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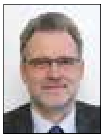

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Contents

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Conference 9342: Solid State Lasers XXIV: Technology and Devices

Sunday - Tuesday 8 –10 February 2015

Part of Proceedings of SPIE Vol. 9342 Solid State Lasers XXIV: Technology and Devices

9342-1, Session 1

Single crystal fiber for laser sources *(Invited Paper)*

Xavier Delen, Institut d'Optique Graduate School (France); Adrien Aubourg, Institut d'Optique Graduate School (France) and Fibercryst SAS (France); Loic Deyra, Institut d'Optique Graduate School (France); Fabien Lesparre, Institut d'Optique Graduate School (France) and Fibercryst SAS (France); Igor Martial, Julien Didierjean, FiberCryst (France); François Balembois, Patrick Georges, Institut d'Optique Graduate School (France)

Single crystal fiber (SCF) is a hybrid laser architecture between conventional bulk laser crystals and active optical fibers allowing higher average powers than with conventional crystals and higher energy than with fibers in pulsed regime. The pump beam delivered by a fiber-coupled laser diode is confined by the guiding capacity of the SCF whereas the signal beam is in free propagation. In this paper, we study the pump guiding in the SCF and give an overview of the results obtained using SCF gain modules in laser oscillators and amplifiers. We report about up to 500 µJ nanosecond pulses at the output of a passively Q-switched Er:YAG SCF oscillator at 1617 nm. High power experiments with Yb:YAG allowed to demonstrate up to 250 W out of a multimode oscillator. High power 946 nm Nd:YAG SCF oscillators followed by second and fourth harmonic generation in the blue and the UV is also presented with up to 3.4 W at 473 nm and 600 mW at 236.5 nm. At 1064 nm, we obtain up to 3 mJ with a nearly fundamental mode beam in sub-nanosecond regime with a micro-chip laser amplified in a Nd:YAG SCF. Yb:YAG SCF amplifiers are used to amplify fiber based sources limited by non-linearities with a narrow linewidth laser and with a femtosecond source. Using chirped pulse amplification, 380 fs pulses are obtained with an energy of 1 mJ and an excellent beam quality (M?<1.1).

9342-2, Session 1

High power Yb:YAG single-crystal fiber amplifiers for femtosecond lasers

Fabien Lesparre, Lab. Charles Fabry (France); Igor Martial, Julien Didierjean, FiberCryst (France); Jean-Thomas Gomes, Lab. Charles Fabry (France); Wolfgang P. Pallmann, Bojan Resan, JDSU Ultrafast Lasers AG (Switzerland); André Löscher, Jan-Philipp Negel, Thomas Graf, Marwan Abdou Ahmed, Univ. Stuttgart (Germany); François Balembois, Patrick Georges, Lab. Charles Fabry (France)

Diode-pumped Yb-doped solid-state lasers implemented in Master Oscillator Power Amplifier (MOPA) configuration clearly dominate the field of high-average power pulsed laser. Thanks to a very efficient thermal management and a high overlap between pump and signal beams brought by the pump guiding, the single-crystal-fiber (SCF) technology has recently shown strong potentialities for the amplification of ultrashort pulses.

In this work, we present the use of Yb:YAG SCF (1% Yb doped 1mm diameter, 40mm long) for high average power amplification. As a seed, we used a passively-modelocked Yb-based laser delivering ultra-short pulses at 20MHz with an average power of 1,5W and a duration of 360fs at 1031nm. The SCF amplifier consists in two double-pass stages based on SCF (Taranis modules). The first amplification stage is pumped by a high brightness fiber-coupled laser diode producing 120W at 940nm. After a double-pass, the output power is multiplied by 10, reaching 15W of average power. The second amplification stage consists in a double-pass booster amplifier pumped by a high power fiber-coupled laser diode producing 200W at 969nm to lower the thermal load. After this double pass, the output power reaches 70W (M2=1.2) with 600 fs pulses. Optimized length and doping rate of each SCF and different experimental configurations are under study to increase the performances. Furthermore, using a polarization converter, the amplification of radially and azimuthally polarized beam will be investigated in order to achieve high-energy cylindrically polarized femtosecond pulses needed for high-speed material processing applications (surface structuring, drilling).

9342-3, Session 1

Rare-earth doped, single-crystal fibers grown from ceramic and single-crystal preforms

Craig D. Nie, Subhabrata Bera, James A. Harrington, Rutgers, The State Univ. of New Jersey (United States); Nathan Taylor, Richard M. Laine, Elizabeth F. C. Dreyer, Stephen C. Rand, S. Trembath-Reichert, Univ. of Michigan (United States)

Single-crystal (SC) YAG fibers with various rare-earth dopants have been grown using the Laser Heated Pedestal Growth (LHPG) technique. The source or preform starting material is either ceramic or single-crystal material. The advantage of starting with ceramic materials is that they are much easier and less costly to fabricate and they may be readily doped with a range of rare-earth dopants. Single-crystal source material is not as readily available with a range of different dopants and concentrations. However, to date we have achieved the lowest loss of about 1 dB/m at 2.94 microns for undoped YAG fibers grown from single-crystal starting material. Results will be given for both single-crystal and ceramic preforms including a comparison of the optical losses for each material.

9342-4, Session 1

Investigation of the amplification in Ho:YAG single crystal fiber

Yuan Li, Zeyu Zhang, Ian Buckley, Eric G. Johnson, Clemson Univ. (United States); Craig D. Nie, James A. Harrington, Rutgers, The State Univ. of New Jersey (United States); Saurabh Sharma, Ramesh K. Shori, SPAWAR Systems Ctr. (United States)

0.5% Holmium (Ho) doped YAG single crystal fiber (SCF) was fabricated using Laser heated pedestal growth (LHPG) methods and amplification properties of the fabricated Ho:YAG SCF were studied. The relatively large length-to-diameter ratio provides guiding for both pump and signal beam propagating in the SCF. The propagation and gain of signals with different modes were studied experimentally. A numerical method based on finite difference beam propagation method combined with rate equation was developed for theoretical simulation. Both experimental and simulation results demonstrate the advantages of SCF for its fiber-like beam guiding and bulk solid state laser gain media properties.

9342-5, Session 2

Crystal fibers for high power lasers

Jasbinger S. Sanghera, Charles G. Askins, Woohong R. Kim, Shyam S. Bayya, L. Brandon Shaw, Daniel J. Gibson, U.S. Naval Research Lab. (United States); John R. Peele, Sotera Defense Solutions, Inc. (United States); Steven Bowman, U.S. Naval Research Lab. (United States)

Crystal fibers offer several advantages over glass fibers (such as silica fiber) due to their higher thermal conductivity and higher SBS threshold, along with excellent environmental stability and higher doping concentrations. Based on their superior properties, it is expected that we can get more than 50kW of single frequency output power from a single mode fiber laser based upon a Yb-doped YAG single crystal fiber. However, it has been difficult to fabricate high quality core/clad crystalline fibers. In this paper, we present our recent results in the development of single crystal singlemode fibers for high power single frequency fiber lasers. We will describe our novel methods to apply claddings to the single crystal fiber and report on their properties including optical loss, gain and laser measurements.

9342-6, Session 2

Beam quality investigation in Nd:YAG crystal fiber amplifier pumped at >110w

Aleksej M. Rodin, Ctr. for Physical Sciences and Technology (Lithuania); Aidas Aleknavicius, EKSPLA UAB (Lithuania); Andrejus Michailovas, Ctr. for Physical Sciences and Technology (Lithuania) and EKSPLA UAB (Lithuania); Aleksandr S. Dementjev, Ctr. for Physical Sciences and Technology (Lithuania)

We present results of numerical and experimental investigation of beam quality in Nd:YAG crystal fiber amplifier seeded by ns, sub-ns and ps laser pulses counter-propagating to continuous pump of > 110 W power at 808 nm wavelength emitted from the fiber coupled laser diode with Bragg grating. The maximum amplified output power of 44 W achieved with ns seed corresponds to extraction efficiency of > 27 %. The output energy of up to 3.2 mJ has been obtained at 10 kHz repetition rate. We observed gain rise to 75 with ps seed of 1,6 mW average power by tuning the emission spectra towards the thermally shifted gain at ~ 1064.3 nm. Beam propagation factor of M2 ~ 1.2 has been obtained even at the maximal pump power with high quality seed of M2 ~ 1.1 emitted by mode-locked fiber laser. Residual amplified beam distortions attributed largely to thermally induced spherical aberration.

9342-7, Session 2

High peak power Er-ZBLAN microchip seeded laser amplifier

Rafael R. Gattass, L. Brandon Shaw, Jasbinder S. Sanghera, U.S. Naval Research Lab. (United States)

Few sources of high peak power laser are available beyond the transparency window of silica glass. Over the past decade several there have been several demonstrations of Er-ZBLAN laser systems with watt-level CW powers and kW peak powers. We present a hybrid bulk-fiber laser architecture for the generation of high peak power pulses (>15 kW) centered around 2.8 μm with a nearly Gaussian beam profile. The seed laser is generated from a Nd:YAG microchip laser emitting 700-ps pulses which is nonlinearly converted to 2.8 μm in a periodically poled lithium niobate crystal. The converted signal is amplified in a double-clad Er-ZBLAN fiber, collinearly pumped by a single 976-nm pigtailed laser diode. The repetition rate of the system can be externally changed up to 100 kHz. At 20 kHz repetition rate, close to 12 dB of amplification is observed with no roll-off in power. The system builds upon well-established microchip technology for Nd:YAG lasers and bypasses the lack of fiber components at 2.8 μm.

9342-8, Session 2

Laser diode pumped high efficiency Yb:YAG crystalline fiber waveguide lasers

Xiaodong Mu, Stephanie Meissner, Helmuth E. Meissner, Onyx Optics Inc. (United States)

YAG crystalline fibers have the potential for higher output power than conventional glass fibers due to their much higher thermal conductivity and lower Stimulated Brillouin Scattering (SBS) threshold. However, current fiber pulling techniques have not yet been successful in producing low loss, double-clad, or even single-clad crystalline fibers. Onyx Optics' well established Adhesive-Free Bond (AFB®) technology circumvents the problems with the fabrication of low-loss crystalline fibers. We report on diode pumped lasing results of single-clad and double-clad Yb:YAG crystalline fiber waveguides (CFWs).

The double clad CFW consists of a 40-um square Yb:YAG waveguide core with un-doped YAG inner cladding, and ceramic spinel outer cladding. The CFW was cladding pumped by a fiber coupled laser diode (LD) at wavelength of 940 nm. Single-mode laser at 1030 nm has been obtained even only with the bare ends of the CFW with a measured laser efficiency of 22%. After attaching a high reflectivity (HR) pump mirror and a 50% output coupler on the two ends of the CFW, an output power of 13.3 W and laser efficiency of 34% have been achieved respectively at pump power of 39.5 W. The beam quality is demonstrated to be near diffraction limited with a measured M2=1.02.

The single-clad CFW consists of a 300-um square Yb:YAG core and ceramic spinel outer cladding. It was core pumped by the same LD. The laser output is multimode with a top-hat beam profile. An output power of 28 W and a slope efficiency of 78% have been achieved respectively.

9342-9, Session 2

Templated growth of II-VI semiconductor optical fiber devices and steps towards infrared fiber lasers *(Invited Paper)*

Pier J. Sazio, Univ. of Southampton (United Kingdom); Justin Sparks, Rongrui He, Mahesh Krishnamurthi, The Pennsylvania State Univ. (United States); Thomas C Fitzgibbons, Department of Chemistry and Materials Research Institute, Pennsylvania State University (United States); Neil F. Baril, Subhasis Chaudhuri, The Pennsylvania State Univ. (United States); Anna C. Peacock, Noel Healy, Univ. of Southampton (United Kingdom); Venkatraman Gopalan, John V. Badding, The Pennsylvania State Univ. (United States)

ZnSe and other zinc chalcogenide semiconductor materials can be doped with divalent transition metal ions to create a mid-IR laser gain medium with active function in the wavelength range 2 – 5 microns and potentially beyond using frequency conversion. As a step towards fiberized laser devices, we have manufactured ZnSe semiconductor fibre waveguides[1] with low (less than 1dB/cm at 1550nm) optical losses, as well as more complex ternary alloys with ZnSxSe(1-x) stoichiometry[2] to potentially allow for annular heterostructures with effective and low order mode core-cladding waveguiding.

[1] J.R. Sparks et al., "Zinc Selenide Optical Fibers", Adv. Mater. 23 1647 (2011)

[2] J.R. Sparks et al., "Conformal coating by high pressure chemical

deposition for patterned microwires of II-VI semiconductors", Adv. Funct. Mater. 23 1647 (2013)

9342-10, Session 3

4.5 W mid-infrared supercontinuum generation in a ZBLAN fiber pumped by a Q-switched mode-locked Tm3+- doped fiber laser

Christian Kneis, Institut Franco-Allemand de Recherches de Saint-Louis (France) and Lab. Ondes et Matière d'Aquitaine, CNRS, Univ. of Bordeaux (France); Brenda Donelan, Antoine Berrou, French-German Research Institute of Saint-Louis (France); Inka Manek-Hönninger, LOMA, University of Bordeaux (France); Benoît Cadier, Thierry Robin, iXFiber (France); Marcel Poulain, Franck Joulain, Le Verre Fluoré (France); Marc Eichhorn, Christelle Kieleck, French-German Research Institute of Saint-Louis (France)

The generation of mid-infrared (mid-IR) supercontinuum (SC) radiation (ranging from 2 - 5 µm) is subject of intense research due to the wide range of applications. The main host medium for mid-IR SC generation is soft glass fibers, where fluoride fibers are very attractive for high-power operation due to their low losses in the mid-IR wavelength region and their relative high glass stability. In this study, a diode-pumped Q-switched mode-locked Thulium (Tm3+) -doped double-clad fiber laser is used to pump a ZrF4-BaF2-LaF3-AlF3-NaF (ZBLAN) fiber for mid-IR SC generation. The Q-switched mode-locked regime of the fiber laser is actively generated by two acousto-optic modulators. The Tm3+-fiber laser provided up to 70 W (50 W) of average output power in continuous wave (mode-locked) operation with a measured beam quality close to diffraction-limit. For mode-locked and Q-switched mode-locked operation, the system delivers pulses with approximately 100 ps pulse width (measured with a fast photodetector and oscilloscope). SC with an average power in all spectral bands of 2.2 W has been achieved with more than 0.7 W after a long wave pass filter (3 dB edge at 2.65 µm) at an incident pump power of 5.4 W. The SC spectra at different pump power levels have been recorded with a Spectrum Analyzer (Yokogawa AQ6375L), measuring the spectral power distribution up to a wavelength of 3.4 µm. A monochromator covering the wavelength range up to 5 µm will be implemented and power scaling will be presented.

9342-11, Session 3

Multi-wavelength resonant pumping of Er:YAG lasers for energy efficient trace gas detection systems

Haro Fritsche, Technische Univ. Berlin (Germany) and DirectPhotonics Industries GmbH (Germany); Oliver Lux, Casey Schuett, Technische Univ. Berlin (Germany); Ronny Juhre, Andreas Grohe, DirectPhotonics Industries GmbH (Germany); Hans Joachim Eichler, Technische Univ. Berlin (Germany)

Resonantly pumped Er:YAG lasers emitting at 1645 nm or 1617 nm are characterized by a high quantum efficiency since the corresponding pumping and lasing processes involve different narrowband Stark sub-levels of the 4I13/2 and 4I15/2 electronic states. In order to obtain high absorption efficiency of Er:YAG, narrowband laser sources emitting at the various available pump wavelengths (e.g. 1455 nm, 1470 nm or 1532 nm) are required. We report on the first realization of a resonantly pumped Er:YAG laser pumped at two wavelengths simultaneously. Compared to single-wavelength pumping, we observed a significant increase of the output power as well as a reduction of the laser threshold. Active Q-switching generates single pulses with pulse duration of less than 60 ns, while the utilization of an intra-cavity etalon provides spectral narrowing of the laser emission, thus enabling methane absorption measurements in the spectral range around 1645 nm.

In our latest experiments we employed a pump laser system operating at 1470 nm and 1532 nm with a power of 50 W per wavelength. The combined narrowband radiation is coupled into one fiber which enables a high power Er:YAG laser system with low footprint (10 x 10 cm? only). Multi-wavelength pumping offers the possibility to develop a compact and highly efficient laser transmitter which meets the strict requirements of a satellite-borne methane LIDAR system while providing very low power consumption. Hence, our research is intended to pave the way towards the realization of energy-efficient laser sources applied in the field of environmental and climate protection.

9342-12, Session 3

Ho:YLF non-planar ring laser with fractional image rotation

Martin Schellhorn, Marc Eichhorn, Institut Franco-Allemand de Recherches de Saint-Louis (France)

A Tm:fiber-laser-pumped Ho:YLF non-planar ring laser with fractional image rotation (77.5 degree per round trip) is presented. The ring laser cavity consists of six flat mirrors with an incident angle on all six mirrors of ?32.7 degree with a total cavity length of 222 mm. The output coupler of the ring cavity has a reflectivity of ~ 90% and the other five mirrors have the same coating, high transmission at the pump wavelength around 1940 nm (T>99.8%), and high reflectivity for s- and p-polarization (R>99.8%) in the 2050-2100 nm wavelength range. The crystal was a 0.5 at.% doped Ho:YLF rod with a length of 30 mm and a diameter of 6 mm. The end faces were antireflection coated for the 1900–2100 nm wavelength range. The spot radius of the pump beam was measured to be ?800 ?m. An infrasil lens with a focal length of 100 mm was used to make the ring cavity stable. Neglecting thermal lensing, the calculated TEM00 beam radius in the crystal was 256 ?m. The spot radius of the pump beam was measured to be ?800 ?m. Unidirectional operation was achieved using an external high reflector.

With this configuration, a maximum laser power of 16.5 W was obtained at a wavelength of 2064 nm, corresponding to a slope efficiency of 26% (57%) with respect to incident (absorbed) pump power. The beam quality will be measured and discussed as a function of focal length of the infrasil lens.

9342-13, Session 3

Gain-switched operation of ultrafast laser inscribed waveguides in Cr:ZnSe

Sean McDaniel, Leidos, Inc. (United States); Patrick A. Berry, Air Force Research Lab. (United States); Kenneth L. Schepler, The College of Optics and Photonics, Univ. of Central Florida (United States); John R. Macdonald, Stephen J. Beecher, Ajoy K. Kar, Heriot-Watt Univ. (United Kingdom)

We report the first demonstration of a gain-switched chromium-doped zinc selenide channel waveguide laser. The guided-wave structure was produced by ultrafast laser inscription, creating an 80 um diameter waveguide. Utilizing a pulsed Ho:YAG laser, the gain-switched Cr:ZnSe laser exhibited output pulse energies up to 12 ?J. The laser exhibited narrow spectral output, with no additional tuning elements. A linewidth of 1 nm was measured from the laser. The beam quality was measured to be M2<7 with a highly multimode output profile. The laser had a maximum slope efficiency of 9.8%, which was likely caused by decreased absorption at Ho:YAG pump wavelength. No deleterious thermal effects were observed up to an average pump power of 3.3 W.

