinal relaxivity (r1=9.45 mM-1•S-1) in water with good colloidal stability. In vivo tumor-bearing animal experiments further verified GCIS/ZnS@PLVs could achieve tumor-targeted MR/fluorescence dual-modal imaging. No toxicity was observed in the in vivo and ex vivo experiments. The GCIS/ZnS@PLVs present great potential as bimodal imaging contrast agents for tumor diagnosis.

10024-169, Session Post

Hyperspectral imaging for skin cancer diagnosis

Lixin Liu, Xidian Univ. (China); Zhigang Zhao, Junle Qu, Shenzhen Univ. (China)

Hyperspectral imaging (HSI) technology is an emerging modality that combines the advantages of both imaging and spectroscopy in one device. Although HSI originated for remote sensing, it has recently developed as a powerful process analytical tool for non-destructive medical imaging and diagnostics with the advantage of acquiring two-dimensional images across a wide range of electromagnetic spectrum. During the progression of disease, the absorption, fluorescence, and scattering characteristics of tissue may change. Therefore, the reflected, fluorescent, and transmitted light from tissue captured by HSI carries quantitative diagnostic information about tissue pathology. In this study, we set up a hyperspectral imaging system for the quantitative measurement and imaging the normal and cancer skin tissue with high spatial and spectral resolution. The approach proposed here may have potential applications in early disease detection and diagnosis.

10024-170, Session Post

Principal component prediction in cartilages by infrared imaging and support vector machine

Jian-Hua Yin, Nanjing Univ. of Aeronautics and Astronautics (China)

Fourier transform infrared imaging (FTIRI) combined Support

Vector Machine (SVM) was used to detect the depth-dependent content variations of principal components, collagen and proteoglycan (PG), in Bovine nasal cartilage (BNC) and articular cartilages. The cartilages were sectioned at 10 ?m thick and dried in air for a couple of hours, and then imaged at 6.25 ?m pixel-size in FTIRI. The infrared spectra extracted from FTIR images were imported into SVM program to predict the quantitative distributions of both collagen and proteoglycan in BNC and (osteoarthritic and healthy) cartilage sections. The principal components distributed homogenously in BNC. The depth dependence of PG content was obtained and showed obvious difference between the cartilage sections of osteoarthritis and health, which is in well agreement with our previous PLS prediction. Relative to health, PG content decreases clearly in the osteoarthritis. This observation demonstrates that this combined imaging and SVM approach could be used as a sensitive tool to accurately predict and resolve the concentration distributions of macromolecules in biological tissues.

10024-171, Session Post

Implementation by laser micromachining of a grid-based visual aid for enhanced diagnostic microscopy in PAP test cytological screening

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Cervical screening based on Papanicolaou (PAP) test has been proved to be an efficient practice for preventing cervico-vaginal cancer in high risk Human Papilloma Virus (HPV) infected women. Introduction of liquid based process, automatization and digital image analysis has led to a more reliable diagnosis compared to conventional management of the slides. However, microscopy based diagnosis in Cytology is characterized by a variety of parameters, including specimens' adequacy, inhomogeneous cell density, fixing/staining procedure quality, observation ability and subjectivity in diagnosis. The paper introduces a real-time screening platform for improved diagnosis in PAP test slides. The presented solution provides a spatial grid with sequentially indexed segments that can be attached to carrier microscope slide acting as a calibration and orientation visual aid to the cytologist during the real-time screening process. Those grids were implemented using an infrared femtosecond Laser Micromachining-FLM system (1064 nm, 1?J) on commercially available borosilicate glass microscope cover slips. Abnormal and formerly diagnosed as negative for intraepithelial lesion or malignancy (NILM) Pap test slides (n=200) were analyzed by conventional and grid-based screening. Grid-based microscopy led to a more reliable diagnosis compared to the conventional by identifying an increased number of abnormal and neoplastic/cancerous cells, and also in shorter screening time. It decreased borderline ASCUS, AGC diagnosis, increasing LGSIL, HGSIL and in situ AdenoCa detection rates closely related with biopsy with excellent statistical agreement. The proposed solution offers a calibration and orientation visual aid during the on-site screening process providing significant advantages compared to expensive digital imaging techniques.

10024-172, Session Post

Blood vessel damage correlated with irradiance for in vivo vascular targeted photodynamic therapy

Jinde Zhang, Tan Zou, Fujian Normal Univ. (China); Xiangyu Niu, Fujian Normal Univ. (China); Lisheng Lin, Buhong Li, Fujian Normal Univ. (China)

Vascular targeted photodynamic therapy (V-PDT) has been widely utilized for the prevention or treatment of vascular-related diseases, including age-related macular degeneration, port-wine stains and prostate cancer. In order to quantitative assessment the blood vessel damage during V-PDT, nude mice were implanted with Titanium dorsal skin window chambers for in vivo studies. For V-PDT treatment, various irradiances including 50, 75, 100 and 200 mW/cm2 provided by a 532 nm semiconductor laser were performed with the same total light dose of 30 J/cm2 after the mice were intravenously injection of rose bengal for 25 mg/Kg body weight. Laser speckle imaging and microscope were used to monitor blood flow dynamics and vessel constriction during and after V-PDT, respectively. The results show that higher blood perfusion rate in blood vessels generally resulted in higher vasoconstriction. In addition, significant difference in blood vessel damage was found between the lower irradiances (50, 75 and 100 mW/cm2) and higher irradiance (200 mW/cm2). This study suggests that the blood vessel damage induced by V-PDT is positively correlated with irradiance, and optimized irradiance is required to enhance therapeutic efficiency.

10024-173, Session Post

Improving the signal-to-noise ratio in ultrasound-modulated optical tomography by a lock-in amplifier

Lili Zhu, Jingping Wu, Guimin Lin, Hui Li, Fujian Normal Univ. (China)

With high spatial resolution of ultrasonic location and high sensitivity of optical detection, ultrasound-modulated optical tomography (UOT) is a promising noninvasive biological tissue imaging technology. In biological tissue, the ultrasound-modulated light signals are very weak and are overwhelmed by the strong unmodulated light signals. It is a difficulty and key to efficiently pick out the weak modulated light from the strong unmodulated light in UOT. Under the effect of an ultrasonic field, the scattering light intensity presents a periodic variation as the ultrasonic frequency changes. So the modulated light signals would be escape from the high unmodulated light signals, when the modulated light signals and the ultrasonic signal are processed cross correlation operation by a lock-in amplifier and without a chopper. Experimental results indicated that the signal-to-noise ratio of UOT is significantly improved by a lock-in amplifier. And the higher the repetition frequency of pulsed ultrasonic wave, the better the signal-to-noise ratio of UOT.

10024-174, Session Post

Synthesis and application of the reduction-sensitive drug delivery system based on water-soluble ZnInAgS quantum dots

Rong Zhang, Rong Zhang, China Pharmaceutical Univ. (China)

High-quality water-soluble quantum dots had been synthesized following the one-step method. Furtherly, the impact factors on the optical properties of quantum dots, which were the feed ratio of S/In and the reflux time, had been concerned emphatically. By changing the reaction parameters, we made the fluorescence emission of ZnInAgS quantum dot tunable from green to orange, and the maximum fluorescence quantum efficiency was up to 30%. We also carried out the cytotoxic study of ZnInAgS QDs, compared with the commonly used fluorescent probes

such as CdTe and CdSe, ZnInAgS showed a lower cytotoxicity, which confirmed it was a potential fluorescent material in the biomedical field. By ligand substitution effect, the dihydro lipoic acid-PEG-FA was modified to the surface of quantum dot ZnInAgS, as a targeting fluorescent probe, the modified ZnInAgS could be applied to early diagnosis of cancer. The results of this study indicated that, as a novel composite nano fluorescent probes, folic acid modified ZnInAgS quantum dots had superior optical properties and good biocompatibility. Through the interaction of folic acid and folate receptors on the tumor cell membrane, the probe could target to the Bel-7402 tumor cells with high expression of folate receptor, which provided a fast, intuitive, and effective method for the detection of cell imaging, and played a catalytic role in the research of tumor early diagnosis.

10024-175, Session Post

Depth-section imaging of swine kidney by spectrally-encoded microscopy

Jiuling Liao, Wanrong Gao, Nanjing Univ. of Science and Technology (China)

The kidneys are essential regulatory organs whose main function is to regulate the balance of electrolytes in the blood, along with maintaining pH homeostasis. The study of the microscopic structure of the kidney will help identify kidney diseases associated with specific renal histology change. Spectrally encoded microscopy (SEM) is a new reflectance microscopic imaging technique in which a grating is used to illuminate different positions along a line on the sample with different wavelengths, reducing the size of system and imaging time. The feasibility of using SEM for visualizing the morphology of gastroesophageal biopsy samples and breast cancer specimens at subcellular resolution has been previously demonstrated. In this paper, a SEM device is described which is based on a super luminescent diode source and a home-built spectrometer. The lateral resolution was measured by imaging the USAF resolution target. The axial response curve was obtained as a reflect mirror was scanned through the focal plane axially. In order to test the feasibility of using SEM for depth-section imaging of an excised swine kidney tissue, the images of the samples were acquired by scanning the sample at 10 ?m per step along the depth direction. Architectural features of the kidney tissue could be clearly visualized in the SEM images, including glomeruli and blood vessels. Results from this study suggest that SEM may be useful for locating regions with probabilities of disease or cancer.

10024-176, Session Post

In vivo multimodal microscope integrating photoacoustics, two-photon, and second-harmonic generation

Wei Song, Shenzhen Institute of Advanced Technology (China)

Recently, we developed a novel photoacoustic microscopy (PAM) with multiple advantages including subwavelength resolution (~300 nm at 532-nm laser illumination), reflection-mode imaging capability, and natural integration with high-speed optical scanning mechanism, which is capable of label-freely imaging optical absorption contrasts in vivo. In order to provide comprehensive physiological and pathological information of biological tissue, a multimodal microscope system is further developed by integrating PAM with two-photon fluorescence and second harmonic generation (SHG) into one platform. Taking advantage of the unique imaging mechanisms of these three technologies, the multimodal microscope reveal complementary optical properties simultaneously, including the optical absorption, two-photon excited fluorescence, and SHG. By imaging mouse ears, PAM visualizes microvessels based on the strong optical absorption of inherent hemoglobin, two-photon microscope images nicotinamide adenine dinucleotide (NADH) and GFP-expressed neurons by acquiring the autofluorescence, and SHG resolves fine structure of collagen fibers, respectively. The three modalities show automatic imaging registration because they share the same laser delivery and scanning mechanisms, as well as they have comparable spatial resolution. The reported results suggest that, by revealing complementary tissue microstructures in vivo, this multimodal microscopy can potentially facilitate a broad range of biomedical studies, such as imaging of the tumor microenvironment and neurovascular coupling.

10024-177, Session Post

Non-invasive optical detection of HBV based on serum surface-enhanced Raman spectroscopy

Zuci Zheng, Qiwen Wang, Cuncheng Weng, Shangyuan Feng, Fujian Normal Univ. (China)

An optical method of surface-enhanced Raman spectroscopy (SERS) was developed for non-invasive detection of hepatitis B surface virus (HBV). Hepatitis B virus surface antigen (HBsAg) is an established serological marker that is routinely used for the diagnosis of acute or chronic hepatitis B virus(HBV) infection. Utilizing SERS to analyze blood serum for detecting HBsAg has not been reported in previous literature. SERS measurements were performed on two groups of serum samples: one group for 50 HBV patients and the other group for 50 healthy volunteers. Blood serum samples are collected from healthy control subjects and patients diagnosed with HBV. Furthermore, principal components analysis (PCA) combined with linear discriminant analysis (LDA) were employed to differentiate HBV patients from healthy volunteer and achieved sensitivity of 80.0% and specificity of 74.0%.This exploratory work demonstrates that SERS serum analysis combined with PCA-LDA has tremendous potential for the non-invasive detection of HBV.

10024-178, Session Post

Development of a new first-aid biochemical detector

Jingfei Hu, Haiyang Liao, Shilin Su, Hao Ding, Suquan Liu, Chongqing Univ. (China)

The traditional biochemical detector exhibits poor adaptability, inconvenient carrying and slow detection, which can't meet the needs of first-aid under field condition like natural or man-made disasters etc. Therefore a scheme of first-aid biochemical detector based on MOMES Micro Spectrometer, UV LED and Photodiode was proposed. An optical detection structure combined continuous spectrum sweep with fixed wavelength measurement was designed, which adopted mobile detection optical path consisting of Micro Spectrometer and Halogen Lamp to detect Cl-, Cre, Glu, Hb. The UV LED and Photodiode were designed to detect K+, CO2, Na+. According to the field diagnosis and treatment requirements, we designed the embedded control hardware circuit and software system, the prototype of first-aid biochemical detector was developed and the clinical trials were conducted. Experimental results show that the sample's absorbance repeatability is less than 2%, the max coefficient of variation (CV) in the batch repeatability test of all 7 biochemical parameters in blood samples is 4.8%, less than the clinical requirements 10%, the correlation coefficient (R2) in the clinical contrast test with AU5800 is greater than 0.98. To sum up, the prototype meets the requirements of clinical application.

10024-179, Session Post

RGD peptide conjugated-RhB probe for detecting the expression of integrin receptor integrin ?v?3

Menglu Zhao, Yueqing Gu, China Pharmaceutical Univ. (China)

RGD peptide conjugated-RhB or cRGDyK-RhB can be used as molecular probes.As the Integrin receptor ?v?3 is capable of combining with RGD peptides , when high-expression cells with Integrin receptor avb3 incubating with RGD peptides which is conjugated with RhB, the phenomenon that peptides probes are attached to the cell membrane integrin receptor can be detected by the confocal microscopy.By contrast, the phenomenon is not shown in low-expression cells.Under this condition,this method can be a fast and convenient way to detect the expression of Integrin receptor ?v?3 using RGD peptide conjugated with RhB probe.Besides,the flow cytometry is also used to certain the method.Incubating the cells with the peptide probe, mean flourscence indensity of high-expression cells with Integrin receptor?v?3 have significantly increased while low-expression cells with Integrin receptor?v?3 remain the same through calculating .Thus,it is proved that the method that using RGD peptide conjugated with RhB probe to detecting the expression of Integrin receptor ?v?3 is reliable.

10024-180, Session Post

Cypate-mediated thermosensitive nanoliposomes for NIR imaging and photo-thermo triggered drug release

Liwei Lv, Zhihao Han, Yueqing Gu, China Pharmaceutical Univ. (China)

The more and more excessive treatments and the resulting serious pain the patients get in the whole period of treatment call for precise diagnosis and effective as well as comprehensive treatments. In this work, we developed a kind of multi-functional photo-thermal sensitive liposomes (PTSL), by doping cypate, with the abilities of near infrared (NIR) imaging, photo-thermo conversion and singlet oxygen generating, into hydrophobic layer of the synthesized thermosensitive liposomes (TSL). Based on the PTSL, a theranostic nanocomposite, DOX@PTSL was established with doxorubicin (DOX) entrapped into the hydrophilic layer of PTSL. The physico-chemical properties were characterized by laser particle size analyzer, transmission electron microscope (TEM), UV-Visable spectrophotometer, infrared thermal imager and differential scanning calorimetry (DSC). For cell experiments, the MTT assay was performd to study the cell toxicities and the confocal laser scanning microscope (CLSM) was used to observe the locating properties and dynamics of DOX@PTSL after incubated with U87 cell lines and irradiated with NIR laser. The biodistribution, thermal images, and therapeutic effects of DOX@PTSL on tumor-bearing mice were investigated in the animal experiments. The size of liposome we synthesized is 90 to 190 nm while the phase inversion temperature falls on 43.1°C. And importantly, the drug release can be traggered by NIR laser, with almost all drugs entering the tumor cells' nucleus. In general, the DOX@PTSL was demonstrated tumor-targeted abilities, enhanced antitumor activities, minimal side effects and significant improved capability to combat with free DOX as results of the comprehensive therapeutic effectiveness of chemotherapy, thermotherapy and cypate-mediated photochemical internalization.

10024-181, Session Post

Retinal image quality and visual stimuli processing by simulation of partial eye cataract

Maris Ozolinsh, Olga Danilenko, Univ. of Latvia (Latvia)

We present a technique that allows control of visual stimuli quality using a polymer dispersed liquid crystal (PDLC) film placed in the optical pathway of one or both human eyes [1]. All equipment was incorporated in a "Virtual Reality" adapter. Visual stimuli were demonstrated on a 5' mobile phone screen inside adapter that allowed separation of the left and right eye visual fields. Contrast of the retina image thus can be controlled by the image on the phone screen and parallel to that by the AC voltage applied to PDLC cell. Such optical pathway separation allows to demonstrate to both eyes spatially variant images, that after visual binocular fusion acquire their characteristic indications. As visual stimuli we used different color (two opponents to vision – red-green in Lab color space) stimuli for left and right eyes; and with spatial content that by addition or subtraction results as clockwise or counter clockwise slanted Gabor gratings. We performed computer modelling of signal processing in brain via stimuli input decomposition in luminance and color opponency components. It revealed the dependence of the psychophysical equilibrium point between clockwise or counter clockwise perception on eye image contrast and color saturation, and on the strength of the retinal aftereffects. Actual observer perception experiments when one eye images were deteriorated by artificial cataract using PDLC approved the shift of mentioned psychophysical equilibrium point on the degree of artificial cataract.

[1] Glass Apps, "Glass Apps, Electrochromic Glass vs. PDLC – Smart Glass Technology Comparison." 2015. http://www.glass-apps.com/electrochromic-glass

10024-182, Session Post

Dual modality In vivo imaging of rodent fundus

Zhiyu Huang, Peking Univ. (China); Richard Johnson, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Xiaoyun Jiang, Qiushi Ren, Changhui Li, Peking Univ. (China)

Confocal scanning laser ophthalmoscopy (CSLO) and optical coherence tomography (OCT) provide complementary information of the animal fundus. Data acquired by CSLO have low axial resolution but high lateral resolution providing sharp images of the retinal structure and vessels, as well as molecular imaging. OCT is capable of creating lateral fundus scans with a high axial resolution. In this work, these two modalities were combined into one device, to simultaneously examine the rodent fundus. To improve the image quality and procedure of the experiment, a home-made contact probe for rodent animals has been designed and employed in this system. The animal's breathing and heartbeat could cause motion artefacts that influence the image quality, especially when the scanning speed is low. Hence both systems are capable to perform real-time imaging, enabling a precise and time-saving position adjustment of the animal during the experiment. The CSLO scan system can reach 15 Hz in C-Scan Mode, while the OCT shows B-Scans with 40 Hz. Our results demonstrated the dual-modality ophthalmoscope system successfully acquired high-quality images of the retina of a SD rat. The integrated CSLO and SD-OCT gives clear anatomical information with high lateral and axial resolution in real-time. Due to its modular setup it can be used for animals with different sizes and can be upgraded with additional functionalities. In all, it can be used widely for various researches,

including, physiology and pathology of fundus diseases, pre-clinical studies, and visual neuron studies.

10024-183, Session Post

Image segmentation of flow sample in Fourier domain Doppler optical coherence tomography

Yong Huang, Shaoyan Xia, Xiaodi Tan, Beijing Institute of Technology (China)

In Fourier domain Doppler optical coherence tomography (FD-OCT), intensity image and phase image can determine sample structure and flow condition, separately. To provide three-dimensional flow field simulation of sample, we employ the active contours method combining intensity and phase information for OCT B-scan images segmentation. In this segmentation process, initial contour of tissue is obtained from the intensity image by active contours method, then the corresponding region of phase image is processed. For phase image segmentation, the gray value of linking flow area is used as threshold for achieving accurate flow region. Thus, the different areas are determined in tissue structure.

10024-184, Session Post

Microencapsulation of indocyanine green in perfluorohexane-shelled microbubbles for application of cancer treatment

Shuya Han, Zhiqiang Zhu, Univ. of Science and Technology of China (China); Rong Ma, Second Affiliated Hospital of Chongqing Medical Univ. (China); Fengjing Zhong, Ting Si, Univ. of Science and Technology of China (China); Ronald X. Xu, The Ohio State Univ. (United States)

Indocyanine green(ICG), a fluorescent dye with a near-infrared spectrum of absorption and fluorescence, has shown promising prospect in cancer treatment because of its minor toxicity, its selectively over-heating effect, its release of reactive oxygen species upon laser irradiation and the penetration of NIR light. However, ICG is unstable in vivo environment and can be quickly removed from circulation by the liver to bile juice. Microencapsulation is a good way to improve the stability of ICG and to prolong its useful life after injection, which also helps improve its contrast effect. Perfluorocarbon-based emulsions(i.e. PFH microbubbles) are promising vehicles for triggered delivery of payloads thanks to their ability to undergo a phase change from liquid to gas upon ultrasound activation. Nonetheless, loading hydrophilic agents(i.e. ICG) into PFH emulsions is difficult due to their insolubility in PFH. Therefore, we use this coaxial flow-focusing technique to encapsulate ICG solution into PFH-shelled microbubbles to overcome these limitations. The effects of main parameters on the process are studied systematically for enhanced microbubble morphology. In cell culture studies, microbubble treatment with ultrasound activation remarkably increases cancer apoptosis and inhibits cell proliferation. Fluorescence imaging is studied after intraperitoneal injection in mice. Our results suggest that this therapy may be a useful method for cancer treatment.

10024-185, Session Post

Visualization of pathological tissues using autofluorescence imaging

Larisa A. Zherdeva, Ivan A. Bratchenko, Oleg O. Myakinin, Samara Univ. (Russian Federation); Alexander A. Moryatov, Sergey V. Kozlov, Samara State Medical Univ. (Russian Federation); Valery P. Zakharov, Samara Univ. (Russian Federation)

Pilot study results of autofluorescence imaging for ex vivo human skin samples with pathological tissues are presented using hyperspectral registration camera.

457 nm laser and a powerful blue LED at 450 nm with a broadband color filter ss-4 (transmission coefficient in the range of 500-690 nm is 0%) are selected as the excitation source of autofluorescence. The system of hyperspectral imaging can display the images with spectral resolution of up to 2.1 nm in the range of 450-750 nm and provides the capability to obtain images at a rate of 3 frames per second with a resolution of 1360x1024 pxl (maximum increase in scanning area is 7x7 cm). Autofluorescence imaging results are compared with the histological analysis of samples provided of Samara State Medical University. The obtained data has been processed in MATLAB R2014a.

Analysis of the autofluorescent data of skin samples based on the spectral ranges of 520-580 nm and 620-690 nm due to the presence of flavins and porphyrins in tissues is performed. Autofluorescent images obtained by excitation of laser (457 nm) and LEDs (450 nm) with a broadband color filter are compared.

As a result, the maps of basic fluorophores of skin with neoplasm are presented, and shown that pigmented melanoma, unlike a normal skin, is characterized by a significant decline of intensity in the range of 520-580 nm relatively to range of 620-690 nm.

10024-39, Session 7

Plasmon-enhanced UV lasing in ZnO whispering-gallery microcavities *(Invited Paper)*

Chunxiang Xu, Qiuxiang Zhu, Junfeng Lu, Yueyue Wang, Zengliang Shi, Southeast Univ. (China)

In recent years, whispering-gallery mode (WGM) lasing from hexagonal ZnO microrods has drawn much attention due to its low loss, low threshold and high Q factor. Ones have made great efforts to improve lasing performance. Surface plasmons (SPs) as a collective electronic oscillation have been successfully introduced on a metal-dielectric interface to improve optical properties, such as enhanced surface Raman scattering and enhanced fluorescence. The metal decorated WGM microcavity constructs a more advantageous coupling configuration between the ZnO interband emission and the surface plasmon (SP) because both of the evanescent waves are mainly confined on the microcavity surface, where the former reflects totally and internally at the ZnO/air boundary while the latter is localized in the metal/ZnO interface. This effective coupling is expected to contribute to improve the lasing performance, but few investigations have been reported so far. Here the plasmon enhanced spontaneous emission and whispering-gallery mode (WGM) lasing from hexagonal ZnO microrod has been investigated through decorating metal nanoparticles (such as Al, Ag and Au) on the cavity surface. About 200-folds and tens-folds enhancement of spontaneous and stimulated emission have been observed in our experiments. The lasing threshold and Q factor have also been improved. The related energy coupling and charge transfer processes have been investigated systematically. These results are helpful for designing high efficient optical and photo-electronic devices.

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10024-40, Session 7

Utrasound-assisted gold nanoparticle beacon for the detection of sensibility of tumor cells to chemotherapy *(Invited Paper)*

Qiumei Zhou, Yi Ma, Yueqing Gu, China Pharmaceutical Univ. (China)

The failure of chemotherapy, a serious problem in anticancer therapy, is substantially caused by either intrinsic or acquired gene mutations or overexpression of specific proteins. However, there is currently a lack of selective and effective platforms for the detection of sensibility of living tumor cells to chemotherapy. Here, we demonstrate a gold nanopartical beacon (hDAuNP Beacon) is capable of detecting the mRNA expression of drug resistance related gene, as well as the responds of tumor cells to anticancer chemotherapy. In this study, based on the relationship between mRNA expression of resistance gene and tumor drug-resistance, the hDAuNP Beacon was designed, synthesized and respectively used to detect multidrug resistance 1 (MDR1) mRNA and breast cancer susceptibility gene-1 (BRCA1) mRNA expression in living cells. With the help of ultrasonic wave, which could improve the permeability of cell membranes, the cellular uptake and the detection sensitivity of hDAuNP beacon are improved notably. The difference in MDR1 and BRCA1 mRNA expression in living cancer cells can be detected exactly by hDAuNP beacon assisted with ultrasound. According to the fluorescent signals in living cells, the sensibility can be recognized for tumor cells to Doxorubicin, Cisplatin and Paclitaxel. Furthermore, the expression of p-glycoprotein (P-gp) was regulated by the antisense DNA sequences of MDR1 hDAuNP beacon, and the Doxorubicin resistance was reversed by MDR1 hDAuNP beacon. Therefore, hDAuNP beacon may be a new strategy for the personalized medicine and the precision medical.

10024-41, Session 7

Optofluidic microresonators in biosensing and imaging *(Invited Paper)*

Xiang Wu, Fudan Univ. (China); Shusen Xie, Fujian Normal Univ. (China)

Hollow-core optofluidic microresonators (OFMRs) currently attract many researchers' attentions due to their potential applications in scientific and industrial fields. OFMRs have the unique capabilities of both the easy integration with microfluidics and the excellent optical confinement of optical microrensonators. The outstanding advantage makes OFMRs as one of promising optofluidic platform for ultra-sensitive bio-sensing and high-resolution imaging. In this talk, we first describe the principle of OFMRs and review the current applications on in-vitro bio-sensing and imaging. We will present the OFMRs based on ring resonators and Fabry–Pérot cavities and the applications on biosensing and imaging. The outlooks of the development and potential applications on in-vivo bio-sensing and imaging are also provided.

10024-42, Session 7

Multiple gold-dimer detection from large scattering background

Xin Hong, Zheng Jin, Dalian Univ. of Technology (China)

Gold nanoparticles exhibit unique plasmonic optical properties in visible to near infrared band. Especially when two particles are closely linked, the coupling effect existing at the gap can produce a strongly enhanced local field. These properties make gold particles more attractive to be employed as molecular probes in biomedical related fundamental and clinical researches. However, in the bio-system exist many large molecules or groups, whose optical signals can strongly depress the gold particles into undetectable. With the aim to detect the targets from the circumstance of scattering disturbance, we employed gold dimer as molecular probes by taking advantage of their plamonic coupling effect. The coupling effect of a gold-dimer is associated with the angle between the excitation polarization and the dimer axis ,while the optical signals strength of other large molecules or groups aren't sensitive to the polarization direction of the excitation light. A good match of excitation condition with the dimer axis is crucial to extract the probe from the background noise. To make the detection without target lose, it requires each randomly placed dimer axis to be matched with the excitation. The simulation results show that 45degrees between the excitation polarization and the dimer axis can produce an optimum signal. We can detect multiple gold-dimer by observing the change of optical signals strength in the same place with the rotation of the polarization. Thus here, in this paper we proposed a method to extract multiple dimer probes from the large background noise without target lose.

10024-43, Session 7

Near-infrared fluorescent polymer dots with durable brightness and long-term stability for in vivo tumor tracking

Liqin Xiong, Fengwen Cao, Yixiao Guo, Shanghai Jiao Tong Univ. (China)

In recent years, conjugated polymer dots have gained interest as a new class of fluorescent probes due to their attractive chemical and optical features. However, to date, only a few studies on whole-body imaging of polymer dots in living mice have been reported, mainly due to the challenges of designing polymer dots that show strong and narrow-band emissions in the near-infrared (NIR) region, and their unfavorable in vivo performance after systemic injection. To address this problem, we prepared the NIR-emitting polymer dots by encapsulating the dye NIR775 into the matrix of MEH-PPV dots using a nanoprecipitation method. The prepared NIR polymer dots exhibited narrow-band NIR emission at 778 nm with a full width at half maximum (FWHM) of 20 nm, and displayed a large Stokes shift (>300 nm) between the excitation and emission maxima. Moreover, these NIR polymer dots showed long-term colloidal stability and photostability in water at 4 oC for at least nine months, and were able to imaging vasculature of xenografted U87MG tumors in living mice after intravenous injection. We further use the NIR775 dye-doped MEH-PPV polymer dot system as a fluorescent nanoprobe for in vitro HeLa cell labeling and in vivo long-term HeLa tumor tracking. These synthesized NIR polymer dots exhibited unique capabilities for in vivo cell tracking, such as long-term luminescence and photostability, and high sensitivity. These studies provide a foundation for the development of the whole-body tumor cell tracking based on the NIR polymer dots as fluorescent nanoprobes.

10024-44, Session 7

Anti-hepatocarcinoma effects of berberine-nanostructured lipid carriers against human HepG2, Huh7, and EC9706 cancer cell lines *(Invited Paper)*

Xiang-ping Meng, Henan Univ. of Science and Technology (China); Hua Fan, Guangdong hinabiotech Co., Ltd.

(China); Yifei Wang, Jinan Univ. (China); Zhi-ping Wang, Guangdong Pharmaceutical Univ. (China); Tongsheng Chen, South China Normal Univ. (China)

Hepatocarcinoma and esophageal squamous cell carcinomas threaten human life badly. It is a current issue to seek the effective natural remedy from plant to treat cancer due to the resistance of the advanced hepatocarcinoma and esophageal carcinoma to chemotherapy. Berberine (Ber), an isoquinoline derivative alkaloid, has a wide range of pharmacological properties and is considered to have anti-hepatocarcinoma and antiesophageal carcinoma effects. However its low oral bioavailability restricts its wide application. In this report, Ber loaded nanostructured lipid carriers (Ber-NLC) was prepared by hot melting and then high pressure homogenization technique. The in vitro anti-hepatocarcinoma and antiesophageal carcinoma effects of Ber-NLC relative to efficacy of bulk Ber were evaluated. The particle size and zeta potential of Ber-NLC were 189.3 ± 3.7 nm and ?19.3 ± 1.4 mV, respectively. MTT assay showed that Ber-NLC effectively inhibited the proliferation of human HepG2 and Huh7 and EC9706 cells, and the corresponding IC50 value was 9.1 μg/ml, 4.4 μg/ml, and 6.3 μg/ml (18.3μg/ml, 6.5μg/ml, and 12.4μg/ml μg/ml of bulk Ber solution), respectively. These results suggest that the delivery of Ber-NLC is a promising approach for treating tumors.

10024-45, Session 7

Optical manipulation of nanoparticles based on whispering gallery mode optical resonators

Haotian Wang, Xiang Wu, Deyuan Shen, Fudan Univ. (China)

The whispering Gallery mode (WGM) optical resonator enables a great optical intensity enhancement in a very small volume, which gives a promising platform for trapping and manipulating the micro- or nano-particles. The light could be coupled into the resonator to excite the WGMs using the waveguide placed close to the resonator or illuminating the resonators directly in the free-space. In the latter case, more interesting is that a special optical field distribution called photonics nanojet (PNJ) is formed even if the resonator is off-resonance. The PNJ also confines the optical field within a very small region on the shadow side of the resonator. In this paper, we demonstrate the localized optical manipulation of nanoparticles in the resonator basing on generating the standing-wave WGM and PNJ. The locations of the trapped particles are controlled by tuning the incident field. The trapping stability of the nanoparticles under the Brownian motion is also analyzed. The manipulation system presented in this paper possess enormous potential in precisely manipulation of nanoparticles, such as directed nanoassembly and manipulating single molecules.

10024-46, Session 7

SERS signals in the transducing process of biosensors

Xiangwei Zhao, Zhongde Mu, Bing Liu, Delong Wang, Zhongze Gu, Southeast Univ. (China)

Raman-scattered photons from a molecule can directly reveal the signature of vibrational energy states of the molecule and their intensities can be greatly enhanced by plasmonic nanostructures or surfaces of plasmonic materials, which leads to high sensitivity. Therefore, surface enhanced Raman spectroscopy (SERS) attracts more and more attentions in bioanalysis recently. The probability of spontaneous Raman scattering is directly proportionally to the photon density of state (DOS) at related frequency. Therefore, structures that can increase DOS are desired in SERS applications. Photonic crystal (PC), which has periodic nanostructures relevant to the length of light, has photonic band gaps that forbidden the propagation of light in some frequency range. Therefore, PC has increased DOS at the band edge with respect to homogenous medium and provides a good candidate medium for the boost of light and plasmonic materials interactions. In this paper, we integrated plamsonic materials with PC to boost SERS signals and discussed the fabrication methods of integration, as well as the factors that affect SERS signals in the transducing process of biosensors with respect to high sensitivity, multiplicity and simplicity. Our results showed that the micro/nano structure of photonic crystal could be used as a good platform for SERS sensors in biomedical applications like point of care testing (POCT), bacteria detection, cell analysis or multiplex bioassays.

10024-47, Session 7

Detection limit improvement for a mobile lateral flow assay reader

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Lateral flow immunoassays are widely used for qualitative measurement in non-specialize laboratory and in low-resource settings. Recent developments in the mobile-phone strip readers have further improved the device's sensitivity as well as other advantages including quantitative results, reading error reduction, compact size and simple data handling. We showed that manually adjusting the camera settings, instead if using the automatic setting mode, to achieve a full scale bit-depth can significantly improve the detection limit of the strip reader. The strip reader was developed based on a CMOS camera and a green LED light source. Camera parameters including exposure time, gain, and contrast were manually adjusted until the full scale of the camera bit depth was achieved. The performance of the strip reader was evaluated for the detection of the Acidovorax avenea subsp. Citrulli (Aac), the bacterial fruit blotch of watermelon. We found that the detection limit of the reader when the optimal camera settings were used was 5x105 CFU/mL which was 10 times better than the detection limit of the reader utilized the camera automatic mode. This technique can be readily applied to any existing camera-based strip readers to significantly improve the reader's performance without hardware modifications.

10024-48, Session 7

Evaluation of free-radical scavenging and anti-oxidative capacity of polydatin-nanostructured lipid carriers

Xiang-Peng Meng, Henan Univ. of Science and Technology (China); Fan Shi, Guangdong Pharmaceutical Univ (China); Yifei Wang, Jinan Univ. (China); Zhi-ping Wang, Guangdong Pharmaceutical Univ. (China); Tongsheng Chen, South China Normal Univ. (China)

Cellular damage induced by free-radicals like reactive oxygen species has been implicated in several diseases. 2, 2-azobis(2-amidino-propane) dihydrochloride(AAPH) generates two potent ROS capable of inducing lipid peroxidation: alkoxy radical(RO-)

and peroxy radical(ROO-). These radicals are similar to those that are physiologically active and thus might initiate a cascade of intracellular toxic events leading to oxidation, lipid peroxidation, DNA damage and subsequent cell death. Hence naturally anti-oxidant play a vital role in combating these conditions. In this study, polydatin loaded nanostructured lipid carriers (Pol-NLC) was prepared by hot melting and then high pressure homogenization technique. The effects of Pol-NLC on free radical scavenging and antioxidative capacity is investigated. The particle size and zeta potential of Pol-NLC were 113.9 ± 1.1 nm and ?16.3 1 ± 0.27 mV, respectively. By free radical scavenging assays, the IC50 value of Pol-NLC were 28.71, 9.83 ?g/mL with DPPH, ABTS assay respectively, and 0.143 mg ferrous sulfate/1 mg Pol-NLC with FRAP assay. These results indicated that the antioxidant properties of Pol-NLC hold great potential used as an alternative to more toxic synthetic antioxidants as an additive in food, cosmetic and pharmaceutical preparations for the oxidative diseases treatment.

10024-49, Session 8

Quantification of reactive oxygen species for photodynamic therapy *(Invited Paper)*

Buhong Li, Fujian Normal Univ. (China)

Photodynamic therapy (PDT) is an effective therapeutic modality that uses a light source to activate light-sensitive photosensitizers to treat both oncologic and nononcological indications. Photosensitizers are excited to the long-lived triplet state, and they react with biomolecules via type I or II mechanism resulted in cell death and tumor necrosis. Free radicals and radical ions are formed by electron transfer reactions (type I), which rapidly react with oxygen leading to the production of reactive oxygen species (ROS), including superoxide ions, hydroxyl radicals and hydrogen peroxide. Singlet molecular oxygen is produced in a Type II reaction, in which the excited singlet state of the photosensitizer generated upon photon absorption by the ground-state photosensitizer molecule undergoes intersystem crossing to a long-lived triplet state. In this talk, the fundmental mechanisms and detection techniques for ROS generation in PDT will be introduced. In particular, the quantification of singlet oxygen generation for pre-clinical application will be highlighted, which plays an essential role in the establishment of robust singlet oxygen-mediated PDT dosimetry.

10024-50, Session 8

Pdot probes for stem cell labeling and phototherapy *(Invited Paper)*

Changfeng Wu, Jilin Univ. (China)

Semiconductor polymer dots (Pdots) have been demonstrated for a wide variety of biological applications. On one hand, the superior properties of Pdots have established their enormous potential in biology and medicine as highly bright probes for cellular imaging and in vivo imaging. However, little is known whether stem cells can be effectively labeled by Pdots for long term cell tracking in vitro and in vivo. On the other hand, semiconductor polymers have been frequently exploited for amplifying the singlet oxygen generation by taking advantages of their large absorption coefficient and efficient energy transfer to the photosensitizers. The energy transfer mechanism provides new opportunities for designing Pdot platforms for phototherapy. In one approach, photosensitizer molecules can be physically encapsulated in Pdots by hydrophobic interactions. The densely packed Pdots comprised conjugated polymer and photosensitizer in close proximity that facilitate the amplification of singlet oxygen generation by energy transfer. In alternative approaches, covalent incorporation of photosensitizer in conjugated polymers could amplify the singlet oxygen generation by energy transfer from the conjugated backbone to photosensitizers.

In this presentation, we will present several new types of Pdot probes for stem cell labeling and phototherapy. The hydrophobic semiconductor polymers tend to form small, stable and densely-packed Pdot probes. The large absorption cross section, high fluorescence quantum yields, and good biocompatibility are promising for stem cell tracking in vitro and in vivo. The Pdots coated with a cell penetrating peptide showed remarkable endocytic uptake efficiency as compared to carboxyl Pdots. The Pdot-labeled stem cells can be traced for 15 generations in vitro and tracked over weeks in vivo after tail-vein injection. For PDT applications, incorporation of photosensitizer inside the Pdots can amplify singlet-oxygen generation by efficient energy transfer. We developed Pdot photosensitizers and then systematically characterized the spectroscopic properties, which showed efficient singlet oxygen generation amplified by inter-particle energy transfer. The effectiveness of Pdots as PDT photosensitizer was demonstrated by in vitro assay, which indicate that the Pdots are able to damage cancer cells under low Pdot concentration and light dose. Moreover, the PDT effect of the Pdots was further investigated in vivo with tumor-bearing mice model, and the xenograft tumors were significantly inhibited or eradicated in certain cases.

10024-51, Session 8

Quantitative photobiomodulation *(Invited Paper)*

Timon Cheng-Yi Liu M.D., Ling Zhu, South China Normal Univ. (China); Quan-Guang Zhang, South China Normal Univ. (China) and Augusta Univ. (United States)

Photobiomodulation (PBM) has been usually studied with statistical approaches, but its reproducibility has been very low. It was reanalyzed with the quantitative difference (QD) in this study. The golden logarithm (GL) was defined as the logarithm to the base the golden ratio, about 0.618. The QD of two parameters was defined as the absolute value of the GL of their ratio. The QD was significant or very significant if it is equal to or larger than a or b. The a/b of the cellular/molecular/psychological QD, the organ/tissue QD and the body QD were 0.80/1.27, 0.47/0.80 and 0.27/0.47, respectively. For NeuroThera Effectiveness and Safety Trial of Infrared Laser Therapy for Ischemic Stroke (NEST), the therapeutic effects were of very significance for NEST-1, of significance for NEST-2, but of no significance for NEST-3 according to organ/tissue QD, which suggested that ischemic stroke should be classified into two categories: PBM-sensitive and PBM-resistant. For the well-known randomized clinical trial of acupuncture for chronic knee pain, QD analyses showed needle, laser, or sham acupuncture significantly changed most of parameters compared with control at 12 weeks or 1 year. The mechanism of signal transduction pathway still held because there were function-specific signal transduction pathways (FSPs) according to molecular QD, and PBM might promote the activation of one or more FSPs if the observation term is long enough. It was concluded that the quantitative PBM may not only of high reproducibility, but also promote the translation of PBM studies into low level laser/light therapy.

10024-52, Session 8

The florescence detection in the treatment of CIN with photodynamic therapy

Lifeng Wang, Defu Chen, Naiyan Huang, Ying Gu, Chinese PLA General Hospital (China)

The cervical intraepithelial neoplasias (CIN) is the abnormal growth of squamous cells on the surface of the cervix, and is

the potentially premalignant transformation. The photodynamic therapy (PDT) is a form of phototherapy in which light interacts with a photosensitizer and singlet oxygen is generated to to kill cells. Compared the traditional cone resection treatment to the CIN, the PDT method introduces less damage to the cervix uteri and the function can be reserved. We have performed PDT treatment to the patients who are intravenously ejected with Hematoporphyrin, the mount of which is proportional to the mass of the patients and irradiated by the 630 nm continues laser. The florescence spectrum of the Hematoporphyrin can help doctors to find out the accumulation of the photosensitizer in the lesion area. Based on a Y-type fiber, we have established a florescence detection system to record the florescence spectrum of the Hematoporphyrin. A 405 nm continuous laser is transmitted in a fiber to simulate the Hematoporphyrin, and the fluorescence with central wavelength at 630 nm and 690 nm is transmitted by another fiber and detected by a spectroscope. A band filter is used to eliminate the 405 nm laser and gather the florescence at maximum amount. The intensity of the fluorescence significantly decreased after the radiation, which means the photosensitizer is consumed by the 630 nm laser but a few amount is still left in the lesion area.

10024-53, Session 8

In vitro photodynamic inactivation effects of cationic benzylidene cyclopentanone photosensitizers on clinical fluconazole-resistant candida albicans planktonic cells and biofilms

Shaona Zhou, Ying Wang, Zulin Ye, Ying Gu, Chinese PLA General Hospital (China)

Background: An increasing prevalence of Candida infections has emerged with the wide use of immune-suppressants and antibiotics. Photodynamic inactivation (PDI) as a new approach to treat localized Candida infections is an emerging and promising field nowadays. This study evaluated the efficacy of photodynamic therapy using two new Cationic benzylidene cyclopentanone photosensitizers(P1 and P2) against strains of clinical fluconazole–resistant Candida albicans.

Methods: Suspensions and biofilms of Candida species were incubated with P1 and P2 concentrations (0.25~50 ?M) for 30 min followed by 532-nm laser irradiation. For planktonic suspensions, viability of cells was assayed by CFU counting. For biofilms, the metabolic activity was evaluated by XTT.

Results: In PDI of a planktonic culture of clinical fluconazole–resistant Candida albicans, P2 showed the higher efficacy. After incubation with 25 μM of P2 for 30 min and irradiation with 532-nm laser (36 J/cm2), the viability of C. albicans planktonic cells decreased by 3.84 log10. For biofilm cells, a higher light dose of 75 mW/cm2 was necessary to achieve 97.71% metabolic activity reduction.

Conclusions: The results of this investigation demonstrated that benzylidene cyclopentanone photosensitizer?P2?is an efficient photosensitizer to kill C. albicans. Moreover, single-species biofilms were less susceptible to PDT than their planktonic counterparts.

10024-54, Session 8

Antimicrobial blue-light inactivation of methicillin-resistant staphylococcus aureus: in vitro and in vivo study

Yucheng Wang, Chinese PLA General Hospital (China) and Nankai Univ. (China); Tianhong Dai, Massachusetts General Hospital (United States); Ying Gu, Chinese PLA General Hospital (China)

Background: With the increasing emergence of multidrug-resistant (MDR) bacterial strains, there is a pressing need for the development of alternative treatment for infections. Antimicrobial blue light (aBL) has provided a simple and effective approach.

Methods: We first investigated the effectiveness of aBL (415 nm) inactivation of USA300 (a Methicillin-resistant Staphylococcus aureus strain) both in the planktonic and biofilm forms. The survival of the bacteria in suspensions was determined by serial dilution and that of the biofilm-embedded bacteria was determined by bioluminescence quantification. Using a mouse model of thermal burn infected with USA300, we further assessed the effectiveness of aBL for treating localized infections. Bioluminescence imaging was performed to monitor in real time bacterial viability in vivo.

Results: In vitro study showed that, for the planktonic counterpart of the bacteria or the 24-h-old biofilms, an irradiance of 55 mW/cm2 for 60 min resulted in a 4.61 log10 or 2.56 log10 inactivation, respectively. In vivo study using infected mouse burns demonstrated that a 2.56-log10 inactivation was achieved after 100-mW/cm2 irradiation for 62 min.

Conclusions: aBL is a potential alternative approach for treating Methicillin-resistant Staphylococcus aureus infections.

10024-10, Session 9

Implantable multifunctional optoelectronic neural probe

Xing Sheng, Tsinghua Univ. (China)

Understanding neural structures and functions is important to resolve the mystery of the complex brain. Recent progresses in the development of genetically encoded actuators and indicators have given birth to versatile and powerful tools for monitoring and manipulating neuronal activities both temporally and spatially, using optical methods. Here we present an integrated optoelectronic probe system based on high performance, microscale photonic devices including LEDs and photodetectors, which can be implanted deeply into the brain and provides new insights on interactions between light and neural systems. A gallium indium nitride (GaInN) blue LED, a gallium indium aluminum phosphide (GaInAlP) yellow LED, as well as a gallium arsenide (GaAs) photodetector are combined and interconnected on a flexible thin-film polymer substrate, forming an injectable needle. New techniques including epitaxial liftoff and transfer printing are developed to fabricate and assemble these thin-film microscale inorganic semiconductor devices onto the organic substrate. The blue LED serves as a light source to excite the genetically encoded calcium indicator GCaMP6. The photodetector with a specifically designed band selective optical coating is used to probe the GCaMP6 fluorescent signal with high sensitivity. The yellow LED allows us to activate the chloride pump halorhodopsin, which inhibits local neural activities. Compared to other light sources like optical fibers, external light sources and detectors, these deeply injected photonic devices will provide collimated, localized and precise light generation and detection. By using such an integrated optoelectronic system, we hope to realize close loop monitoring and manipulation of neural activity in vivo.

10024-55, Session 9

Wavelet phase coherence analysis of cerebral tissue oxyhemoglobin concentrations and arterial blood pressure signals in subjects with sleep deprivation

Lingguo Bu, Jianfeng Li, Fangyi Li, Heshan Liu, Shandong Univ. (China); Zengyong Li, Shandong Univ. (China) and National Research Ctr. for Rehabilitation Technical Aids (China)

There are occupational risks in sailors due to long term work in the sea, especially cardiovascular and cerebrovascular diseases. Sleep deprivation is one of the risk factors in sailors. This study aims to assess the relationship between spontaneous oscillations in changes in cerebral tissue oxyhemoglobin concentrations (Delta [HbO2]) and arterial blood pressure (ABP) signals in subjects with sleep deprivation using wavelet phase coherence analysis (WPCO).

Total 20 healthy subjects (including 10 male and 10 female, age: 25.5 ± 3.5 years) were recruitedfrom Shandong University and divided into two groups: one was without deprivation group (Group A) and the other was with 24 hour sleep deprivation group (Group B). Continuous recordings of near-infrared spectroscopy (NIRS) and ABP signals were obtained from simultaneous measurements in each subject during the rest and task, respectively. The coherence between Delta [HbO2] and ABP oscillations in six frequency intervals (I, 0.6–2 Hz; II, 0.145–0.6 Hz; III, 0.052–0.145 Hz; IV, 0.021–0.052 Hz; V, 0.0095–0.021 Hz; and VI, 0.005–0.0095 Hz) was analyzed using wavelet coherence analysis.

At rest, the WPCO in intervals III was significantly lower in Group B than in Group A ($F = 4.367$, $p = 0.044$ for III). In task, Group B's WPCO in intervals IV was significantly higher than Group A ($F = 8.045$, $p = 0.007$ for interval IV). The results suggest that wavelet-based coherence analysis of NIRS signal can provide a method to assess the risks of cardiovascular and cerebrovascular diseases in sailors with sleep deprivation.

10024-56, Session 9

Quantitatively differentiating microstructural variations of skeletal muscle tissues by multispectral Mueller matrix imaging

Yang Dong, Honghui He, Chao He, Tsinghua Univ. (China); Hui Ma, Graduate School at Shenzhen, Tsinghua Univ. (China)

Polarized light is sensitive to the microstructures of biological tissues and can be used to detect physiological changes. Meanwhile, spectral features of the scattered light can also provide abundant microstructural information of tissues. In this paper, we take the backscattering 3?3 linear polarized Mueller matrix images of bovine skeletal muscle tissues during the 24-hour experimental time, and analyze their multispectral behavior using quantitative Mueller matrix parameters. In the processes of rigor mortis and proteolysis of muscle samples, multispectral frequency distribution histograms (FDHs) of the Mueller matrix elements can reveal rich qualitative structural information, and their corresponding four central moment parameters can be used as quantitative indicators for the characteristic microstructural features of tissues. In addition, we analyze the temporal variations of the sample using the multispectral Mueller matrix transformation (MMT) parameters. The experimental results indicate that the different stages of rigor mortis and proteolysis for bovine skeletal muscle samples can be judged by these MMT parameters. Contrast mechanism of the multispectral Mueller matrix imaging for skeletal muscle tissues is revealed by Monte Carlo (MC) simulations based on the sphere-cylinder birefringence model. The relationship between the multispectral features of the MMT parameters and the microstructures of the samples is studied. The results presented in this work show that combining with the multispectral technique, the FDHs, central moments and MMT parameters can characterize the microstructural variation features of skeletal muscle tissues. The techniques have the potential to be used as tools for quantitative assessment of meat qualities in food industry.

10024-57, Session 9

Accurate assessment of liver steatosis in animal models using a high-throughput Raman fiber-optic probe

Kevin C. Hewitt, Ian P. Alwayn, Dalhousie Univ. (Canada); Haishan Zeng, Hanna C. McGregor, Michael A. Short, BC Cancer Research Ctr. (Canada); Samia B. Fashir, Heidi Sapp, Javad G. Rad, Dalhousie Univ. (Canada)

Due to the shortage of healthy donor organs, steatotic livers are commonly used for transplantation, placing patients at higher risk for graft dysfunction and lower survival rates. Raman Spectroscopy is a technique which has shown the ability to rapidly detect the vibration state of C–H bonds in triglycerides. The aim of this study is to determine whether conventional Raman spectroscopy can reliably detect and quantify fat in an animal model of liver steatosis. Mice and rats fed a methionine and choline-deficient (MCD) and control diets were sacrificed on one, two, three and four weeks' time points. A confocal Raman microscope, a commercial Raman (iRaman) fiber optic probe and a highly sensitive Raman fiber optic probe system, the latter utilizing a 785 nm excitation laser, were used to detect changes in the Raman spectra of steatotic mouse livers. Thin layer chromatography was used to assess the triglyceride content of liver specimens, and sections were scored blindly for fat content using histological examination. Principal component analysis (PCA) of Raman spectra was used to extract the principal components responsible for spectroscopic differences with MCD week (time on MCD diet). Confocal Raman microscopy revealed the presence of saturated fats in mice liver sections. A commercially available handheld Raman spectroscopy probe could not distinguish the presence of fat in the liver whereas our specially designed, high throughput Raman system could clearly distinguish lobe-specific changes in fat content. In the left lobe in particular, the Raman PC scores exhibited a significant correlation ($R2 = 0.96$) with the gold standard, blinded scoring by histological examination. The specially designed, high throughput Raman system can be used for clinical purposes. Its application to the field of transplantation would enable surgeons to determine the hepatic fat content of the donor's liver in the field prior to proceeding with organ retrieval.

Next steps include validating these results in a prospective analysis of human liver transplantation implant biopsies.

10024-58, Session 9

Polarized light imaging for non-destructive quantitative assessment of vulvar lichen sclerosis

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Vulvar lichen sclerosis (VLS) is a chronic skin disorder of extragenital skin with an increasing risk of developing vulvar cancer, which often goes undetected for years. Hyperkeratosis and areas of sclerosis often occur, which leads to the structural changes of the affected area. One of the underlying causes is associated with the decrease and homogenization of collagen fibers causing the changes of fiber orientation. However, few method is available for quantitative detection of VLS. Clinician's examination is subjective and may lead to misdiagnosis. Polarized light imaging is a potentially effective method for noninvasive detection of VLS. In this paper, we studied the optical properties of vulvar tissue and developed a polarized light imaging system for quantitative assessment. First, a five-layered optical model was proposed for simulating Mueller matrix of vulvar tissue. Then a polarized light imaging system was developed for noninvasive detection of the order of alignment of the fibrous structure in tissues,?or structural anisotropy ,and the orientation of the fibers via the analysis of Mueller matrix. Thus, structural anisotropy and fiber orientation quantification can be achieved for the superficial layer with optical sectioning. We demonstrated on the VLS optical sectioning that this polarized light imaging method had a technical potential for non-destructive quantitative assessment of VLS.

10024-59, Session 9

Hyperspectral-stimulated Raman scattering imaging of cholesteryl ester accumulation: new avenue to diagnosis of human prostate cancer

Jun Du, Beihang Univ. (China); Ping Wang, Huazhong Univ. of Science and Technology (China); Shuhua Yue, BeiHang Univ. (China)

Most prostate cancers (PCa) are slowly growing, and only the aggressive ones require early diagnosis and effective treatment. The current standard for PCa diagnosis remains histopathology. Nonetheless, for the differentiation between Gleason score 6 (low-risk PCa), which can be left without treatment, and Gleason score 7 (high-risk PCa), which requires active treatment, the inter-observer discordance can be up to 40%. Our previous study reveals that cholesteryl ester (CE) accumulation induced by PI3K/AKT activation underlies human PCa aggressiveness. However, Raman spectromicroscopy used in this study could only provide compositional information of certain lipid droplets (LDs) selected by the observer, which overlooked cell-to-cell variation and hindered translation to accurate automated diagnosis. Here, we demonstrated quantitative mapping of CE level in human prostate tissues using hyperspectral stimulated Raman scattering (SRS) microscopy that renders compositional information for every pixel in the image. Specifically, hundreds of SRS images at Raman shift between 1620-1800 cm-1 were taken, and multivariate curve resolution algorism was used to retrieve concentration images of acyl C=C bond, sterol C=C bond, and ester C=O bond. Given that the ratio between images of sterol C=C and ester C=O (sterol C=C/C=O) is nonlinearly proportional to CE percentage out of total lipid, we were able to quantitatively map CE level. Our data showed that CE level was significantly greater in high Gleason grade compared to low Gleason grade, and could be a factor that significantly contributed to cancer recurrence. Our study provides an opportunity towards more accurate PCa diagnosis and prediction of aggressiveness.

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10025-1, Session 1

Fiber Bragg grating-based temperature sensor for neutral gas in capacitively-coupled plasmas *(Invited Paper)*

Zigeng Liu, Daoman Han, Xinpu Zhang, Yongxin Liu, Wei Peng, Younian Wang, Dalian Univ. of Technology (China)

In this paper, a fiber Bragg grating (FBG) has been utilized in capacitively coupled plasmas (CCP) for thermometry of neutral gas. The FBG was put into the single-frequency and dual-frequency power argon plasma respectively, which is manufactured by ourselves. We studied the effects of high frequency and low frequency power on radial distribution of neutral gas temperature. The result shows that the neutral gas temperature is higher than the room temperature by 10 ~ 120? in CCPs and shows significant non-uniformity in space. The neutral gas temperature increases with the increase of high frequency power due to the enhancive collisions with Ar+ ion density. The neutral gas heating is mainly caused by the elastic collisions of Ar+ ion with neutral atoms when traversing the sheath region after Ar+ ion gaining substantial energy. However, the presence of low frequency power will decrease the neutral gas temperature. Particularly, we eliminated the effect of iron bombardment on neutral gas temperature by the temperature measurement of plasma sheath near the electrode. The temperature sensitivity of proposed FBG is 10.4pm/?, which is calibrate by a programmable tubular furnace. With features of immune to electromagnetic interference, high precision, and spatial resolving power, the FBG is a commendable candidate for CCP or other radio-frequency plasmas thermometry in both laboratory and industry.

10025-2, Session 1

Simultaneous measurement of temperature and strain based on composite long-period fiber grating

Chengguo Tong, Zhanjing Bao, Cuiting Sun, Xudong Chen, Jiang He, Tao Geng, Harbin Engineering Univ. (China)

Long period fiber grating is a kind of transmission type optical fiber grating. Due to the advantages such as low insertion loss,wide bandwidth, low-level reflection, high sensitivity, low cost and ease of compactness, LPFGs have been widely applied in optical fiber sensing and optical fiber communication.

The Mode coupling of LPFG is the coupling between the fiber core mode and the cladding mode in the same transmission direction.If the ordinary LPFG is combined with bitaper or taper, we can effectively change the original LPFG's transmission spectrum to obtain the composite LPFG, which can stimulate new resonant peaks in the original wavelength-dependent transmission loss of the gtating basis, thus applying to the dual-parameter simultaneously measuring field.

We report a novel all-fiber narrow-bandwidth intermodal Mach–Zehnder interferometer (MZI) based on a long-period fiber grating (LPFG) combined with a fiber bitaper.The LPFG is written by high-frequency CO2 laser pulses, and the bitaper is connected in series with the LPFG, forming the Mach–Zehnder interferometer (MZI). Experimental results indicate that the MZI has good temperature sensitivity, The temperature sensitivity of the two loss peaks are 55.35pm/°C and 48.18pm/°C respectively. The strain sensitivity of the two loss peaks are 3.35pm/?? and -4.925pm/?? respectively.By using the different temperature and strain response characteristics of the loss peaks , the temperature and strain measurement can be realized simultaneously. the proposed device has good repeatability and stability, which would be a promising candidate for precise dual-parameter sensing application.

10025-3, Session 1

Temperature insensitive measurements of displacement using fiber Bragg grating sensors

Shuang Yang, Anhui Institute of Optics and Fine Mechanics (China) and Univ. of Science and Technology of China (China); Jun Li, Anhui Institute of Optics and Fine Mechanics (China); Shengming Xu, Miao Sun, Anhui Institute of Optics and Fine Mechanics (China) and Univ. of Science and Technology of China (China); Yuquan Tang, Anhui Institute of Optics and Fine Mechanics (China); Gao Gang, Fengzhong Dong, Anhui Institute of Optics and Fine Mechanics (China) and Univ. of Science and Technology of China (China)

Optical fiber Bragg grating (FBG) displacement sensors play an important role in various areas due to the high sensitivity to displacement. However, it becomes a serious problem of FBG cross-sensitivity of temperature and displacement in applications with FBG displacement sensing. This paper presents a method of temperature insensitive measurement of displacement via using an appropriate layout of the sensor. A displacement sensor is constructed with two FBGs mounted on the opposite surface of a cantilever beam. The wavelengths of the FBGs shift with a horizontal direction displacement acting on the cantilever beam. Displacement measurement can be achieved by demodulating the wavelengths difference of the two FBGs. In this case, the difference of the two FBGs' wavelengths can be taken in order to compensate for the temperature effects. Four cantilever beams with different shapes are designed and the FBG strain distribution is quite different from each other. The deformation and strain distribution of cantilever beams are simulated by using finite element analysis, which is used to optimize the layout of the FBG displacement sensor. Experimental results show that an obvious increase in the sensitivity of this change on the displacement is obtained while temperature dependence greatly reduced. A change in the wavelength can be found with the increase of displacement from 0 to 10mm for a cantilever beam. The physical size of the FBG displacement sensor head can be adjusted to meet the need of different applications, such as structure health monitoring, smart material sensing, etc.

10025-4, Session 1

Sensing behavior of smart CFRP embedded with FBG and its application in stay cables

Feng Li, Xu Sun, Weigang Zhao, Shijiazhuang Tiedao Univ. (China); Feng Shen, Nanjing Fenghui Composite Co., Ltd. (China)

A smart CFRP bar embedded with FBGs was developed through an online manufacturing process. Sensing characteristics of the smart CFRP bar was investigated under static and fatigue loading. A sensitivity coefficient of 1.19 pm/?? and a limiting strain of about 8000 ?? were obtained. And the smart bar has remained a good sensing behavior after 2 million cycles. Then,

an application of the smart bar was carried out in the cable force monitoring. Super tension test and field test were carried out on the smart stay cable. The results show that the smart cable can represent the overall stress and successfully track its changes.

10025-5, Session 1

Optical fiber refractometer based on tapered tilted-fiber Bragg grating

Tao Wang, Tiegen Liu, Kun Liu, Junfeng Jiang, Zhe Yu, Meng Xue, Tianjin Univ. (China)

Tilted fiber Bragg gratings (TFBGs) have been demonstrated to be accurate refractometers as they couple light from the fiber core to the cladding and TFBGs have been used in many field, such as refractive detection, TFBG-SPR sensor and temperature detection. In our experiment, a tapered TFBG is manufactured by tapering the grating section of TFBG through a hydrogen-oxygen flame brushing technique. The character of the tapered TFBG was studied. The result shows that the tapered TFBG maintains the similar feature as the original TFBG, they both have the cladding modes and core mode. The refractive sensitivity of the tapered TFBG and the original there is only a slight difference in the range of 1-1.4027. However, after tapered, not only the Bragg wavelength of the TFBG shifts but also the full width half-maximum (FWHM) of the core mode and cladding modes change. The FWHM of the core mode of the tapered TFBG is 265pm and the FWHM of the core mode of the original TFBG is 120pm. The FWHM of the core mode of the tapered TFBG is more than twice than the FWHM of the core mode of the original TFBG. Thus we can use the low resolution spectrum analyzer in the tapered TFBG refractive sensing system to get the similar refractive sensitivity as in the TFBG refractive sensing system with high resolution spectrum analyzer. So the whole cost of the sensing system falls without sacrificing the feature of the system.

10025-6, Session 2

Interrelation of the effects caused by the rotation of the whispering gallery modes resonator *(Invited Paper)*

Anna D. Dmitrieva, Yurii V. Filatov, Egor V. Shalymov, Vladimir Y Venediktov, Saint Petersburg Electrotechnical Univ. “LETI” (Russian Federation)

Whispering gallery modes are specific eigenmodes of a field (sound, electromagnetic etc) inside an axially symmetrical resonators with smooth edges. ?ptical whispering gallery modes resonators are characterized by unique properties: ultrahigh quality factor, small amount of the modes and small size. It allows to use them in compact high-precision measuring devices. In particular these resonators can be used in the composition of gyros. For today all researches, devoted to the application of the whispering gallery modes resonators in gyros, deals only with one of induced by the rotation effects (Sagnac effect or the influence of centrifugal forces on the resonator size). In this work we study the interrelation of the effects caused by the rotation of the whispering gallery modes resonator. Also in work is presented the way of angular speed measurement of due to simultaneous use of Sagnac effect and the influence of centrifugal forces on the resonator size.

10025-7, Session 2

Temperature effect on refractive index sensing performance of a U-shape tapered plastic optical fiber

Chuanxin Teng, Jilin Univ. (China); Ning Jing, North University of China (China); Fangda Yu, Jilin Univ (China); Jie Zheng, Jilin Univ. (China)

A refractive index (RI) sensing probe based on a U-shape tapered plastic optical fiber (POF) is proposed since the sensitivity could be enhanced by cascading of bend and tapered POF geometry. Recently, RI sensors based on POFs attract much attention of researchers due to the POFs with some unique advantages compared with glass optical fibers (GOFs), but the thermo-optic coefficient of POFs is an order of magnitude higher than the one of GOFs. Therefore, the temperature influence to the RI sensing probe was investigated experimentally in this paper. It is found that the changes in light propagation loss in the probe induced by temperature are of the same order of magnitude as those induced by measured RI changes, so there is clearly a temperature dependence issue. The temperature dependence loss and temperature dependence RI deviation of the sensing probe were measured (at the wavelength of 635 nm) in temperature of 10-60 °C over an RI range of 1.33-1.41. By extracting pure temperature dependence of the sensing probe alone, the influence of temperature to the sensor was characterized.