9342-14, Session 3

A continuous wave Fe:ZnSe laser pumped by efficient Er:Y2O3 laser

Jonathan W. Evans, Air Force Research Lab. (United States); Tigran Sanamyan, U.S. Army Research Lab. (United States); Patrick A. Berry, Air Force Research Lab. (United States)

Fe:ZnSe lasers have been pumped by several lasers, including Cr:Er:YSGG (2800 nm) [i], Cr:CdSe (2970 nm) [ii], and Er:YAG (2698 nm [iii], 2937 nm [iv]) diode-pumped solid state lasers. None of these sources has exceeded 1.5 W of true continuous-wave output power. In this work, we report demonstration of a continuous-wave Fe:ZnSe laser pumped by a 10 W Er:Y2O3 laser emitting at 2740 nm [v], which had never before been attempted. The pump laser was characterized with respect to propagation losses, beam quality, mode size, and pointing stability. It was determined that the limit of output power from the Fe:ZnSe laser was limited by the output stability of the pump laser. The Fe:ZnSe laser operated with >17% slope efficiency and >500 mW output power was achieved at approximately 4050 nm. It was calculated that, with optimal pump-mode overlap, >3.5 W of output power from the Fe:ZnSe laser would be possible if the pump laser design could be adjusted to improve the pointing stability of the Er:Y2O3 output beam.

i Proc SPIE 7912, 79121C, Feb 2011

ii Quantum Electronics, vol 38, no. 12, p. 1113, 2008.

iii Opt. Lett. 24, 1720-1722 (1999).

iv Opt. Lett. 37, 5021-5023 (Dec 2012)

v CLEO:2011, CMY1

9342-15, Session 3

Radiation-enhanced thermal diffusion of transition metal and rare earth ions into II-VI semiconductors

Lamario J. Williams, Alan D. Martinez, The Univ. of Alabama at Birmingham (United States); Ozarfar Gafarov, Dmitry Martyshkin, University of Alabama at Birmingham (United States); Vladimir V. Fedorov, Sergey B. Mirov, The Univ. of Alabama at Birmingham (United States)

Recent progress in fabrication of diffusion doped Cr:ZnSe and Cr:ZnS gain elements for tunable mid-IR solid state lasers has resulted in the development of high efficiency widely tunable laser system (2-3 um) operating in CW, free running, gain-switched, and mode locked regions. Further progress in the development of solid state laser systems operating in 4-7 um spectral range is related to iron doped II-VI binary and ternary compounds. The main drawback of iron post-growth thermal diffusion is the limited coefficient of diffusion. In this work we report on study of gamma radiation-enhanced thermal diffusion of Transition Metal ions into II-VI semiconductor crystals. ZnSe and ZnS samples with of iron or chromium thin film deposited on one facet were sealed in evacuated quartz ampoules at 10-3 Torr. The crystals were annealed for 14 days at 950°C under g-irradiation from Co60 source. The irradiation dose rates of 44.9 R/s, 1.8 R/s were varied by distance between Co60 source and furnaces. For comparison, the samples were also annealed without irradiation at the same temperature. The spatial distributions of transition metal were measured by absorption of focused laser radiation at 5T2-5E mid-IR transitions of iron and chromium ions. The gamma irradiation results in better admittance of the iron ions from the metal film and increase of the diffusion length by ~25%.

9342-16, Session 4

Radiation tests on erbium-doped garnet crystals for spaceborne CH4-Lidar applications

Ansgar Meissner, Martin Kreitler, Philipp Kucirek, Bastian Gronloh, Marco Höfer, Hans-Dieter Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

Direct generation of single-frequency laser pulses at 1645 nm with lasers based on Erbium-doped garnet crystals has advantages compared to state-of-the-art nonlinear frequency conversion stages as beam sources for CH4-detection by lidar-methods. Complexity is lower, spectral purity and efficiency is potentially higher. New compositionally tuned laser crystals made of Er:YAG/Er:LuAG have been grown and used for generating single-frequency laser pulses that are applicable for CH4-detection. For potential application in an instrument in earth orbit, radiation hardness of these crystals needs to be assessed. To the best of our knowledge, there is no literature on radiation hardness tests of Er:YAG or Erbium-doped mixed garnet crystals. In the test campaign reported here a number of different laser crystals (Er:YAG, Er:YAG/Er:LuAG mixed garnet and Er,Ce:YAG/Er,Ce:LuAG mixed garnet) was irradiated with high-energy protons. The transmission spectra and the performance (slope and threshold) of these crystals in a test laser oscillator were measured before and after irradiation with different proton fluences and the measurement results were compared afterwards. Also, volume-absorption measurements were carried out with a photo-thermal common-path interferometer. The test procedure was approved by the European Space Agency. The results indicate that the tested crystals are sufficiently radiation hard for usage in the assumed mission scenario and that codoping with Cerium reduces the susceptibility of the crystals to proton-induced transmission losses. Another test campaign with gamma radiation is currently ongoing.

9342-17, Session 4

Multi-pulse detection technique to improve the timing resolution in a scanning LADAR system

Yury Y. Markushin, Renu Tripathi, Gour S. Pati, Delaware State Univ. (United States)

The range resolution of a scanning LADAR system is limited by the pulse duration of the laser source used. Typically, a pulse rise time in the order of 1-2 nanoseconds corresponds to a range resolution of 7.5 – 15 cm. However, due to additional timing jitters introduced by electronic pre-amplifiers, object separations less than 20 – 30 cm cannot be resolved without ambiguity. The time-to-amplitude converter (TAC) measures the range by directly measuring the time interval between pulses sent to its 'start' and 'stop' inputs. In our scanning LADAR system, we using a TAC paired with two Constant Fraction Discriminators (CFD) and pre-amplifiers for both 'start' and 'stop' signals. Each vexel of the target is illuminated with a single laser pulse and the data is processed using computer software. This configuration theoretically yields about 10-15 cm in timing resolution. However, due to fluctuations in the laser intensity and the timing jitter in the signal, the actual resolution degrades to about 15-20 cm. In this presentation, we will discuss a multi-pulse detection technique that we are using to improve the timing resolution in ranging. Illuminating each vexel of the target with multiple laser pulses, collecting the timing information by using a Multichannel Analyzer (MCA), and processing the data it is possible to significantly improve the timing resolution of the LADAR system. We have been able to achieve a temporal resolution up to 4 times higher. Also, by reducing the noises associated with transmission of the high frequency signals to the MCA we are able to increase the timing resolution of the system even further.

9342-18, Session 4

Single frequency and wavelength stabilized near infrared laser source for water vapor DIAL remote sensing application

Ti Chuang, Brooke Walters, Timothy Shuman, Andrew Losee, Tom Schum, Fibertek, Inc. (United States); Charles Kent Puffenberger, Fibertek Inc (United States); Ralph L. Burnham, Fibertek, Inc. (United States)

Fibertek has demonstrated a single frequency, wavelength-stabilized near infrared laser source for NASA airborne water vapor DIAL application. The application required a single-frequency laser source operating at 935 nm near infrared (NIR) region of the water vapor absorption spectrum, capable of being wavelength seeded and locked to a reference laser source and being tuned at least 100 pm across the water absorption spectrum for on/off measurements. The demonstrated NIR laser source was based on a single frequency, diode-pumped Nd:YAG laser operating at 1064 nm and 1 KHz repetition rate. Through steps of frequency conversion, the target NIR wavelength was achieved with output energy of 2 mJ. A DFB laser was chosen as the seed laser, whose wavelength was temperature tuned and stabilized in the 935 nm region. A Pound-Drever-Hall feedback loop was employed to achieve the wavelength locking of the NIR laser source to the DFB seed laser. The wavelength of the NIR laser source was able to be tuned across more than 100 pm while remaining seeded and locked to the seed laser. The wavelength-stabilized NIR laser linewidth was measured and calculated to be about 30 MHz – 40 MHz (transform limited). Fibertek is building an airborne DIAL transmitter based on the reported demonstration with the output energy scaled to near 4 mJ and rapid on/off wavelength switching capability. NASA plans to field the DIAL transmitter in a high altitude airborne instrument to perform autonomous global water vapor DIAL remote sensing field campaign.

9342-19, Session 4

Monolithic solid state lasers for spaceflight

Michael A. Krainak, Anthony W. Yu, Mark A. Stephen, Scott Merritt, NASA Goddard Space Flight Ctr. (United States); Leonid B. Glebov, Larissa Glebova, Aleksandr Ryasnyanskiy, Vadim Smirnov, OptiGrate Corp. (United States)

A new solution for building high power, solid state lasers for space flight is to fabricate the whole laser resonator in a single (monolithic) structure or alternatively to build a contiguous diffusion bonded or welded structure. Monolithic lasers provide numerous advantages for space flight solid state lasers by minimizing misalignment concerns. The closed cavity is immune to contamination. The number of components is minimized thus increasing reliability. Bragg mirrors serve as the high reflector and output coupler thus minimizing optical coatings and coating damage. The Bragg mirrors also provide spectral and spatial mode selection for high fidelity. The monolithic structure allows short cavities resulting in short pulses. Passive saturable absorber Q-switches provide soft aerturing fro spatial mode filtering and improved pointing stability. With an industry partner, we developed a prototype monolithic CW solid-state laser in Yb-doped photo-thermo-refractive (PTR) glass using an interferometrically recorded Distributed FeedBack (DFB) hologram throughout the entire volume to form the resonator. We achieved single-frequency (< 250kHz linewidth) tunable output at 1066 nm. We present a scalable monolithic solid-state design that incorporates a waveguide laser oscillator and a photonic lantern for the amplifier diode-pumping array to be prototyped on a direct-write femtosecond laser system. We present a seam welded monolithic solid-state laser design with oscillator, passive Q-switch and amplifier sections.

9342-20, Session 4

ICESat-2 laser transmitter technology readiness level evolution

Nicholas W. Sawruk, Floyd E. Hovis, Fibertek, Inc. (United States)

We report on the completion of the space qualification testing program for NASA's Goddard Space Flight Center ICESat-2 (Ice, Cloud, and land Elevation Satellite) program. This paper describes the final performance results of the fully integrated (laser and electronics) flight laser system with an emphasis on the system design evolution from a breadboard demonstration to a fully space-qualified laser system. The 532 nm ICESat-2 laser transmitter generates diffraction limited pulse energies of 1 mJ, pulse widths of < 1.5 ns, 10 kHz pulse repetition frequency and has minimum lifetime of one trillion pulses on-orbit. A combination of engineering design units and correlated structural thermal optical analysis were utilized to systematically improve reliability and performance over the operating environment. The laser system qualification and acceptance test programs included electromagnetic interference, vibration and thermal vacuum testing. This paper presents key laser performance results and lessons learned on the multi-year laser development to facilitate future space-qualified laser developments, improve reliability and increase performance.

9342-21, Session 4

Laser amplifier development for the remote sensing of CO2 from space

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Accurate global measurements of tropospheric CO2 mixing ratios are needed to study CO2 emissions and CO2 exchange with the land and oceans. NASA Goddard is developing a pulsed lidar approach for an integrated path differential absorption (IPDA) lidar to allow global measurements of atmospheric CO2 column densities from space. Our group has developed, and successfully flown, an airborne pulsed lidar instrument that uses two tunable pulsed laser transmitters allowing simultaneous measurement of a single CO2 absorption line in the 1570 nm band, absorption of an O2 line pair in the oxygen A-band (765 nm), range, and atmospheric backscatter profiles in the same path. Both lasers are pulsed at 10 kHz with ~25 μJ per pulse. The two absorption line regions are sampled at typically a 300 Hz rate.

A space-based version of this lidar must have a much larger lidar power-area product due to the ~x40 longer range and faster along track velocity compared to airborne instrument. Initial calculations indicated that for a 400 km orbit, a 1.5 m diameter telescope and a 10 second integration time, a ~2 mJ laser energy is required to attain the precision needed for each measurement. To meet this energy requirement, we have pursued parallel paths for the laser amplifier. These include a multi-element large mode area fiber, as well as a single a multi-pass Er:Yb:Phosphate glass based planar waveguide amplifier (PWA). In this paper we will present our laser amplifier design approaches and preliminary results.

9342-22, Session 5

1W frequency doubled VCSEL pumped blue laser with high pulse energy

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High average power pulsed blue lasers with high pulse energy are needed for certain applications such as long-range underwater detection and imaging. We previously reported on an externally frequency-doubled actively Q-switched VCSEL side-pumped Nd:YAG laser operating at 946 nm that produced 10 mJ blue pulses at 5 Hz pulse repetition frequency[1]. Here we will describe our recent efforts to significantly increase the repetition rate of the blue laser. To minimize thermal effects surface cooling of the Nd:YAG rod was implemented using chilled water as a coolant. The cylindrical gain medium was symmetrically pumped by three 808 nm VCSEL side-pumping modules each operating in QCW mode with 1 kW peak power. A laser cavity was designed to operate in a near hemi-spherical configuration with the Nd:YAG rod acting as a thermal mirror. In this configuration the cavity mode diameter is large at the laser rod, which eliminates higher order transverse modes and results in a good beam quality output required for efficient second harmonic generation. Various laser cavity configurations were investigated. More than 1 W blue output was achieved at 210 Hz with 4.9 mJ pulse energy and at 340 Hz with 3.2 mJ pulse energy with 42% and 36% second harmonic conversion efficiency respectively. Higher pulse energy was obtained at lower repetition frequencies, up to 9.3 mJ at 70 Hz with 52% conversion efficiency.

[1] Van Leeuwen, R., Xiong, Y., Watkins, L. S., Seurin, J. F., Xu, G., Wang, Q., and Chuni Ghosh; Proc. SPIE 7912, 79120Z (2011).

9342-23, Session 5

High power lasers for gamma source

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A unique Gamma Source is under construction, based on Compton Scattering. This high brightness source will involve three energetic and powerful ultrafast laser sources : one to produce the initial photoelectrons, i.e. the photocathode laser, and two lasers to interact with the accelerated electrons at two different levels of energy, i.e. the interaction lasers.

In order to overcome the 100Hz repetition rate limitation of the accelerating sections, the photocathode laser is designed to produce bursts of up to 32 pulses with 300µJ energy @266nm. This laser source is based on Ti:Sa, allowing to take benefit of its broad bandwidth to temporally shape the UV pulses. At the interaction points, each interaction laser will produce single laser pulses, that will sequentially scatter on each of the 32 electron bunches using a carefully synchronized optical recycling cavity. The interaction lasers, that will produce 200mJ each @515nm and 100Hz repetition rate with 3,5ps pulse duration, are based on Yb:YAG diode-pumped technology.

In the frame of the Interaction Laser development for the Gamma Source, we report an efficient 100mJ level laser source at 100Hz repetition rate based on Yb:YAG thin disk technology, that will be used as the front-end of the whole laser chain, in order to seed the main Yb:YAG amplifier.

Additionnally, coherent combining of the two interaction lasers is foreseen, in order to increase the pulse energy by a factor of two. A description of the concept for beam combining these two decorrelated lasers will be presented.

9342-24, Session 5

Development of high coherence 200mW 193nm solid state laser at 6 kHz

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The high coherent, high power 193-nm ArF lasers are useful for interference lithography and microprosessing applications. In order to achieve high coherence ArF lasers, we have been developing a high coherence 193 nm solid state laser for the seeding to a high power ArF laser.

We used the sum frequency mixing of the fourth harmonic (FH) of a 904-nm Ti;sapphire laser with a Nd:YVO4 laser (1342 nm) to generate 193-nm light. The laser system consists of a narrow-band Ti:sapphire oscillator seeded by a 904-nm external cavity laser diode, a Pockels cell, a 6-pass amplifier, a 4-pass amplifier, a 2-pass amplifier and a wavelength conversion stage. The required repetition rate of 6 kHz corresponding to the ArF laser, along with a low gain at 904 nm induces serious thermal lens effects; extremely short focal lengths of the order of cm and bi-focus in the vertical and horizontal directions. From the analysis of thermal lens depending on pump intensity, we successfully compensated the thermal lens by dividing a 527-nm pump power with 15, 25 and 28 W to 3-stage amplifiers with even passes, resulting in the output power above 10W with a nearly diffraction limited beam. This 904-nm output was converted to 3.8 W in the second harmonic by LBO, 0.5 W in FH by BBO sequentially. Finally the output power of 210 mW was obtained at 193 nm by mixing the FH with a 1342-nm light in CLBO.

9342-25, Session 5

Annealing temperature dependence of random lasing properties in a diamond nanoparticle film

Ryo Niyuki, Hideaki Takashima, Hideki Fujiwara, Keiji Sasaki, Hokkaido Univ. (Japan)

Random lasers have recently attracted much attention because of their unique laser oscillation phenomena without a clear cavity structure. The random structures such as nanoparticle assembly can be utilized for easily fabricated and low-cost applications such as surface emitting devices, because the disorder plays an important role for randomly distributed feedback due to the interference effects of recurrent multiple scattered light.

On the other hand, diamond nanoparticles are one of the attractive choices for composing a random laser, because diamond has excellent physical properties, i.e., a wide band gap, high thermal conductivity, various color centers, transparency from ultraviolet to near infrared regions with a high refractive index. Therefore, by using diamond nanoparticles, we expected to develop an easily fabricated and low-cost ultraviolet random laser, which would be applicable to sterilization and cleaning, medical applications, high-density recording, and a high color-rendering white light source. However, the application of diamond nanoparticles as a laser light source still remains challenging.

In this presentation, we succeeded to demonstrate a novel ultraviolet random laser using diamond nanoparticles. In the experiments, commercially available monocrystalline synthetic diamond nanoparticles (mean diameter ~25 nm) were used as scatterers and gain medium. By optically exciting the diamond nanoparticle film at an excitation wavelength of 355 nm, we observed that the nonlinear evolution of discrete sharp peaks randomly appeared at the wavelengths around the broad emission maximum (~382 nm) and their threshold intensity was estimated to be several tens of MW/cm^2.

9342-26, Session 5

Demonstration of miniaturized 20mW CW 280 and 266nm UV laser sources

Nicolas Landru, Thierry Georges, Julien Beaurepaire, Bruno Le Guen, Guy Le Bail, Oxxius SA (France)

Thanks to the strong absorption and fluorescence of Tryptophan, 280nm is the preferred wavelength for protein detection. In this paper we present the first compact laser at 280 nm that is compatible with OEM applications. The laser is based on the external cavity frequency doubling of a 300mW 561nm visible laser source. Since both the external and the visible laser cavities are based on a monolithic design, their resonance frequencies are fully insensitive to mechanical vibrations. External cavity locking on the laser frequency is thus simply obtained through temperature control. A second advantage of a monolithic design is compactness: laser and external cavities are as short as 14 mm and 20 mm respectively. Powers up to 20 mW at 280nm were obtained. So far, aging up to 1000 hours was demonstrated without degradation. Power stability, noise measurement and longer term operation will be presented at the conference. Scaling up the output power is possible through the increase of the Q-factor of the external cavity or of the visible power. The same design is also applied to build a 20 mW 266 nm laser. The way to reach even lower wavelengths will be discussed at the conference. Thanks to the diversity of available wavelengths, other applications such as deep UV resonant Raman spectroscopy could also benefit from these laser sources.

9342-27, Session 5

Nanosecond pulsed green laser source based on an extra-cavity frequency conversion from a 20μm core Yb-doped fiber amplifier

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Our aim here is to demonstrate a compact nanosecond pulsed laser source operating at 532 nm (and potentially 355 nm). Our motivation in this work is to reduce the complexity (and cost) of a nanosecond pulsed system by using only one amplification stage, few optical components and a single-pass, extra-cavity frequency conversion by using an LBO crystal. The nanosecond pulsed laser source is based on a hybrid solid state laser (SSL)/fiber amplifier operating at 1064 nm where the key component is a custom made, passively Q-switched ring cavity SSL. The Q-switched seed laser operates in single frequency, has an ultra-low noise, low timing jitter and an excellent beam quality and can be designed for pulse durations between ~5 – 50 ns and pulse repetitions rates up to ~50 kHz. Pulse durations between 9 and 30 ns and repetitions rates from 10 – 50 kHz have been evaluated in this work. The amplifier stage is made by using polarization maintaining (PM) fiber components with relatively small core/cladding diameters of 20/125 ?m. A short (30-50 cm) and highly Yb-doped fiber is used to amplify the nanosecond pulses with pulse energies up to ~340 uJ . The effect of Stimulated Brillouin Scattering (SBS) is mitigated by applying a strain distribution technique to the active fiber. Results so far are promising with pulse energies at 532 nm up to 80 uJ (@ 10 kHz, 9 ns). Higher pulse energies are believed to be reached by further improving the SBS strain distribution technique.

9342-28, Session 6

Front end for high repetition rate thin disk-pumped OPCPA beamline at ELI-beamlines

Jonathan T. Green, ELI Beamlines (Czech Republic); Jakub Novák, ELI Beamlines (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Roman Antipenkov, ELI Beamlines (Czech Republic); Frantisek Batysta, ELI Beamlines (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Charalampos Zervos, Jack A. Naylon, Tomás Mazanec, Martin Horácek, Pavel Bakule, Bedrich Rus, ELI Beamlines (Czech Republic)

The topic of this presentation is the performance of the front end for the ELI-Beamlines 1kHz short pulse beamline. The current system consists of a 25mJ picosecond thin disk pump laser which is pumping 3 stages of OPCPA in BBO. To achieve stable amplification we have constructed a jitter stabilization system to stabilize the relative delay of pump and signal picosecond pulses in the OPCPA crystals. The level of stabilization is 10fs RMS. In preliminary OPCPA amplification we have achieved 100uJ which was compressed to below 20fs and we expect to have >1mJ soon. Also to be discussed will be a high energy regenerative amplifier operating at 100mJ, 1kHz, compression, and status of 4th stage high energy OPCPA in LBO. In addition to discussing these existing systems we will present the layout of the beamline itself including the additional amplification systems which are currently under development by external suppliers and design of kW power level compressor and OPCPA.

9342-29, Session 6

Multi-pass thin disk amplifier

Karsten R. F. Schuhmann, ETH Zürich (Switzerland); Aldo S. Antognini, Paul Scherrer Institut (Switzerland); Randolf Pohl, Max-Planck-Institut für Quantenoptik (Germany); Marwan Abdou Ahmed, Andreas Voss, Thomas Graf, Univ. Stuttgart (Germany); Klaus S. Kirch, ETH Zürich (Switzerland); Birgit Weichelt, Univ. Stuttgart (Germany); David Taqqu, Max-Planck-Institut für Quantenoptik (Switzerland) and ETH Zuerich (Switzerland); Franz Kottmann, Paul Scherrer institute (Switzerland); Theodor W. Hänsch, Max-Planck-Institut für Quantenoptik (Germany) and Max-Planck-Institut für Quantenoptik (Germany)

In the context of the Lamb shift measurement in muonic helium we developed a thin-disk laser composed of a Q-switched oscillator and a multi-pass amplifier delivering pulses of 150 mJ at a pulse duration of 100 ns. Its peculiar requirements are stochastic trigger and short delay time (< 500 ns) between trigger and optical output.

The concept of the thin disk laser allows for energy and power scaling (by enlarging beam waist and pumping spot) at a high efficiency. However the single pass gain is small (about 1.2) and residual absorption in the unpumped regions is non negligible. Therefore a multi-pass scheme with precise mode matching for large beam waists (w = 2 mm) is required.

Instead of using the standard 4f design, we have developed a multi-pass amplifier with a beam propagation designed to compensate for thermal lens effects and misalignments. The beam propagation is equivalent to multiple roundtrips in an optically stable resonator.

To support the propagation we used an array of 2 x 8 individually adjustable plane mirrors. Astigmatism has been minimized by a close placement of the mirrors. To provide precise alignment the kinematic array made use of interlaced L-shaped mirror mounting flats.

We extracted pulses of up to150 mJ with a gain of 5 for 8 passes and a pump power of 500 W. The laser was running for more than 3 months without the need of realignment.

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9342-30, Session 6

Ultrafast thin-disk multipass amplifier with 1.4 kW average power and 4.7 mJ pulse energy at 1030nm converted to 820 W and 2.7 mJ at 515nm

Jan-Philipp Negel, André Löscher, Andreas Voss, Univ. Stuttgart (Germany); Dominik Bauer, Dirk H. Sutter, Alexander Killi, TRUMPF Laser GmbH (Germany); Marwan Abdou Ahmed, Thomas Graf, Univ. Stuttgart (Germany)

In recent years, there has been a growing interest in increasing the output power of ultrafast lasers to the kW-range. This allows higher productivity for laser material processing, e.g. for cutting of carbon-fiber reinforced plastics (CFRP) or for micro-machining. We developed an Yb:YAG thin-disk multipass amplifier delivering sub-8 ps pulses with 1.4 kW average power which is – to the best of our knowledge – the highest output power reported for an ultrafast laser system so far. The amplifier is seeded by a regenerative amplifier with 6.5 ps pulses and 115 W of average power at a repetition rate of 300 kHz. Taking this repetition rate into account, the energy of the amplified pulses is as high as 4.7 mJ. This was achieved using a scheme with 40 mirrors in an array to geometrically fold the seed beam 40 times over the thin-disk. The beam quality was measured to be better than M?=1.4. This system was used in first experiments to cut CFRP with very good quality and with unprecedented efficiency. Additionally, the output beam of the amplifier was frequency-doubled in an LBO crystal to 820 W output power at the second-harmonic wavelength (515 nm). In the presentation, we will show new results on further power scaling of the system, as well as third-harmonic generation to a wavelength of 343 nm.

9342-31, Session 6

First demonstration of passively mode-locked Yb:CaF2 thin-disk laser

Benjamin Dannecker, Xavier Délen, Katrin S. Wentsch, Birgit Weichelt, Univ. Stuttgart (Germany); Clemens Hönninger, Amplitude Systèmes (France); Andreas Voss, Marwan Abdou Ahmed, Thomas Graf, Univ. Stuttgart (Germany)

The need for ultra-short (sub-ps) pulsed laser systems with high power and high energy has advanced the mode-locked Ytterbium-doped thin-disk technology in the last decade. Therefore several research groups have made efforts to explore new laser crystals e.g. Yb:SSO, Yb:CAlGO or Yb:Lu2O3 for the generation of sub-500 fs pulses in thin-disk oscillators. Another promising and known candidate for ultra-short pulsed lasers is Yb:CaF2, which has been so far only used in bulk laser architecture. In this contribution, we present the first demonstration of a mode-locked Yb:CaF2 laser in thin-disk configuration. The resonator cavity was designed for eight passes through the disk per roundtrip at a repetition rate of 35 MHz. A saturable absorber mirror was used to obtain the soliton mode-locking. We achieved close-to transform-limited pulses with a pulse duration of less than 445 fs and an emission spectral width of 2.6 nm at FWHM (i.e. time-bandwidth product of 0.323). At the average output power of 6.6 W this corresponds to a peak-power of 430 kW and pulse energy of 190 nJ. To the best of our knowledge, this is the highest average output power and pulse energy using Yb:CaF2 as gain material reported to date. Taking into account the dispersion, self-phase modulation, pulse energy, output coupling ratio and laser gain, the pulse-duration estimated from the soliton-equation and our numerical calculations of pulse-propagation is in good agreement with the pulse-duration obtained in the experiment. Higher powers and shorter pulse-durations with this material are the subject of our future investigations.

9342-32, Session 6

Polarization and wavelength selective grating mirror enables efficient generation of kW-class CW green radiation

Marwan Abdou Ahmed, Martin Rumpel, Univ. Stuttgart (Germany); Montasser Bouzid, Christian Stolzenburg, Alexander Killi, TRUMPF Laser GmbH & Co. KG (Germany); Thomas Graf, Univ. Stuttgart (Germany)

Applications such as deep penetration welding of copper have been reported to be more efficient with green laser radiation due to the approximately 7-10 times higher absorption at room temperature of green radiation on copper as compared to that of near infrared (NIR) radiation. Due to the high thermal conductivity, welding of copper additionally requires high average powers to achieve reproducible and stable processes.

In the present contribution, we report on an intracavity frequency-doubled continuous wave Yb:YAG thin-disk laser with a green output power of 1045W at an optical efficiency of ~40%. This was enabled by a highly efficient polarization and wavelength selective intra-cavity grating mirror. The investigated grating mirror is operated under Littrow incidence (-1st order diffracted beam collinear to the incident beam). For TE polarization at a wavelength of 1030 nm it exhibits a nominal diffraction efficiency of >99.9% in the -1st order. With only 11%, the diffraction efficiency for TM polarization is much lower which ensures high polarization selectivity. The grating mirror is composed of a fully dielectric mirror in which a sub-wavelength grating with a period of 580nm and a depth of 80 nm is etched. The measured diffraction efficiency of approximately 99.8% over a broad spectral range from 1025 nm to 1040 nm is in good agreement with the design value and shows the high reliability of this grating mirror concept.

The design, fabrication, characterization of the grating mirrors together with its implementation inside the laser system will be presented and discussed during the talk.

9342-33, Session 6

Latest advances in high brightness disk lasers

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In the last decade diode pumped solid state lasers have become an important tool for many industrial materials processing applications. They combine ease of operation with efficiency, robustness and low cost. This paper will give insight in latest progress in disk laser technology ranging from kW-class CW-Lasers over frequency converted lasers to ultra-short pulsed lasers.

The disk laser enables high beam quality at high average power and at high peak power at the same time. The power from a single disk was scaled from 1 kW around the year 2000 up to more than 10 kW nowadays. Recently was demonstrated more than 4 kW of average power from a single disk close to fundamental mode beam quality (M?=1.38). Coupling of multiple disks in a common resonator results in even higher power. As an example we show 20 kW extracted from two disks of a common resonator.

The disk also reduces optical nonlinearities making it ideally suited for short and ultrashort pulsed lasers. In a joint project between TRUMPF and IFSW Stuttgart more than 1.3 kW of average power at ps pulse duration and exceptionally good beam quality was recently demonstrated.

The extremely low saturated gain makes the disk laser ideal for internal frequency conversion. We show >1 kW average power and >6 kW peak power in multi ms pulsed regime from an internally frequency doubled disk laser emitting at 515 nm (green). Also external frequency conversion can be done efficiently with ns pulses. >500 W of average UV power was demonstrated.

9342-34, Session 7

Double beam mode controlling diode side-pumped Nd:YLF laser with near 60% efficiency

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The double-beam mode-controlling (DBMC) is a compact side-pumped laser design that has achieved higher efficiencies than longitudinally, Ti:sapphire pumped designs. Record optical efficiency of 53.6% (63.5% slope efficiency) has been achieved with diffraction limited beam quality for a Nd:YLF laser emitting at 1053 nm. The narrower laser line of the pump diode bar used in this work is achieved by a volume Bragg gratings (VBG) and increases the spectral overlap with the Nd:YLF absorption cross section. Even more important, the spectrally narrow emission generates equal absorption depths at all pump frequencies allowing for good spatial overlap with the laser beam, which is of paramount significance in side pumped designs. At 115 W of absorbed power this new setup delivers 67 W of qcw fundamental mode output power, resulting in near 60% optical-to-optical efficiency which is, to the best of our knowledge, the highest efficiency ever reported for a Nd:YLF laser. These results highlight the advantages of the sidepumped DBMC laser scheme that in addition to its record efficiency and fundamental mode laser operation presents great simplicity and ease of power scalability.

9342-35, Session 7

LED side-pumped Nd3+:YVO4 laser at room temperature

Adrien Barbet, Hugo Grardel, Institut d'Optique Graduate School (France); Amandine Paul, Jean-Philippe Blanchot, EFFILUX (France); François Balembois, Frédéric Druon, Patrick Georges, Institut d'Optique Graduate School (France)

The lighting market has latterly made LED performance improved by orders of magnitudes. In parallel, massive production decreases dramatically LED price. Those improvements triggered new interests and since the 2000's, several research teams start to revisit the concept of LED pumped lasers, in standby since the early 80s. Polymer laser, fiber laser and semiconductors have recently demonstrated laser effect under visible LED pumping. However, no experimental results were lately presented about LED pumping bulk crystals.

For our study, we used an a-cut, 1 at.% doped, 20 mm long Nd:YVO4 crystal with a 2x2 mm2 square section. Laser faces were AR coated and two transverse faces were polished for pumping. As pump source, 2 LED arrays consisting of 18 1x1 mm2 dices and emitting at 850 nm were used in pulsed operation. In this regime, each chip emitted 100 µs pulses at 250 Hz with an intensity of 200 W/cm?. We designed a plano-concave cavity with a 500 mm radius of curvature end mirror and a plane output coupler with a transmission varying between 0.5% and 6% at 1064 nm.

We investigated the laser threshold for different output couplers and deduced the small signal gain versus the pump energy. A gain of 6% has been obtained at maximum pump energy. The laser emitted 65 µs pulses with an energy of 40 µJ (obtained with the 1% output coupler) for a pump energy of 7.4 mJ. This represents, to our best knowledge, the first demonstration of a Nd:YVO4 laser pumped by LED.

9342-36, Session 7

Direct vortex generation from a diode-pumped Alexandrite laser

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Optical vortices exhibiting orbital angular momentum have attracted significant interest lately due to their application in wide-ranging fields, such as super-resolution microscopy and laser materials processing. Wavelength versatility can increase this application base and vibronic gain media are an attractive source of wavelength-versatile lasers. Alexandrite belongs to this class of lasers, boasting numerous properties that make it suitable for high power/energy operation in the wavelength region ~700—850nm. A key feature is the capability for high-power diode-pumping using red laser diodes, so compact and efficient Alexandrite laser sources can be realised. This work investigates the potential of diode-pumped Alexandrite as a source of wavelength-versatile optical vortices.

We demonstrate the direct generation of an optical vortex from a diode-pumped Alexandrite laser, utilising spherical aberration of a thermally-induced lens in the gain medium to preferentially select LG01 (vortex) mode. This is the first time, to our knowledge, that an optical vortex has been generated directly from a vibronic laser.

We present results of diode-pumping an Alexandrite slab laser, producing an optical vortex with 2W output power at ~755nm, with measured M2 values of M2x = 2.29 and M2y = 2.44. Spiral and fork interferograms are demonstrated, verifying that the beam has angular momentum: a single spiral and fork indicate a vortex whose phase traverses 2ϖ. Handedness of the vortex could be controlled by adjusting intra-cavity elements. The spatial profile shows the beam retains its 'doughnut' shape through the focus of a lens, and in the farfield.

9342-37, Session 7

Testing of antireflective surface structures on windows for high energy laser systems in operational environments

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The practical use of high transmission windows for kW-level high-energy laser applications is often limited by the antireflection coatings required to maximize transmission. Such AR coatings can be sensitive to laser damage as well as environmental degradation in land- and sea-based applications, whereby sand or salt water can erode the coatings and reduce transmission. We report on tests simulating operational environments that were conducted on silica glass windows with novel, anti-reflective (AR) surface structures etched directly into the surface of the windows. These AR surfaces provide high transmission (> 99.9% T) with no extraneous materials present on the window and have been shown to have high laser damage thresholds at 1.06 µm. Tests to simulate operational environments were conducted according to standard military specifications for temperature cycling, rain and sand erosion, and salt fog testing on windows with and without AR surfaces as well as with traditional AR coatings. We also report results for fabrication of the AR surface structures on windows approaching practical sizes of 20 cm to 30 cm diameter.

9342-38, Session 8

Generation of radially-polarized and azimuthally-polarized beams in the two-micron band using a space-variant half-wave plate

Di Lin, Peter Shardlow, Alex C. Butler, Martynas Beresna, Peter G. Kazansky, W. Andrew Clarkson, Optoelectronics Research Ctr. (United Kingdom)

Radially and azimuthally polarized beams have attracted growing interest for use in a variety of applications. The most popular way to obtain these beams at relatively low power levels is to transform a linearly-polarized TEM00 beam into a radially or azimuthally-polarised beam using an external polarisation mode converter. Traditionally, these converters were constructed from an arrangement of half-wave plates bonded together to form a segmented spatially-variant retardation plate and, as a consequence, they generally suffered from low polarization purity and low transformation efficiency. However, recent work on femtosecond laser writing of nanostructure gratings in silica glass has allowed the realization of a new type of polarization converter with improved performance. In these converters the grating structures induce birefringence with slow and fast axes aligned parallel and perpendicular to the grating direction respectively, allowing the construction of a continuously space-variant half-wave plate (S-waveplate). S-waveplate provides dramatically improved polarization purity compared to segmented retardation plates. Here we report on an S-waveplate designed for use in ~2μm wavelength band for use with Tm-doped and Ho-doped solid-state lasers and fiber laser. The S-waveplate was tested with a relatively low power (~1.5 W) tunable Tm fiber laser yielding a donut-shaped radially-polarized (or azimuthally-polarized) beam with a polarization extinction ratio (PER) of 18dB and a transmission efficiency of ~86%. The beam propagation factor (M2) was measured to be ~ 2.1 and hence in close agreement with the theory. The prospects for further scaling output power and improving efficiency will be discussed.

9342-39, Session 8

Fully vectorial laser resonator modeling by vector extrapolation methods

Daniel Asoubar, Friedrich-Schiller-Univ. Jena (Germany) and LightTrans VirtualLab UG (Germany); Michael Kuhn, LightTrans Virtual Lab UG (Germany); Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

As a consequence of the rising number of optical components used in a laser resonator, the design freedom and the number of free parameters are rising. The optimization of such multi-parameter resonator setups requires flexible simulation techniques beyond the scalar approximation. Therefore we generalize the scalar Fox and Li algorithm for the dominant transversal resonator eigenmode calculation to a fully vectorial model, which is based on a set of coupled operator equations. This modified eigenvalue problem is solved by using two polynomial-type vector extrapolation methods, namely the minimal polynomial extrapolation (MPE) and the reduced rank extrapolation (RRE). Compared to other eigenvalue solvers these techniques also can be applied to resonators including nonlinear components. As an example we show the calculation of a pure azimuthally polarized eigenmode emitted by a resonator setup with an intracavity discontinuous phase element and a nonlinear active medium. The simulation is verified by experimental results.

9342-40, Session 8

Fully dielectric high efficiency and broadband pulse compression gratings for CPA laser systems

Martin Rumpel, Univ. Stuttgart (Germany); Michael Moeller, AMO GmbH (Germany); Marwan Abdou Ahmed, Thomas Graf, Univ. Stuttgart (Germany)

Chirped pulse amplification is a well-recognized concept for scaling of laser pulse energies. This is done by stretching, amplifying and recompressing of laser pulses. Diffraction gratings have proven to be especially useful for the task of stretching and compressing. These key components need to have high diffraction efficiencies, high damage thresholds and are ideally inexpensive. Our approach to realize all these requirements is the combination of a planar optical waveguide to a sub-wavelength diffraction grating and a dielectric mirror, which is known to exhibit very interesting spectral and polarizing properties. With this concept, we could so far demonstrate gratings with measured diffraction efficiencies of 99.9% and total compressor efficiencies of >96% (4 grating passes). New design approaches allow obtaining high efficiencies of > 99.7% over a broad spectral bandwidth of 60 nm. This is by far enough to cover most of the novel Yb-doped gain materials. Additionally, improved designs allow compensating most of the typical manufacturing tolerances that are inherent in the manufacturing process. LIDT measurements of our gratings so far revealed ~ 0.2J/cm2 in the fs domain. New gratings based on improved coating materials such as HfO2 will be presented. It is expected to improve the LIDT to up to 1J/cm. In this presentation we will discuss the manufacturing of the gratings, summarize the laser experiments and introduce and discuss our improved design concepts, especially for gratings which require a high LIDT and large dispersion.