10025-8, Session 2

Thermal sensing performance of the nested fiber ring resonator

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We compare the temperature sensitivity between the nested fiber ring resonator (NFRR) and the nested fiber ring resonator coupled Mach-Zehnder interferometer (NFRRCMZI) under same intensity scheme. Utilizing the transfer matrix theory, their thermal performances were analyzed. Theoretical results indicate that temperature sensitivity of the NFRR is almost twelve times higher than that in NFRRCMZI with same parameters, hence the complex MZI system can be avoided and the whole sensing system will be more compatible.

Taking the U-shape feedback waveguide instead of the whole resonator as the sensing element in NFRR structure, we can acquire arbitrary sensitivity by setting the feedback waveguide length arbitrarily. It is more feasible in application for its simple construction and integration. For R=5 the sensitivity and the detection limit can achieve 23.19 /K and 0.000125 K, respectively. The longer the feedback waveguide length, the higher sensitivity and the narrower detection range we can obtain. And the detection range is decided by the length of the feedback waveguide: the detection sensitivity and detection range go through a period when the feedback waveguide phase shift by two pi. In practical applications, we can balance between the sensitivity and the detection range and set the structure parameters according to the requirements.

One of the advantages for the NFRR structure based sensor is that its transmission spectrum would not shift horizontally under certain shape. Therefore, the sensitivity of this sensor is not limited by its optical quality factor. In this thesis, the transmission spectrum of the sensor under different temperatures are displayed to illustrate this unique property.

10025-10, Session 2

The dispersion and spectrum output characteristics in series-coupled double-ring resonator

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In this paper, we theoretically investigate the series-coupled fiber double-ring resonator which have different perimeters, when the double-ring resonator cannot be completely in resonance state, the output characteristics and dispersion characteristics of spectrum and its manifestations. we observe that light exhibits different spectral output characteristics in the double-ring resonator, when the two rings' length ratio?=1,1.1,1.5,2. Among them, ?=2 is particularly representative. When ?=2, there exist two kinds of fixed pattern during the 2ϖ period. When the value of ?_2⁄ϖ is even, the double-ring resonator produce traditional symmetrical division resonance mode because they are in complete resonance state (?_(i,i=1,2) is single-pass phase shift). When the value of ?_2⁄ϖ is odd, ?_1 is in complete resonance state while ?_2 is in anti-resonance state, and it will generates periodic strong absorption narrowband dip line shape with a larger group refractive index at the same time. When the second ring has the same parameters, the group refractive index of the double-ring resonator whose length ratio is 2 which is two or three orders higher than the single ring resonator. These results indicate that we could improve the sensitivity of the double-ring resonator because sensitivity is directly related to the group refractive. The double-ring provides a nice platform and experimental architecture for achieving high sensitivity of the spectrometer. At the same time, it provides a possibility application in interference and optical sensing fields for the high sensitivity of the spectrometer.

10025-11, Session 3

A gain compensation method for the long-range distributed fiber disturbance sensor *(Invited Paper)*

Chunyu Ma, Tiegen Liu, Kun Liu, Junfeng Jiang, Liang Pan, Miao Tian, Zhichen Li, Tianjin Univ. (China)

We proposed a gain compensation method to overcome the amplitude fading induced by the gain-bandwidth product (GBP) of the detector, which will seriously deteriorate the positioning accuracy of the distributed disturbance sensor at a long sensing range. To guarantee the performance of this method, we used the time-frequency distribution of the interference signal to distinguish the normal signal and the one need to compensate. A positioning measurement experiment using an asymmetric dual Mach-Zehnder interferometric sensor (ADMZI) was carried out to verify the effectiveness of the proposed method. The experiment result showed that the sensing range can reach 120km, which was improved by over 40% compared to the traditional positioning method without gain compensation.

10025-12, Session 3

Seismic Wave Detection System Based on Fully Distributed Acoustic Sensing

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Distributed optical fiber vibration and acoustic sensors have proven to be an efficient mean for interrogating a large number of points along a single optical fiber, a capability which has attracted substantial interest from industries involved in oil, gas and structural health monitoring.

This paper presents a seismic wave detection system based on fully distributed acoustic sensing (DAS). The architecture and principle of the system are introduced. Combined with ?-OTDR and PGC demodulation technology, the system can detect and acquire seismic wave in real time. The system has a 3.05dB flatness of frequency response from 5Hz to 1kHz, which with sampling interval of each channel of one meter on total sensing distance up to 10 km.

Experiments are carried out to demonstrate the performance of DAS system. Compared experiments with geophone are carried out in laboratory, results show two waveforms coincide consistently, and the correlation coefficient could be larger than 0.98. Other compared experiments are carried out in the fields, results indicate that DAS system has a consistent time domain and frequency domain response, and a clearer trail of seismic wave signal as well as a higher signal to noise ratio.

The system we proposed can not only provide remarkable results, but also reduce the complexity of the practical applications. Also, DAS has many characteristics, like light weight, small volume, low cost, high temperature and high pressure resistance, anti-electromagnetic interference. This system uses an optical fiber to be a sensing unit and exposes significant advantages in multi-channel information acquisition and weak signal detection. Due to its wideband frequency response and low manufacturing cost, the system is expected to be the next generation of oil and gas exploration equipment.

10025-13, Session 3

A study on frequency-shifted pulse light stability control for DP-MZM in coherent-OTDR

Wenjie Chen, Junfeng Jiang, Tiegen Liu, Kun Liu, Xuezhi Zhang, Zhe Ma, Zhe Yu, Tianjin Univ. (China)

In digital coherent-OTDR disturbance sensing system, a dual-parallel Mach-Zehnder modulator (DP-MZM) is employed to modulate the signal light and to generate frequency-shifted pulse light. However, the environment temperature strongly influence the stability of the DP-MZM. To stabilize the quality of the frequency-shifted pulse light, we proposed a bias control method to keep the modulator at the optimum bias. This bias control method search for the optimum bias by changing three bias voltages at the same time based on chaotic particle swarm optimization algorithm. The experimental results show obvious effect on locating the optimum bias voltages for the DP-MZM.

10025-14, Session 3

Spatial resolution enhanced distributed disturbance fiber sensing system employing modified TDE algorithm

Liang Pan, Tiegen Liu, Kun Liu, Junfeng Jiang, Chunyu Ma, Tianjin Univ. (China)

A novel method to enhance the spatial resolution of distributed disturbance fiber sensor is proposed in this paper. The proposed scheme combines a high speed data acquisition system and a

modified time delay estimate algorithm. The sensor performance is significantly improved by eliminating the impact of fluctuation of the interference signal generated by the environment disturbance. Theoretical analysis shows that with the proposed spatial resolution enhanced method, the disturbance sensing system is more suitable for various environments and provides low uncertainty in long term operation with meter-scale spatial resolution. Compared with the traditional time delay estimate method in distributed disturbance sensing system based on the criterion of spatial resolution, the positioning error of the sensor using our proposed method has been reduced at least an order of magnitude.

10025-15, Session 3

Study on error budget of large deployable optical remote sensor

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High resolution earth observation missions are based on large aperture optical remote sensor (LDORS). Given that size, weight and launch ability constraints, as well as cost consideration, the traditional monolithic aperture optical system cannot satisfy the requirements. The deployable optics is an effective way of realizing the large aperture remote sensing. The key point of deployable optics is the primary mirror?The large primary mirror is segmented and folded when is launched and stitched the total common phase mirror after the entry into orbit. With the adjustment of the adaptive optical system, the whole optics can achieve high imaging quality. Differently from traditional optical remote sensor, the imaging quality of the deployable optical sensors may be influenced by many kinds of error sources, including the wavefront error (WFE) of the optical remote sensor system, the error from vibration of the satellite platforms, etc. The WFE of the optical remote sensor system include the engineering from the fabrication processing, the position from deploying of segmented mirrors in orbit. In the process of feasibility demonstration, the total WFE error budget of large deployable optics plays a vital role in the general design of the remote sensor. According to results of calculation and iteration, in order to ensure the optical performance of the remote sensor in orbit, the WFE of the remote sensor is required to achieve ?/8rms?@ ?=632.8nm?, and the WFE of the optical system is required to achieve ?/10rms. In this paper, the error from optical system design, which based the mission realization of optical fabrication and optical alignment.

10025-16, Session 3

Doppler Laser Radar for Range and Speed Measurement of Road Targets

Yanfang Lin, Xuesong Mao, Jianchao Fang, Tao Zhang, Wuhan Univ. of Science and Technology (China)

Laser radars measure target range and speed by two methods: pulsed method or continuous wave (CW) method. CW method modulates frequency of transmitting signal in the form of triangular wave and gain range and speed by measuring frequency difference between echo signal and local signal. The method has an advantage of high precision due to the wideband of transmitting signal. However, the method is not adopted in vehicle laser radar for road target sensing due to many factors such as low transmitting peak power, multipath interference, etc. On the other hand, pulsed laser radars transmit short pulses with large peak power, thus meet the requirement of sensing in complex environments such as roads. It measures target range by light flight time, while gain target speed by averaging range differentiation. Although the pulsed method succeeds in road target sensing, it has large errors in the speed if time window for averaging is short. In this paper, we propose a pseudo random noise code modulated laser radar, which measures range and speed by correlation function and Doppler frequency shift, respectively, to improve measurement precision and real time property. For obtaining target range, we use the traditional method of locating correlation peak of echo signals and local modulating codes. In search of Doppler frequency, we propose a novel method for solving spectrum of non-uniformly sampled data. We verify the proposed method by theoretical analysis and numerical simulations. The results show that our proposed method works well for obtaining range and speed with high precision.

10025-17, Session 4

Optical sensors interrogated by means of spectral interferometry: noise sources and approaches for resolution improvement

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One of the key factors, determining the resolution and dynamic range of an optical sensor, is interrogation approach. Among the others, spectral interferometry (sometimes referred to as white-light or low coherence interferometry), is very attractive due to ability to provide measurements of absolute OPD value. However, in practical situation, the measurement result contains some erroneous component, which value is governed by specific characteristics of the interrogation unit.

In the presentation, the main error sources, stipulated by noises and fluctuations in the interrogation hardware, will be considered. It is shown that one of the most crucial error sources is wavelength scale jitter of the optical spectrometer, incorporated in the interrogator. The main attention will be paid to approaches, enabling one to eliminate the influence of interrogator fluctuations on the measurement results.

The first approach is suitable for use with multi-channel interrogation devices, utilizing a tunable laser source, divided into several (2-4) channels and single photodetector for each channel as a receiver. If sensing and reference interferometers are switched to different optical channels of the interrogation device, the readings of a reference interferometer can be used for compensating the errors in the readings of sensing interferometer.

Another approach is suitable for use with all kinds of interrogation hardware and requires a single interferometer. However, light diffraction and multibeam propagation must take place in the interferometer, so it must be an extrinsic Fabry-Perot or similar. In order to estimate and compensate the wavelength scale jitter, the information about diffraction-induced phase shift is used.

10025-18, Session 4

Fundamental theory and algorithm based on spatial light modulator

Hua Liu, Science and Technology on Electro-Optic Control Lab. (China)

The principle approach, modeling, and error analysis are analyzed, and the system configuration based on SLM is advanced in algorithm analysis. For to improve the resolution of the imaging system, and achieve the theoretical limit, we introduced that the core methodology, which is that in the deep understanding and research of the photoelectric information

control, the basic theory of the spatial light modulator and the algorithm based on space-time adaptive system is discussed deeply which used to the core of the photoelectric system configuration by which key components applied to solve the control function. This paper discusses the hardware system. Usually, an SLM modulates the intensity of the light beam. However, it is also possible to produce devices that modulate the phase of the beam or both the intensity and the phase simultaneously. Besides, the discuss includes the control on the SLM for spatial information of the amplitude, phase, frequency, polarization, and the intensity of energy research. A typical model is used to illustrate the feasibility, and the criteria is developed. The technology principle of super resolution restructure from the point of view on theory and engineering. Three kinds of restructure technologies, that prototype, micro scanning and sub pixel are described, and how to decrease their shortcomings are discussed in detail. Furthermore, to improve the band width by reconstruction without the spectral alias in super resolution technologies, a new coding technology combining a optical encoding and the sub pixel is proposed. With the global method, simulation results show that the system can meet the application requirements in MTF, REA, RMS and other related criteria.

10025-19, Session 4

Multi-sensor data fusion and estimation with poor information based on bootstrap-fuzzy model

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Multi-sensor data fusion and estimation with poor information is a common problem in the field of stress measurement. Small and distribution unknown data sample obtained from multi-sensor makes the data fusion and estimation much difficult. To solve this problem, a novel bootstrap-fuzzy model is developed. This model is different from the statistical methods and only needs a little data. At first, the limited stress multi-sensor measurement data is expanded by the bootstrap sampling. Secondly, the data fusion sequence is constructed by the bootstrap distribution. Finally the true value and the interval of the stress multi-sensor measurement data are estimated by the fuzzy subordinate functions.

The method involves two parts: one is the bootstrap method for multi-sensor data fusion which expands the data sample and resamples the very few original sensor measurement data greatly; the other is the fuzzy subordinate functions which obtain the estimated true value and interval of the sensor data successfully. The experimental results show that the full conditions of the measurement parameters can be attained totally through bootstrap-fuzzy model. So the failing and false data predictions can be avoided. Referring to the stress measurement system, bootstrap-fuzzy model can be employed to increase the measurement confidence, reduce the ambiguity, improve the reliability, and boost the accuracy. Moreover, bootstrap-fuzzy model can be considered as complementary to the existing data fusion theory in use. The accuracy of the estimated interval can reach 85%. Therefore, the effect of the proposed bootstrap-fuzzy model is validated.

10025-20, Session 4

Tomographic reconstruction using 4 views and tunable diode laser

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Tomographic Reconstruction Using 4 Views And Tunable Diode Laser: Called the 'Reduced Back Projection' technique(or RBP), this new method is an improvement on existing tomographic reconstruction techniques in the field of laser diagnostics in a combustor exhaust. The highlight of this technique is the use of only FOUR views to create a planar reconstruction from path averaged data which is obtained from water absorption spectroscopy in the IR region near 1377nm. Water sensitive wavelengths are generated by using a Tunable Diode laser working in the IR region. For the purpose of this paper, work is done on a plane in the exhaust of a burner perpendicular to the flame direction. The geometry of the burner decides the distribution of water molecules in the interrogation plane. This technique is based on the back projection method but has been extensively modified and improved to work with just four views instead of the hundred or so views used in medical tomography. Simulations have been run to check the working of the new technique, and compared with other current methods in tomography (SART, back projection, etc.). Preliminary experimentation over a simple two burner geometry has been performed. In both simulation and experiment, the RBP technique has yielded better results than existing methods by virtue of the new method being able to capture features where the other methods have failed. Thus, RBP can be used in situations where there are constraints in resources, time and space.

10025-9, Session Post

Changes of shape of the whispering gallery modes resonators due to their movement in inertial space

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The whispering gallery modes resonators are axially symmetrical resonators with smooth edges, supporting the existence of the whispering gallery modes. In recent years, optical whispering gallery modes resonators are attracting ever-growing interest of the scientific community. It is connected with their unique properties: ultrahigh quality factor, small amount of the modes and small size. For today various types of such resonators were developed, namely the ball-shaped, tor-shaped, bottle-shaped, disk-shaped etc. The movement of whispering gallery modes resonators in inertial space causes changes of their shape. Optical methods allow to register these changes with high precision. It can be used for measurement of angular velocities and linear accelerations in inertial orientation and navigation systems. In this work we performed a multiphysical simulation in OOFELIE::Multiphysics software to investigate changes of shape of the whispering gallery modes resonators due to their movement in inertial space.

10025-38, Session Post

A new vibration monitoring system based on fiber-optic micro-cantilever

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This paper mainly introduces a new vibration monitoring based on fiber optic micro-cantilever. Such sensor is typically constructed directly onto the endface of fiber and consists of a cleaved facet which is sensitive to vibration.

Compared with the traditional Fabry-Perot interferometer, for example, the sensor consists of an optical fiber and sensitive diaphragm, or the sensor constructed on two fiber endfaces. Optical fiber cantilever based structure is capable of measuring wider range of vibration signal with higher sensitivity.

Fiber endface and micro-cantilever is composed of Fabry-Perot cavity as a sensing section of the sensor, the external signal is transmitted to the sensor, which causes the vibration of the micro-cantilever, which changes the length of the Farby-Perot cavity. The information of the external vibration signal can be obtained by using the 3 wavelength interrogation algorithm.

The mechanical vibration characteristics of the micro-cantilever with different materials and the influence of the reflectivity change caused by the coating on the surface of the micro-cantilever are simulated and analyzed. The resonance frequency range of the cantilever beam varies with different material, therefore, the detected frequency range of the system is limited. The demodulation precision of the system can be improved by coating the cantilever surface with different material. Based on the simulation results, the appropriate cantilever beam structure and coating materials are selected to build optical fiber micro-cantilever vibration detection system. A relatively flat frequency response is achieved from 1 kHz to 20 kHz. Compared with the traditional microphone, the sensitivity of the proposed structure can be improved through the selection of suitable materials.

10025-39, Session Post

The research of autonomous obstacle avoidance of mobile robot based on multi-sensor integration

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The object of this study is the bionic quadruped mobile robot. The study has proposed a system design plan for mobile robot obstacle avoidance with the binocular stereo visual sensor and the self-control 3D Lidar integrated with modified ant colony optimization path planning to realize the reconstruction of the environmental map. Because the working condition of a mobile robot is complex, the result of the 3D reconstruction with a single binocular sensor is undesirable when feature points are few and the light condition is poor. A Lidar sensor can detect the information of obstacles well because it is an active probe, so it will not be disturbed by external environment factors easily. Therefore, this system integrates the stereo vision sensor blumblebee2 and the Lidar sensor together to detect the cloud information of 3D points of environmental obstacles. What's more, this study has designed a fast 3D scanning Lidar system which consists of a 2D Lidar, a pitching mechanical device driven by a stepper motor and its relevant control units. This design will satisfy the reconstruction result with low cost and high precision. This paper proposes the sensor information fusion technology to rebuild the environment map.

Firstly, according to the Lidar data and visual data on obstacle detection respectively, and then consider two methods respectively to detect the distribution of obstacles. Finally fusing the data to get the more complete, more accurate distribution of obstacles in the scene. Then the thesis introduces ant colony algorithm. It has analyzed advantages and disadvantages of the ant colony optimization and its formation cause deeply, and then improved the system with the help of the ant colony optimization to increase the rate of convergence and precision of the algorithm in robot path planning. Such improvements and integrations overcome the shortcomings of the ant colony optimization like involving into the local optimal solution easily, slow search speed and poor search results. This experiment deals with images and programs the motor drive under the compiling environment of Matlab and Visual Studio and establishes the visual 2.5D grid map. Finally it plans a global path for the mobile robot according to the ant colony algorithm. The feasibility and effectiveness of the system are confirmed by ROS and simulation platform of Linux.

10025-40, Session Post

Thin-core fiber modal interferometer with polyelectrolyte membrane for dissolved ammonia sensing

Xinyue Huang, Xueming Li, Yu Li, Huifei Chen, Jianchun Yang, Chongqing Univ. (China)

With the unhealthy development of the industry and agriculture, the pollutant emissions were increased dramatically, which has caused serious pollution to the aquatic environment. Ammonia nitrogen is an important indicator among water environmental monitoring parameters. Thus, a simple and portable sensor is desirable to achieve sensitive detection of ammonia nitrogen. The construction of poly(acrylic acid) (PAA) and poly(allyamine hydrochloride) (PAH) films on the side surface of the thin-core fiber modal interferometer (TCFMI) using the layer-by-layer (LbL) self-assembly technique for dissolved ammonia detection is presented and investigated in this paper. The sensor is made by inserting a small section of thin-core fiber to the standard single mode fiber (SMF). A beam propagation method (BPM) is employed for numerical simulation and design of the proposed TCFMI. Based on the simulation results, a TCFMI with a length of 2 cm of thin-core fiber is fabricated and experimentally studied. The fabricated sensing nanocoating is characterized by surface profiler, and scanning electron microscopy (SEM). The sensing capability of TCFMI with PAH/PAA film is demonstrated by optical spectrum analyzer (OSA). PAA could act as a receptor for binding of amine compounds, which would induce changes in the film properties, thus influencing the transmission spectrum of the TCFMI. Experimental results show that the characteristic wavelength shift has an approximately linear relationship with the change of the ammonia concentration. The optimal detection range of this sensor is around 1-250 ppm. The experimental results fit well with the numerical simulation results.

10025-41, Session Post

Design of a micro-uncooled infrared imaging system based on VOx IRFPA

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Compared with the infrared focal plane array (IRFPA) based on amorphous silicon (?-si), IRFPA based on vanadium oxide (VOX) has the advantages of big temperature coefficient of resistance, low noise and so on. Therefore, it is believed that VOX IRFPA has important application in both military and civil field. On the other hand, generally, the infrared imaging system based on VOX IRFPA has the disadvantages of high cost and big size, which limits its application in the field of civil consumption.

In this paper, a design of a micro uncooled infrared imaging system based on VOx IRFPA is proposed, of which a low cost 384?288 VOX IRFPA produced by China North Guangwei

Technology, Inc. is used for photoelectronic conversion, and the parameter configuration and consistency correction are implemented by using a low-cost FPGA (Altera cyclone IV EP4CE55).

In this paper, firstly, the hardware designs of the proposed system is discussed, which includes the system structure, VOX IRFPA module, drive and signal output module and the signal processing module based on FPGA. Secondly, the designs of the configuration program as well as the consistency correction, image enhancement algorithm are also introduced. Finally, experiments were carried out to verify the validity of the developed models and the whole infrared imaging system, the experimental results indicated that our work will help to promote the application of infrared imaging technology in the field of civil consumption, such as security monitoring, temperature monitoring and smart home, etc.

10025-42, Session Post

Medical respiratory monitoring sensor based on optical fiber microbend loss

Yong Zhao, Northeastern Univ. (China)

In this work, a medical respiratory monitoring sensor based on the microbend effect of optical fiber on light transmission is proposed. The microbend effect of multimode optical fiber is analyzed theoretically using optical theory. A respiratory signal modulator with a “sandwich” microbender structure is designed enabling the noninvasive real-time monitoring. In vitro testing showed that the proposed sensor has excellent following characteristics and can automatically discern respiratory condition, the signal-to-noise ratio can be better than 28dB.

In this paper, we proposed a medical respiratory monitoring sensor based on the microbending effect of optical fiber. The model and presumption are proved feasible in principle. The sawtooth structure makes the respiratory signal modulator easy for fabrication and low cost, the respiratory signal modulator’s design parameter is optimized by deduction and simulation. The trails conducted on human showed our sensor was able to detect breathing rate efficiently. This study has achieved certain result by observing the breathing waveforms in different subjects at different frequency, and at the end the difference between the monitored respiratory rate and the frequency is less than 1 time per minute. It has good accuracy with multiple measurements.

However, there still are some deficiencies needing to be improved. For the noise, with further improvement to the device, the signal-to-noise ratio can be up to 28dB. And texture of the used materials, location and manner of the measuring person will maybe have influence on the measurement results.

10025-43, Session Post

Development of fiber optical temperature sensor based on fluorescence lifetime

Yong Zhao, Northeastern Univ. (China)

In order to realize the on-line monitoring of high voltage switchgear’s contact temperature, this paper puts forward a kind of optical fiber temperature sensor based on fluorescence lifetime. It can be applied to measurement in strong electromagnetic, strong corrosion and other harsh environment by using the approximate linear relationship between temperature and fluorescence lifetime of rare earth fluorescent material. A small volume, long service life, strong anti-jamming capability of fluorescence temperature sensor was designed by matching rare earth fluorescent material with longer fluorescent lifetime with tee optical coupler. The experimental results show that this method has a high measuring precision within the scope of 0-90?, and in the case of good calibration, temperature measurement channel can meet the requirements of measurement error (±0.1 ?).

10025-44, Session Post

Research on high-temperature sensing characteristics based on modular interference of single-mode multimode single-mode fiber

Zhaozhuang Peng, Li Wang, Beijing Univ. of Technology (China)

Application of high temperature fiber sensing system is very extensive. It can be mainly used in high temperature test aerospace, such as, materials, chemicals, and energy. In recent years, various on-line optical fiber interferometric sensors based on modular interference of single-mode-multimode-single-mode(SMS) fiber have been largely explored in high temperature fiber sensor. In this paper we use the special fiber of a polyimide coating, its sensor head is composed of a section of multimode fiber spliced in the middle of Single-mode fiber. When the light is launched into the multimode fiber(MMF) through the lead-in single-mode fiber(SMF), the core mode and cladding modes are excited and propagate in the MMF respectively. Then, at the MMF-SMF spliced point, the excited cladding modes coupled back into the core of lead-out SMF interfere with SMF core mode. And the wavelength of the interference dip would shift differently with the variation of the temperature. By this mean, we can achieve the measurement of temperature. In theory, we can obtain multimode optical fiber transmission of light waves through simulation. The experimental results also show that the fiber sensor based on SMS structure has a highly temperature sensitivity. With the temperature increasing, the interference dip slightly shifts toward longer wavelength and the temperature sensitivity coefficient is 0.0205nm/?. With high sensitivity, simple structure, immunity to electromagnetic interferences and a good linearity of the experimental results, the structure has an excellent application prospect in engineering field.

10025-45, Session Post

Optical fiber sensing parameter measurement using wavelength division multiplexer and FBG

Huanhuan Yan, Beijing Univ. of Technology (China)

In this experiment, the optical parameters of optical fiber sensing measurements with the wavelength division multiplexer (WDM) and Fiber Bragg grating have obtained in temperature-controlled cabinet. The wavelength division multiplexer device not only make different wavelength illuminant input at the same time be possible, but also can achieve multi-channel output based on the feature of WDM. We design and put forward a new method which can realize various parameters measured at the same time, such as temperature and the refractive index or stress measurement. In addition, it can measure the same parameters with different wavelengths of laser at the same time. The contrast analysis results of different wavelengths of illuminant on the same parameter sensitivity and reliability of the measurement will use to provide reference to design the same illuminant with different parameter measurements.

10025-46, Session Post

Hybrid MEFPI/FBG sensor for simultaneous measurement of ultrasound and magnetic field

Yong Zhao, Northeastern Univ. (China)

Simultaneous physical parameters measurement has been the focus of the research works and problem in physics, which is an efficient method of measurement, and has many additional advantages such as small volume, decreasing transmission data, and low cost. In this Paper, A hybrid fiber-optic sensor consisting of a micro extrinsic Fabry-Perot Interferometer (MEFPI) and an etched fiber Bragg grating (FBG) is proposed, which can measure ultrasonic and magnetic field simultaneously. The measurement of magnetic field is realized by the etched FBG, which is sealed in a capillary with ferrofluids. The resonant wavelength of FBG shifts when the magnetic field which is perpendicular to the axis of FBG changed. Simulation prove that the center wavelength of etched FBG shifts to longer wavelength with the increase of ambient refractive index, and it shifts sharply when the ambient refractive index near 1.460, in addition, the FBG with small diameter will be more sensitive to magnetic field, these are also confirmed in experiment. The MEFPI sensor that is prepared through welding a short section of hollow core fiber (HCF) with single-mode fiber (SMF) is effective for ultrasonic-wave detection. The length of FPI cavity can be controlled precisely by a high precision optical fiber cutting platform. The shorter the cavity length has the higher strain sensitivity and the larger free spectral range (FSR), which is advantageous for sensing applications. The experiment shows that the etched FBG has a reversible response on magnetic fields under 21 mT with a high sensitivity, and the measurement results of ultrasonic-wave by the MEFPI sensor agree well with those by the piezoceramic needle hydrophone; moreover, the detections of ultrasonic and magnetic field have little effect on each other, hence it is feasible to measure ultrasonic and magnetic field simultaneously based on hybrid MEFPI/FBG sensor.

10025-47, Session Post

Modeling of a long-period fiber-optic grating-assisted surface plasmon resonance refractive index sensor

Wenhua Wang, Weina Wu, Jiang Huang, Xiuyun Tian, Xianxiang Fei, Guangdong Ocean Univ. (China)

A fiber-optic refractive index sensor assisted surface Plasmon resonance of metal dielectric layer around a long-period grating with hollow fiber core has been proposed and comprehensively analyzed. Its operation principle is based on the efficient energy transfer between the fiber waveguide mode and the co-directional surface Plasmon waves excited with a long-period fiber-optic grating properly designed by the light refracted through the interface between the waveguide area and the metal dielectric film. The long-period fiber-optic grating is fabricated on a waveguide area of a specially designed fiber-optic with hollow fiber core. Simulations have been carried out in coupled mode theory of fiber-optic gratings in the wavelength ranges from 1500 to 1600nm, and for sensing characteristics of refractive index. Unlike a previous proposed short-period fiber Bragg grating fabricated on this kind of fiber, the refractive index sensitivity of the long-period fiber-optic grating is 15 times higher than that of the fiber Bragg grating. The proposed long-period fiber-optic refractive index sensor assisted surface Plasmon resonance is compact, light weight, and highly sensitive with a large sensing range.

10025-48, Session Post

Porous silicon-based two-dimensional photonic crystal for biochemical sensing applications

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In recent years, various novel porous silicon-based photonic devices have been exploited for the detection of chemical and biological species, including grating waveguide, resonant photonic structures, and diffraction gratings. We have designed and characterized a two dimensional photonic crystal based on porous silicon with a defect embedded in its middle as an optical sensor for sensing of various chemical and biological species. The two-dimensional photonic srystal is composed of square-lattice dielectric cylinders made of porous silicon.Simulations are carried out by changing the refractive index, which is due to the binding of biological molecules on the porous silicon pore can increase the refractive index of porous silicon. The change of the refractive index of the porous silicon caused by the entry of the biomolecule, which caused the change of the field strength of two dimensional photonic crystal.The theoretical reflectances of PSi-based two dimensional photonic crystal throughout the paper were calculated using the commercial codes Comsol 5.0.This novel porous silicon based two dimensional photonic crystal opens the door for design all-silicon sensor for sensing of various chemical and biological species and can also be good applied in narrow bandpass filter.

10025-49, Session Post

Temperature robustness of reflecting multichannel all-fiber current sensor based on time-division multiplexing

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ALL-FIBER current sensors (AFCSs) have attracted considerable attention for more than 20 years because of their simple configurations, good optical integration, and outstanding flexibility compared with other optical current sensors such as bulk-glass current sensors or space coupling optical current sensors. However, some obstacles hinder the application of the AFCS. Among them, their temperature sensitivity are a crucial weakness. High sensitivity to temperature will disturb current measurement, reduce the current sensitivity, and make it difficult to apply the AFCS in actual environments.

In 2014, we reported temperature and vibration robustness of reflecting all-fiber current sensor using common single-node fiber. A theoretical analysis shows that the temperature sensitivity of the AFCS based on a fiber mirror and ortho-conjugate retroreflector [(OCR), 90°Faraday rotating mirror] are almost entirely independent of the birefringence condition of the fiber.

In order to improve the sensor efficiency and reduce cost, we proposed a temperature robustness of reflecting multichannel all-fiber current sensor based on the principle of time-division multiplexing. The multichannel all-fiber current sensor used a sensor to synchronously monitor the currents at many different points. The multichannel fiber sensor signals were then multiplexed using fiber-delay coils. Time-division multiplexing can be conveniently implemented to increase the amount of information gained about the sensor. Since a multichannel fiber current sensor needs only a pulse laser, detector, and data-processing system, the cost can be kept low relative to more complex sensors.

10025-50, Session Post

Demonstration of distributed fiber-optic temperature sensing with PM fiber using polarization crosstalk analysis technique

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Polarization crosstalk is a phenomenon that the powers of two orthogonal polarization modes propagating in a polarization maintaining (PM) fiber couple into each other. Because there is certain mathematical relationship between the polarization crosstalk signals and external perturbations such as stress and temperature variations, stress and temperature sensing in PM fiber can be simultaneously achieved by measuring the strengths and locations of polarization crosstalk signals. In this paper, we report what we believe the first distributed temperature sensing demonstration using polarization crosstalk analysis in PM fibers. Our experimental setup was composed of a polarization crosstalk analyzer (PXA), a length of PM fiber and a temperature control chamber. The PXA can obtain the locations and values of temperature variations along the PM fiber by measuring the spacing changes between two crosstalk peaks caused by temperature induced birefringence change in PM fiber. The experimental results show that the temperature sensing coefficient is approximately ?0.76 ?m/(?•m), which means that the spacing between two crosstalk peaks induced at two locations changes by 0.76 ?m when the temperature changes by 1 ? over a fiber length of 1 meter. Sub degree temperature resolution with center meter spatial resolution with over 5 km range is expected with this method. Furthermore, the proposed distributed sensing system can simultaneously measure the temperature and stress/strain with high precision. As a new type of distributed fiber temperature sensing technique, we anticipate that our method will find broad applications in the near future.

10025-51, Session Post

Surface plasmon resonance sensor based on grapefruit-type photonic crystal fiber with silver nano-film

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In this article, surface plasmon resonance sensors based on grapefruit-type photonic crystal fiber (PCF)with different silver nano-film structure have been analyzed and compared though the finite element method (FEM) by using COMSOL Multiphysics software. The regularity of the resonant wavelength changing with refractive index of the sample has been numerically simulated. The surface plasmon resonance (SPR) sensing properties have been numerically simulated in both areas of resonant wavelength and intensity detection. Numerical results show that excellent sensing characteristics of the silver nanowires filling structure can be achieved as the thickness of the nanofilm is 30nm, with both spectral and intensity sensitivity in the range of 6?10-5~7?10-5RIU.

10025-52, Session Post

Photonic crystal fiber sensor based on surface-enhanced Raman scattering for explosives detection

Chuanyi Tao, Rong Chen, Chongqing Univ. of Technology (China); Jingke Li, Chongqing Medical and Pharmaceutical College (China)

The detection of explosives and their residues is of great importance in antiterrorism, public health, and homeland security applications. One of the most common constituents in these explosives is 2,4,6-trinitrotoluene (TNT) and its by-product, 2,4-dinitrotoluene (DNT). The vapor pressures of most explosive compounds are extremely low and attenuation of the available vapor is often great due to diffusion in the environment, making direct vapor detection difficult. In this paper, we report fast and sensitive detection of DNT and TNT vapors using gold nanoparticles (Au-NPs) as the SERS substrate. The Au-NPs are formed a monolayer on the air channels in a photonic crystal fiber (PCF) through polymer-mediated self-assembly. The SERS substrate such prepared has high SERS enhancement, high affinity towards explosive vapor, and rapid response to the explosive adsorption/desorption. The PCF SERS probes can achieve higher sensitivity than that obtainable by directly focusing the excitation laser light into the sample without using any fiber probes (direct sampling). The higher sensitivity achieved by the PCF SERS probe is shown to be due to the confinement of the excitation light and the Raman scattered light, as well as the analyte, inside the air channels that increased the effective interaction volume. This work will lead to the development of fast and highly sensitive optical fiber SERS devices for explosive molecules identification and monitoring outside the laboratory. The sensor device therefore is capable of field operation.

10025-53, Session Post

Torque transducer based on fiber Bragg grating

Tao Li, Shu Jiang, China Shipbuilding Industry Corp. (China); Jiang Li, No. 704 Institute, China Shipbuilding Industry Corporation (China); Jiejun Lin, Hongli Qi, China Shipbuilding Industry Corp. (China)

In order to obtain the accurate torque measurements in harsh condition, such as marine environment, a torque transducer based on fiber Bragg grating is proposed in this paper. According to its optimized elastomer design and fiber Bragg grating patching tactics, the new proposed torque transducer realizes automatic compensations of temperature and bending moment which avoids influences from environment. The accuracy and stability of the torquetransducer, as well as its underwater performance are tested by loading tests both in air and in underwater environment, which indicate the designed torque transducer is not only able to realize high-accurate and robust measurements, but also can be applied in torque sensing in harsh environment. We believe the proposed design detailed illustrated in this paper provides important reference for studies and applications on torque measurements in marine environment.

10025-54, Session Post

A spherical-structure-based fiber sensor for measuring simultaneous measurement of both ammonia gas concentration and temperature

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A novel fiber sensor for simultaneously measuring both the ammonia gas concentration and temperature is proposed. The sensor is fabricated from two sections of single-mode fiber which are cleaved and then a fusion splicer is used to fabricate the spherical-shape structures at the end facets. The fusion arc is used to soften the glass which naturally assumes a spherical shape due to surface tension. A short section of multimode fiber is then fusion spliced with the two spherical-shaped ends of the single mode fibers so both the core modes and the cladding modes of the multimode fiber are excited to create two kinds of interference dips: One is created by core modes only which is not sensitive to ammonia gas and the other is created by the coupling of the core mode and cladding mode which is sensitive to ammonia gas. Silica sol-gel was prepared and coated on the fiber surface as a sensing layer for detecting ammonia gas concentration. The experiment results show that the two dips have linear wavelength shift responses but with different sensitivities to ammonia gas concentration (5.03e-4 nm/ppm for dip1 and -2.5e-5 nm/ppm for dip2) and temperature (0.0067 nm/ºC for dip1 and 0.0149 nm/ºC for dip2. By constructing a wavelength shifts matrix for the two dips vs. ammonia gas concentration and temperature, both the ammonia gas concentration and temperature can be measured simultaneously.

10025-55, Session Post

A refractive index sensor based on taper Michelson interferometer in multimode fiber

Xinghu Fu, Guangwei Fu, Wa Jin, Weihong Bi, Yanshan Univ. (China)

Normally, the liquid concentration corresponds to different refractive index. By measuring the refractive index of liquid, its concentration can be obtained indirectly. With the wide application of various optical fiber, the optical fiber refractive index sensor has become one of research hotspots. Currently reported fiber refractive index sensors have a lot of kinds, such as refractive index based on fiber Bragg grating, long period fiber grating, the structure of cascaded single-mode and multimode fiber, and so on. Therefore, optical fiber sensor has the very good development prospect in the field of liquid refractive index detection. Especially, tapered fiber have many advantages including high sensitivity, small size and simple structure. Sp it is used to measure the liquid refractive index more extensively. By fused tapering or corrosion technology, the internal structure and transport properties of multimode fiber is changed, a tapered multimode fiber sensor can be obtained. In this paper, a refractive index sensor based on taper Michelson interferometer in multimode fiber is proposed. The Hydrofluoric acid corrosion processing is studied in the preparation of single cone multimode optical fiber sensor and the taper Michelson interferometer is fabricated by changing corrosion time. The relationship between fiber sensor feature and corrosion time is analyzed. For different taper Michelson interferometer in multimode fiber, the refractive index sensing property is presented in experiment. The experimental results show that there is a blue shift phenomenon. Namely, the interference spectrum shift in the direction of short wave with the increase of the refractive index. The refractive index sensitivity can reach 115.8008 nm/RIU. Thereby, it can be used in detecting the refractive index in different areas including the environmental protection, health care and food production.

10025-56, Session Post

Research into multispectral TDI-CCD imaging and fusion technology

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A scanning imaging system based on 6144?96 multi-band five-color TDI-CCD was built, which is featuring Real-time imaging capability with high sensitivity and high dynamic range in multi-spectral bands for the same targe.In this paper, the respective pixel topology for five TDI-CCD was obtained on the basis of their spatial relationship in five bands. Finally, high resolution gray-scale image and color image reconstruction for the scenic target were achieved by multi-Spectral fusion Algorithms.

10025-57, Session Post

Detection of nitrogen dioxide by CW cavity-enhanced spectroscopy

Guo Jie, Yu ZhiWei, Hangzhou Zetian Technology Co., Ltd. (China)

In urban areas, high NO2 concentrations have significant effects on human health, which also lead to photochemical “smog” formation, and the visibility will decrease due to secondary aerosol formation. Therefore, NO2 concentration is one of the important monitoring parameters of air monitoring station. In the paper, an accurate and sensitive system was used to monitor the ambient atmospheric NO2 concentrations. This system utilizes cavity attenuated phase shift spectroscopy(CAPS), a technology related to cavity ring down spectroscopy(CRDS). Advantages of the CAPS system include such as: (1) cheap and easy to control the light source, (2) high accuracy, and (3) low detection limit. This work aims to provide an initial validation of the CAPS NO2 concentrations monitor in laboratory and field environments. The minima (~0.1 ppb) in the Allan plots show the optimum average time(~100s) for optimum detection performance of the CAPS system. Over a 5-day-long period of the ambient atmospheric NO2 concentrations monitoring, a comparison of the CAPS system with an extremely accurate and precise chemiluminescence-based NOx analyzer showed that the CAPS system was able to reliably and quantitatively measure both large and small fluctuations in the ambient nitrogen dioxide concentration. Moreover, the nitrogen dioxide concentrations from the CAPS system are highly correlated(0.9) with the standard NOx analyzer.

10025-58, Session Post

Remote canopy hemispherical image collection system

Xuefen Wan, North China Institute of Science and Technology (China); Bingyu Liu, Northeastern University (China); Yi Yang, Donghua Univ (China); Fang Han, Donghua University (China); Jian Cui, Beijing University of Aeronautics and Astronautics (China)

Leaf area index (LAI) is a crucial variable in agronomic and environmental studies, because of its importance for estimating the amount of radiation intercepted by the canopy and the crop water requirements. The LAI can be achieved by hemispheric images which are obtained below the canopy with high accuracy and effectiveness. But existing hemispheric images canopy-LAI measurement technique is based on digital SLR camera with a fish-eye lens. User needs to collect hemispheric image manually. The SLR camera and fish-eye lens is not suit for long-term canopy-LAI outdoor measurement too. In recent years, with the development of embed and image technology, low cost remote canopy hemispheric image acquisition technology is becoming possible.

In this paper, we present a remote hemispheric canopy image acquisition system with in-field/host configuration. In-field node

based on imbed platform, low cost image sensor and fish eye lens is designed to achieve hemispherical image of plant canopy at distance with low cost. Solar radiation and T/H data are obtained for invalid hemispherical image elimination and node maintenance too. Host computer interacts with in-field node by 3G network. The hemispherical image calibration and super resolution are used to improve image quality in host computer. Result show that the remote canopy image collection system can make low cost remote canopy image acquisition for LAI effectively.

10025-59, Session Post

Concepts for compact mid-IR spectroscopy in photochemistry

Phuong-Ha Cu-Nguyen, Hans Zappe, Univ. of Freiburg (Germany)

Mid-infrared (mid-IR) spectroscopy is among the most widely-applied tools for monitoring chemical reactions in photochemistry. The unique and varied absorption spectra of precursors as well as reaction products serve as distinct “fingerprints” for the molecules in question, such that absorption spectroscopy represents an essential means for analysis of a wide range of photochemical reactions. Most of the relevant spectral features are in the mid-IR range, at wavelengths ranging roughly between 2 and 8 micrometers.

An academically-exciting and industrially-relevant development in photochemistry is the use of micro-reaction chambers: very compact, millimeter-sized cavities with controlled flow conditions in which reactants combine to yield the desired products, typically under adverse pressure and temperature conditions. There is an explicit need for on-line, in-situ but non-invasive monitoring of the chemical constituents in the chamber, a measurement for which mid-IR spectroscopy is again ideally suited. However, classical mid-IR spectrometers, most popularly Fourier Transform (FTIR) spectrometers are bulky, complex and expensive, making them unsuitable as miniaturized monitoring systems.

We present here new concepts for ultra-miniaturized mid-IR spectroscopy using passive optical components which can be directly integrated with micro-reaction chambers thus enabling spectrally as well as spatially-resolved monitoring of chemical species. The spectrometer is based on micro-machined Fabry-Perot resonator filters realized using pairs of Bragg mirrors and a precisely defined high-finesse resonant cavity, all fabricated using silicon-based materials. A spatial variation of the cavity thickness leads to discretized transmission spectra with high resolution. The small size of the spectrometer, coupled with its realization using highly-parallel microfabrication technologies, allows realization of laterally-distributed spectrometers for spatially resolved measurements.

Design considerations and system simulation results will be presented to demonstrate the flexibility and wide applicability of the approach. Spectroscopy performance for chemistry with relevant absorption features around 3 micrometers will be outlined and measurement results of transmission spectra in this mid-IR range will be considered.

10025-21, Session 5

Experimental and modeling study of off-beam quartz-enhanced photoacoustic detection of nitrogen monoxide (NO) using a quantum cascade laser

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This article presents the experimental and modeling study of quartz-enhanced photoacoustic detection of nitrogen monoxide (NO) using the off-beam configuration and a distributed-feedback (DFB) quantum cascade laser (QCL) at 5.26 ?m as excitation source. Trace gas monitoring of NO is one important subject for both environmental protection and human health monitoring. Quartz-enhanced photoacoustic spectroscopy (QEPAS) with on-beam configuration is mostly adopted for gas detection. Compared to on-beam configuration, off-beam approach has not only comparative detection sensitivity but also significant advantage of simpler installation and optical alignment. We systematically investigated the sensor performance by measuring the signals corresponding to different horizontal and vertical distances between the center of the micro-resonator (mR) and the QTF prongs. Pressure and humidity are two important factors for gas photoacoustic signal detection, especially, water vapor is usually a normal and critical component in gas samples such as human breathe. Hence, the effect of both parameters on the NO concentration determination were investigated. Theoretical simulations were also performed to interpret the experimental results.

10025-22, Session 5

Amphiphilic block copolymer-based photonic platform towards efficient protein detection

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Use of novel functional materials can provide an efficient route to the performance enhancement of sensing devices when combined in appropriate platforms even by employing simple interrogation schemes. Selective and low cost biosensors, especially for protein detection can have a number of applications in different sectors. Here, the development of a low complexity fiber optic based protein sensor by functionalizing the surface of silica optical fibers using specially designed block copolymer materials is presented. The copolymers utilized are comprised of cationic blocks that can electrostatically bind selected proteins and also appropriate functional groups for reversible or non-reversible binding of protein molecules. Non-reversible protein binding can lead to sensing elements based on protein-analyte interactions. The coexistence of both hydrophobic and hydrophilic blocks in the thiol-functionalized PMMA117-b-P(DMAEMA17-TEMA2) and the vinyl-sulfone-functionalized PMMA117-b-P(DMAEMA17-VSTEMA2) block copolymers used in this work can provide the formation of stable overlayers on fiber’s silica surface. At low pH PDMAEMA is extensively protonated. Proteins having opposite charge relative to the cationic PDMAEMA block can be absorbed by the overlayer, changing its refractive index and enabling the sensing. The PMMA117-b-P(DMAEMA17-TEMA2) has approximately two –SH groups per chain that can react with the protein –SH groups giving a reversible binding. On the contrary the vinyl-sulfone functionalized polymer facilitates non-reversible binding of proteins. The non-functionalized PMMA-b-PDMAEMA copolymer was also tested for comparison. The developed platforms have been evaluated for Bovine Serum Albumin (BSA) sensing, a negatively charged protein at neutral pH, exhibiting linear response to different BSA concentrations with very good repeatability.

10025-23, Session 5

Photo-acoustic spectroscopy gas detection method based on multiple reflection of optical path

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Gas absorption spectroscopy has been widely used in environmental monitoring, industrial production, medical diagnosis, biological technology and monitoring of power facilities. In a number of gas absorption spectrum technique, Photo-acoustic spectroscopy gas detection technology has the advantages of high sensitivity, good selectivity, small size and real time monitoring, has a widely used in the above fields. Photo-acoustic spectroscopy based on photo-acoustic spectroscopy is a Laser Absorption Spectroscopy Technique to converts optical signals into sound signals. In this paper, a method to improve the sensitivity of photo-acoustic spectroscopy system is presented, which is combined with the technique of Herriott type multiple pass cell. This novel technology was used to detect the CO2 concentration in ambient, selecting wavelength ?=1608.7nm as a center wavelength of the laser light source ,and erecting two concave mirrors in the two ends of photo-acoustic cell, which ensures two concave mirrors curvature radius and spacing to meet the conditions of stable resonator in order to make the beams repeatedly through photo-acoustic cell. In this experimental apparatus, the design of the experimental device can make the beam pass the cell 18 times. By comparing the single reflection and multiple reflection measurement results, it is obvious that the signal is increased, and the feasibility of this method is verified. By this method, the sensitivity of Photo-acoustic spectroscopy system was exactly improved without increasing the source power, at the same time reducing the detection limit. Therefore, the application of Photo-acoustic spectroscopy technology will be used more and more widely, such as the detection of the isotope abundance, aerosol concentration, the diagnosis of the gas concentration from transformer and so on.

10025-24, Session 5

Slotted-core photonic crystal fiber in gas-sensing application

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Combustible or harmful gasses noticeable all around are adequate to decimating a geographical region of bringing about a flame, explosion, and venomous exposure. This paper presents a Slotted-core photonic crystal fiber gas sensor which shows high relative sensitivity. The proposed PCF contains rectangular holes in a slotted manner in the core region. The cladding contains five rings of circular air holes arranged in a hexagonal shape. The geometrical parameters like air hole diameters of cladding, cladding pitch, major and minor axis diameter of the rectangular air holes and core pitch are varied to optimize the best outcomes. Better guiding properties are shown by the proposed slotted-core PCF than the previous PCFs. Finite element method (FEM) with perfectly matched layer boundary (PML) circular boundary condition is applied to investigate the guiding properties. The proposed Slotted-core PCF shows the higher sensitivity of 48.26% and a low confinement loss of 1.26? 10 -5 dB/m at 1.33 ?m wavelength of the absorption line of methane (CH4) and hydrogen fluoride (HF) gases. The whole numerical investigation takes place in a wider range of wavelength from 1.3?m to 2.2 ?m. Other optical properties like Effective area, Beat length, Splice loss are also analyzed and presented in this paper. V-parameters are also examined which shows that the Proposed PCF supports single mode.. Using the advanced technology like capillary method and sol-gel method the proposed PCF may be fabricated. The proposed PCF may use to detect colorful and toxic gas.

10025-25, Session 5

Small-molecule microarray-compatible optical-biosensor-based high-throughput screening

Chenggang Zhu, Yiyan Fei, Fudan Univ. (China)

We present a novel high-throughput screening platform based on small-molecule microarrays (SMMs) and label-free oblique-incidence reflectivity difference (OI-RD) microscope. Firstly, we developed OI-RD microscope which is a microarray compatible label-free high-throughput detection method. OI-RD is the special form of an ellipsometry measuring the phase change of the reflected beam which is proportional to the surface mass density of biomolecules on surface so that OI-RD enables label-free detection of biomolecular interactions, getting rid of problems associated with labeling. Compatible with microarray, OI-RD is able to monitor over 15,000 interactions in a single experiment, providing a novel platform for high-throughput screening. Secondly, we developed isocyanate chemistry to prepared SMMs which is able to immobilize compounds with any nucleophilic residue on phenyl-isocyanate functionalized glass slides with high efficiencies. By printing 3,375 compounds on phenyl-isocyanate functionalized glass slides followed by 45?C post-printing annealing of SMM, over 73% compounds can be successfully immobilized on surface. Based on combination of label-free OI-RD microscope and as-prepared SMMs, we screened some non-labeled target proteins in high-throughput and label-free mode and we found hits for respective target protein. The novel high-throughput screening platform enables target proteins with unknown structure and/or unknown function to be effectively screened. In addition, the advantages, low sample consumption, high sensitivity, and multi-target screening, make it have wide applications in high-throughput screening.

10025-26, Session 5

Person identification by using 3D palmprint data

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With the rapid development of network technology, information security has attracted more and more attention. Palmprint recognition is an emerging biometric recognition technology [1]. Compared with 2D (Two Dimension) palmprint, 3D (Three Dimension) palmprint has several advantages of non-contact measurement, one more dimension information and hard to forge, et al. However, most of the existing 3D palmprint matching methods are designed for one-to-one verification and they are not efficient to cope with the one-to-many identification case [2,3].

In order to acquire the 3D palmprint quickly, a capturing system based on structure light and triangulation measurement is developed. Using a DLP (Digital Light Processing) projector to trigger a CCD camera to realize synchronization, 3D palmprint data could be gathered within 1 second. With the purpose of rapid and real-time identifying 3D palmprint, a novel 3D palmprint identification method based on Gabor filter and binary code list is presented, and its applied algorithms such as

feature extraction and matching are investigated. Firstly, using the curvature information of palmprint, ST (Surface Type) is calculated. Then the orientation feature of each point which could be binaryzation and listed in a table is further extracted by convolving with Gabor filters. Finally, the test sample and training samples are compared point by point and larger sums are chosen as the discrimination criterion. Experimental results indicate that the proposed approach can identify a person within 240ms in the case of 4000 samples. Compared with the traditional 3D palmprint recognition methods, the proposed method has high accuracy, speed and robustness, and is suitable for a large sample database.

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10025-27, Session 5

Micro-capillary-based self-referencing surface plasmon resonance fiber-optic biosensor

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A novel self-referencing surface plasmon resonance (SPR) fiber-optic biosensor is demonstrated using the micro-capillary as the sensing element. The fiber-optic sensor is fabricated by splicing a piece of capillary between multimode fibers (MMFs). MMFs act as the lead-in and lead-out fibers while the micro-capillary is used as the sensing element. The sensor employs SPR mode as a measuring signal and localized surface plasmon resonance (LSPR) mode and Febry-Perot (FP) mode as the referencing signals. The SPR mode is generated in the gold film coated on the outer wall of the micro-capillary; instead, the LSPR mode is generated on the gold nanoparticles (GNPs) immobilized on the outer wall of the micro-capillary and the FP mode is excited in the micro-capillary filled with the deionized water. Because SPR effects, LSPR effects and FP interference can occur in the capillary simultaneously, the spectrum of the sensor exhibits SPR absorption, LSPR absorption and FP interference fringe. LSPR mode is sensitive to refractive index (RI) and insensitive to temperature; instead, FP mode is sensitive to temperature and insensitive to RI. Therefore, LSPR mode and FP mode can be used as the referencing signals to compensate the effects caused by the bulk RI and the temperature fluctuation, respectively. Experimental results show that this approach we presented can compensate bulk RI and temperature effect and develop this sensor as a practicable high-sensitivity sensing device. The simple and low-cost SPR biosensor can be used for sensing in the field of biochemical.

10025-28, Session 5

Application of LaserBreath-001 for breath acetone measurement in subjects with diabetes mellitus

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Breath acetone is a promising biomarker of diabetes mellitus in both humans and animals. At present, using breath acetone as a noninvasive alternative for diabetes screening and management is still a challenge. A fundamental question, the quantitative relationship between breath acetone concentration and established clinical diagnostic parameters, remains unaddressed because of limited clinical data and physiological process complexity. With an integrated standalone, on-site cavity ringdown breath acetone analyzer, LaserBreath-001, we tested breath samples from 42 type 1 diabetic (T1D) patients, 312 type 2 diabetic (T2D) patients, 52 healthy subjects, and 126 T1D rats. The relevant clinical information, such as simultaneous blood glucose (BG) level, blood beta-hydroxybutyrate (BHB) level, glycohemoglobin (A1c), gender, age, body weight, and fasting status, was also recorded.

In the cross-sectional studies, the obtained breath acetone concentrations were higher in the diabetic human and rat subjects compared with those in the control groups. A moderate positive correlation between the mean individual breath acetone concentrations and the mean individual BG levels was observed in the 20 T1D patients without ketoacidosis. No correlation between individual breath acetone and individual simultaneous BG was observed in the T1D, T2D, and healthy human, or the rat subjects. In the longitudinal studies, the breath acetone concentrations in a T1D patient with ketoacidosis decreased significantly and remained stable within 5 days during the hospitalization. Also, a 30-day continuous observation among 20 T1D outpatients and 5 healthy subjects demonstrated that breath acetone measurement was a promising tool for diabetes screening and management with a screening rate of 74% or higher under specifically controlled condition. The breath acetone influencing factors, such as age, gender, body mass index, A1c, and fasting status, were investigated individually and comprehensively.

10025-29, Session 6

Optical properties of silicon microtube doped with upconversion nanocrystals

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Nanocrystals of ?-NaLuF4 :Yb3+/ Ho3+with average diameter about 400nm were integrated in silica-based microtube by a simple flame heating method. The fabricated microtube has a diameter range from 2 μm to 30 μm and lengths up to hundreds microns. The fluorescence of upconversion nanocrystals (UCNCs) can propagate along the single microtube. To prove the single UCNCs doped MT can be used as an active waveguide we measured the guiding performance of it. Optical temperature sensing based on the single UCNCs doped microtube was also demonstrated, the sensitivity of UCNCs doped microtube is significant sensitivity for temperature sensor applications in the range of 300-375K.

10025-30, Session 6

Light propagation in strip and slot waveguide arrays for sensing

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Light propagations in strip and slot waveguide arrays for sensing are proposed and analyzed with a new theory of quantum walk. The waveguide arrays are designed on silicon-on-

insulator and can be fabricated with mature and cost-efficient complementary metal-oxide semiconductor technology. A new slot waveguide array modified by conventional strip waveguide array with electric field mainly confined in the cladding region is investigated. Quantum walks have an exact mapping to classical phenomena as verified by experiments using bright laser light, so that they are introduced in our work as theoretical foundation. The weakly coupled-mode theory is used to extract the coupling coefficient of waveguide arrays, which is simulated by Finite Element Method. By a series of analysis we take the width of waveguide of 450 nm and the coupling distance of 200 nm for strip waveguide array. And for slot waveguide array we take the waveguide width and coupling distance of 420 nm and 180 nm respectively, with a 100nm slot in the center of waveguide. At last the waveguide array covered by a thin layer of graphene is investigated, which brings higher sensing property as well as a much better biocompatibility. With the monochrome light injection the intensity distribution at the end of the arrays changes with the refractive index of the sensing area (cladding region) and it can be explained by quantum walks theory. While both arrays show excellent sensing characteristics, the designed slot array can possess compact footprint and high refractive index resolution, reaching 1E-11 RIU theoretically.

10025-31, Session 6

Multimode interference structures as sensing elements integrated into Mach-Zehnder interferometers in polymer foils

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Integrated Mach-Zehnder interferometers (MZIs) based on flexible polymer materials have been demonstrated as evanescent field sensors for the detection of refractive indices or molecule concentrations. Optical polymers, with their tunable refractive indices and viscosities, enable cost-efficient roll-to-roll manufacturing on flexible foils leading to cheap and disposable sensors. Compared to rigid inorganic sensor systems, foil-based systems exhibit a lower sensitivity due to their material properties, in particular available refractive indices and thermo-optical instabilities. Additionally, the commonly used application of a measurement window becomes more difficult in a real roll-to-roll fabrication process. We have previously demonstrated foil-based asymmetric MZIs with different widths in sensing and reference arm which do not need a measurement window. These systems are perfectly compatible with roll-to-roll fabrication but attain lower sensitivities than symmetric systems using a measurement window.

We present here the use of a multimode interference structure (MMI) inserted into the sensing arm of the interferometer to increase the sensitivity. We consider the expected interference signal from numerical simulations and optimize the system in terms of sensitivity, dimensions and absorption losses. The designed MMI-MZI systems are fabricated by hot-embossing the waveguides into a PMMA foil serving as substrate and lower cladding. The core layer, consisting of a customized co-monomer, is applied by spin-coating followed by polymerization, thereby forming inverted rib waveguides with a total height of 3 μm and widths between 2 and 3.5 μm. The selected MMI has a width of 7 μm and a length of around 10 mm. Finally, we apply water/-glucose solutions in different fractions to demonstrate the functionality of the MMI-MZI system as refractive index sensor.

10025-32, Session 6

Optimizing the loss of one-dimensional photonic crystal towards high-sensitivity Bloch-surface-wave sensors under intensity interrogation scheme

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The reflected intensity change of the Bloch-surface-wave (BSW) resonance influenced by the loss of a truncated one-dimensional photonic crystal structure is numerically analyzed and studied in order to enhance the sensitivity of the Bloch-surface-wave-based sensors. The finite truncated one-dimensional photonic crystal structure is designed to be able to excite BSW mode for water (n=1.33) as the external medium and for p-polarized plane wave incident light. The intensity interrogation scheme which can be operated on a typical Kretschmann prism-coupling configuration by measuring the reflected intensity change of the resonance dip is investigated to optimize the sensitivity. A figure of merit (FOM) is introduced to measure the performance of the one-dimensional photonic crystal multilayer structure under the scheme. The detection sensitivities are calculated under different device parameters with a refractive index change corresponding to different solutions of glycerol in de-ionized (DI)-water. The results show that the intensity sensitivity curve varies similarly with the FOM curve and the sensitivity of the Bloch-surface-wave sensor is greatly affected by the device loss, where an optimized loss value can be got. For the low-loss BSW devices, the intensity interrogation sensing sensitivity may drop sharply from the optimal value. On the other hand, the performance of the detection scheme is less affected by the higher device loss. This observation is in accordance with BSW experimental sensing demonstrations as well. The results obtained could be useful for improving the performance of the Bloch-surface-wave sensors for the investigated sensing scheme.

10025-33, Session 6

Rapid wasted-free microfluidic fabrication based on ink-jet approach for microfluidic sensing applications

Ungkarn Jarujareet, Ratthasart Amarit, Sarun Sumriddetchkajorn, National Electronics and Computer Technology Ctr. (Thailand)

Realizing that current microfluidic chip fabrication techniques are time consuming and labor intensive as well as always have material leftover after chip fabrication, this research work proposes and demonstrates an innovative approach for rapid microfluidic chip production. The key idea relies on a combination of a widely-used inkjet printing method and a heat-based polymer curing technique with an electronic-mechanical control, thus eliminating the need of masking and molds compared to typical microfluidic fabrication processes. In addition, as the appropriate amount of polymer is utilized during printing, there is no material wasted. Our inkjet-based printer can print out the desired microfluidic chip pattern directly onto a heated glass surface, where the printed polymer is suddenly cured. Our proof-of-concept demonstrations for widely-used single-flow channel, Y-junction, and T-junction microfluidic chips, which are utilized in several microfluidic sensing applications, are described. The whole microfluidic chip fabrication process of our demonstration

reveals that it requires only 3 steps with a fabrication time of < 6 minutes.

10025-34, Session 6

Magneto-optic sensor based on electrogyration compensation and single-quartz crystal

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Magnetooptic sensors have potential applications to the measurement of magnetic field or current in many fields including electric power system and scientific experiments. Most of them are based on various magnetooptic effects in optical crystal or fiber, e. g. Faraday effect. To date, the most successful optical current sensor is based on Sagnac interferometer and closed-loop signal processing scheme. However, this closed-loop sensing scheme is achieved by using an electrooptic phase modulator which is separated from current sensing fiber or crystal due to the need of electrical insulation, thus it is easily influenced by various external interferences. To solve this problem, a magnetooptic sensor based on electrogyration compensation and single lead molybdate crystal has been proposed recently (refer to IEEE Sensors J. 16(9), 2982-2987, 2016). However, the compensating voltage is as high as 16V/Gs due to a small electrogyration coefficient of the crystal.

In this paper, another magnetooptic sensor based on electrogyration compensation is proposed and demonstrated experimentally by using single quartz crystal. Compared with previous magnetooptic sensor using lead molybdate crystal, the compensating voltage is remarkably decreased to 0.8V/Gs for a single crystal with a length of 23mm and 50Hz ac magnetic field less than 267Gs. In addition, besides electrogyration and Faraday effects, quartz crystal also exhibits electrooptic Pockels effect and natural optical activity which don't exist in lead molybdate crystal, thus the sensing principle is different from that of the magnetooptic sensor using lead molybdate crystal. The proposed sensor can be used for the closed-loop measurement of strong magnetic field.

10025-35, Session 7

High-sensitivity fiber optic acoustic sensor technology *(Invited Paper)*

Ping Lu, Huazhong Univ. of Science and Technology (China)

In recent years, our research group has proposed a series of high-sensitivity fiber opticacoustic sensor(FOAS) technology solutions. Such as a kind of differential intensity modulation method based on non-standard fiber optic coupler, whose intensity sensitivity can be 2.63 mW/Pa. This sensor has good response in the range of 20Hz-20kHz; Including another novel solution based on passively mode-locked multi-longitudinal-mode fiber laser for sound pressure sensing, a highly acoustic pressure sensitivity of 147.2Hz/Pa is achieved at the sound pressure range 0-20Pa; Besides,a MI based low-frequency FOAS employing plastic diaphragmis alsoresearched, whose sensitivity can be -118dB at 90-500 Hz. Furthermore, specially for infrasound sensing, EFPI sensors based on composite film or polymer film are also fabricated. And experimental results show high sensitivity -138.3 dB re 1 V/μPa @1 Hz and infrasound working frequency 1-20Hz. In addition, a quasi-distributed fiber optic acoustic sensing scheme based on optical vernier effect principle is also raised, the sensitivity is as high as 45.3rad/Pa, and employing the WDM technology, quasi-distributed fiber optic acoustic sensing application can be realized. In short, our research group has implemented a lot of highly sensitive fiber acoustic sensing applications in terms of intensity, beat frequency, phase, and so on.

10025-36, Session 7

Temperature sensor based on one-dimensional photonic crystal with defect

Kulandisamy Wilson, Arul Anandar College (India); Nambi Ramanujam, K.L.N. College of Engineering (India)

The temperature dependence of the defect mode in a one dimensional photonic crystal (PC) are theoretically investigated by transfer matrix method. The effect of temperature on each layers are carried out by considering the thermal expansion effect and thermo-optical effect. By simultaneously incorporating these two effects, the PC structure is designed as (HL)NH(HL)N with SiO2 (H) and air (L) layers. The sensitivity is determined by the shift in wavelength of the transmittance peak with temperature and the average shift is 0.787 nm /K. It is also found that the wavelength of the transmission peak is shifted towards the higher wavelength region with increase of temperature.