9342-41, Session 8

Tube solid-state laser with zigzag propagation of pump and laser beam

Michael S. Savich, Consultant (United States)

This paper describes design of the Tube Solid-State laser with Zigzag Propagation of Pump and Laser Beam.

Tube solid state laser (SSL) combines many of the attractive properties of rod, slab, and disk lasers and overcame many of the disadvantages. An ideal annular laser resonator configuration may combine the advantage of beam quality, which is inherent in the unstable linear resonator with advantages of efficient use of area and thus high power, and of symmetry inherent in the annular configuration. This also includes an optical element known as an axicon (waxicon or reflaxicon) to convert the annular beam to a compacted cylindrical one. Configuring the lasing medium a cylindrical shape allows large lasing volume to be realized with compactness and, structural rigidity extract High Power from lasing medium, while maintaining good beam quality. Biggest problem to develop laser tube configuration for high-average power (HAP) SSL was before possibility manufacturing crystal or poly crystalline laser tube with acceptable size to generate HAP SSL. Today many company can manufacture and machine single crystal and crystalline tube. Additional using new MAGNETORHEOLOGICAL (MR) JET medium and annular technology can provide inner surface finish of laser C-YAG tube up to 50-10 Angstrom range resonator configuration. It will be permits designers of High Power lasers shift today their attention to cylindrical lasing. Patent No. US 7,430,230 B2 –Side Pumping HAP Tube Solid State Laser overcomes some thermal lensing problems, eliminates birefringence and bifocussing scrambling polarization and sophisticated alignment problems of tube SSL. But a single tube laser has some limitation in selecting lasing (gain media) material because of the short absorption path and required high absorption cross-section of the lasing material. The short absorption path in combination with small absorption cross-

section necessitates high doping, which in turn can require very high pump intensities, which may be some times unpractical. Also was not solve thermal stress-distortion problem.

Novel resonator and pumping design with Zigzag propagation of pumping and laser beams permits improved tube SSL and solve problem described above and producing a high power laser beam (e.g. from 100 kW to 1000kW). Novel design providing amplifier module comprising: a tube having an interior and exterior surfaces, a gain elements with not doping ends or endcups; a first substrate adjacent the interior surface; a second surface adjacent the exterior surface of tube; a plurality of fiber coupled diode laser with collimating lenses placing around the surface of a laser tube and inserting on both not dopping ends of laser gain element to provide optical pump radiation to the laser gain elements; a vacuum chamber with optical bench and front and back windows, vacuum free oil system , feed through plate, coolant manifold. The amplifier module further comprising one high reflection mirror instead optics operably coupled at end of tube and scraper mirror outside vacuum chamber or using instead front window outcupler-feedback mirror, amplifier can be transformed to laser oscillator.

The tube-shaped SSL includes a gain element fiber-optically coupled to a pumping source. The fiber optic coupling is such that light entering at compound Brewster's angle of incident to the laser gain element and use Total Internal Reflection follows a "zigzag" path in a generally spiral direction along the length of the tube. The tube-shaped SSL also includes optics and a cooling system to provide zigzag propagation of a laser beam and to permit use of a continuous wave operation and high energy pulse configuration.

Novel pumping geometry permits to pump the material with high pump power density and uniformity for reaching threshold without increasing the temperature of the crystal too much, that reducing the thermal effects like thermal lensing and stress in the crystal. Using high pump density through the crystal is therefore key to achieve low threshold and high efficiency because this help to reduce the thickness of crystal and the doping concentration, simultaneous. Also permits use Quasy-three-level materials with cryogenic cooling system to build laser with highest efficiency and beam quality.

A novel method of lasing permits reach high volume of gain medium, high pump density and uniformity, high gain amplification, high power extraction from lasing medium, high pumping and lasing efficiency, high beam quality, minimize thermal and stress-distortion effect and combining a plurality of amplifier modules to one another for amplification of laser beam.

9342-42, Session 8

In-phase synchronization of array laser using intra-Talbot-cavity second harmonic generation

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Talbot cavity is passive method to synchronize the phase of array lasers. Because the Talbot cavity does not need any electrical feedback systems, we believe that Talbot cavity is the most suitable technique to combine a considerable number of laser array into a compact system. A well-known drawback of the Talbot cavity is that it can produce out-phased array and their far-field image has 2-peak profile. To solve this drawback, we developed a frequency doubled laser array based on intra-Talbot-cavity second harmonic generation. Basic concept is second harmonic generation of the out-phased array generated from the Talbot cavity. Because the second harmonic wave is generated proportionally to the square of the fundamental wave, out-phase flips to in-phase. Our Talbot cavity is composed of a pumping 808-nm laser diode array with 15 emitters, an Nd: YVO4 planar waveguide, a PPLN planar waveguide, an f=10 cylindrical lens, and an output coupler (high reflection for 1064 nm and high transition to 532 nm). The pump laser beams are directly launched into the Nd: YVO4. The fundamental wave (1064 nm) oscillates between the Nd: YVO4 and the output coupler and generates second harmonic wave (532 nm) at the PPLN placed next to the Nd: YVO4. The round-trip optical path of the cavity length is set to 1/2 Talbot length so that Talbot cavity forms for the fundamental wave. As a result, we obtained 1-peak far-field image of second harmonic wave from the intra-Talbot-cavity second harmonic generation.

9342-43, Session 8

Control of random lasing properties within a submicrometer-sized ZnO spherical particle film

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Random lasers have attracted much attention because of their unique laser oscillation phenomena without a clear cavity structure, in which the disorder plays an important role for providing randomly distributed feedback due to the interference effects of recurrent multiple scattered light. Recently, we have succeeded to develop an unique random laser exhibiting quasi-single-mode, low background emission spectrum, and low lasing threshold by using a homogenized submicrometer-sized zinc oxide particle film dispersed with intentionally introduced polymer particles as point defects. In this structure, we expect that the controls of the resonant frequency, localization position, and the probability of single mode lasing can be realized by adjusting the sizes of individual scatterers and defect particles.

In this presentation, in order to verify the controllability of random lasing properties within our proposed unique random structure, we examined the characteristics of random lasers by changing the sizes of defects and scatterers. From the results, we confirmed that the lasing wavelengths were blue-shifted by decreasing the size of ZnO spherical nanoparticles, but the thresholds and the number of lasing peaks almost unchanged. On the contrary, by decreasing the defect particle size, the number of lasing peaks also decreased and the probability of the single mode random lasing increased, while the lasing wavelengths unchanged. These results suggested that our proposed structure could provide the controllability of lasing properties even in random structures.

9342-44, Session 9

Metrology of low-symmetry monoclinic crystals for laser applications: The case of europium-doped borate crystals

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Among natural and synthesized crystals, many belong to the monoclinic system, thus appertaining to the biaxial optical group. Despite their inherent complexity to handle and to properly orientate, there are many existing applications based on the use of monoclinic crystals as nonlinear optical parametric frequency conversions with BiB3O6, self-frequency conversion with bi-functional laser and nonlinear crystals as Nd:YCa4O(BO3)3, slow light creation with Eu:YSO, or commercially available femtosecond laser systems (Yb:KGW).

Nevertheless, spectroscopic studies in monoclinic crystals are still largely performed as if such biaxial materials were from the orthorhombic system, a crystallographic system with a higher level of symmetry. Indeed, optical properties in a monoclinic crystal are partially free from the crystallographic structure. In this framework, we have recently demonstrated that the angular distributions in polarized light of linear absorption or fluorescence emission, show extreme values along specific directions that differ from the principal axes of the dielectric frame [1]. For instance, for laser [2] or scintillation [3] applications based on monoclinic crystals, it appears as a real challenge to determine first the dielectric frame orientation [4], and then these optimal directions, to access the optimal absorption/emission cross-sections and thus to optimally exploit the applicative potential of any crystal candidate.

These last years, we developed the fundamental description (both analytical and numerical) and methodological tools to perform the relevant metrology of spectroscopic properties in monoclinic crystals. Here, we will present our recent advances to optimally cope with monoclinic systems, especially by studying rare earth doped Eu3+:Li6(Ln=Y,Gd)(BO3)3 borate monoclinic crystals.

9342-46, Session 9

Er and Yb co-doped glasses for eye-safe lasers

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Erbium-doped bulk glasses are of high interest to many applications in the defense and medical fields. The Er3+ laser performance in materials, especially in glass, can be enhanced by co-doping with large amounts of Yb3+, thus enabling laser diode pumping of Yb3+near 980 nm. In order to enhance the absorption of the flash-lamp light, Cr is added. Ce is introduced into these glasses as an anti-solarant. In recent years, q-switched and uncooled operation of Er-glass lasers and resonantly pumping Er3+ with diodes has gained popularity. Depending on the pump scheme, one or more of these ions in the glass may not be necessary and may prove to be deleterious to the laser performance. Thus, for the development of future eye-safe laser products, an internal research program focused on examining the complex interactions between the active and sensitizing ions was conducted and recently completed.

As part of this effort, 26 different glasses were manufactured, with each containing various amounts of the four ions in the 3+ valence state. Over the course of the last two years, each glass was characterized for it's optical, mechanical, thermal, and laser properties. The collected data was grouped and analyzed to form a generalized picture of thermal, mechanical and laser performance from solid-state architectures that utilize the bulk glasses as the active gain material. Special attention was given to laser performance characterizations of these glasses.

The laser properties, the absorption/emission cross-section, bandwidth, radiative lifetime, and the gain coefficient for 50% inversion are all calculated from the absorption and emission data. These properties are calculated from the measured absorption data with McCumber or Reciprocity calculation methods or we can use the Füchtbauer–Ladenburg equation with an observed emission curve. The problem with the latter is the emission measurement. The collected emission signals from the same glass with three different instruments and have produced a different curve from each instrument. Thus, it became apparent that the measurement conditions for absorption and emission have a significant impact on the calculated laser properties. The main contributor to such dramatic changes in the measured data is identified to be the Yb3+ in these glasses. Yb is typically incorporated in large amounts (10's of wt%) in glass where it is known to absorb its own light. Thus, for an accurate analysis of laser properties with the variations in active ion concentrations, it is necessary to standardize these measurements. Instrument related contributions to the collected data are tediously analyzed and isolated until stable measurement conditions for accurate results are identified. The fluorescence lifetimes of erbium and ytterbium were measured separately by selecting 1550 nm and 1000 nm emitted light with 10 nm FWHM interference filters. Analysis of the temporal emission from ytterbium also allowed for the determination of energy transfer efficiency for each of the samples doped with both erbium and ytterbium. After the pulse has been absorbed and the excitation pulse removed (defined as t = 0) the 1550nm emission (assigned to the 4I13/2 to 4I11/2 transition in erbium) from the sample was observed to decay. Sample thickness effects on lifetime are determined by extrapolating to zero concentration lifetimes for both Er and Yb.

Preliminary reports on this data were discussed in previous conferences. In this paper, a summary of the methodology required for calibrating spectrophotometric and fluorescence emission measurements are detailed for general consumption. A method for achieving wavelength calibration of the fluorescence unit to be better than 0.2nm is also detailed. A comparison of the calculated laser properties and measured laser performance for the different glasses in the study is outlined with any observable correlations to active ion concentrations. Laser output is measured from these glasses by end-pumping with a fiber-coupled diode and by side-pumping rods and slab geometries using both diodes and flash-lamps. We attempt to compare doping effects on side-pumped and q-switched configurations as well.

9342-47, Session 9

Glass development for an exawatt laser architecture

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Current high power laser systems are classified into two groups. High energy laser systems produce a large amount of energy that is delivered over relatively long periods of time. The NIF laser perhaps the best known of these, delivering 2 megajoules with a peak power of 500 Terawatts. The other main type is short pulse lasers such as Ti:Sapphire lasers and the Texas Petawatt laser, which can deliver up to 100J and peak powers of up to 1 Petawatt. In order to assess the feasibility of producing laser pulses that are one thousand times more powerful than any yet produced, SCHOTT, along with National Energetics and LOGOS Technologies were contracted by the High Energy Laser- Joint Technology Office materials development and systems modeling. The proposed Exawatt laser combines key elements of the previously demonstrated high energy and short pulse lasers as demonstrated at the Texas Petawatt Laser facility at the University of Texas, Austin [1].

The Texas Petawatt Laser has proven that it is possible to combine two laser glasses with different gain spectra together to create laser powers exceeding the world's largest Ti:Sapphire systems, but at a fraction of the cost. While this technology is a proven route to high power compressed-pulse Petawatt lasers, the laser glasses at its heart still do not provide the necessary bandwidth to allow further scaling to the Exawatt level. SCHOTT North America, the world's leading manufacturer of laser glass, proposed the creation of two new laser glasses which would allow the extreme energies and pulse compression necessary to reach one Exawatt. Additionally, these new materials and architectures provide the opportunity to construct Petawatt systems with greatly reduced size, complexity and cost as compared to existing Ti:Sapphire designs, which has implications in the scientific and commercial laser markets and the defense industry.

The glass development portion of the project sought to not only create and test these new glasses, but to define the architecture of the laser systems in which they could be used. It was discovered through the numerical modeling performed by LOGOS and National Energetics that it is not the gain-bandwidth, as originally supposed, but the difference in the peak wavelength of the gain spectra for the two laser glasses to be used which is most important for providing high compressibility laser pulses. SCHOTT was

able to meet all requirements of the new laser architecture defined by the program. The most highly red-shifted glasses developed for this program have emission peak wavelengths beyond 1068nm and are expected to prove sub-100fs pulse durations at gains of up to 106. For comparison the best current production glasses could only supply a gain of 103 at this pulse duration. Simultaneously, the thermo-mechanical properties of the glasses have been improved as compared to the commercial glass types, allowing higher repetition rates and greater average power for Petawatt applications. In addition to the glass compositions themselves, novel melting and forming technique were utilized to enable high quality glass to be produced from these challenging new formulations. This result exceeds the overall target of the glass development effort and is predicted to be sufficient for the creation of an Exawatt laser facility with pulse durations of only 100 fs.
In this paper, we outline the targets of the program, the properties of the newly developed glasses, and the calculated performance expectations from these glasses as was determined at the completion of the project.

9342-48, Session 9

Schlieren imaging of bulk scattering in transparent ceramics

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Bulk scattering in polycrystalline laser materials (PLM) is regarded as the primary loss mechanism leading to degradation of laser performance. A modified white light Schlieren imaging technique is developed to accurately and rapidly image the local spatial variations in the refractive index across the entire ceramic laser material sample. The high sensitivity of the technique developed allows for direct imaging of the slightest spatial refractive index variations (and thus bulk scatter loss) in the PLMs over the entire cross sectional area of the sample.

9342-49, Session 9

Energy transfer upconversion measurements for popular neodymium-doped crystals

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We report our investigations on measuring the energy transfer upconversion (ETU) parameter in various neodymium-doped laser crystals (YAG, YVO4, GdVO4, KGW, and YLF) via the z-scan technique. Starting with a simple two-level macro-parameter spatially dependent rate equation model we obtain a good correlation for Nd:YAG at different concentrations and crystal temperatures, however the other crystals illustrate significant deviation between simulation and measurement. Currently we attribute this difference to energy migration between neighbouring ions in the respective samples, for which a more detailed model is currently being considered. Of the tested materials Nd:YAG appears to have the lowest ETU macro parameter, at around 0.35 x10-16cm3/s for a 0.6at.% doping concentration, compared with nominally thrice this for 0.5at% Nd:YLF and almost an order of magnitude higher for the 0.5at.% vanadates (YVO4 and GdVO4). These values are significant for determining additional heat load in the respective gain media, especially when trying to increase the output power/energy from lasers employing these crystals, typically achieved by increasing the pump and cavity mode size.

9342-50, Session 10

First experimental results towards a 100 W wavelength tunable femtosecond OPCPA

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Optical parametric chirped-pulse amplification (OPCPA) is the most promising method for providing compact, wavelength-tunable, high power femtosecond lasers. We have recently achieved 100 W at 800 nm with 30 fs pulse duration in burst mode (100 kHz in a 800 µs burst at 10 Hz). Furthermore, up-to-date measurements of the absorption coefficients at 515 nm of borate crystals, BBO, LBO and BiBO have been performed [1]. These measured absorption coefficients are a factor of 10-100 lower than reported by the literature for BBO and LBO. These results demonstrate the possibility of high power (continuous mode, with powers greater than 100 W), ultrabroadband optical parametric chirped-pulse amplifiers [2]. As a first OPCPA stage, we developed a compact wavelength-tunable, sub-30 fs amplifier with 11.4 W average power, with 20.7% pump-to-signal conversion efficiency [3]. In this work, we discuss the challenges in developing compact, wavelength-tunable, high power femtosecond lasers using OPCPA. In particular, power scaling limits and various dispersion management schemes will be discussed.

1. R. Riedel, et al., "Thermal properties of borate crystals for high power optical parametric chirped-pulse amplification," Opt. Express 17607—17619 (2014).

2. M. J. Prandolini, et al., "Design considerations for a high power, ultrabroadband optical parametric chirped-pulse amplifier," Opt. Express 22, 1594–1607 (2014).

3. R. Riedel, et al. "Power scaling of supercontinuum seeded MHz-repetition rate optical parametric chirped pulse amplifiers," Opt. Lett. 39, 1422–1424 (2014).

9342-51, Session 10

High energy multiwatt femtosecond diode-pumped Yb:CaAlGdO4 and Yb:CaF2 regenerative amplifiers

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High peak power, high energy, femtosecond laser pulses are the key element in many scientific and industrial applications such as non-linear optics and high precision micromachining.

Yb:CaAlGdO4 (Yb:CALGO) and Yb:CaF2 are very promising laser gain materials for high power ultrashort pulse generation, as they combine two very important properties: high thermal conductivity allowing for high-power pumping and comparatively broad emission spectra among all Yb-doped materials.

Here we report - to the best of our knowledge - the first single-crystal, Ytterbium-doped regenerative amplifiers delivering pulse energies >1 mJ at 5 kHz and room temperature with pulses shorter than 400 fs.

The first setup consists of a diode-pumped Yb:CALGO oscillator with a grating-based pulse stretcher, seeding a 4-mm long, 2% doped Yb:CALGO regenerative amplifier followed by a grating compressor. With this setup and at 65 W of pump power, pulse energies of up to 1.13 mJ at 5 kHz and 380 fs pulse duration could be demonstrated, corresponding to an average output power of >5.5 W and a peak power of ≈2.6 GW. The M2 value was ≈ 1.3 in both axes up to full pump power. In the second setup, we simply changed the crystal in the regenerative amplifier to a 4-mm long, 2.7% doped Yb:CaF2 crystal. At 5 kHz, we obtained compressed pulses of 334 fs with an energy of 1.02 mJ, corresponding to ≈3 GW of peak power. An M2 value of ≈ 1.1 was measured up to full pump power.

9342-52, Session 10

Single grating mirror intracavity stretcher design for chirped pulse regenerative amplification

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In this contribution, we report for the first time, to the best of our knowledge, a simple and innovative approach for intracavity pulse stretching in regenerative amplifiers (RAs). The intracavity stretcher relies on a single-reflection grating based on a leaky-mode grating-waveguide design. The grating is placed at one side of the RA cavity followed by a lens and a high-reflectivity end-cavity mirror. In this configuration, during the odd round trips, the beam is propagating spatially dispersed in the cavity, whereas in the even round trips the wavelengths are spatially recombined.

We experimentally proved the effectiveness of this new concept in a Yb:CALGO based RA followed by a standard grating compressor. The system layout consisted of a Yb:CALGO seeder providing 95-fs-long pulses and a RA employing a 4-mm-long, 2% doped Yb:CALGO crystal as active medium. After amplification and compression we obtained 193-fs-long pulses (stretched pulses ≈140 ps) with a maximum energy of 204 µJ at 20 kHz repetition rate. The performance of the system can be further improved both in terms of pulse energy and pulse duration. The spot size on the grating can be increased in order to allow pulse energy scaling and a better matching between the grating stretcher and grating compressor should allow a significant pulse shortening. With a higher stretching factor (≈400 ps), a pulse energy of up to ≈700 µJ was obtained before compression. Even without compressing these pulses, the potential and robustness of leaky-mode grating-waveguide gratings could be demonstrated successfully.

9342-53, Session 10

Compact, multi-pass OPCPA system at 100kHz repetition rate with a CPA-free pump source

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We present a multi-pass 100 kHz OPCPA system pumped by a multi-stage solid state amplifier design. It enables a compact CPA free pumping scheme and thus allows for a very compact (75 cm x 210 cm) OPCPA system. It is seeded by a commercial Ti:sapphire oscillator (VENTEON PULSE : ONE OPCPA SEED) capable of directly seeding a fiber based pre-amplifier operating at 1064 nm. After pulse picking to 100 kHz, the solid state Nd:YVO4 main amplifier (neoVAN-2P, neoLase GmbH) delivers 190 µJ of pulse energy with about 10 ps of pulse duration. Due to the absence of stretcher and compressor, no additional losses occur after amplification, so that a very efficient conversion to 532 nm is achieved and pump energy of 32 µJ / 93 µJ is obtained for the first / second OPA stage respectively. Broadband parametric amplification takes place in two BBO crystals which were operated in a double-pass configuration. This allows for high efficiency even with a shorter pulse duration of the ultra-broadband signal pulse which is then easier to recompress by a chirped mirror compressor. Detailed investigations of the benefits and drawbacks of this method are presented. With a pulse duration around 10 fs and several µJ of pulse energy obtained in this first study, this technique is a promising alternative to more complex pumping schemes as thin-disk regenerative amplifiers or rod-type fibers, allowing more compact OPCPA systems with less complexity.

9342-54, Session 10

CEP-stable, few-cycle OPCPA system at high repetition rates

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Many applications like high-order harmonic generation (HHG) and photoemission electron microscopy (PEEM) will benefit from recent development in high repetition rate few-cycle OPCPA laser systems. This was recently demonstrated by using a compact, CEP-stable, few-cycle OPCPA system with 10 µJ of pulse energy and pulse durations of 6.3 fs pulse duration at 200 kHz repetition rate [STh3E.3 CLEO:2014]. The OPCPA system is seeded by a commercial CEP-stabilized Ti:sapphire oscillator (VENTEON PULSE : ONE OPCPA SEED) delivering without any external spectral broadening an octave-spanning spectrum from 600-1200 nm. The spectrum serves on the one hand as broadband signal for the parametric amplification process and on the other hand as narrowband seed for an Ytterbium-based fiber preamplifier with subsequent main amplifier and frequency doubling. Currently, the available pulse energy is limited by nonlinearities from the fiber amplifier and the compression efficiency. By changing the stretching and compression scheme, higher pump energies of several hundred µJ will be possible. Further improvements, such as additional or multi-pass OPA stages allow for dramatic upscaling of the achievable parametric output power. Through these changes higher average as well as peak power for the few-cycle pulses is possible, making the up-scaled OPCPA system an ideal light source for HHG experiments. Compared to the current system, the increased pulse energy will relax the focusing conditions for HHG and lead to higher photon flux.

9342-55, Session 10

High average power picosecond laser for selective material processing at 1342nm wavelength

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We demonstrate results of design and optimization of high average output power picosecond laser operating at 1342 nm wavelength for selective material processing. This laser is comprised of mode locked master-oscillator, regenerative amplifier and output pulse control module. Passively mode locked by means of semiconductor saturable absorber (SESAM) and pumped with 808 nm wavelength Nd:YVO4 master-oscillator emits ~10 ps pulses at repetition rate of 55 MHz with average output power of ~140 mW. The four-pass confocal delay line with image relay is used as a longest part of the oscillator cavity in order to suppress thermo-mechanical misalignment. Optimization of intracavity incident fluence applied to semiconductor saturable absorber (SESAM) ensures significant lifetime improvement. This oscillator was used for efficient seeding of regenerative amplifier based on composite diffusion-bonded Nd:YVO4 rod pumped with 880 nm wavelength. When operating at 300 kHz repetition rate laser delivers high quality output beam with average power in excess of 10 W at 1342 nm wavelength.

9342-56, Session 11

1mJ single-rod fiber Er:glass laser for rangefinding

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Experimentally, the pumping source was 16 W semiconductor laser diode bar with high- and antireflection coatings on the cylindrical lens beam collecting system and maximum of the emission spectrum at 940 nm. 5 ms pulsed electrical double-pass pumping with diffuse reflector was used to achieve efficient output power operation. The optimal length (5 mm) and diameter (1mm) of the active rod were calculated for efficient ytterbium (2.5 x 10^21 per cm3) and erbium (2.7 x 10^19 per cm3) concentrations. Free-running pulse mode output energy was 12 mJ with a slope efficiency of 16%.

To ensure Q-switching we used a passive gate which operates in a temperature range and provides transverse mode selection. Different passive gates were examined to implement Q-switch mode, and the contrast and the residual transmittance were determined. Transparent glass-ceramics containing Co2+:MgAl2O4 nanocrystals was selected as the optimal passive gate.

Thus, we created a low-power compact eye-safe laser with length 60 mm and 15 mm diameter, working in a wide temperature range. Average power consumption at 1 Hz and 3 Hz pulse repetition frequency is 0.18 W and 0.54 W respectively. It works with a repetition rate of 1 Hz with the possibility of short-term operation with 3 Hz repetition rate. Small size and effectiveness of our laser are promising for the development of compact rangefinding systems.

9342-57, Session 11

A cryo-cooled high-energy DPSSL system delivering ns pulses at 10 J and 10 Hz

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Lasers generating multi-J to kJ ns-pulses are required for many types of laser-plasma interactions. Such lasers are either used directly for compressing matter to extreme densities or they serve as pump lasers for short-pulses laser chains based on large-aperture Ti:sapphire or parametric amplifiers. The thus generated high-energy fs-pulses are most useful for laser driven secondary sources of particles (electrons, protons) or photons (from THz to gamma). While proof-of-principle experiments have been carried out with flashlamp-pumped glass lasers, lasers with much higher efficiency and repetition rate are required to make this applications practically viable. We have developed a scalable new laser concept called DiPOLE (diode pumped optical laser for experiments) based on a gas-cooled ceramic Yb:YAG multi-slab architecture operating at cryogenic temperatures. While the viability of this concept has been shown earlier [1], we have now reached our target performance of 10 J pulse energy at 10 Hz repetition rate at an optical-to-optical efficiency of 21 %. To the best of our knowledge, these are record values for average power and efficiency for lasers of this type. We have also upgraded the system by adding a fibre-based front-end system with arbitrary pulse shaping capability and by installing an image-relayed multipass system enabling up to eight passes of the main amplifier. We have then used this system to demonstrate frequency doubling with 65 % conversion efficiency and a long-term shot-to-shot stability of 0.5% rms over a total of nearly 2 million shots, achieved in runs extending over 4 to 6 hours.

[1] S. Banerjee, K. Ertel, P. D. Mason, P. J. Phillips, M. Siebold, M. Loeser, C. Hernandez-Gomez, and J. L. Collier, "High-efficiency 10 J diode pumped cryogenic gas cooled Yb:YAG multislab amplifier, " Opt. Lett. 37, pp. 2175-2177 (2012)

9342-59, Session 12

Mode-locking in intracavity frequency doubled Nd:YVO4 laser

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Passively mode-locked Nd lasers using intracavity second harmonic generation already find applications in medicine, nonlinear optics and spectroscopy. The advantages of these laser sources are to create an alternative to the conventionally used SESAM mode-locked devices which currently dominate the market but are more expensive, and have a limited range of the power scaling.

Experimentally studied Nd:YVO4 laser has 109 mm cavity length with 1*3*3 mm3 active element pumped by commercial 808 nm diode laser, and 5*3*3 mm3 KTP crystal. A stable mode-locked operation was achieved by pumping Nd:YVO4 with 600 mW which resulted in 67 mW average output power.

In order to investigate the mode-locked operation properties, we characterized RF spectra and optical spectra versus pump power, the KTP crystal temperature and position, the output coupler reflectivity, and the intracavity polarizer. To model the dynamics of our device, we considered cascaded ?(2) lensing in KTP, frequency doubling nonlinearity, and Kerr lens formed in Nd:YVO4.

Effective mode-locking formed ultra-low noise beat signal at 1.378 GHz that can be used for controlled and stable RF generation. The intracavity polarizer implements a Lyot filter allowing selecting a group of modes from ~100 GHz width spectrum without hindering mode-locking capability. We found that additional cavity length modulation at the frequency 10 kHz via PZT mounted on an output coupler does not affect the RF signal stability. These results are promising for development of a feasible alternative to SESAM based devices for 532/1064 nm spectral range applications and open a new perspective for stable RF signal generation by transferring optical reference stability (iodine absorption lines) into RF domain.

9342-60, Session 12

Current status of Kumgang laser system

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In this presentation, the authors will introduce the current status of the Kumgang laser system, a 4 kW laser system using stimulated Briillouin scattering phase conjugation mirrors (SBS-PCMs). The Kumgang laser system consists of a front-end (FE), a pre-amplifier (PA), a coherent beam divider/combiner, and 4 main amplifiers (MA). FE system is a hybrid master oscillator-power amplifier (MOPA). Hybrid MOPA FE produces a single frequency seed beam of 1064nm, at a repetition rate 10 kHz. The line-width of the seed beam is 95 MHz, and the pulse width of the seed beam is typically 8.5 ns. The average output power of FE is 5.1 W (0.51 mJ / 8.5 ns / 10 kHz). The seed laser beam from FE is amplified by PA from 5.1 W to 200 W (20 mJ / 8.5 ns / 10 kHz). PA utilizes a Nd:YAG rod as its gain medium. After the amplification process, the laser beam will be divided into 4 sub-beams by the coherent beam divider/combiner. MA is double-pass amplifier. The sub-beams will be amplified by MA and as a result, the output power of each sub-beam is expected to be 1 kW (0.1 J / 8.5 ns / 10 kHz). The wave-front distortion of the each sub-beam during the double-pass amplification can be compensated by self-controlled SBS-PCMs. The sub-beams will be combined by the coherent beam divider/combiner. The output power of the entire system is expected to be 4 kW (4 x 0.1 J / 8.5 ns / 10 kHz).

9342-61, Session 12

50W CW output power and 12mJ pulses from a quasi-2-level Yb:YAG ceramic rod laser end-pumped at the 969nm zero-phonon line

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With the advent of high power and narrow bandwidth 969 nm pump diodes, direct pumping into the upper laser level of Yb:YAG and hence Quasi-2-level lasers became possible. Pumping directly into the emitting level allows for higher quantum efficiency and reduction of non-radiative decay. Hence thermal load, thermal lensing and risk of fracture are reduced significantly. Moreover pump saturation and thermal population of uninvolved energy-levels in ground and excited states are benefical for a homogenous distribution of the pump beam as well as the reduction of reabsorption loss compared to 3-level systems, which allows for high-power DPSS lasers. Beside cw operation nanosecond pulses with a repetition rate between 1 and 5 kHz are an attractive alternative to flashlamp-pumped systems (10-100 Hz) in various measurement applications that require higher data acquisition rates because of new faster detectors.

Based on measurements of the absorption and a detailed numerical model for pump beam distribution, including beam propagation and saturation factors, power-scaling of a ceramic rod Yb:YAG oscillator was possible. Finally a cw output power of 50 W with 33 % pump efficiency at 1030 nm has been demonstrated (M? < 1.2). Nanosecond pulses have been produced by cavity-dumping of this system. The cavity dumped setup allowed for 3-10 ns pulses with a pulse energy of 12.5 mJ at 1 kHz (M? < 1.1). In order to achieve these results a systematic experimental and numerical investigation on gain dynamics and the identification of different stable operating regimes has been carried out.

9342-62, Session 12

Investigation of mechanically Q-switched lasers

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Mechanical Q-switching was a technique implemented early in laser development; it enabled the Army's first eye-safe, 1.5 um laser range-finders based on Q-switched Erbium glass lasers. However, issues with long term reliability for the mechanical components, low laser efficiency and its large size and weight led to the development of the compact "Monoblock" laser for generating 1.5μm pulses. Mechanical Q-switching was also explored for 1 micron lasers based on Nd:YAG. However, it was quickly found that the maximum switching speed for mechanical Q-switching was too slow due to the higher cross section and cavity gain in Nd:YAG, resulting in poor efficiency and double pulsing. Due to the poor performance, and subsequent development of alternative Q-switching techniques, mechanical Q-switching was effectively abandoned for 1 micron lasers.

With maturation of technologies for fast-scanning mirrors, such as compact motors, small resonant-mirror scanners activated by an electro-magnetic coils, and Si MEMS, we investigated the use of these devices for Q-switching of lasers based on Nd:YAG and Er/Yb glass. The use of a mechanical Q-switch offers the possibility of a simpler and lower cost laser; and this approach also circumvents some of the drawbacks associated with commonly used active-EO and passive Q-switching methods. By optimization of laser resonator configuration, we demonstrate compact, mechanically Q-switched, lasers that generate >30 mJ at 1 μm and >3 mJ at 1.5 μm; these pulse energies meet the requirements for long-range laser markers and eye-safe laser range-finders. This paper will discuss the merits of mechanical Q-switching for these applications.

9342-63, Session PTue

Numerical simulations of the optical gain of crystalline fiber doped by rare earth and transition ion

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A fiber laser is a laser whose gain medium is a doped fiber, although lasers whose cavity is made wholly of fibers have also been called fiber lasers. The gain media in a fiber laser is usually fiber doped with rare-earth ions, such as erbium (Er), neodymium (Nd), ytterbium (Yb), thulium (Tm), or praseodymium (Pr), which is doped into the core of the optical fiber, similar to those used to transmit telecommunications signals. Fiber lasers find many applications in materials processing, including cutting, welding, drilling, and marking metal. To maximize their market penetration, it is necessary to increase their output power. In this work, we present a detailed study based on the numerical simulation using MATLAB, of one of the principal characteristics of a fiber laser doped with rare earth ions. The gain depends on several parameters such as the length of the doped fiber, the density, the pump power, noise, etc.). The used program resolves the state equations in this context together with those governing the light propagation phenomena. The developed code can also be used to study the dynamic operating modes of a doped fiber laser.

9342-64, Session PTue

Diode-pumped actively Q-switched Nd:YLF/SrWO₄ Raman laser

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A diode-pumped actively Q-switched Raman laser is demonstrated. The pump source is a fiber-coupled 808 nm laser diode. The resonator has a concave-plane configuration. The rear mirror is a concave mirror with a curvature radius of 300 mm. The output coupler is a plane mirror and the transmittance at 1159 nm is 16%. The laser medium is 1.0 at % Nd:YLF crystal with a dimension of 3?3?10 mm3. The a-cut 4?4?33 mm3 SrWO4 crystal is Raman medium. A 35 mm long acousto-optic Q switch is placed between the Nd:YLF crystal and SrWO4 crystal. The overall cavity length is approximately 13 cm.

To begin with, we observed the output powers of the 1159 nm at pulse repetition rates (PRF) of 5 kHz, 6 kHz and 7 kHz, respectively. The corresponding thresholds were 1 W, 1.1 W and 1.2 W at the PRFs of 5 kHz, 6 kHz and 7 kHz. The maximum output powers were 2.19 W, 2.17 W and 2.17 W at the PRFs of 5 kHz, 6 kHz and 7 kHz, respectively.

At 5 kHz PRF, we observed the pulse width, output power and beam quality of the 1159 nm laser. With a pump power of 10.57 W, the output power was 2.19 W and the pulse width was 8.6 ns. The corresponding optical-to-optical conversion efficiency was 20.7%. The beam quality factors (M2) were 1.8 and 1.9 in horizontal and vertical directions, respectively.

9342-67, Session PTue

Temperature influence on diode pumped Er:CaF2 laser

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The goal of this work was an investigation of the temperature influence (in range from 80 up to 330 K) on the laser properties of Er:CaF2 ceramics, which is suitable as a gain medium for generation of radiation at 2.7 um. The tested Er:CaF2 ceramics sample, prepared using a hot-forming technique, was doped with 5.5 % of ErF3. The sample was in the form of plane-parallel face-polished 3.5 mm thick plate (without AR-coatings). It was mounted in a temperature controlled cupreous holder, placed inside the vacuum chamber of the liquid nitrogen cryostat. A fiber coupled laser diode, operating in pulsed regime (3 ms pulse length, 20 Hz repetition rate) at wavelength 968 nm, was used for Er:CaF2 sample pumping. The 145 mm long semi-hemispherical laser resonator consisted of a flat pumping mirror (HR @ 2.65-2.95 um, HT @ 0.97 um) and a curved (r=150 mm) output coupler with a reflectivity of 97 % @ 2.65-2.85 um. From the results it follows that the temperature of the active medium has a strong influence mainly on laser threshold (more than 7 times lower threshold power corresponded to temperature 80 K in respect to 330 K). The highest slope efficiency (2.4 % in respect to absorbed power), obtained for temperature 80 K, was more than twice higher than slope efficiency for 330 K.

9342-68, Session PTue

Wavelength tunability of laser based on Yb-doped YGAG ceramics

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The wavelength tunability of diode pumped laser based on Yb-doped mixed garnet Y3Ga2Al3O12 (Yb:YGAG) ceramics was investigated. The tested Yb:YGAG sample (10 % Yb/Y) was in the form of 2 mm thick plane-parallel face-polished plate (without AR coatings). A fiber (core diameter 100 mm, NA =0.22) coupled laser diode (LIMO, LIMO35-F100-DL980-FG-E) with emission at wavelength 969 nm, was used for longitudinal Yb:YGAG pumping. The laser diode was operating in the pulsed regime (2 ms pulse length, 10 Hz repetition rate). The duty-cycle 2 % ensured a low thermal load even under the maximum diode pumping power amplitude 20 W (ceramics sample was only air-cooled). The 145 mm long semi-hemispherical laser resonator consisted of a flat pumping mirror (HR @ 1.01-1.09 um, HT @ 0.97 mum) and curved (r=150 mm) output coupler with a reflectivity of ~ 97 % @ 1.01-1.09 um. Wavelength tuning of the ytterbium laser was accomplished by using a birefringent filter (single 1.5 mm thick quartz plate) placed inside the optical resonator at the Brewster angle between the output coupler and the laser active medium. The laser was continuously tunable over ~ 58 nm (from 1022 nm to 1080 nm) and the tuning band was mostly limited by the free spectral range of used birefringent filter. The maximum output power amplitude 3 W was obtained at wavelength 1046 nm for absorbed pump power amplitude 10 W. The laser slope efficiency was 34 %.