10025-37, Session 7

A novel quarter wave plate and its applications to the reflective fiber-optic current sensor

Ruibin Zhang, Beijing Univ. of Technology (China)

In this paper, a novel quarter wave plate which is composed of two segments high birefringence fibers which are orthogonally welded is proposed and demonstrated. By tuning the uniform strength beam onto which one of the two fibers is adhered, the length of the fiber can be precisely controlled and so quarter wave plate can be got. The theory model of the reflective current sensing system with the novel quarter wave plate is established using Jones matrix method. The influences of the deviation of welding angle and phase difference of the quarter wave plate on the sensing system is studied in detail, respectively. The temperature stability of the quarter wave plate is studied in detail. Based on the characteristics of the high birefringence fiber (panda) under the temperature and axial strength change, a temperature compensation method is proposed. The method is realized by adhere part of the high birefringence fiber to the unique strength beam which is made of acrylic. When temperature changes, the effect on the beat length change can be compensated by the effect of strength change which is brought by thermal expansion. The quarter pate has the advantages of high stability and easy for precisely controlling.

Conference 10026: Real-time Photonic Measurements, Data Management, and Processing II

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10026-1, Session 1

Honeycomb lattice meshes for reconfigurable universal microwave photonics processors *(Invited Paper)*

Jose Capmany, Ivana Gasulla, Daniel Perez, Univ. Politécnica de Valencia (Spain)

General programmable processors are called to play key role in the implementation of future general programmable integrated processors, which will be required in massive scale application scenarios such as 5G communications and the Internet of Things. Bringing the promise of implementing several functionalities by suitable programming of one common photonic hardware architecture, these devices feature additional advantages in terms of low cost and enhanced reliability fabrication when combined with Generic Integration (GIM) and Generic Foundry (GFM) Models. The central element of the proposed reconfigurable optical processors is a versatile reconfigurable optical core, where the main signal processing architectures can be set up in response to different electronic control signals. The main proposed configurations are based on cascade of finite and infinite impulse response cells (MZIs and ORRs). A different approach based on a 2D tuneable-coupler-based square mesh network inspired by the photonic FPGA-like concept employs 3-dB balanced Mach-Zehnder Interferometers (MZIs) as its basic building block, enabling the synthesis of any kind of optical core circuit topology. In this paper we propose a honeycomb mesh topology for the implementation of a specific class of reconfigurable processor for Microwave Photonics (MWP) applications. We and carry out an analysis that highlights its superior metrics compared to the previously proposed square mesh in terms of integration capabilities and photonic integrated circuit (PIC)-synthesis performance. We illustrate its applicability in implementing medium-complexity MWP processors. We provide also an evolution roadmap for this device.

10026-2, Session 1

Distributed radiofrequency signal processing using multicore fibers *(Invited Paper)*

Ivana Gasulla, Sergi Garcia, Univ. Politécnica de Valencia (Spain)

Next generation fiber-wireless communication paradigms will require entirely new technologies to address the current limitations to massive capacity and connectivity, enabling multigigabit-per-second 5G wireless systems and the era of Internet of Things. We envision the application of spatial division multiplexing technologies to these upcoming fiber-wireless networks as a firm candidate to increase the end user capacity while providing adaptive radiofrequency-photonic interfaces. This approach leads to the novel concept of “fiber-distributed signal processing”, providing radio access distribution and MIMO antenna connectivity while simultaneously implementing broadband Microwave Photonics processing. In particular, we capitalize on the spatial parallelism inherent to multicore fibers to implement a broadband tunable true time delay line for radiofrequency signals, which is the basis of multiple processing applications such as signal filtering, arbitrary waveform generation and squint-free radio beamsteering.

While keeping comparable propagation characteristics in all the fiber cores is important in digital communications, tunable true time delay lines for analog radiofrequency processing require to design each single core so that it features an independent group delay behavior. We present the design of trench-assisted heterogeneous multicore fibers optimized in terms of higher-order dispersion, crosstalk and bend sensitivity designed to operate as a broadband sampled delay line. This work opens the way towards the development of broadband fiber-distributed microwave signal processing benefiting from the stability, versatility and compactness brought by the proposed multicore fiber approach.

10026-3, Session 1

Photonics-based radar for coherent multi-band differential phase estimation for enhanced displacement measurements *(Invited Paper)*

Antonella Bogoni, Consorzio Nazionale Interuniversitario per le Telecomunicazioni (Italy); Sergio Pinna, Scuola Superiore Sant’Anna (Italy)

Landslides and other ground failures are responsible for great damages. Radars have been exploited for controlling these ground movements, providing complete and precise deformation maps of large areas.

Commercial radar relies on the Stepped-Frequency Continuous-Wave (SFCW) technique with differential interferometry. It exploits several coherent sinusoids to synthesize a large signal bandwidth and to reduce the system noise for an improved measure resolution.

Currently this technique is limited to the use of coherent sinusoids in a single RF band, due to the issues in generating multi-band coherent signals. Moreover, the lack of highly stable tunable RF oscillators leads to exploit only a fixed RF band.

However, the capability to exploit coherent multi-bands would further increase the synthesized signal bandwidth, and would allow to tune the operative RF carriers for adapting the system to the environment and to the observation range.

Recently, the authors realized the first demonstrator of a photonics-based coherent radar, with the possibility of simultaneously generating and detecting several RF signals, in different RF bands guaranteeing an intrinsic high phase coherence.

This paper reports for the first time, the use of this photonics-based radar for a SFCW technique and differential interferometry based system. The intrinsic high phase coherence between the used bands avoids the use of correction algorithms. Moreover the use of a single photonics-based transceiver for generating all the RF carriers allows for a reduction of the whole system power consumption and footprint.

An accuracy lower than < 200um over a range up to 3km has been obtained.

10026-4, Session 1

Microwave photonic signal processing based on distributed feedback semiconductor optical amplifier *(Invited Paper)*

Ye Deng, Ming Li, NuanNuan Shi, Jian Tang, Shuqian Sun,

Lihong Zhang, Ninghua Zhu, Institute of Semiconductors (China)

Microwave photonic signal processing combines the advantages of electronic technique (ubiquitous, flexible and high frequency spectrum resolution) with the advantages of photonic technique (broad bandwidth, high speed, and low power consumption). It is considered as one solution to overcome the inherent limitations of transmission speed and power consumption in conventional electronic-based system. Over the last few years, an impressive range of microwave photonic signal processors have been proposed, but few of them come with reconfigurability, a feature highly needed for practical signal processing applications. In this paper, we propose and experimentally demonstrate an analog optical signal processor based on a phase-shifted distributed feedback semiconductor optical amplifier (DFB-SOA). The proposed analog optical signal processor can be reconfigured to perform signal processing functions including ordinary differential equation solving and temporal intensity differentiation. The reconfigurability is achieved by controlling the injection currents. In addition, The DFB-SOA can also be used to realize a widely tunable microwave photonic filter (MPF) with a single passband. Furthermore, our proposed DFB-SOA based MPF also shows a potential application as an optical vector network analyzer (OVNA). Finally, our demonstration provides a simple and effective solution for integrated microwave photonic signal processing.

10026-5, Session 1

A broadband optically-steered phased radar for target detection

NuanNuan Shi, Ye Deng, Lihong Zhang, Shuqian Sun, Jian Tang, Ming Li, Wei Li, Ninghua Zhu, Institute of Semiconductors (China)

A broadband X-band optically-steered phased array radar (PAA) is proposed and applied to demonstrate the target detection ability. In the proposed photonics-based PAA, high-dispersion fiber is employed to realize the true-time delay (TTD) technique with the variable time delay between each adjacent channel from -43.3 ps to 43.3 ps. Low amplitude ripple of ±0.5 dB and small phase error of -0.13 ps/nm are realized by the power equalization and the phase compensation. By tuning the optical wavelength over C band, the beam steered angle in far field covers from -54 degree to 54 degree and the maximum error of the beam steered angle is up to 7 degree with the frequency of 8.5 GHz~11.5 GHz. Moreover, the beam patterns at 10 GHz are measured in the wavelength of 1545 nm and 1538.5 nm and the error of which are less than 3 degree compared with the simulation results. As an application of the setup optically-steered phased array antenna system, the detection ability of photonics-based radar is also verified using X-band chirp signal. It is capable to rapidly detect the target by simple tuning the optical wavelength. After the pulse compression of the received signal, the ranging resolution is less than 2 cm. Therefore, it is able to realize the beam forming steering with the broadband and the large scanning angle. We believe that the demonstration can preferably promote the practicality of optically-steered phased array radar.

10026-6, Session 2

Recent progress in on-chip linear and nonlinear microwave photonic signal processing *(Invited Paper)*

Jian Wang, Huazhong Univ. of Science and Technology (China)

We review our recent progress in on-chip linear and nonlinear microwave photonic signal processing based on photonic integrated devices on silicon platforms. By employing the designed and fabricated silicon microring resonators, silicon photonic crystal nanocavities, and silicon Mach-Zehnder modulator, we experimentally demonstrate diverse on-chip linear and nonlinear microwave photonic signal processing: 1) bandstop microwave photonic filter; 2) bandpass microwave photonic filter; 3) optically-controlled tunable microwave photonic filter; 4) ultra-high peak rejection notch microwave photonic filter; 5) photonic-assisted microwave signal multiplication and modulation. The operation performance of on-chip linear and nonlinear microwave photonic signal processing is comprehensively evaluated in the experiment.

10026-7, Session 2

High-accurate optical vector analysis based on optical single-sideband modulation *(Invited Paper)*

Min Xue, Shilong Pan, Nanjing University of Aeronautics and Astronautics (China)

Most of the efforts devoted to the area of optical communications were on the improvement of the optical spectral efficiency. Varies innovative optical devices are thus developed to finely manipulate the optical spectrum. Knowing the spectral responses of these devices, including the magnitude, phase and polarization responses, is of great importance for their fabrication and application. To achieve high-resolution characterization, optical vector analyzers (OVAs) based on optical single-sideband (OSSB) modulation have been proposed and developed. Benefiting from the mature and high-resolution microwave technologies, the OSSB-based OVA can potentially achieve a resolution of sub-Hz. However, the accuracy is restricted by the measurement errors induced by the unwanted first-order sideband and the high-order sidebands in the OSSB signal, since electrical-to-optical conversion and optical-to-electrical conversion are essentially required to achieve high-resolution frequency sweeping and extract the magnitude and phase information in the electrical domain. Recently, great efforts have been devoted to improve the accuracy of the OSSB-based OVA. In this paper, the influence of the unwanted-sideband induced measurement errors and techniques for implementing high-accurate OSSB-based OVAs are discussed.

10026-8, Session 2

All-optical pulse compression for broadband microwave signal based on Brillouin scattering in optical fiber *(Invited Paper)*

Weiwen Zou, Xin Long, Jianping Chen, Shanghai Jiao Tong Univ. (China)

Pulse compression processing based on stimulated Brillouin scattering (SBS) in an optical fiber is theoretically and experimentally demonstrated. Broadband microwave signal is electro-optically modulated onto the pump lightwave that is launched into one end of the fiber.

Acoustic wave in the fiber inherits the amplitude and phase information of the pump lightwave and thus the coupling between the acoustic wave and pump lightwave leads to the auto-correlated process of the pump lightwave as well as the modulated microwave signal. Derivation of the SBS coupling equations shows that the short-pulse probe lightwave amplified by the pump lightwave possesses the nature of auto-correlation

formula. All-optical pulse compression of the broadband microwave signal is implemented after a subtraction between the detected probe pulse with and without SBS. A proof-of-concept experiment with a linear frequency-modulated microwave signal (1 GHz sweep range) is carried out .

10026-9, Session 2

Ultrafast optical signal processing enabled by plasmonics *(Invited Paper)*

Maurizio Burla, Romain Bonjour, Felix Abrecht, W. Heni, Claudia B. Hoessbacher, C. Haffner, Yannick Salamin, Yuriy M. Fedoryshyn, Juerg Leuthold, ETH Zürich (Switzerland)

Plasmonic organic hybrid modulators recently demonstrated ultra-low power consumption (a few fJ/bit) and ultrafast operation (>100 Gbit/s) on ultra-compact footprints (100s μm2) [1-8]. Novel ultrafast signal processing platforms on-a-chip may be enabled by employing these unique characteristics. We will first report recent progress on plasmonic modulation devices, and discuss how the same basic concepts can be applied to ultrafast optical signal processing applications. Novel plasmonic phase modulators (PPMs) [5], Mach-Zehnder [7] and IQ-modulators [8] will be introduced. We will briefly discuss the state of development of several applications based on these devices, ranging from optical interconnects [9] to ultrafast analog signal processing of microwave and millimeter wave signals [10, 11]. For these applications PPMs promise special benefits, thanks to their theoretically unlimited RF bandwidth and compactness [1]. Finally, a perspective on the potential of using plasmonic modulators for processing of ultrafast optical signals will be given, e.g. in ultrafast optical phase shifters and delay lines [11], which can find applications e.g. in in-line processing techniques, on-chip arbitrary waveform generators [12], and more.

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10026-10, Session 2

On-chip pulse shaper for optical and microwave arbitrary waveform generation

Shasha Liao, Xu Wang, Jianji Dong, Huazhong Univ. of Science and Technology (China)

Arbitrary waveform generation attracts a lot of interests in recent years because of its widely applications in many different fields. We have proposed and experimentally demonstrate two on-chip pulse shaper schemes for microwave and optical arbitrary waveform generation. These schemes are all fabricated on the silicon-on-insulator (SOI) chips for its compactness and capability to integrate with electronics. The two schemes based on finite impulse response (FIR). By thermally controlling the amplitude and phase of each path, we can obtain different applications of arbitrary waveform generation. The pulse shaper of optical arbitrary waveform generation can be a programmable filter with central wavelength tunable, bandwidth tunable and passband shape variable functions, and a high-order differentiator which may obtain the first-order, second-order and third-order differentiations likewise. It can also implement several typical optical waveforms, such as the square waveform, triangular waveform, sawtooth waveform and Gaussian waveform. The pulse shaper for microwave arbitrary waveform generation can obtain several microwave waveforms with the central frequency at 125GHz. Comparing with the proposed schemes by frequency shaping and frequency-to-time mapping, our schemes do not require any spectral dispersers or large dispersion mediums. And all units in our schemes are broad-band devices, so there is no bandwidth limitation in our schemes.

10026-11, Session 2

Optical true time delay based on contradirectional couplers with single sidewall-modulated Bragg gratings

Xu Wang, Jianji Dong, Shasha Liao, Huazhong Univ. of Science and Technology (China)

We propose and demonstrate optical true time delay using tapered SOI contradirectional couplers with single sidewall-modulated Bragg gratings. The contradirectional couplers consist of two tapered rib waveguides with different width, and the Bragg gratings is modulated in the inner sidewall of the wider one. The optical signal is launched from the wider waveguide and coupled to the narrow waveguide through the Bragg gratings structure. In the direction of light propagation, the waveguide width varies linearly, so the reflection wavelength is different at different position. Therefore, linear delay line can be realized in the reflectance spectrum using the present structure. In the simulation, grating period is 310nm and grating number is 2400, so the grating length is 744?m. Using 2.5D FDTD simulation, the current structure can realize optical group delay of 20ps within bandwidth of 20nm. The proposed device is fabricated on a 220nm SOI chip with Electron Beam Lithography (EBL) and Inductively Coupled Plasma (ICP) etching. In the experiment, continuous light is modulated by 10GHz radio-frequency signal through the optical intensity modulator and travel through the chip, which is finally detected by the oscilloscope. By adjusting the wavelength of input light, group delay of different wavelength are recorded by the oscilloscope. The experimental results show that group delay of 20ps is realized in the bandwidth of 12nm. In the end, the drift of the reflection spectrum and delay lines under different temperature is analyzed. The reflection spectrum drifts 0.1nm/°C and causes redshift of the corresponding delay line.

10026-12, Session 3

Tunable optical frequency combs generation in a CMOS-compatible high-Q micro-ring resonator *(Invited Paper)*

Wenfu Zhang, Weiqiang Wang, Leiran Wang, Guoxi Wang, Wei Zhao, Xi'an Institute of Optics and Precision Mechanics (China)

We demonstrate a dual-pump approach, which allows the comb spacing tuning freely, to generate tunable and robust optical frequency comb (OFC) in a high–Q CMOS-compatible micro-ring resonator (MRR) in this paper. In our approach, the dual-pump is generated by self-locked oscillation technique which is immune to the thermal or mechanical perturbations, and the self-termination is effectively avoided for its intrinsic feedback mechanism. The two pumps can lase stably and be tuned flexibly by programming the tunable filter embedded in the laser cavity loop, as the mode competition in the erbium-doped-fiber laser is suppressed effectively by nonlinear interaction in the MRR. By tuning the pump wavelength, broadband OFC with the bandwidth of >200 nm and the frequency-spacing tunability from 6- to 46-fold free-spectral-ranges (FSRs) is realized at a low pump power. This approach could find potential and practical applications in many areas, such as optical metrology, optical communication, and signal processing systems, for its excellent flexibility and robustness.

10026-13, Session 3

Photonic-assisted compressive sampling systems *(Invited Paper)*

Qiang Guo, Hongwei Chen, Minghua Chen, Sigang Yang, Shizhong Xie, Tsinghua Univ. (China)

Compressive sampling (CS) has attracted considerable attention as a novel data sampling technique and widely applied in diverse fields including wideband spectrum sensing and biomedical imaging in recent years. Compared with traditional electric CS systems, photonic-assisted CS technique can overcome the bandwidth limitation of electronic devices. Meanwhile, it can significantly reduce the sampling rate of the back-end analog-to-digital converter (ADC), easing the burden of data acquisition, transmission and storage. A photonic-assisted four-channel wideband CS system based on wavelength division multiplexing is proposed for the first time and multi-tone signals in the 5-GHz frequency range are reconstructed faithfully with only a 120-MHz ADC. Moreover, a CS platform for radar pulse signal acquisition is built and numerous radar pulses in the 0.5-5 GHz range are spectrally sensed with a 500-MHz ADC. In imaging applications, one-dimensional and 2-dimensional high-speed time-stretch-based single-pixel imaging systems are implemented with high frame rates three orders of magnitude faster than conventional single-pixel cameras. To show the utility of our scheme in biomedical applications, an imaging flow cytometer with a throughput of 100,000 cells/s is demonstrated, which has settled the big data problem caused by high-throughput image acquisition. In general, photonic-assisted CS systems show great potential in both wideband spectrum sensing and biomedical imaging applications.

10026-14, Session 3

Microwave frequency measurement based on photonic sampling analog-to-digital conversion

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Broadband microwave frequency measurement is critical important for extensively applications, including wireless communications, radar systems and electronic warfare. The electronic techniques of microwave frequency measurement are usually susceptible to electromagnetic interference (EMI) and the bandwidth is limited by electronic bottleneck. Fortunately, various photonic techniques for frequency measurement which have large bandwidth and immunity of EMI have been investigated, such as frequency-power mapping technique, frequency-time mapping technique and channelizing technique. However, it is a contradiction in obtaining a large bandwidth and a high resolution simultaneously.

In this paper, a novel approach to implement microwave frequency measurement based on photonic analog-to-digital converters (ADCs) is proposed. Specifically, three low repetition frequency mode-locked lasers (MLLs) with co-prime repetition frequencies are used to generate three ultra-short optical pulse trains. The unknown microwave signal is down-converted sampled by the three optical pulse trains through Mach-Zender Modulators respectively. The modulated optical pulse trains are translated to electronic pulse trains by photodetectors (PDs), and then converted into digital signals by the corresponding electronic ADCs. The Fourier frequencies are gained by the Discrete Fourier transform (DFT) and the final result of the frequency measurment is obtained by calculating the three Fourier frequencies based on frequency reconstructing algorithm. The simulation results indicate that a large measurement range of 0-50GHz and an accuracy of ±4MHz are achieved. Therefore, both high resolution and large bandwidth are acquired by utilizing the proposed scheme.

10026-15, Session 3

Dual-frequency comb metrology with one fiber laser

Xin Zhao, BeiHang Univ. (China); Yasui Takeshi, The Univ. of Tokushima (Japan) and JST (Japan); Zheng Zheng, BeiHang Univ. (China) and Collaborative Innovation Ctr. of Geospatial Technology (China)

Optical metrology techniques based on dual optical frequency combs have emerged as a hotly studied area targeting a wide range of applications from optical spectroscopy to microwave and terahertz frequency measurement. Generating two sets of high-quality comb lines with slightly different comb-tooth spacings with high mutual coherence and stability is the key to most of the dual-comb schemes. The complexity and costs of such laser sources and the associated control systems to lock the two frequency combs hinder the wider adoption of such techniques.

Here we demonstrate a very simple and rather different approach to tackle such a challenge. By employing novel laser cavity designs in a mode-locked fiber laser, a simple fiber laser setup could emit dual-comb pulse output with good coherence and high stability between the pulse trains. Based on such lasers, comb-tooth-resolved dual-comb optical spectroscopy is demonstrated. Picometer spectral resolving capability could be realized with a fiber-optic setup and a low-cost data acquisition system and standard algorithms. When applied to the terahertz region, high accuracy measurement of CW terahertz wave is realized based on dual terahertz comb, excited by one fiber dual-comb laser. Similarly, the frequency of microwave signals over a large range can be determined based on a simple setup.

Our results unequivocally show the capability of such single-fiber-laser-based dual-comb scheme to realize different dual-comb applications with excellent quality for many real-world applications. Greatly reducing the complexity and cost of a dual-

comb system could result in a significant change in the paradigm of dual-comb-based metrology technologies.

10026-16, Session 4

Secure key distribution applications of chaotic lasers *(Invited Paper)*

Ning Jiang, Chenpeng Xue, Kun Qiu, Univ. of Electronic Science and Technology of China (China)

Secure key distribution is the most crucial issue for a cryptosystem. There are two types of secure key distribution schemes that are based on the computational principles and physical principles, respectively. In this talk we discuss the physical-principle-based secure key distribution systems adopting chaotic lasers. Differing from the conventional key distribution systems where the key generation is based on a deterministic algorithm, the key generation is based on the physical random generation which is not deterministic. The security only depends on the probability that the eavesdropper guess the precise physical operations which is usually controlled by random parameters, and then the security of key can be greatly improved. We will introduce the theoretical model and principles of the secure key distribution based on chaotic lasers, and demonstrate its performance and analyze the challenges for practical implementation.

10026-17, Session 4

Spatial mode analyzer based on rotational Doppler effect *(Invited Paper)*

Jianji Dong, Huazhong Univ. of Science and Technology (China)

The function to measure the mode distribution of orbital angular momentum (OAM) light is essential to characterize OAM performance. Although there are lots of works to measure OAM modes, it is difficult to measure the power distribution of OAM modes quantitatively and instantaneously, let alone measure the phase distribution. In this work, we demonstrate an OAM complex spectrum analyzer, which enables to measure the power and phase distribution of OAM modes simultaneously by employing rotational Doppler Effect. The original OAM mode distribution is mapped to electrical spectrum of beating signals with a photodetector. The power distribution and phase distribution of OAM superimposed beams are successfully obtained by analyzing the electrical spectrum. We also extend the measurement to other spatial modes, such as linear polarization modes. These results represent a new landmark of spatial mode analysis and show great potentials in optical communication and optics quantum tomography.

10026-18, Session 4

Coherence loss: The emergence of optical polarization rogue waves *(Invited Paper)*

Lei Gao, Tao Zhu, Chongqing Univ. (China); Stefan Wabnitz, Univ. degli Studi di Brescia (Italy); Yu Jia Li, Cong Gao, Min Liu, Wei Huang, Chongqing Univ. (China)

We demonstrate a new kind of optical rogue waves, polarization rogue waves (PRW) that appear with greatly deviated and unpredictable positions of states of polarization (SOPs), in forming partially mode-locked fiber laser based on parametric frequency conversion, where laser redistributes its energy from center to sidebands through parametric instability (PI), and subsequently longitudinal modes are populated via cascaded four-wave-mixing (FWM). The coherence of the PI gain lobes is investigated based on statistical analysis of single-shot spectra obtained from disperse Fourier transformation. We find that the PI, which exhibits great fluctuations when it is spontaneously grown from noise in conservative systems, possess a high degree of coherence in dissipative laser system with gain. Adjusting the intracavity polarization state controls the process of loss of coherence. During this process, the SOPs of frequencies generated by cascaded FWM shows a tendency from fixed state to bifurcation, and finally to randomization. Experiments reveal that the polarization deviation from the mean positions is due to chaotic competition of cascaded FWM processes, including both scalar and vector FWMs, through which the energy of longitudinal modes with a SOP along the cross is transferred into newly-generated SOPs. Different from the physical origin of breather for temporal or spectral rogue waves, the emergence of PRW is attributed to the appearance of various types of multiple photons mixing, where molecular-scale accuracy of dispersion in commercial single mode fiber together with nonlinear phase response of graphene leads to abrupt variation of phase-matching condition.

10026-37, Session Post

An instrument for on-line chemical oxygen demand and nitrate in-water monitoring

Weiwei Feng, Dan Li, Zongqi Cai, Yongchun Zhang, Xiao Xu, Yantai Institute of Coastal Zone Research (China)

Chemical Oxygen Demand (COD) and Nitrate concentration data are of vital importance in coastal water quality monitoring. The traditional method for monitoring these two parameters is a chemical method that consumes chemical reagent. The drawbacks of these chemical methods are the waste they generate, and the difficulty in implementing in-situ long term monitoring. A new instrument based on an optical method to measure Chemical Oxygen Demand and Nitrate concentration without reagent is described in this paper. According to the different water quality, optical path length of flow cell is variable in this system. A 10mm path length is selected in this paper. And a Y type of structure of quartz optical fibers is used for real-time compensation. Concentration calculation principle is based on the analysis of absorption spectrum and partial least square method. Comparison between model calculation and experimental data is also discussed in detail with several test samples. The implementation of standard test and measurements for the collected water samples is presented in this paper.

10026-38, Session Post

An improved calculation model of weight coefficient for three-dimensional flame chemiluminescence tomography based on lens imaging theory

Ying Jin, Yang Song, Wenchao Wang, Xiangju Qu, Zhenhua Li, Yunjing Ji, Anzhi He, Nanjing Univ. of Science and Technology (China)

Flame tomography of chemiluminescence is a necessary combustion diagnostic technique that provides instantaneous 3D information on flame structure and excited species concentrations. However, in most research, the simplification of calculation model of weight coefficient based on lens imaging theory always causes information missing, which influences the result of further reconstructions. In this work, an improved calculation model is presented to determine the weight coefficient by the intersection areas of the blurry circle with the

square pixels, which is more appropriate to the practical imaging process. The numerical simulation quantitatively evaluates the performance of the improved calculation method. Furthermore, a flame chemiluminescence tomography system consisting of 12 cameras was established to reconstruct 3D structure of instantaneous non-axisymmetric propane flame. Both numerical simulating estimations and experiments illustrate the feasibility of the improved calculation model in combustion diagnostic.

10026-39, Session Post

Study on glucose photoacoustic signals denoising based on a modified wavelet shift-invariance thresholding method

Zhong Ren, Jiangxi Science and Technology Normal Univ. (China) and Nanchang Univ. (China); Guodong Liu, Jiangxi Science and Technology Normal Univ. (China)

During the monitoring of blood glucose concentration by using photoacoustic technique, the photoacoustic signals of blood glucose are easily contamined by noises. The denoising is a necessary work because the polluted photoacoustic signals will seriously impact the prediction precision of glucose concentration. To improve the denoising effect of the glucose photoacoustic signals, a modified wavelet thresholding combined shift-invariance algorithm was used in this paper. Meanwhile, an improved wavelet threshold function was proposed. The improved wavelet threshold function can be regarded as the compromise between the Donoho's hard-threshold function and soft-threshold function because it not only can overcome the pseudo-oscillation, but also can reduce the deviation between the denoised signals and the original signals. In addition, the shift-invariance method was added into the improved algorithm, which will greatly improve the denoising effect. To verify the feasibility of the modified wavelet shift-invariance threshold denoising algorithm, the simulation experiments were performed by using the software MATLAB. In experiments, the standard test signal contained by Gaussian noise was denoised by several different wavelet denoising methods. Results show that the denoising effect of the modified wavelet shift-invariance thresholding algorithm is better than that of others because its signal-to-noise ratio is largest and the root-mean-square error is lest. Finally, the modified wavelet shift-invariance threshold denoising was used to remove the noises of the photoacoustic signals of glucose aqueous solutions. The good denoising effect was obtained. Therefore, the modified wavelet shift-invariance threshold denoising algorithm has a potential value in the denoising of the glucose photoacoustic signals.

10026-40, Session Post

A real-time implementation method of second-order DP algorithm based on FPGA

Chenggang Sun, Shuo Wang, Yiqun Zhang, China Aerospace Science & Industry Corp. (China)

The Dynamic Programming (DP) algorithm is an effective algorithm for target detection?but its detection performance for moving target is low. The faster the speed of target is, the lower detection performance is. In order to solve this problem, we have proposed an improved algorithm (denoted as second-order DP). A second-order random walk model is assumed in the second-order DP for the target state innovations, which improves the DP's target searching accuracy and detection performance. As the second-order model is adopted, the searching process of second-order DP is extended to two steps compared with DP's one step, which highly increases its calculation amount. The process of second-order DP, comparing with DP's process which has one more cycle, makes its calculation amount at least nine times of the DP's. In order for real-time processing of this complex algorithm, we propose a parallel structure for the second-order DP.

The searching process of the second-order DP is a loop structure with three layers: the first layer corresponds to the pixels of the current frame, the second and the third layer corresponds to the pixels in the first and the second search region respectively. So the problem of the parallelization of the second-order DP amounts to the problem of the parallelization of the multi-layer nested loop. We utilize the loop parallelization method to design and realize the parallelization of the second-order DP, which reduces the process time greatly. The parallel algorithm has been used on FPGA successfully. According to the experimental result, the time consumption of the second-order DP can be significantly reduced to the level of that of the traditional DP algorithm.

10026-41, Session Post

Spatial sparse scanned imaging based on compressed sensing

Qiaoyue Zhang, Yuntao He, BeiHang Univ. (China); Yuedong Zhang, Beijing Institute Of Space Mechanics and Electricity (China)

A new passive millimeter-wave(PMMW) image acquisition and reconstruction method is proposed based on compressed sensing(CS) and spatial sparse scanned imaging. In this method, the images are sparse sampled through a variety of spatial sparse scanned trajectories, and are reconstructed by using conjugate gradient-total variation recovery algorithm. The principles and applications of CS theories are described, and the influence of the randomness of the measurement matrix on the quality of reconstruction images is studied. Based on the above work, the qualities of the reconstructed images which were obtained by the sparse sampling method were analyzed and compared. The research results show that the proposed method can effectively reduce the image scanned acquisition time and can obtain relatively satisfied reconstructed imaging quality.

10026-42, Session Post

Design of non-contact optic measurement system for lunar sample sealing device

Chunyong Wang, Lanzhou Institute of Physics (China)

According to the thermal control coatings and of lunar sample sealing device and the requirement of lunar sample sealing device parameters measurement , Non-contact image measurement system is designed and calibrated using Contact measurement system. some relevant experimentation is carried out. Experiment result shows that:the data measeured using Non-contact image measurement system is consistent with contact measurement system ,and Non-contact image measurement can be used to measure characteristic parameters of lunar sample sealing device.

10026-43, Session Post

Short pulse acquisition by low sampling rate with phase-coded sequence in lidar system

Long Wu, Qingheng Zhang, Wentao Lv, Xiaocheng Yang, Jiajia Xu, Jindi Yan, Zhejiang Sci-Tech Univ. (China); Yong

Zhang, Harbin Institute of Technology (China)

Normally lidar systems require the collection and determination of every returned laser pulse for the judgement of object, which works for low frame rate lidar system due to the limited response speed of detectors. It is not practical for imaging lidar system with high resolution, which demands high frame rate as high resolution needs short laser pulses, especially for phase coded lidar systems. This paper proposes a phase coded sequence acquisition method for signal preprocessing through detector. The system employs an m-sequence with N bits for demonstration. The laser pulses are modulated into a phase coded sequences and illuminate targets while the detector is controlled to accumulate N+1 bits of the echo signals with the correlation calculation revealing the time delay of the echo signals. An indoor experiment achieved 2 us resolution with the sampling period of 28 us by employing a 15-bit m-sequence. This method achieves the acquisition of m-sequence with narrow subpulse width whereas the sampling frequency is kept low. This paper also presents the phase coded imaging lidar simulation, which achieved 1.5m range resolution with a 50 kHz sampling frequency by employing a 2047-bit m-sequence. The simulation shows a potential method to improve the detection capabilities of narrow laser pulses with the detectors at a low frame rate, especially for the imaging lidar systems. Meanwhile, the lidar system is able to improve the range resolution with available detectors of restricted performance.

10026-44, Session Post

Measuring the relaxation time of the xenon atoms and the rubidium atoms

Peng Jiang, Zhiguo Wang, Yingying Li, Qiyuan Jiang, Hui Luo, National Univ. of Defense Technology (China)

In the nuclear magnetic resonance gyroscope, the detection of polarization of nuclear spins and motion information is usually achieved by the atomic spin of alkali atoms and noble gas. But the spin parameters of the work atoms are mainly evaluated by the relaxation time. Relaxation time is so important that can influence signal to noise ratio, dynamic range, start time and other parameters of the gyroscope. So its accurate measurement is an important problem in the study of nuclear magnetic resonance gyroscope performance. Here we are given a variety of measurement methods of the transverse relaxation time and the longitudinal relaxation time. First of all, we are given the industry standard methods for measuring spin lifetimes- the Free Induction Decay Method. Then we are also given the improved free induction decay method, the ratio method and the Magnetic resonance broadening fitting method to measure the transverse relaxation time. We are given the flipped polarization method in measuring the longitudinal relaxation time. At the same time by changing the experimental conditions, we get the longitudinal relaxation time with the flipped polarization method under a variety of conditions. Finally, comparing the several methods of measurement, and we can get the best methods of measurement in different conditions.

10026-45, Session Post

Data acquisition and processing platform in the real-time distance measurement system with dual-comb lasers

Kai Ni, Lanlan Wang, Qian Zhou, Xinghui Li, Hao Dong, Xiaohao Wang, Graduate School at Shenzhen, Tsinghua Univ. (China)

The real-time distance measurement system with dual femtosecond comb lasers combines time-of–flight and interferometric measurement. It has advantages of wide-range, high-accuracy and fast speed at the rate about 10000 pts/s. Such a distance measurement system needs dedicated higher performance of the data acquisition and processing hardware platform to support. This paper introduces the dedicated platform of the developed absolute distance measurement system.

This platform is divided into three parts according to their respective functions. First part is the data acquisition module, which function is mainly to realize the A/D conversion. In this part we designed a sampling clock adjustment module to assist the A/D conversion module to sample accurately. The sampling clock adjustment module accept a 250MHz maximum reference clock input, which from the same femtosecond laser source as the optical measurement system, then generate an output clock for the A/D converter that can be delayed up to 20ns with a resolution of 714ps. This data acquisition module can convert the analog laser pulse signal to digital signal with a 14 bits resolution and a 250 MSPS maximum sample rate. Second is the data processing and storage module consists of FPGA and DDR3 modules. The FPGA module calculates the test distance by the 16 bits digital sampling signal from the front data acquisition module. The DDR3 module implements sampling data caching. Finally part is the data transmission and peripheral interfaces module based on three DB9 and USB2.0. We can easily debug the platform in the PC and implement communication with upper machine. We tested our system used dedicate test bench in real-time. The scope of the measurement system range is 0 to 3 meters and the measurement deviation is less than 10um.

10026-46, Session Post

Tunable microfiber nonlinear effects

Shihan Tang, Zhenxing Wu, Fei Xu, Nanjing Univ. (China)

Nano/micro-fibers (NMFs) have unique optical characteristics such as strong confinement of light, which can contribute to the high nonlinearity and be applied in frequency conversion including surface second-harmonic generation and four-wave mixing. Phase matching is a critical issue and depends on the fiber size and dispersion. It is difficult to tune the diameter of a fabricated NMF, however, it is we can much more easily to change the dispersion by controlling the ambient refractive index. A number of common pure and mixed liquids, such as water, methanol, ethanol can be used to shift the dispersion of the NMF and achieve phase-matching condition.

For surface second harmonic generation at the wavelength of 1064 nm phase matching diameter of the air-cladding NMF, is 525 nm. The water- and ethanol- cladding NMF increase the diameter to 767 nm and 832 nm separately. Then we can realize the continuous shift of the dispersion and achieve phase matching condition by controlling the liquid concentration if the diameter of a NMF is in the range of 767 nm – 832 nm, which means that we don't need fabricate a NMF with an accurate diameter.

For degenerate four-wave mixing, the phase matching anti-Stokes and Stokes have the same frequency shift from pump wavelength. Here we investigate two liquid claddings: water and methanol, which have the similar refractive index at 1064 nm. The effective phase mismatch of degenerate four-wave mixing can be expressed as ? =?k+2?P, where ?k is the phase mismatch, ? is the nonlinear coefficient, and P is the pump power. The ? changes with different cladding material and different anti-Stokes (Stokes) frequency shift. When the pump wavelength is 1064 nm, the peak power is 2.2 kW and the diameter of 1.7 ?m, the phase matching anti-Stokes (Stokes) wavelengths of a water-cladding and a methanol-cladding NMF, is 689 nm (2334 nm) and 657nm (2792 nm), respectively. It shows that we can get tunable visible and infrared sources by mixing water and methanol.

10026-47, Session Post

Comparison of correlation algorithms with correlating Shack-Hartmann wave-front images

Hangcheng Zhou, Lanqiang Zhang, Lei Zhu, Hua Bao, Youming Guo, Xuejun Rao, Libo Zhong, Changhui Rao, Institute of Optics and Electronics (China)

Correlating Shack-Hartmann wavefront sensor is widely used in solar adaptive optics in which the relative shift between different subapertures by correlation algorithm is computed, and then the control voltage by wavefront reconstruction can be estimated to use for correcting the wavefront distortion induced by atmospheric turbulence. In this paper, several different correlation algorithms including Cross-Correlation Coefficient, Absolute Difference Function, Absolute Difference Function-Squared, and Square Difference Function are used to estimate relative shift in correlating Shack-Hartmann wavefront sensor with the different observed solar structure such as sunspot, solar pore and solar granulation. The measurement noise RMS error is computed to compare the performance of the correlation algorithms. The results show the correlation algorithm precision is directly related to the solar structure. The measurement noise is relatively small with the relatively high contrast target, and vice versa. At the same time, the size of reference image also could influence the measurement noise, the larger size of the reference image, the smaller the measurement noise is.

10026-48, Session Post

Impacts of PM concentrations on visibility impairment

Guo Jie, Hangzhou Zetian Technology Co. Ltd. (China); Yu ZhiWei, Hangzhou Zetian Technology Co., Ltd. (China)

Visibility, as a standard of human visual perception of the environment, and has directly associated with air quality and atmospheric climate. Recently, atmospheric visibility range degradation has become an environmental issue in most urban areas in China. PM2.5 are believed to be mostly responsible for the scattering and absorption of visible light and to cause the decrease of visibility. In the paper, an accurate and sensitive cavity attenuated phase shift spectroscopy (CAPS) sensor was used to monitor the atmospheric visibility. The optical sensor mainly includes a LED light source, a band-pass filter, an optical resonant cavity (composed of two high mirror, reflectivity is greater than 99.99%), a photoelectric detector and a lock-in amplifier. The 2L / min flow rate, the optical sensor rise and fall response time is about 15 s, so as to realize the fast measurement of visibility. For a month to monitor the air quality in Hangzhou, atmospheric visibility measurement results from optical sensor, PM10 and PM2.5 mass from Hangzhou monitoring station standard analysis equipment. Air temperature and humidity datas are also from the monitoring station. The monitoring results show that the correlation between the atmospheric extinction coefficient and PM is very high, and the correlation between the extinction coefficient and PM10 is more than 0.9. Elevated PM2.5 mass was associated with visibility (Vr<10 km), and a PM2.5 threshold value of 90μg /m3 (i.e., low visibility occurs when PM2.5 > 90 μg /m3).

10026-49, Session Post

A novel scattered pilot-aided channel compensation for CO-OFDM systems

Haoran Sun, Yong Yao, Harbin Institute of Technology (Chile)

A new pilot structure is developed aiming at improving both spectral efficiency and accuracy. Two groups of scattered pilots are inserted in one training symbol. In each group, the scattered pilots are inserted with the same space just like the conventional scattered pilots.

For each group, the scattered channel response corresponding to the scattered pilots are firstly estimated through LS algorithm. Secondly, the whole channel response is estimated through linear interpolation.Then intra-symbol frequency domain averaging method is used to further improve the accuracy. What sets it apart from the conventional method is we take the average of the two groups' channel response.

We have simulated the channel equalization method in CO-OFDM transmission systems and numerically studied its transmission performance over a 100 km optical fiber link at 40 Gb/s.For convenience we define the pilot filling ratio as ?=(pilot number)/(subcarrier number). It is found that the proposed method have a 0.25dB improvement performance relative to the conventional method when ? is both 50 ? to achieve the BER of 10-3 . The proposed ?=17? offers a similar performance to the conventional ?=50?, and has about 0.5dB and 1.1dB improvement correspond to the conventional ?=33? and ?=25? to achieve the BER of 10-3. The spectral efficiency of the proposed method has been improved considerably.

10026-50, Session Post

Video coding for 3D-HEVC based on saliency information

Fang Yu, Ping An, Shanghai Univ. (China)

As an extension of High Efficiency Video Coding (HEVC), 3D-HEVC has been widely researched under the impetus of the new generation coding standard in recent years. Compared with H.264/AVC, its compression efficiency is doubled while keeping the same video quality. However, its higher encoding complexity and longer encoding time are not negligible. To reduce the computational complexity and guarantee the subjective quality of virtual views, this paper presents a novel video coding method for 3D-HEVC based on the saliency information which is an important part of Human Visual System (HVS). First of all, the relationship between the current coding unit and its adjacent units is used to adjust the maximum depth of each largest coding unit (LCU) and determine the SKIP mode reasonably. Then, according to the saliency information of each frame image, the texture and its corresponding depth map will be divided into three regions, that is, salient area, middle area and non-salient area. Afterwards, different quantization parameters will be assigned to different regions to conduct low complexity coding. Finally, the compressed video will generate new view point videos through the renderer tool. As shown in our experiments, the proposed method saves more bit rate than other approaches and achieves up to highest 38% encoding time reduction without subjective quality loss in compression or rendering.

10026-51, Session Post

Research on the laser tracking system for measuring moving target based on APD

Liu Hua, Liu Ke, Yinxiao Miao, Beijing Aerospace Institute for Metrology & Measurement Technology (China)

In order to measure the coordinate of moving target, the laser tracking system for measurement of moving target was proposed,in which the receiver of four-quadrant APD was adopted as the detector and the DC motor was used to drive the reflector to move in two dimensions. The principle of the measurement system was analyzed first.Then the main part of the system was introduced.The tracking experiment showed that ,this system could realized the function of automatic tracking and measuring the coordinate of moving target according to the pulsed laser ranging and angle sensors.

10026-19, Session 5

Time-stretch imaging system with OTDM detection scheme *(Invited Paper)*

Xu Wang, Heriot-Watt Univ. (United Kingdom); Bo Dai, Univ. of Shanghai for Science and Technology (China)

The time-stretch imaging system has the capability of ultra-fast information acquisition. We demonstrate a 38.88 MHz line-scan time-stretch imaging system in which multiplexing detection scheme is used to double the number of pixels. A 20 GS/s sampling rate is achieved by employing a 10 GS/s electronic digitizer so that aliasing problem can be addressed. The proposed scheme can improve the image quality by 4.16 dB comparing to the conventional system and has a better performance of at least 2.3 dB image enhancement in contrast to the numerical interpolation and re-sampling techniques.

10026-20, Session 5

High-throughput optofluidic profiling of euglena gracilis with morphological and chemical specificity *(Invited Paper)*

Baoshan Guo, Cheng Lei, Takuro Ito, Yiyue Jiang, Yasuyuki Ozeki, Keisuke Goda, The Univ. of Tokyo (Japan)

The world is faced with environmental problems and the energy crisis due to the combustion and depletion of fossil fuels. The production of biofuel from Euglena gracilis is expected to become a practical solution due to their fast growth rates and cultivation on non-arable land areas. However, their lipid productivity is still a problem for E. gracilis to be an economically realistic biofuel feedstock. One potential way is to use lipid-induced E. gracilis. Hence, effectively classifying the lipid-induced E. gracilis is necessary for high-efficiency biofuel production. Here we present a high-throughput optofluidic Euglena gracilis profiler which consists of an optical time-stretch microscope and a fluorescence analyzer on top of an inertial-focusing microfluidic device that can detect fluorescence from lipid droplets in their cell body and provide images of E. gracilis cells simultaneously at a high throughput of 10,000 cells/s. Lipid-induced and fresh E. gracilis are used as an example. With the multi-dimensional information, we can classify the lipid-induced E. gracilis cells from fresh cells more precisely than traditional microscopy and fluorescence analysis without sacrificing throughput. The error rate of identifying lipid-induced E. gracilis can drop to ~1%, which is over 10% with only one-dimensional information. This method provides a promise for evaluating the efficiency of lipid-inducing techniques for biofuel production. The integrated system is also potentially applicable for identifying biomedical samples such as blood cells and cancer cells.

10026-21, Session 5

High-throughput optofluidic microalgal cell analyzer with single-cell resolution for biofuel production *(Invited Paper)*

Cheng Lei, The Univ. of Tokyo (Japan); Takuro Ito, Keio Univ. (Japan); Dino Di Carlo, Univ. of California, Los Angeles (United States); Yasuyuki Ozeki, Keisuke Goda, The Univ. of Tokyo (Japan)

The development of reliable, sustainable, and economical sources of alternative fuels is an important, but challenging goal for the world. As an alternative to liquid fossil fuels, algal biofuel is expected to play a role in solutions to global warming since algae absorb atmospheric CO2 via photosynthesis. Among various algae for fuel production, Euglena gracilis is an attractive microalgal species as it is known to produce wax ester and triacylgricerol within lipid droplets. To date, while there exist many techniques for inducing microalgal cells to produce lipid with high efficiency, few analytical methods are available for characterizing a heterogeneous population of such lipid-induced microalgae including E. gracilis with single-cell resolution. To address the need, we demonstrate a high-throughput label-free single-cell image analyzer at 15,000 cells/s based on time-stretch microscopy and microfluidic techniques for classifying live lipid-induced E. gracilis cells under different culture conditions. From our statistical image analysis, we identify cell-to-cell differences in intracellular phenotypes between various culture conditions including nitrogen deficiency for lipid induction. This result indicates that our method is an effective tool for evaluating the outcome of lipid induction techniques in a rapid and non-invasive manner and holds promise for optimizing the efficiency of biofuel production based on E. gracilis and potentially other microalgae.

10026-22, Session 5

Four-dimensional visualization of a small-scale flame based on deflection tomography *(Invited Paper)*

Bin Zhang, Zhigang Liu, Minmin Zhao, Qingdao Univ. of Science and Technology (China)

Optical computed tomography plays an important role in visualizing and diagnosing various flow fields. Deflection tomography with limited angle projections was investigated to visualize a small-scale premixed flame. A projection sampling system for deflection tomography was presented to obtain the chronological deflectograms with a pair of gratings. The deflectograms were processed based on wave-front retrieval to obtain the deflection angles of the rays. This two-dimensional data extraction method expanded the usability of deflection tomography and was suitable for the projection extraction of small-scale combustion. Temperature distributions in 10 cross sections for each deflectogram were reconstructed in different instants. The Sobel operator was applied to the threshold segmentation of two-dimensional temperature distributions. Visualization tool kit with the marching cube and ray casting algorithms was employed to reconstruct the flow structure. The experiment demonstrated three-dimensional dynamic visualization of the temperature distributions and the flame structures of a small-scale premixed combustion. The experimental reconstruction was then compared with the result obtained from computational fluid dynamic analysis.

10026-23, Session 5

Morphology-based cancer detection with optofluidic time-stretch microscopy

Hirofumi Kobayashi, Cheng Lei, Ailin Mao, Yiyue Jiang, Baoshan Guo, Keisuke Goda, The Univ. of Tokyo (Japan)

Cancer cell detection plays an important role in biomedical research and clinical diagnosis. It is believed that cancer metastasis, which is the primary cause of cancer deaths, occurs via circulating tumor cells (CTCs) – precursors to cancer that trigger the spread of cancer. Detecting CTCs in the blood is expected to be helpful for cancer diagnosis and treatment at its early stage. However, CTCs are extremely rare, and hence, it takes a considerable amount of time to detect CTCs with current methods, such as centrifugation, inertial focusing, and fluorescence- or magnetic-activated cell sorting, which either have low throughput, low specificity, or low sensitivity. To address these problems, we propose and experimentally demonstrate morphology-based cancer detection with optofluidic time-stretch microscopy using breast cancer cells (MCF-7). By properly controlling the condition of the treatment, MCF-7 cells express unique morphological changes, which can be used as natural morphological markers for our image-based detection. Our optofluidic time-stretch microscope consists of a time-stretch microscope with a high spatial resolution of 780 nm at a 1D frame rate of 75 MHz, a microfluidic device that focuses and orders cells, and an image analyzer that identifies the cancer cells from blood cells via the morphological biomarkers. With these biomarkers, we successfully detect breast cancer cells spiked in blood cells with a high throughput of 10,000 cells/s. The technique holds great promise for cancer diagnosis.

10026-24, Session 5

High-throughput time-stretch imaging cellular assay based on a DVD spinning platform

Anson H. L. Tang, Antony C. S. Chan, Kelvin C. M. Lee, Edmund M. Y. Lam, Kenneth K. Y. Wong, Kevin K. Tsia, The Univ. of Hong Kong (Hong Kong, China)

Innovations in imaging flow cytometry together with biochemical labeling technologies have successfully realized high throughput single-cell monitoring with multiparametric diagnostics. However, classical approaches still run short of extracting biophysical knowledge of cells. Several approaches have been established for cell biomechanics studies, for example, cell stiffness studies through microfluidic forces, and adherent force determination by non-imaging spinning disk system. The throughput of these image-based methods is primarily limited by the compromise between static field-of-view (FOV) and imaging speed (fps) in standard imaging sensors. Alternative methods such as automated microscope systems incorporating high-speed camera and mechanical scanning devices can image with a large FOV without sacrificing image resolution. However, the throughput is still inherently bottlenecked by the mechanical inertia. We here report a new type of imaging cellular assay on which the cells are fixed on a solid spinning substrate at known radial position and rotational speed. We implement this assay by modifying a commercial digital versatile disc (DVD) drive such that the rotational speed can arbitrarily and stably controlled. Human breast cancer cells (MCF-7) are pre-cultured on polycarbonate substrates, which are essentially the commercial DVD, and imaged under high spinning speed (900 rpm). The system, integrated with time-stretch imaging, can provide cellular resolution (~2 μm in radial direction) at high line-scan rate (11 MHz) and wide arbitrary spinning rate (900-4000 rpm). We also discuss strategies to implement studies on circulating tumor cells (CTC) based on our current system.

10026-25, Session 5

Survey of the baseline correction algorithms for real-time spectroscopy processing

Yuanjie Liu, Yude Yu, Institute of Semiconductors (China)

In this paper, we will survey and evaluate several widely used baseline correction algorithms, including Shirley background, CROMWELL, LIMPIC, airPLS, AIMA and corner cutting methods. These algorithms are able to detect the baseline drift of one dimensional spectroscopy data trace and remove it automatically. However, each method has particular range for application. Some are limited to the monotone decreasing assumption, some are not able to treat the situation when baseline behaves complex fluctuation. This paper will analyze the function and performance of each method, summarize each one's features and draw a clear map for understanding the defects and advantages for the choice of them in practical use. The baseline correction approaches are categorized according to several patterns, for example, by the basic techniques based on: wavelet decomposition, polynomial fitting or adaptive integration; then, by their computing manners: global iteration, key points interpolating or random mixing. Finally, all of these algorithms will be tested and evaluated under a specific criteria- SVM gap gain, for performance ranking. The evaluating procedure will assess each algorithm quantitatively to present an order for choice under various situation. This result will be the first time to propose a concrete list for guidance in baseline correction processing when carrying out practical spectroscopy analysis.

10026-26, Session 5

Automated classification of phytoplanktons based on time-stretch imaging

Queenie Tsz Kwan K. Lai, Andy K. S. Lau, Kelvin C. M. Lee, Anson H. L. Tang, Kenneth K. Y. Wong, Kevin K. Tsia, The Univ. of Hong Kong (Hong Kong, China)

Optical time-stretch imaging can capture single-cell images with high sensitivity (e.g. high resolution) and throughput (>MHz line scan rate). With such advantages, optical time-stretch imaging flow cytometry has profound impact in the biomedical (e.g. rare cancer cell detection) and biological research fields. However, its potential in marine research has not been fully explored. Phytoplankton serves as foundation of carbon cycle and ecosystem, and a remarkable indicator for the aquatic system health and water quality but there is lack of efficient methods for profiling single-cell of phytoplankton other than manual inspection. Optical time-stretch imaging could fulfil the unmet need to classify and count ultralarge-scale phytoplankton with single-cell analysis in marine or biofuel research. So far, two-class classification involving manual inspection (e.g. gating) has been the common approach implemented with time-stretch imaging flow cytometry. These current methods are however incompatible with the need for multi-class classification on large amount of images with cells of multiple classes. We here report an automated multi-class classification of phytoplankton based on high-resolution time-stretch imaging. Specifically, we extracted a total of 40 features from the grey-scale time-stretch images including various geometrics – size, circularity, elongation factor and morphological information – contrast, energy ,entropy as higher dimensional features for automated classification by using support vector machine (SVM) as the training approach to identify more than 10 species of phytoplankton with a cross-validated accuracy of >90%. Optical time-stretch imaging flow cytometry could be an efficient and effective tool to achieve single-cell counting and analysis, especially for continuous monitoring of the aquatic system from tidal to seasonal.

10026-27, Session 5

Research of aerial imaging spectrometer data acquisition technology based on USB 3.0

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With the emergence of UVA (unmanned aerial vehicle) platform for aerial imaging spectrometer,research of aerial imaging spectrometer DAS(data acquisition system) faces new challenges. Due to the limitation of platform and other factors, the aerial imaging spectrometer DAS requires Light-weight and compact ,low-cost and universal. Traditional aerial imaging spectrometer DAS system is expensive, bulky, non-universal and unsupported plug-and-play based on PCIe.So that has been unable to meet promotion and application of the aerial imaging spectrometer.

In order to solve these problems, the new data acquisition scheme bases on USB3.0 interface.USB3.0 can provide guarantee of Light-weight and compact, low-cost and universal relying on the forward-looking technology advantage. USB3.0 transmission theory is up to 5Gbps.And the GPIF programming interface achieves 3.2Gbps of the effective theoretical data bandwidth.USB3.0 can fully meet the needs of the aerial imaging spectrometer data transmission rate.The scheme uses the slave FIFO asynchronous data transmission mode between FPGA and USB3014 interface chip. Firstly system collects spectral data from TLK2711 of high-speed serial interface chip.Then FPGA receives data in DDR2 cache after ping-pong data processing. Finally USB3014 interface chip transmits data via automatic-dma approach and uploads to PC by USB3.0 cable.

During the manufacture of aerial imaging spectrometer, the DAS can achieve image acquisition, transmission, storage and display. All functions can provide the necessary test detection for aerial imaging spectrometer. The test shows that system works stably and no data lose. Average transmission speed and storage speed of writing SSD can stabilize at 1.28Gbps . Consequently ,this data acquisition system can meet application requirements for aerial imaging spectrometer.

10026-28, Session 6

GeSn/SiGeSn photonic devices for mid-infrared applications: experiments and calculations *(Invited Paper)*

Genquan Han, Xidian Univ. (China); Qingfang Zhang, Chongqing University (China); Yan Liu, Xidian University (China); Chunfu Zhang, Xidian (China); Yue Hao, Xidian Univ. (China)

GeSn and SiGeSn alloys as the new photonic materials for mid-infrared optoelectronic monolithic integration have attracted tremendous interests, for their tunable bandgap and the compatibility with Si CMOS technology. Adding Sn to Ge to form the GeSn alloy can cause the lowering of the bandgap and the transition of indirect-to-direct bandgap, which can promote the red-shift of the cut-off wavelength and the emission peak at the same time. We will report the experimental results of GeSn photodetectors with operation wavelength in 2-5 ?m midinfrared region, which have many potential applications, such as chemical-biological-physical sensing, medical diagnostics, environmental monitoring, active imaging, and free-space laser communications. Furthermore, applying tensile strain to GeSn can lead to a further red-shift by lowering the energy of ? conduction valley. In this work, we also introduce the novel tensile strained GeSn/SiGeSn detector, modulator, and LED/laser devices wrapped in Si3N4 liner stressor for mid-infrared optoelectronic applications. As the releasing of the residual stress in Si3N4 liner, a large tensile strain is induced into GeSn layer, which will significantly improve the device performance and shift the operation wavelength to midinfrared region.

10026-29, Session 6

New method of writing long-period fiber gratings using high-frequency CO2 laser

Gaoran Guo, Institute of Semiconductors (China); Ying Song, Shijiazhuang Tiedao Univ. (China); Wentao Zhang, Li Fang, Institute of Semiconductors (China)

Long period fiber grating (LPFG) has found increasing application in optic communication and sensing systems. LPFGs are widely used to fabricate fiber sensors, gain-flattening filters, wavelength rejection filters, and tunable filters because of its advantages, such as the low insertion losses, low background back-reflection, polarization independence, and relatively simple fabrication. LPFG allows light coupling between the fundamental mode and the cladding modes in the same direction, which results in several attenuation bands centered at discrete wavelengths in the transmission spectrum.

In the paper, the LPFGs were fabricated in a single-mode fiber using a high frequency CO2 laser system through the point-to-point technique. The experimental setup consists of a CO2 laser controlling system, a beam and a focusing system located at a motorized translation stage, a fiber alignment stage, and a measuring system for the transmission spectrum of the LPFG.

In our configuration, the period of the LPFG is precisely controlled by periodically turning on/off the laser shutter and meanwhile the motorized translation stage is driven to move forward at a constant speed. The heating process is more stable in this way. For LPFG's spectrum measurement, an amplified spontaneous emission (AE) source and an optical spectral analyzer (OSA) are used. The experiment of one-time writing LPFG is performed. It not only improves the efficiency of fiber writing process, but also solves the problem of point-to-point mismatching in the conventional multi-writing process.

10026-30, Session 6

Two-step phase-shifting SPIDER

Shuiqin Zheng, Shixiang Xu, Shenzhen Univ. (China)

Comprehensive characterization of ultrafast optical field is critical for ultrashort pulse generation and its applications. This paper presents a novel method to improve the optical-field reconstruction of ultrashort pulses by combining two-step phase-shifting (TSPS) with the spectral phase interferometry for direct electric-field reconstruction (SPIDER). The method records two spectral interferograms with ϖ phase-shifting to remove experimentally the effect of the dc portion occurring in traditional SPIDER method. Our results show the method can remove experimentally the effect of the dc portion occurring in traditional SPIDER method. Compared with the traditional SPIDER measurement, the method makes the reconstructed results be much less disturbed by the time delay ? between the test pulse replicas and the width of filtering temporal window ?w, so the measurements become more reliable and robust. What is more, the absence of the dc component allows SPIDER device to work efficiently even the time delay ? is so small that strong overlap happens between the dc and ac portions. Consequently, the SPIDER device can choose ? more flexibly, which extends no doubt the ability of the SPIDER device to characterize the pulses both with complicated temporal/spectral structures and with narrow bandwidth. We believe this work will not only enlarge the

application fields of SPIDER, but also be very helpful to improve the diagnosis quality of ultrashort pulses for the laboratories possessing a traditional SPIDER device, because our TSPS SPIDER just needs actually a traditional SPIDER device plus a quarter-wave plate.

10026-31, Session 6

The study of in-line DFB-tunable laser based on REC technique

Renjia Guo, Hao Wang, Jun Lu, Yuechun Shi, Xiangfei Chen, Nanjing Univ. (China)

An in-line structure, current-tuned tunable laser based on REC technique is design, test and studied. Through 3 in-line DFB lasers with a wavelength spacing of about 3.2nm, continues tuning range of about 11nm is obtained. At the temperature of 20 °C, each laser can be tuned about 3.4-3.6 nm with SMSRs over 35 dB from 30 to 170 mA, and the tuning speed is about 10-30 microseconds, which is much faster than that by the thermal-electric cooler (TEC). The algorithm to obtain an equal output power in such current tuning is also studied for this in-line laser. The results may help to realize very low cost tunable lasers in the future.

10026-32, Session 6

Characterization of phase-shifted Brillouin dynamic gratings in a polarization maintaining fiber

Dengwang Zhou, Yongkang Dong, Pengbai Xu, Lei Teng, Harbin Institute of Technology (China); Hongying Zhang, Harbin Univ. of Science and Technology (China); Zhiwei Lu, Harbin Institute of Technology (China)

We numerically calculate and experimentally investigate the characterization of phase-shifted Brillouin dynamic gratings (PS-BDGs) in a polarization maintaining fiber (PMF). A phase shifted point is induced into the middle of a conventional BDG through phase-modulating one of the two pump pulse, generating a PS-BDG thanks to the stimulated Brillouin scattering (SBS). When the frequency difference between a high frequency pump1 pulse with 1ns and ϖ-1ns and a low frequency pump2 pulse with 100ps is equal to the Brillouin frequency shift of the PMF, a transient PS-BDG with a 3dB-bandwidth of 354MHz of the notch spectrum is simulated based on the coupled-wave equations of BDG. By increasing the repetition rate up to 250MHz, an enhanced PS-BDG with a deep notch depth is obtained since the residual acoustic wave of the former SBS process is enhanced by the optical waves of the latter SBS process. Then a proof-of-concept experiment is built to verify the transient PS-BDG and the results show that the notch feature is consistent with the simulation results and the notch frequency of the PS-BDG can be changed by tuning the phase shift . The proposed PS-BDGs have important potential applications in optical fiber sensing, microwave photonics, all-optical signal processing and RoF (radio-over-fiber) networks.

10026-33, Session 7

Detection of low-power RF signals using a tunable optoelectronic oscillator

Yuchen Shao, Dalian Univ. of Technology (China); Ming Li, Institute of Semiconductors (China); Xiuyou Han, Mingshan Zhao, Dalian Univ. of Technology (China)

The detection of very low-power radio-frequency (RF) signals in a cluttered environment is very important in many applications such as electronic warfare and radio astronomy. Photonic technique offers a potential way to implement the role with the advantages of wide band, small size and immunity to electromagnetic interference. In this paper, a novel method to detect low-power RF signals with the frequency selective amplification is proposed and experimentally demonstrated.

The detection system is assembled with a tunable optoelectronic oscillator (OEO), which is mainly composed of a tunable laser source, a phase modulator and a phase-shifted fiber Bragg grating (PS-FBG) with a narrow notch in the reflection band. The principle to detect low-power signal is: The OEO works at the threshold state. When the low-power RF signals are fed to the RF input port, the RF signal with a frequency matching the oscillation frequency of the OEO is selected and amplified by the oscillation gain. The oscillation frequency can be tuned by changing the frequency difference between the frequency of the TLS and the notch frequency of the PS-FBG.

The proposed low-power RF signal detection system is evaluated. The results show that the established tunable OEO can detect the RF signal as low as -75 dBm with a dynamic range of 80 dB. The RF signal with frequency from 1.5 to 4.5 GHz is selectively detected with a gain of about 7 dB. The detectable frequency range could be extended by a PS-FBG with a large reflection band.

10026-35, Session 7

Fiber-optic sensing system for simultaneous measurement of temperature and transversal loading based on a microwave photonic filter

Shiwei Zhang, Rui Wu, Hao Chen, Hongyan Fu, Xiamen Univ. (China)

Fiber-optic sensors have attracted much research attention due to their overwhelming advantages, and have been successfully applied to remote sensing and parameter measuring. In this paper, a fiber-optic sensing system for simultaneous measurement of temperature and transversal loading based on a single-passband RF filter has been proposed and experimentally demonstrated. This sensing system consists of a fiber Mach-Zehnder Interferometer (FMZI) as the sensing device and a dispersive medium. The FMZI also acts as the spectrum slicer to induce continuous sampling, which results in the single-passband frequency response together with the dispersive medium. Two arms of the FMZI are used to measure the temperature and transversal loading respectively. The temperature changes on one arm will introduce the variation of refractive index, which will change the central frequency of the RF filter's passband, while the transversal loading will induce the change of polarization state of the light transmitted in the other arm, and thus the amplitude of the RF filter's passband will be changed accordingly. By tracking the central frequency and the amplitude changes of the RF filter's passband, the temperature and transversal loading can be monitored simultaneously. With the proposed fiber-optic sensing system, the temperature and transverse loading variation induced optical spectra changes can be converted to the variation of frequency and amplitude of the RF filter's passband, which greatly facilitates the measurement. Meanwhile, this proposed sensing system is simple in construction, easy to implement and suitable for multiplexing and remote sensing, thus shows good potential in practical applications.