9342-69, Session PTue

On the efficiency of Tm-doped 2μm lasers

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A potassium double tungstate layer with the composition KY(0.40)Gd(0.29) Lu(0.23)Tm(0.08)(WO4)2 was grown onto a pure KY(WO4)2 substrate by liquid-phase epitaxy, microstructured by standard lithography and Ar-ion etching, and overgrown by a pure KY(WO4)2 layer. The end-facets were polished. Laser experiments were performed on these buried, ridge-type channel waveguides in a resonator with one butt-coupled mirror and Fresnel reflection from the other end-facet, resulting in a high output-coupling degree of 89%, compared to intrinsic round-trip losses of only 2%. By pumping with a Ti:Sapphire laser at 794 nm, 1.6 W of output power at 1.84 ?m with a maximum slope efficiency of ~80% was obtained. To the best of our knowledge, this result represents the most efficient 2-?m channel waveguide laser to date.

We determined the optimum Tm3+ concentration in double tungstate channel waveguides to be at least 8at.% for efficient lasing. The theoretical limit of the slope efficiency depends on the Stokes efficiency which here is 43.2%, the outcoupling efficiency which here is 99%, and the pump quantum efficiency. The pump quantum efficiency of a 2-μm Tm3+ laser pumped around 800 nm hinges on the efficiency of its cross-relaxation process. By fitting the macroscopic cross-relaxation parameter which linearly depends on the Tm3+ concentration to concentration-dependent luminescence-decay data, calculating the overall decay rate of the pump level, and deriving the concentration-dependent pump quantum efficiency, we obtain a theoretical limit for the slope efficiency of 83% for the chosen Tm3+ concentration. The experimental slope efficiency of ~80% closely approaches this limit.

9342-70, Session PTue

Fe:ZnSe and Fe:ZnMgSe lasers pumped by Er:YSGG radiation

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The aim of the presented work was to design and characterize bulk Fe:ZnSe and Fe,Cr:ZnMgSe lasers coherently pumped by electro-optically Q-switched Er:YSGG laser. Both crystals were grown by Bridgman technique and their thicknesses were 3.4 mm (Fe:ZnSe) and 2.9 mm (Fe,Cr:Zn0.81Mg0.19Se). The wavelength of pumping laser was 2.79 um, maximum generated energy 50 mJ, pulse length 80 ns, and repetition-rate was set at 1 Hz. The resonator of Fe:ZnSe and Fe,Cr:ZnMgSe lasers was formed by plan mirror with transmission T=79 % @ 2.79 um and reflectivity ~ 100% @ 4-5 um and plan output coupler with reflectivity 88 % @ 4-5 um. The resonator length was 25 mm. Laser was working at room temperature. Measured maximum output energy/slope efficiency to the absorbed energy was ~ 3.8 mJ/42 % for Fe:ZnSe laser and ~ 0.45 mJ/10 % for Fe,Cr:ZnMgSe laser. The generated output pulse duration was 150 – 200 ns in both cases. The output beam spatial profile was approximately Gaussian. Fe:ZnSe and Fe:ZnMgSe output spectra have their maxima at 4.55 um and 4.8 um, respectively, with the line-width of ~ 200 nm. The comparison with the pumping by 2.94 um Er:YAG laser will be given.

9342-71, Session PTue

Moderate high power 1 to 20µs and kHz Ho:YAG thin disk laser pulses for laser lithotripsy

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An AOM-pulsed or self-oscillation pulsed thin disk Ho:YAG laser system at 2.1 µm with an average power in the 10 W range will be presented for laser lithotripsy. In the case of cw operation the thin disk Ho:YAG is either pumped with InP diode stacks or with a thulium fiber laser which leads to a laser output power of 20 W at an optical-to-optical efficiency of 30%. For the gain switched mode of operation a modulated Tm-fiber laser is used to produce self-oscillation pulses. A favored pulse lengths for uric acid stone ablation is known to be at a few µs pulse duration which can be delivered by the thin disk laser technology. In the state of the art laser lithotripter, stone material is typically ablated with 250 to 500 µs pulses at 5 to 10 Hz and with pulse energies up to a few Joule. The ablation mechanism is performed in this case by vaporization and fragmentation. With the thin disk laser technology, 1 to 20 µs-laser pulses with a repetition rate of a few kHz and with pulse energies in the mJ-range are available. The ablation mechanism is in this case due to a local heating of the stone with a decomposition of the crystalline structure into calcium carbonate powder which can be handled by the human body. As a joint process to this thermal effect, imploding water vapor bubbles between the fiber end and the stone produce sporadic shock waves which help clear out the stone dust material.

9342-72, Session PTue

Influence of temperature on spectroscopic and lasing properties of Pr:YLF crystal

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In this contribution, temperature influence on spectroscopic and lasing properties of Pr:YLF crystal as an fluoride laser host representative is reported. Fluorescence lifetime and polarization-resolved absorption and emission spectra down to the cryogenic temperature are described, as well as the laser operation in the orange spectral range at 607 nm wavelength (3P0 ? 3H6 transition). This particular laser transition is supposed to especially benefit from the decreased active material temperature due to the reduction of possible reabsorption losses originating from the higher laying level of the ground state manifold to the 1D2 manifold.

In our experiment, 0.4 at. % doped 5 mm long Pr:YLF crystal mounted on a liquid-nitrogen-cooled copper finger in the vacuum chamber of the cryostat was employed. The temperature of the sample was controlled within the range from 80 up to 320 K. As a pump source, 1-W InGaN laser diode was used. Three output couplers of 150 mm long laser resonator with reflectivity of 97 %, 75 %, and 40 % were tested and compared. The highest slope efficiency of 47 % (with respect to absorbed pump power) was reached at 80 K crystal temperature using 40% output coupler reflectivity. The corresponding maximum output power and lasing threshold were 170 mW and 400 mW, respectively.

From the results it follows that the temperature of the Pr:YLF active medium has a strong influence on the laser input-output characteristics.

9342-73, Session PTue

60W Ho:YLF oscillator-amplifier system

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We developed a compact Ho:YLF oscillator–amplifier system end-pumped by two 54 W unpolarised Tm:fiber lasers, and produced 60.2 W of output power at 2064 nm.

The oscillator consisted of a flat input coupler mirror, a 50 mm long 0.5 % doped Ho:YLF crystal rod, a 45 degree folding mirror, an AOM, and a concave output coupler mirror. The oscillator operated vertically polarised on the holmium crystal's ?–polarisation, ensuring good beam quality from the weak thermal lens. The concave output coupler had a radius of 300 mm and a reflectivity of 82 % at 2064 nm. The oscillator gave a maximum output of 24 W with an M2 of 1.06.

The single-pass amplifier consisted of two 40 mm long, 0.5 % doped, Ho:YLF crystal rods and four folding mirrors. While the seed laser was pumped by a single fiber laser, the amplifier utilized the transmitted pump light from the seed laser in addition to the second fiber laser. With the first crystal amplifying on the ?–polarisation and the second crystal on the ϖ-polarisation, the amplifier delivered 60.2 W with an M2 of 1.09, representing a gain of 2.5 while achieving an optical-to-optical efficiency of 55.5 %. When Q-switched with the AOM, the system delivered pulse lengths of between 43 and 113 ns at repetition rates from 15 to 40 kHz.

9342-74, Session PTue

Development of a closed-loop cryogenically cooled sub-picosecond regenerative amplifier

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We are developing a joule level sub-picosecond laser system at repetition rate of 120Hz for a single shot bio-imaging source via laser-Compton scattering. The laser system consists of a mode-locked fiber laser and two cryogenically cooled amplifier stages, namely, a single slab regenerative amplifier and a multi-pass amplifier. To build a compact, cost-effective and low-vibration system, we employed a pulse tube cryostat in both amplifiers. The vibration of cryostat was evaluated by a combination of He-Ne laser and quadrant photo detector. We found that the pointing instability caused by the mechanical vibration of cryostat was less than 0.7-urad. We have developed a spatial and spectral resolved gain measurement system for solid state gain media. A tunable narrow band probe beam is irradiated

to a gain medium, and the spatial gain distribution is calculated from the intensity change of the probe beam with and without pumping. We found that the optimum temperature of Yb:YAG to obtain picosecond pulses is around 150-K. Also, we measured the emission bandwidth of Yb:YGAG ceramic at cryogenic temperatures, and found that the emission bandwidth at 160-K is around 7-nm. Note that the bandwidth of Yb:YGAG is three times boarder than that of Yb:YAG. We modified the probe light source for the gain measurement system to generate a microsecond pulse with a spectral bandwidth of less than 50-pm. This pulsed narrowband probe source makes it possible to analyze the temporal gain dynamics of laser material. The gain measurement and regenerative amplification of cryogenically-cooled Yb:YAG and Yb:YGAG ceramics will be presented.

9342-75, Session PTue

Continuous-wave hybrid index-antiguided and thermal-guided planar waveguide laser with large mode area

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A continuous-wave index-antiguided planar waveguide laser with a 220-μm Nd:YAG active layer is investigated. The waveguide is composed of a 1% Nd-doped YAG (refractive index = 1.820), sandwiched by 2 pieces of Terbium Gallium Garnet, or TGG as cladding (refractive index 1.954) using fusion bonding. Robust fundamental mode oscillation in the antiguided (bound) direction is demonstrated with negligible thermal index focusing for incident pump power up to 25 W (source limited). In the orthogonal (unbounded) direction the laser is dominantly thermally guided with a small contribution of gain guiding. A maximum output power of 2.45 W is obtained with a slope efficiency of 10% with respect to incident pump power. Polarization is dominantly TE at threshold with a polarization extinction ratio of nearly 8 dB, and diminishes at increasing pumping power. An analytical model is developed for finding the fundamental mode of laser oscillation with arbitrary index antiguiding and gain guiding in orthogonal directions with simultaneous thermal index guiding in both directions. Experimental results are compared to theory with good agreement.

We have also conducted lasing experiments with an AR-coated 400-μm-thick IAG waveguide. Fundamental mode oscillation in antiguided (bound) direction is only observed near the lasing threshold, beyond which higher-order modes prevail. In contrast to the robust fundamental mode observed in the 220-μm IAG waveguide, our finding suggests that the maximally allowed core width in IAG waveguides for single-transverse mode operation is dependent on the strength of index antiguiding. Theoretical analysis is currently in progress.

9342-76, Session PTue

Underwater laser detection system

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The conventional method used to detect an underwater target is by sending and receiving some form of acoustic energy. However, acoustic systems have limitations in the range resolution and accuracy. While, the potential benefits of a laser-based underwater target detection include high-directionality, high response, and high range accuracy. Lasers operating in the blue-green region of the light spectrum (420:570 nm) have a several applications in the area of detection and ranging of submersible targets due to minimum attenuation through water (less than 0.1 m-1) and maximum laser reflection from estimated target (like mines or submarines) to provide a long range of detection. In this paper laser attenuation in water was measured experimentally by new simple method by using high resolution spectrometer. The laser echoes from different targets (metal, plastic, wood, and rubber) were detected using high resolution CCD camera; the position of detection camera was optimized to provide a high reflection laser from target and low backscattering noise from the water medium, digital image processing techniques were applied to detect and discriminate the echoes from the metal target and subtract the echoes from other objects. Extraction the image of target from the scattering noise is done by background subtraction and edge detection techniques. As a conclusion, we present a high response laser imaging system to detect and discriminate small size, like-mine underwater targets. Keywords: Blue-green lasers, laser absorption, reflection, target detection, laser imaging system, and image processing.

9342-77, Session PTue

Transmitted beam profile for determining bulk scattering in transparent ceramics

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Bulk scattering in polycrystalline laser materials (PLM) due to non-uniform refractive index variations across the bulk is regarded as the primary loss mechanism leading to degradation of laser performance in terms of higher threshold and lower output power. There exists a need for rapid and quantitative technique to characterize bulk scatter and assess the optical quality of PLMs. Transmitted Beam Wavefront Profiling (TBWP) technique is shown to enable direct imaging of the spatial distortion of a transmitted laser beam introduced by bulk scattering in a PLM sample.

9342-78, Session PTue

Angle resolved scatter measurement of bulk scattering in transparent ceramics

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Angle Resolved Scatter (ARS) technique is evaluated as a means to allows for the spatial mapping of scattered light at all possible angles in a PLM sample. The cumulative scattered light intensity in the forward scatter direction, away from the specular beam, is used for the comparison of bulk scattering between samples. This technique employ the detection of scattered light at all angles away from the specular beam directions and represented as a 2-D polar map. The high sensitivity of the ARS technique allows one to compare bulk scattering in different PLM samples which otherwise had similar transmitted beam wavefront distortions.

9342-80, Session PTue

Multiplexed pulsed quantum cascade laser based hypertemporal real-time headspace measurements

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Recently developed real-time hypertemporal headspace spectroscopic measurements systems have made it possible to gather cavity enhanced spectra over a wide-bandwidth, with the aim to make headspace measurements of molecules at trace levels. These new systems can measure spectral regions in excess of 1400nm in a few seconds and contain at least 150, 000 spectral wavelength datapoints. However, the spectral fingerprint of medium to heavy molecules (such as nitromethane, acetonitrile, acetone, nitroglycerin, and so on), cover a much wider wavelength range. In most cases the molecular fingerprint can be anywhere in the 3?m to 20?m wavelength range.

The standard configuration to produce a wide-band, cavity enhanced spectrometer, such as multipass cells or multiple lasers, combine multiple lasers into a single optical beam then pass the combined beam though the cavity enhanced mirrors, but they require an optical setup to split the laser beams at the output so that they can be detected on separate detectors.

A more desirable approach is to detect the light exiting the cavity is on a single photo receiver. This setup cannot be used by standard cavity enhanced schemes unless the laser sources are addressed in series, hence allowing only one laser to monitor the sample at a time. This, in turn, makes the measurement process substantially longer.

Alternatively, the spectra could be obtained by illuminating the cavity with all the lasers simultaneously, but a new digital signal processing method is required to deal with this multiplexed spectroscopic system. The advantage of this approach is that only one detector is required and the optics separating the beams at the output of the cavity can be eliminated.

9342-81, Session PTue

Spectroscopic characterization of Cr2+ ions in ZnSe/ZnS crystals under visible excitation

Jeremy M. Peppers, Vladimir V. Fedorov, Sergey B. Mirov, The Univ. of Alabama at Birmingham (United States)

Recent efforts in the development and study of Cr2+:II-VI chalcogenide (e.g. ZnSe, ZnS) crystals have yielded laser systems broadly tunable over the 1.9-3.3 μm spectral range through intra-shell excitation of Cr2+. We report on detailed spectroscopic characterization of Cr2+:ZnS under visible excitation into the charge transfer band of Cr2+ and compare with previous results from Cr2+:ZnSe under similar excitation. Middle-infrared (mid-IR) photo-luminescence (PL) of Cr2+ in ZnS under 10 ns pulsed 459 nm excitation into the charge transfer band was compared with direct (5T2 ?5E) 1907 nm excitation. The quantum yield of Cr:ZnS mid-IR luminescence under short pulse excitation into the charge transfer band was estimated as close to 100%, which contrasts with low (~14%) quantum yield measured in Cr:ZnSe under 532 nm pulsed excitation. Mid-IR PL kinetics of Cr:ZnS under visible nanosecond and picosecond scale pulsed excitation exhibit similar rise times ~150 ns, significantly shorter than those measured in Cr:ZnSe (~5-10 μs). Short rise time is indicative of fast relaxation process from higher-lying energy levels to the 5E upper laser level. This rate of population is significantly faster than the room temperature lifetime in Cr:ZnS of ~6 μs. Therefore, there exists the possibility of obtaining laser oscillation in Cr:ZnS as a result of the 2+?1+?2+ ionization transition by excitation into the charge transfer band without the limitations associated with lasing through this mechanism in Cr:ZnSe. Results of laser experiments with Cr:ZnS under visible excitation are reported.

Conference 9343: Laser Resonators, Microresonators, and Beam Control XVII

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Part of Proceedings of SPIE Vol. 9343 Laser Resonators, Microresonators, and Beam Control XVII

9343-1, Session 1

Asymmetric response function of the transduction spectrum for a microsphere pendulum

Jonathan M. Ward, Yong Yang, Ramgopal Madugani, Síle G. Nic Chormaic, Okinawa Institute of Science and Technology (Japan)

A micropendulum coupled to an optical waveguide is a special optomechanical system where neither dissipative nor dispersive mechanisms can be neglected. To study this, a whispering gallery resonator in the form of a microsphere was fabricated on a thin flexible stem (micropendulum) and coupled to a tapered optical fiber. The low spring constant of the stem allowed the microsphere to swing in and out from the fiber with a frequency ~ 1 kHz. This mechanical motion was detected as a modulation in the transmitted power. The pendulum motion resulted in a red shift (dispersion) of the optical mode. However, since the mechanical motion was of the order of nanometres, the external coupling rate (dissipation) was also modulated. Both of these oscillations were optically mapped to the transmission output. When the contributions from the dissipation and dispersion were comparable, the response function of the system was asymmetric to zero detuning from the optical mode. We show this by numerically solving the coupled mode equation of the system to get the Fourier transformed spectrum. The experimental data was then fitted with the numerical results. In the response spectrum the transduced mechanical signal gave an asymmetric line shape which changed shape and amplitude as a function of the optical dispersion rate, external coupling rate, gap, optical linewidth and modulation amplitude. We provide a theory that takes all mechanisms into account and show that the experimental result is well explained. The detailed transduction function could be important for future applications such as vibration sensing.

9343-2, Session 1

Electrooptomechanical systems for microwave-optical information transfer *(Invited Paper)*

Andrew N. Cleland, Univ. of Chicago (United States)

I will report on our development of microfabricated devices aimed at the high fidelity, coherent transfer of information between optical and microwave frequencies. The approach is based on the use of one dimensional optomechanical crystals fabricated from aluminum nitride, a strong piezoelectric material. The mechanical degree of freedom in these system serves as an intermediary between microwave electrical fields, which couple to mechanics via the piezoelectric response of the base material, and optical signals at a telecommunications wavelength, which couple to mechanics via a combination of moving boundary and photoelastic effects within the microscopic confines of an optomechanical defect state. The ultimate goal is to achieve the rapid coherent transfer of energy from an optical signal via a microwave frequency mechanical mode to a microwave electrical signal, and vice versa, using an electrical signal to generate frequency-encoded signals on an optical carrier. If good classical performance can be achieved, this device could provide for the coherent transfer of quantum information from optics to electronics and vice versa, thus possibly allowing the optical control of e.g. superconducting qubits, or the high speed generation of entangled photons originating from a superconducting qubit. These could even ultimately serve as a key element in a long-distance quantum communication network, providing the essential functionality of a quantum repeater, including error correction.

9343-3, Session 1

Observation of optical non-reciprocity in a Brillouin optomechanical system

Junhwan Kim, Univ. of Illinois at Urbana-Champaign (United States); Mark C Kuzyk, University of Oregon (United States); Kewen Han, Univ. of Illinois at Urbana-Champaign (United States); Hailin Wang, University of Oregon (United States); Gaurav Bahl, Univ. of Illinois at Urbana-Champaign (United States)

Time-reversal symmetry is a fundamental property of optical systems, leading to symmetric response independent of propagation direction. A break in time-reversal symmetry, i.e. non-reciprocity, is required for many applications including optical isolation. Presently, optical non-reciprocity is achieved using magneto-optic effects in ferrites that can be challenging or impractical to implement in many applications. Optomechanical transparency [1] and angular momentum biasing through spatiotemporal modulation [2] have been theoretically suggested as alternatives that enable magnet-free non-reciprocity, but have never been experimentally demonstrated. Here, we provide the first experimental evidence of non-reciprocity in a Brillouin optomechanical system. The effect is generated through opto-acoustic interaction with the unidirectionally-propagating spatiotemporal modulation created by an acoustic wave.

Our experiment is performed using a silica microsphere at 1550nm. We find a Brillouin triplet consisting of two optical WGMs and one acoustic WGM that satisfies the energy-momentum conservation for Brillouin scattering. A strong control laser pumps the low-frequency optical WGM while a weak laser probes the high-frequency WGM. A transparency effect is observed when the pump and probe are co-propagating, similar to EIT and optomechanically-induced transparency [3]. However, Brillouin phase-match is not satisfied [4] when the signals are counter-propagating and no transparency occurs. Significant non-reciprocity is observed in the probe transmission amplitude and phase responses.

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9343-4, Session 1

Brillouin scattering induced transparency in a silica microsphere *(Invited Paper)*

Chunhua Dong, Zhen Shen, Chang-Ling Zou, Guang-Can Guo, Univ. of Science and Technology of China (China)

Stimulated Brillouin scattering (SBS) is a very fundamental interaction between light and travelling acoustic waves, which is mainly attributed to the electrostriction and photoelastic effects with the interaction strength being orders of magnitude larger than other nonlinearities. Here, we experimentally demonstrated the Brillouin scattering induced transparency in a high quality optical microresonantor. Benefit from the triple-resonance in the whispering gallery cavity, the photon-phonon interaction is enhanced, leading the light storage. In addition, due to the phase matching condition, the stored circulating acoustic phonons can only interaction with certain direction light. Our work paves the way towards the low power consumption integrated all-optical switching, isolator and circulator, as well as quantum memory.

9343-5, Session 1

Acoustic whispering gallery modes within the theory of elasticity

Ingo Breunig, Univ. of Freiburg (Germany); Boris I. Sturman, Institute of Automation and Electrometry (Russian Federation); Karsten Buse, Univ. of Freiburg (Germany) and Fraunhofer-Institut für Physikalische Messtechnik (Germany)

The recent upsurge of interest to acoustic whispering gallery modes (AWGMs) is related to the excitation of acoustic modes in optical WGM resonators via stimulated Brillouin scattering (SBS). The latter is one of the strongest nonlinear processes controlling/affecting the operation of optical devices, such as, e.g., Brillouin lasers, already at modestly low light powers. Recent attempts to describe AWGMs in solid-state resonators give numerical examples for spheres and shells made of silica glass. An important feature of these calculations is an artificial reduction of the initial elasticity equations in order to single out pure longitudinal waves. However, transversal and longitudinal displacements are coupled at the boundary of the resonator in such a way that a pure longitudinal wave is very unlikely.

We investigate the resonant frequencies and eigenfunctions (displacements) for AWGMs in cylindric and spherical resonators made of isotropic materials within the theory of elasticity. The acoustic modes can be qualified as pure transverse (t) and hybrid transverse-longitudinal (tl). Among the latter we find surface Rayleigh waves, modes with a dominating t-part, and pseudo-longitudinal modes. Pure longitudinal modes are absent. The results obtained are of relevance for experiments on excitation of acoustic modes in optical whispering gallery resonators via stimulated Brillouin scattering.

9343-6, Session 2

Brillouin lasers, frequency combs, and optical frequency division using high-Q silica resonators *(Invited Paper)*

Kerry J. Vahala, California Institute of Technology (United States)

No Abstract Available

9343-7, Session 2

Dynamical characteristics of AlGaInAs/InP microdisk lasers subject to optical injection *(Invited Paper)*

Yong-Zhen Huang, Ling-Xiu Zou, Bo-Wen Liu, Yue-De Yang, Heng Long, Jin-Long Xiao, Yun Du, Institute of Semiconductors (China)

Semiconductor lasers subject to optical injection can lead to a number of dynamical states, and can be utilized for the enhancement of direct modulation speed and the photonic generated microwave. In this talk, we report the characteristics of dynamic states for a microdisk laser under optical injection. For a 10-?m-radius microdisk laser with a 2-?m-width output waveguide, the measured lasing spectra clearly indicates that the nonlinear dynamical states, such as four-wave mixing, period-one and period-two oscillations, injection locking, and chaos states are realized by varying the injection optical power and the frequency detuning between the lasing mode and the injection light. Furthermore, the small signal modulation responses at different dynamical states are investigated, and the enhancement of small signal modulation response induced by the optical injection locking is demonstrated with the 3dB bandwidth increases from 5.6 to 17.6 GHz at an injection optical power of 3 mW. In addition, the photonic generated microwaves are measured and compared corresponding to different dynamic states for the microdisk laser unde optical injection. As the whispering-gallery mode microdisk lasers are suitable to be a part of photonic integrated circuits, we can expect to realize an integrated device for high speed modulation and photonic microwave generation based on microdisk lasers.

9343-8, Session 2

Connecting microwave and optical frequencies with a vibrational degree of freedom *(Invited Paper)*

Reed W. Andrews, Robert W. Peterson, Thomas P. Purdy, JILA (United States); Katarina Cicak, Raymond W. Simmonds, National Institute of Standards and Technology (United States); Cindy A. Regal, Konrad W. Lehnert, JILA (United States)

We simultaneously couple a vibrational degree of freedom to both a microwave circuit and an optical cavity. This simultaneous coupling enables information in the microwave domain to stream through the mechanical resonator and emerge as optical light, and vice versa. We show that the transformation is bidirectional and coherent, and further demonstrate a photon number efficiency of 0.086 ± 0.007 and a transfer bandwidth of 30 kHz. The vibrational degree of freedom consists of a thin silicon nitride membrane embedded in a Fabry–Pérot cavity. As the membrane vibrates, it moves along the intensity standing wave of the Fabry–Pérot cavity and modulates its resonant frequency. Additionally, the membrane is partially coated with a thin layer of niobium, and this electrically conductive portion is part of a capacitor in an inductor–capacitor microwave circuit. As the membrane vibrates, it modulates the capacitance of the microwave circuit, and thus its resonant frequency. This mechanically mediated approach to frequency conversion is compatible with cryogenic temperatures and superconducting circuity, and provides a potential route to quantum-state-preserving frequency conversion.

9343-9, Session 2

Superfluid optomechanics *(Invited Paper)*

Glen I. Harris, David L. McAuslan, Eoin E. Sheridan, Warwick P. Bowen, The Univ. of Queensland (Australia)

Surface waves on a thin superfluid helium film were first discussed by K. R. Atkins in the 1950s [1, 2]. These surface waves, known as third sound, have traditionally been studied using rotational drive resonators where the motion is driven and readout capacitively [3]. Here we use an optical cavity, coupled to the superfluid, to measure and control its mechanical motion. Optomechanical systems such as this have very high displacement sensitivity, which has allowed us to make the first observation of the thermal motion of a single sound wave in superfluid helium. Moreover, by detuning the optical field we have used radiation pressure and photothermal dynamical back-action to both cool and amplify the third sound mechanics. The high optomechanical coupling between the optical cavity and the superfluid layer has allowed precise characterization of some of the interesting properties of the film. This includes measurements of optomechanical instability at very low threshold power, and when driven with intracavity intensities of a few hundred optical photons, observation of strong Duffing non-linearity. Superfluid helium mechanical resonances have received some interest recently due to their potential to exhibit extremely high mechanical quality factors, which is advantageous for performing quantum optomechanics experiments [4].

Mechanical motion of liquid helium can be described in terms of the two-fluid model, where it is composed of a normal fluid and a superfluid component which intermingle without any viscous interaction. The two-fluid model describes several types of wave motion, denoted, first, second, third,

and fourth sound. First and second sound refers to waves propagating in bulk fluid, whilst fourth sound describes waves propagating in a channel. We are interested in third sound waves, which are surface waves occurring on thin helium films (~10 nm thick). In this case the film is so thin that the normal component is clamped to the substrate, leaving only the superfluid component which oscillates parallel to the surface. The restoring force is provided by the Van der Waals interaction, and the wave velocity (cs) is dependent on the film thickness [5].

A tapered fibre was used to couple 1550 nm laser light into a microtoroid, mounted in a helium-3 cryocooler. The microtoroid is in an exchange gas chamber filled with helium-4 to provide thermal anchoring between the microtoroid and the coldhead of the cryocooler [6]. When the chamber is cooled below the superfluid transition temperature of the helium-4, a thin (4-20 nm) layer of superfluid helium coats every surface in the chamber, including the microtoroid. Third sound resonances on the microtoroid surface optomechanically couple to the evanescent field of the microtoroid and can be monitored with high-sensitivity using balanced homodyne detection. Amplitude modulating the laser light coupling into the microtoroid allows the third sound resonances to be driven so that network analysis can be performed.

The high displacement sensitivity of optomechanical systems has enabled us to directly observe the thermal motion of a superfluid film for the first time. We also observe radiation pressure dynamical back-action of the superfluid by detuning the laser with respect to the optical cavity resonance. Furthermore when the laser is blue detuned, optomechanical instabilities arise from input laser powers of less than 50 nW. By driving the superfluid resonance using an amplitude modulated optical probe field it was discovered that it exhibits a strong Duffing nonlinearity. This nonlinear behaviour appears with less than 1 nW of optical power in the amplitude modulated sidebands.

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9343-10, Session 3

Diamond frequency combs *(Invited Paper)*

Marko Loncar, Harvard Univ. (United States)

Owing to its unique optical, thermal and mechanical properties, diamond is well-suited for the development of high efficiency, low noise microresonator frequency combs. In particular, its high linear (n ~ 2.4) and nonlinear (n2 = 1.3x10-19 m2/W) refractive index, wide bandgap (5.5eV) and negligible nonlinear loss mechanisms due to multi-photon processes, as well as excellent thermal properties (high thermal conductivity in excess of 2000W/mK at room temperature, low thermal expansion coefficient, and small thermo-optic coefficient) are of great importance and may enable realization of stable microresonator combs that operate over wide wavelength range with low threshold powers. I will present our recent result on frequency comb generation at telecom wavelenghs using high Q factor (>106) diamond ring resonator. Threshold powers as low as 20 mW are measured, and up to 20 new wavelengths are generated from a single-frequency pump laser. In addition, I will discuss our efforts towards realization of diamond comb operating at visible wavelengths.

9343-11, Session 3

On chip temporal solitons and coherent dispersive waves in SiN optical micro resonators for octave spanning frequency combs *(Invited Paper)*

Tobias J. Kippenberg, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

No Abstract Available

9343-12, Session 3

Precision frequency metrology with microresonator combs *(Invited Paper)*

Scott Diddams, Scott B. Papp, National Institute of Standards and Technology (United States)

A new class of optical frequency combs has recently emerged based on optical microresonators, and they provide a chip-scale platform to realize a variety of precise time and frequency measurements. Here we describe experiments at NIST in which we generate phase-locked frequency combs around 1550 nm using high-Q silica resonators. The phase-locking mechanisms and intrinsic noise processes are studied, and techniques have been developed to stabilize the comb spectrum to optical and microwave references. These advances have allowed us to realize a micro-resonator frequency comb optical clock that accurately divides terahertz frequencies associated with atomic transitions to the microwave domain. Efforts aimed at generating octave-spanning combs and their frequency control will also be discussed.

9343-13, Session 4

Terabit/s communications using chip-scale frequency comb sources *(Invited Paper)*

Christian Koos, Karlsruher Institut für Technologie (Germany); Tobias J. Kippenberg, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Larry R. Dalton, Univ. of Washington (United States); Liam P. Barry, Dublin City Univ. (Ireland); Wolfgang Freude, Karlsruher Institut für Technologie (Germany); Juerg Leuthold, Karlsruher Institut für Technologie (Germany) and ETH Zürich (Switzerland); Joerg Pfeifle, Claudius Weimann, Matthias Lauermann, Stefan Wolf, Karlsruher Institut für Technologie (Germany); Victor Brasch, Tobias Herr, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Delwin L. Elder, Univ. of Washington (United States); Vidak Vujicic, Regan T. Watts, Dublin City Univ. (Ireland)

Terabit/s optical interconnects rely on advanced wavelength-division multiplexing (WDM) schemes, where information is transmitted by a multitude optical channels of different wavelengths. In this context, frequency combs are a particularly attractive option for generating the associated optical carriers. In this paper, we give an overview on our recent demonstrations of terabit/s communications using chip-scale optical frequency comb sources. Our experiments exploit different comb generation schemes, comprising electro-optic modulation in highly efficient silicon-organic hybrid (SOH) devices [1] - [4], gain switching of injection-locked distributed-feedback (DFB) lasers [5], and Kerr comb generation in highly nonlinear microresonators [6].

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9343-14, Session 4

Towards efficient octave-spanning comb with micro-structured crystalline resonator *(Invited Paper)*

Nan Yu, Ivan S. Grudinin, Jet Propulsion Lab. (United States)

Optical frequency combs, typically produced by mode locked lasers, have revolutionized many applications in science and technology. Frequency combs were recently generated by micro resonators through nonlinear Kerr processes. However, the comb span from micro resonators was found to be limited by resonator dispersion and mode spectrum. While dispersion engineering has been reported in on-chip devices, monolithic crystalline resonators offer an advantage of high optical quality factor. Moreover, most resonators used for comb generation support many mode families, leading to unavoidable crossings in resonator spectrum. Such crossings strongly influence comb dynamics and may prevent stable coherent mode-locking and soliton states. We report a new crystalline resonator appraoch supporting dispersion control and single mode spectrum while maintaining high quality factor. Dispersion engineering by waveguide micro-structuring is used to flatten the dispersion in our MgF2 resonator. Both absolute magnitude of dispersion and its slopes can be altered over a wavelength span exceeding an octave. Dispersion flattening leads to generation of an octave-spanning frequency comb with repetition rate of 46 GHz and coupled pump power below 100 mW. We also demonstrate that the micro-structuring dispersion engineering approach can be used to achieve flattened and anomalous dispersion in a CaF2 resonator near 1550 nm wavelength. In addition, we describe observation of discrete steps between the modulation instability states of the primary comb and on the three-stage comb unfolding dynamics. The micro-structured resonators may enable efficient low repetition rate coherent octave spanning frequency combs without external broadening, ideal for applications in optical frequency synthesis, metrology, spectroscopy, and communications.

9343-15, Session 4

Making microwaves visible: Parametric frequency conversion in whispering gallery mode resonators *(Invited Paper)*

Harald G. L. Schwefel, Max-Planck-Institut für die Physik des Lichts (Germany)

Efficient coherent conversion of microwave or THz radiation into the visible or near infrared is a challenging but worthwhile endeavor. With coherent detection, large THz detector arrays are possible to detect for example weak variations in the cosmological background radiation. Coherent microwave conversion will connect the well-established optical telecommunication domain with the growing field of integrated superconducting microwave circuits, which are the most likely route towards the quantum computer. Nonlinear parametric sum-frequency generation is a process that conserves both the phase and amplitude of the initial state and is thus ideal for such attempts. Non-linear interactions require intense optical fields. A good, high quality optical resonator can provide such fields even at low pumping powers. Some of the best optical resonators with a small footprint are whispering gallery mode (WGM) resonators. Their principle is based on continued total internal reflection at the interface of an azimuthally symmetric dielectric. We report on utilizing WGM resonators to mix optical and microwave fields inside of a high quality lithium niobate WGM resonator. The evanescent coupling of microwave and THz radiation into WGM resonators is discussed and we provide the theory of phase-matched non-linear interactions inside WGM resonators. First results from a lithium niobate WGM resonator with mixing optical and microwave/THz fields in the same WGM resonators will be presented with record conversion efficiencies.

9343-16, Session 4

Advances in Kerr optical frequency comb generation *(Invited Paper)*

Guoping Lin, Khaldoun Saleh, Souleymane Diallo, Romain Martinenghi, Yanne K. Chembo, FEMTO-ST (France)

Kerr optical frequency combs have generated a broad interest in recent years. From a fundamental point of view, they enable to investigate various phenomena related light-matter interactions, while from the applied viewpoint, these combs are considered as as promising central elements for both aerospace and communication engineering systems.

In this communication, we present some recent advances in the field, and we discuss some perspectives for further research in this area.

9343-17, Session 4

Analysis of third order nonlinearity effects in high-Q WGM resonator by cavity ring down *(Invited Paper)*

Patrice Féron, Vincent Huet, Alphonse L. Rasoloniaina, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France); Maurizio Ferrari, Istituto di Fotonica e Nanotecnologie (Italy); Stéphane Balac, Yannick Dumeige, Ecole Nationale Supérieure des Sciences Appliquées et de Technologie (France)

We propose a simple model using the time domain coupled-mode theory (CMT) to take into account third order optical nonlinear effects in high-finesse whispering-gallery-mode (WGM) resonators. This method allows cavity-ring-down under modal-coupling analysis since it is directly formulated in the time domain. The experiments are carried out in silica WGM micro-spheres. In the linear regime we are able to deduce from cavity-ring-down spectroscopy signals the coupling regime, the Q-factor and the mode-coupling strength. We have shown that the method can be extended to the non linear regime and that enables the input power and the mode volume to be estimated for silica micro-spheres. The mode volume deduced from nonlinear experiments is consistent with estimations made from the frequency splitting due to the mode coupling resulting from enhanced Rayleigh backscattering. Consequently, this shows that for a given material the combination of measurement of backscattering strength and nonlinear effects power threshold can be used to deduce the nonlinear index of this material at the cost of the knowledge of several physical parameters (thermal and thermo-optic properties; scatterers' density and polarisability). This technique could be developed to infer both linear and nonlinear properties of high-finesse coated WGM micro-spheres or to determine the nonlinear properties of novel optical materials.

9343-18, Session 5

Hydrogen gas sensing using palladium-coated microdisk microresonators

Mustafa Eryurek, Koç Univ. (Turkey); Yasin Karadag, Marmara Univ. (Turkey); Nevin Tasaltin, TÜBITAK Marmara Research Ctr. (Turkey); Necmettin Kilinc, Koç Univ. (Turkey) and Gebze Institute of Technology (Turkey); Alper Kiraz, Koç Univ. (Turkey)

Thanks to its high energy conversion efficiency, non-toxic side products and sustainable nature, hydrogen attracts a lot of attention as an energy source. Main challenges in using hydrogen as fuel stem from its low flammable limit (4 %) and small molecular volume. These bring together challenges in hydrogen storage and sensing. Here, we demonstrate hydrogen gas sensing using palladium-coated polymer microdisk microresonators. Microdisk microresonators host high quality optical resonances called whispering gallery modes (WGMs) whose spectral positions are very sensitive reporters of the microresonator size. Our sensor detects the hydrogen gas via the spectral position of the WGMs that changes due to the swelling of the palladium sensing layer. We report hydrogen detection below the flammable limit down to 0.3 %.

Microdisk microresonators with 200 um diameter and 1.5 um thickness were fabricated from SU-8 photoresist on a silicon wafer covered with a 5 um thick oxide layer using standard UV photolithography. A thin (thickness: 150 nm) layer of palladium with 150 um diameter was coated on the microresonators using RF plasma sputtering followed by a lift-off step. The WGMs were excited using SU-8 waveguides fabricated together with the microresonators. Transmission spectra were measured by recording the transmitted optical power of a tunable laser (tuning range: 1500-1630 nm) during consecutive laser wavelength sweeps. The sample was kept in a home-made gas chamber. Nitrogen and hydrogen gases were flown into the chamber using two mass flow controllers. During the experiments, the gas chamber was constantly purged with nitrogen at a constant flow of 1000 mL/min while hdrogen flow rate was adjusted for desired concentrations. At the beginning of each experiment, before initiating the hydrogen flow, nitrogen was flown for at least 30 mn in order to rule out effects due to humidity in the chamber.