10026-36, Session 7

Pump sweeping time evaluation of stimulated Brillion scattering-based rectangular optical filter

Mengyue Shi, Lilin Yi, Wei Wei, Weisheng Hu, Shanghai Jiao Tong Univ. (China)

Optical narrowband filtering ranging from MHz to several GHz plays an important role in high-resolution optical signal processing, especially in the context of flexible switching in high speed optical transmission systems [1] and band-pass filtering in microwave photonics [2]. An ideal tunable passband filter has a rectangular response consisting of an ultra-flat passband and very steep edges which bring about many benefits. We have realized rectangular optical filters with tunable bandwidth from 50MHz to 4GHz based on stimulated Brillouin scattering (SBS) in optical fiber [3-4]. Both multi-tone pump and sweeping pump schemes have been used to generate rectangular Brillouin pump spectra and feedback control scheme has been used to compensate the non-flat frequency response of the used opt-electronics components therefore achieving rectangular SBS gain spectra. In comparison, sweeping pump scheme can achieve better rectangular shape since no four-wave mixing (FWM) effects happen within pump spectra therefore no out-of-band SBS gain is generated. The pump sweeping time is a key parameter to achieve both flat spectral response and acceptable signal performance. In the previous experiment, the frequency sweeping duration is set at 1 us, which is much shorter than the signal propagation time in fiber and can achieve effective feedback compensation as well [4]. The seeping time is very important especially for short-fiber cases. However, the optimal pump sweeping time has not been extensively studied yet.

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10027-203,

Quantum dot photonics: from science to practical implementation

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Recent advances in growth and physics of quantum dots have led to the commercialization of quantum dot lasers for telecommunications and other applications. Moreover, single quantum dots coupled to photonic crystal nanocavities have enabled the investigation of fundamental physics such as solid-state cavity quantum electrodynamics (QED). In this presentation, we discuss the current state of the art of quantum dot lasers, and also future prospects including their application to hybrid silicon photonics and the development of ultra-small nanolasers. We also describe the demonstration of a single photon emission from a III-Nitride nanowire-based quantum dot operating above room temperature.

10027-1, Session 1

Recent advances in chip-scale grooming optical data processing on silicon platform *(Invited Paper)*

Jian Wang, Huazhong Univ. of Science and Technology (China)

Silicon photonics is considered to be a promising photonic integration platform enabling chip-scale optical data processing. We will review our recent advances in chip-scale grooming optical data processing on silicon platform. Using designed and fabricated silicon nanophotonic devices, we demonstrate various optical data processing functions: 1) chip-scale wavelength/polarization/mode (de)multiplexing; 2) chip-scale wavelength conversion of advanced modulation formats; 3) chip-scale bidirectional optical data exchange; 4) chip-scale two-input and three-input high-base optical computing (addition, subtraction, hybrid addition/subtraction); 5) chip-scale optical coding/decoding; 6) chip-scale optical signal regeneration. The experimental results show favorable operation performance of chip-scale grooming optical data processing on silicon platform.

10027-2, Session 1

Group IV compounds for micrometre scale device and systems *(Invited Paper)*

Frederic Y. Gardes, Univ. of Southampton (United Kingdom)

No Abstract Available

10027-3, Session 1

Large-scale silicon optical switches for optical interconnection *(Invited Paper)*

Lei Qiao, Tao Chu, Chinese Academy of Sciences (China)

Large-scale optical switches are greatly demanded in building optical interconnections in data centers and high performance computers (HPCs). Silicon optical switches have advantages of being compact and CMOS process compatible, which can be easily monolithically integrated. However, there are difficulties to construct large ports silicon optical switches. One of them is the non-uniformity of the switch units in large scale silicon optical switches, which arises from the fabrication error and causes confusion in finding the unit optimum operation points. In this paper, we proposed a method to detect the optimum operating point in large scale switch with limited build-in power monitors. We also propose methods for improving the unbalanced crosstalk of cross/bar states in silicon electro-optical MZI switches and insertion losses. Our recent progress in large scale silicon optical switches, including 64 ? 64 thermal-optical and 32 ? 32 electro-optical switches will be introduced. To the best our knowledge, both of them are the largest scale silicon optical switches in their sections, respectively. The switches were fabricated on 340-nm SOI substrates with CMOS 180-nm processes. The crosstalk of the 32 ? 32 electro-optic switch was -19.2dB to -25.1 dB, while the value of the 64 ? 64 thermal-optic switch was -30 dB to -48.3 dB.

10027-4, Session 1

Silicon photonics process development based on a 200-mm CMOS platform

Zhihua Li, Jiang Yan, Bo Tang, Guilei Wang, Lingkuan Meng, Institute of Microelectronics (China)

Silicon photonics, which takes advantages of the mature silicon CMOS manufacturing infrastructure, has attracted much attention for its potential to realize massive commercial application in optical communication and interconnection. Though compatible with Si CMOS process is the greatest advantage for silicon photonics compared with other photonic devices based on III-V compound semiconductor or planar lightwave circuit (PLC), there are some different processes between silicon photonics and silicon CMOS that need to be developed before reliable silicon photonics fabrication. In this paper, the process difference between silicon photonics and silicon CMOS is discussed and process development for silicon photonics based on a 200 mm CMOS platform is presented. Firstly, the sensitivity of process parameters of waveguide is studied which are not attached so much importance in CMOS process. Process control including waveguide dimension, Line-edge roughness (LER), steepness and etching without stop layer are then introduced. Ion implantation for photonic active devices can be transferred from existing CMOS process module, but the implant depth and density should be adjusted according to the device structure, which is analyzed next. The germanium process is applied in CMOS fabrication to improve the carrier mobility in recent years and it can also be used for silicon photonics to integrate photodector. The optimization of germanium epitaxy on silicon and electrode metallization for photodector purpose is presented. Finally, a complete silicon photonics process flow including passive and active components developed in our 200 mm CMOS platform is presented.

10027-5, Session 1

Double Doppler effect in two-dimensional photonic crystal with negative effective index

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Inverse Doppler effect in photonic crystal (PhC) was proved

experimentally by our team in 2011. In this paper, we studied the double Doppler effect in PhC with negative refractive index, using a triangular silicon rod array prism with a vertex angle of triangle geometry of 30°. The FDTD simulation showed the normal incident light exits from the slope of PhC on both sides of the normal of the slope. The main spatial harmonic components were extracted from the Bloch wave propagating in the photonic crystal by using Fast Fourier Transform and inverse Fourier Transform.The phase evolution of these two main harmonic components were analyzed, one of them showed unusual character that the direction of phase velocity is opposite to the wave vector direction, as vp·k <0, which leads to the negative refraction, and the other showed normal feature, as vp·k >0, leading to the normal refraction. To verify the Doppler phenomenon in this photonic crystal, a dynamic FDTD method was improved, in which the electric field data and magnetic field data of the former time were added to the newly field data of the later time to form a new field data as the initial field for each object moving step. With this new FDTD method, the Doppler effect was studied at four different velocities, as 0.005c, 0.008c, 0.02c and 0.05c. The simulation exhibited the normal and inverse Doppler effect happened in this photonic crystal simultaneously, and the simulative Doppler frequency shifts were consistent with the theoretical values

10027-6, Session 2

III-V quantum dot lasers monolithically grown on Si platform *(Invited Paper)*

Huiyun Liu, Jiang Wu, Univ. College London (United Kingdom)

No Abstract Available

10027-7, Session 2

Optical deposition of topological insulator bismuth telluride for Q-switched ytterbium fiber laser

Muhammad Aizi Mat Salim, Univ. of Malaya (Malaysia) and Univ. Teknologi Malaysia (Malaysia); Harith B. Ahmad, Saaidal Razali Azzuhri, Mohd Zulhakimi Ab Razak, Sulaiman Wadi Harun, Univ. of Malaya (Malaysia)

We have demonstrated a Q-switched ytterbium-doped fiber laser (YDFL) based on a few-layer bismuth telluride Bi2Te3 saturable absorber (SA). A few layer bismuth telluride within a suspension was bringing onto a fiber ferrule through an optical deposition method at room temperature. Stable pulsed was obtained at 88.6 mW pump threshold. The Q-switched repetition rate varied from 17.00 to 29.63 kHz. The maximum pulse energy and narrowest pulse width were 3.37 nJ and 14.54 ?s respectively. Therefore, this showed that bismuth telluride was also well suited at 1 ?m region, and considered as a potential saturable absorber for generation of short pulses.

10027-8, Session 2

Studies on the amplified spontaneous emission of a polymer fiber

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The random lasers attract worldwide attentions for the merits, such as the miniature in volume and simplicity in structures. In recent years, the polymer materials have been used in random lasers for their high luminescence efficiency. The amplified spontaneous emission is an important property when the polymer material is lighted by external pump laser.

In this paper, a polymer fiber was constructed by siphoning the xylene solution of a polymer into a capillary tube with 300 ?m inner diameter. After the solvent evaporating, the polymer fiber was lighted by an external pump beam and the amplified spontaneous emission (ASE) of the polymer fiber is investigated. The optical photos show the details of polymer fiber. The emission spectra are recorded, and the intensity and the full width at half maximum (FWHM) as a function of pump power intensity are analyzed. The absorption coefficient of polymer F8BT is obtained from a polymer F8BT film with a thickness of 200 nm. For the high absorption of polymer, the pump beam can not penetrate the long F8BT fiber. However the ASE can been detected along the fiber for the low absorption around 567 nm. The sketch up diagram and an optical photo show it in vividly.

This fabrication method provides a cheap way for application of micro polymer fiber.

10027-9, Session 2

Erbium integration in silicon-slotted photonic devices for light amplification

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Achieving light sources and light amplification in silicon photonics has met several challenges for now due to the silicon indirect bandgap. Alternatively, light sources in silicon photonic circuits have been realized through hybrid integration of III-V semiconductor materials and strained Ge layers on silicon. These kinds of hybrid integration routes rely on semiconductor techniques, either by epitaxial growth or hetero-bonding of dies or wafers. Another possible route is based on the integration of active soft-materials (eg polymers) or oxides by lighter techniques like spin-coating or CVD processes. Therefore, low cost, hybrid integration of these active materials, such as Er3+ doped materials, semiconductor carbon nanotubes, quantum-doped polymers, etc, has been recently studied for the demonstration of various integrated functions [1] [2]. Er3+ materials, for example, which emit light covering telecom C&L bands, have recently been used to demonstrate high net gain up to 31dB/mm in submicron silicon wires [1]. Such promising results indicate that integrating Er-materials in silicon nanophotonic devices is possible for future Erbium-based lasing in silicon photonics regarding the current propagation losses of silicon waveguides.

Here, we report our recent progress regarding the integration Er3+ doped materials in silicon and silicon nitride slot waveguides/devices. Two kinds of Er3+ material: Erbium doped polymers and Er2O3/Al2O3 atomic layer, integrations in silicon and silicon nitride has been studied, which includes the optimization of waveguide losses, PL properties of the Erbium materials and hybrid integration methods. The light propagation and gain measurements before and after Erbium integration with our slotted photonic devices prove good potentials for high net gain amplifiers in future hybrid silicon and silicon nitride photonic circuits.

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10027-10, Session 2

n-type reverse-rib germanium laser structures doped by phosphorus diffusion process

Chan-Hyuck Park, Kookmin Univ. (Korea, Republic of); Motoki Yako, Yasuhiko Ishikawa, The Univ. of Tokyo (Japan); Kazumi Wada, Massachusetts Institute of Technology (United States); Donghwan Ahn, Kookmin Univ. (Korea, Republic of)

Germanium (Ge) is a promising gain medium for monolithic integrated laser on silicon platform. In this paper, we report light emission from a reverse-rib Ge cavity structures that were made using P diffusion to an epitaxial lateral overgrowth (ELO) layer. Such structures enabled concentrating greater portion of the optical mode to be positioned in the Ge gain medium. In contrast to the ion implantations that may induce irreversible Ge lattice damage to prevent emission of Ge, we employed P diffusion method, which achieved 1?1019 /cm3 in the reverse-rib Ge structures. We achieved 10 times enhancement of PL intensity compared with undoped Ge. Developing such ex-situ diffusion process instead of using in-situ doping method during the Ge epitaxy also means that one can achieve different doping profiles tailored for different types of Ge photonic devices such as laser (LD), photodetectors (PD), and modulators (MOD) integrated in one chip even after one unified one intrinsic Ge epitaxy, which is more realistic than performing multiple epitaxies for many different types of Ge devices.

10027-11, Session 3

Optical waveguide materials, structure, and dispersion modulation *(Invited Paper)*

Zhisong Xiao, BeiHang Univ. (China)

No Abstract Available

10027-12, Session 3

Inherent error in interferometric surface plasmon microscopy

Bei Zhang, BeiHang Univ. (China) and Univ. of Nottingham (United Kingdom); Peng Yan, Feng Gao, BeiHang Univ. (China); Le Wang, Renmin Univ. of China (China)

Surface plasmon microscopy (SPM) is a kind of surface plasmons optical system which employs high refractive index prism or high numerical aperture (NA) objective lens as coupling agent to excite surface plasmon considering the conservation of momentum of k vector in SPs. Here we apply high NA oil-immersion objective lens considering k vector conditions of SPs and localization of SPs which provides better lateral resolution and less cross-table between adjacent areas. Fundamentally, image contrast or sensing sensitivity of a SPM arises from surface plasmon wave coupling and specific specimen-chemical interaction, however, the optimum resolution, contrast or sensitivity can be achieved only if the illumination profile is of the appropriate form. That means the performance of an objective lens based SPM is often limited by the optical field profile of light probe incident on the pupil of objective lens which may has distorted pupil, finite aperture stop, etc. Here we assume the undistorted pupil and only consider how the finite aperture stop distorts the emission and affects the performance of SPRM. Physically, finite aperture of a physical objective lens refers to sudden transition on the clear aperture edge and limited bandwidth of the system. Here we give a simplified model of the SPM and numerically calculate how the sudden transition on the clear aperture edge causes inherent error. A spatial light modulator will be applied to modulate the illumination beam profile and suppress the inherent error.

10027-13, Session 3

Hybrid WGM-SPP modes in metal-coated microcylinder

Yadong Miao, Zhuo Zhang, Mi Li, Yu Xiang, Yunchong Peng, Qiang Chen, Yuejiang Song, Nanjing Univ. (China)

It is well known that surface plasmon polariton (SPP) has potential application in biochemical sensing but with a limit of low quality factor. In the paper, we study the mode characteristics and sensing characteristics of metal-coated cylindrical microcavity with Mie theory. According to its eigenequation, mode characteristics, including the field distribution, dispersion curve, and Q factor of silver coated microcylinder, can be achieved by the analytic method. The mode index of SPPs mode decreases with the increase of the microcylinder radius, while other mode increases with radius. Due to the extraordinary mode index of SPPs mode, it can couple with other TM modes when they have approximate mode index. The generated hybrid TM-SPPs modes (or supermodes) have both high Q factor and high surface enhancement factor, which is different from the traditional SPP mode and dielectric whispering gallery mode (WGM).

Also the sensitivity and the figure of merit (FoM) of the hybrid modes are studied. The hybrid TM-SPPs modes have high sensitivity (~260 nm/RIU), more than one order of magnitude higher than traditional WGM modes in dielectric microcavity, and high FoM (~1100), higher than traditional SPP mode. These hybrid modes can be widely used in many applications due to both its high Q factor and high refractive sensitivity.

10027-14, Session 3

Manipulating the effective index of the hybrid plasmonic waveguide based on subwavelength grating

Rui Zhang, Bowen Bai, Zhiping Zhou, Peking Univ (China)

The properties of grating based hybrid plasmonic waveguide is first investigated in this paper. Due to the existence of metal layer on top of the grating, this structure exhibits unique features compared with conventional silicon based waveguide. Three main factors influence effective index of the waveguide, which are grating period, duty cycle and width, respectively. By controlling duty cycle and grating period, the function which maps effective index variable to waveguide width can be changed. It is worth noting that the function might be concave function or convex function, which is different from the traditional hybrid plasmonic waveguide. Moreover, at certain duty cycle and grating period, the slope of the function is similar to TM mode of silicon based waveguide, which is of great potential for SPPs based applications.

10027-15, Session 4

Ultrahigh-Q asymmetric microcavity photonics *(Invited Paper)*

Yun-Feng Xiao, Peking Univ. (China)

No Abstract Available

10027-16, Session 4

Enhanced CNT photoluminescence in integrated silicon photonic resonators

Weiwei Zhang, Elena Durán-Valdeiglesias, Samuel Serna, Thi-Hong-Cam Hoang, Carlos Alonso-Ramos, Xavier Le Roux, Univ. Paris-Sud 11 (France); Arianna Filoramo, Commissariat à l'Énergie Atomique (France); Francesco Sarti, Ughetta Torrini, Univ. degli Studi di Firenze (Italy); Hongliu Yang, Gianaurelio Cuniberti, TU Dresden (Germany); Massimo Gurioli, Univ. degli Studi di Firenze (Italy); Viktor Bezugly, TU Dresden (Germany); Eric Cassan, Laurent Vivien, Univ. Paris-Sud 11 (France)

The on-chip integration of all electronic, photonic, optoelectronic, memory blocks on the silicon platform is the ultimate goal of future processors. A further step of perusing high efficiency and low energy consuming, device miniaturization in the chip is restricted by the CMOS compatible materials themselves. New materials like carbon nanotubes (CNTs) and graphene have been recently reported as key materials both in electronics and optoelectronics for the realization of nano devices such as electronic new transistors, as well as light emitting, modulating and detecting devices [1].

We propose here to integrate high concentration selected semiconductor CNTs into silicon photonic structures to improve the hybrid properties of silicon-compatible silicon devices. CNTs have indeed the ability to emit, modulate and detect light in the telecommunication wavelength range.

We report the study of the light emission from CNTs coupled into optical resonators/nanocavities implemented on the silicon-on-insulator (SOI) platform. A theoretical and experimental analysis of the light interaction of CNTs with micro-ring resonators based on strip/slot waveguides, slot photonic crystal heterostructure cavities and air mode nanobeam cavities has been carried out. Enhanced photoluminescence (PL) into two types of ring resonators: strip ring resonators and slot ring resonators, have been measured and polarization sensitivity has been demonstrated also. The PL collected through coupled bus waveguides shows 20dB signal extinction ratio. Additionally, Purcell effects have been investigated in different types of high Q slotted photonic cavities and air mode nanobeam cavities, a crucial step towards a CNT-laser.

1. P. Avouris, M. Freitag, and V. Perebeinos, "Carbon-nanotube photonics and optoelectronics," Nat. Photonics 2, 341–350 (2008).

10027-17, Session 4

Stability and non-linear optical properties of nanocarbon dispersions

Anastasia V. Venediktova, Andrey Y. Vlasov, Saint Petersburg State Univ. (Russian Federation); Ivan M. Kislyakov, ITMO Univ. (Russian Federation); Vladimir Y. Venediktov, Saint Petersburg Electrotechnical Univ. "LETI" (Russian Federation) and Saint Petersburg State Univ. (Russian Federation)

Fluid systems containing nanocarbon particles have a plethora of applications, nonlinear optical power limiting (OPL) and photodynamic therapy being among them. We've focused on two types of systems: suspensions of fullerenes and dispersions of single-walled carbon nanotubes (SWCNT). We've studied correlations between the stability of SWCNT suspensions, stabilized by various amphiphiles, and aggregative properties of the used stabilizers in mixed media. Non-linear optical behavior of all the suspensions was checked. Further, the correlation between stability of the aggregated suspensions of fullerenes and their photo-dynamic properties was investigated.

The results show principal viability of nonlinear optical filters and singlet-oxygen generators on the platform of variously aggregated carbon nanoparticles for application in eye-protective optical devices, oxygen therapy of pathogens and environmentally compatible oxygen-iodine lasers.

10027-18, Session 4

High-performance one-way transmission using pyramid-shaped silicon grating-coupled hyperbolic metamaterial

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An asymmetric transmission device has been demonstrated to realize high-contrast one-way pass transmission for incident visible plane wave. Non-symmetric pyramid-shaped silicon gratings and narrow band metal/dielectric multilayer structure were incorporated to display the one-way transmission with high performance with contrast ratio exceeding 20dB. Simulation results demonstrate pyramid-shaped silicon gratings will greatly enhance the coupling and decoupling efficiency between the propagating wave in free space and the coupling plasmon modes supported by the metal/dielectric multilayer. The improved the one-way transmission performance offered by pyramid-shaped silicon grating coupling may hold great potential in many applications such as super-resolution plasmonic lithography, isolator and polarizer for super-compact photonic integrated circuit.

10027-37, Session Post

Wavelength conversion enhancement by using electric dipole and magnetic dipole resonance of nanocylinder

Kihwan Moon, Young Jin Lee, Seokhyeon Hong, Soon-Hong Kwon, Chung-Ang Univ. (Korea, Republic of)

Upconversion (UC) materials, which absorbs near-infrared (NIR) light and emits visible light, are promising to harvest visual light. However UC process efficiency is very low to apply for device. Therefore, we propose nanocylinder-shaped structure into UC material, inducing electric dipole (ED) and magnetic dipole (MD) resonances, to increase efficiency of UC process. The nanocylinder is not only able to increase the light absorption but also tailor scattering direction of induced light by Mie resonance, called ED and MD. Resonant wavelength of ED and MD can be tuned by controlling the parameter of nanocylinder, height and diameter. When the absorption wavelength, NIR light, of UC material is matched to MD resonance, interaction between the nanocylinder and incident light is enhanced

owing to MD resonance. In order to achieve uni-directional emission of visible light, we introduce gold substrate below UC nanocylinders as a reflector. We investigate the amount of useful visible light emission, which is emitted into vertical direction from UC nanostructure. For comparison of UC process per unit volume, the reference structure consisting of UC layer and gold substrate is set to same to volume of UC nanocylinder. The vertically emitted light is strongly enhanced by ED resonances. In summary, we obtained absorption enhancement of 7.3 times and vertical directional emission enhancement of 155 times in finite-differential time domain (FDTD).

10027-38, Session Post

Silver nanoparticles plasmonic effect on eosin and rhodamine 6G luminescence in various media

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The plasmonic enhancement and quenching of phosphorescence and fluorescence of the anionic (eosin) and cationic (rhodamine 6G) dyes have been studied in various environments: silver nanoparticles of silver hydrosol citrate in water, in polymer films and on the surface of nanoporous silica in order to determine the kinetic and spectral effects on the dye luminescence. Depending on the silver nanoparticles concentration both the enhancement and quenching of the dyes phosphorescence and fluorescence have been detected. The mechanism of interaction between the excited molecules and silver nanoparticles has been discussed. In this paper we aimed to perform comparative study of the silver nanoparticles effect of the average size of 35 nm in the silver hydrosol citrate on the fluorescence of the anionic and cationic dyes in various environments: in water, in polymer films and on the surface of nanoporous silica. Comparative study of the role of the total charge of the dye seams quite important in the elucidation of the interaction mechanism between the dye and the surface plasmonic resonance. The research has been carried out within the state assignment of the Ministry of Education and Science of Russian Federation (project No. 3.809.2014/?).

10027-39, Session Post

Luminescence quantum yields of gold nanoparticles varying with excitation wavelengths

Yuqing Cheng, Guowei Lu, Peking Univ. (China)

Luminescence quantum yields (QYs) of gold nanoparticles including nanorods, nanobipyramids and nanospheres are measured elaborately at a single nanoparticle level with different excitation wavelengths. It is found that the QYs of the nanostructures are essentially dependent on the excitation wavelength. The QY is higher when the excitation wavelength is blue-detuned and close to the nanoparticles' surface plasmon resonance peak. A phenomenological model based on the plasmonic resonator concept is proposed to understand the experimental findings. The excitation wavelength dependent QY is attributed to the wavelength dependent coupling efficiency between the free electron oscillation and the intrinsic plasmon resonant radiative mode. These studies should contribute to the understanding of one-photon luminescence from metallic nanostructures and plasmonic surface enhanced spectroscopy.

10027-40, Session Post

Optical resolution improvement by nanoparticle's amplitude and phase pattern

Xin Hong, Xiaoyaun Sun, Dalian Univ. of Technology (China)

Optical detection of nanoparticle with ultra-high sensitivity plays an important role in bio- / nano- and their relative research fields. However, it is a rather hard task to detect a single nanometer sized non-luminescent particle directly by optical method due to its very small cross section. By using highly focused Gaussian beam, we recently developed a method which can detect a single nanoparticle by producing both amplitude and phase images. Each particle exhibits unique 4-lobes pattern both in the amplitude and phase distribution respectively, which open a window to explored the possibility of resolution improvement by a particle pair. When two particles are attaching each other, the total field resulted from their interaction will be changed. In consequence it will lead to the scattering amplitude and phase distribution pattern changes. Based on which, a particle pair was employ to test the resolution. In this paper two polystyrene beads at the diameter of 100nm were employed with the gap distance ranging from 100-400nm. The amplitude and phase distribution of the particle pair were simulated by FDTD solver. The simulation results show that the images are sensitive to the geometrical parameters of the two particles, such as gap distance and direction and the calculation result suggests a resolution of 100nm.

10027-41, Session Post

Tunable optical properties of the core-shell nanoparticles

Xin Hong, Chencheng Wang, Dalian Univ. of Technology (China)

Noble metallic nanoparticle exhibits unique optical properties in visible to near infrared band when its localized surface plasmon resonance (LSPR) is excited. This is because when the incident photon frequency in consistent with the collective oscillation of metal nanoparticles internal free electrons frequency, the nanoparticle producing resonance absorption or resonance scattering, at the same time the electric field intensity near the surface of the nanoparticles getting greatly enhanced . For example, a sharp absorption peak is at 525nm for a gold nanoparticle at the diameter of 60nm. The strong dependence of plasmonic properties on its geometrical structure makes them more attractive to obtain artificially tunable properties. In the biomedical applications, a broad band adjustment is expected in order to obtain an optimum measurement window. This requirement needs a selected nanostructure design in advance of synthesis. In this paper, we theoretically get the optical properties by calculating its cross sections of scattering, absorption and extinction of a single solid nanoparticle. However, the peak position makes rather low change. Keep it as a reference, we explored in detail a core-shell structure, whose structure was composed of dielectric core and a gold shell. The simulation results show that the core-shell structure can reach a much broader tunable band and the shell thickness plays a dominant role. Further by employing a core-shell pair, more flexible properties can be reached.

10027-42, Session Post

Angular sensitivity for a Fabry-Perot structure incorporating different dielectric materials

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Color filters based on different Fabry-Perot structures are investigated extensively, and incident angle dependency is an important characteristic in practical applications. Here, we investigated a color filter incorporating a Fabry-Perot structure, discussing its reflective angular sensitivity related to refractive index of its dielectric material. By finite difference time domain(FDTD) theory, the refractive index of the dielectric material is found to influence the angular sensitivity greatly while the optical thickness keeps constant. The simulated results shows that the higher the dielectric layer's refractive index is, the more angular insensitive of the reflection will be obtained and a good angular insensitive will achieved when the refractive index is larger than 2. Finally, samples with different dielectric layer are fabricated in experiment and the measured results verify influence of the refractive index of dielectric layer on the spectra angular sensitivity, which is helpful for the application of color filter in color display, image sensors and decoration.

10027-43, Session Post

Improvement of metal-semiconductor contact on silicon microstructured surface by electroless nickel technique

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Si micro-structures served as anti-reflection layer are widely employed in Si-based solar cells and detectors to enhance light harvesting. However, performance of these devices is suffered from the poor contact between the metal electrode and micro-structured surface. Conventional vacuum deposited metal electrode makes only superficial contact with the top of micro-structured surface and unable to fill the pores in the micro-structures. In this paper, instead, electroless nickel technique is applied to form low resistance ohmic contact. The surface micro-structures were fabricated by electrochemistry etching while the metal electrodes were deposited by several approaches including thermal evaporation, sputtering and electroless. Specifically, two different electroless nickel processes (acidity or alkalinity) were carried out and their effects were compared. The morphology of micro-structured surface and covered metal layer was presented by SEM, and the electrical contacts between them were measured by Keithley4200 semiconductor characterization system. Results show that only electroless nickel layer could fully fill the pores and achieve good ohmic contact before rapid annealing. Furthermore, a higher temperature rapid annealing process could improve the contact of all samples prepared by different ways. The lowest specific contact resistance achieved by alkalinity electroless nickel is 1.34?10-1?•cm2.

10027-44, Session Post

Near-infrared absorptance enhancement and device application of nanostructured black silicon fabricated by metal-assist chemical etching

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We use metal-assist chemical etching (MCE) method to fabricate nanostructured black silicon on the surface of C-Si. In our MCE process, a chemical reduction reaction of silver cation (Ag+) will happen on the surface of silicon substrate, and at the same time the silicon atoms around Ag particles are oxidized and dissolved, generating nanopores and finally forming a layer called black silicon on the top of the substrates. The nanopores have diameter and length of about 400 nm and 2 ?m, respectively. Furthermore, these modified surfaces show higher light absorptance in near-infrared range (800 to 2500 nm) compared to that of C-Si with polished surfaces, and the maximum light absorptance increases significantly up to 95% in the wavelength region of 400 to 2500 nm. The Si-PIN photoelectronic detector based on this type of black silicon, in which the black silicon layer is directly set as the photosensitive surface, has a substantial increase in responsivity with about 80 nm red shift of peak responsivity, particularly at near-infrared wavelengths, rising to 0.57 A/W at 1060 nm and 0.37 A/W at 1100 nm, respectively. Our recent novel results clearly indicate that nanostructured black silicon made by MCE has a potential application in near-infrared photoelectronic detectors.

10027-45, Session Post

Model of blocking dislocations for III-V semiconductor grown on nano-trench patterned Si substrates

Haoyuan Ma, Jun Wang, Zhuo Cheng, Yibing Fan, Ran Zhang, Beijing Univ. of Posts and Telecommunications (China); Yuanyuan Liu, Institute of Semiconductors (China); Yongqing Huang, Xiao-Min Ren, Beijing Univ. of Posts and Telecommunications (China)

In epitaxial lateral overgrowth (ELOG) of III-V semiconductor grown on nano-trench patterned Si substrates, the most important mechanism is aspect ratio trapping, which uses high aspect ratio nano-trenches to trap threading dislocations. A model based on the theory of dislocation is proposed to calculate proportion of blocking threading dislocations in ELOG of GaAs or InP on nano-trench patterned Si substrates. The model establishes relationship with the structure of nano-trenches and the proportion of blocking threading dislocations. It is found that, the proportion is determined by thickness of the masks, width of the trenches and direction of the nano-trenches (the angle of opening orientations lies off the [110] direction). The proportion gradually increases until 100% as aspect ratio increases with fixed trench direction; With the same aspect ratio, the proportion firstly decreases from 0°to 45°, and symmetrically increases from

45°to 90°. It is worth noting that the proportion abruptly reduces to 50% when the direction is 45°and the aspect ratio is more than 1; But it does not happen if the aspect ratio is less than or equal to 1. The reported experimental results are well consistent with the model. The model provides a method for optimization of nano-trench patterned substrates for more effectively blocking threading dislocations on III-V semiconductor grown on nano-trench patterned Si substrates.

10027-46, Session Post

CdS quantum-dot sensitized solar-cell-based ZnO nanorods grown on a Ti substrate

Chunyan Zhou, Qian Chen, Xiaoshan Zhang, Fangfang Gao, Jiehua Xu, Liya Zhou, Guangxi Univ. (China)

Comparatively long zinc oxide (ZnO) nanorods (NRs) was successfully prepared on a polished Ti substrate by the hydrothermal method. Then the NRs were further sensitized by 3-mercaptopropionic acid (3-MPA)-capped CdS quantum dots (QDs) with a cubic structure and excellent crystallinity as a photoanode of QD-sensitized solar cells (QDSSCs) via the direct adsorption (DA) technique. The effect of sensitization time of CdS QDs on performance of the QDSSCs was systematically investigated. The absorption band of sensitized NRs red-shifted and broadened to the visible spectrum, thereby improve light-harvesting efficiency of the photoelectrode. For the CdS QD-sensitized ZnO NRs polished Ti substrate, the conversion efficiency can reach a maximum of 0.702%, which was enhanced by 350% compared with that of the cell based on CdS QD-sensitized ZnO NRs (0.201%).

10027-47, Session Post

Photoelectrochemical performance research of CdTe:Eu3+ quantum-dot-sensitized TiO2 nanotube array solar cells

Qian Chen, Chunyan Zhou, Fangfang Gao, Xiaoshan Zhang, Liya Zhou, Guangxi Univ. (China)

Quantum dots (QDs) sensitized solar cells (QDSSCs) based on TiO2 nanotube arrays (TNTAs) have attracted considerable interest because of their outstanding sunlight conversion efficiency. To decrease the band-gap of TNTAs and widen the absorption spectra to the visible region, doped-QDs have been modified in the surface of TNTAs. In this paper, CdTe: Eu3+/ TNTAs prepared by using a novel one-step synthesis process with Thioglycolic acid (TGA) as stabilizer. X-ray powder diffraction and high-resolution transmission electron microscopy analyses confirmed that the obtained CdTe: Eu3+ quantum dots (QDs) possess cubic structures. The influences of sensitization time and Eu3+ ion concentrations are investigated systematically. The photocurrent of the CdTe: Eu3+ QDs/ TNTAs appear at the main absorption region of 300–510 nm. Compared with that of the TNTAs and CdTe/TNTAs, the photoelectric conversion efficiency of CdTe:3% Eu3+/TNTAs (0.29%) increased apparently. This scenario exhibits the potential applications of QDs in photochemical solar cells.

10027-48, Session Post

Purcell enhancement of emitting from the quantum-dot-in-nanowire structure surrounded by Au

Fengling Tang, Xin Yan, Xia Zhang, Xiao-Min Ren, Beijing Univ. of Posts and Telecommunications (China)

Single photon sources are key devices for quantum communication and quantum computation. Recently, photonic nanowires with an embedded quantum dot have demonstrated to provide remarkable extraction efficiency due to the axial waveguide configuration and nanocavity function of nanowire. However, for thin nanowires, stable modes cannot be supported, resulting in very poor Purcell factor which is an important parameter of single photon sources.

In this paper, a novel single photon source structure with a high Purcell factor is proposed and simulated. The structure consists of a GaAs nanowire embedded with an InAs quantum dot surrounded by Au. The enhancement of the Purcell factor is simulated by finite difference time domain (FDTD) method. Without Au shell, the Purcell factor quickly drops as the diameter of nanowire decreases. When the diameter is decreased to 50 nm, the nanowire cannot support any stable modes, resulting in a rather low Purcell factor of 0.009. After the Au shell is introduced, the Purcell factor is dramatically enhanced, and the enhancement ratio increases as the nanowire diameter decreases. The highest enhancement ratio of 1028 can be obtained at a nanowire diameter of 50 nm and Au shell thickness of 75 nm. The enhancement of the Purcell factor is attributed to the decrease of the cavity effective mode volume, which is inversely proportion to the Purcell factor. This work may offer a way to achieve single photon sources with an ultrasmall size and ultrahigh Purcell factor.

10027-50, Session Post

Optical switching of scattering direction in silicon-gold dimer

Bona Ku, Young Jin Lee, Seokhyeon Hong, Kihwan Moon, Soon-Hong Kwon, Chung-Ang Univ. (Korea, Republic of)

Resonant scattering of nanodimer composed of silicon (Si) and gold (Au) enables controlling of scattering direction depending on the wavelength of incident light. Silicon has two representative resonances based on Mie resonance, called electric dipole (ED) and magnetic dipole (MD). But, gold shows dipole like resonance for incident light. because of its plasmonic resonance phenomenon. We make a dimer structure consisting of Si and Au spheres which are separated by airgap of 20 nm. In this study, the direction of forward scattering in proposed dimer is tuned by changing the wavelength of incident light. In dimer, Si and Au spheres have 100 nm and 130 nm diameters, respectively. We simulate scattering cross-section and the far-field of scattering light in the dimer as the wavelength changes from the ED wavelength (610 nm) to MD wavelength (770 nm) of Si nanosphere. In contrast to strong forward scattering with same direction of incident light in the single nanosphere, the scattering in the hybrid dimer shows deflection of incident light depending on the wavelength. The maximum angle of forward scattering is shifted 15° when the wavelength of incident wave is changed from 610 nm to 770 nm. The scattering angle at certain wavelength can be controlled by changing sphere structures and gap spacing in dimer.

10027-51, Session Post

Optimized design of metal-coated optical fiber tips with embedded plasmonic slot nano-resonators for maximum field enhancement

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Plasmonic Nano-Resonators (PNRs) are subwavelength-sized metallic apertures that offer high field confinement and enhancement. Their integration to optical fibers tips with thin metallic claddings forms plasmonic slot nano-resonators (PSNRs) providing ease of light coupling from the fiber's core modes to the slot. It is demonstrated here that the placement of the PSNR at the cut-off radius of the fiber tip where the group velocity tends to zero and light slows down leads to the optimization of field's enhancement. Finite Element Method (FEM) simulations were performed for the calculation of the cut-off radius and of the intensity enhancement factors (Ef) of PSNR's embedded in metal-coated fiber tips at different radii. A number of different fiber tips with different geometrical characteristics were also tested and studied in order to identify optimal conditions for loss minimization. Maximum intensity enhancement of PSNR's placed at different radii shows a linear dependence between excitation wavelength and radius, making it feasible to select the proper radius for a specific wavelength for maximum enhancement. The designed plasmonic system provides Ef greater than 5x10^5 and can find many practical applications in nano-optics and sensing.

10027-52, Session Post

Study of waveguide directly writing in LiNbO3 crystal by high-repetition-rate femtosecond laser

Chuan Wu, Feng Jie, Southwest Univ. of Science and Technology (China); Yongjia Yang, Southwest University of Science and Technology (China); Jiangui Mao, Anlin Luo, Southwest Univ. of Science and Technology (China); Zigang Zhou, Southwest University of Science and Technology (China)

In this paper, we demonstrate the buried waveguides directly writing in LiNbO3 crystal by a tightly focused femtosecond laser with repetition rate 75MHz, and the femtosecond laser is focused by the microscope objective of which NA is 0.65. Fabricating nine carved paths in LiNbO3 crystal by moving three-dimensional electric translation stage at different speeds varying from 2mm/s to 10mm/s, controlled by a computer. Analyzing the structure of the end face of the directly writing region by laser Raman, which shows the large-scale defects are generated in the center of the etching region, densification induced by the thermal effect of high repetition rate femtosecond laser interaction of LiNbO3 are generated below and down of the center of the etching region. Using a He-Ne laser focused by a microscope objective with NA 0.65 coupling to the end face of the prefabricated nine carved paths, which shows two waveguides are generated in the top and below of the inscribing region. Testing the insert loses of these waveguides with an optical power meter, the result shows that the insert loses of the waveguides fabricated at speed of 8~10mm/s is low to 3dB·cm-1, and the insert loses is low to 1.5 dB·cm-1 when the scanning speed is 9mm/s, moreover, the insert loses of the below region is low to the top region.

10027-53, Session Post

Optical reflection efficiency modulation based on graphene film

Junbo Yang, Jie Huang, Wenjun Wu, Dingbo Chen, Jingjing Zhang, National Univ. of Defense Technology (China)

This paper presents a comprehensive study of light reflection modulation in graphene through external applied voltage and shows a strategy to realize both broadband and strong reflection enhancement. The influence of chemical potential, applied voltage and carrier concentration on reflection efficiency are investigated by numerical simulations. By employing an applied voltage, the maximum of difference of reflected coefficient can reach up to 30% for 3THz radian frequency. Thus, using external voltage to control optical reflection efficiency is testified to be reasonable and feasible based on graphene film. Furthermore, the reflection efficiency modulation can be realized at a wideband of frequency.

10027-54, Session Post

Enhanced absorption in graphene monolayer with guided mode resonance

Jun Wu, Hongchao Cao, Shanghai Institute of Optics and Fine Mechanics (China)

The complete absorption in graphene monolayer through the critical coupling effect is investigated. It is achieved by sandwiching the graphene monolayer between a dielectric grating and a Bragg grating. The optimized structure parameters with the operating wavelength at about 1550 nm are obtained by use of the rigorous coupled-wave analysis (RCWA). The designed graphene absorber exhibits near-unity absorption at resonance, which is attributed to the combined effects of guided mode resonance with dielectric grating and the photonic band gap with Bragg grating. Moreover, the designed graphene absorber has perfect absorption/emission with highly directional and acts similar to an antenna. In contrast to the numerical simulation, a coupled-mode theory model is also presented to verify the correctness of the numerical result. Furthermore, the electric field distributions are illustrated to provide a physical understanding of the perfect absorption effect. It is believed that the method proposed here may benefit the design of novel graphene-based optoelectronic devices, such as photodetector, modulator and absorber/thermal emitter.

10027-19, Session 5

Defect-free fabrication of nano-disk and nano-wire by fusion of bio-template and neutral beam etching *(Invited Paper)*

Seiji Samukawa, Shuichi Noda, Tohoku Univ. (Japan); Manabu Yasuda, Kazumi Wada, The Univ. of Tokyo (Japan)

It has been suggested that by 2020, Moore's Law will break down and we will reach the physical limits of transistor operation. Work is therefore under way in several countries to develop nano-devices based on new principles using quantum effects. To fabricate quantum effect devices, it is essential that defect-free nanostructures (dots and wires) can be formed with precision down to the atomic layer level. For this purpose, we proposed and are researching the formation of quantum nanodots and nano-wires of less than 10 nm in size by means of a top-down process using a low-energy neutral beam capable of defect-free processing. An advantage of the top-down process is that

it can form nanostructures with an arrangement that can be uniformly controlled no matter what combination of materials is used. Instead of photolithography, we used a bio-template as an etching mask with dots of a few nm in size. By combination of bio-template and defect-free neutral beam etching, the sub-10-nm quantum nano-dots (discs) and –wire (-columns) for any materials such as Si, Ge, GaAs, InGaAs and InGaN could be fabricated in an array configuration with uniform spacing. It can be seen that the bandgap can be controlled over a wide range with high precision by varying the nano-disc (column) size and material. No other quantum dot fabrication techniques can offer this kind of flexible and precise bandgap control. We are currently developing high efficiency quantum dot energy/optical devices (Solar Cells, Laser/LED).

10027-20, Session 5

1?5 optical splitter for TE modes in air-hole photonic crystal based on self-collimation effect

Weijuan Chen, Yuanyuan Lin, Fujian Normal Univ. (China); Guimin Lin, Ping Fu, Minjiang Univ. (China); Chengkun Liu, Junzhen Jiang, Yishen Qiu, Hui Li, Fujian Normal Univ. (China); Xiyao Chen, Minjiang Univ. (China)

We propose a novel 1?5 optical splitter (OS) for TE modes based on self-collimation effect in an air-hole type 2D silicon photonic crystal. The OS consists of two cascaded resonators which is formed by eight beam splitters. We obtain the theoretical transmission spectra of OS by using multiple-beam interference theory. With our analysis of transmission spectra, we find that the transmission spectra at five drop ports will reach the maximum values while the transmission spectra at two through ports reach zero for resonant frequencies. By scanning the radius of a beam splitter, the relationship between the radius and the reflectivity is obtained. Therefore, by changing the radii of the air-hole in eight beam splitters, we can manipulate the output light-intensity ratio at five drop ports to meet requirement.

Theoretically, when R1=2/11, R2=8/11, R3=5/8, R4=2/5, R5=7/12, R6 =6/7, R7=1/2, R8 =2/3 ,(Ri is reflectivity of beam splitters), the light intensity ratio at five drop ports is 1:1:1:1:1. When R1=2/7 ?R2=6/7?R3=1/2?R4=2/3?R5=1/7,R6=6/7 ,R7=2/3 ,R8 =1/4 , the light intensity ratio at five drop ports is 2:2:1:2:3. By means of finite-difference time-domain (FDTD) simulations, we simulate the numerical transmission spectra of OS. The simulation results are consistent with the theoretical results. Considering micro processing technology of silicon materials is already available, this OS can be used in the photonic integrated circuits because of its small-size, whole-silicon material and low insertion loss.

10027-21, Session 5

Gold nano sphere based fiber optic LSPR probe for biosensing measurement

Lixia Li, Zigeng Liu, Shimeng Chen, Jianye Guang, Wei Peng, Dalian Univ. of Technology (China)

In this paper, we report on localized surface plasmon resonance (LSPR) studies of gold nano sphere (GNS) immobilized outside the fiber core. Different immobilization methods were studied to verify the better performance. The amino silane method and polyelectrolyte layer by layer (LBL) self-assembly methods were used to prepare GNS-based fiber LSPR probe respectively. Different self-assembly layers were respectively studied in the polyelectrolyte layer by layer self-assembly method (PDDA monolayer, PDDA/PSS bilayer, PDDA/PSS/PAH three layer and PDDA/PSS/PAH/PSS/PAH five layer self-assembly methods) to explore the optimum layer number of the method.

The refractive index detection experiments were carried out using the fiber LSPR probe prepared by the above five methods. Details of the operation steps and the experimental results were compared and analyzed. The results show that PDDA/PSS/PAH three layer self-assembly method demonstrates the best LSPR spectra. The LSPR light intensity changes gradually when varying the refractive index of sodium chloride solution outside the sensor. Comparing to the amino silane method, polyelectrolyte layer by layer self-assembly method is time saving, simple operating and more stable.

Finally, biomolecule specific recognition and detection experiment were carried out using LSPR fiber probe based on the three layer self-assembly method. Through this method, Ribonuclease B can recognise Con A specifically. The LSPR spectra also have good linear relation with the variation of concentration of Con A.

10027-22, Session 5

Steady- and excited-state dynamics of mixed halide Perovskite films

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Lead halide perovskites which are organic-inorganic hybrid structures, have recently been discovered to be highly efficient as light absorbers in solar cells [1]. They exhibit broad absorption below 800 nm and have an absorption coefficient far greater than conventional organometallic dyes used in dye sensitized solar cells [2,3]. Non-stoichiometric precursor formed mixed iodide-bromide lead halide perovskites were grown by the inter-diffusion method and films with good morphology and varying bandgaps with sharp optical band edges were obtained. These films were investigated to probe their excited state dynamics and emission properties using steady-state and time-resolved spectroscopic measurements. Steady state fluorescence was observed for the perovskite films and they demonstrated photoluminescence emission of very high intensities which are necessary for light emitting and photovoltaic applications; the different compositions exhibited considerably different emission features. The transient absorption experiments also revealed that the different iodide-bromide compositions exhibited unique spectral features of the perovskite material relative to the varying ratios of the halogens present in them [4].

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10027-23, Session 5

Gold nanoparticle-induced diameter reduction and enhanced Raman shift in self-rolled-up InGaAs/GaAs microtubes

Xiankun Wang, Qi Wang, Zhaoer Chai, Guoming Mao, Hao

Liu, Jia Chen, Bingfei Liu, Xiao-Min Ren, Beijing Univ. of Posts and Telecommunications (China)

We have grown an epitaxial structure by metal-organic chemical vapor deposition (MOCVD). From the GaAs (100) substrate, the sequences are GaAs buffer layer, 50nm AlAs sacrificial layer and the In0.2Ga0.8As (10 nm)/ GaAs (20 nm) strained bilayers. Photolithography and etching techniques have been used to design square patterns which etch to sacrificial layer. Before selectively etching the AlAs to release the strained bilayers, 2 nm Au-film was deposited on mesas by Magnetron Sputtering for embed Au nanoparticles (NPs) in tube wall, which was formed by Rapid thermal annealing (RTA) under the N2 atmosphere at 650 degrees centigrade for 300s. After annealed in high temperature, Au film formed small islands just as NPs and attach on the surface closely.

Comparing with microtubes without NPs, diameter reduction from 2.7μm to 2.4μm has been observed for Au-NPs assistant microtubes, characterized by the scanning electronic microscopy (SEM). For understand the morphology change in Au-assistant microtubes, room temperature (RT) Raman measurements have been employed to study the strain effects reflected by the GaAs longitudinal optical (LO) phonon mode shifts when compared LO mode of microtubes with as-grown planar. The spectrum showed that there were about 10 wavenumbers and 2.6 wavenumbers blue-shifts for Au-assistant and non-Au-assistant structures respectively. Larger blue shifts induced larger strain change were obtained for structure with Au NPs compared with structure without Au, which demonstrate the reason for the diameter reduction observed by SEM. This investigation on the method of reducing diameters of rolled-up microtubes need not to change the component or thickness of strained layers, NPs can be benefit to SERS.

10027-24, Session 5

Title to be determined *(Invited Paper)*

Bumki Min, KAIST (Korea, Republic of)

No Abstract Available

10027-25, Session 5

Fabrication of tunable two-dimensional nanostructures by improved nanosphere lithography

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A modified nanosphere lithography method that using an ordered monolayer of composite PS sphere/silica gel arrays as template to form a diverse range of tunable nano-patterns in a small area with good reproducibility was demonstrated. The critical improvement of this method is that it flexibly using PS spheres and silica gel as combined etching masks to produce different patterns. Silica gel is infiltrated in gaps of the PS spheres in self-assembly progress. The factors that affect the infiltration height and uniformity are experimentally investigated and discussed. Annular cavity/gaps arrays, bowl arrays, close packed ring arrays, cylindrical column arrays and hole arrays are demonstrated by this method. Geometry size of these nano-patterns can be tuned over the range 10 nm to ?500 nm with steps of ?5 nm during the fabrication progress. Formation mechanisms of the close-packed ring arrays are experimentally investigated. More importantly, most of the nano-patterns produced by this method could be integrated on thin films with conventional semiconductor fabrication techniques, which is desirable for integrated optics circuits and bio-sensing applications. The produced nanostructures are demonstrated to be used as SERS substrates and structural color printing.

10027-26, Session 5

The far-field intensity distribution modulation of the beam cross-section using specially designed and fabricated nanostructure

Jiannong Chen, Ludong Univ. (China)

Obtaining a light beam with arbitrarily desired intensity distribution is constructive and significant. The nanoslit milled on the nobal metal film deposited on the substrated can only allow the electric component perpendicular to the slit to transmit. Based on the transmission-selective property of the nanoslit to the perpendicular polarization componenet, we designed and fabricated a nanostructure composed of MxM square units in each of which there is an azimuthally different-rotated nanoslit. When a linearly polarized beam is vertically directed onto this nanostructure, a light beam with modulated intensity distribution in the far-field is obtained. An arbitrary desired intensity distribution can be demonstrated with correspondingly designed and fabricated nanostructure. The optical setup for generating light beam with any intensity distribution can be very simple and compact. This method of intensity distribution modulation may be a potentially powerful tool in many fields such as light information processing, surface plasmon polaritons excitation and optical data recording.

10027-27, Session 5

InGaAsP/InP-air-aperture microcavities for single-photon sources at 1.55-um telecommunication band

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For sold-state quantum information processing, microcavities containing semiconductor quantum dots have been demonstrated effective as indispensable devices such as efficient and indistinguishable single photon sources, and coherent quantum-control devices. Ideal micropillar cavities for 1.55 um quantum communication is still lacking. Hybrid micropillar cavities, such as Ta2O5/SiO2-InP, Si/SiO2-InP, have been designed and used as 1.55um quantum-dot single-photon sources. However, monolithically fabricated microcavities are more attractive and necessary to quantum communication at 1.55um band. In this work, we propose monolithically producible InGaAsP/InP-air-aperture microcropillar cavities as single photon sources at 1.55-um telecommunication band. The design of air-aperture resolves the problem of small refractive index contrast in InP-based distributed-Bragg-reflector micropillars. Together with tapered (layer thickness adiabatically decreased towards the cavity center layer) distributed-Bragg-reflector structures, the lateral size (diameter) of these micropillar cavities can be decreased to submicrometer scale. There are two modes with quality factors of ~1e4 and ~1e5, which are high enough for efficient single photon emission from 1.55-um quantum dots. The latter mode, especially, is able to realize coherently controllable single-photon devices at 1.55 um. Compared with hybrid micropillar cavities, such as Ta2O5/SiO2–InP or Si/SiO2-InP with

similar pillar heights, the present cavities are of high quality and/or small size. Together with the easy, economic and monolithic fabrication process, here proposed microcavities are better candidates for 1.55-um InAs/InP quantum -dot single photon sources and other quantum devices applied in silica-fiber based quantum information system.

10027-28, Session 6

Versatile asymmetric directional couplers on silicon *(Invited Paper)*

Daoxin Dai, Zhejiang Univ. (China)

The coupling in a directional coupler (DC) has attracted lots of attention as a basic block for photonic integrated circuits. Most of previous work was focused on symmetrical directional couplers (DCs) consisting of two identical optical waveguides, in which case light power can be transferred from one waveguide to the other one completely when choosing the length L of the coupling region appropriately. Recently, an asymmetric DC (ADC) consisting of non-identical waveguides in the coupling region has been attracting more and more attention because of the versatility for various useful applications. ADCs can be formed by combining two ore more waveguides with different dimensions, shapes as well as bending radii for the core regions. In particular, silicon nanophotonics developed in the recent years provides a very good platform to make ADCs on silicon very useful and interesting. In this paper, we give a review for recent progresses of versatile ADCs on silicon, including the following three parts: (1) ADCs for realizing ultracompact and broadband PBSs; (2) ADCs for realizing mode (de)multiplexers; (3) ADCs for power splitter used in microring resonators and Mach-Zehnder interferometers.

10027-29, Session 6

Wavefront shaping through emulated curved space in waveguide settings *(Invited Paper)*

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Wavefront shaping for generating non-diffracting optical beams can be achieved by various methods, ranging from annular slits, axicon lenses, holograms, spatial light modulators, gratings, metasurfaces and diffraction from nanoparticles. Importantly, non-diffracting beams can also be generated in inhomogeneous media, such as photonic crystals and photonic lattices. All these require wavefront shaping, that is typically done externally, outside the medium within which the beam is propagating. However, wavefront shaping can also be done by shaping the EM environment in which the wave is propagating. The fact that the propagation of EM waves in static curved space is analogous to that in inhomogeneous media is the underlying principle of emulating General Relativity (GR) phenomena in transformation optics. Here, we show that using ideas inspired by GR yields efficient beam shaping in waveguide settings. The concept is general, applicable to many cases where wavefront beam shaping in a waveguide platform is required. First, we fabricate the micro-structured optical waveguide with the specific refractive index emulating the curved space environment generated by a massive gravitational object. This dielectric structure yields a very narrow beam that remains non-diffracting for many Rayleigh lengths. Second, with the same experiment system, we demonstrate the Einstein's rings phenomenon, matching Einstein's 80 years old formula. Finally, we present a general formalism to transform Gaussian beams to considerably narrower shape-invariant beams accelerating (bending) along arbitrary trajectories. This work is published at Nature Communications 7:10747 (DOI: 10.1038/ncomms10747) (2016).

10027-30, Session 6

Experimental investigation of light propagation in engineered slotted photonic crystal waveguides

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Photonic Crystal Waveguides are key components to study diverse phenomena in the linear and nonlinear regimes for integrated circuits and rise as a promising platform to host novel materials. Nevertheless, serious limitations are manifest when slow light is targeted, mainly the propagation losses. Even though, photonic crystals are theoretically lossless, the practical implementation is limited by the fabrication accuracy, mainly during the lithographic and etching steps. Interesting studies have been performed in W1-like photonic crystals in order to engineer the losses for given group indices. Further, slot waveguides are known to suffer from larger roughness-induced scattering extrinsic losses than Si wires due to a higher electric field interaction regarding the continuity of the electrical displacement vectors.

We have performed a rigorous experimental study under different approaches to determine the best compromise regarding electronic beam lithography, group index, propagation length and losses in engineered slotted photonic crystal structures [Serna et al., Sci. Rep. 2016, in press]. The waveguide transmission and dispersion were studied with different refractive indices around n=1.45+/-0.05. The photon group delay was measured as a function of the wavelength with integrated MZI and in external OCT techniques for long structures between 200 and 700 ?m. During the evaluation of SEM images, only statistical variations were observed around the calibrated values. Nevertheless, the optical characterization allowed studying the statistical fluctuations and the propagation optical losses. Furthermore, the presence of the flattened band was always observed with the same bandwidth, offering robust dispersion engineered long hybrid waveguides for that are particularly interesting for quantum, nonlinear and all-optical processing integrated applications.

10027-31, Session 6

Lossless coupled modes in symmetric waveguide array with non-uniform gain and loss

Zhenzhen Liu, Jun Jun Xiao, Harbin Institute of Technology Shenzhen Graduate School (China)

Non-Hermitian systems in optics, are a fascinating platform providing a lot of interesting applications. A typical example is the well-known parity-time (PT) symmetric waveguides, which experience a phase transition from the unbroken phase to the broken one crossing the exceptional point. In optical PT-symmetric system the gain and loss are generally uniformly distributed. While for a non-uniform distribution of gain and loss, there arises more fascinating phenomena, such as loss-induced transmission, reversed pump dependence in lasers. In these cases, the eigenvalues are always complex. To achieve lossless

propagation in such systems is of importance. We show that in four coupled waveguides of identical geometry, that is always possible by introducing additional gain or loss to balance the energy propagating in the whole structure. We verify that by the general coupled mode theory and the finite element method. In addition, beam oscillation phenomenon is explored. Our results prompt that non-uniform distribution of gain and loss offers extra control of the eigenvalue dynamics in non-Hermitian system.

10027-32, Session 6

Highly reflective polarization-independent subtractive tri-color filters exploiting a silicon nanodisk array overlaid with aluminum

Wenjing Yue, Sang-Shin Lee, Eun-Soo Kim, Kwangwoon Univ. (Korea, Republic of); Duk-Yong Choi, The Australian National Univ. (Australia)

Silicon (Si), known as the second-most-abundant material in nature, has been predominantly adopted in the commercial microelectronics industry. Owing to its salient features, such as low cost and compatibility with the existing complementary metal-oxide-semiconductor processing, Si is regarded as the best candidate for the construction of optical devices. It was reported that a Si nanowire (NW) formed on a Si substrate is suitable for multi-color generation, whereby a wavelength-selective coupling of the incident light with the guided modes of a vertical Si NW renders a specific color. The reflection efficiency of Si NW, however, is less than 40% due to the low reflectivity of Si. Moreover, Si NW has extremely large aspect ratio, resulting in the untenable fragility and unstable performance.

In this paper, we propose and demonstrate polarization-independent structural subtractive tri-color filters of cyan, magenta, and yellow with high reflection efficiency and robustness, by taking advantage of a aluminum (Al)-coated low-aspect-ratio Si nanodisk (ND) array that is formed on the Si substrate. The Si ND, serving as a high index nanoscatterer, can excite both magnetic dipole and electric dipole resonances in the visible band. The light stored in the ND resonator is preferably coupled to the high index Si substrate, giving rise to a highly suppressed reflection dip. By virtue of the Al overlay and the symmetrical shape of ND, the proposed tri-color filters can enable the high reflection efficiency of ~72%, which exhibit threefold increment as compared with the Si ND-based structure, and polarization-independent property, respectively.

10027-33, Session 7

Silicon and silicon carbide nonlinear and quantum photonics *(Invited Paper)*

Qiang Lin, Univ. of Rochester (United States)

No Abstract Available

10027-34, Session 7

Investigation of Ge1-xSnx/Ge quantum-well structures as optical gain media

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An efficient Si-based laser is one of the most important components for photonic integrated circuits to break the bottleneck of data transport over optical networks. The main challenge is to create gain media based on group-IV semiconductors. Here we present an investigation of using low-dimensional Ge1-xSnx/Ge quantum well (QW) structures pseudomorphically grown on Ge-buffered Si substrates as optical gain media for efficient Si-based lasers. Theoretical analysis of band structures indicates that Ge1-xSnx well sandwiched by Ge barriers can form type-I alignment at ? point with a sufficient potential barrier height to confine carriers in the Ge1-xSnx well, thereby enhancing efficient electron-hole direct recombination. Our calculations also show that Ge1-xSnx/Ge QW can provide a larger optical gain than the bulk Ge1-xSnx counterpart, thus reaching the transparent condition with a much smaller carrier density. Furthermore, epitaxial growth of such Ge1-xSnx/Ge QW structures was performed on Ge-buffer Si substrate using low-temperature molecular beam epitaxy techniques. Photoluminescence spectra from the grown Ge1-xSnx/Ge QW structure were observed and analyzed. These results suggest that Ge1-xSnx/Ge QW structures are promising as optical gain media for efficient Si-based light emitters.

10027-35, Session 7

Wavelength-controlled manipulation of colloidal quasi-resonant quantum dots under pulsed laser irradiation

Aleksey S. Tsipotan, Siberian Federal Univ. (Russian Federation); Aleksandr S. Aleksandrovsky, Kirensky Institute of Physics (Russian Federation); Vitaliy V. Slabko, Siberian Federal Univ. (Russian Federation)

Production of nanostructures consisting of semiconductor nanoparticles (NPs) is of interest for number of applications. Development of new methods of NPs' manipulation and aggregation of NPs into nanostructures with pre-defined geometry is also of considerable interest from the fundamental point of view. Under laser irradiation with properly chosen wavelengths, excitonic excitations will be induced. Electrodynamical interaction between excited NPs is rather universal and allows formation of wide variety of nanostructures both of homo- and heterogeneous content. Theoretical approach for study of interaction of NPs' ensembles with laser light includes dipole-dipole approximation for NPs' attraction and Brownian dynamics computer modelling of NPs stabilized by DLVO barrier. Main predictions of these studies are 1) Controlled self-assembly of nanostructures containing mixed metal and semiconductor NPs is possible via proper choice of wavelength of laser inducing electrodynamical interaction. 2) Efficient self-assembly of a pair of NPs must be expected in the region of wavelengths redshifted with respect to plasmonic/excitonic resonance. 3) Efficient self-assembly is possible in the regime of nanosecond laser pulses with high enough repetition rate.

Experimental results are obtained for CdTe QDs with the excitonic resonance at 520 nm. Six different samples of the same colloid solution were irradiated at wavelengths from 540 to 570 nm. Modifications of absorption spectra of solutions after irradiation was detected, being most prominent at 555 and 560 nm irradiation wavelengths. Analysis of spectra shows that up to 47% of QDs were assembled into pairs. Therefore, possibility of precise QDs manipulation via laser-induced electrodynamical interaction is demonstrated.

10027-36, Session 7

Study of electro-absorption in tin-incorporated group-IV alloy-based strain-balanced quantum well

Prakash Pareek, Ravi Ranjan, Mukul K. Das, Indian School Of Mines (India)

Electroabsorption modulators (EAMs) have widely drawn attention due to their application in optical processing, high speed switching, low power dissipation etc. It would be very useful to design Group IV semiconductors (Si,Ge) based EAM to realize monolithic integrated chip. Fortunately, alloying Germanium with ?-Sn(Tin) can effectively reduce the direct-bandgap of Germanium more than its indirect bandgap and, hence, a direct-bandgap GeSn alloy can be realized. This work focuses on the potential of GeSn quantum well as an EAM in midinfrared range. A 76Å thick Ge0.83Sn0.17layer is sandwiched between two tensile strained Si0.09Ge0.8Sn0.11 layers to form a type-I single strain compensated quantum-well (SSCQW). A fully relaxed Ge0.872 Sn0.128 layer is used as a buffer layer. Firslty, the band profiles of conduction band and valence band in SSCQW are calculated by Van de Walle model solid theory. Then, Eigen state energies in SSCQW are evaluated for ? valley conduction band (?CB), heavy hole band (HH) and light hole band (LH) from the self consistent solution of coupled Schrödinger and Poisson equations in presence of external electric field by finite difference method. After evaluating Eigen energies, excitonic electroabsorption coefficient for transverse electric (TE) mode is calculated by using Fermi golden rule.

A significant absorption (1.2 x 104 cm-1) observed for ?CB1-HH1 transition at 3.5 μm due to higher oscillator strength of excitons. Quantum-confined Stark effect is also demonstrated by redshifting of absorption peak wavelength. A significant change in refractive index (?n) by using Kramers-Kronig integral, performance parameters like extinction ratio, figure of merit and chirping factor are also calculated.

10028-1, Session 1

Tailoring Light with Reflective Metasurfaces *(Invited Paper)*

Pin Chieh Wu, National Taiwan Univ. (Taiwan) and Research Ctr. for Applied Sciences - Academia Sinica (Taiwan); Wei Ting Chen, Yao-Wei Huang, Wei-Yi Tsai, Pei Ru Wu, Ting-Yu Chen, National Taiwan Univ. (Taiwan); Ching-Fu Chen, National Taiwan Univ. (Taiwan) and Research Ctr. for Applied Sciences - Academia Sinica (Taiwan); Hui Jun Wu, Chun Yen Liao, National Taiwan Univ. (Taiwan); Din Ping Tsai, Research Ctr. for Applied Sciences - Academia Sinica (Taiwan) and National Taiwan Univ. (Taiwan)

Metasurfaces enable abrupt changes to the electromagnetic amplitude as well as phase of scattering light within a subwavelength spatial region. They provide a great flexibility in light manipulation and benefit the development in flat optics and optically thin optoelectronic components. Metasurfaces therefore show the abilities to tailor the properties of light and offer a promising way for potential applications on integrated devices. Here, we demonstrated reflective metasurfaces with broad working bandwidth in visible frequencies. Several practical applications will also be performed and discussed. For example, by using a 4-level phase gradient metasurface made of gold cross nano-antennas, a dual-image meta-hologram with high efficiency is performed. A multi-color meta-hologram can also be achieved by the implement of aluminium plasmonics. Furthermore, a reflective polarization state generator is proposed for the generation of arbitrary polarization states under a linear polarized illumination.

10028-2, Session 1

Modelling and ultrafast imaging of dynamic near-field hybridization in strongly coupled plasmonic nanosystem

Alemayehu Nana Koya, Zuoqiang Hao, Jingquan Lin, Changchun Univ. of Science and Technology (China)

In a series of numerical and analytical studies of plasmon hybridization in closely spaced metal nanostructures, it has been demonstrated that the spectral and spatiotemporal characteristics of the local fields in gap regions can be controlled and enhanced by tailoring polarization and temporal profiles of the driving femtosecond pulses [1, 2].

In this report, we experimentally demonstrate the coherent control of near-field excitation and coupling in gold nanosystem comprised of split-ring dimer and nanorod that are separated by a sub-20 nm gap. The near-field responses of gap plasmons are controlled by manipulating the polarization and time delay of the femtosecond excitation laser pulses. The spatiotemporal dynamics of the near-fields are mapped by the time-resolved photoemission electron microscope (TR-PEEM) technique. The experimental findings are supported by corresponding numerical results calculated by the finite-element-time-domain (FDTD) method.

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10028-3, Session 1

Metasurfaces for high-efficiency surface plasmon coupler and active dispersion compensation *(Invited Paper)*

Lei Zhou, Fudan Univ. (China)

Surface plasmon polaritons (SPPs) have recently found numerous applications in photonics, but traditional devices to excite them all suffer inherent low-efficiency issues. Here, we propose a new SPP-excitation scheme and numerically demonstrate that it exhibits inherently high efficiency (~94%). We fabricated a meta-coupler in the microwave regime and demonstrated that the achieved excitation efficiency for spoof-SPP reaches ~73%. On the other hand, metasurfaces realized so far largely reply on passive resonant meta-atoms, whose intrinsic dispersions limit such passive meta-devices' performances at frequencies other than the target one. Here, based on active meta-atoms with varactor diodes involved, we establish a scheme to resolve these issues for microwave metasurfaces, in which the dispersive response of each meta-atom is precisely controlled by an external voltage imparted on the diode. We show that an active gradient metasurface exhibits single-mode high-efficiency operation within a wide frequency band, and the functionality of our metasurface can be dynamically switched from a specular reflector to a surface-wave convertor.

10028-4, Session 1

Passive and active metasurface based on metal-insulator-metal structure *(Invited Paper)*

Junichi Takahara, Tianji Liu, Hideaki Hatada, Yusuke Nagasaki, Osaka Univ. (Japan)

Metal-insulator-metal (MIM) structure is one of the promising plasmonic structure for wide variety of applications from visible to infrared region. It can be used as a nano-optical resonator as a meta-atom composed of metasurface beyond the diffraction limit of light. A MIM resonator harvests light into a nano-gap as an optical antenna and efficiently absorbs light into the gap as gap surface plasmon (GSP) mode. However, applications are limited as long as optical properties of the resonator is static due to its fixed structures. Active control of optical properties of the resonator is needed for further functionality.

Here, we review principles and recent progress of a passive metasurface based on the absorption control using static MIM resonators. Applications of MIM resonators to plasmonic color and a sky radiator are presented. In plasmonic color, we are able to control colors by designing reflection spectra that is determined by two absorption peaks between lower and higher mode of GSP resonance, which is attributed to Fabry-Perot interference of GSP. In a sky radiator, we design absorption spectra matched to atmospheric window of 8-3micron by using multi-sized MIM resonators. This also can be directly applied to infrared emitters based on thermal radiation.

Then, we demonstrate an active metasurface composed of reconfigurable plasmonic resonator based on metal-air-metal (MAM) structure. We realized the MAM resonator by a metal nanowire (NW) suspended on a metal substrate. By applying electrostatic voltage, the suspended NW can be pull down by electrostatic force. This electromechanical response changes the resonant properties of MAM resonator.

10028-5, Session 2

Nanoscale imaging of local few-femtosecond near-field dynamics within individual nanostructures *(Invited Paper)*

Anders Mikkelsen, Lund Univ. (Sweden)

The local enhancement of few-cycle laser pulses by nanostructures opens up for spatiotemporal control of optical interactions on a nanometer and few-femtosecond scale. However, spatially characterization of this dynamics poses a major challenge due to the extreme length and time scales involved. To resolve this issue we combine the femtosecond and attosecond time resolution of advanced laser systems with the nanoscale spatial resolution of PhotoEmission Electron Microscopy (PEEM) to study electron dynamics in nanoscale structures. This allows for very sensitive measurements of plasmonics fields, surface chemistry and pump-probe experiments on ultrafast time scales - all in the same picture. Using 5.5 fs laser pulses with a central energy around 1.6 eV in an interferometric time-resolved PEEM setup, we observe differences in near-field enhancement inside a variety of nanostructures [1,2,3] already within the first few optical cycles . The experiments are supported by finite-difference time-domain simulations of similar structures. We find that field enhancement effects can also be observed in III-V semiconductor nanowires, time and polarization changes are discussed.

We will finally demonstrate imaging using <100 attosecond laser pulses with central energies between 30-100eV in combination with PEEM (attoPEEM)[4,5]. We outline the clear pathway for using such pulses for direct investigations of photon excitations with sub-femtosecond precision

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10028-6, Session 2

Graphene oxide coated Au nanoparticles composite structure for improved SERS sensing

Bingfei Liu, Qi Wang, Tian Tian, Guoming Mao, Hao Liu, Jia Chen, Xiankun Wang, Xiao-Min Ren, Beijing Univ. of Posts and Telecommunications (China)

Surface-enhanced Raman scattering (SERS) is an effective spectral analysis technique as its advantage of molecular fingerprint, ultra-sensitivity and non-contact. It is the most popular and easiest method to create SERS metal nanoparticles (NPs) combining magnetron sputtering deposition of noble metal with rapid annealing. In this study, we have demonstrated an approach to improve the SERS effect by using graphene oxide (GO) Au NPs composite structure. Here, we obtain the Au NPs coated SOI substrate prepared by magnetron sputtering 4 nm Au film and followed by rapid annealing treatment. The experimental results indicate that the SERS intensity is maximum of the Au NPs coated SOI substrate with the average particle diameter of 50 nm when the rapid annealing time is 30s and temperature is 500 degrees. Then, graphene oxide solution is spin coated on the Au NPs to form the GO-Au NPs composite structure. The morphology of GO-Au NPs have been characterized by scanning electron microscope (SEM) and atomic force microscope (AFM). Rhodamine 6G is used as the probe molecule to detect the SERS intensity. The GO-Au NPs has an excellent SERS effect which can detect rhodamine 6G as low as 10-9M. Besides, compared to the Au NPs without GO the GO-Au NPs has two times Raman intensity enhancement of bands at 1365 cm-1 because of the GO improving the SERS properties through strong ability of adsorption the probe molecule and chemical enhancement effect. Therefore, the GO-Au NPs composite structure shows a promising future to detect low concentration material.

10028-7, Session 2

Photoluminescence of Ag/Sn core/shell nanoparticles

Bin Li, Lin Zhu, Ying Hu, Ying-Wei Lu, Hefei Univ. of Technology (China)

Recently, one of the promising applications of plasmonics is the integration with Si-based photovoltaics. Particularly, the near-field effect has attracted intense attention since the metallic nanoparticles embedding in the crystalline or amorphous Si layers could confine the electromagnetic field to enhance the optical absorption cross-section of the photosensitive matrix, and eventually to improve the photovoltaic performances of Si-based solar cells. It is well known that the frequently used metallic nanoparticles are either Ag or Au due to their fantastic surface plasmon properties in the visible range. However, both noble metals have energy levels close to the middle of the band gap of Si and therefore act as efficient recombination centers for the minority carriers. Instinctively, metallic Sn, a group-IV element, has been proposed to be the ‘antenna’ in the plasmon assisted solar cells. However, comparing with that of Ag nanostructures the plasmon response of metallic Sn is too weak to be employed. We therefore chemically synthesized Ag/Sn core/shell nanoparticles to take advantages of both Ag and metallic Sn. In addition to the morphology and phase determinations by TEM and XRD, photoluminescence and absorption properties have been characterized to analysis the surface plasmon effect depending on the configurations of the core/shell nanoparticles. Furthermore, the near-field mappings of different configurations have been performed by the finite element method as well.

10028-8, Session 2

Optical interactions of a single AuNp on a gold film

Xin Hong, Jingxin Wang, Dalian Univ. of Technology (China)

Localized surface plasmon (LSP) and surface plasmon-polariton (SPP) effects have been hot topics in the last several decades The coupling between two plasmonic modes associated with metallic nano-particle and thin film plays an important role in bio-photonics. Especially for a single particle/film model which can build a fundamental base for advanced nano-photonic elements design and nano-optical measurement. However there is little literature work can be found. In this paper, the interaction between LSPR and SPR is studied in detail based on a structure composed of 60nm gold nano-particle, dielectric spacer and 50nm gold film by finite difference time domain (FDTD) method. The LSPR mode influenced by the gold film was studied by calculating its cross sections of scattering, absorption and extinction. With the aim to explore the coupling interaction, a dielectric spacer with the thickness ranging from 2nm to 10 nm was introduced to block the interaction. The results show that at the thickness of 2nm, the LSPR associated with the particle is strongly affected by producing a large red-shift to the red band. This influence is very sensitive to the gap, when the particle is further away from the film, the peak LSPR wavelength is tuned backwards. By changing the spacer thickness between the particle and the film, the LSPR can be tuned to be closer to the

SPP, thus lead to an enhanced extinction cross section. The SPP mode influenced by the AuNp was studied by calculating its peak SPR wavelength. The calculation result indicates the addition of the particle to the film causes the SPR curve broaden but the peak wavelength shift is rather ignored.

10028-9, Session 2

Polarization state of light scattered from quantum plasmonic dimer antennas *(Invited Paper)*

Zhipeng Li, Capital Normal Univ. (China)

Plasmonic antennas are able to concentrate and re-emit light in a controllable manner through strong coupling between metallic nanostructures. Only recently has it found that quantum mechanical effects can drastically change the coupling strength as the feature size approaches atomic scales. Here, we present a comprehensive experimental and theoretical study of the evolution of the resonance peak and its polarization state as the dimer-antenna gap narrows to sub-nanometer scale. We clearly can observe the classical plasmonic regime, a cross-over regime where nonlocal screening plays an important role, and the quantum regime where a charge transfer plasmon appears due to interparticle electron tunneling. Moreover, as the gap decreases from tens of to a few nanometers, the bonding dipole mode tends to emit photons with increasing polarizability. When the gap narrows to quantum regime, a significant depolarization of the mode emission is observed due to the reduction of the charge density of coupled quantum plasmons. These results would be beneficial for the understanding of quantum effects on emitting-polarization of nanoantennas and the development of quantum-based photonic nanodevices.

10028-10, Session 3

Theory for the eigenstates of the full Maxwell equations in some simple composite structures *(Invited Paper)*

David J. Bergman, Asaf Farhi, Tel Aviv Univ. (Israel)

Eigenstates of Maxwell's equations in the quasistatic regime were used recently to calculate the response of a Veselago Lens [1] to the field produced by a time dependent point electric charge [2, 3]. More recently, this approach was extended to calculate the non-quasistatic response of such a lens. This necessitated a calculation of the eigenstates of the full Maxwell equations in a slab structure where the electric permittivity [epsilon]1 of the slab differs from the electric permittivity [epsilon]2 of its surroundings while the magnetic permeability is equal to 1 everywhere [4]. These eigenstates were used to calculate the response of a Veselago Lens to an oscillating point electric dipole source of electromagnetic (EM) waves. A result of these calculations was that, although images with sub-wavelength resolution are achievable, as first predicted by John Pendry [5], those images appear not at the points predicted by geometric optics. They appear, instead, at points which lie upon the slab surfaces. This is strongly connected to the fact that when [epsilon]1/[epsilon]2 = -1 a strong singularity occurs in Maxwell's equations: This value of [epsilon]1/[epsilon]2 is a mathematical accumulation point for the EM eigenvalues. Unfortunately, many physicists are unaware of this crucial mathematical property of Maxwell's equations.

We have now constructed a theory for the EM eigenstates of the full Maxwell equations in a composite structure, without any restriction on the values of the constituent moduli [epsilon]i and [mu]i. This will be described, as will some simple applications. In particular, it is now possible to analyze in detail the response of a Veselago Lens when both [epsilon]1/[epsilon]2 = -1 and mu1/mu2 = -1.

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10028-11, Session 3

Active multiple plasmon-induced transparencies with detuned asymmetric multi-rectangle resonators

Dongdong Liu, Xuzhou Institute of Technology (China); Jicheng Wang, Jiangnan Univ (China); Jian Lu, Nanjing Univ. of Science and Technology (China)

The phenomenon of plasmon-induced transparency (PIT) is realized in surface plasmon polariton waveguide at near-infrared region. By adding one and two resonant cavities, the PIT peaks were achieved due to the destructive interference between the side-coupled rectangle cavity and the bus waveguide. The proposed structures were analyzed by the coupled-mode theory and demonstrated by the finite element method. The simulation results showed that for three rectangle resonators, not only can we manipulate each single PIT window, but also the double PIT windows simultaneously by adjusting one of the geometrical parameters of them; for four rectangle resonators, by changing the widths, the lengths and the refractive index of three cavities simultaneously, we would realize treble PIT peaks and induce an off-to-on PIT optical response. Our novel plasmonic structures and the findings pave the way for new design and engineering of highly integrated optical circuit such as nanoscale optical switching, nanosensor, and wavelength-selecting nanostructure.

10028-12, Session 3

Mechanism of resonant perfect optical absorber, design rules, and applications *(Invited Paper)*

Zhiqiang Guan, Hongxing Xu, Wenqiang Wang, Wuhan Univ. (China)

The mechanism of resonant perfect optical absorber is revealed by coupled mode method. A fully mode dispersion analysis is provided by the phase plots of scattering coefficients on each interface. The structures include dielectric/structure/dielectric system and dielectric/structure/film/dielectric system. The negative role of modes at input surface and the positive role of modes at output surface are shown for the perfect optical absorption. And the non-zero order quasi waveguide mode in the dielectric film is proved to play a key role for the perfect optical absorption when the film is on output surface. The sufficient and necessary conditions of perfect optical absorption are given by three analytical formulae and serve as the design rules. The dependence of perfect optical absorption wavelength on geometry parameters can be explained by the three formulae.

The advantages of widely tunable perfect optical absorption wavelength, high Q factor and the wide applications such as sensing, modulation and detection are reviewed for the resonant perfect optical absorbers.

10028-13, Session 3

Plasmonic 3D conductive coupling in a 3D metamaterial *(Invited Paper)*

Jiafang Li, Zhi-Yuan Li, Institute of Physics (China)

In this talk, we report our recent studies on a 3D conductive coupling mechanism, which induces significant Fano resonances in a 3D metamaterial (MM). The 3D MMs are formed by integrating vertical U-shape split-ring-resonators (SRRs) or vertical rectangular plates along a planar metallic hole array with extraordinary optical transmission (EOT) built by means of homemade focused ion-beam (FIB) folding technique. In such a configuration, intensified vertical E-field is induced along the metallic holes and naturally excites the electric resonances of the vertical structures, which form non-radiative “dark” modes due to the symmetry constraints. These 3D conductive “dark” modes strongly interfere with the “bright” resonance mode of the EOT structure, which generate significant Fano resonances with both prominent destructive and constructive interferences. Moreover, compared with the capacitive and inductive coupled Fano resonances that degrade drastically upon small structural deviations, the demonstrated 3D conductive coupling induced Fano resonances are highly scalable, universal, robust and immune against both fabrication and illumination imperfections. These 3D MMs with prominent and robust Fano resonances exhibit an extremely high sensitivity to refractive index of the environments in the near infrared wavelength region.

10028-14, Session 3

Superlens imaging with surface plasmon polariton cavity in object space

Haiyang Chen, Chinhua Wang, Soochow Univ. (China)

In this paper, superlens imaging with double surface plasmon polarition cavity in object space is proposed. A silver layer is added to above the object mask to form surface plasmon polariton cavity in object space, which helps to greatly enhance evanescent waves generated by objects. As a result, better object imaging contrast can be obtained compared with the surface plasmon polariton cavity in imaging space by amplifying the higher frequency componments while suppressing the long range plasmon mode. Due to the SPP resonance, in the cavity, the image field exhibits a much extended depth of imaging field . We almost can obtain the same image within the entire cavity of length of 20nm when the linewidth of the object layout of traces is set to 45 nm (about 1/9 wavelength). The proposed method provides a practically feasible and relatively simple way to achieve images beyond the optical diffraction limit with both high resolution and large depth of imaging field. This is confirmed by the electric field distributions and optical transfer function of the system. The distinguishing feature of the cavity structure is that the higher frequency wave vectors become dominant and the low-frequency evanescent waves will be far away from the resonance. The physical mechanism of the imaging quality improvements based on surface-plasmon polaritons theory is discussed. Finite-difference time-domain analysis method is used in the simulation.

10028-15, Session 4

Weyl points in plasmonic photonic crystals *(Invited Paper)*

Mingli Chang, Meng Xiao, Wenjie Chen, Che Ting Chan, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Weyl point is a stable nodal point with two bands degenerate at one point. Such a topological point behaves as if it is a magnetic monopole in momentum space and can act as a source or sink of Berry flux. It cannot be removed until two Weyl points with opposite topological charges annihilate with each other. Weyl points have been observed in the electronic system and the analog in classical wave, such as EM wave and acoustic wave have also been studied. However, Weyl photonic crystals typically possess complicated structure and therefore such Weyl points are difficult to be designed at the plasmonics scale and visible light frequency. In this work, we propose a structurally simple plasmonic photonic crystal with Weyl points in its band structure. By analyzing the tight binding model of the system, we find that the Hamiltonians at some high symmetry k points can be reduced to a Weyl form with topological charges 1 or 2. Also we design the real structures with plasmonic photonic crystal and verify that such Weyl points can be designed and realized at optical frequencies. Furthermore we also calculated the gapless boundary modes connecting the upper and lower cones and the robust one-way transport has also been checked in this system. Such materials with Weyl points provide us more possibilities to explore the interesting physics of topological bands in metallic structures at the nano-scale.

10028-16, Session 4

Control and mapping ultrafast plasmons with PEEM

Boyu Ji, Jiang Qin, Peng Lang, Alemayehu Nana Koya, Zuoqiang Hao, Toshihisa Tomie, Jingquan Lin, Changchun Univ. of Science and Technology (China)

Plasmon resonance assisted strong near field enhancement has attached great attention in various fields. On one hand, effort has been made to pursuit resonant field enhancement in the research of excitation and control of localized surface plamsons (LSP). On the other hand, off-resonant excitation of LSP in nanostructure is also found to have great potential applications in some fields, e.g. biomedicine. We demonstrate subwavelength imaging and control of the localized near-field distribution under resonant and off-resonant excitation of identical gold bow-tie nanostructure through photoemission electron microscopy (PEEM). The results show that the near field can be controlled and a better control effect is achieved for the resonant excitation than the case of off-resonant excitation. Furthermore, we found that phase of the localized near field goes inverted after its position shift for the single pulse control scheme, while the phase keeps unchanged after position shift for the two orthogonally pulses control. The LSP in bowtie structure is imaged by a pair of ultrafast femtosecond laser pulses. The results show that by combining the pump-probe technology with PEEM, a series of images of LSP modes temporal evolution on different tips of the bowtie are obtained. We also theoretically investigated the optical response of asymmetric nanocross and a coupled ring dimer-rod nanosystem under ultrafast laser illumination in this work. These works opens the way for the applications of ultrafast plasmon such as in the field of ultrafast optical switching.

10028-17, Session 4

Plasmonic nanostructure fabrication and near-field optical characterization *(Invited Paper)*

Zheyu Fang, Peking Univ. (China)

Plasmonics deals with the phenomena of collective vibration of electrons in the interface between metallic and dielectric media. With the advanced nanofabrication techniques, a broad variety of nanostructures can be designed and fabricated for plasmonic investigations at nanoscale. In this presentation, we will demonstrate our latest results of the design of new plasmonic nanostructures and the characterization of surface plasmon nanostructures with 2D materials by using Scanning Near-field Optical Microscopy (SNOM), which is one of the unique characterization tools for nano-optical detection, and other techniques, and discuss some fundamental properties for both localized surface plasmons and surface plasmon polaritons arise a new insight and understanding for the electro-optical devices, such as plasmonic PL control, active plasmonic modulator and detectors for energy harvesting.

10028-18, Session 4

Photocurrent enhancement by utilizing unidirectional excitation of surface plasmons

Mehdi Afshari Bavil, Zhi Liu, Wuwen Zhou, Chuanbo Li, Buwen Cheng, Institute of Semiconductors (China)

For optical communication technology photodetectors which converts optical signals into electrical signals have great importance. Si has been recognized as the excellent photodetector material compared to III-V based devices due to lower multiplication noise. Ge is introduced to adjust the absorption at telecommunication wavelengths which is compatible with complementary metal oxide semiconductor (CMOS) process.

Nanoplasmonics exploiting surface plasmons, with the ability of controlling andmanipulating of optical signals, provides a platform for developing and optimizing various nanophotonic components,especially photodetectors. Potential geometries to excite SPPs are direct-coupling configurations such as subwavelength nanohole arrays and nanoslits or side-coupling of SPPs via grooves, patches and circular grating which the SPPs can be controlled and unidirectionally propagate.

In this paper we propose, design and demonstrate a novel plasmonics based photodetector for operating wavelength of 1550 nm. Our proposed structure is a circular configuration including sub-wavelength slit and grooves in a metallic layer surrounding a Si-Ge photodetector located at the center. By tailoring the distance between slit and grooves and the separation between the core and slit, SPPs can be steered to predominantly propagate toward center. The most important feature of this structure is that top electrode ring can considered as much as possible narrow to avoid light reflection.

Our results shows that SPPs assists in light absorption and enhances the photodetection and downscals the dimensions. Moreover the structure is Si-based and CMOS process compatible which make it very attractive for industrial purposes. The photodetection was enhanced about 13 times which is very considerable.

10028-37, Session Post

A Fabry-Perot plasmonic modulation with graphene-based silicon grating in mid-infrared region

Xiaosai Wang, Jicheng Wang, Jiangnan Univ. (China)

We propose an ultra-compact graphene-based plasmonic modulation that is compatible with complementary metal-oxide-semiconductor (CMOS) processing. The proposed structure uses a monolayer graphene as a mid-infrared surface waveguide, whose optical response is spatially modulated using electric fields to form a Fabry-Perot cavity. By varying the voltage acting on the cavity, the transmitted wavelength of the device could be controled at room temperature. The finite element method (FEM) has been employed to verify our designs. This design has potential applications in the graphene-based silicon optoelectronic devices as it offers new possibilities for developing new ultra-compact spectrometers and low-cost hyperspectral imaging sensors in mid-infrared region.

10028-38, Session Post

Polarization to the field enhancement by a gold dimer

Xin Hong, Zheng Jin, Dalian Univ. of Technology (China)

Due to the effect of plasmonic coupling, gold nanoparticle dimers have been paid more attentions especially in bio-imaging. The coupling effect existing at the gap between a closely linked particle pair can make the local field strongly enhanced. It is well established that the angle between the excitation polarization and the dimer axis plays a dominant role in the excitation of plasmonic coupling. However due to the demand to remove the illumination beams in the cross-polarization detection method, the excitation and collection is vertical to each other which makes the angel relationship to the polarization can not follow the established one. Thus, in this paper, we present a model to calculate the electric amplitude field distribution of a gold dimer by using finite-difference time-domain (FDTD) method. we simulate a gold dimer under the illumination of a highly focused beams from a microscopy objective. The scattering field collected on a single detector is amplified by heterodyne interference with a reference light. The far-field scattering distributions both in Ex and Ey vary with the polarization rotation were calculated. This method provides a way to evaluate a gold dimer size down to nanometer level. The simulation results show that for such a model, 45degrees between the excitation polarization and the dimer axis can produce an optimum signal. The enhancement thus obtained is ~7.26 fold while the variation between peak-peak can reach ~ 4.41 fold compared to a single plasmoic particle during the rotation of the polarization.

10028-39, Session Post

Surface plasmon resonance scattered by a dielectric sphere

Xin Hong, Xuejie Yin, Dalian Univ. of Technology (China)

It is well known that when total internal reflection occurs at the interface between high to low refractive index, evanescent field will go into the media with low refractive index. This field can be scattered by a small dielectric particle on the surface. With the development of near field optics in which evanescent filed plays a dominant role, the scattering by a particle becomes crucial to understand the underneath physics for the design of novel nano-photonic device. To amplify the scattering signal, an enhanced filed is desirable. Thus in this paper, with the aim

to enhance the scattering field we introduced a thin gold film. Based on Fresnel equation, the introduction of the metallic film causes an amplified transmission coefficient resulted from the excitation of surface plasmon resonance on the thin metallic film. Further a polystyrene bead at the diameter of 200nm and 800nm was employed to test the model. The microscopic local refractive index associated with the polystyrene beads increases when the diameter becomes bigger, thus larger angle is needed to excite the local surface plasmon resonance. Polystyrene beads at diameter of 800nm requires a larger angle which is beyond the numerical aperture of the objective can provide. In this case the condition to excite SPR can not be matched, which in turn shuts up the enhancement. Theoretical and experimental results agree well with each other that the locally excited surface plasmon play a dominant role in the field enhancement scattered by the sphere.

10028-40, Session Post

Analysis of asymmetric hybrid rib-slot-rib surface plasmon waveguide with high-confinement mode

Kai Zheng, Zuxun Song, Northwestern Polytechnical Univ. (China)

The hybrid rib-slot-rib surface plasmon waveguide where a combined rib-slot-rib structure is added on the metal substrate within a low-index gap region with asymmetric structures is proposed using finite element method. Two types of asymmetric structures are introduced and their modal properties are discussed and compared to the traditional long range surface plasmon waveguide. Our designed structures can provide enhanced confinement energy within the gap region at proper parameters. Our simulation results is a guide for turning properties of plasmonic waveguide and providing ways for improved electromagnetic energy confinement in surface plasmon waveguide.

10028-41, Session Post

Multi-wavelength band-pass plasmonic splitter with nanodisk cavity

Maojin Yun, Kai Li, Qingdao Univ. (China)

A novel and simple multi-wavelength band-pass filter based on metal-insular-metal (MIM) waveguide with different nanodisk cavity is proposed and investigated numerically by Finite-Element-Method (FEM) simulations. According to resonant theory of nanodisk, multi-wavelength band-pass filter can be achieved for different wavelength. It also shows that the transmission characteristics of the filter and the resonant wavelength can be easily manipulated by changing the gap between nanodisk and straight waveguide or changing the radius of the nanodisk. This kind of plasmonic waveguide filter may become important promising application in highly plasmonic integrated circuits.

10028-42, Session Post

Cavity-enhanced ultra-thin aluminum plasmonic resonator for surface-enhanced infrared absorption spectroscopy

Wei Wei, Jinpeng Nong, Chongqing Univ. (China); Linlong Tang, Chongqing Institute of Green and Intelligent Technology (China); Xiao Jiang, Na Chen, Peng Luo, Chongqing Univ. (China)

Owing to the advantages of natural abundance, low cost, and amenability to manufacturing processes, aluminum has recently been recognized as a highly promising plasmonic material that attracts extensive research interest. Here, we propose a cavity-enhanced plasmonic resonator for surface enhanced infrared absorption spectroscopy using patterned ultra-thin aluminum micro/nano structure. The considered resonator consists of a patterned ultra-thin structure, a dielectric layer and a reflective layer. In such structure, the resonance absorption is enhanced by the Fabry-Perot cavity formed between the patterned structure and the reflective layer. An optical model is built employing the finite element method to investigate the influence of the structural parameters on the absorption characteristics of the resonator, including the thickness, occupation ratio, period of the patterned structure and the thickness of the dielectric layer. The enhanced infrared absorption characteristics can be used for infrared sensing of the adsorbed molecules. When the resonator is covered with a molecular layer, the resonator can be used as a surface enhanced infrared absorption substrate to enhance the absorption signal of the bimolecular. A high enhanced factor of 5?104 can be achieved when the resonance wavelength of resonator is adjusted to match the desired vibrational mode of the molecular. Such a cavity-enhanced plasmonic resonator, which is easy for practical fabrication, is expected to have potential applications for infrared sensing with high-performance.

10028-43, Session Post

simulation of two-dimensional gratings for SERS-active substrate

Wenlong Zou, Jianhong Wu, Soochow Univ. (China)

Raman spectroscopy provides intrinsic vibrational and rotational mode of molecules in materials, which is widely used in chemical, medical and environmental domain. As known, the magnitude of surface enhanced Raman scattering can be amplified several orders. Nowadays, common Raman scattering has been gradually replaced by surface enhanced Raman scattering in low concentration detection domain. Generally speaking, the signal of surface enhance Raman scattering on periodic nanostructures is more reliable and reproducible than on irregular nanostructures. In this paper, two-dimensional gratings coated by noble metal are used as SERS-active substrate. The surface plasmon resonance can be obtained by tuning the period of two-dimensional grating when the excitation laser interacts on the grating. The local electric field distribution is simulated by finite-difference-time-domain (FDTD). The wavelength of 632.8nm and 785nm are usually assembled on commercial Raman spectrometer. The optimization procedure of two-dimensional grating period is simulated by FDTD for above two wavelengths. The relation between the grating period and surface plasmon resonance is obtained in theory. The parameters such as depth of photoresist and thickness of coated metal are systematic discussed. The simulation results will greatly guide our post manufacture, which can be served for the commercial Raman spectrometer in SERS detection.

10028-44, Session Post

Hydrogen-regulated chiral nanoplasmonics

Xiaoyang Duan, Simon Kamin, Max-Planck-Institut für Intelligente Systeme (Germany); Florian Sterl, Harald Giessen, University of Stuttgart (Germany); Na Liu, Max-Planck-Institut für Intelligente Systeme (Germany) and University of Heidelberg (Germany)

In this paper, we demonstrate a hydrogen-regulated chiroptical response in hybrid plasmonic metamolecules in the visible

spectral range. Here, Mg works not only as active material for hydrogen uptake but also as plasmonic material for resonant coupling with the satellite gold (Au) particles. Each metamolecule consists of coupled hybrid components that are arranged in a prescribed chiral geometry to generate a chiroptical response. Au particles are particularly employed here to assist Mg particles for achieving sharp and pronounced CD spectra. Such chiroptical response can be switched on/off by dynamically unloading/loading hydrogen in real time. In addition, energy dispersive X-ray spectroscopy (EDX) reveals the morphology changes of the Mg particles that result from hydrogenation and dehydrogenation processes. With integration of appropriate active materials, our design scheme can be generalized to create sensitive chiral platforms for a variety of gas detection, given the high sensitivity of CD spectroscopy. This could provide a powerful addition to the conventional sensing paradigm.

10028-45, Session Post

Spin-controlled directional launching of surface plasmons at the subwavelength scale

Huang Tao, Jiajian Wang, Wei Liu, Ziwei Li, Zheyu Fang, Feng Lin, Xing Zhu, Peking Univ. (China)

Unidirectional SPP (Surface plasmon polaritons) couplers which can couple the SPPs from the free-space light to a desired direction or regio, especially actively tuning the propagation direction of SPPs by additional external control, is very important for the on-chip plasmonic devices. In previous studies, actively controlled and unidirectional SPP launchers usually have large longitudinal dimensions (>10?, perpendicular to the SPP propagation direction along the metal surface). In this paper, we demonstrated spin-controlled directional launching of surface plasmons at the subwavelength scale. The total size of the SPP launcher is only about 320 nm in horizontal direction and 180 nm in vertical direction. The principle is based on optical spin's effect for the geometric phase of light. The slope of the structures decides the spin-related geometric phase and their relative positions decide the distance-related phase. Therefore we can introduced the spin's effects on the phase of the SPPs excited by a curved slit through the slope. Based on this idea, we designed a curved nanoslit pair and studied the spin's control towards the propagation direction of the SPPs, in this nanoslit pair, in both theory and simulation. The results showed that the launched SPPs propagate towards the right direction when the incident light is right-handed circularly polarized light and the launched SPPs propagate towards the left direction when the incident light is left-handed circularly polarized light. Further, we conducted the SNOM experiment to testify our theory and simulation and the shape and period of the interference fringes has good agreement with the theory and increase the credibility of our experiment results.

10028-46, Session Post

Controllable unidirectional emission of electric dipole coupled to plasmonic bowtie antenna

Jun-Jun Xiao, Harbin Institute of Technology Shenzhen Graduate School (China); Xiao Ming Zhang, Harbin Institute of Technology (China)

Nanoantennas have been proved to be a good platform to tune the emission properties of a localized source (e.g. an active electric dipole). Besides the enhancement of the emission efficiency, it is also feasible to control the radiation directivity of a dipole by utilizing the plasmon resonance modes of these antennas. Here, we analyze the angular emission on the in-plane electric dipole modes of gold bowtie antenna. When the nanostructure is excited by a nearby dipole source, highly emission directionality can be obtained. Furthermore, by controlling the the position of the dipole source, strong modulation in the angular emission of the dipole source occur due to variation of the amplitude, the relative phase difference, and the orientation of the induced dipolar modes in the system. We show the directional effects with full-wave numerical simulations and a model of two electric dipoles interference .

10028-19, Session 5

Metal nanogap structure-based plasmonics and biomedical applications *(Invited Paper)*

Jwa-Min Nam, Seoul National Univ. (Korea, Republic of)

Designing, synthesizing and controlling plasmonic nanostructures with high precision and high yield are of paramount importance in optics, nanoscience, chemistry, materials science, energy and nanobiotechnology. In particular, synthesizing and utilizing plasmonic nanostructures with ultrastrong, controllable and quantifiable signals is key to nanoantenna, plasmonics-driven chemical reaction, various chemical and biological detection and biological imaging applications. Here, I will introduce newly emerging DNA-engineered plasmonically coupled and enhanced nanoprobes with strong, controllable and quantifiable signals including nanogap-enhanced Raman scattering, show their potentials in addressing some of important challenges in science, and discuss how these new materials can lead us to new breakthroughs in various technologies including biomedical technologies.

10028-20, Session 5

Changing surface plasmon modes by optical spin-orbit interaction

Feng Lin, Jiajian Wang, Wei Liu, Xing Zhu, Peking Univ. (China)

The optical spin-orbit interaction is that a coupling of the intrinsic angular momentum (photon spin) and the extrinsic momentum (orbital angular momentum) [1-2]. The effect is usually observed when the light passes through an anisotropic and inhomogeneous medium. For instances, the optical spin Hall effect, beam displacement and momentum shift due to the optical spin, was observed at the medium interface. In plasmonic structures, the surface plasmons travel along the path that can be defined to within a subwavelength scale by the geometric patterns of the structures, which generate a significant optical orbital angular momentum. In our work, on the Au thin film deposited on glass substrates, we fabricate the subwavelength holes by focused ion beam, which form the ring shape. Using the scanning near-field optical microscope, the different propagation modes of surface plasmons has been observed for the excitation light with the left and right handed circular polarization, respectively. Based on the conservation of total optical angular momentum in this circular system, the coupling effect of the spin and orbital angular momentum can be deduced from the measured and simulated distribution of electric fields.

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10028-21, Session 5

Controlling the polarization state of light with plasmonic metastructures *(Invited Paper)*

Ruwen Peng, Renhao Fan, Xiang Xiong, Mu Wang, Nanjing Univ. (China)

In this talk, we present our recent work on controlling the polarization state of light with plasmonic metastructures. First, we illustrate an approach to tune efficiently the phase difference of light in two orthogonal directions by controlling the time retardation with a microstructured surface. Second, we demonstrate the general mechanism to construct the dispersion-free metastructure, in which the intrinsic dispersion of the metallic structures is perfectly cancelled out by the thickness-dependent dispersion of the dielectric spacing layer. By selecting the structural parameters, the polarization state of light can be freely tuned across a broad frequency range, and all of the polarization states on the Poincaré sphere can be realized dispersion free. Third, we present a freely tunable polarization rotator for broadband terahertz waves using a metastructure, which can conveniently rotate the polarization of a linearly polarized terahertz wave to any desired direction with nearly perfect conversion efficiency. The investigations provide some guidelines to control the polarization state of light at subwavelength scale.

10028-22, Session 5

Tailored and reconfigurable optical properties using plasmonics *(Invited Paper)*

Maiken H. Mikkelsen, Duke Univ. (United States)

Hybrid materials structured on the molecular scale hold the promise to realize optical properties that are drastically different from their bulk counterparts. For example, metal-dielectric nanocavities may tightly confine light to small mode volumes resulting in strongly increased local density of states. In this talk, I will describe recent experiments utilizing a dynamically-tunable plasmonic platform where emitters are sandwiched in a sub-10-nm gap between colloidally synthesized silver nanocubes and a metal film. Incorporating CdSe/ZnS semiconductor quantum dots into the nanocavities enables demonstration of an ultrafast (<11 ps) yet efficient source of spontaneous emission, corresponding to an emission rate exceeding 90 GHz [Nat. Commun. 6, 7788 (2015)]. We show an increase in the spontaneous emission rate of a factor of 880 and simultaneously a 2,300-fold enhancement in the total fluorescence intensity, which indicates a high radiative quantum efficiency of ~50%. Additionally, at a surface fill fraction of ~20%, these film-coupled nanocubes behave as spectrally selective perfect absorbers which can be tuned from the visible to the near-infrared utilizing inherently large-area solution-based deposition techniques [Adv. Mater. 27, 8028 (2015)]. Finally, the plasmon resonance can be tuned electrically over 100?nm in the visible wavelength range by applying a bias across the nanoscale gap which causes changes in the gap thickness and dielectric environment [Appl. Phys. Lett. 108, 183107 (2016)]. The observed tuning range is greater than the full-width-at-half-maximum of the plasmon resonance, resulting in a tuning figure of merit of 1.05 and a tuning contrast greater than 50%.

10028-23, Session 5

Robust plasmonic tips fabricated by the tapering of composite hybrid silicate microfibers with metallic core *(Invited Paper)*

Afroditi Petropoulou, National Hellenic Research Foundation (Greece) and Univ. of Peloponnese (Greece); Grigoris Antonopoulos, National Hellenic Research Foundation (Greece); Paul Bastock, Christopher Craig, Univ. of Southampton (United Kingdom); Georgios Kakarantzas, National Hellenic Research Foundation (Greece); Daniel W. Hewak, Michalis N. Zervas, Univ. of Southampton (United Kingdom); Christos Riziotis, National Hellenic Research Foundation (Greece)

The development of plasmonic devices for sensing applications can offer high sensitivity and a dramatic improvement to the detection limits due to the high field enhancement at the metal surfaces. The platform proposed here is a hybrid microfiber comprising a metal core and a glass silicate cladding that can be further engineered by a suitable diameter tapering process in order to achieve a field enhancement at the metal/dielectric interface. The existence of a glass cladding not only serves as a mechanical host for the metal core, but also provides ease of handling regarding the tapering process providing also an environmentally robust platform for device's manipulation. The advantages of this composite material system over pure metal tips are the absence of impurities and the multiple excitations of the plasmon modes due to the total internal reflection at the glass/air interface. The improved field enhancement at the apex of these tapered microwires was calculated through Finite Element Method (FEM) simulations. Enhancement factors up to 10^4 were theoretically observed for this type of tapered microwires. The use of different metals having different melting points, viscosity and thermal expansion coefficients as well as the use of composite fibers with different glass and metal core diameter has enabled the optimization of the fiber tapering process conditions in order to achieve tapered microwires with the desirable geometrical and operational characteristics.

10028-24, Session 5

The electric field enhancement and spatial resolution of a metal-coated tapered fiber tip using internal radially polarized vector beam

Fanfan Lu, Ting Mei, Northwestern Polytechnical Univ. (China)

No Abstract Available.

10028-25, Session 5

Steering the scattering direction of plasmonic nanoantenna by spin-orbit coupling effect

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It has been found that optical surface waves have intrinsic transverse spin angular momentum (TSAM) whose direction is locked by the corresponding complex wave vector. This TSAM-locking feature allows unidirectional excitation of typical optical

surface waves [such as surface plasmon polaritions (SPPs)] by a nanoscatter due to the spin-orbit coupling effect. Here we show that the spin-orbit coupling effect of SPPs can be implemented to tune the far field scattering direction of carefully designed plasmonic nanoantenna. By analyzing the angular spectrum of the fields produced by a circular polarized electric dipole (CPED), we reveal that the TSAM locking feature of surface waves is inherently related to the asymmetric interference of CPED in the near field regime rather than in the far field regime. However, it is shown that in a plasmonic nanoantenna involving the spin-orbit interaction of SPPs, the far field scattering pattern of the antenna can also be controlled by the helicity of the incident wave. As an illustration, we exemplify that by a nanoantenna combining a silver sphere and a silver nanorod. The theoretical results are confirmed by numerical calculations. Our results may be useful in spin-dependent photonic applications such as directional light emission and optical micromanipulation.

10028-26, Session 5

Strong coupling between plasmonic resonances and molecular excitons *(Invited Paper)*

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Strong light-matter interactions build upon fast energy exchange between atoms (molecules) and electromagnetic modes in a cavity, which leads to cavity-atom mode hybridization, with great potentials to be applied in quantum information processing and the manipulation of atomic (molecular) properties. On the other hand, plasmonic cavities represent a very promising platform towards the fundamental limit of controlling light-matter interaction, e.g. single atom-photon couplings, since these nano-cavities can provide ultrahigh density of optical states in an exceptionally small mode volume. Here we compress the mode volume by squeezing light fields into a super narrow nano-gap between a gold nanocube and a metallic substrate, which comprise a novel plasmonic nanocube-film cavity. We experimentally demonstrate the strong coupling between molecular excitons and plasmonic resonances (so-called plexcitonic coupling) in such a cavity, which can induce profound and significant spectral and spatial modification to the plasmonic gap modes. Within the spectral span of a single gap mode in a nanotube-film cavity with a 3-nm wide gap, the introduction of narrowband J-aggregate dye molecules enables an anti-crossing behaviour in the spectral response, splitting the single mode into two distinct spatial modes that are easily identified by their far-field scattering profiles. Simulation results confirm the experimental findings. Our work not only provides us significant insights into the nature of coherent light-matter interaction, but also contributes to the nanophotonic quantum electrodynamics applications, e.g. reshaping radiative properties of plasmonic cavities and effectively enhancing interaction with single emitters.

10028-47, Session 5

Electrically-driven plasmonic nanorod metamaterials

Pan Wang, Alexey V. Krasavin, Mazhar E. Nasir, Wayne Dickson, Anatoly V. Zayats, King's College London (United Kingdom)

Typically, surface plasmons in metal nanostructures are excited by external illumination. Low-energy inelastic tunneling electron (few eV) is an alternative way to excite surface plasmons with high compactness. However, the difficulty in fabrication of required tunneling gaps (~1 nm) in metal nanostructures hinders the practical applications. Here, by taking advantage of the high-density gold nanorods, we demonstrated a facile method for electric stimulation of plasmonic excitations and related light emission in metamaterials using inelastic electron tunneling.

To form tunneling gaps, a plasmonic nanorod metamaterial was first ion-milled to achieve the gold nanorods ~1 nm shorter than surrounding alumina matrix. Then, a droplet of eutectic gallium and indium (EGaIn) was added onto the sample surface working as an upper electrode, forming approximately 1010 of ~1-nm air gaps between the nanorod tips and the EGaIn electrode. When a low voltage was applied between the gold nanorods and the EGaIn, strong light emission was observed from the substrate side of the sample. The effect is due to the excitation plasmonic modes of individual nanorods that subsequently couple to the modes of the nanorod metamaterial, which in turn is converted to free-space photons at substrate side. The measured spectra of the emitted light obtained under different bias voltages show the intensity increase of the emitted light along with the blue shift of the high frequency cutoff with the increased applied voltage, covering hyperbolic dispersion range of the metamaterial. The observed effect provides new opportunity for designing electrically driven integrated light sources for metamaterial-based biochemical sensors as well as integrated nanophotonic applications.

10028-27, Session 6

Quantum optics with graphene plasmons *(Invited Paper)*

Javier García de Abajo, ICFO - Institut de Ciències Fotòniques (Spain)

Plasmons in highly doped graphene are extremely tunable by external means (electrically, thermally, magnetically, nonlinearly) and exhibit record levels of confinement. Consequently, the interaction with optical quantum emitters is extraordinarily intense, rendering these excitations an excellent platform for the implementation of quantum optics phenomena at the nanometer scale. In particular, the strong-coupling regime is expected to be reached at the single plasmon level. In this presentation, we will discuss the physics and phenomenology of quantum optics phenomena enabled by graphene plasmons, as well as their application in light modulation at the nanoscale.

10028-28, Session 6

Plasmonic detour phase meta-hologram

Changjun Min, Ting Lei, Zhenwei Xie, Xiaocong Yuan, Shenzhen Univ. (China)

As a powerful optical device for manipulating phase and amplitude of light, detour-phase hologram has widely been employed in applications of beam shaping, three-dimensional display, optical signal processing, and others. However, traditional detour phase hologram is not sensitive to the polarization of light, and thus it cannot shape the polarization status of light or work as polarization-multiplexing devices. Thus, to improve the performance of traditional detour phase hologram, especially in polarization response, we introduce the light-metasurface interaction mechanism to the traditional detour phase hologram, and design a novel polarization selective detour phase meta-hologram assisted by plasmonic nano-slits, which shows attractive advantages of polarization multiplexing ability, broadband response, and ultra-compact size. The meta-hologram relies on the dislocations of plasmonic slits to achieve arbitrary phase distributions, showing strong polarization selectivity to incident light due to the plasmonic response of deep-

subwavelength slits. To verify the polarization selectivity and broadband responses, we demonstrate two holographic patterns of an optical vortex and an Airy beam at p- and s-polarized light with wavelengths of 532nm, 633nm and 780nm, respectively, by both experiments and FDTD calculations. In addition, we realize an application example of the meta-hologram for generating two 3 x 3 OAM arrays for p- and s-polarizations, respectively, and detecting the incident OAMs, to further demonstrate its great potential as a photonic device for OAM generation, detection and modulation. Such plasmonic detour phase meta-hologram could find applications in a wide field of photonics, such as chip-level beam shaping and high-capacity OAM communication.

10028-29, Session 6

Coherent control of plasmonic spin-hall effect

Shiyi Xiao, The Univ. of Birmingham (United Kingdom); Fan Zhong, Hui Liu, Shining Zhu, Nanjing Univ. (China); Jensen Li, The Univ. of Birmingham (United Kingdom)

In recent years, many attentions have been paid to the spin-orbit interaction (SOI) of light using geometric-phase enabled optical and plasmonic systems. Together with the recent developments of metasurfaces, it offers an alternative route to excite SPPs through SOI with opposite geometric phases for the two spins. The associated spin-dependent phenomena can be regarded as the optical spin-Hall effect (OSHE). However, the time-reversely related SPP profiles, from the opposite geometric phases, generated with the two normal incident spins in these cases have so far only demonstrated simple and symmetric splitting of the two spins, known as optical spin Hall effect. Without a proper geometric phase design scheme, the generated SPP profiles are far from arbitrary and independent for the two spins. It refrains us to fully exploit the potential of OSHE and to allow the two spins to work cooperatively in a flexible manner. Here we demonstrate coherent and independent control of SPP orbitals for the two opposite spins using multiple rings of nano-slots with properly designed orientations on a metasurface. This scheme provides us to achieve arbitrary optical spin-Hall effect. We demonstrate the two opposite spins can cooperate with each other. Such coherent control can further provide us the capability to assemble a series of individually designed “time” frames as a motion picture being played back by rotating the linear polarization of the incident light. This is a form of spin-enabled coherent control and provides a unique way in achieving tunable orbital motions in plasmonics.

10028-30, Session 6

Ultrafast on-chip all-optical switch in integrated photonic circuits

Zhen Chai, Xiaoyong Hu, Yu Zhu, Xiaoyu Yang, Feifan Wang, Zibo Gong, Hong Yang, Qihuang Gong, Peking Univ. (China)

Ultrafast on-chip all-optical switch is an essential component of ultrahigh-speed information processing chips. Several significant indexes are stringently required, i.e. on-chip trigger, ultralow energy consumption, and wideband (or multiple-wavelength) operation. To date, such an all-optical switch has not been demonstrated due to intrinsic bottleneck limitations of materials. Here, we report, for the first time, a picosecond and low-power all-optical switch with multiple operating wavelengths in integrated photonic circuits, on-chip-triggered by a control light. The sample configuration combines the advantages of plasmonics and photonics, i.e. plasmonic nanostructures used as core units interconnected by ultralow-loss dielectric slot waveguides. A large nonlinearity enhancement is obtained based on resonant excitation, local field effect, and field enhancement effect, while fast response is maintained by intermolecular energy transfer. A fast response of 63 ps and ultralow control light intensity of 450 kW/cm2 are achieved.

10028-31, Session 6

Coupling of single quantum dot and a plasmonic nanowire *(Invited Paper)*

Hong Wei, Institute of Physics (China)

The interactions between surface plasmons (SPs) and excitons in the coupled systems of metal nanostructures and quantum emitters (QEs) lead to many interesting phenomena and potential applications, which are strongly dependent on the efficiency of excitons converting to SPs, i.e., the quantum yield of SPs. As is known, there are three channels for the recombination of the excitons in coupled plasmonic systems, which are the direct free space radiation channel, SP generation channel and nonradiative damping channel. The difficulty in distinguishing all the possible exciton recombination channels hinders the experimental determination of SP quantum yield.

The propagating SPs supported by the metal nanowire (NW) make it possible to separate the directly radiative photons and the generated SPs in the QE-NW coupling structure, which provides a suitable system to disentangle the exciton recombination channels and obtain the SP quantum yield. Here, we carefully analyzed the exciton-plasmon coupling process in the coupled system of a single quantum dot (QD) and a silver NW. The quantum yield of single SP generation is experimentally determined for the first time by disentangling all the exciton recombination channels. Moreover, we used Al2O3 film of different thickness to control the QD-NW separation and studied the distance-dependent exciton recombination dynamics. Our results show that the optimum QD-NW coupling distance for the largest SP quantum yield is about 10 nm, resulting from the different distance-dependent decay rates of the three channels.

10028-32, Session 6

Plasmonic interference for classical and quantum logical gates *(Invited Paper)*

Tao Li, Shuming Wang, Yulin Wang, Shining Zhu, Nanjing Univ. (China)

Plasmonic has provided versatile solutions to confine the light at sub-wavelength scale together with strong field enhancement, which enables great possibilities for compact photonic integration and other applications. In this talk, I would firstly show an interesting composite plasmonic interference resulted from two crossed strip-metallic waveguides with a narrower gap, where the vectorial field configuration gives rise to two quite different interferences (synchronous and antisynchronous). Based on this interference effects, compact SPP switches are proposed and demonstrated with respect to external phase modulations [1]. These plasmonic switches under different phase conditions are found to work as photonic logical gates for some specific functionality. Secondly, in a further step, classical plasmonic interference is extended to quantum regime. By coupling the entangled photons into the plasmonic system, quantum plasmonic interference has been revealed in single plasmon level [2,3]. Nevertheless, here, I would like to report the first realization of a plasmonic Control-NOT gate for two polarization-entangled plasmonic qubits based on the metal/dielectric hybrid waveguide, which is the very fundamental block for integrated quantum processing. This device is implemented by a polarization sensitive beam splitter that is formed by a proper grating in the hybrid waveguide. It enables an R/T ratio of 2/1 for the TM wave (SPP) while direct transmission for TE wave, which satisfies the requirement of the CNOT gate. Finally, we

realize, to our knowledge, the smallest CNOT gate (14*14 micro) with an estimated fidelity of 63.7%< F<80.3% [4]. This result demonstrates the validation of plasmonic system to quantum information science and technology.

10028-33, Session 7

Deep UV plasmonics and Raman microscopy *(Invited Paper)*

Satoshi Kawata, Osaka Univ. (Japan)

Recent development of deep UV light sources opens a new world of nanophotonics, as exemplified by deep UV photo-lithography, photo-catalysis, sterilization, and molecular-sensing, analysis and imaging. If deep UV optics is combined with Raman scattering microscopy, the distribution of nucleotides and proteins in a cell is imaged and analyzed without labelling. However, the use of deep UV light for bio-imaging is limited because it can destroy or denature target bio-molecules. Recently, we proposed a method for suppressing the photo-degradation of molecules using lanthanide ions in solution as energy quenchers [1]. This approach directly removes excited energy at the fundamental origin of cellular photo-degradation. For sub-wavelength imaging, we need a plasmonic tip, which works in deep UV to enhance Raman scattering at molecules. We have found that aluminum is one of the best metals that exhibit plasmonic field enhancement effect in deep-UV, while not in visible because the imaginary part of the dielectric constant for aluminum is very large in the visible range [2]. We also found that Indium is another good candidate in deep UV and is useful in practice for vapor deposition due to the relatively low meting point [3], which is important for producing multi-grain tips for highly reproducible enhancement [4].

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10028-34, Session 7

Unidirectional antenna by spoof-localized surface plasmon resonators

FeiFei Qin, Jun-Jun Xiao, Harbin Institute of Technology Shenzhen Graduate School (China)

We propose a deep sub-wavelength unidirectional antenna that is realized by spoof localized surface plasmon resonators (SLSPR). This kind of resonator can support both magnetic dipole modes and electric dipole modes and derive their properties from structural resonance rather than from the electronic resonance [1]. By carefully adjusting the geometry of the composite structures, the magnetic and electric dipole resonances can overlap spectrally. With that, strong directional light scattering in the forward direction, which can act as a directive RF antenna with nearly zero backscattered fieldcan be achieved. Such behavior is similar to the Kerker's scattering by hypothetic magneto-dielectric particles [2] and provides different platform for engineering directional antenna in microwave or THz bands.

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10028-35, Session 7

Circular dichroism and plasmonic properties of noble metal assemblies *(Invited Paper)*

Chuanlai Xu, Liguang Xu, Xiaoling Wu, Hua Kuang, Jiangnan Univ. (China)

Chiral nanoscale photonic systems typically follow either tetrahedral or helical geometries that require four or more different constituent nanoparticles. Smaller number of particles and different chiral geometries taking advantage of the self-organization capabilities of nanomaterials will advance understanding of chiral plasmonic effects, facilitate development of their theory, and stimulate practical applications of chiroplasmonics. Here we show that gold nanorods self-assemble into side-by-side orientated pairs and "ladders" in which chiral properties originate from the small dihedral angle between them. Spontaneous twisting of one nanorod versus the other one breaks the centrosymmetric nature of the parallel assemblies. Two possible enantiomeric conformations with positive and negative dihedral angles were obtained with different assembly triggers. The chiral nature of the angled nanorod pairs was confirmed by 4p full space simulations and the first example of single-particle CD spectroscopy. Self-assembled nanorod pairs and "ladders" enable the development of chiral metamaterials, (bio)sensors, and new catalytic processes. Similarly, heterodimers of Au NPs were fabricated with DNA or NaCl respectively.Taking into account that the shapes of the NPs are nonspherical, chiral properties of heterodimers were attributed to the cooperative effect of the small dihedral angle between two adjacent NPs and the plasmonic coupling of NPs, which break the symmetric nature of two uniform spheres; this conclusion was confirmed by 4ϖ full space simulation. Impressively, the chiroptical response was tunable and reversible, and it was achieved by changing the size of building blocks and the temperature.

10028-36, Session 7

A high-Q plasmonic-photonic hybrid mode *(Invited Paper)*

Yun-Feng Xiao, Peking Univ. (China)

Localized-surface plasmonic resonances (LSPRs) supported by metal nanoparticles (MNP) enable subwavelength confinement of light, forming an ideal bridge between light and matter. However the Ohmic loss intrinsic to metal limits the life time of plasmon and leads to quenching phenomena. Such undesirable effects are successfully inhibited by introducing an optical cavity and forming a high-Q plasmonic-photonic hybrid mode, which possesses both small mode volume of plasmonic resonators and long life time of photonic resonators. We analytically study the interaction of LSPRs with the microcavity and demonstrate that the property of the hybrid mode can be easily tuned, showing great advantages in various applications. Particularly, we focus on the interaction of such a plasmonic-photonic mode with a quantum emitter, such as atom, molecular, quantum dot, etc. In this composite system, the microcavity serves as a low-loss storage of the optical field, while the MNP plays the role of an optical antenna which creates a hot spot and magnifies the local optical field. Therefore, the cooperativity parameter between the cavity mode and emitter achieves a more than 100-fold increase, compared with bare cavity. In addition, quantum yield is enhanced by an order of magnitude compared with care MNP. It is achieved by forming a low-loss dark state in this system, which consists of cavity mode and emitter while bypassing the lossy MNP. With the greatly improved cooperativity parameter and quantum yield, we claim that the high-Q plasmonic-photonic hybrid mode holds potential for highly sensitive sensing and precise quantum manipulation.

10029-1, Session 1

Temporal purity and Hong-Ou-Mandel quantum interference of single photons from two independent cold atomic ensembles *(Invited Paper)*

Jiefei Chen, East China Normal Univ. (China); Weiping Zhang, Shanghai Jiao Tong Univ. (China)

The temporal purity of the single photons is crucial to the indistinguishability of independent photon sources for fundamental study of quantum nature of light and to the development of the photonic technologies. Currently the technique for single photons heralded from time-frequency entangled biphotons created in nonlinear crystals doesn't guarantee the temporal quantum purity, except using spectral filtering. Nevertheless, an entirely different situation is anticipated for narrow-band biphotons with a coherence time far longer than the time-resolution of single photon detector. Here we demonstrate temporally pure single photons with coherence time of 100 ns, directly heralded from the time-frequency entangled biphotons generated by spontaneous four-wave mixing in cold atomic ensembles, without any supplemented filters or cavities. A near-perfect purity and indistinguishability are both verified through the Hong-Ou-Mandel quantum interference using single photons from two independent cold atomic ensembles without synchronization.

10029-2, Session 1

Farfield superlocalization of two close incoherent sources via linear optics *(Invited Paper)*

Ranjith Nair, Xiao-Ming Lu, Shan Zheng Ang, Mankei Tsang, National Univ. of Singapore (Singapore)

Rayleigh's criterion for resolving two incoherent point sources has been the most influential measure of farfield optical imaging resolution for over a century. In the context of statistical image processing, violation of the criterion is especially detrimental to the estimation of the separation between the sources, and modern superresolution techniques rely on suppressing the emission of close sources to enhance the localization precision. Using quantum optics, quantum information theory, and statistical analysis, here we show that, even if two close incoherent sources emit simultaneously, measurements with linear optics and photon counting can estimate their separation almost as precisely as conventional methods do for isolated sources, rendering Rayleigh's criterion irrelevant to the problem. Our results demonstrate that superresolution can be achieved not only for fluorophores but also for stars.

10029-3, Session 1

Multiplexed entangled photon sources for all fiber quantum networks

Zhiyuan Zhou, Bao-Sen Shi, Univ. of Science and Technology of China (China)

The ultimate goal of quantum information science is to build a global quantum network, which enables quantum resources to be distributed and shared between remote parties. Such quantum network can be realized by all fiber elements, which takes advantage of low transmission loss?low cost, scalable and mutual fiber communication techniques such as dense wavelength division multiplexing (DWDM). Therefore high quality entangled photon sources based on fibers are on demanding for building up such kind of quantum network. Here we report multiplexed polarization and time-bin entanglement photon sources based on dispersion shifted fiber (DSF) operating at room temperature. High qualities of entanglement are characterized by using interference, Bell inequality and quantum state tomography. Simultaneous presence of entanglements in multi-channel pairs of a 100GHz DWDM shows the great capacity for entanglements distribution over multi-users. Our research provides a versatile platform and moves a first step toward constructing an all fiber quantum network.

Though there are many works reported on preparing entangled photon source based on DSF, no one reported wavelength multiplexed entangled source based on DSF, which has the same figure of merits suc as: realizing entanglement over multi-frequency modes, which enable engineering a complex quantum state; compatible with contemporary telecom fiber and quantum memories, and with chip-scale semi-conductor technology, which is capable for compact, low cost and scalable applications.

10029-4, Session 1

Quadrature squeezed state preparation for quantum remote sensing at 1064nm

Zhiqiang Wu, Xuling Lin, Song Yang, Xuan Zhang, Beijing Institute of Space Mechanics and Electricity (China); Yaohui Zheng, Shanxi Univ. (China)

Squeezed state light field can surpass the shot noise limit and improve the signal-to-noise ratio of the sensor measurement. We present employs a semi-monolithic cavity to reduce the intra-cavity loss of optical parametric amplifier (OPA) and miniaturization design to improve system stability. In this paper, the bright quadrature squeezed state field of noise reduces more than 6dB is obtained at 1064nm by pumped the PPKTP crystal via 532nm laser with the power of 130mW. The light field characteristics of the quantum state source are analyzed. This work provides a foundation for further application in quantum remote sensing detection.

10029-6, Session 2

Non-equilibrium quantum phase transition via entanglement decoherence dynamics in photonic systems *(Invited Paper)*

Wei-Min Zhang, Yu-Chen Lin, Pei-Yun Yang, National Cheng Kung Univ. (Taiwan)

We investigate the decoherence dynamics of continuous variable entanglement in photonic systems as the system-environment coupling strength varies from the weak-coupling to the strong-coupling regimes. Due to the existence of localized states in the strong-coupling regime, the system cannot approach equilibrium with its environment, and a nonequilibrium quantum phase transition occurs. We analytically solve the entanglement decoherence dynamics for arbitrary spectral density. The nonequilibrium quantum phase transition is demonstrated as the system-environment coupling strength varies for all the Ohmic-type spectral densities. The entanglement quantum phase diagram is obtained.

10029-7, Session 2

From Einstein-Podolsky-Rosen paradox to quantum nonlocality *(Invited Paper)*

Jin-Shi Xu, Chuan-Feng Li, Guang-Can Guo, Univ. of Science and Technology of China (China)

In 1935, Einstein, Podolsky and Rosen published their influential paper proposing a now famous paradox (the EPR paradox) that threw doubt on the completeness of quantum mechanics. Two fundamental concepts “entanglement” and “steering” were given in the response of Schrödinger to the EPR paper, which both reflect the nonlocal nature of quantum mechanics. In 1964, John Bell obtained an experimentally testable inequality (Bell’s inequality), in which its violation contradicts the prediction of local hidden variable models and agrees with that of quantum mechanics. Since then, great efforts have been made to investigate the nonlocal feature of quantum mechanics and many distinguished quantum properties were observed. In 2001, quantum correlation was shown to even exist in separated states (have not entanglement) and the total quantum correlation is defined as quantum discord. In 2007, an operational approach was used to define entanglement, EPR steering and Bell nonlocality. It is shown that EPR steering strictly stands between entanglement and Bell nonlocality. In this report, along with the discussion of the development of quantum nonlocality, we would focus on our recent experimental efforts in investigating the corresponding distinguished quantum properties in optical systems, including the sudden death of quantum entanglement, entanglement-assisted entropic uncertainty principle, the sudden change in behavior in the decay rates of quantum discord, the All-Versus-Nothing demonstration of EPR steering and the one-way EPR steering.

10029-8, Session 2

On-chip quantum optics with quantum dots and superconducting resonators *(Invited Paper)*

Guang-Wei Deng, Univ. of Science and Technology of China (China)

Hybrid systems that couple nano-devices to microwave resonators have rapidly been developing with recent advances in circuit quantum electrodynamics. In our first work, we demonstrated a successful coupling between an on-chip superconductor resonator and a graphene double quantum dot. We are very proud of our accomplishment as the coupling between cavity and randomly located graphene flakes is a technical challenge. A number of technical innovations, including cavity design and nano-fabrications, are made to create such a hybrid nanostructure. Using the resonator as a sensitive meter, we are able to measure the dephasing rate of graphene qubit, which has not been achieved by conventional means up to now. In the second work, we have demonstrated for the first time a successful coupling between an on-chip superconductor resonator and two double quantum dots made of graphene. This kind of coupling can be explained by the Tavis-Cummings model. Such model has been explored in a number of systems, such as optics and superconducting qubits. However, it has not yet been demonstrated in gate-defined quantum-dot hybrid devices. Another significant finding of our work is the achievement of the nonlocal transport current through two distant DQDs, the current cross-noise spectrum is measured for the first time, which can be mediated by the photons in the resonator. This nonlocal transport observed here may serve as one step toward entangling distant electrons and employing superconducting resonators as microwave photonic buses.In addition, this hybrid system demonstrates the possibility to exploit the microwave photonic bus to link different nano-electronic devices as it becomes increasingly apparent that future integrated circuits may consist of both electronic and optical devices.

10029-9, Session 2

Quantum-enhanced long-baseline optical interferometers with noiseless linear amplification and displacement operation

Song Yang, Yun Su, Ningjuan Ruan, Zhiqiang Wu, Xuling Lin, Beijing Institute of Space Mechanics and Electricity (China)

For an optical imaging system- a telescope or camera, diffraction limit has been considered as a fundamental maximum to its resolution. According to diffraction limit, the resolution of a single telescope with circular aperture is proportional to the diameter of its aperture D , and inversely proportional to the wavelength ? of the incoming light. In astronomy, a single telescope always cannot satisfy some needs of high resolution imaging application, since the size of a telescope cannot increase boundlessly.

In the past few decades, advances in the optical interferometry enable us to sidestep the diffraction limit of a single telescope. The optical interferometry could achieve high resolution due to the technique of aperture synthesis, collecting signals from a cluster of comparatively small telescopes. The resolution of interferometry is limited by? / 2b , which is proportional to the maximum separation(i.e. baseline) b between the telescopes. Thus, long baseline would enhance the imaging resolution. In some sense, the optical interferometry with a cluster of telescopes canbe equivalent to an expensive monolithic telescope with a very large aperture size b . In astronomy, the high imaging resolution of long baseline optical interferometry paves the way for its promising applications in some new fields like imaging stellar surfaces and exploring stellar evolution.

However, the astronomical observations from Earth are seeing-limited due to atmospheric effects. The noise and photon loss in the transmission between the telescopes would limit the length of baseline of interferometer to a few hundred meters. Here, we present a scheme for enhancement of long baseline optical interferometer by using quantum resources- noiseless linear amplifier (NLA) and displacement operation at the photon transmission channels. We exhibit this enhancement quantitatively by calculating higher fisher information compared with those of conventional optical interferometer.

10029-10, Session 2

Demonstration of a triggered single-photon source based on a trapped single cesium atom

Jun He, Bei Liu, Gang Jin, Junmin Wang, Shanxi Univ. (China)

We report the generation of a 10-MHz-repetition-rate triggered single-photon source at 852 nm based on a trapped single cesium atom in a far-off-resonance microscopic optical dipole trap. The statistics show strong anti-bunching with a value for the second-order correlation at zero delay less than 0.09, which indicates single-photon characters. The optical dipole trap beam is focused by a high numerical aperture (NA = 0.29) objective lens assembly mounted outside the vacuum chamber. the trapping beam has a 1/e2 radius of ?0 = 2.3 ?m. The trap depth is about 2 mK for a laser power about 63 mW. The P7888 card (two-input multiple-event time digitizers, FAST Com Tech.) is used to record the arrival times of atomic fluorescence detected by the SPCM. With an optimized time sequence, we have experimentally demonstrated the Rabi oscillation between the

ground state and the excited state, and measured the temporal envelope of single photons. We have experimentally verified the heating of the single atom by using of a gated pulses exciting/cooling technique and optimized cooling laser's parameters. In case of resonant light pulse excitation, the typical trapping lifetime of single cesium atom is extended from ~56 ms to ~2536 ms. The corresponding number of excitation is improved from 1600 to 72000. In the future, we will encode the orbital angular moment on single photon with the help of spatial light modulation, which provides a promising resource for high-dimensional quantum information protocols. We will study the interaction between the neutral atom and single photon.

10029-11, Session 2

Traceable quantum sensing and metrology relied up a quantum electrical triangle principle

Yan Fang M.D., Fudan Univ. (China)

Hybrid quantum state engineering in quantum communication and imaging1-2 needs traceable quantum sensing and metrology, which are especially critical to quantum internet3 and precision measurements4 that are important across all field of science and technology-. We aim to set up a mode of traceable quantum sensing and metrology. We developed a method by specially transforming an atomic force microscopy (AFM) and a scanning tunneling microscopy (STM) into a conducting atomic force microscopy (C-AFM) with a feedback control loop, wherein quantum entanglement enabling higher precision was relied upon a set-point, a visible light laser beam-controlled an interferometer with a surface standard at z axis, diffractometers with lateral standards at x-y axes, four-quadrant photodiode detectors, a scanner and its image software, a phase-locked pre-amplifier, a cantilever with a kHz Pt/Au conducting tip, a double barrier tunneling junction model, a STM circuit by frequency modulation and a quantum electrical triangle principle involving single electron tunneling effect, quantum Hall effect and Josephson effect5. The average and standard deviation result of repeated measurements on a 1 nm height micro-region of nanomedicine cystal hybrid qauntum state engineering surface and its local differential pA level current and voltage (dI/dV) in time domains by using C-AFM was converted into an international system of units: Siemens (S), an indicated value 0.38?10-12 S (n=6) of a relative standard uncertainty was superior over a relative standard uncertainty reference value 2.3?10-10 S of 2012 CODADA quantized conductance6. It is concluded that traceable quantum sensing and metrology is emerging.

10029-59, Session 2

A doubly folded quantum security scheme for a nearly perfect direct quantum communication protocol *(Invited Paper)*

Jihong Min, Byoung S. Ham, Gwangju Institute of Science and Technology (Korea, Republic of)

Sharing a secure key between two remotely separated parties has been an important issue in communications to human history. According to Heisenberg's uncertainty principle, simultaneous measurements on both conjugate variables (e.g., position and momentum) in an unknown quantum state are impossible. This physical limitation is the basis of the 'no cloning' theorem in quantum information, and applied to the unconditional security in quantum communications. Here, quantum key distribution (QKD) techniques such as BB84 and E91 adapt the conjugate variables to conjugate bases for unconditional security. In BB84, for example, a set of linearly polarized light perpendicular to each other forms a basis. A rotation by 45 degrees of this basis with respect to one polarization forms another basis. These two bases satisfy the conjugate variables in the Heisenberg's uncertainty principle, where measurement by one basis results in a complete random output to the other basis. Here we propose a doubly folded quantum security scheme for a nearly perfect quantum secure direct communications (QSDC) based on polarized single photons. Unlike QKD, the QSDC techniques encode and decode a message directly without key distribution. Thus, perfect security must be an essential part to protect message itself from any chance of eavesdropping. Most QSDC protocols, thus, rely on quantum entanglement rather than photon polarizations, where single photons have shown many loopholes to noisy channels and imperfect detectors. However, entanglement based schemes have more difficulties in implementations compared with the polarized single photons. Our QSDC protocol uses not only polarizations but also phases of single photons to form two sets of conjugate variables. The addition of phase basis to polarization basis forms a nearly perfect security even to super attackers who can measure unknown quantum states or the sender's choice of bases.

10029-12, Session 3

Detecting high-dimensional multipartite entanglement via some classes of measurements *(Invited Paper)*

Ting Gao, Hebei Normal Univ. (China)

Mutually unbiased bases (MUBs) represent maximally non-commutative measurements, which means the state of a system described in one mutually unbiased base (MUB) provided no information about the state in another. Many quantum information protocols depend upon the use of MUBs, such as quantum key distribution, the reconstruction of quantum states, etc. The concept of MUBs was generalized to mutually unbiased measurements (MUMs) due to the open problem of the maximum number of MUBs for non-prime power dimensions limits its application. The construction of a complete set of $d+1$ MUMs were found in a finite, d-dimensional Hilbert space, no matter whether d is a prime power. Symmetric informationally complete positive operator-valued measures (SIC-POVMs) is another related topic in quantum information, which has many helpful connections with MUBs, such as operational link, quantum state tomography and uncertainty relations. Since it has some similar limitation as MUBs, the concept of SIC-POVMs is generalized to general symmetric informationally complete measurements (GSIC-POVMs), which were constructed without requiring to be rank one.

These quantum measurements have been used to detect entanglement recently. We investigate entanglement detection using these notions and derive separability criteria for arbitrary high-dimensional bipartite systems of a d_1-dimensional subsystem and a d_2-dimensional subsystem, and multipartite systems of m multi-level subsystems. It is proved that these criteria are of the advantages of more effective and wider application range than the previous ones. They provide experimental implementation in detecting entanglement of unknown quantum states.

10029-13, Session 3

How discord underlies the noise resilience of quantum illumination *(Invited Paper)*

Mile Gu, Ctr. for Quantum Technologies (Singapore)

Quantum illumination offers a radical departure from conventional quantum protocols. Most quantum technologies require fragile entangling correlations to be preserved,

whereas quantum illumination operates in extremely-adverse environments with entanglement-breaking noise. Specifically, quantum illumination aims to detect a low reflective target basked in bright noise by probing it with one arm of an entangled state. The protocol demonstrates significant improvement over the use of conventional probes, even though the environmental noise destroys all initial entanglement. This appeared paradoxical, how can the benefits of entanglement outlast entanglement itself? In this presentation, I will first review quantum discord, a form of quantum correlations that exist beyond entanglement. While discord has been conjectured to have operation benefits, it remains a topic of significant debate. A significant rationale being that discord is non-zero for almost every mixed state and its practical merit conflicts with the preconception that `quantum' effects are fragile. I will then show that it is precisely the resilience of discord that explains the resilience of quantum illumination and highlight discord's role in preserving entanglement's benefits in quantum illumination.

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10029-14, Session 3

Quantum information tapping using a fiber optical parametric amplifier with noise figure improved by correlated inputs *(Invited Paper)*

Xiaoying Li, Tianjin Univ. (China)

In a network, information distribution requires information tapping. The easiest and usual way to do so is to tap the signal by using a beam splitter (BS). However, in this case, the signal to noise ratio (SNR) of the tapped signal is lower than that of the input signal. Because of the vacuum noise introduced from the unused port of the BS, the sum of the information transfer coefficient in the each output port of the beam splitter is less than 1 (classical limit). In order to read out information without degrading the SNR, the extra noise added in the information distribution process need to be minimized.

In this talk, we experimentally demonstrate a quantum information tap by using a fiber optical parametric amplifier (FOPA) with correlated inputs, whose noise is reduced by the destructive quantum interference through quantum entanglement between the signal and the idler input fields. We find that the noise figure (NF) of the FOPA with correlated inputs is better than that of a regular FOPA with one unused input port. Since the NF is inversely proportional to the corresponding information transfer coefficient, therefore, our experimental system, working at 1550 nm telecom band and compatible with the current optical fiber network, can act as the quantum information tap to split the encoded information into the signal and idler output ports with an overall information transfer coefficient larger than the classical limit.

10029-15, Session 3

Towards multi-photon experiments with quantum dots *(Invited Paper)*

Chao-Yang Lu, Univ. of Science and Technology of China (China); Sven Höfling, Julius-Maximilians-Univ. Würzburg (Germany); Jian-Wei Pan, Univ. of Science and Technology of China (China)

Self-assembled InGaAs quantum dots (QD) are promising single-photon emitters with high quantum efficiency and fast decay rate. In the past decades, extensive efforts have been devoted to producing single photons with high purity (that is, vanishing two-photon emission probability), near-unity indistinguishability [1], and high extraction efficiency. These key properties have been compatibly combined simultaneously on the same QD-micropillar very recently [2,3].

An important next challenge is to extend the single-photon sources to multiple photonic quantum bits [4], as required by various quantum information protocols such as boson sampling, quantum teleportation [5], and quantum computation. To this end, by pulsed s-shell resonant excitation of a single QD-micropillar, we generate long streams of thousands of single photons with high indistinguishability [6]. Interference of two photons are measured as a function of their emission time separation varying from 13 ns to 14.7 us, where the visibility slightly drops from 95.9% to a plateau of 91.8% through a slow dephasing process occurring at time scale of 0.7 us. Such an efficient and highly indistinguishable single-photon source allowed scalable multi-photon Boson sampling experiments [7] with a performance beating the best conventional nonlinear optics. The single photons are time-bin encoded and interfered in an electrically programmable loop-based network. With further refinement of the system efficiency, our approach may be feasible to be scaled up to ? 20-boson sampling to outperform classical computers, and thus provide experimental evidence against the Extended Church-Turing Thesis.

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10029-16, Session 4

Experimental quantum secure direct communication with single photons *(Invited Paper)*

Gui Lu Long, Tsinghua Univ. (China)

Quantum secure direct communication (QSDC), Quantum secret sharing and quantum key distribution are the major branches of quantum cryptography. Using QSDC, secret message are sent directly over a quantum channel with security. QSDC offers higher security and instantaneousness in communication. It is also a powerful basic quantum communication primitive to build other quantum communication protocols such as quantum bidding, quantum signature and quantum dialogue and so on. Since the first QSDC protocol proposed in 2000[G L Long and X S Liu, Phys. Rev. A 65 , 032302 (2002)], it has become one of the hot research areas. In this invited talk, after a brief introduction to the basic ideas of QSDC, we will concentrate on the experimental progress in QSDC, in particular, the experimental demonstration of the DL04 QSDC protocol in a noisy environment [Jian-Yong Hu et al, Light: Science & Applications, 2016; doi: 10.1038 / lsa.2016.144.]

10029-17, Session 4

Quantum memory with rare-earth ion doped crystal *(Invited Paper)*

Chuan-Feng Li, Univ. of Science and Technology of China (China)

Quantum memory is the key element of quantum repeater, long distance quantum communication and quantum network. Usually, hot atoms, cold atoms, trapped single atom and Bose-Einstein Condensate have been used as quantum memories. From the year of 2008, solid state memory based on rare-earth ion doped crystal becomes one of the most promising quantum memories.

I report on some of our recent results of solid state memory. 1) We realized high-fidelity solid state memory for photonic polarization qubit. By designing a sandwich-like solid state memory, we can get photon polarization storage process fidelity up to 99.9%. 2) We demonstrated solid state memory of three-dimensional orbital-angular-momentum entanglement with process fidelity up to 99.3%. We further showed that the memory is highly reliable for 51 spatial modes. 3) For the first time, we further experimentally realized the storage of multiple single-photon pulses emitted from a quantum dot in solid state quantum memory. Multi-temporal-mode memory with up to 100 narrow single-photon pulses was demonstrated. The solid-state properties of both sub-systems make this configuration more stable and easier to be scalable. Our work will be helpful in the construction of efficient quantum repeaters based on all-solid-state devices.

We also present the first experimental violation of Leggett-Garg type of inequalities with solid state memory. By separately benchmarking the Markovian character of the evolution and the translational invariance of the conditional probabilities, the observed violation is attributed to the quantum coherent character of the process.

10029-18, Session 4

Entanglement in multimode bosonic systems *(Invited Paper)*

Tim Byrnes, New York Univ. Shanghai (China)

We model and examine the quantum states produced between multi-mode Bose-Einstein condensates. In contrast to standard approaches which use an exact time evolution and work in the framework of continuous variables (CV), we use the approximation-free time evolution and obtain the wavefunction of the ensemble state after the entangling procedure. For short entangling times, this produces a two-mode squeezed state in agreement with CV based predictions. For longer entangling times the state evolves into a non-Gaussian form, and the two-mode squeezed state characteristics start to diminish. These types of entangled states are quite difficult to detect using standard entanglement criteria, which only work in the CV regime. We propose some alternative entanglement criteria which can detect these types of entanglement. These criteria can be used also for other bosonic systems, and potentially give a more sensitive criteria for entanglement.

10029-35, Session Post

Dirac monopoles with polar-core vortex induced by spin-orbit coupling in spinor Bose-Einstein condensates

Wu-Ming Liu, Ji Li, Institute of Physics (China)

In this work, we report Dirac monopoles with polar-core vortex induced by spin-orbit coupling in ferromagnetic Bose-Einstein condensates, which can be detected through directly imaging vortex lines. The condensates are subjected to three-dimensional gradient magnetic field, and two dimensional Rashba-type SO coupling induced by magnetic pulses. Unlike monopole studies in spin ices, our results demonstrate the fundamental quantum features and topological structures of the monopoles predicted by Dirac. In our case, there exist two Dirac monopoles with the polar-core vortex, locating at the endpoints of two nodal lines in the condensates, which behaves as a singly vortex line in the component, a soliton in the component and a singly anti-vortex line in the component.

When spin-orbit coupling increases, the monopoles with the square lattice appear, which behave as the square lattice structure in the horizontal direction in the central zone of Bose-Einstein condensates and the stripe structure of density distribution in the vertical direction. The anti-monopoles emerge simultaneously.

In the presence of spin-orbit coupling, increasing the strength of spin-independent interaction can induce a cyclic phase transition from Dirac monopoles with polar-core vortex to those with Mermin-Ho vortex.

Our work explores the spin-orbit coupling effect on a new physics of monopoles, and can not only shed lights on the discovery and illumination of new structures of monopoles, but also provide a better grasp of fundamental theory on the monopole in non-Abelian gauge fields. Our findings opens a new window to realize exotic topological defects and phase transitions in quantum systems.

References:

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10029-36, Session Post

Evolution of temporal soliton solution to the generalized nonlinear Schrödinger equation with variable coefficients and PT-symmetric potential

Yangbao Deng, Hunan City Univ. (China)

In this paper, the evolution of temporal soliton is investigated analytically when the laser pulse propagates in the inhomogeneous nonlinear medium with a Scarff II parity-time (PT)-symmetric potential. Firstly, the temporal soliton solution is found by analytically solving the generalized nonlinear Schrödinger equation with variable coefficient and Scarff II PT-symmetric potential. Then the intensity evolution of temporal soliton is discussed. Finally, the evolution of the pulse width (PW) of temporal soliton is analyzed in detail by calculating second-order intensity moments. It is find that under the condition of Scarff II PT-symmetric potential, the dispersion coefficient, nonlinear coefficient and chirp affect the evolution behavior of temporal soliton. The chirped-free and chirped temporal soliton are stable when the dispersion coefficient is a periodic modulated function. So the chirp has no effect on the evolution behavior of temporal soliton. When the dispersion coefficient are the constant and the exponential decreasing function, the chirped-free temporal soliton is stable, while the chirped temporal soliton is gradually compressed. Therefore, the chirp has a great effect on the evolution behavior of temporal soliton.

10029-37, Session Post

Generation of polarization squeezing resonant to the rubidium D1 line at 795 nm

Xin Wen, Yashuai Han, Jun He, Junmin Wang, Shanxi Univ. (China)

Squeezed light has significant potential in quantum physics. With the noise of one quadrature component reduced below the standard quantum limit, the squeezed light could be used in weak field measurements, precise spectroscopy and other fields in quantum physics with an enhanced signal-to-noise ratio. In our work, a polarization squeezed light will be used as a probe light in the precise measurement of magnetic field and inertia for the reduction of the optical polarization noise, thus increase the detection sensitivity.

An optical parametric oscillator (OPO) is utilized for the generation of the polarization squeezed light. The fundamental laser is provided by a cw Ti:Sapphire laser tuned to 795nm at rubidium D1 line. 111mW ultra-violet laser at 397.5nm is achieved from 191mW fundamental power via a frequency doubling cavity, the corresponding conversion efficiency is 58.1%. The generated ultra-violet laser is used to pump the OPO with a PPKTP nonlinear crystal, the maximum vacuum squeezing of -5.6dB is realized. With a probe light inject into the OPO cavity, the OPO works under the condition of optical parametric amplifier, and a dim amplitude/phase squeezed light is produced. Combine the squeezed light and a bright coherent light with fixed relative phase, the polarization squeezed light is obtained. The quantum Stokes parameters are used to depict the polarization squeezing, -3.75dB of the S2 component is accomplished at the analysis frequency of 2 MHz with the relative phase between probe and pump light locked to π, and relative phase between local oscillator and amplitude squeezed light at 0. For the further usage in magnetic field measurement, the squeezing bandwidth down to hertz or hundreds-hertz regime is needed. At such low frequency band, the degradation of squeezing need to be overcome by the careful control of the intensity noise, beam jitter, parasitic interference etc.

10029-38, Session Post

Realization of 318.6-nm high-power ultraviolet laser for single-photon Rydberg excitation of cesium atoms

Jieying Wang, Jiandong Bai, Jun He, Junmin Wang, Shanxi Univ. (China)

Rydberg atoms are of great significance in quantum information process and quantum optics area. The strong interaction between neighboring Rydberg atoms make the Rydberg blockade mechanism become a promising candidate to observe atoms entanglement, Rabi oscillation, and implementation of C-NOT two-qubit gate. For highly excited Rydberg state, if we choose a single-step excitation to a desired Rydberg state, the problem arising from the population of intermediate state can be avoided. But the photon energy of single-step transition from the ground state to the Rydberg state is very large, the excitation laser usually needs to work in ultra-violet (UV) region. To drive the cesium-133 atoms from 6S1/2 state to nP3/2 (n=70~100) Rydberg state via single-step transition, we prepare a high-power and narrow-linewidth UV laser system at 318.6 nm by single-pass sum-frequency generation (SFG) from two infrared fiber lasers to 637.2nm red laser and then by cavity-enhanced second-harmonic generation (SHG).

Based on the commercially available components and efficient nonlinear frequency conversion technology, we demonstrate 8.75 W single-frequency 637.2 nm red light by single-pass SFG of two infrared lasers at 1560.5 nm and 1076.9 nm in PPMgO:LN crystal, and corresponding optical-optical conversion efficiency is 38.0%. The output red laser has good power stability and beam quality. Then it is converted to UV by cavity-enhanced SHG. Over 2.26 W tunable 318.6 nm laser is generated with 4.0 W of incident red laser, and the doubling efficiency is 56.5%. The output UV laser can be continuously tuned over 6 GHz, and the typical power fluctuation is less than 0.87% (root-mean-square value) over 30 minutes. The beam quality factors, M2 X and M2 Y, are measured to be 1.16 and 1.48, respectively. Besides, we estimate the linewidth of the UV laser should be less than 10 kHz. This 318.6 nm UV laser provides a solid foundation for the subsequent single-step 6S1/2-nP (n = 70 ~ 100) Rydberg excitation of cesium atoms.

10029-39, Session Post

Two-step quantum secure direct communication with frequency coding

Xueliang Zhao, Dong Ruan, Tsinghua Univ. (China)

Quantum secure direct communication (QSDC) is an important component of quantum communication, it can transmit the secret information directly without establishing a key first. The first QSDC protocol is two-step protocol. It was designed based on ideal channel. When it comes to practical application, noisy should be considered. Recently, the frequency encoded DL04 QSDC protocol has been proposed and experimentally demonstrated [Jianyong Hu et al, Experimental quantum secure direct communication with single photons. Light: Science & Applications, 2016; doi: 10.1038/lsa.2016.144.]. Inspired by this paper, we propose a two-step protocol with frequency coding, which makes robust against noise and loss. Frequency coding scheme encodes information on an EPR pair block as periodic sequences of different frequencies, rather than encoding the information directly on individual EPR pairs. When the receiver get the sequences, he can read out the information by analyzing its frequency by using the discrete time Fourier transform. Every EPR pairs have four states, it suggest that four different amplitude values can be used, so that one sequence can obtain three different frequencies. Meanwhile, we have numerically simulated the scheme in a noisy channel, and find it has a strong ability to resist channel loss and error. In addition, we also give a rough estimate of channel noise upper limit.

10029-40, Session Post

Efficient simulation of open quantum system in duality quantum computing

ShiJie Wei, Gui Lu Long, Tsinghua Univ. (China)

We proposed an efficient quantum algorithm for simulating Hamiltonian in an open quantum system on a duality quantum computer. In the algorithm, the time evolution of open quantum system is realized by using Kraus operators which is naturally realized in duality quantum computing. The query complexity of the algorithm is reduced from d^4 to d^3 , where d is the dimension of the open quantum system. The duality quantum algorithm provides an exponential improvement in precision than Lloyd's algorithm because of use of a truncated Taylor series of evolution operators.

10029-41, Session Post

Tunable and flat optical delay line based on double rings resonators

Kaiyue Qi, Yundong Zhang, Yongfeng Wu, Chang Qiu Yu, Hui Li, Ping Yuan, Harbin Institute of Technology (China)

We theoretically investigate a fundamental structure which consists of series-coupled double ring resonators and two straight waveguides. To be more specific, two rings and three straight waveguides are included in the structure, and they are connected by four couplers. The transmission and phase shift in the structure are calculated through transfer matrix theory. The simulation results show that the series-coupled double ring resonators can be used to realize flat optical delay line, and this delay line is tunable which are achieved by adjusting four tunable self-coupling coefficients and two ring perimeters. Additionally, an EIT-like resonance can be obtained in this structure. And we could adjust the attenuation factor of ring waveguide and coupling coefficients to realize a flatter delay line. The group delay can vary from 80ns to 1.5us through changing the values of four coupling coefficients. The group delay can vary from 2?10-5ns to 1.5us for different ring perimeters. We could also achieve a tunable bandwidth through choosing different coupling coefficients .These results indicate that this structure can be well applied in slow slight and will mitigate the deleterious effects of group delay dispersion. At the same time, we can observe an EIT-like spectrum that the transmission line shape has a higher transmission rate and a smaller loss at the resonance point. The EIT-like phenomenon has a very wide range of applications in optical pulse reduction, storage and release. The ability to realize these phenomena is important for applications such as optical switch, as well as tunable bandwidth filter.

10029-42, Session Post

Observation of EIT-like spectrum in the eye-like ring resonator

Kai Ma, Yundong Zhang, Yongfeng Wu, Chang Qiu Yu, Hui Li, Ping Yuan, Harbin Institute of Technology (China)

In this paper, we theoretically analyze the electromagnetically induced transparency(EIT)-like spectrum in the Eye-like resonator configuration. The eye-like structure is composed of two bus waveguides coupling with the outer ring and the two rings coupling together which have different perimeters. The whole structure looks like an eye as it is called. The EIT-like spectrum results from the interference between the inner ring and the outer ring. We choose the 4 coupling coefficients and the attenuation factors of the ring waveguide for us to control, other parameters are carefully picked for beautiful EIT-like line shape. We obtain a tunable group delay and the tunable bandwidth of the transparency window through changing the coupling coefficients and the attenuation factor of inner and outer ring. And the group delay can access to 0.3ns for the slow light with the transmittance up to 98.76%. We can also obtain the group delay lower than -50ns for the superluminal light. And the transmittance window can vary from 24THz to less than 7.4THz as we control the coupling coefficients. Some other interesting work have also being done that the tunable group delay can be achieved through choosing different attenuation factors of the inner and the outer ring, but at the same time it may lose line shape if the parameter is small enough. The tunable group delay and the bandwidth which are realized by choosing appropriate parameters will have potential application in optical switching or tunable delay lines and tunable bandwidth filter.

10029-43, Session Post

Highly-coherent supercontinuum generation in strip/slot hybrid As2S3 waveguide with low and ultra-flat dispersion

Shuangxiang Yan, Chao Mei, Jinhui Yuan, Kuiru Wang, Xinzhu Sang, Binbin Yan, Chongxiu Yu, Beijing Univ. of Posts and Telecommunications (China)

Highly coherent supercontinuum (SC) has many applications such as broadband optical sources and frequency comb generation. In previous works, low and flat dispersion characteristic plays an important role in highly coherence SC generation.

In this work, two kinds of strip/slot hybrid As2S3 waveguides with the silicon dioxide slots, which are demonstrated to have low and flat dispersion profiles are proposed. And the nonlinear optical dynamics of SC generation are studied numerically by using the nonlinear Schrödinger equation. For the waveguide with a vertical silicon dioxide slot, the dispersion between ±22 ps/(nm?km) from 1432 to 2809 nm and the nonlinear coefficient of 5.842 /W/m at 2000 nm are simultaneously obtained by adjusting the structure parameters. Moreover, when the 120-fs pulses with central wavelength of 2 ?m and peak power of 100 W are used as the pump, the SC covering from 1392 to 2916 nm at -35 dB level is generated in a 5.5-mm waveguide with high coherence of ~1 in the spectrum range considered. For the waveguide with a horizontal silicon dioxide slot, the dispersion between ±4 ps/(nm?km) from 1685 to 2770 nm and the nonlinear coefficient of 10.7 /W/m at 2 ?m can be achieved. Under the same pump condition, the -35 dB bandwidth of SC with coherence of ~1, generated in a 5.5-mm waveguide, spans from 1212 to 3979 nm. The simulation results show the horizontal slot structure is more suitable for generating wider SC with high coherence which can be applied to generate broadband optical frequency comb.

10029-44, Session Post

Characteristics of 1.9-um laser emission from hydrogen-filled hollow-core fiber by stimulated Raman scattering

Bo Gu, Yubin Chen, Zefeng Wang, National Univ. of Defense Technology (China)

Due to the high Raman gain coefficient and large Raman frequency shift, stimulated Raman scattering (SRS) of gases has been recognized as an effective means to obtain tunable, narrow linewidth sources of otherwise unobtainable wavelengths, especially in the ultra violet and infrared range. Historically, due to the very short effective interaction length, SRS in gases has required high pump powers. And the conversion efficiency to the desired wavelength is usually very low, due to additional generation of other unwanted lines. Hollow core fibers have made it possible to obtain high conversion efficiency for SRS in gases, as it can provide a very long effective interaction length, high pump intensity, and the possibility of control of the effective gain spectrum. In our previous works, we have demonstrated the first effective 1.9 ?m Raman converter with hydrogen-filled negative curvature hollow-core fiber pumped with a 1064 nm pulse microchip laser. Here, we give the detailed pulses, linewidth, polarization and modes characteristics of the 1.9 Raman source for the first time. We found that the pulse duration of the 1.9 ?m Raman is compressed observably compared to the pump pulse duration; the linewidth is about 1GHz, which is the same level of the pump laser; the output light spot is a nearly perfect fundamental mode although the pump is multi-mode in the hollow core fiber; the Raman conversion efficient is closely related to the polarization properties of the pump laser and the hollow core fiber.

10029-45, Session Post

Nonlinear generation of higher-order modes by intermodal four-wave mixing in multimode fibers

Tong Liu, Sheng-Ping Chen, Jing Hou, National Univ. of

Defense Technology (China)

Higher-order modes of optical fibers have recently attracted renewed interest in applications covering high-speed optical communication, nonlinear extension of laser spectrum, novel design of high-power fiber lasers, to name just a few. Their exotic intensity patterns and phase/polarization structures are favorable in many situations, which make them be useful alternatives or supplements to the commonly employed fundamental mode. There are many approaches to generate such modes in a multimode fiber; however, most of them are subject to specific qualifications and limited in efficiency and applicability. To controllably excite specific higher-order modes with high purity is still not a trivial task. Here we present our experimental results and analysis on the generation of higher-order modes by intermodal four-wave mixing, which is a nonlinear effect that requires phase-matching between interacting waves. When intense light is injected into a multimode fiber and excite a mixture of various modes, the phase-matching condition of intermodal four-wave mixing acts as a mode filter and specific mode combinations are generated at well-predicted Stokes and anti-Stokes wavelengths. Although this phenomenon was found decades ago, only few attempts have been made to exploit it as a useful tool. Moreover, despite a significant amount of reports mentioning the observation of such effects, there is still a lack of detailed investigations. In this manuscript, we systemically study the intermodal four-wave mixing in multimode fibers with different geometric parameters and find that it is feasible to generate high-quality higher-order modes in a controlled manner.

10029-46, Session Post

Study of the nonlinear optical absorption and refraction of indium-doped zinc-oxide thin-films (IZO) using Z-scan technique

Maung Htwe Zin, Yundong Zhang, Harbin Institute of Technology (China); Chengbao Yao, Harbin Normal Univ. (China); Hui Li, Ping Yuan, Harbin Institute of Technology (China)

We report the nonlinear optical properties of indium doped zinc oxide thin film (IZO). IZO thin films were grown on sapphire substrate by radio frequency (RF/DC) magnetron sputtering technique. During the IZO thin film sputtering process, ZnO and In disc were install on RF and DC target respectively. The sputtering power of In (DC target power) was kept at (2 and 5 W) while ZnO target power was 100 W. The structural characterization, surface morphology and linear optical properties of IZO thin films were carried out using X-ray diffraction (XRD), scanning electron microscopy (SEM) and UV-VIS spectrometer. The XRD result shows that IZO thin films exhibit the polycrystalline characteristics and still retained hexagonal wurtzite structure of ZnO. The crystallite size of IZO are increased with In content. This result reveals that the crystallinity of IZO thin films are improved with DC power increasing. The SEM images of IZO agreed with XRD results because of the grain size of IZO are increased. For linear optical studies, IZO thin films show high transmittances at visible region (above 50 %) and the band gap values are increased due to indium is the donor type semiconductor materials which provides more electrons and lead to increased the optical band gap. In addition, the nonlinear optical absorption and refraction of IZO thin films were investigated using nanosecond Z-scan technique. The Q-switch Nd-YAG laser with 532 nm wavelength is used as the excitation laser source. The pulse duration and energy are 6 ns and 9 uJ respectively. The incident laser wavelength was collected using lens with 300 mm focal length. In order to study the nonlinear optical absorption, we carried out the open aperture (OA) Z-scan method. The IZO thin films exhibit valley shape normalized transmittance. This result reveals that OA results show reverse saturable (RSA) and studied the two-photon nonlinear optical absorption of IZO thin films. Moreover, we carried out the closed aperture (CA) Z-scan to study the nonlinear refraction. The CA normalized transmittance curves are exhibit self focusing (valley-peak) characteristics which reveal the IZO thin films have positive nonlinear refractive behaviors. These studies make the IZO thin films as the applications in nonlinear optical devices.

10029-47, Session Post

Silicon photonic chips for improved-glued-binary-tree problem

Fan Qi, Qingyan Ma, Yufei Wang, Wanhua zheng, Institute of Semiconductors (China)

Quantum walks can be used to accelerate search in graphs, which is useful in computer science and promising for future universal quantum computers. A typical example of quantum acceleration is about the improved-glued-binary-tree problem. For a tree of depth n, the arrival time of a classical random walk is O(2n) and the arrival time of a quantum walk is O(n). As we can see, quantum algorithm brings about an exponential speedup. The quantum algorithm is based on a one-dimension continuous time quantum walks, which can be implemented by an integrated waveguide array. Here we construct the array on a silicon-on-insulator, which has a 220 nm-thick waveguide layer and 3 ?m-thick buried oxide layer. The waveguides are constructed by etching 70 nm into the waveguide layer and the width of the rib is 420 nm. For a tree of depth 4, there should be 10 waveguides in the array. The coupling constant between waveguide 5 and waveguide 6 is 0.0274 ?m-1; the coupling constants elsewhere are 0.0194 ?m-1. When the wavelength of the injecting photon is 1550 nm, the gap between waveguide 5 and waveguide 6 is 0.99 ?m and the gap elsewhere is 1.1 ?m. After propagation a distance of 304?m in the array, we can find a maximum arrival probability 0.723. Since only single-photon quantum walks are involved in the algorithm, we can completely simulate this with classical coherent light. The above design is verified with classical light propagation simulation.

10029-48, Session Post

Tunable Q-switched random fiber laser

Jiangming Xu, Jun Ye, Hu Xiao, Jinyong Leng, Hanwei Zhang, Pu Zhou, National Univ. of Defense Technology (China)

Random fiber lasers (RFL) are of great importance in many fields, such as illumination sources, sensing technology and spectroscopic monitoring for their typical features of modeless, cavity-less and low coherence length. In most of previous investigations, RFLs normally work in continuous-wave with special wavelength. A tunable Q-switched RFL takes advantages of the high peak power and relatively wide gain bandwidth. In this manuscript, we propose and experimentally investigate a tunable Q-switched RFL. The pump source is a tunable (1035~1090 nm) fiber laser with maximal output power of about 6.5 W. Half-opened cavity of the tunable Q-switched RFL is composed by a piece of 3 km single mode fiber (SMF) and 50:50 wideband coupler (~100 nm), which function as distributed feedback mirrors and fiber loop mirror (FLM), respectively. The FLM is switched on/off by means of the AOM thus changing the Q-factor of the distributed cavity. As a result, 1087~1144 nm tunable pulsed random lasing can be obtained by adjusting the operation wavelength of pump laser. The repetition frequency is 500 kHz, which is determined by the operation parameters of AOM. And the pulse width is about 30~75 ns, which is far narrower than the pulse width of the driving electrical signal for the pump depletion and is changing in the power scaling process.

To the best of our knowledge, this is the first reported tunable Q-switched RFL, and further power scaling and tuning range exploration is available in the case of more powerful pump source and optimization of system parameters.

10029-49, Session Post

Duration-controllable square-wave pulse from an L band dissipative soliton fiber laser based on the dispersive Fourier transformation technique

Dan Yan, Hebei Normal Univ. (China)

We experimentally demonstrate the duration-controllable square-wave pulse from an L band dissipative soliton (DS) fiber laser based on the dispersive Fourier transformation (DFT) technique. The rectangular spectrum emitted from an L band dissipative soliton fiber laser is mapped into a time-domain coherent rectangular waveform through the DFT technique. The duration of the square-wave pulse can be controllable with the adjustments of the pump power. The results demonstrate that it is an effective and flexible way to achieve duration-controllable square-wave pulses by combinating with DFT technique and DS fiber laser.

10029-50, Session Post

Simulation and measurement of threshold pump power for the stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) in ytterbium-doped double-clad CW fiber amplifiers

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Ytterbium-doped fiber amplifiers and lasers have attracted much attention in recent years because of their unique properties such as broad gain. In many applications such as remote sensing and nonlinear frequency generation high-power narrow-linewidth CW sources are required to posses high conversion efficiency. Master Oscillator Power Amplifiers (MOPAs) are suitable configurations for these purposes in terms of appropriate control over signal wavelength and bandwidth. Getting high level of powers encounters serious problems that originate from nonlinear effects such as SBS (mostly because of narrow-linewidth) and SRS that are detrimental phenomena. So it's of prime importance to suppress these effects in order to get high level of powers. In our work we've considered a general description about amplifying process of narrow-linewidth CW signals in different regimes (small-signal and large-signal) by including all affecting terms in coupled differential equations which sheds light on important concepts. ASE terms together with nonlinear ones can give a great description about this process. Also in experimental setups we've used Yb-1200-LMA-20/400 active fiber made by nlight company that's very common in high power CW Ytterbium-doped fiber amplifiers and examined it's threshold pump powers under both forward and backward pumping configuration that's, to the best of our knowledge, the first report on using backward pumping configuration to suppress nonlinear effects. We also discuss some practical issues in experimental setups regarding measuring the threshold of nonlinear effects. Our work can be considered as an interactive work in which experimental results shed light on theoretical ones.

10029-51, Session Post

Highly-coherent octave-spanning supercontinuum generation in CS2-filled photonic crystal fiber with strong slow nonlinearity

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In this paper, the supercontinuum (SC) generation in a carbon disulfide (CS2)-filled photonic crystal fiber (PCF) with strong slow nonlinearity was investigated. CS2 is a material that has high nonlinearity coefficient and well transparency in infrared. What's more, the slow nonlinearity is very strong in this material. When the PCF was pumped at 1.55 ?m in the anomalous dispersion region, the generated SC was within the range from 0.99 to 2.32 ?m, at -40 dB level with high coherence in the anomalous dispersion region. Moreover, the influences of the slow nonlinearity, the temperature, the pump pulse width, the peak power,and the fiber length on the supercontinuum generation (SCG) was studied. To our best knowledge, this is the first demonstration on generating the octave-spanning SC with high coherence in the CS2-filled PCF and the first time to simulate the role of the slow nonlinearity in enhancing the coherence of the generated spectrum specifically.

10029-52, Session Post

Two-photon absorption-induced optical power limiting behavior of strong femtosecond hyper-Gaussian pulses

Ji-Cai Liu, Xing-Zhe Li, Ying Zhang, North China Electric Power Univ. (China)

The propagation of strong femtosecond hyper-Gaussian pulses in an organic molecular medium is studied by solving numerically the Maxwell–Bloch equations using an iterative predictor-corrector finite-difference time-domain technique. The temporal shape of the hyper-Gaussian laser field is written as F(t)=F_0 exp(-ln2/2 (t-t_0)^(2^n)/(?/2)^(2^n)), where ? is the full-width at half-maximum of the temporal profile F^2 (t), F_0 is the peak value of the field amplitude, and n=1,2,3? is the order of the hyper-Gaussian pulse. The carrier-wave frequency of the field is tuned in two-photon resonance with the molecular system simplified by a cascade three-level model. Strong optical power limiting behavior is observed for the hyper-Gaussian pulses of different orders. Usually for long pulses, the dynamics of two-photon absorption is determined by the "two-photon area" of the pulse, which is proportional to the time integral of F^2 (t). For the ultrashort hyper-Gaussian pulses, it is found that the "two-photon area" is no further the deciding quantity of the two-photon induced dynamics. With the same value of the "two-photon area", pulses with different temporal profiles and different values of the pulse duration and field strength will induce different two-photon absorption and optical limiting processes. With the same pulse duration ? and field amplitude F_0, pulses of a lower order (smaller n) is found to have a larger input "two-photon area" but a smaller output area, and therefore show a better optical limiting behavior. Pulses of a low order has a narrow bandwidth, and therefore the intermediate state of the molecule is less involved in the two-photon absorption process.

10029-54, Session Post

Influence of Doppler effect on the phenomenon of electromagnetically-induced transparency

Qiyong Tao, Guiyin Zhang, Haiming Zheng, North China Electric Power Univ. (China)

Electromagnetically induced transparency (EIT) which enables propagation of light through an opaque medium without significant attenuation is one of the many unusual and interesting phenomena produced by atomic coherence and interference effects. Up to now, a large amount of research has been carried out where the atoms were taken as static. In fact, atoms often show random thermal motion. There exists very strong Doppler effect, especially in the situation of high temperature.

In this article, we presented a theoretical study about the influence of Doppler effect on EIT phenomenon with the theory of density matrix equation. A cascade type three-level system and the function of Maxwell velocity distribution is adopted during the course. The results indicate that without considering Doppler effect, EIT windows depends on Rabi frequency of the coupling and probing field, while regardless of temperature. When took the Doppler effect into consideration, an apparent transparent window can be observed only when the temperature is less than 50K due to Doppler broadening of the absorption curve. With the increase of temperature, transparent phenomenon quickly disappeared and the double peaks of Aulter-Townes will instead of the EIT transparent window as the temperature get to the room one. This is why most of the experimental investigation about EIT was taken in cold atomic systems. At room temperature, we can only detect Aulter-Townes double peaks with a strong coupling field but not the EIT window.

10029-55, Session Post

Fibre amplifying loop mirror with nonlinearity independent of the intensity of intra-cavity radiation

Sergey M. Kobtsev, Sergey V. Smirnov, Alexey V. Ivanenko, Novosibirsk State Univ. (Russian Federation)

Among the demerits of standard nonlinear amplifying loop mirrors (NALM), one can single out the dependence of its reflectivity upon the intensity of the intra-cavity. This results in a relatively narrow range of radiation power, within which stable mode-locked operation of a fibre laser with NALM can be achieved. NALM's function due to an asymmetric distribution of amplification (loss) along the fibre and/or due to an asymmetric coupler with coupling ration differing from 50/50. Although counter-propagating waves cover an exactly identical distance within the non-linear loop, their non-linear phase incursion is different because of an asymmetric position of the active fibre. Consequently, the counter-propagating waves exiting the nonlinear loop interfere differently at different levels of radiation power, thus leading to dependence of NALM reflectivity upon the radiation power. However, as the power level is raised, stable laser operation requires that condition "nonlinear phase incursion < pi" hold true. Otherwise, the dependence of NALM reflectivity upon radiation power becomes non-monotonic, leading to disruption of generation and/or to formation of pulse trains stochastically filled with sub-pulses. This work reports for the first time that in the process of generation, the NALM reflectivity may be controlled independently of the intra-cavity radiation power by using two different active media with independent pump sources. The newly proposed layout allows stable mode locking within a substantially broader radiation power range and enables achievement of record-high pulse parameters.

10029-56, Session Post

Feedback spectroscopy of dynamically-excited coherent population trapping resonance in Rb vapour

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For the first time, this work presents exploration of CPT resonance properties in the lambda-configuration of D1 line in 87Rb atoms with dynamic excitation using a feedback spectroscopy method. Introduction of feedback loop in quasi-stationary mode when the frequency of CPT resonance scanning does not exceed 1 Hz results in a dramatic improvement of the resonance magnitude, tens of times that without feedback [1], even though this requires relatively deep modulation of the pump intensity. The present work demonstrates, for the first time, that application of the proposed feedback spectroscopy method to a system with dynamic CPT resonance excitation when the CPT resonance scan frequency exceeds 100 Hz also leads to a crucial enhancement (tens of times) of the resonance magnitude, which is similar to the enhancement obtained in the quasi-stationary mode. It is quite remarkable that the resonance strength enhancement in the dynamic excitation mode can be reached at an order of magnitude shallower depth of pump radiation modulation. Our work presents the results obtained in study of the dependence of CPT resonance parameters upon the frequency at which it is scanned over the range of 1 Hz to 3 kHz, both with and without the feed-back loop. The effect of feed-back loop parameters on the shape of dynamically induced CPT resonances has been identified. Further discussed are the possibilities of using the proposed feed-back spectroscopy method in order to improve metrological performance of compact atomic clocks based upon CPT resonance references.

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10029-57, Session Post

Performance analysis of passive optical network systems based on the IM/DD OFDM modulation format

Sofien Mhatli, Besma Wchir, Abderrazek Ben Abdallah, Ecole Polytechnique de Tunisie (Tunisia); Mutsam Jarajreh, Tabuk Univ. (Saudi Arabia); Rabah Attia, Ecole Polytechnique de Tunisie (Tunisia)

Motivated by the robust immunity to interference caused by dispersive channels as well as the higher spectrum efficiency, Orthogonal Frequency Division Multiplexing has been widely considered as one of the strongest contenders for high-speed NG-PONs, which satisfies the huge surge in demand of high-speed broadband services. However, due to the nonlinear nature of the transmitting medium, optical OFDM systems will suffer from signal degradation which limits the system capacity and the maximum transmission distance. This paper investigates these impairments in the context of IM/DD systems. In this respect, a theoretical description of the nonlinear Kerr effect based on the first order perturbation effect is presented in accordance to previous works.

10029-58, Session Post

Analytical model of an IMDD optical OFDM modem

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In this paper, we present an analytical formula of an optical OFDM modem. Bit-Error-Ratio (BER) of intensity modulated optical orthogonal frequency division multiplexing (OFDM) system is analytically evaluated accounting for nonlinear digital baseband distortion in the transmitter and additive noise in the photo receiver. The system BER is evaluated for the OFDM system with multi-level quadrature amplitude modulation (QAM) applied to the optical signal subcarriers. Results obtained by changing the fiber length, laser parameters and using single mode fiber with negative and positive dispersion are calculated in order to demonstrate the validity and versatility of the theory provided in this paper. Therefore, a novel analytical formulation is presented as a versatile tool for the description and study of IM/DD OOFDM systems with variable design parameters.The results presented in this paper are validated by numerical simulations.

10029-19, Session 5

Novel optical properties of graphene oxide films *(Invited Paper)*

Baohua Jia, Swinburne Univ. of Technology (Australia)

Graphene and its derivatives have attracted unprecedented enthusiasm during the past decade due to their exceptional mechanical, thermal, optical, and electrical properties. In particular, graphene oxide (GO), seen as the graphene sheet covalently decorated with various oxygen functional groups either on the basal plane or at the edge, becomes an attractive material itself due to a unique set of physical and chemical characteristics arising from the hybridization of sp2 and sp3 carbon atoms.

This article investigates the optics and applications of GO and reduced graphene oxide (rGO) films by using the one-step mask-free direct laser printing (DLP) method [1-3]. Firstly, the synthesis and laser reduction of GO films are discussed in details. Then the fundamental optical properties of both GO and rGO films have been investigated, including their linear and nonlinear optical properties. Finally based on the characterization and understanding of their optical activities, various optical functional components have been designed and realized both experimentally and theoretically. Our results have demonstrated the great potentials of GO films as an emerging integratable platform for ultrathin, light-weight and flexible photonic devices.

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10029-20, Session 5

Biomedical imaging with stimulated Raman scattering (SRS) microscopy *(Invited Paper)*

Minbiao Ji, Fudan Univ. (China)

Stimulated Raman scattering (SRS) microscopy is a coherent version of Raman microscopy. SRS has unique capabilities of label-free imaging with high chemical specificity and sensitivity. It could selectively image the distributions of biomolecules (such as lipids, protein and DNA) based on their characteristic vibrational spectra. We've applied SRS microscopy to a few biomedical applications, including brain tumor imaging, DNA imaging and drug deliveries.

10029-21, Session 5

Parametric wavelength conversion in photonic crystal fibers *(Invited Paper)*

Sigang Yang, Zhaohui Wu, Yi Yang, Minghua Chen, Shizhong Xie, Tsinghua Univ. (China)

Nonlinear wavelength conversion provides flexible solutions for generating wideband tunable radiation in novel wavelength band. Parametric process in photonic crystal fibers (PCFs) has attracted comprehensive interests since it can act as broadband tunable light sources in non-conventional wavelength bands. The current state-of-the-art photonic crystal fibers can provide more freedom for customizing the dispersion and nonlinearity which is critical to the nonlinear process, such as four wave mixing (FWM), compared with the traditional fibers fabricated with doping techniques. Here we demonstrate broadband parametric wavelength conversion in our homemade photonic crystal fibers. The zero dispersion wavelength (ZDW) of PCFs is critical for the requirement of phase matching condition in the parametric four wave mixing process. Firstly a procedure of the theoretical design of PCF with the ZDW at 1060 nm is proposed through our homemade simulation software. A group of PCF samples with gradually variable parameters are fabricated according to the theoretical design. The broadband parametric gain around 1060 nm band is demonstrated pumped with our homemade mode locked fiber laser in the anomalous dispersion region. Also a narrow gain band with very large wavelength detune with the pump wavelength in the normal dispersion region is realized. Wavelength conversion with a span of 194 nm is realized. Furthermore a fiber optical parametric oscillator based on the fabricated PCF is built up. A wavelength tunable range as high as 340 nm is obtained. This report demonstrates a systematic procedure to realize wide band wavelength conversion based on PCFs.

10029-22, Session 5

Giant optical nonlinearity of a single plasmonic nanostructure *(Invited Paper)*

Pavel N. Melentiev, Institute of Spectroscopy (Russian Federation)

Nonlinear optical interaction of laser light with metal nanoparticles is limited by high metal losses that leads to dramatic temperature rise and to catastrophic meltdown of nanoparticle, making plasmonic nanoparticles a poor match for applications requiring high efficiency, such as harmonics generation and wavelength conversion [1]. There is another type of structures - nanoholes made in thin metal films. Our research [2] shows that nanoopenings created in a metal film are capable of withstanding a considerably higher intensity of the radiation incident on it than isolated nanoparticles, and, correspondingly, as a nonlinear element, can be more efficient.

We present results of experimental research of a strong nonlinearity of a single plasmonic nanostructure in a geometry of Split – Hole Resonator (SHR): (1) generation of harmonics in UV and visible spectral ranges [3], (2) multi-photon induced luminescence; (3) the practical application of the giant optical nonlinearity of plasmonic nanoholes to implement (i) all-optical display, (ii) nanolocalized and femtosecond laser sources, (iii) optical nanoscale multi-order auto correlator.

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10029-23, Session 5

Fiber-based polarization-entangled photon pair sources for quantum coding

Feng Zhu, Wei Zhang, Yidong Huang, Tsinghua Univ. (China)

In this paper, a generation scheme of telecom band frequency-degenerate polarization entangled state is proposed and demonstrated experimentally. It is based on the vector spontaneous four wave mixing (SFWM) process in a Sagnac dispersion shifted fiber loop, in which two frequency-degenerate and polarization orthogonal biphoton states generate along the clockwise and counter-clockwise directions, respectively. The quantum interference between them at the 50:50 fiber coupler of the fiber loop separates the two frequency-degenerate photons in a pair, leading to the generation of polarization entanglement. The pump light is from a 40 MHz mode-locking fiber laser. It is amplified by an Erbium Doped Fiber Amplifier (EDFA). A cascade Dense Wavelength Division Multiplexing (DWDM) is used to narrow the width of the pump light. Two other cascade Dense Wavelength Division Multiplexing (DWDM) are used to filter the noise photons from signal and idler photons. The photons are detected by the NbN superconducting nanowire single photon detectors (SNSPDs). The events are recorded by a time correlated single photon counting module (TCSPC). The raw fringe visibilities of the two-photon interferences under two non-orthogonal polarization bases are higher than 89%. The coincidence and accidence ratio (CAR) can be higher than 50. Quantum coding using the polarization entangled Bell states can be realized by the generated pairs, which is demonstrated by a simplified Bell state measurement with a fringe visibility of 76%.

10029-24, Session 5

Nonlinear polarization evolution of hybrid polarized beams by isotropic Kerr nonlinearity

Bing Gu, Bo Wen, Guanghao Rui, Yiping Cui, Southeast Univ. (China)

Theoretically, we propose an investigation of the structured light field interacting with the isotropic Kerr medium. We obtain the analytical expression of the focal field of the hybrid polarized beam based on the vectorial Rayleigh-Sommerfeld formulas under the paraxial condition. We determine the third-order nonlinear refractive indexes of an isotropic medium excited by the vector field with arbitrary ellipticity. Then we numerically simulate the far-field vectorial self-diffraction behavior and nonlinear ellipse rotation of a hybrid polarized beam by isotropic Kerr nonlinearity. We systematically study the dependence of the self-diffraction behaviors on both the physical origin of the optical nonlinearity and the nonlinear phase shift. Experimentally, we observe the vectorial self-diffraction and nonlinear ellipse rotation behaviors of the femtosecond-pulsed hybrid polarized beam in carbon disulfide at 800 nm, which is in good agreement with the theoretical predictions. Our results demonstrate that the self-diffraction intensity pattern, the distribution of state of polarization (SoP), and the spin angular momentum (SAM) flux of a hybrid polarized beam could be manipulated by tuning the magnitude of the isotropic optical nonlinearity, which may find interesting applications in nonlinear mechanism analysis, nonlinear characterization technique, and SAM manipulation.

10029-25, Session 5

Design and demonstration of a novel broadband frequency conversion system

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A novel conversion system for broadband chirped pulses is presented in this report. Three gratings are successively included in the system, in which the front two of them are of equal line density and the third grating is twice of the line density. The nonlinear crystal, like BBO, is placed between the front two gratings as the second harmonic generator (SHG).The SHG phase matching for broad spectrum can be realized based on the fundamental frequency (FH) angular dispersion, provided by the first grating with certain grating constant and perpendicular incident beam. Diffraction at the second grating separates the FH and SH, which backtracks cross the crystal and is successively reflected by a dichroic mirror or polarizer into the third grating. The angular dispersion and spatial chirp can be compensated at the same time by accurate adjustment of the third grating. As a spatial chirped free dispersive unit, the grating assemble is useful to regular the SH chirped ratio by changing distance between the second and third gratings. Theoretical analysis indicates that the system can realize effective frequency conversion for FH bandwidth larger than 20nm, and experimental demonstration is expected to be carried out soon.

10029-26, Session 5

A novel method for fabrication of fiber pump combiners

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At this research, a 3x1 pump fiber combiner is fabricated without using tapering system and expensive cleaver. This component is made as the follow stages:

1. Three 200/220 is cleave and putting to a appropriate capillary and heated to enough temperature until they are attached together.

2. After that the fiber bundle endface is heated up to make micro sphere at the end of that.

3. On the other hand, a double clad 20/400 fiber is prepared and we repeat the stage 2 again.

4. At final stage, to micro sphere is spliced together.

Please note that, the critical point is the specification of micro spheres which are specify the amount of pump fiber combiner losses.

Our 3x1 pump combiner is studied with maximum power handling, 220W/port experimentally for several hours without any problem.

10029-27, Session 6

Experimental realization of optically-induced transparency in a micro-cavity *(Invited Paper)*

Yuanlin Zheng, Jianfan Yang, Zhenhua Shen, Jianjun Cao, Xianfeng Chen, Shanghai Jiao Tong Univ. (China); Xiaogan Liang, Univ. of Michigan (United States); Wenjie Wan, Shanghai Jiao Tong Univ. (China)

Electromagnetically induced transparency (EIT) has its unique ability of optically controlling transparency windows with low light in atomic systems. However its practical applications in quantum physics and information science are limited due to rigid experimental requirements. With whispering-gallery mode (WGM) micro-resonators, the analogue of EIT-like effect on a chip scale has been realized. And various schemes have been proposed and demonstrated. The advantage is about their all-solid configuration, miniaturization and controllability, which offers a unique platform for a compact, integrated solution to all-optical manipulation of light.

We experimentally demonstrated a new mechanism of optically induced transparency (OIT) in ambient environment. The new scheme relies on the introduction of a parametric gain by four-wave mixing (FWM) in the micro-cavity in order to couple nonlinearly two separated resonances of the WGMs. A signature Fano-like resonance is observed owing to the nonlinear interference of two coupled resonances. Moreover, we show that the unidirectional gain of four-wave mixing can lead to a striking effect of non-reciprocal transmission at the transparency windows, since the FWM gain is a unidirectional one owing to the conservation law of momentum.

Our unique OIT scheme offers a new platform to study analogical atomic quantum interference effects in a simpler manner; moreover, it can be further exploited for critical on-chip photonics applications such as optical isolator, all-optical switching, and wavelength conversion. Since OIT only relies on the nonlinearity and resonance properties of the medium, hence similar features should be ubiquitously expected among any other physical systems with these characteristics.

10029-28, Session 6

Experimental realization of stimulated Raman shortcut-to-adiabatic passage with cold atoms *(Invited Paper)*

Shi-Liang Zhu, Nanjing Univ. (China)

Accurate control of a quantum system is a fundamental requirement in many areas of modern science ranging from quantum information processing to high-precision measurements. A significantly important goal in quantum control is to prepare a desired state as fast as possible with sufficient high-fidelity allowed by available resources and experimental constraints. Stimulated Raman adiabatic passage (STIRAP) is a robust way to realize high-fidelity state transfer while satisfying the requirement of a sufficiently long operation time for the adiabatic evolution. In this talk, I will present our recent work on speeding up the STIRAP. We theoretically propose and then experimentally demonstrate a shortcut-to-adiabatic protocol to speed up the STIRAP. By modifying the shapes of the Raman pulses, we experimentally realize a fast and high-fidelity stimulated Raman shortcut-to-adiabatic passage (STIRSAP) that is robust against control parameter variations. The all-optical, robust, and fast protocol demonstrated here provides an efficient and practical way to control quantum systems.

10029-29, Session 6

pre-chirp managed nonlinear amplification for >100-W ultrafast sources *(Invited Paper)*

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High power, high repetition-rate ultrafast fiber-laser sources are an enabling technology for scientific applications, such as high photon flux extreme ultraviolet light sources. To avoid detrimental nonlinear effects inside fiber amplifiers, these fiber-laser sources normally employ the well-known chirped-pulse amplification (CPA) technique. Limited by gain narrowing and residual dispersion mismatch, the compressed pulse duration is typically limited to values around 200 fs. A further reduction in pulse duration necessitates an external nonlinear pulse-compression stage, which increases the system complexity and reduces the throughput efficiency.

Recently we proposed and demonstrated pre-chirp managed amplification (PCMA), in which the seeding pulse was nonlinearly amplified such that the amplified spectrum was substantially broadened. By properly pre-chirping the seeding pulse, the amplified pulse can be compressed with a duration much shorter than the transform-limited duration allowed by the seeding spectrum. Using an Yb-doped rod-type large-pitch fiber (LPF) as the power amplifier, PCMA has enabled us to generate 75 MHz, ~60 fs, linearly-polarized pulses with >100-W average power.

We further investigate the energy scalability of PCMA using circularly polarized seeding pulses. Because the nonlinear refraction coefficient for the circularly polarized light is 2/3 of that for linearly polarized light, using circularly polarized seed can scale up the pulse energy (and average power) by 1.5 times without changing the spectral bandwidth of the amplified pulse.

10029-30, Session 6

Controlled cavity quantum optomechanics with Bose-Einstein condensate

Kashif Ammar Yasir, Wu-Ming Liu, Institute of Physics (China)

Cavity-optomechanics, a tool to manipulate mechanical effects of light to couple optical field with other physical objects, is the subject of increasing investigations. We investigate controlled dynamics of such hybrid optomechanical system composed of cigar-shaped Bose-Einstein condensate (BEC) trapped inside high-finesse optical cavity with one moving-end mirror and driven by a single mode optical field. We use another transverse field, which directly interacts with BEC and scattering photons inside the system, to control bistable behavior as well as electromagnetically induced transparency (EIT) by manipulating out-going optical field. By increasing transverse field, we can suppress bistability which may act as optical switch. It is detected that the strength of transverse field is not only efficiently amplifying or attenuating out-going optical mode but also providing an opportunity to enhance the strength of Fano-interactions which leads to the amplification of EIT-window. We further investigate SO interaction tuning optomechanical dynamics of hybrid cavity with SO-coupled BEC. The collective density excitations of hyperfine states -- serving as topological oscillators equally coupled to the cavity field -- trigger strongly driven atomic back-action. The strength of SO-coupling tunes atomic back-action which not only revamps topological properties and low-temperature dynamics of its own

but also controls the effective-temperature of mechanical mirror and squeezes nonlinear quantum noises, like thermo-mechanical and photon shot noise associated with system, which enhances optomechanical features beyond the previous investigations. Our findings are testable in a realistic setup and provide foundations to manipulate SO-coupled topological states in the field of quantum optics and quantum computation. (References: 1. Kashif Ammar Yasir & Wu-Ming Liu, Tunable bistability in Hybrid Bose-Einstein condensate optomechanics, Sci. Rep. 5, 10612 (2015). 2. Kashif Ammar Yasir & Wu-Ming Liu, Controlled Electromagnetically Induced Transparency and Fano Resonances in Hybrid BEC-Optomechanics, Sci. Rep. 6, 22651 (2016). 3. Kashif Ammar Yasir & Wu-Ming Liu, Cavity-Optomechanics with Spin-Orbit Coupled Spinor Bose-Einstein Condensate, arXiv:1511.01109 [quant-ph]).)

10029-31, Session 6

Power dependence on the nonlinear interaction enhancement in a coherently-excited microcavity

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One of the advantages of photonic crystal microcavities is to strengthen the interactions between an incident beam and the cavity material. This reinforcement, which is accompanied by nonlinear index or loss/gain changes in the cavity limits the amount of energy that is coupled into the effective cavity mode. Index variations caused by non-linearities, shift the resonance frequencies precluding the coincidence with the excitation signal frequency, thereby decreasing the injection efficiency.

In order to maintain the benefit of light localization throughout the pulsed excitation, we have experimentally and numerically studied the behavior of a silicon nanobeam cavity excited by different power tailored chirped pulses whose spectral phase relation compensates for the nonlinear frequency drift of the cavity resonance. Even though the coherent excitation technique is currently used to control light-matter interactions in atomic and molecular systems, its transposition to optical resonators has been only subject of theoretical studies. Our results represent the first experimental demonstration of enhancing nonlinear interactions in a coherently excited integrated silicon cavity [Serna et al. Optics Express 23.23 (2015)]. Our numerical simulations based on a coupled mode theory are in good agreement with our experimental results. They also illustrate the capability to manipulate the nonlinear dynamics of a cavity by means of a coherent excitation, which can be applied to more complex structures like coupled cavities. Furthermore, we report a deeper understanding on this dependency and provide insights for system optimization such as materials, quality factors, input powers and required compensation chirp.

10029-32, Session 7

Strong-field double ionization of hydrocarbon molecules *(Invited Paper)*

Jian Wu, Xiaochun Gong, Qingying Song, Qinying Ji, Kang Lin, Webin Zhang, Junyang Ma, Peifen Lu, Heping Zeng, East China Normal Univ. (China)

Driven by strong laser fields, multiple electrons can eject from atoms and molecules in either tunneling or multiphoton ionization regions. As compared to the tunneling regime of ionization where the electron escapes to the continuum through the laser field suppressed potential barrier, the above-threshold ionization in the multiphoton regime produces electron of discretized energy by vertically absorbing many photons. Here, by measuring the three-dimensional momenta of all ejected electrons and ions in coincidence, we experimentally investigate the strong- field double ionization of acetylene in both the multiphoton and tunneling regions.

In the multiphoton ionization region, as compared to the sequential process, diagonal lines in the electron-electron joint energy spectrum are observed for the nonsequential above-threshold double-ionization (ATDI) owing to the correlative sharing of the absorbed multiphoton energies. In the tunneling ionization region, a molecule experiences significantly enhanced ionization rate if the molecular axis is parallel to the field vector, which is referred to as the electron localization-assisted enhanced ionization.

Here, for the double ionization of acetylene using femtosecond laser pulses, we resolve the molecular ATDI into distinct channels and probe the electron-localization scenario in C-H bond breaking in the multiphoton and tunneling ionization regions, respectively. Our findings will shed some light on the understanding and controlling of the rich multielectron and nuclear dynamics of complex polyatomic, in particular hydrocarbon, molecules in strong laser fields.

10029-33, Session 7

Nonlinear photo-association spectroscopy near a narrow d-wave Feshbach resonance *(Invited Paper)*

Yuqing Li, Shanxi Univ. (China); Jizhou Wu, Sahnxi University (China); Jie Ma, Shanxi Univ. (China); Liantuan Xiao, Suotang Jia, Sahnxi University (China)

Some experimental and theoretical investigations have demonstrated that enhanced photoassociation (PA) can be obtained near a Feshbach resonance. The PA near Feshbach resonance presents many potential applications, such as the giant formation of ground cold molecules and the precision measurement of some physical constants. In our work we construct a quantum interference in a three-level system, and find a great nonlinear Fano effect in ultracold atom-molecule coupled system. Ultracold Cs atoms, prepared by an optimized degenerated three-dimensional (3D) Raman sideband cooling, are loaded into a crossed optical dipole trap using magnetic levitation technique. We have measured the effect of magnetic field near a narrow d-wave Feshbach resonance on the rate, stimulated line width of excited molecules and light-induced frequency shift of a PA resonance in ultracold 133Cs atoms. We have observed the nonlinear variation of PA rate with magnetic field near the Feshbach resonance, where the asymmetric line shape of PA rate results from quantum interference between two competing PA processes from free-atom continuum state and underlying bound d-wave Feshbach molecular state. The broadening of stimulated PA line width and spectral shift of PA are also strongly dependent on the magnetic field near the Feshbach resonance, and show the dispersive changes that

indicate the nonlinear Fano effect. The obtained suppressing of broadening of stimulated PA line width and enhancement of PA spectral shift occur on the location of the minimum in PA rate. We have developed a theoretical model to give a good agreement with experimental results.

10029-34, Session 7

Quasi-phase matching in periodically-grooved thin-film lithium niobate waveguides

Xiao Xiong, Univ. of Science and Technology of China (China) and Harvard Univ. (United States); Cheng Wang, Harvard Univ. (United States); Nicolas Andrade, Virginia Commonwealth Univ. (United States) and Harvard Univ. (United States); Vivek Venkataraman, Harvard School of Engineering and Applied Sciences (United States); Xifeng Ren, Guang-Can Guo, Univ. of Science and Technology of China (China); Marko Loncar, Harvard School of Engineering and Applied Sciences (United States)

Lithium niobate is an excellent second order nonlinear optical material that has been widely used in modern optics. Integrated lithium niobate platform has recently emerged as a promising candidate for next-generation wavelength conversion systems that feature high conversion efficiency and allow mass production. Here we demonstrate efficient second harmonic generation in lithographically-defined thin film lithium niobate waveguides. Both perfect phase matching in fixed-width waveguides and quasi-phase matching in periodically-grooved waveguides are theoretically proposed and experimentally characterized. Our low-loss (~ 2.45 dB/cm) waveguides possess normalized conversion efficiencies as high as 41% W-1cm-2, and are promising for future on-chip quantum wavelength conversion.

10030-1, Session 1

Terahertz radiation from nonlinear surface plasmon polaritons in graphene *(Invited Paper)*

Chao Zhang, Univ. of Wollongong (Australia)

Understanding the optical properties of graphene and graphene nanostructures is of importance in the development of graphene-based optoelectronic devices. We have carried out a theoretical and computation study of optical response of graphene over a wide frequency range, from terahertz to ultraviolet. It is found that the optical response is highly anisotropic at high frequencies and highly nonlinear in the terahertz to far-infrared regime. Due to the nature of graphene's nonlinear conductivity, both TE (transverse electric) and TM (transverse magnetic) modes are supported on a graphene sheet. We demonstrate that, nonlinear conductivity can the energy of surface plasmon polariton (SPPs) in graphene. As a result dispersion of SPPs crosses the light line. This gives rise to the possibility that SPPs can be transformed to radiation by an electron beam moving at speed fast than the speed of light in the dielectrics. This type of nonlinear SPPs can induce an optical bistability in an air-graphene-dielectric structure. Under a moderate electric field in the terahertz frequency regime, the third nonlinear optical conductivity is comparable to the linear conductivity. Both the energy and frequency of the surface plasmon polaritons depend on the strength of the nonlinear current in the graphene layer. Under an opaque incident, the reflectance as a function of frequency exhibits bistability. The origin of the bistability is the field dependent plasmon mode. We have determined the parameter regime for the occurrence of bistability in this structure.

10030-2, Session 1

THz air photonics at micrometer scale *(Invited Paper)*

Xi-Cheng Zhang, Fabrizio Buccheri, Kang Liu, Univ. of Rochester (United States)

Micrometer size laser induced plasma is generated by focusing a laser beam with microscope objectives with high numerical aperture (NA). The THz emission pattern is off from the optical beam propagation direction. We have measured THz emission with the laser pulse energy less than a micro joule. We also report the recent study of THz wave sensor using micro-plasma.

10030-3, Session 1

Strong terahertz fields on the nanoscale: Near-field streaking, electron control, and terahertz field emission *(Invited Paper)*

Georg Herink, Georg-August-Univ. Göttingen (Germany)

Coupling light to metal surfaces can break the diffraction limit and concentrate optical fields at the nanoscale. In this talk, I will present recent results on the interaction of intense THz-pulses with metallic nanotips. First, I will introduce a sub-cycle interaction regime which is unique to nanostructures and strong, long-wavelength excitation. This is employed for THz near-field streaking - a scheme that is implemented as a two-color experiment at a single nanostructure. It allows to experimentally map local THz-nearfield waveforms, e.g., to characterize the electromagnetic response of nanostructures. Furthermore, the scheme allows for a control of electron motion on ultrafast timescales. I briefly sketch new ultrafast instruments, which are developed in our group, to image ultrafast dynamics at surfaces and nanostructures. I will also present results on THz-induced field emission and its application to map ultrafast non-equilibrium carrier dynamics in nanostructures. Finally, I will discuss the presented results in the light of novel nano-electronic devices which enable the control of electron motion on ultrafast timescales on the nanoscale.

10030-4, Session 1

Terahertz pulse generation from metal nanoparticle ink *(Invited Paper)*

Kosaku Kato, Keisuke Takano, Yuzuru Tadokoro, Khoa T. N. Phan, Makoto Nakajima, Osaka Univ. (Japan)

Terahertz pulse generation from metallic nanostructures irradiated by femtosecond laser pulses is of interest because the conversion efficiency from laser pulses to terahertz waves is increased by the local field enhancement resulting from the plasmon resonance. In this talk we present our recent study on terahertz generation from metal nanoparticle ink. We baked a silver nanoparticle ink spin-coated onto a glass coverslip in various temperatures. Observation by an atomic force microscope revealed that on the surface of the baked ink bumpy nanostructures are spontaneously formed, and the average size of bumps depends on the baking temperature. These structures are expected to lead to local field enhancement and then large nonlinear polarizations on the surface. The baked ink was irradiated by regeneratively amplified Ti:sapphire femtosecond laser pulses at an incidence angle of 45 degrees. Waveforms of generated terahertz pulses are detected by electro-optical sampling. The generation efficiency was high when the average diameter of bumps was around 100 nm, which is realized when the ink is baked in 205 to 235 degrees centigrade in our setup. One of our next research targets is terahertz wave generation from micro-patterned metallic nanoparticle ink. It is an advantage of the metal nanoparticle ink that by using inkjet printers one can fabricate various patterns with micrometer scales, in which terahertz waves have a resonance. Combination of microstructures made by a printer and nanostructure spontaneously formed in the baking process will provide us terahertz emitters with unique frequency characteristics.

10030-5, Session 1

Homogeneous broadband terahertz quantum cascade lasers *(Invited Paper)*

Hua Li, Jun-Cheng Cao, Shanghai Institute of Microsystem and Information Technology (China)

The terahertz quantum cascade laser (QCL) is the unipolar emitting device based on the electron intersubband transitions in the multiple-quantum-well active region. Among all the electrically pumped semiconductor lasers, the terahertz QCL shows the highest performance in the frequency range between 1 and 5 THz. Followed by the fast development of frequency combs in the visible and infrared wavelengths, the research on terahertz QCL-based broadband combs has attracted wide interest.

In this work, we employ an active region structure combining the bound-to-continuum and resonant-phonon designs. The molecular beam epitaxy-grown wafer is processed into single plasmon waveguide ridge lasers. At the low temperature of 10 K, the fabricated lasers show ultralow threshold current density around 60 A/cm2 in the continuous wave (cw) mode. We systematically investigate the electrical inter-mode beat note of a 6-mm long cavity QCL and its eye diagram to show the stability of the laser longitudinal modes. Since the inter-mode beating frequency is the result of the mixing between the adjacent longitudinal modes and the frequency falls in the radio frequency (RF) range, the laser can be modulated with the external RF signal. With RF modulation, we finally observe a homogeneously spectral spanning of 320 GHz which continuously covers the spectral range from 4.01 to 4.33 THz. The modes are evenly spaced by the external RF frequency at 6.1 GHz. The homogenous emission spectra can be used for spectroscopic applications with a spectral resolution of few GHz. As examples, we use the long cavity QCL to measure the transmission of a GaAs etalon sample and the oscillation feature in the transmission can be clearly observed; we also show that the QCL can be used to identify NH3 gas by measuring the spectra around 4.2 THz and the measured results show good agreement with the HITRAN data.

10030-6, Session 2

Electro-optic sampling detection of THz pulses based on Cherenkov phase-matching *(Invited Paper)*

Masahiko Tani, Takeshi Furuya, Hideaki Kitahara, Univ. of Fukui (Japan); Elmer S. Estacio, Univ. of Philippines Diliman (Philippines); Kazuyoshi Kurihara, Kohji Yamamoto, Daiki Gotoh, Takuro Yasumoto, Univ. of Fukui (Japan); Takashi Notake, Hiroaki Minamide, RIKEN (Japan); Michael I. Bakunov, N.I. Lobachevsky State Univ. of Nizhni Novgorod (Russian Federation)

For detection of pulsed terahertz (THz) pulsed radiation, the electro-optic (EO) sampling detection technique is commonly used as well as the photoconductive sampling. Recently, we have demonstrated the non-collinear EO sampling detection of THz pulsed radiation based on the Cherenkov-phase matching. The advantage of it is relaxation of the velocity matching condition between THz waves and optical sampling waves. Based on the Cherenkov-phase matching, we have developed the “heterodyne EO sampling”, where the EO sampling signal is observed as the direct intensity changes in the probe beam without using any polarization optics. The advantages of the heterodyne EO sampling compared to the ordinary ellipsometric EO sampling are the simplicity in the optical detection system and its applicability to birefringent EO crystals, for which a complicated optics are required for compensation of the intrinsic phase-retardation due to the birefringence. An interesting feature of the heterodyne EO sampling is its spatial distribution of the EO sampling signal over the probe beam cross section. Corresponding to the difference and sum frequency generation, we observe polarity reversed EO signal in each half of the probe beam cross section and the signal maxima are observed at points near the edge of the probe beam. In this paper, we review the advantages and properties of the electro-optic sampling detection of THz pulses based on Cherenkov phase-matching, showing several experimental measurements as examples.

10030-7, Session 2

Broadband high-power terahertz radiation from laser-produced plasmas *(Invited Paper)*

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The interaction of ultrashort intense laser pulses with plasmas either at gas or solid densities is promising to produce broadband terahertz (THz) radiation with the highest peak power. Recent progressesboth in theoretical and experimental studies on this problem will be presented. In the interaction of intense lasers with a solid target, it is shown that the large flux of hot electrons with charge of a few nC per pulse can lead to THz radiation via coherent transition both in the front and at the rear side of the solid target. Terahertz field strength as high as sub GeV/cm is illustrated in numerical simulation. When a large preplasma is formed in front of a solid target, it is shown that THz radiation can be produced via linear mode conversion from electron plasma wave excitation. With gas targets, the two-color laser scheme for THz radiation due to field ionization currents has been investigated for a wide range laser and gas parameters, including the laser wavelength, laser intensity, pulse duration, relative phase of the two lasers, and gas species. Our experimental results are supported by theory models.

10030-8, Session 2

High-sensitive THz superconducting hot electron bolometer mixers and transition edge sensors *(Invited Paper)*

Wen Zhang, Purple Mountain Observatory (China); Wei Miao, Kangmin Zhou, Jiaqiang Zhong, ShengCai Shi, Purple Mountain Observatory (China) and Key Lab. of Radio Astronomy (China)

Terahertz band, which is roughly defined as 0.1 THz to 10 THz, is an interesting frequency region of the electromagnetic spectrum to be fully explored in astronomy. THz observations play key roles in astrophysics and cosmology. High sensitive heterodyne and direct detectors are the main tools for the detection of molecular spectral lines and fine atomic structure spectral lines, which are very important tracers for probing the physical and chemical properties and dynamic processes of objects such star and planetary systems. China is planning to build an THz telescope at Dome A, Antarctica, a unique site for ground-based THz observations. We are developing THz superconducting hot electron bolometer (HEB) mixers and transition edge sensors (TES), which are quantum limited and back-ground limited

detectors, respectively. Here we first introduce the working principles of superconducting HEB and TES, and then mainly present the results achieved at Purple mountain Observatory.

10030-9, Session 2

THz and x-ray emission as a tool for study of ionization dynamics in gas clusters *(Invited Paper)*

Alexei V. Balakin, M. S. Dzhidzhoev, V. M. Gorgienko, M.V. Lomonosov Moscow SU (Russian Federation); Mikhail N. Esaulkov, Institute on Laser and Information Technologies (Russian Federation); Irina A. Zhvania, M.V. Lomonosov Moscow SU (Russian Federation); I. A. Kotelnikov, Budker Institute of Nuclear Physics SB RAS (Russian Federation) and Novosibirsk State Univ. (Russian Federation); N. A. Kuzechkin, Institute on Laser and Information Technologies (Russian Federation); Ilya A. Ozheredov, Andrey B. Savel'ev, Artem Sidorov, Petr M. Solyankin, M.V. Lomonosov Moscow SU (Russian Federation); M. B. Smirnov, Russian Research Ctr. Kurchatov Institute (Russian Federation); Alexander Pavlovich Shkurinov, M.V. Lomonosov Moscow SU (Russian Federation) and Institute on Laser and Information Technologies (Russian Federation); Vladislav Ya. Panchenko, Institute on Laser and Information Technologies (Russian Federation)

Interactions of laser radiation with gas cluster targets have been investigated in the past two decades. Cluster jet, obtained by the adiabatic condensation of gas flow, has pronounced nonlinear optical properties and combines the advantages of solid-state and gas target. Cluster inherits high local density and this implies high value of nonlinear response. At the same time cluster beams are not exposed to ablation and renew their properties before each act of interaction with the laser pulse. There were observed and predicted various nonlinear effects during interaction of intense laser pulses with cluster jets: generation of X-ray radiation, generation of optical harmonics, self-focusing, Stimulated Raman Scattering. It was shown theoretically and experimentally that absorption of laser radiation in cluster beam can reach high value (up to 95%) which is related to linear (Mie) and nonlinear resonance interactions. Resonance absorption of pulse energy results in efficient production of X-Ray and fast charged particles. In this way, further studies of interaction of intense laser pulses with clusters seems reasonable due to the possibility of usage in various practical applications and solving fundamental problems of behavior of matter under intense laser fields.

In some recent publications, intense THz generation in cluster beam excited by ultrashort laser pulses was reported. It was observed more than two orders of magnitude enhancement of THz pulse intensity in Ar cluster jet compared to that in gaseous Ar with equal average atomic density. With increasing of excitant pulse energy up to its maximum value of 70 mJ (corresponding to the vacuum intensity ~ 1017 W/cm2) THz pulse energy increased by the square law without saturation. There was reported in that the directivity pattern of terahertz radiation from clustered plasma has four-lobed structure.

At the present moment there is no clear theoretical interpretation of the experimental results and complete understanding of the mechanism of low-frequency emission in cluster plasma. It seems reasonable to carry out further study of terahertz generation in a clustered plasma, and examine this process in both ways: as a fundamental issue of laser-matter interaction on the way to solving a problem of the dynamics of laser-cluster interaction, and as a practical goal of obtaining an effective source of pulsed THz radiation. In addition, there is possible to apply two-color excitation scheme, which has been successfully used in the past to increase the efficiency of the optical to terahertz conversion in laser-induced plasma of gas media. In this scheme, the fundamental laser frequency at ? is mixed with its second harmonic at 2?. Two-color scheme allows to increase THz yield by 2...3 orders of magnitude and nowadays this scheme is widely used for THz generation in gaseous media. Nevertheless, optical to terahertz conversion efficiency in laser-plasma generation method is still low [16]. In addition, there was observed a saturation of THz yield in a two-color scheme at high excitant pulse energy that originates from THz absorption in dense plasma. Cluster target seems to be attractive to solve these problems.

In this paper we present the results of experimental and theoretical studies of generation of terahertz emission in the laser-induced clustered plasma. We have performed experiments using both single-color and two-color excitation schemes. Simultaneously with the control of terahertz emission of clustered plasma we measured the power of accompanying X-ray radiation, which is an important source of information about the processes that occur in a cluster plasma. In the theoretical section we made an attempt to explain the experimental results.

10030-10, Session 2

High-repetition-rate widely-tunable terahertz generation in GaSe pumped by a dual-wavelength KTP-OPO

Dexian Yan, Degang Xu, Yuye Wang, Wei Shi, Kai Zhong, Pengxiang Liu, Chao Yan, Quan Sheng, Jialin Mei, Jia Shi, Jianquan Yao, Tianjin Univ. (China)

We report a widely tunable terahertz source by using GaSe crystals pumped by a walk-off compensated dual-wavelength KTP OPO around 2.128 ?m, based on difference frequency generation (DFG). The KTP OPO was intracavity pumped by an acousto-optical Q-switched side-pumped Nd:YAG laser with the repetition rate of 10 kHz. The tunable THz radiation from 0.2 THz to 3 THz has been achieved in 8 mm GaSe crystal while the tuning range extended continuously from 2.057 ?m to 2.185 ?m. The maximum output average power is reach ?W-level around 1.48 THz.

10030-11, Session 2

THz-wave parametric oscillator with a surface-emitted ring-cavity configuration

Zhen Yang, Yuye Wang, Degang Xu, Longhuang Tang, Chao Yan, Pan Duan, Wentao Xu, Tianjin Univ. (China)

The terahertz wave (THz wave), located at the boundary between the microwave and optical bands, is of great interest for various applications, such as imaging, molecular analysis, life science, and nondestructive evaluation. For many practical applications of THz technologies, high-energy output and frequency-agile THz wave sources with continuous tunability over a wide spectral range are expected to improve the sensitivity, resolution, and speed of measurement.

In this work, a surface-emitted ring-cavity terahertz (THz) wave parametric oscillator has been demonstrated for high-energy THz output and fast frequency tuning in a wide frequency range. Through the special optical design with a Galvano optical scanner and four-mirror ring-cavity structure, a maximum THz output of 12.9 ?J/pulse is achieved at 1.359 THz under the pump pulse energy of 172.8 mJ with the repetition rate of 10 Hz. The beam characteristics are analyzed and optimized for this cavity. The M2

at horizontal and vertical directions is 1.64 and 2.51, respectively. It is expected that this high-power THz-wave system with a fine beam profile can provide useful advantages and find numerous applications in several areas.

10030-12, Session 2

Performance of a mm-wave adaptive beam-formed phased array system for indoor communication

Kinnan Amjad, Huaping Xu, Beihang Univ. (China)

Millimeter waves (mmWaves) spectrum ranging from 30GhZ to 300Ghz is emerging as a potential solution to the bandwidth problem faced by the wireless communication now a days. The advancements in the antenna technology has enabled the fabrication of antenna arrays or phased array systems which when used with techniques like spatial multiplexing and beamforming has enabled the use of mmWaves for both indoor and outdoor communication systems by providing gain and selectivity. This has also opened the doors for its potential use in long range and cellular communications. The 60GHz band also know as the oxygen absorption band due to its higher attenuation and unlicensing is a good candidate for use in secure and confined communications. In this paper we have investigated the performance of a beamformed phased array system in the mmWave spectrum. The performance is measured for varying source and noise locations and for different array types.

10030-13, Session 3

Terahertz free-electron laser spectroscopy of excitons in III-V semiconductor quantum wells and single quantum dots *(Invited Paper)*

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Using intense, spectrally narrow terahertz pulses from the free-electron laser facility FELBE in Dresden, Germany, we have investigated exciton population dynamics in III-V QWs and single quantum dots (QD). To this end, carriers are optically injected by picosecond near-infrared pulses to populate the lowest excitonic level. Using narrowband terahertz pulses, excitons are resonantly excited into higher levels. Time-dependent photoluminescence (TDPL) measurements based on a streak camera system and on time-correlated photon counting, respectively, then allow us to study the transient population of dipole-allowed higher exciton levels and to access the relaxation dynamics.

In QWs, the most prominent transition is from the excitonic 1s ground state into the 2p excited state (using hydrogen notation), which rapidly scatters into the 2s state. TDPL originating from the 1s and 2s excitons thus provides a unique signature which allows us to explore the relaxation dynamics involving 1s, 2s, and 2p [1]. Now turning to QDs, single QDs rather than QD ensembles should be investigated in order to prevent strong inhomogeneous broadening. We have therefore developed a micro-TDPL setup to become sensitive to one single QD [2]. In particular, we investigate the dynamics of the s-to-p inter-sublevel transition, which occurs in the range 13-20meV for the QDs under study. Resonant terahertz excitation, about 0.7ns time delay after interband excitation, causes an instantaneous reduction of the ground state TDPL. The signal recovers within about 100ps towards a value which depends on the near-infrared excitation energy. In particular, qualitatively different behavior has been observed and analyzed using a phenomenological rate equation for interband excitation of the GaAs matrix, the InGaAs wetting layer, and quasi-resonant QD excitation.

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[2] D. Stephan et al., Appl. Phys. Lett. 108, 082107 (2016)

10030-14, Session 3

Trace amount liquids sensing by means of near-field THz emission spectroscopy *(Invited Paper)*

Masayoshi Tonouchi, Osaka Univ. (Japan)

Considering biological application using terahertz (THz) waves in the future, we have developed a nonlinear optical crystal (NLOC) -based THz micro-total analysis system (THz-?TAS) for measuring trace amounts of liquids using THz waves. The THz-?TASs with and without metamaterials are fabricated on a 500-?m-thick (110)-oriented GaAs wafer by wet etching. We demonstrate to distinguish commercial mineral waters with a amount of several 100 nL (less than 60 femto mol) successfully.The metamaterials consist of periodically-arranged a few meta-atoms (sprit-ring resonators with the diameter of 84?m) equipped with two gaps and a micro-fluid channel. In the conference we report their design, fabrication procedures, and sensitivity with and without metamaterials.

10030-15, Session 3

High-conductivity mechanism of conducting polymer PEDOT:PSS studied by terahertz and infrared spectroscopy *(Invited Paper)*

Masatsugu Yamashita, Yusuke Yamada, Chiko Otani, RIKEN (Japan)

PEDOT:PSS, one of the most commercially successful conducting polymer, has attracted wide attentions from both academic and technological aspects because of its excellent conductivity, transparency in visible region, high thermal stability coupled with the merit of low cost wet-process. PEDOT has a pai-conjugated chain and can deliver the charge carrier along its chain via ?-orbital. The charge carriers are doped in PEDOT chain through the oxidative polymerization with the insulating PSS. The highly conducting PEDOT:PSS film can be obtained by the addition of ethylene glycol (EG). XRD study captured the existence of PEDOT nano-crystal which increase from 1 to 5 nm by the addition of EG. On the other hands, AFM study clearly shows the macroscopic changes in the film morphology due to the aggregation of PEDOT by the EG. However, it is not clear whether the metallic state in PEDOT:PSS is realized or not.

In this study, we studied high conductivity mechanism of conducting polymer PEDOT:PSS with the temperature dependence of THz and infrared (IR) spectra. While IR spectra show plasma reflection which has temperature independent behavior, THz complex conductivity spectra shows thermally activated and carrier localization behaviors. The localization modified Drude model explains well the temperature dependence

of the THz and IR spectra The results suggests the high conductivity of PEDOT:PSS is realized with an weak carrier localization state where PEDOT nano-crystals aggregate to form the disordered metallic conducting path.

10030-16, Session 3

Application of terahertz waves for polymer science *(Invited Paper)*

Hiromichi Hoshina, RIKEN (Japan)

In this presentation, potential of the terahertz (THz) waves as a new tool for polymer science will be discussed. In the first part, THz spectroscopy of polymers will be presented. Absorption spectra of polymer reflect their higher-order conformation which provides information about polymer crystallization, degradation and water adsorption. We have succeeded to develop method for the assignment of low-frequency vibrational modes of polymers and obtained information of their higher-order conformations. By the temperature dependent THz spectra, the change of the hydrogen-bond interaction and the structure of the polymers during the phase transition were observed. In the second part, THz-wave manipulation of polymer structure will be presented, in which we succeed in altering polymer morphology using THz wave irradiation. We irradiate a poly(3-hydroxybutylate) (PHB) / chloroform solution during cast crystallization using a THz wave generated by a free electron laser (FEL). Morphological observation shows the formation of micrometer-sized single crystals via the THz wave irradiation. Further, a 10-20% increase in crystallinity is observed through analysis of the infrared (IR) absorption spectra. The power density of the irradiating THz wave is 40 MW/cm2, which is significantly lower than the typical laser intensities used for material manipulation.

10030-17, Session 3

A study of vibrational spectra of leucine and isoleucine in terahertz domain

Lijuan Huang, Xin Zhang, Guo Wang, Zhuoyong Zhang, Capital Normal Univ. (China)

Amino acid isomers detection is useful for the quality control of the food and pharmaceutical potency. Leucine and isoleucine are homologous isomers. They have very similar molecular structures, but different chemical and physical properties. To distinguish different amino acid isomers, researchers commonly use gas chromatography, liquid chromatography, capillary electrophoresis, LC-MS, GC-MS etc. Those methods normally need sample preparation, which is time consuming and destructive. Terahertz wave refers to the frequency in the 0.1-10 THz spectra of electromagnetic radiation and its wavelength is between 0.03 to 3 mm. THz time domain spectroscopy (THz-TDS) can provide the structure information of the material and configuration. Biological macromolecular terahertz absorption are related with intermolecular hydrogen bond vibration and rotational level about the dipole transition, and it can be used for fingerprint identification of molecular dipole transition. In the present the terahertz time-domain spectroscopy (THz-TDS) and Fourier transform infrared spectroscopy (FTIR) was used to measure the absorption spectroscopy of leucine and isoleucine at room temperature. A number of different well-resolved THz absorption peaks for the two components were observed, but their infrared absorption peaks were almost overlapped. In parallel with the experimental study, the computed vibrational spectra were also obtained by using first principles calculations based on the density functional theory (DFT). The theoretical results fit well with the experimental results.

10030-18, Session 3

Feasibility study of determination of high-fructose-syrup content of acacia honey by terahertz technique

Wen Liu, Yuying Zhang, Donghai Han, China Agricultural Univ. (China)

The production of honey with high nutritional value is difficult to meet the needs of the market in China, so that the authenticity problem of honey with difficult identification and great economic value highlights the certain limitations of the existing examination methods to distinguish the inauthentic honey.

Considered the strong absorption of water and its low energy, terahertz technique is promising in the food industry. Terahertz technique is sensitive to water and has amount of information about carbohydrates' intermolecular interactions, causing terahertz spectroscopy a potential technique to detect honey quality.

We got the THz absorption coefficient spectra of Acacia honey with different high-fructose-syrup content in attenuated total reflection module, which from the bottom up represent the different adulterated high-fructose-syrup content of honey from 10% to 100%. The growth of THz absorption coefficient is matched by an increasing of high-fructose-syrup.

We find that Acacia honey and high-fructose-syrup have different content of fructose, glucose and water. Except for water sensitive to terahertz, fructose and glucose as monosaccharide also have absorption in the terahertz band. Then we build a PLS model for high-fructose-syrup content in adulterating honey, finding that RMSEC: 0.0375, RMSEP: 0.0449, RPD: 7.08, showing a good prediction and training of PLS model.

This work shows that it was possible to determine high-fructose-syrup content of Acacia honey by terahertz technique. The work here is only a feasibility study, and further studies using considerably more samples are required before the developed model can be adopted.

10030-19, Session 4

Terahertz nonlinear interactions, spectroscopy, and coupled modes *(Invited Paper)*

Keith A. Nelson, Massachusetts Institute of Technology (United States)

Strong THz fields have been used to drive nonlinear responses in every phase of matter. These include highly nonlinear responses including phase transitions, chemical reactions, visible light emission, and dramatic changes in electrical conductivity and other material properties. A wide range of nonlinear THz spectroscopy methods have been used including probing of THz-induced responses at frequency ranges from THz to hard x-rays. 2-dimensional THz spectroscopy has also been demonstrated on resonant responses including those of molecular rotations in the gas phase, driven by THz electric fields, and those of collective spin excitations (magnons), driven by THz magnetic fields. Strong coupling between THz fields and material excitations to form THz polariton modes has been exploited for THz signal generation, control, and visualization as well as THz spectroscopy. Recent results including spectroscopy and interactions involving THz electric and magnetic fields will be emphasized.

10030-20, Session 4

Manipulating magnetic and optical properties of condensed matter with intense terahertz pulses *(Invited Paper)*

Christoph P. Hauri, Paul Scherrer Institut (Switzerland)

Laser pulses in the low-frequency Terahertz range (1-15 THz) with field strength up to several GV/m and several Tesla have become available only very recently. Such pulses offer novel opportunities to explore ultrafast magnetization dynamics in a regime differing from the commonly used optical lasers where the magnetization control is mediated by heat deposition. We show that strong THz fields allow coherent spin excitation even without exciting a magnetic mode [1]. Our investigations on the classical conducting ferromagnets (Fe, Co, Ni) unravel the onset of a co-existence of precessional motion and ultrafast magnetization quenching as function of the THz field strength. While the coherent precessional motion is induced by the magnetic field the concomitant electric field component give rise to fast demagnetization.

Likewise we will show that intense Terahertz pulses propagating in semiconductors can change the optical and electronic properties on a sub-cycle timescale. As an example we will present THz-assisted octave-spanning spectral broadening of a near IR femtosecond pulse by cross-phase modulation and an advanced high-resolution 2-dimensional THz detector based on conventional silicon CCD technology [2].

1. C. Vicario et al. , Nature Photon. 7, 720 (2013)

2. M. Shalaby, C.P. Hauri, Nature Commun. 6:5976 doi: 10.1038/ncomms6976 (2015)

10030-21, Session 4

Efficient structure resonant energy transfer from EM waves to viruses for virus inactivation *(Invited Paper)*

Chi-Kuang Sun, National Taiwan Univ. (Taiwan)

Recently we found that when confined acoustic vibrations modifies the dipole moments of nanoparticles, incoming electromagnetic waves oscillating at the same vibrational frequencies will resonantly couple with the confined acoustic modes and result in terahertz photon absorption. Throught the same prinicple, we recently observed the 3D acoustic quantization mode in spherical viruses, which allows the strong dipolar coupling with the resonant EM waves. Following the previous findings, in this presentation, the efficiency of energy transfer from free-space electromagnetic wave to confined acoustic vibrations in viruses is reviewed. Based on a damped mass-spring model, we established the relationship between the displacement of vibrating viruses and the illuminated power of microwaves. We propose to define the efficiency of energy transfer from microwave to displacement vibration through exploring the virus inactivation ratio. For experimental verification, we studied the inactivation ratio of Influenza A (H3N2) viruses in the phosphate buffer saline with different microwave frequencies. The plaque assay study on the inactivation ratio indicates high efficacy of the structure resonance energy transfer from electromagnetic wave to confined acoustic vibrations in spherical viruses. Our work not only demonstrates the existance of the dipolar resonant modes of viruses with microwaves, but also establishes a model to fomulate the structure resonance energy transfer from EM wave to confined acoustic vibrations in viruses. Above all, our study can form the fundation to plan the future strategy to inactivate airborne viruses in open space through microwave induced confined acoustic vibrations.

10030-22, Session 4

Removal of instrumental etalon oscillations in broadband terahertz spectra for accurate material characterization

Jindoo Choi, Jinwoo Lee, Kyung-Soo Kim, Soohyun Kim, KAIST (Korea, Republic of)

Terahertz time-domain measurements display various reflection waves in the form of echo pulses, leading to oscillations in the frequency domain. There are two origins for these multiple reflections, one, the sample under investigation, and two, optical components in the spectrometer setup. The echoes produced from the sample provide meaningful supplementary information about the sample, with which the determination accuracy of the material parameters can be greatly enhanced. Instrumental echoes on the other hand, do not possess such valuable information and only hinder accurate spectroscopic analysis. Therefore, it is advantageous to selectively remove these instrumental echoes, in which the sample-induced echoes remain unaltered in the process. However, previous reports were unsuccessful in addressing how to distinguish the two types of echo signals, and hence, were only able to present algorithms that remove these etalon effects altogether. In this work, we point out this important but often neglected aspect for accurate material characterization – the necessity of selective removal of only the instrumental etalon effect from terahertz spectra. A signal processing algorithm is introduced, dedicated to effectively eliminate only the instrumental echoes. Mathematical derivation is presented, followed by several experimental results that validate the proposed method. Application experiments include water vapor absorption measurements, high-resistivity silicon wafer characterization, and explosive pellet sample evaluation. Results clearly show an effective and selective removal of the instrumental etalon effect, ultimately presenting highly accurate determination of material parameters.

10030-48, Session Post

A high-speed and low-noise intelligent test system for infrared detectors

Tianshi Jia, Yulong Xue, Fansheng Kong, Shanghai Institute of Technical Physics of the Chinese Academy of Sciences (China)

With the development of infrared focal plane technology, the scale of the detector becomes larger and larger, and the pixel noise level is lower and lower. Therefore, the rate and the noise level of the infrared measurement system are put forward. This paper designed and implemented a set of infrared high-speed low noise intelligent test system based on OPENVPX standard, which is used to test the index, long term monitoring and life of infrared detector. OPENVPX architecture is far beyond the VMEbus and CompactPCI architecture in transmission rate, board level reinforcement, compatibility and other aspects. The system is mainly composed of high speed back board, image acquisition board, temperature acquisition board and the main control board, which has high speed image acquisition, processing, temperature monitoring and alarm function. High speed backplane uses full interconnection structure. RapidIO is used as the way of data transmission to ensure high-speed data transmission; image acquisition board uses a 16 channel mode, each channel consists of a low noise conditioning circuit and high precision analog to digital converter (ADC). Temperature measurement board monitors the detector status in real time and has the wireless alarm function; As the control and processing core of the system, the main control board is used to realize complex algorithm. Differential amplifier and differential ADC are used to achieve low noise, multi-channel high precision and low noise

DAC achieves bias adjustable. Test results show that the system noise is less than 100uV, the dynamic range reaches 100dB, and the data throughput rate reaches 4Gbps, which can meet the requirements of the infrared detector test currently.

10030-49, Session Post

Investigation on terahertz generation from zinc-blend crystal waveguide at polariton resonance

Zhongyang Li, Silei Wang, Mengtao Wang, North China Univ. of Water Resources and Electric Power (China)

Terahertz (THz) wave generation from zinc-blende crystal waveguide, such as GaAs, InP, ZnTe and CdTe, at polariton resonance region (PRR) with a transverse-pumping geometry is investigated. It is shown that by using grating vector of periodically inverted crystal THz wave can be efficiently generated by difference frequency generation (DFG) with a transverse-pumping geometry. Parametric gain coefficient in the low-loss limit and absorption coefficient of THz wave during DFG process in the vicinity of PRR are analyzed. The frequency tuning characteristics of THz wave via varying wavelength of difference frequency waves and poling period of periodically inverted crystal are numerically analyzed.

10030-51, Session Post

Oil spill detection using infrared hyperspectral infrared camera

Hui Yu, Huazhong Institute of Electro-Optics (China) and Wuhan National Lab. for Optoelectronics (China); Zhen Zhang, State Oceanic Administration (China); Zhijie Zhang, Huazhong Institute of Electro-Optics (China); Song Yue, Hubei Jiuzhiyang Infrared System Co., Ltd. (China); Chensheng Wang, Wuhan National Lab. for Optoelectronics (China) and Huazhong Institute of Electro-Optics (China)

Oil spill pollution is a severe environmental problem that persists in the marine environment and in inland water systems around the world. Visual detection of an oil spill is not reliable since oil on ocean environment is often confused with other substances, such as sea weeds, fish sperm etc. especially in the low visibility condition, e.g. fog and darkness. Hyperspectral imaging can be considered as a very reliable manner to detect and monitor oil spill on ocean environment. The hyperspectral images can not only provide the space information but also the spectral information. Pixels of interests generally incorporate information from disparate component that requires quantitative decomposition of these pixels to extract desired information. Oil spill detection can be implemented by applying hyperspectral camera which can collect the hyperspectral data of the oil. By extracting desired spectral signature from hundreds of band information, one can detect and identify oil spill area in vast geographical regions. There are now numerous hyperspectral image processing algorithms developed for target detection. In this paper, we proposed a target detection algorithm for the identification of surface oil spills in ocean environment. The proposed method mainly contains three steps: the first step is the preprocessing method which is used to de-noise the acquired hyperspectral images; the second step is to abstract the features of spectral data; and the second step is to detect the oil by using the target recognition method. In the experiments, we applied a hyperspectral camera to collect the real life oil spill. The experimental results shows the feasibility of oil spill detection using hyperspectral imaging and the performance of hyperspectral image processing algorithms were also validated.

10030-52, Session Post

Analyzing terahertz time-domain transmission spectra with multi-beam interference principle

Maorong Wang, Kai Zhong, Degang Xu, Yuye Wang, Wei Shi, Jianquan Yao, Tianjin Univ. (China)

In the past decade, terahertz time domain spectroscopy has become a powerful technique for measuring the optical constants of materials in a wide terahertz range. As is known, this technique is based on recording the time-dependent electric field of a terahertz pulse. The ratio of the Fourier transforms of the electric field data recorded with and without the sample yields the complex transmission coefficient of the sample in the frequency domain. As to a huge number of transparent materials such as thin-film dielectrics or semiconductors, remarkable Fabry-Perot echoes in the time domain or transmittance oscillations in frequency domain caused by multiple reflection can be observed, which will be cut out during data processing but that should lose some useful information. Here we present an accurate analyzing method based on multiple beam interference and Fresnel's formula that extract simultaneously the refraction index and the extinction coefficient from terahertz time domain spectroscopy transmission spectra with oscillations, which are the basis for calculating permittivity. Typical THz-TDS system worked in transmission mode is utilized for direct measurement of the transmission spectra with a frequency accuracy of 7.6 GHz and range from 0.3 THz to 3 THz at room temperature. This method is verified with a polished 350 ?m 100-cut GaAs wafer, and the reasonable average relative error for refractive index in the whole range is less than 0.36% comparing with conventional method, which provides a new approach to process the original transmission spectra with oscillations.

10030-53, Session Post

A novel wavefront-based algorithm for numerical simulation of quasi-optical systems

Xiaoling Zhang, Purple Mountain Observatory (China) and Key Lab. of Radio Astronomy (China) and Shanghai Normal Univ. (China); Zheng Lou, Purple Mountain Observatory (China) and Key Lab. of Radio Astronomy (China); Jie Hu, Purple Mountain Observatory (China) and Key Lab. of Radio Astronomy (China) and Chinese Academy of Sciences (China); Kangmin Zhou, Yingxi Zuo, Shengcai Shi, Purple Mountain Observatory,CAS (China) and Key Lab of Radio Astronomy, CAS (China)

This paper proposes a novel wavefront-based algorithm for the beam simulation of both reflective and refractive optics in quasi-optical system. The algorithm can be regarded as the extension to the conventional Physical Optics algorithm to handle dielectrics. Internal reflections are modeled in an accurate fashion, and coating and lossy materials can be treated in a straightforward manner. A parallel implementation of the algorithm has been developed and numerical examples show that the algorithm yields sufficient accuracy by comparing with experimental results, while the computational complexity is much less than the full-wave. The algorithm offers an alternative approach to the modeling of quasi-optical system in addition to the Geometrical Optics modeling and full-wave method.

10030-54, Session Post

Cost-effective bidirectional digitized radio-over-fiber systems employing sigma delta modulation

Kyung Woon Lee, Korea Univ. (Korea, Republic of); HyunDo Jung, Electronics and Telecommunications Research Institute (Korea, Republic of); Jung Ho Park, Korea Univ. (Korea, Republic of)

We propose a cost effective digitized radio-over-fiber (DRoF) system employing a sigma delta modulation (SDM) and a bidirectional transmission technique using phase modulated downlink and intensity modulated uplink. Delta-sigma modulation is transparent to different radio access technologies and modulation formats, and more suitable for a downlink of wireless system because a DAC can be avoided at the base station(BS). Also, Central station and BS share a same light source by using a phase modulation for the downlink and an intensity modulation for the uplink transmission. Avoiding DACs and light sources have advantages in terms of cost reduction, power consumption, and compatibility with conventional wireless network structure.

We designed cost effective bidirectional DRoF system using low pass SDM and measured downlink and uplink transmission performance in terms of error vector magnitude, signal spectra, and constellations, which are based on the 20MHz LTE 64-QAM standard.

10030-55, Session Post

Infrared image segmentation method based on interest point detection and superparamagnetic clustering

Songtao Liu, Ning Jiang, Zhenxing Liu, Dalian Naval Academy (China)

The advantages of superparamagnetic clustering include that: (1) the clustering data does not make any assumptions; (2) the number of clusters is not required and the initial conditions are robust; (3) the parameters are fewer and adaptable; (4) the clusters of different shapes, sizes and densities can be found; (5) it has the global optimality, therefore, when the superparamagnetic clustering is applied to infrared image segmentation directly, the results are satisfactory and stable, but the algorithm's computation time is slightly long. In this paper, after interest point detection and description, superparamagnetic clustering is used for image segmentation, which overcomes the deficiency of the traditional superparamagnetic clustering method. Considering that the detector based on the direction of the edge is more robust to intensity changes and background clutter, the edge foci points are used as interest points, which are points in the image that are roughly equidistant from edges with orientations perpendicular to the point. This detector has three stages. First, locally normalized edge magnitudes and orientations are computed. Second, orientation dependent filtering on the resulting edges is performed, and their results are aggregated. Finally, local maxima in the resulting aggregated filter responses in both spatial position and scale is found. When describing the interest points, the intensity order pattern is used. The basic principle is that the relative order of pixel intensities remains unchanged when the intensity changes are monotonic. Specifically, a local intensity order pattern is adopted to encode the local ordinal information of each pixel. This descriptor is invariant to rotation and intensity changes. In conclusion, the main feature of this novel method is the combination of the interest point detection and superparamagnetic clustering, which not only ensures the effectiveness of infrared image segmentation, but also improves the efficiency of the clustering algorithm.

10030-56, Session Post

FPGA design large-area array infrared detector video processing circuit of infrared camera

Tao Liu, China Academy of Space Technology (China)

Satellite infrared camera to achieve a large-array imaging infrared detectors, this paper analyzes the characteristics of large-array infrared detectors, equipment work environment, miniaturization, signal sampling precision and high-speed serial data transmission, using a clock management chip clock network design, improved signal sampling accuracy and improve the reliability of high-speed serial data transmission; the use of signal processing to achieve orbit correction channel inconsistencies and improve the signal to noise ratio of the image; the use of electronic current limiter prevent single event latch-made devices, the device improves reliability; ground adaptive pixel correction, programmable blind yuan replace experiments in orbit for future applications of the technology experiment, from the infrared imaging camera location imaging results It can be seen on the design ideas and feasible and meets mission requirements.

10030-57, Session Post

Active terahertz wave imaging system for detecting hidden objects

Yuner Gan, Beijing Institute of Technology (China)

Terahertz wave can penetrate the common dielectric materials such as clothing, cardboard boxes, plastics and so on. Besides the photon energy of the terahertz wave is low, and does not cause ionization, which is especially suitable for the safety inspection of the human body. Terahertz imaging technology has a tremendous potential in the field of security inspection at stations, airports and other public places. Terahertz wave imaging system is divided into two categories: active terahertz imaging system and passive terahertz imaging system. So far, most terahertz imaging system works at point to point mechanical scan pattern with the method of passive imaging. The imaging effect of passive imaging tend to have low contrast and the image is not clear enough. This paper designs and implements an active terahertz wave imaging system combining terahertz wave transmitting and receiving with a Cassegrain antenna. The terahertz wave at the frequency of 94GHz is created by impact ionization avalanche transit time (IMPATT) diode, focused on the feed element for Cassegrain antenna by high density polyethylene (HDPE) lens, and transmitted to the human body by Cassegrain antenna. The reflected terahertz wave goes the same way it was emitted back to the feed element for Cassegrain antenna, focused on the horn antenna of detector by another high density polyethylene lens. The scanning method is the use of two-dimensional planar mirror, one responsible for horizontal scanning, and another responsible for vertical scanning. Our system can achieve a clear human body image, has better sensitivity and resolution than passive imaging system, and costs much lower than other active imaging system in the meantime.

10030-58, Session Post

Terahertz liquid sensor

Jing Liu, Beijing Institute of Technology (China); Jian Zuo, CunLin Zhang, Capital Normal Univ. (China)

We demonstrate a novel method to identify liquid such as HCl and NaCl by terahertz sensor in this paper. When certain liquid is added to the gap of sensor, the electromagnetic response peak shifts towards red. Different liquid can be distinguish clearly by comparison of different levels of the red-shifts. The simulation results show that it is a sensitive method to detect different substances in terahertz band.

10030-59, Session Post

Widely-tunable terahertz parametric oscillator based on MgO-doped near-stoichiometric LiNbO3 crystal

Longhuang Tang, Yuye Wang, Degang Xu, Zhen Yang, Chao Yan, Wentao Xu, Pan Duan, Yixin He, Jia Shi, Meitong Nie, Jianquan Yao, Tianjin Univ. (China)

The terahertz wave (THz wave), connected the microwave region and the infrared region, has a great potential in various applications, such as biomedical imaging, security and nondestructive evaluation. For many practical applications of THz technologies, terahertz parametric oscillator (TPO),using nonlinear crystal such as LiNbO3 and KTP crystal, has been demonstrated as a promising THz source for its possessing the advantages of widely tunable ,high energy output and room temperature operation.

In this study, we proposed a wider tunable, high energy output TPO based on MgO-doped near-stoichiometric LiNbO3 (SLN) crystal, which was pumped by 1064 nm nanosecond pulsed laser. The tunability was in the range of 1.2-4.7 THz. The maximum THz wave output energy was 14.6?J/pulse at 2.19 THz under the pump energy of 165 mJ/pulse, corresponding to the maximum THz wave conversion efficiency of 8.8?10-5 and the maximum photon conversion efficiency of 3.8?10-3, respectively. Moreover, under the same experimental conditions, the THz tuning range was 0.8-2.6 THz with MgO-doped congruent LiNbO3 (CLN) crystal. It is demonstrated that the TPO had better performance with SLN crystal than that with CLN crystal.

10030-60, Session Post

Identification of four kinds of rheum which was gained by means of different processing methods

Lei Xu, Capital Normal Univ. (China)

Recent along with organism high-tech in traditional Chinese medicinal materials study domanial use, rheum study all the more go deep into, all the more systematization. Rheum is one of the most commonly used traditional Chinese medicine. Due to the different processing methods, the drug efficacy of rhubarb will be different. The absorption spectra of rheum with three different processing methods can be gained by far-infrared Fourier-transform infrared spectrometer (Far-infrared FTIR) and terahertz time-domain spectroscopy (THz-TDS). By means of comparing the discrepancies of spectra of three rheum, it is found that the positions of their vibration absorption peaks are distinctly different. On the other hand, the refractive index of cooked rheum is the largest, followed by rheum and the minimum is wine processing rheum. Three kinds of rheum can be identified. In addition, the properties of traditional Chinese medicine will be discussed in greater depth by using these methods.

10030-61, Session Post

Compact high-repetition-rate terahertz source based on difference frequency generation from an efficient 2-um dual-wavelength KTP OPO

Jialin Mei, Kai Zhong, Maorong Wang, Pengxiang Liu, Degang Xu, Yuye Wang, Wei Shi, Jianquan Yao, Tianjin Univ. (China); Robert A. Norwood, Nasser N. Peyghambarian, The Univ. of Arizona (United States)

A compact optical terahertz (THz) source was demonstrated based on an efficient high-repetition-rate doubly resonant optical parametric oscillator (OPO) around 2 ?m with two type-II phase-matched KTP crystals in the walk-off compensated configuration. The KTP OPO was intracavity pumped by an acousto-optical (AO) Q-switched Nd:YVO4 laser and emitted two tunable wavelengths near degeneracy. The tuning range extended continuously from 2.068 ?m to 2.191 ?m with a maximum output power of 3.29 W at 24 kHz, corresponding to an optical-optical conversion efficiency (from 808 nm to 2 ?m) of 20.69%, believed to be among the highest reported. The stable pulsed dual-wavelength operation provided an ideal pump source for generating terahertz wave of micro-watt level by the difference frequency generation (DFG) method. A 7.84-mm-long periodically inverted quasi-phase-matched (QPM) GaAs crystal with 6 periods was used to generate a terahertz wave, the maximum voltage of 180 mV at 1.244 THz was acquired by a 4.2-K Si bolometer, corresponding to average output power of 0.6 ?W and DFG conversion efficiency of 4.32?10-7. The acceptance bandwidth was found to be larger than 0.35 THz (FWHM). As to an 8-mm-long GaSe crystal used in the type-II collinear DFG, a tunable THz source ranging from 0.503 THz to 3.865 THz with the maximum output voltage of 154 mV at 1.85 THz would be achieved, and the corresponding average output power and DFG conversion efficiency were 0.5 ?W and 3.6?10-7 respectively. This provides a potential practical palm-top tunable THz sources for portable applications.

10030-62, Session Post

The properties of electromagnetic responses and optical modulation in terahertz metamaterials

Wei Chen, Beijing Institute of Technology (China) and National Space Science Ctr., CAS (China); Yulei Shi, Wei Wang, Qingli Zhou, Cunlin Zhang, Capital Normal Univ. (China)

Metamaterials with subwavelength structural features show unique electromagnetic responses that are unattainable with natural materials. Recently, the research on these artificial materials has been pushed forward to the terahertz (THz) region because of potential applications in biological fingerprinting, security imaging, and high frequency magnetic and electric resonant devices. Furthermore, active control of their properties could further facilitate and open up new applications in terms of modulation and switching. In our work, we will first present our studies of dipole arrays at terahertz frequencies. Then in experimental and theoretical studies of terahertz subwavelength L-shaped structure, we proposed an unusual-mode current resonance responsible for low-frequency characteristic dip in transmission spectra. Comparing spectral properties of our designed simplified structures with that of split-ring resonators, we attribute this unusual mode to the resonance coupling and splitting under the broken symmetry of the structure. Finally, we use optical pump–terahertz probe method to investigate the spectral and dynamic behaviour of optical modulation in the split-ring resonators. We have observed the blue-shift and band broadening in the spectral changes of transmission under optical excitation at different delay times. The calculated surface currents using finite difference time domain simulation are presented to characterize these resonances, and the blue-shift can be explained by the changed refractive index and conductivity in the photoexcited semiconductor substrate.

10030-63, Session Post

Wavelength scaling of terahertz radiation in plasma gas targets

Hang Zhao, Suxia Huang, Cunlin Zhang, Liang-liang Zhang, Capital Normal Univ. (China)

In our experiments, terahertz radiation via two-color generated laser plasma gas targets is studied using nitrogen and the noble gases (helium, neon, argon, krypton, and xenon) as the generation media. Carried out at the infrared beam line of the advanced laser light source, we studied the effects of different pump wavelengths ?between 1200 nm and 1600nm?on THz generation. Terahertz pulse energy and power spectra are measured as function of input pulse energy , gas species, gas pressure, and 5 different pump wavelengths between 1200 nm and 1600nm delivered by a commercial optical parametric amplifier (TOPAS). The experimental results show that the terahertz output pulse energy has a regular change with the different variables.

10030-64, Session Post

Wavelength scaling of terahertz generation via two-color photoionization in pre-formed plasma

Suxia Huang, Hang Zhao, Cunlin Zhang, Liang-liang Zhang, Capital Normal Univ. (China)

For the further fundamental understanding of the mechanism of the THz wave generation in laser-induced plasma, the generation of terahertz radiation using an effective wavelength scaling mechanism is examined when two-color laser fields are mixed in pre-formed plasma created by another 800nm laser pulse. In our experiment, the effect of pre-formed plasma is investigated using an orthogonal pumping geometry. With a pre-formed plasma, the THz yield is reduced significantly, and the radiated THz modulation changes regularly as a function of increasing pump wavelength. Possible mechanism of the result is discussed in terms of tunneling ionization in the terahertz generation mechanism.

10030-65, Session Post

Chirped distributed Bragg reflector for broadband group velocity dispersion compensation in terahertz quantum cascade lasers

Chao Xu, Dayan Ban, Univ. of Waterloo (Canada)

We present a theoretical study on designing and optimizing a chirped distributed Bragg reflector (DBR) to achieve group velocity dispersion compensation over an ultra wide frequency range from 2 THz to 4 THz in metal-metal waveguides. A one-dimensional (1D) model based on transfer matrix method is firstly adopted to reveal the fundamental behaviors and characteristics of the chirped DBR structures. Then a more accurate three-dimensional (3D) model is deployed by using a COMSOL RF package to verify the 1D simulation results and finalize the DBR structure. The simulation results show that the design parameters of the DBR structures, such as the corrugation depth of the chirped periods and the distribution profile of the period length, play a critical role in determining how well the group velocity dispersion is compensated. Substantial modulations in calculated group delay curves emerge if the DBR structures are not properly designed. These group delay modulations are related to Gires-Tournois interferometer effect, which is caused by the abrupt interface between the waveguide sections with and without the chirped DBR. By including a buffer section between the two waveguide sections to achieve a smooth transition in effective refractive index, the group delay modulations can be significantly minimized, yielding flat dispersion compensation over a wide frequency range 2 THz to 4 THz in THz QCLs.

10030-66, Session Post

A fast detection method for small weak infrared target in complex background

Bo Lei, Wuhan National Lab for Optoelectronics (China) and Huazhong Institute of Electro-Optics (China); Pu Hong, Huazhong Institute of Electro-Optics (China) and Wuhan National Lab. for Optoelectronics (China); Song Yue, Hubei Jiuzhiyang Infrared System Co., Ltd. (China)

Observe from long distance, most targets appear to be weak and small, such as missile, aircraft and vehicle. However, for missile guidance, locking the target in longer distance means more time would be used to control the flight of the missile, thus more chance to hit the target; for menace warning, detect the target in longer distance means more time to maneuver, thus more chance to survive. This paper introduced a fast and effective method to detect small weak infrared target in complex background, which is suitable for missile guidance and menace warning.

First, a template is created to detect the local maxima in the image, which is regarded as seeds for the following region growth. The current point whose gray value is much greater than the average gray value of the neighbors in the template is marked as local maxima.

Secondly, a constrained double criteria region growth algorithm is performed to form separate regions. The region growth begins from every seed, i.e. local maxima, and those points whose gray values are similar to and are adjacent to the seeds are determined to be in the same region. Nevertheless, to avoid unnecessary growth calculation in large regions, the growth is constrained by a given point number threshold.

Thirdly, extracted regions are selected by a small round target filter, which filter out large regions and long regions that are not likely to be targets. Those regions whose minimum enclosing rectangles' lengths are much longer than their widths are marked as non-targets, and those regions which are constrained in region growth are marked as non-targets because of their large areas.

Finally, a double check is performed to erase those regions where there are other high gray value points in their neighbors.

Experimental results show the method introduced in this paper is fast and effective, which is suitable for the imbedded platform.

10030-67, Session Post

A new hyperspectral image classification approach based improved similarity measurement

Hui Yu, Pu Hong, Huazhong Institute of Electro-Optics (China) and Wuhan National Lab. for Optoelectronics (China); Song Yue, Hubei Jiuzhiyang Infrared System Co., Ltd. (China); Chensheng Wang, Huazhong Institute of Electro-Optics (China)

Hyper-spectral images can not only provide spatial information but also a wealth of spectral information. A short list of applications includes environmental mapping, global change research, geological research, wetlands mapping, assessment of trafficability, plant and mineral identification and abundance estimation, crop analysis, and bathymetry. A crucial aspect of hyperspectral image analysis is the identification of materials present in an object or scene being imaged.

Classification of a hyperspectral image sequence amounts to identifying which pixels contain various spectrally distinct materials that have been specified by the user. Several techniques for classification of multi-hyperspectral pixels have been used from minimum distance and maximum likelihood classifiers to correlation matched filter-based approaches such as spectral signature matching and the spectral angle mapper.

In this paper, an improved hyperspectral images classification algorithm is proposed. In the proposed method, an improved similarity measurement method is applied, in which both the spectrum similarity and space similarity are considered. We use two different weighted matrix to estimate the spectrum similarity and space similarity between two pixels, respectively. And then whether these two pixels represent the same material can be determined. In order to reduce the computational cost the wavelet transform is also applied prior to extract the spectral and space features.

The proposed method is tested using hyperspectral imagery collected by the National Aeronautics and Space Administration Jet Propulsion Laboratory. Experimental results the efficiency of this new method on hyperspectral images associated with space object material identification.

10030-68, Session Post

Hyperspectral image compressing using adaptive band selection method

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Hyperspectral imaging sensors can acquire images in hundreds of continuous narrow spectral bands. Therefore each object presented in the image can be identified from their spectral response. However, such kind of imaging brings a huge amount of data, which requires transmission, processing, and storage resources for both airborne and space borne imaging. Due to the high volume of hyperspectral image data, the exploration of compression strategies has received a lot of attention in recent years. Compression of hyperspectral data cubes is an effective solution for these problems. Lossless compression of the hyperspectral data usually results in low compression ratio, which may not meet the available resources; on the other hand, lossy compression may give the desired ratio, but with a significant degradation effect on object identification performance of the hyperspectral data. Moreover, most hyperspectral data compression techniques exploits the similarities in spectral dimensions; which requires bands reordering or regrouping, to make use of the spectral redundancy.

In this paper, we explored the spectral cross correlation between different bands, and proposed an adaptive band selection method to obtain the spectral bands which contain most of the information of the acquired hyperspectral data cube. The proposed method mainly consist three steps: the first step is to segment the spectral space into a series of sub-space; the second steps is to estimate the intrinsic dimension of sub-space data cube; the last step is to select the bands from the sub-space by applying the wavelet-based method. The performance of the proposed method was tested by using k-means classification method.

10030-69, Session Post

Spectral radiance characteristic measure method based on passive imaging FTIR spectrometer

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The spectral characteristics of infrared radiation from target provide significant characteristics information for target's detection and track including radiance brightness, radiance intensity and spectrum characteristics of target. And the same time, the spectral characteristics provide the basis of target detection and recognize equipment's waveband optimization design and detection capability analysis. This paper using the passive imaging Fourier transformation infrared spectrometer measure the infrared spectral characteristic of target. The spectral range cover the medium wave and long wave infrared. And the instrument can interference imaging in 320?256 spatial resolution or other window size. This paper designs a set of calibration and test processes to realize the infrared spectral radiance measurement of target. The specific operating steps are as follows: First of all, through the multiple points radiance calibration, the radiance response characteristic of instrument is obtained. Secondly, the calibration result is applied in the spectral test result of target scene to get the absolute infrared spectral radiance curve. Then reducing the dimension of target spectrum though principle component analysis can remove the interference of background and noise to abstract the characteristic component of target to get the spectral radiance characteristic. Using this method, this paper test some typical infrared target. After the radiance calibration, the calibrated result is verified by standard radiance source. Thereby, the remote measurement of infrared background outdoors is taken as the comparison test. Finally, the typical infrared target spectral features are extracted and measured. The test results show that the method mentioned in this paper is practical.

10030-71, Session Post

A fast pyramid matching algorithm for infrared object detection based on region covariance descriptor

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In order to achieve the purpose of infrared target detection , there are two phases?Feature Selection and Feature Matching. Good Features should be discriminative, robust and easy to compute. The matching strategy affects the accuracy and efficiency of matching. In the first stage, Instead of the joint distribution of the image statistics, we use region covariance descriptor and calculated region covariance using integral images and the computational cost is independent of the size of the region. The covariance of 7-features, e.g., the one one-dimensional intensity image, the norm of first and second derivatives of intensity with respect to x and y., characterizes a region of interest. The idea presented here is more general than the image sums or histograms, which were already published before. In the second feature matching stage, we describe a new and fast pyramid matching algorithm under the distance metric, which performed extremely rapidly than a brute force search. We represent an object with five covariance matrices of the image features computed inside the object region. Instead of brute force matching, we constructed the image pyramid and decomposed the source image and object image into several levels, which included different Image resolutions. After the completion of rough match, fine-match is essential. The performance of region covariance descriptor is superior to other methods, and the pyramid matching algorithm performs extremely rapidly and accurately, as it is shown, and the large rotations and illumination changes are also absorbed by the covariance matrix.

10030-72, Session Post

Non-uniformity correction method of IRFPA based on lookup table

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The non-uniformity correction method of the infrared focal plane array based on the blackbody calibration is widely used in engineering applications. In this kind of method, the correction parameters obtained from the variation of the radiation energy will be unavailable, when the integration time changes, and vice versa. To solve this problem, this paper presents a method for non-uniformity correction of IRFPA based on lookup table. In this method, the three-dimensional pixel response data with the variation of the radiation energy and the integration time is stored in a lookup table. Taking into account that the pixel response output contains the instrument background radiation, and the instrument background is greatly affected by the environment, so the response data needs to subtract the instrument background, which is also required in the course of correction. During correction, the radiation energy interval is queried depending on the real response value of pixel, according to the current integration time. The radiation energy value is then estimated by nonlinear interpolation algorithm. The normalized function is used to obtain the corrected gray value corresponding to the estimated radiation energy. In the case of that the current integration time is not stored, the relation curve between the response output and the radiation energy in this integration time should be estimated by using the nonlinear interpolation firstly. When the pixel response rate is stable, the correction effect of the method this paper presents is better than the traditional multi-point non-uniformity method. In addition, it's very suitable for the application that pixel with large response rate nonlinearity and integration time changing frequently.

10030-73, Session Post

A novel visible and infrared image fusion algorithm based on detail enhancement

Bo Wang, Huazhong Institute of Electro-Optics (China)

In order to improve the characteristic information of the fused images, we propose a novel infrared and visible image fusion algorithm based on image detail enhancement in this paper, the bilateral filter and dynamic range partitioning (BF & DRP) are used to improve the original infrared image, and the multi-scale retinex transform (MRT) also is used to deal with image fusion.

Firstly a method of bilateral filter and dynamic range partitioning (BF & DRP) was used to improve the details of the low SNR and low contrast original infrared image, by which the edges of targets were strengthened, the noises were suppressed, and the constrast of infrared image was enhanced. Secondly, and finally, the multi-scale retinex transform was used to improve the fusion of visible and infrared image, by combining the multi-scale transform and regional fusionwhere the adaptive low frequency and high frequency coefficient were considered, which effectively suppressed the noises and enhanced the details..

Experimental results proved the effectiveness of the proposed image fusion method. The salient color and texture feature of visible image was well preserved, the important details of infrared and visible image were highlighted. The results show that this algorithm is better than traditional image fusion method, such as wavelet transform, non-sampled contourlet transform, in mean square error, standard deviation, entropy, cross entropy and cross-correlation etc.. the algorithm of this paper is able to preserve the details of image, increase the amount of importance characteristic information, is advantageous to the visual performance and distinguishability of fused image for human observation.

10030-74, Session Post

Terahertz characteristics of graphene deposits on different substrates

Chen Gong, Jian Zuo, Cunlin Zhang, Capital Normal Univ. (China)

Graphene is a promising candidate material for ultra-broadband photodetectors, as it interacts with light strongly from microwave to ultraviolet. We have characterized terahertz (THz), IR and UV-visible response from monolayer graphene samples deposited on Cyclo Olefin Polymers (COP) and Polymethylmethacrylate (PMMA) substrates. The transmittance, sheet conductivity, and attenuation of graphene samples were obtained from transmission terahertz time-domain spectroscopy (THz-TDS). The carrier density of graphene is calculated to analyze the mechanism underlying this photoconductive response. The mechanisms that contribute to the optical response of graphene were quite diverse among the different substrate media used. The results are promising for the development of modulators and switchable photoelectric devices.

10030-75, Session Post

Reducing the uncertainty in terahertz time-domain reflection spectroscopy

Xie Yijun, Ping Sun, Beijing Normal Univ. (China); Wenai Wang, Capital Normal Univ. (China)

The terahertz time-domain reflection spectroscopy (THz-TDRS) has recently emerged as a powerful tool in investigation of materials. The parameter extraction process based on THz-TDRS is nearly perfect. The traditional method to extract optical parameters of materials based on THz-TDRS is that using the total reflection mirror as reference. However, the measurements for signals still contain errors, which affect the quality of the extracted optical parameters. Several sources of random and systematic errors exist throughout the measurement process. These sources are, for instance, signal noise, sample misalignment, thickness measurement variation, phase error, etc. Thus, reducing uncertainty is critical in the optimization of measurement accuracy. In this paper, we used the self-referenced method proposed in our previous study to extract the optical parameters. As a result, the intrinsic phase error existing in the traditional method was eliminated. In addition, the variance of the time-domain signal is lower. We also reduced the error originated from sample thickness by using genetic algorithm through design the thickness as an optimized parameter. We draw a conclusion that the self-referenced method can obtain more accurate optical parameters. Through analyzing the combined uncertainties we can understand the systemic and random influences on optical parameters.

10030-76, Session Post

Standoff gas identification and application with FTIR imaging spectrometer

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Fourier transform infrared imaging spectrometer has the advantages of high spectral resolution, good sensitivity and staring mode, and it is considered as an ideal solution for long distance and mobile gas identification. This feature has significant meaning in the fields like industrial plume emission monitoring and public security monitoring. In this paper, a LWIR FTIR imaging spectrometer is applied to realize the field gas identification experiment. First, the structure and design of this spectrometer is indicated and discussed. Based on the specific interferometer design and high performance infrared imaging module, this instrument can provide stable performance in field application. Then, the basic principle of FTIR imaging data process is described, which includes the reconstruction method of data-cube and the spectral identification and unmixing in gas detection. Based on the algorithms research and operation mode analysis, the related gas identification software is developed to achieve a high-efficiency detection work. To verify this design, both lab and field experiments are realized. At lab, SF6 and NH3 gas are applied to verify the spectral identification algorithm and test the spectral resolution of the spectrometer, and the results show that this spectrometer can meet the requirements of field gas identification application. After that, the field trial is completed with the permission from the local environmental protection agency. The instrument is delivered via van to the industrial area located in Wuhan City, and applied to analyze the components in the plume emission gas. The field test results show that this FTIR imaging spectrometer can be easily operated to identify the gas elements in real time, and give the reasonable analysis results.

10030-77, Session Post

Spectrum modulation of terahertz radiation from air plasma via femtosecond laser pulses control

Ying Zhang, Wenfeng Sun, Yan Zhang, Capital Normal Univ. (China)

Terahertz (THz) generation from air plasma can greatly reduce the energy-loss of THz waves in air than the ones from optical rectification crystal and photoconductive antenna, owing to the lower absorption of water suffering in the propagation of femtosecond laser. This superior makes it potentially useful for the detection of remote targets. More efforts have been put on increasing the amplitude of THz waves generated from air plasma, yet few focuses have been on the spectrum of these THz waves. Therefore, the detection efficiency will be greatly improved if the desirable THz spectrum can be obtained from air plasma. In this paper, we propose a method to modulate the spectrum of THz waves by controlling the wavefront of the femtosecond laser pulses. The wavefront control has been performed by loading phase maps on a Liquid Crystal Spatial Light Modulator. The two serially-formed femtosecond filaments with different length and diameter radiate THz waves under the mechanism of Cherenkov radiation respectively. The spectrums of THz waves have been modulated by varying the spatial separation and electron density of the two filaments. With this method, the central frequency and the spectral bandwidth of the

generated THz waves can be modulated as well. The modulated spectrums that measured in the experiment are simulated theoretically and discussed. The result indicates that this method of dynamic modulation for THz spectrum will widely extend the application of THz remote sensing.

10030-78, Session Post

Vibrational spectral investigation of anhydrous glucose in the terahertz range

Wenai Wang, Capital Normal Univ. (China); Ping Sun, Beijing Normal Univ. (China); Wei Liu, Capital Normal Univ. (China); Yijun Xie, Beijing Normal Univ. (China)

As a powerful tool for the research of molecular structure, infrared absorption spectrum has been extensively studied in the field of biomedical photonics. The infrared absorption spectrum of anhydrous glucose has been measured by Fourier transform infrared spectrometer (FTIR). The experimental results provide an important reference for diabetes research and diagnosis. The origins of the absorption features are generally attributed to intermolecular vibrations and intramolecular torsions. To investigate the physical specific structure and the molecular interaction in far-infrared band, the sample structure properties were analyzed meticulously by solid-state density functional theory (DFT) calculations. CASTEP quantum chemical calculation software package was utilized to simulate the infrared spectroscopy. of glucose crystal structure based on periodic boundary condition and plane wave pseudopotential method. In order to obtain glucose infrared absorption spectrum, linear response approach and norm conserving pseudopotentials are essential. Besides, the performance of the generalized gradient approximation (GGA) functional has been commendably examined. The results show that the standard Perdew-Burke-Ernzerhof (PBE) approach along with its line Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) algorithm tends to be superior. The agreement between theory and experiment indicates that the crystal simulation calculation based on solid-state density functional theory can identify substance absorption peaks and vibration attribution accurately in THz region.

10030-79, Session Post

The design of circuit for THz time domain spectroscopy system based on asynchronous optical sampling

Hailin Cui, Mile Zhang, Yihan Li, Jingsuo He, Capital Normal Univ. (China)

Terahertz time domain spectroscopy (THz-TDS), as a new method of spectrum analysis, will play a more and more important role in basic scientific research in the future. However, the traditional THz-TDS system takes a few to more than ten minutes to obtain a THz pulse. Because of the way to scan a terahertz pulse is by the mechanical step of mechanical delay platform, which can sample only one point of a terahertz pulse every step. Therefore, there is a limitation of the THz-TDS system based on the mechanical step delay device is that the system cannot be detected quickly. The optical asynchronous sampling technique is the way to realize the fast detection of terahertz pulse. Not only studying the physical process, the technology can also achieve high time resolution and high frequency resolution.

To solve the problem above, a circuit for THz-TDS Based on Asynchronous Optical Sampling, which is the most important of the THz-TDS system, is designed in this thesis. This thesis focuses on the researching, designing and experiment of this circuit. Firstly, the circuit is designed overall. Then the selection of the key device and the designing of the circuit principle is done by myself. Secondly, the test of the circuit to phase locked the master and slave fiber femtosecond lasers has been done. As a result, the two lasers can phase locked on two repetition frequencies with a small frequency difference calculated by the circuit.

10030-80, Session Post

Research on trace gas measurement by ICOS with WMS

Zhenglong Ni, Jie Shao, Haibo Zhou, Kunyang Wang, Zhejiang Normal Univ. (China)

Integrated cavity output spectroscopy (ICOS) is a very sensitive method of trace gas measurement. It is widely known as its extremely long optical path and characteristics of direct absorption. Wavelength Modulation Spectroscopy (WMS) is another sensitive measurement method. It adds modulation on the direct absorption so that achieves the noise suppression. We combine the ICOS technique and WMS technique to research the trace gas measurement using a narrow band tunable diode laser. First?we set up a normal ICOS system. It can measure some low line strength position. Then we modulate the laser with high frequency sinusoidal signal and demodulation the output signal from ICOS system into 2f signal by a lock-in amplifier. By this method we get several absorption peaks of carbon dioxide in atmosphere. To combine ICOS and WMS the sensitivity of trace gas measurement has a significantly increase.

10030-81, Session Post

Investigation on optical properties of BSA protein on single-layer graphene using terahertz spectroscopy technology

Yiwen Sun, Shengxin Yang, Shenzhen Univ. (China)

Graphene has been wildly interested in developing novel devices for electronics, photonics and optoelectronics recent years. Single-layer graphene is a gapless two-dimensional material with unusual properties such as high electric and thermal conductivity etc.. Also terahertz (THz) spectroscopy is sensitive to probe several aspects of biological systems. In the terahertz frequency region, electrically controllable Drude-like intraband absorption makes graphene a promising platform for building active, graphene-based optoelectronic devices such as THz biosensor. Recently we demonstrate a highly sensitive terahertz time-domain spectroscopy method to monitor optical properties of silicon-based single-layer graphene and BSA protein on graphene in the frequency range of 0.1-3 THz. BSA protein thin films with different thicknesses were spin coated on single-layer graphene by controlling the spin coating speed. 808 and 1064 nm IR lasers with different output power were used as the pump light to stimulate the sandwich-like sample (protein-graphene-silicon substrate) respectively. The dispersion of substrates complex refractive indices were extracted by comparing the signal spectrum with the reference spectrum using the transmission method. The graphene monolayer complex conductivity was also calculated. The terahertz optical properties of protein on graphene was strongly affected by the power of the pump light. As expected, the conductivity increased with the power increasing. Additionally, the absorption peaks obviously appeared at 1.7 THz for BSA protein on graphene monolayer by stimulating 808 and 1064 nm pump light but with the opposite phase, while there was none absorption appearance for sandwich-like sample.

10030-82, Session Post

Terahertz wavelength encoding compressive imaging

Qiong Zhang, Xinke Wang, Yan Zhang, Capital Normal Univ. (China)

Terahertz (THz) compressive imaging can obtain two dimensional image with a single or line detector, which can overcome the bottleneck problem of lacking of THz two dimensional detector. In this presentation, a method is proposed to obtain two dimensional image using a line detector.

A plano-convex cylindrical lens is employed to preform Fourier transform and to encode the one dimensional information of object into wavelengths. After recording both amplitude and phase information at each pixel of the line detector, the two dimensional image of the object can be reconstructed. Numerical simulation demonstrates the validity of the proposed method.

10030-83, Session Post

Terahertz microfluidic chips for detection of amino acids in aqueous solutions

Bo Su, Cong Zhang, Ning Fan, Cunlin Zhang, Capital Normal Univ. (China)

At present, the detection methods widely used in biochemistry are mostly labeled. Although they are precise, labeled matters may pollute the samples. In order to overcome the shortcoming, many researchers study the optical properties of biochemistry samples in the range of terahertz (THz). Consequently, the characteristic vibration modes of many biological macromolecules, such as DNA or protein, are just located in the range of THz, so THz has the potential to detect biochemistry samples.

Water plays very important roles in the functions of biological molecules and the structure of proteins. Hydration, namely the interaction between water and other molecules, involves many biological phenomena. As a result, studying the characteristics of aqueous solutions is closer to the demand.

Microfluidic technology is able to control the fluidic thickness accurately in less than 100 micrometers. So the combination of terahertz and microfluidic technology becomes one of the most interesting directions towards biological detection. We designed microfluidic chips for terahertz spectroscopy of biological samples in aqueous solutions. The microfluidic chips were fabricated using the material of Zeonor 480, which is both mechanically robust and optically transparent. Using the terahertz time-domain spectroscopy (THz-TDS) system, we experimentally measured the transmittance of the chips and the THz absorption spectra of threonine and arginine with different concentrations, respectively. The experimental results demonstrated the feasibility of performing high sensitivity THz spectroscopy of amino acids in aqueous solutions. Therefore, the microfluidic chips are able to realize real-time and label-free measurement for biochemistry samples in THz-TDS system.

10030-84, Session Post

Simulation study of microstrip line on THz on-chip system

Cong Zhang, Bo Su, Ning Fan, Cunlin Zhang, Capital Normal Univ. (China)

At present, terahertz time-domain spectroscopy (THz-TDS) system has important applications in many fields such as semiconductors, pharmaceuticals, biological molecule and so on. Though the present THz-TDS systems using THz waves propagating in free space work quite well, it also has many limitations like large sample, low spectral resolution, large system size and strong water absorption. So this system is desired to integrate it in a solid state chip to make the system more compact and functional. In this paper, we put forward a terahertz on-chip system which integrates terahertz generating device, detection device and waveguide transmission device. Waveguides suitable for such high frequency electromagnetic waves in solid state chips are coplanar waveguide (CPW) and micro-strip-line (MSL) familiar in microwave devices. The CPW is a structure in which all the conducting media are coplanar. The dielectric beneath the conductors need be sufficiently thick to prevent field leakage. The MSL consist of a strip conductor and a ground plane separated by a dielectric medium. The material of dielectric substrates is benzocyclobutene (BCB) in our experiment. In the on-chip system, the evanescent terahertz-bandwidth electric field extending above the MSL interacts with overlaid dielectric samples, thus the characteristics of the samples can be probed. The HFSS software was used to simulate and analyze the transmission characteristics of the CPW and MSL based on the on-chip system researched by University of Leeds (America) and Hiroshima University (Japan). The simulation results show that the scattering parameters of the two waveguides are similar to the known literatures. Therefore, our simulation work can accelerate the fabrication progress of the on-chip THz system.

10030-85, Session Post

The optical constants of two liquid crystals in terahertz band

Huijuan Sun, Beijing Union Univ. (China); Qingli Zhou, Capital Normal Univ. (China)

As the breakthrough of terahertz emitter and detection technology, the unique and superior feature of terahertz waves has been discovered and shows wide and promising applications in communication, materials science, biological and medical imaging, nondestructive testing, etc. It is impossible to the extensive application of terahertz technology without practical function devices which can meet the special requirements in different application fields. Liquid crystals (LCs) have been the subject of active research for more than a century. The most prominent LC based device is the flat panel display, which enjoys an ongoing commercial success and has revolutionized the electronics industry. Apart from this mainstream application, the unique properties of LCs also led to the development of many other optical components such as light valves, tunable filters and tunable lenses. The optical properties of LCs have been investigated in detail covering the range from UV to microwave frequencies. For the application of LCs in the THz frequency range, knowledge of the dielectric anisotropy and electro-optic properties of LCs in this frequency range is most important. However, knowledge of the dielectric of LCs in the THz range is still incomplete. THz time-domain spectroscopy (THz-TDS) has recently emerged as a powerful spectroscopic technique to measure optical properties of materials in the THz frequency range. THz spectroscopy contains rich physical, chemical, and structural information of the materials, and one unique attribute of THz is their ability to sensitively measure

the induced molecular dipole moments of many liquid crystals. In this paper, we prepared the testing cell by sandwiching commercially available TEB300, 9023 LCs between two fused-silica windows. The thickness of the two fused-silica windows is 0.701mm and 0.702mm. The measurements were made at room temperature(25?). For each kind of liquid crystals, we scanned three times for getting average value to decrease the error. The transmission spectra of the liquid crystals such as TEB300, 9023 LCs were measured by THz time-domain spectroscopy technique and free-space electro-optic sampling method. The absorption coefficient and refractive index of liquid crystals in the THz range are calculated. Furthermore, the optical constants are compared and analyzed, expecting to fill the spectrum gap of liquid crystals in the THz range and provide the experimental and theoretical foundation for the application of liquid crystals.

10030-86, Session Post

Nitrocellulose membrane sample holder for terahertz time domain spectroscopy

Xiaojing Zhao, Cuicui Wang, Jian Zuo, Cunlin Zhang, Capital Normal Univ. (China)

Terahertz (THz) technology has promising applications for the detection and identification of materials because it has a great advantage in measuring material fingerprint spectrum. Terahertz time-domain spectroscopy (THz-TDS) is a key technique that is applied to spectroscopic measurement of materials. However, it is difficult to press a pellet with small mass of sample and a bulking medium such as polyethylene (PE) powder usually need to be added. Characteristic absorption peaks of the solution in liquid cell is hard to be observed due to the interaction between materials and water molecules. Therefore, one method using the hydrophilic nitrocellulose (NC) membrane as a sample holder was applied to detect samples in an aqueous medium by THz-TDS. In this study, the ?-lactose samples were mixed with 20 ?l of deionized water and then applied directly onto the double-layered NC membrane sample holder. This mixture is located on the gap of two piece of NC membranes. Firstly the NC membranes with different pore sizes were tested in the experiment. And then the ?-lactose solutions with different concentrations were measured on the NC with different pore sizes. Consequently, the small mass of samples can be detected and the characteristic absorption peaks become stronger with the increase of NC pore size. Moreover, compared to the traditional pellet-making and liquid cell detection, this membrane method is more convenient and easy to operate.

10030-87, Session Post

Design and research for biosensing THz microfluidic chips

Ning Fan, Bo Su, Cong Zhang, Cunlin Zhang, Capital Normal Univ. (China)

Many Biomolecules vibration frequencies are in THz (0.1THz-10THz) frequency range, so terahertz technology is an essential tool for detecting biological molecules. However, due to terahertz strongly absorbed by water, it is difficult to detect these molecules for biological and chemical liquid samples. Therefore, we present a novel detection method by combining terahertz technology with microfluidic technology. The strong absorption of water is effectively overcome by controlling the length that terahertz passes through liquid samples. What's more, a higher signal to noise ratio is obtained through using less samples. In this paper, we designed a THz microfluidic chip that is easy to be fabricated by using the materials of zeonex and polydimethylsiloxane (PDMS). Using terahertz time-domain-spectroscopy (THz-TDS) system, we find that the chip has a high transmittance above 85% in the range from 0.1 THz to 2.4 THz. Then the THz spectra of deionized water and different kinds of electrolyte solutions with different concentrations in the microfluidic chip were measured, respectively. In our research, it is found that different kinds of electrolyte solutions have different absorption coefficients for THz. In addition, the absorption indexes of some electrolyte solutions markedly increased and others significantly reduced comparing with deionized water. In addition, the THz absorption spectrum changes with the concentration of the same kind of electrolyte.

10030-88, Session Post

Investigation of transient temperature's influence on damage of high-speed sliding electrical contact rail surface

Yuyan Zhang, Shasha Sun, Yanshan Univ. (China)

In the high speed sliding electrical contact with large current, the temperature of contact area rises quickly under the coupling action of the friction heating, the Joule heating and electric arc heating. The rising temperature seriously affects the conductivity of the components and the yield strength of materials, as well affects the contact state and lead to damage, so as to shorten the service life of the contact elements. Therefore, there is vital significance to measure the temperature accurately and investigate the temperature effect on damage of rail surface. Aiming at the problem of components damage in high speed sliding electrical contact, the transient heat effect on the contact surface was explored and its influence and regularity on the sliding components damage was obtained. A kind of real-time temperature measurement method on rail surface of high speed sliding electrical contact is proposed. Under 2.5 kA current load condition?based on the principle of infrared radiation non-contact temperature sensor was used to measure the rail temperature. The dynamic distribution of temperature field was obtained through the simulation analysis, further, the connection between temperature changes and the rail surface damage morphology, the damage volume was analyzed and established. Finally, the method to reduce rail damage and improve the life of components by changing the temperature field was discussed.

10030-89, Session Post

Space-time adaptive: ratio, resolution, and multiple configuration

Hua Liu, Science and Technology on Electro-Optic Control Lab. (China)

The principle approach, modeling, and error analysis are analyzed, and the system configuration based on SLM is advanced in algorithm analysis. For to improve the resolution of the imaging system, and achieve the theoretical limit, we introduced that the core methodology, which is that in the deep understanding and research of the photoelectric information control, the basic theory of the spatial light modulator and the algorithm based on space-time adaptive system is discussed deeply which used to the core of the photoelectric system configuration by which key components applied to solve the control function. This paper discusses the hardware system. Usually, an SLM modulates the intensity of the light beam. However, it is also possible to produce devices that modulate the phase of the beam or both the intensity and the phase simultaneously. Adaptive configuration, for a complicate sensor is accomplished by an implementation of structured programming, based on global optimization algorithm , which explores the available configuration space formed by powers of individual components and inter-component separations. Besides, the

discuss includes the control on the SLM for spatial information of the amplitude, phase, frequency, polarization, and the intensity of energy research. A typical model is used to illustrate the feasibility, and the criteria is developed.The technology principle of super resolution restructure from the point of view on theory and engineering. Three kinds of restructure technologies, that prototype, micro scanning and sub pixel are described, and how to decrease their shortcomings are discussed in detail. Furthermore, to improve the band width by reconstruction without the spectral alias in super resolution technologies, a new coding technology combining a optical encoding and the sub pixel is proposed. With the global method, simulation results show that the system can meet the application requirements in MTF, REA, RMS and other related criteria.Results show that they are effective solutions.

10030-90, Session Post

Detection of NaCl solutions using terahertz time-domain spectroscopy

Cuicui Wang, Xiaojing Zhao, Jian Zuo, Cunlin Zhang, Capital Normal Univ. (China)

Terahertz spectrum is corresponding with vibration and rotation of liquid molecules. It is suitable to identify and research the liquid molecular dynamics. As a powerful spectral detection technology, terahertz time-domain spectroscopy (THz-TDS) is widely used in solution detection. The absorption coefficient, refractive index and dielectric function of solutions can be extracted based on terahertz time-domain spectroscopy. NaCl exists in most biological tissues, and it is very important for life. In this paper, we detected NaCl solutions with different concentrations at room temperature by THz-TDS technique in the range of 0.2-1.5 THz. The liquid cell with a thickness of 0.2mm is made of quartz. A linear increase of the real and imaginary part of the dielectric function was observed when compared with pure water with increasing concentrations of NaCl solutions. We fitted the terahertz dielectric function of the NaCl solutions by Debye model, Where the dielectric relaxation time can be obtained. By means of dielectric relaxation process, it was found that the characteristic time of molecular movement and the information related to the liquid molecular structure and movement was obtained.

10030-91, Session Post

Detection of text information hidden in an envelope using terahertz imaging

Zhenwei Zhang, Cunlin Zhang, Capital Normal Univ. (China)

Multiply pages text information hidden in an envelope can be observed clearly and by utilizing the frequency modulation continuous wave terahertz imaging technology. The delay time between the probe and reference signal was calculated and then the positions of the object in depth were estimated. The phase information and two-dimensional scanning were combined together to obtain the three-dimensional tomographic imaging data. Layer resolution is better than 1mm. The spatial resolution is 1 mm. Layered images can clearly show the text at the different page. By further improving the accuracy of the hardware and increasing data denoising algorithm in order to improve the layer resolution and spatial resolution, we can achieve a more clear and intuitive image. Meanwhile, the method can be further applied to non-destructive testing of other sealed objects and skin burns.

10030-92, Session Post

Design and simulation of a tunable metamaterial absorber

Yanan Fu, Guozhong Zhao, Capital Normal Univ. (China); yonghua li, capital normal university (China)

A photo-excited tunable and broadband metamaterial absorber in the terahertz region is proposed. The metamaterial absorber is composed of three layers like the sandwich, the top layer is acirclr metal-semiconductor circle split ring and the bottom layer is a metallic ground plane, these two layers are separated by a dielectric spacer, which we choose as the polyimide. The conductivity of the silicon can be tuned actively with the incident pump power. We use the full wave simulation and the equivalent circuit model to analysis this absorber, and interpreted the phenomena showed when the conductivity of the silicon filled in the gap of ring is changed by the surface current and the electric field. The proposed equivalent circuit model can save more time to design this kind of absorber in need. The proposed photo-excited tunable metamaterial absorber can also be used as terahertz modulators and switches.

10030-93, Session Post

Electrically controlled terahertz wave switch based on prism/liquid crystal

Meng Yao He, Jian-rong Hu, Jiu-sheng Li, China Jiliang Univ. (China)

It is well known that there has a lateral displacement between the centre of a practical reflected beam and the prediction of geometrical optics on the reflection interface. This phenomenon is called as Goos-Hanchen (GH) shift. The GH shifts were studied both theoretically and experimentally in the fields of microwave, infrared wave, and visible light region. Meanwhile, some unique effects have already been revealed in terahertz region. Based on this, in this work, a novel terahertz wave switch scheme can be developed utilizing prism/liquid crystal structure. A terahertz wave detector is fixed at the prism external position of the reflected terahertz wave beam (i.e. the detector locates at the prediction position of geometrical optics). It can control the position of the reflected terahertz wave beam (e.g. When the fixed detector receives the terahertz wave signal, named “ON”, i.e. compared to 1; or else, named “OFF”, i.e. compared to 0). The terahertz wave ON–OFF mechanism of the novel switch is based on a dynamic shift of the lateral GH shift of the reflected terahertz wave beam. This proposal provides a convenient tool for controlling the lateral shift of the reflected terahertz wave beam by adjusting the external applied electric field without change the configuration. The stationary phase theory (SPT) method and the finite element method (FEM) are used to verify and analyze the characteristics of the proposed switch. Numerical simulation results show that the presented switch has a high extinction ratio, simplicity, small size, and a low cost. Because of its excellent characteristics, the novel terahertz wave switch can be used in future terahertz communication integrated circuits. Moreover, it may also be easily extended to other terahertz wave frequencies switching through changing the structure parameters.

10030-94, Session Post

Tunable terahertz power divider based on graphene plasmonic waveguide

Yang Li, Jian-rong Hu, Jiu-sheng Li, China Jiliang Univ. (China)

In this letter, a tunable terahertz power divider based on graphene ribbon embedded in the PMMA substrate is analyzed. The numerical simulations are carried out in the configuration using the finite element method (FEM). In order to obtain a better extinction ratio, the optimized structure with five graphene ribbons is proposed. The power divider effects can be dynamically controlled by varying the Fermi energy of the graphene waveguides and the coupling length between the graphene plasmonic waveguides. The tunable terahertz power divider phenomenon has been observed in our five graphene ribbons system. The total size of the presented terahertz wave beam splitter is of 5?m?4?m. With the help of the graphene plasmonic waveguide, the dimensions of the power splitter are reduced dramatically when comparing with the traditional waveguide power splitter. It is believed to be applicable for future plasmonic circuit in terahertz ranges. This work may pave the ways for the further development of ultracompact high-performance terahertz wave devices.

10030-95, Session Post

Pepper seed variety identification based on visible/near-infrared spectral technology

Cuiling Li, Xiu Wang, Zhijun Meng, Pengfei Fan, Jichen Cai, Beijing Academy of Agriculture and Forestry Sciences (China)

Pepper is a kind of important fruit vegetable, with the expansion of pepper hybrid planting area, detection of pepper seed purity is especially important. This research used visible/near infrared (VIS/NIR) spectral technology to detect the variety of single pepper seed, and chose hybrid pepper seeds “Zhuo Jiao NO.3”, “Zhuo Jiao NO.4” and “Zhuo Jiao NO.5” as research sample. VIS/NIR spectral data of 80 “Zhuo Jiao NO.3”, 80 “Zhuo Jiao NO.4” and 80 “Zhuo Jiao NO.5” pepper seeds were collected, and the original spectral data was pretreated with standard normal variable (SNV) transform, first derivative (FD), and Savitzky-Golay (SG) convolution smoothing methods. Principal component analysis (PCA) method was adopted to reduce the dimension of the spectral data and extract principal components, according to the distribution of the first principal component (PC1) along with the second principal component(PC2) in the two-dimensional plane, similarly, the distribution of PC1 coupled with the third principal component(PC3), and the distribution of PC2 combined with PC3, distribution areas of three varieties of pepper seeds were divided in each two-dimensional plane, and the discriminant accuracy of PCA was tested through observing the distribution area of samples’ principal components in validation set. This study combined PCA and linear discriminant analysis (LDA) to identify single pepper seed varieties, results showed that with the FD preprocessing method, the discriminant accuracy of pepper seed varieties was 98% for validation set, it concludes that using VIS/NIR spectral technology is feasible for identification of single pepper seed varieties.

10030-96, Session Post

Research of biological liquid albumin based on the terahertz time-domain spectroscopy

Shuai Yang, Capital Normal Univ. (China)

For no corresponding fingerprint characteristic spectrum detecting complex ensemble biological samples in liquid, in the paper, such urine of kidney disease patients as samples, using terahertz time-domain spectroscopy emphatically explores response characteristics of the urine albumin in the terahertz region. Combined with stoichiometric method, we find a certain kind of relationship between terahertz spectrum data and the content of urine albumin, which offsets the defects of other spectroscopy in measuring liquid protein, and in accordance with hospital clinical data. This study established a semi-qualitative method about using terahertz spectroscopy in detecting non-purification of biological liquid sample, which provides a simple, nondestructive, cheap and fast reference method in identifying the early nephropathy for medical test.

10030-97, Session Post

Processing and fusion for human body terahertz dual-band passive image

Li Tian, Beijing Institute of Technology (China); Yanchun Shen, Capital Normal Univ. (China); Weiqi Jin, Beijing Institute of Technology (China); Guozhong Zhao, Capital Normal Univ. (China); Yi Cai, Beijing Institute of Technology (China)

Compared with microwave, THz has higher resolution, and compared with infrared, THz has better penetrability. Human body radiate THz also, its photon energy is low, it is harmless to human body. So THz has great potential applications in the body searching system. Dual-band images may contain different information for the same scene, so THz dual-band imaging have been a significant research subject of THz technology. Base on the dual-band THz passive imaging system which is composed of a 94GHz and a 250GHz linear-array detector, this paper researched the de-noising algorithm and the fusion algorithm for THz dual-band images. Firstly, the intensity of THz waves radiated by human is small, and superadded the limitation of detector and optical mechanical scanning imaging mode, THz images have such problems: large noise, low SNR, low contrast, low details. Secondly, the stability problem of the optical mechanical scanning system makes the images less repetitive, obvious stripes and low definition. Aiming at these situations, this paper used the BM3D de-noising algorithm to filter noise and correct the scanning problem. Furthermore, translation, rotation and scaling exist between the two images, after registered by the intensity-base registration algorithm, and enhanced by the adaptive histogram equalization algorithm, the images are fused by image fusion algorithm based on wavelet. This effectively reduced the image noise, scan distortion and matching error, improved the details, enhanced the contrast. It is helpful to improve the detection efficiency of hidden objects too. Method in this paper has a substantial effect for improving the dual-band THz passive imaging system’s performance and promoting technology practical.

10030-98, Session Post

Detailed signal model of coherent wind measurement lidar

Yuechao Ma, Sining Li, Wei Lu, Harbin Institute of Technology (China)

Lidar is short for light detection and ranging, which is a tool to help measure some useful information of atmosphere. In the recent years, more and more attention was paid to the research of wind measurement by lidar. Because the accurate wind information can be used not only in weather report, but also the safety guarantee of the airplanes. In this paper, a more detailed signal model of wind measurement lidar is proposed. It includes the laser transmitting part which is described the broadening of the spectral, the laser attenuation in the atmosphere, the backscattering signal and the detected signal. A Voigt profile is used to describe the broadening of the transmitting laser spectral, which is the most common situation that is the convolution of different broadening line shapes. The laser attenuation includes scattering and absorption. We use a Rayleigh scattering model and partially-Correlated quadratic-Speed-Dependent Hard-Collision (pCqSDHC) model to describe the molecule scattering and absorption. When calculate the particles scattering and absorption, the Gaussian particles model is used to describe the shape of particles. Because of the Doppler Effect occurred between the laser and atmosphere, the wind speed can be calculated by the backscattering signal. Then, a two parameter Weibull distribution is proposed to describe the wind filed, so that we can use it to do the simulation. After all the description, the signal model of coherent wind measurement lidar is decided. And the simulation is also given by MATLAB. This signal model can describe the system more accurate and more detailed, so that the following work will be easier and more efficient.

10030-99, Session Post

Primary study on scattering property for irregular suspended particles in water with T-matrix theory

Yanan Liu, Chongqing Technology and Business Univ. (China); Peng Feng, Chongqing Univ. (China)

In this paper, based on T-matrix theory we describe how scattering spectrum by small non-spheroid suspended particles can be computed and measured; spheroid, finite circular cylinder and generalized Chebyshev, three non-spheroid particles of light scattering model is constructed. Results for non-spherical suspended particles scattering intensity will be presented. Analyze the relationship among suspended particles of size parameters, the relative refractive index, and the light scattering intensity. In addition, the change of the suspended particles in water of relative scattering intensity using different wavelength, size parameter, and scattering angle has been calculated. Our numerical results show that when the particles size and the wavelength of incident light changes, the scattered light intensity is significantly changed with the different types of suspended particles. These results provide a new approach to conduct effective water quality testing data preprocessing by UV - visible absorption spectroscopy.

10030-100, Session Post

Performance of passive terahertz imaging system

Jia Wang, Guozhong Zhao, Capital Normal Univ. (China)

Terahertz (THz) radiation has the higher penetration to clothing, cardboard boxes, plastic packaging materials and other similar dielectrics. Its lower photon energy compared with X-rays make the detected material and the human being to be not destroyed. THz application in field of security are developed by many countries. In this research, we present a multiband of passive terahertz imaging by the thermal radiation measurement. The Noise Equivalent Temperature Difference?NETD? is obtained. The result shows that NETD of the passive imaging system is 0.8K@17? and 24? at 94 GHz, and 1.5K@17? and 24? at 250GHz. We found that the main source of noise is the noise from detection circuit. Finally, the improvement methods of detecting sensitivity are analyzed and discussed.

10030-101, Session Post

Research on THz stepped-frequency ISAR imaging

Meiyan Liang, Shanxi Univ. (China)

With the bandwidth of 12 GHz, a 0.2THz stepped-frequency radar system is designed in the paper. Then, the principle of THz inverse synthetic aperture radar (ISAR) imaging is introduced. Based on the small rotate angle and the far field approximation, the Range-Doppler algorithm is used in the simulation of ISAR imaging. The simulation results show that THz stepped-frequency radar can achieve high resolution ISAR images of aircraft, the resolution of ISAR images can reach centimeter-scale, which laid a theoretical foundation for radar imaging in THz band.

10030-102, Session Post

FPGA-based hardware optimized implementation of signal processing system for LFM-pulsed radar

Noor Ul Azim, Wang Jun, Beijing Univ. of Aeronautics and Astronautics (China)

Signal processing is one of the main parts of any radar system. Different signal processing algorithms are used to extract information about different parameters like range, speed, direction etc, of a target in the field d of radar communication. This paper presents LFM (Linear Frequency Modulation) pulsed radar signal processing algorithms which are used to improve target detection, range resolution and to estimate the speed of a target. Firstly, these algorithms are simulated in MATLAB to verify their concept and theory. After the conceptual verification in MATLAB, the simulation is converted into implementation on hardware using Xilinx FPGA. Chosen FPGA is Virtex-6 (XC6LVX75T). For hardware implementation pipeline optimization is adopted and also other factors are considered for resources optimization in implementation process. Focusing algorithms in this work for improving target detection, range resolution and speed estimation are hardware optimized fast convolution processing based pulse compression and pulse Doppler processing

10030-23, Session 5

2D and 3D THz imaging: necessity of automated data processing tools *(Invited Paper)*

Patrick Mounaix, Hugo Ballacey, Jean-Paul Guillet, Frederic Darracq, Fréderic Fauquet, Jean Baptiste Perraud, Joyce Bou Sleiman, Univ. Bordeaux 1 (France); Benoit Recur, NOCTYLIO (France)

In the field of non-destructive testing, 3D Terahertz (THz) ability offers a modern solution to inspect opaque objects or thin multilayer. Time of flight considerations or tomographic procedure, reconstruct a 3D volume of the acquired sample by intensive calculations of a huge quantity of data. This resulting depth information is then extracted either from spectro terahertz imaging or from several projections acquired around the object at different viewing angles in the case of tomographic acquisitions. This property has made THz tomography a very powerful technique for non destructive control. In this paper, we present a complete image processing sequence to perform and render non-destructive inspection from 3D terahertz (THz) images. We implement advanced data and image processing, including 3D visualizations of hierarchical or selected information. That software includes, for example, all the steps starting from a 3D tomographic reconstruction of a sample from radiographs acquired with a monochromatic millimeter wave imaging system to an automated segmentation, extracting the different volumes of interest (VOI) composing the sample. That leads to 3D visualization and dimensional measurements. This inspection is completed by a skeletonisation and caliber analysis, providing an accurate assessment of the structure, geometry and the morphology of the acquired object

10030-24, Session 5

Terahertz super-focusing and super-resolution *(Invited Paper)*

Yiming Zhu, Univ. of Shanghai for Science and Technology (China)

We report two methods to achieve the terahertz (THz) super-focusing and super-resolution imaging, respectively. The first method is based on the spiral array plasmonic lens, which is consist of the archimede helix and the circular antenna. This method is characterized by high intensity focusing and polarization sensitivity. Our results demonstrate that it can generate a focal spot with an FWHM of almost ?0.38? under right circular polarized light (CPL) illunimation. We also compare with the plasmonic lens illuminated under linearly polarized light (LPL) and right circularly polarized light (CPL). The results demonstrate that our designed plasmonic lens has a good focusing performance as well as an advantage in focusing intensity. The second method to obtain the THz super-resolution imaging is by using the transformation optics (TO). As well known, TO is a new way to manipulate transmission path of electromagnetic waves. And, we propose another new kind of method to realize super-resolution imaging in the far field by using shifting media based on TO theory. Unlike hyperlenses and metalenses engineered by anisotropic materials, and superlenses based on left-hand media, an alternating layered structure of homogeneous and isotropic materials with positive permittivity and permeability (i.e. positive index of refraction) can be used to design this shifting media due to the effective medium theory. The results demonstrate that this shifting media may open a new perspective for super-resolution imaging.

10030-25, Session 5

New progress of active and passive terahertz imaging *(Invited Paper)*

Guozhong Zhao, Capital Normal Univ. (China)

The progress of terahertz imaging at Capital Normal University in Beijing is presented. Our works on Terahertz Imaging include the active and passive imaging. For the active terahertz imaging, the pulse and continue wave terahertz imaging are studied, respectively. The active terahertz pulse imaging is based on the terahertz time-domain spectroscopy with the probe-beam-expanded femtosecond pulse laser and an infrared CCD detection. The active terahertz continuous wave imaging is based on a CO2-laser-pumped terahertz coherent source and a NEC terahertz camera. For the passive terahertz imaging, the low frequency of terahertz radiometers are used to detect the beam-scanned terahertz signal by the point-to-point method. The related components and methods are developed and used for the improvement of the imaging speed and the resolution of images.

The polarization terahertz imaging is studied based on the active continuous wave imaging technology. The higher resolution of terahertz imaging is achieved at 3.1 THz of operating frequency. The polarization imaging provide more information on the measured targets. However, the imaging distance of the high frequency, such as 3.1 THz, of terahertz imaging is limited due to the vapor absorption. The focal plane terahertz imaging is developed to obtain more frequency domain of spectral information. The focal plane imaging can be realized as a quasi-near field imaging so that it can achieve at a higher resolution. But the visual field of focal plane imaging is limited due to the size of electro-optic crystal. The passive terahertz imaging is developed for the longer imaging distance and the larger imaging visual field. The sensitivity of terahertz radiometer is a key factor for the contract and resolution of passive terahertz imaging.

In summary, the active and passive terahertz imaging are investigated at Capital Normal University. The advantage and disadvantage of different terahertz imaging technology can be seen and compared. Of course, they depend on the different requirements of application, too. Some further investigations of terahertz imaging are necessary.

10030-26, Session 5

Application advances of terahertz digital holography *(Invited Paper)*

Xinke Wang, Yan Zhang, Capital Normal Univ. (China)

With the maturation of terahertz (THz) technology, THz sensing and imaging systems have gradually demonstrated their significant impact in the modern optics due to the properties of THz radiations, such as low photon energy, high transmission, broad spectral information. Herein, THz imaging technology, which can coherently reconstruct the two-dimensional information of a sample, is one of the most important development directions. In this presentation, we will review some attempts we carried out in the THz digital holography system. A THz holographic imaging system is built and its main performances are elucidated, including higher spatial resolution, better signal-to-noise ratio and polarization-selected measurement. Utilizing this system, various THz imaging applications are performed, including demonstration of THz planar elements, exploitation of optical tunable THz devices, observation of the THz longitudinal field in a free space and the THz surface wave on a metallic sub-wavelength structure. These works push forward the development of THz integration system and broaden application fields of THz imaging

10030-27, Session 6

Tunable and reconfigurable THz devices *(Invited Paper)*

Jinghua Teng, Institute of Materials Research and Engineering (IMRE) (Singapore)

Terahertz wave is the fingerprint spectral range for many molecules and has far-reaching applications from molecular spectroscopy to security screening and bio-imaging. The wide adoption of THz technology requires the development of high performance and compact THz sources, detectors and various components. Tunable devices will add functionality and flexibility to the THz system design and application, besides other advantages. The unique properties of surface plasmons and metamaterials such as the strong field localization and enhancement and the flexible control of the permittivity and permeability bring new ways and opportunities to THz technology development. In this talk, I will introduce several of our work on tunable and reconfigurable THz devices using plasmonics and metamaterials. They include the high efficiency continuous wave THz emitter using a nano-electrode incorporated photomixer, broadband response with concurrent filed localization and optical tuning of THz transmission using InSb plasmonic response in the THz range, the graphene based multi-layer structure for compact optical switching, modulation and substantial Faraday rotation, and reconfigurable metamaterials using MEMs structure and phase change materials.

10030-28, Session 6

Integrated terahertz optoelectronics *(Invited Paper)*

Qi Jie Wang, Nanyang Technological Univ. (Singapore)

Terahertz (THz) quantum cascade laser (QCL) is a semiconductor based heterostructure laser based on intersubband transitions. Although THz QCLs have been developed with relatively high performance, there is always a need to further improve the device performance, for example, achieving high beam collimated, polarization arbitrarily controlled, and high speed modulation. It is also desired that those performance could be achieved through an integrated approach for miniaturalization, easy alignment and reducing cost.

In this presentation, we will demonstrate high collimated THz quantum cascade lasers through plasmonic collimation designs with a record beam divergence, electrically tunable THz polarizations by designing integrated THz metasurfaces on a hybrid dielectric-plasmonic waveguides, and broadband graphene-based integrated THz modulators with a fast modulating speed.

10030-29, Session 6

Active terahertz device based on optically-controlled organometal halide perovskite *(Invited Paper)*

Bo Zhang, Capital Normal Univ. (China)

An active all-optical high-efficiency broadband terahertz device based on an organometal halide perovskite (CH3NH3PbI3, MAPbI3)/inorganic (Si) structure is investigated. Spectrally broadband modulation of the THz transmission is obtained in the frequency range from 0.2 to 2.6 THz, and a modulation depth of nearly 100% can be achieved with a low-level photoexcitation power (~0.4 W/cm2). Both THz transmission and reflection were suppressed in the MAPbI3/Si structure by an external continuous-wave (CW) laser. Enhancement of the charge carrier density at the MAPbI3/Si interface is crucial for photo-induced absorption. The results show that the proposed high-efficiency broadband optically-controlled terahertz device based on the MAPbI3/Si structure has been realized.

10030-30, Session 6

Development of high-performance terahertz metasurface flat lens *(Invited Paper)*

C.-C. Chang, The Ctr. for Integrated Nanotechnologies (United States); D. Headland, Withawat Withayachumnankul, Derek Abbott, The Univ. of Adelaide (Australia); Hou-Tong Chen, The Ctr. for Integrated Nanotechnologies (United States)

Conventional optical lenses focus electromagnetic waves by imparting position-dependent phase delay through shaping their geometry. This poses difficulties in eliminating the geometric aberrations in high numerical aperture lenses, in addition to the fabrication challenges when operating at short wavelengths (e.g. visible light), and bulky devices operating at long wavelengths (e.g. microwaves). In contrast, metasurfaces realize full control of phase through tailoring the subwavelength resonant structures, allowing for the demonstration ultrathin flat lens without suffering from geometric aberrations, although the efficiency is still rather low using single-layer metasurfaces. Here we report the demonstration of high-performance flat lens in the terahertz frequency range using few-layer metasurfaces. The three-layer metasurface structure is capable of rotating the incident linear polarization by 90° with a very high efficiency over a bandwidth of two octaves. More importantly, the phase of the output light can be tuned over the entire 2? range with subwavelength resolution through simply tailoring the structure geometry of the basic building blocks. Based on this success, we design, fabricate, and characterize a metasurface lens operating at 0.4 THz. With a lens diameter and focal length both 5 cm, we realize a high numerical aperture of 0.44 and diffraction-limited focal diameter of 2 mm. Terahertz time-domain spectroscopy measurements show that the metasurface lens is capable of achieving the same signal intensity as compared to a TPX lens of the same diameter and focal length.

10030-31, Session 6

Electromagnetically-induced transparency-enabled asymmetric surface plasmon excitation *(Invited Paper)*

Xueqian Zhang, Quan Xu, Quan Li, Yuehong Xu, Jianqiang Gu, Zhen Tian, Chunmei Ouyang, Jiaguang Han, Ctr. for Terahertz Waves of Tianjin Univ. (China); Weili Zhang, Ctr. for Terahertz Waves of Tianjin Univ. (China) and Oklahoma State Univ. (United States)

Surface plasmons (SPs) has promised a variety of cutting-edge applications, such as deep-subwavelength lasing, high-resolution imaging, and ultrasensitive biomedical sensing. Freely control over SPs is highly desired in developing next generation of integrated photonic devices. Recently, excitation of asymmetric SPs using structured metallic surface has drawn huge interest, which is quite potential in plasmonic circuitries and communications. Among these studies, such excitation was realized either by engineering the phase gradient at the metal-dielectric interface so as to make the momentum matching condition satisfied in a selective SP excitation direction, or by controlling the SP interference of two or more separated couplers with different SP excitation phases. However, the coupling effects among the excitation units were usually ignored, which actually could also be very useful in controlling SP excitation. In this work, we demonstrated an exotic approach in exciting asymmetric SPs in the terahertz regime by introducing the electromagnetically-induced-transparency (EIT) coupling mechanism. In the free-space regime, EIT metamaterials have been widely investigated to manipulate the electromagnetic waves by designing the coupling between a bright and a dark resonator. Here, in the near-field regime, we also applied such coupled bright and dark resonators as basic excitation units. By changing their relative position, the coupling strength and thus the asymmetric level of the excited SP pattern can be freely adjusted. Furthermore, we also applied such controlling strategy into SP focusing. The experimental results were characterized by our recently developed near-field scanning terahertz microscope (NSTM) system, which agree well with the theoretical predictions.

10030-32, Session 7

Infrared spectroscopy with visible light *(Invited Paper)*

Leonid Krivitsky, Dmitry Kalashnikov, Anna Paterova, Data Storage Institute (Singapore); Sergei Kulik, Department of Physics, M.V. Lomonosov Moscow State University (Russian Federation)

The concept of nonlinear interference was introduced by Mandel et al. in 1999. It is based on the interference of parametric down conversion (PDC) beams from two non-linear crystals. The interference pattern depends on the total phase acquired by three interacting modes: the pump, the signal, and the idler in the gap between the two crystals. In case, when PDC is operated in the frequency non-degenerate regime, the interference pattern of the signal mode in the visible wavelength depends on the phase of the idler photon in the infrared wavelength. In 2001 this idea was used to measure dispersion of paraffin oil, and in 2014 it was used for imaging phase objects.

Here we use the nonlinear interferometer for measurements of refractive indices and absorption coefficients of materials in the Infrared range without the need for IR optical elements and sensors. We built a nonlinear Mach-Zender interferometer, where mirrors are substituted by two nonlinear crystals, where the PDC occurs. PDC is operated in the frequency non-degenerate regime, and the interference pattern of the signal photon (in the visible range) depends on the phase of the idler photon (in the infrared range). The intensity distribution of signal photons shows distinctive fringes. When the sample with resonance absorption in IR-range is placed between the crystals, the fringes shift and their visibility is reduced. From modifications of the interference pattern for the signal photon both, the refractive index and the absorption coefficient at IR-wavelength can be easily calculated.

10030-33, Session 7

Analysis on blue and green pigments from the Thangka of Dhritarashtra *(Invited Paper)*

Rui Zhang, Xiaoji Fang, Ningchang Shi, Qian Zhou, Jironge Song, The Palace Museum (China)

The purpose of this article is to analysize the dark blue and light green pigments particles fallen off from the Thangka of Dhritarashtra portrait collected by the Palace Museum. The crystal morphology and extinction phenomenon under single polarized and polarized light of these particles were observed through polarizing microscope. The chemical component and crystal structure of these particles were measured through two vibration spectroscopy methods including of laser Raman spectrum and Fourier transform infrared spectrum. The results showed that the dark blue particles were azurite and the light green particles were malachite. The clear conclusion could supply scientific basis for conservation of the Thangka of Dhritarashtra portrait.

10030-34, Session 7

Measurement of high-temperature spectral emissivity using integral blackbody approach

Yijie Pan, Wei Dong, Hong Lin, Zundong Yuan, Pieter Bloembergen, National Institute of Metrology (China)

Spectral emissivity is a critical material's thermophysical property for heat design and radiation thermometry. Specifically, for a thermal protective material in an aerospace application such as re-entry vehicle, hypersonic glide vehicle, its spectral emissivity determines the heat exchange of the surfaces, and it directly influences the heat design and corresponding optimization process of the system. For a high temperature measurement application, for example a liner pyrometer based radiation thermometry, spectral emissivity directly influence the accuracy of results.

A prototype instrument based upon an integral blackbody method was developed to measure material's spectral emissivity above 1000?. The system was implemented with an optimized commercial variable-high-temperature blackbody, a high speed linear actuator, a linear pyrometer, and an in-house designed synchronization circuit. The variable-high-temperature blackbody had a graphic tube as an electrical heating furnace. A sample was placed in a crucible at the bottom of the furnace, by which the sample and the tube formed a simulated blackbody which had an effective total emissivity greater than 0.985. During the measurement, the sample was pushed to the end opening of the tube by a graphite rod which was actuated through a pneumatic cylinder. The pushing process was fast. Therefore, the temperature drop of the sample was small. A linear pyrometer was used to monitor the brightness temperature of the sample surface through the measurement. The corresponding opto-converted voltage signal was fed and recorded by a digital multimeter.

A physical model was proposed to numerically evaluate the temperature drop along the process. Tube was discretized as several isothermal cylindrical rings, and the temperature profile of the tube was measurement. View factors between sample and rings were calculated and updated along the whole pushing process. The radiation heat transfer among the surfaces was conducted. The actual surface temperature of the sample at the end opening was obtained. Taking advantages of the above measured voltage profile and the calculated true temperature, spectral emissivity under this temperature point was calculated.

Graphite sample at 1000?, 1300?, and 1500?, respectively, was measured to prove the validity of the method. The preliminary result of sintered silicon carbide, carbon composite, and ceramic thermal protection material were provided as well.

10030-35, Session 7

Analytic technology of infrared absorption spectrum based on time-frequency analysis

Xiyang Liu, Nan Gao, Hebei Univ. of Technology (China); Zhenhui Du, Tianjin Univ. (China); Chao Chen, Zonghua Zhang, Hebei Univ. of Technology (China)

Infrared absorption spectroscopy has been widely used in the field of quantitative analysis. The overlapped spectral lines of different components make the component recognition and concentration calculation of the mixture difficult to realize. In order to solve this problem, in this paper the analytic technology of infrared absorption spectrum was researched in order to establish an effective, accurate and stable component identification method. The derivative spectrum of direct absorption spectral line was calculated to eliminate the influence of background and noise. The wavelet analysis method with appropriate wavelet basis and scale resolution was used to make the time-frequency analysis of the derivative spectrum to obtain the two dimensional time-frequency characteristics matrix. The correlation analysis in both time and frequency dimensions to the time-frequency characteristics matrix of different components and mixtures was researched to realize the component identification in combination with the morphological characteristics of the derivative spectral line. Experimental results show that the proposed method can effectively identify the target component from the their mixture spectral line. The research in this paper provides a method and technical route for simultaneous detection and spectral analysis of multi-component.

10030-36, Session 7

Using hyperspectral imaging technology to identify diseased tomato leaves

Cuiling Li, Xiu Wang, Xueguan Zhao, Zhijun Meng, Wei Zou, Beijing Academy of Agriculture and Forestry Sciences (China)

In the process of tomato plants growth, due to the effect of plants genetic factors, poor environment factors, or disoperation of parasites, there will generate a series of unusual symptoms on tomato plants from physiology, organization structure and external form, as a result, they cannot grow normally, and further to influence the tomato yield and economic benefits. Hyperspectral image usually has high spectral resolution, not only contains spectral information, but also contains the image information, so this study adopted hyperspectral imaging technology to identify diseased tomato leaves, and developed a simple hyperspectral imaging system, including a halogen lamp light source unit, a hyperspectral image acquisition unit and a data processing unit. Spectrometer detection wavelength ranged from 400nm to 1000nm. After hyperspectral images of tomato leaves being captured, it was needed to calibrate hyperspectral images. This research used spectrum angle matching method and spectral red edge parameters discriminant method respectively to identify diseased tomato leaves. Using spectral red edge parameters discriminant method produced higher recognition accuracy, the accuracy was higher than 90%. Research results have shown that using hyperspectral imaging technology to identify diseased tomato leaves is feasible, and provides the discriminant basis for subsequent disease control of tomato plants.

10030-37, Session 7

TDDA technology for high spatial resolution SWIR InGaAs imaging

Yueming Wang, Shanghai Institute of Technical Physics of the Chinese Academy of Sciences (China)

Infrared remote sensing imaging technology as one of the high-tech of today's rapid development, more and more widely used in weather forecasting, natural disaster detection, earth environmental monitoring, navigation, agriculture, astronomy, and other fields. Whether in civilian areas or astronomy research, study high sensitivity infrared detection imaging technology has a positive significance. SWIR (shortwave infrared) has got more and more attention because of its spatial resolution approaching the level of visible light, through the fog ability.

High spatial resolution SWIR imaging often requires high frame frequency. If the frame frequency is too high, it could cause the shortage of the image's SNR (signal to noise ratio), seriously affecting the image quality. Some foreign remote sensing satellites use image motion compensation technology to increase SNR. But this requires additional control mechanism, which increases system structure's complexity and leads to scan blindness. Digital TDA (time delay and accumulation) technology is proposed in this paper to improve system's SNR and image quality.

This paper introduces the image motion compensation technology and TDI (time delay and integration) technology, analyzes the noise model of different remote sensing devices and compares the difference of PA (pixel accumulation) technology, digital TDI technology and digital TDA technology. A prototype of SWIR imaging system based InGaAs detector is designed, which demonstrates digital TDA technology. The experiment result indicates digital TDA technology can increase system's SNR of the square root of TDA's stage and improve image's uniformity. The results in this paper are helpful for the improvement and application of high spatial resolution SWIR imaging technology.

10030-38, Session 7

Tunable mid-infrared emission from acetylene-filled hollow-core fiber

Zefeng Wang, Zhiyue Zhou, Zhixian Li, Naiqian Zhang, Yubin Chen, National Univ. of Defense Technology (China)

Mid-infrared fiber lasers have wide application in defense, security, atmosphere monitoring, and medicine, and have attracted enormous attentions. Usually, due to the low damage threshold, solid-core fiber lasers lack the ability to provide the same power levels as conventional gas lasers, which can reach MW levels in chemical gas lasers. Because of nonlinear effects, the spectral linewidth of light generated in glass fibers will broaden at high powers. Additionally because the number of rare earth materials is limited, only certain laser wavelengths are available. Gas lasers have been demonstrated to be an effect

method to generate mid-IR emission. In traditional gas cells the effective interaction length is very short and the system is bulky and cumbersome, limiting the applications of these lasers. The advent of hollow core fibers and their excellent properties make it possible to develop a novel type of laser, fiber gas lasers. In our previous works, we have reported firstly efficient diode-pumped 3?m mid-infrared emission from acetylene-filled hollow-core fiber. Here, we use a modulated, two-stage Er-doped fiber amplified, narrowband, tunable 1.5 ?m diode laser as the pump, and a wavelength, pulse width, repetition rate tunable mid-infrared single-pass fiber acetylene laser is demonstrated for the first time. The wavelength is step-tunable in the range of 3.1~3.2 ?m when the pump laser is precisely tuned to different absorption lines of P-branch of acetylene. The shortest pulse width is about 10 ns and the highest repetition rate is several tens of MHz, which is limited by the acousto-optical modulator.

10030-39, Session 7

The initial design of LAPAN'S IR microbolometer using mission analysis process

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As new player in Infra Red (IR) sector, uncooled, small, and lightweight IR Micro Bolometer has been chosen as one of payloads for LAPAN's next micro satellite project. Driven the desire to create our own IR Micro Bolometer, mission analysis design procedure has been applied. After tracing all possible missions, the Planck's and Wien's Law for black body, Temperature Responsivity (TR), and sub-pixel response had been utilized in order to determine the appropriate spectral radiance. The 3.8 – 4 ?m wavelength were available to detect wild fire (firest fire) and active volcanoes, two major problems faced by Indonesia. In order to strengthen and broaden the result, iteration process had been used throughout the process. The analysis, then, were continued by calculating Ground pixel size, IFOV pixel, swath width, and focus length. Meanwhile, regarding of resolution, at least it is 400 m.

The further procedure covered the integrated of optical design, wherein we combined among optical design software, Zemax, with mechanical analysis software (structure and thermal analysis), such as Nastran and Thermal Desktop / Sinda Fluint. The integration process was intended to produce high performance optical system of our IR Micro Bolometer that can be used under extreme environment. The results of all those analysis, either in graphs or in measurement, show that the initial design of LAPAN'S IR Micro Bolometer meets the determined requirement. However, it still needs the further evaluation (iteration). This paper describes the initial design of LAPAN's IR Micro Bolometer using mission analysis process

10030-50, Session 7

A design on low noise imaging circuit for SWIR sensor

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SWIR(Short Wave Infrared) imaging is an important imaging technology in space remote sensing. According to the characteristics of SWIR detector, the whole scheme of low noise imaging circuit is presented. For the certain key circuit that is noise sensitive in the design, such as bias generation circuit, an analysis on noise sources and the calculation of theoretical noise value on actual circuit that is usually ignored in previous researches are proposed in order to estimate the level of circuit noise and find way to optimize the circuit to reduce noise.The structure of analog filter amplifier circuit is also analyzed by introducing noise-factor analytic approach and based on the analysis result some design principles of the circuit are proposed. The noise suppression methods in the design are separated analyzed in both time suppression and space suppression, some specific methods for these two kinds of measures are listed. The finally experiment results indicate that the low noise design of imaging circuit based on above methods is reasonable and effective, the circuit has a higher SNR and could work normally in home temperature with a clear imaging, the whole design meets the original requirement on low noise. This low noise circuit for SWIR detector and its methods to analyze and calculate the theoretical noise value are valuable examples for future similar designs.

10030-40, Session 8

Optical feedback effects on terahertz quantum cascade lasers: modelling and applications *(Invited Paper)*

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Terahertz (THz) quantum cascade lasers (QCLs) are compact sources of electromagnetic radiation in the 1–5 THz frequency range with significant potential for applications in sensing, imaging and communications due to their ability to generate coherent, continuous-wave (cw) and high-power pulsed emission with quantum noise-limited linewidths.

In this work we will discuss the effects of optical feedback on the dynamics of THz QCLs and explore the relationship between the electrical, optical and thermal processes in these devices.

Laser feedback interferometry (LFI) with THz QCLs is a novel sensing technique, well-suited to the development of compact THz sensing systems, in which the radiation is reflected back into the QCL cavity from an external target. The retroinjected wave gives rise to measurable changes in the electronic and optical behavior of the laser, through a phenomenon frequently referred to as self-mixing.

Most THz LFI systems to date have employed THz QCLs operating in the continuous-wave cryogenic regime. In this work we will discuss the potential for the development of pulsed THz LFI techniques, which would unlock pathways to new applications in higher-temperature THz QCL imaging, long-range screening, and materials identification.

We will then focus on the interferometric schemes for biological tissue imaging due to its sensitivity to hydration levels, as a consequence of high absorption of THz radiation in water. We will show that the confocal nature of the QCL LFI systems with their innate capacity for depth sectioning makes them suitable for skin diagnostics with well-known advantages of more conventional confocal microscopes.

10030-41, Session 8

Localized spoof surface plasmon resonances at terahertz range

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We theoretically demonstrated and experimentally verified terahertz multipolar spoof localized surface plasmons(LSP) modes by introducing symmetry breaking in a textured metallic disk in normal incidence. Through exact numerical simulations, at normal incidence, we show the emergence and near-field properties of these multipolar spoof LSP resonances in two asymmetrical metal particles: a defective corrugated metallic disk structure and a hybrid structure consisted of a C-shaped resonator and a corrugated metallic disk. Their occurrence and spectral properties are measured and characterized experimentally by using terahertz time domain spectroscopy (THz-TDS), showing an excellent agreement with theoretical predictions.

10030-42, Session 8

Completely evolution of Gouy phase shift in terahertz wave

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We experimentally and theoretically investigate the Gouy phase shift of the longitudinal and transverse terahertz wave in the entire focal region. By comparing the pulses shape and orientation before and after the focus, we find that the complete Gouy shift for the longitudinal field components is same to that of the transverse field components, with the value of ϖ. The only different between them is their phase difference $\varpi/2$. Additionally, we found that an external longitudinal electric field (-6~+6 kV) can be used to control the time-domain waveform and then the corresponding Gouy phase shift. These results have important implications for the near-field optical microscopy and super-resolution imaging.

10030-43, Session 8

Terahertz beam shaping with metasurface

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Metasuface is composed of a subwavelength optical antenna array, which can be used to modulate the phase and amplitude of the cross-polarized scattered wave. Based on this principle, we design some terahertz (THz) beam shapers, such as THz ring-Airy beam shaper and THz multi-focus lens. Each beam shaper consists of gold C-shaped slot antennas with various opening angles and azimuthal angle of the axis of symmetry. A THz holographic imaging system is utilized to measure the field of the generated beams. The ring-Airy beam shaper is designed by replacing phase and amplitude of its initial electric field with the corresponding antennas. In the experiment, an abrupt focus following a parabolic trajectory is subsequently observed. This method can be expanded to other wavebands, such as the visible band, for which the ring-Airy beam shaper can replace traditional computer-generated holography to avoid undesirable multiple diffraction orders. The phase distribution of the multi-focus lens is obtained by using the Yang-Gu algorithm and then encoded to the antennas. Both the focusing and imaging properties are demonstrated. This designed THz multi-focus lens performs over a broad frequency band of 0.3–1.1 THz. This type of transmissive metasurface serves as an attractive alternative to conventional diffractive optical elements based on its broadband operation, small area, ease of fabrication, and low cost.

10030-44, Session 9

Terahertz magnetic and electric Mie resonances of an all-dielectric one-dimensional grating and their sensing capability *(Invited Paper)*

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Here, high-resolution resonant phenomena in a silicon-based, 1D grating are theoretically and experimentally demonstrated at terahertz frequencies. The periodic grating used in the experiment was fabricated on a double-side polished Si wafer with a length, period, width, and thickness of 5000, 205, 110 and 110 m, respectively.A series of high-qualify Mie resonances were excited in the all-dielectric grating, and displayed strong frequency-selection and polarization-sensitivity behaviors.

For the application of the resonator as a sensor, all 105-m thick gaps between the silicon pillars are filled by a dielectric layer with refraction index ranging from 1.0 to 2.0 at =0 and 20 S/m. Simulations show that the position, intensity and linewidth of the second TE Mie resonance explicitly dependent on the dielectric condition of surrounding media with the increased redshift in wavelength and broadening in linewidth when the refraction index increases. In case of =20 S/m, the intensity of the transmission dip is also much sensitive to the change of the refraction index.

10030-46, Session 9

Gas trade detection with cavity-enhanced absorption spectroscopy: a review of CEAS' process

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Cavity-enhanced absorption spectroscopy (CEAS) is a technology that uses cw laser to directly detect substances' absorption spectrum with a high finesse optical cavity and it is used to detect or calculate samples' parameters, such as species, concentrations and absorption cross section. It was found out in 1998 by R. Engeln or A. O'Keefe for improving sensitivity of Cavity Ring-down spectroscopy(CRDS). This technology has extraordinary detection sensitivity, high resolution and good practicability, so it is projected to be use in many fields at near future, such as clinical medicine, gas detection and basic physics research. In this paper, we present the basic theory of CEAS and its development over the past two decades. First, the key points of CEAS, such as optical cavity, optical source and gas cells, would be discussed in this paper. Next, we would introduce the newest research progresses in labs. And finally, we would simply compare the CEAS with other detection technologies and predicate of the CEAS's development direction in the future.

10030-47, Session 9

Ripple FPN reduced algorithm based on temporal high-pass filter and hardware implementation

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Cooled infrared detector arrays always suffer from undesired Ripple Fixed-Pattern Noise (FPN) when observe the scene of sky. The Ripple Fixed-Pattern Noise seriously affect the imaging quality of thermal imager, especially for small target detection and tracking. It is hard to eliminate the FPN by the Calibration based techniques and the current scene-based nonuniformity algorithms. In this paper, we present a modified space low-pass and temporal high-pass nonuniformity correction algorithm using adaptive time domain threshold (THP&GM). The threshold is designed to significantly reduce ghosting artifacts based on the local gray-level gradient. We test the algorithm on real infrared in comparison to several previously published methods. This algorithm not only can effectively correct common FPN such as Stripe, but also has obviously advantage compared with the current methods in terms of detail protection and convergence speed, especially for Ripple FPN correction. Furthermore, we display our architecture with a prototype built on a Xilinx Virtex-5 XC5VLX50T FPGA. The hardware implementation of the algorithm based on FPGA has two advantages: (1) low resources consumption, and (2) small hardware delay(less than 20 lines). The hardware has been successfully applied in actual system.

10030-70, Session 9

Multicasting of signal-carrying Gaussian mode to multiple orbital angular momentum (OAM) modes *(Invited Paper)*

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Recently, orbital angular momentum (OAM) beams have unlimited orthogonal states (in principle, l can take arbitrary integer number ranging from -∞ to +∞), showing great potential to multiplex a large number of OAM beams and tremendously increase the available information bandwidth. Lots of research efforts have been devoted to increase the transmission capacity and spectral efficiency in both free-space and fiber-optical communication systems by employing OAM multiplexing. In addition to OAM multiplexing, OAM-based networking functions such as data exchange, add/drop multiplexing and multicasting have also proposed to advance the usefulness of OAM for multi-user communication applications. Among these functions, OAM multicasting is a very important one which can duplicate data of one single channel onto multiple OAM channels, without the need of detection and remodulation processes. In this paper, we review our recent works on N-fold orbital angular momentum (OAM) multicasting links. By exploiting optimized complex phase pattern, the data information carried by an input Gaussian mode can be copied and delivered to multiple OAM modes which are distinguishable from each other owing to their own distinct spiral phase fronts. Experiment demonstration of 1-to-34 OAM multicasting, adaptive power-controllable OAM multicasting, and compensation of a distorted OAM multicasting link are presented. It is expected that the proposed OAM multicasting schemes, facilitating flexible and efficient OAM manipulation, may find wide potential use in future grooming OAM communications and networks.