9343-19, Session 5

Non-linear fluorescence excitation of Rhodamine 6G and TRITC labeled IgG in whispering gallery mode microresonators

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Many novel approaches based on different optically resonant platforms have been developed for the detection of antibodies. We report the use of microspherical whispering gallery mode resonantors (WGMR) combined with non-linear two-photon fluorescence for the detection of IgG. The microspheres were first functionalized with an epoxy silane, then we immobilized an orienting layer (protein G) and finally we covalently bonded IgG labeled with tetramethyl rhodamine isothiocyanate (TRITC) at a concentration of 8 ?g/?l. The quality factor of the microspheres was over 106 after the functionalization procedure. We also report the observation of two photon fluorescence in microbubbles filled with a 10-6 M solution of Rhodamine 6G. The microbubble diameter was about 510 ?m, with a Q factor of about 5 107. All measurements were performed in a modified confocal microscope; we coupled the excitation light with a 10x objective and detected the TPF signal with a CCD. The pump laser is a femtosecond Ti:Sapphire (Coherent). The fluorescent signal shows a nonlinear dependence on the pump power, as expected. These preliminary results show the great potential of WGMR for nonlinear detection of biological material and organic compounds.

9343-20, Session 5

Raman lasing dynamics in split-mode microcavity and single-nanoparticle detection *(Invited Paper)*

Yun-Feng Xiao, Peking Univ. (China)

Stimulated Raman scattering holds great potential for various photonic applications, such as label-free high sensitivity biomedical imaging, and for extending the wavelength range of existing lasers, as well as for generating ultra-short light pulses. In high Q microcavities, stimulated Raman scattering, also called Raman lasing, has been experimentally demonstrated to possess ultra-low thresholds, due to the greatly increased light densities in microcavities. Such microcavity Raman lasers have great potential for sensing applications, using the following mechanisms. Raman lasing can initially occur in any of the two initially degenerate counter-propagating traveling wave modes. These two traveling wave modes couple to each other due to backscattering when a nanoscale object binds to the microcavity surface. For a sufficiently strong coupling, in which the photon exchange rate between the two initial modes becomes larger than the rates of all the loss mechanisms present in the system, two new split modes form and can lase simultaneously. Thus, by monitoring the mode splitting, i.e., the beat frequency of the split-mode Raman lasers, ultrasensitive nanoparticle detection can be realized.

In this talk, we report the experimental demonstration of single nanoparticle detection using split-mode microcavity Raman lasers. The principles underlying this Raman lasing sensor are first analyzed and demonstrated in air, by controllably binding or removing single 50-nm-radius polystyrene (PS) nanoparticles to and from the cavity surface using a fiber taper, and measuring the changes in the beat frequency of the two split Raman lasers. We then perform real-time single nanoparticle detection in an aqueous environment using this method. By monitoring the discrete changes in the beat frequency of the Raman lasers, detection of single nanoparticles with radii of both 40 nm and 20 nm is realized.

9343-21, Session 5

Optically active silica and polymeric materials for microcavity lasers and sensors *(Invited Paper)*

Andrea M. Armani, Michele Lee, Andre Kovach, Eda Gungor, Kelvin Kuo, Vinh Diep, The Univ. of Southern California (United States)

Silica and silica-doped high quality factor (Q) optical resonators have demonstrated ultra-low threshold lasers based on numerous mechanisms (eg rare earth dopants, Raman). To date, the key focus has been on maintaining a high Q, as that determines the lasing threshold and linewidth. However, equally important criteria are lasing efficiency and wavelength. These parameters are governed by the material, not the cavity Q. Therefore, to fully address this challenge, it is necessary to develop new materials.

We have synthesized a suite of silica and polymeric materials with nanoparticle and rare-earth dopants to enable the development of microcavity lasers with emission from the near-IR to the UV. Additionally, the efficiencies and thresholds of many of these devices surpass the previous work.

Specifically, the silica sol-gel lasers are co- and tri-doped with metal nanoparticles (eg Ti, Al) and rare-earth materials (eg Yb, Nb, Tm) and are fabricated using conventional micro/nanofabrication methods. The intercalation of the metal in the silica matrix reduces the clustering of the rare-earth ions and reduces the phonon energy of the glass, improving efficiency and overall device performance. Additionally, the silica Raman gain coefficient is enhanced due to the inclusion of the metal nanoparticles, which results in a lower threshold and a higher efficiency silica Raman laser. Finally, we have synthesized several polymer films doped with metal (eg Au, Ag) nanoparticles and deposited them on the surface of our microcavity devices. By pumping on the plasmonic resonant wavelength of the particle, we are able to achieve plasmonic-enhanced upconversion lasing.

9343-22, Session 5

Explore optical gain in whispering-gallery microresonators for functional devices *(Invited Paper)*

Sahin K. Ozdemir, Bo Peng, Jiangang Zhu, Huzeyfe Yilmaz, Faraz Monifi, Steven H. Huang, Lan Yang, Washington Univ. in St. Louis (United States)

Traditionally optical gain has been used for light amplification in amplifiers or lasers. Here we will talk about functions enabled or enhanced by optical gain in photonic devices. Specifically, we explore the effect of optical gain in Whispering-Gallery-Mode (WGM) optical microcavities, which have attracted lots of attentions for their superior capabilities to significantly enhance light-matter interactions stemming from their microscale mode volumes and ultra-high-quality factors. In this talk, I will review the development of a laser assisted processing method to create optical microresonators with Q-factors in excess of 100 million. Next, the adaptation of this process to a sol-gel film to create active devices with optical will be described. To illustrate this method, I will present results from microlasers on a silicon chip by doping high-Q microresonators with rare-earth ions. A few examples will be demonstrated to show the diverse functions benefiting from optical gain in high-Q optical resonators. For example, we have fabricated a new type of add-drop filter with tunable bandwidth and add-drop efficiency controlled by the level of gain in the resonator. We have demonstrated that by adding optical gain in a photonic-molecule structure composed of two coupled resonators, parity-time-symmetric photonic systems can be formed, and nonreciprocal light transmission can be observed in such a new structure. Finally one of the recent discoveries of using optical gain in ultra-high-Q microresonators for ultra-sensitive self-referencing detection of single virion, dielectric and metallic nanoparticles will be discussed.

9343-23, Session 5

High frequency ultrasound detection with ultra high Q silica microspheres

Maria V. Chistiakova, Andrea M. Armani, The Univ. of Southern California (United States)

The development of ultrasound imaging methods relies on a combination of innovation in sensor technology and signal analysis. To date, ultrasound detection and imaging using whispering gallery mode optical resonators has been focused on polymer microring resonators. In this approach, detection is based on the deformation of the cavity, and the sensitivity is limited by the quality factor (Q). In the present work, we transition to a silica ultra-high-Q (UHQ) cavity and leverage the photo-elastic effect to detect 40MHz, sub-microsecond ultrasound pulses.

The photo-elastic effect describes the change in refractive index of a material as a strain is applied. In ultrasound detection, the strain arises from the ultrasound wave propagating through the cavity, and the change in index results in a resonant wavelength shift. To verify this mechanism, two sets of experiments are performed in conjunction with COMSOL Multiphysics modeling. First, the sensor response and reproducibility to the 40MHz ultrasound is verified by directing the transducer at the cavity. Second, a steel sphere is included in the chamber, and the echo generated is detected. Finally, the finite element model including the optical and acoustic components is compared to the experimental results, and the predictive accuracy is calculated.

9343-24, Session 6

generation of shape invariant flat top laser beams

Kamel Äit-Ameur, ENSICAEN (France); Darryl Naidoo, Sandile S. Ngcobo, Council for Scientific and Industrial Research (South Africa); Michael Fromager, ENSICAEN (France); Igor A. Litvin, Council for Scientific and Industrial Research (South Africa); Abdelkrim Hasnaoui, Ali Hasnaoui, Univ. des Sciences et de la Technologie Houari Boumediene (Algeria); Andrew Forbes, Council for Scientific and Industrial Research (South Africa)

A great number of laser applications need in place of the usual Gaussian beam a flat-top intensity profile in the focal plane of a focusing lens. In general the transformation of the laser beam from the Gaussian to the flat-top shape is made by a diffractive beam shaping technique. It is worthwhile to note that this transformation occurs in the vicinity of the focal plane. If a flat-top laser beam keeping its shape during propagation is needed then this can be obtained by a weighted incoherent mixing of LG00 and LG01 eigenmodes. Here, we consider the generation of these two transverse modes by a solid-state laser axially pumped by a laser diode. The idea is to design the laser cavity so as to make identical the losses of LG00 and LG01 modes. To reach this objective we have used two techniques. The first one called as diffractive lies to insert an adequate amplitude mask inside the cavity. The second one called as interferometric consisted to couple the laser to an external cavity. It is important to note that LG00 and LG01 modes are not spatially in concurrence, i.e. the peak of the LG00 appears in the dip of the LG01 mode. As a result, the energy extraction from the amplifying medium is improved increasing thus the laser slope efficiency. Theory and experimental verifications have been done for the diffractive and interferometric techniques allowing the generation of a flat-top laser beam keeping its shape from the near-field to the far-field.

9343-25, Session 6

Optical trapping with superfocused high-M2 laser diode beam

Grigorii S. Sokolovskii, Vladislav V. Dudelev, Ioffe Physical-Technical Institute (Russian Federation); Vasileia Melissinaki, Foundation for Research and Technology-Hellas (Greece); Sergey N. Losev, Ioffe Physical-Technical Institute (Russian Federation); Ksenya K. Soboleva, Saint-Petersburg State Polytechnical Univ. (Russian Federation); Anton G. Deryagin, Ioffe Physical-Technical Institute (Russian Federation); Vladimir I. Kuchinskii, Saint Petersburg Electrotechnical Univ. "LETI" (Russian Federation) and Ioffe Physical-Technical Institute (Russian Federation); Maria Farsari, Foundation for Research and Technology-Hellas (Greece); Wilson Sibbett, Univ. of St. Andrews (United Kingdom); Edik U. Rafailov, Aston Univ. (United Kingdom)

Many applications of high-power laser diodes demand tight focusing. This is often not possible due to the multi-mode nature of semiconductor laser radiation possessing beam propagation parameter M2 values in double-digits. We propose a method of 'interference' superfocusing of high-M2 diode laser beams with a technique developed for the generation of Bessel beams based on the employment of an axicon fabricated on the tip of a 100 um diameter optical fiber with high-precision direct laser writing. Using axicons with apex angle 140deg and rounded tip area as small as ~10 um diameter, we could demonstrate 2-4 um diameter focused laser 'needle' beams with approximately 20 um propagation length generated from multimode diode laser with beam propagation parameter M2=18 and emission wavelength of 0.96 um. This is few-fold reduction compared to the minimal focal spot size of ~11 um that could be achieved if focused by an 'ideal' lens of a unity numerical aperture. The same technique using an 160deg axicon allowed us to demonstrate 7 um-wide laser 'needle' beams with nearly 100 um propagation length, and use them for optical trapping of 5-6 um sized rat blood red cells in a water-heparin solution. Our results indicate the good potential of superfocused diode laser beams for applications relating to optical trapping and manipulation of microscopic objects including living biological cells towards novel lab-on-chip configurations.

9343-26, Session 6

Formation of the desired light intensity distribution on the target with bimorph deformable mirror

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It is desired to use some special intensity distribution on the target for various industrial applications. The adjusting of the intensity profile can be implemented by means of adaptive optics. In this paper we present laser beam control in the focal plane of lens with bimorph deformable mirrors.

Hill-climbing method and stochastic algorithm are compared. Advantages and disadvantages of two methods are discussed.

9343-27, Session 6

Transverse intensity transformation by laser amplifiers

Hencharl J. Strauss, CSIR National Laser Ctr. (South Africa); Gary King, Council for Scientific and Industrial Research (South Africa); Oliver J. P. Collett, Heriot-Watt Univ. (United Kingdom); Igor A. Litvin, Council for Scientific and Industrial Research (South Africa)

Lasers beams with a specific intensity profile such as super–Gaussian, Airy or Dougnut-like are desirable in many applications such as laser materials processing, medicine and communications. We propose a new technique for laser beam shaping by amplifying a beam in an end-pumped bulk amplifier that is pumped with a beam that has a modified intensity profile. Advantages of this method are that it is relatively easy to implement, has the ability to reshape multimode beams and is naturally suited to high power/energy beams.

Both three and four level gain materials can be used as amplifier media. However, a big advantage of using three level materials is their ability to attenuate of the seed beam, which enhances the contrast of the shaping.

We first developed a numerical method to obtain the required pump intensity for an arbitrary beam transformation. This method was subsequently experimentally verified using a three level system. The output of a 2.07 μm seed laser was amplified in a Ho:YLF bulk amplifier which was being pumped by a 1.89 μm Tm:YLF laser which had roughly a TEM10 Hermit Gaussian intensity profile. The seed beam was amplified from 0.3 W to 0.55 W at the full pump power of 35 W. More importantly, the beam profile in one transverse direction was significantly shaped from Gaussian to roughly flat-top, as the model predicted. The concept has therefore been shown to be viable and can be used to optimise the beam profile for a wide range of applications.

9343-28, Session 8

Optical alignment influenced aberrations in laser beam delivery systems and their correction

Michael J. Scaggs, Gilbert J. Haas, Haas Laser Technologies, Inc. (United States)

Industrial high power laser systems are often evaluated based upon spatial profile of the beam before they are brought to focus for processing materials. It is therefore often assumed that if the raw beam profile is good that the focus is equally as good. The possibility of having good optics and poor alignment or bad optics and good alignment and therefore not achieve a good focal spot is quite high due to the fact that a raw beam spatial profile does not manifest third order aberrations. In such instances the focal spot will contain aberrations when there are slightly misaligned poor quality high power optics in the system such as a beam expander or eye piece and objective of a 3-axis galvo. Likewise, if the beam itself is not on axis, the third order aberrations of astigmatism and coma are likely to appear but again not be seen in the unfocused beam's spatial profile. The third order aberrations of astigmatism, coma and spherical aberration can significantly alter both the size and spatial profile at the focus resulting in out of spec performance. The impact of beam and zoom expanders and their alignment in beam delivery systems is investigated by measuring both the far field unfocused and the far field focus beams using an all passive beam waist analyzer system.

9343-29, Session 8

Beam uniformity of flat top lasers

Chao Chang, Larry Cramer, Don Danielson, James Norby, Continuum (United States)

Many beams output from standard commercial lasers are multi-mode, with each mode having a different shape and width, and show an overall non-homogeneous energy distribution across the spot size. There may be satellite structures, halos and other deviations from beam uniformity. However, many scientific, industrial and medical applications require flat top spatial energy distribution with high uniformity in the plateau region and free of hot spot. Reliable standard methods for the evaluation of beam quality are of great importance not only for correct characterization in application but also for tight quality control in laser manufacturing. The International Organization for Standardization (ISO) has published standard procedures and definitions for this purpose, which however has not been widely adopted by commercial laser manufactures, and they are found unreliable as an unrepresentative single-pixel value can seriously distort the result. We hereby propose a definition of beam uniformity, procedures to characterize hot spots, and present our latest results on simulations and applications in our high energy laser production.

9343-30, Session 8

Ultra-narrow UV laser lines for surface processing

Mikhail M. Ivanenko, Vyacheslav Grimm, Lisa Kleinschmidt, Aliaksei Krasnaberski, Markus Wiesner, LIMO Lissotschenko Mikrooptik GmbH (Germany)

Laser lines with top-hat distribution in long axis are important tools in surface technologies like crystallisation of Si layers for advanced displays or lift-off in production of flexible plastic screens. For most of the processes UV light is a favourable choice, because of its strong absorption in material. Traditionally excimer lasers are used for these applications. Yet, the recent progress in the development of powerful diode pumped solid-state UV lasers (DPSS) open a way to use DPSS with potentially low cost of ownership in the mass production. Multimode DPSS´s work with a high repetition rate (10 - 20 kHz) and relatively low pulse energy of 10 - 20 mJ. For the application a fluence of 0.5 - 0.2 J/cm2 in a 100 - 1000 mm long light line is usually required. To attain this, a multiplexing of several lasers and reduction of the line width down to 15 - 30 µm are necessary. Further a relatively long depth of focus and working distance are essential. This combination may be achieved with an anisotropic beam quality transformation, developed in our company. It allows to improve the beam quality for narrow axis several tens of times and provides simultaneously best possible degree of homogenisation in the long focus axis.

General optical approach to the beam shaping with micro-optical beam transformation units and characteristics of LIMO UV optical systems will be discussed. Especially an UV line of > 600 mm length with a super-gauss profile in narrow axis (FWHM 32 µm) will be presented.

9343-56, Session PTue

Selective higher order fiber mode excitation using a monolithic setup of a phase plate at a fiber facet

Johannes Wilde, Christian Schulze, Robert Brüning, Michael Duparré, Friedrich-Schiller-Univ. Jena (Germany); Siegmund Schröter, Leibniz-Institut für Photonische Technologien e.V. (Germany)

The perturbations induced into a fiber via external influences [e.g. bending, pressure, temperature] are usually spatially inhomogeneous. This inhomogeneity in the fiber thereby generally varies in both the axial and transversal direction.

The higher the excited modes in a single core step index fiber are, the more likely they are going to be affected by external disturbances of the fiber. Thus the sensitivity of a fiber is adjustable by choosing the appropriate mode.

Using a monolithic setup of a phase plate at a fiber face, i.e. a passive, spatially phase shifting element directly at the input of the fiber, the excitation of a higher order mode needing minimal room is easily possible.

By employing a phase-only element, the field distribution at the fiber input may not be perfectly matched to the desired mode; nevertheless a high purity of theoretically more than 99% can be expected. The monolithic setup of fiber and phase plate thereby ensures, that the perturbations by free space propagation are kept to a minimum.

We investigated the capabilities of this approach by complete modal decomposition of the fiber output signals, considering the achievable mode purity with respect to several possible imperfections of the setup like a transversal displacement of the incoupling beam, an unadapted beam waist or a wrongly chosen phase shift of the phase plate.

The experiments were performed for the LP_11 as well as the LP_21 modes and were in very good agreement with numerical simulations.

9343-62, Session PTue

Investigation of the impact of fiber Bragg grating bandwidth on the efficiency of a Raman resonator

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There is interest in frequency doubling an 1178 nm narrow linewidth fiber laser source for sodium guidestar laser applications. Briefly, broad linewidth 1069 nm pump is amplified and injected along with narrow linewidth 1178 nm into a completely polarization maintaining 10/125 system. The 1069 nm is then Raman converted to 1121 nm in a resonator cavity comprised of silica or germanosilicate fiber along with two high reflector fiber Bragg gratings (FBGs). Linewidth broadening in the resonator cavity has been found to lead to significant power leakage around the FBGs, decreased 1121 nm power buildup in the resonator cavity and decreased amplification of the 1178 nm. In order to study what impacts this, FBGs having 1 and 3 nm bandwidths were investigated for an approximate 65 m cavity comprised of germanosilicate fiber. Two .01% tap couplers were inserted into the cavity, next to the input and output FBGs. Significant linewidth broadening was observed as 1121 nm power traversed the resonator cavity in both the forward and backward directions. Upon comparing the performance of 1 and 3 nm FBGs, it was seen that greater 1121 nm intracavity power buildup (43% more) and less 1121 nm power leakage (6.2% versus 15.3%) occurred for a cavity using 3 nm versus 1 nm FBGs. This leads one to believe that better system performance will occur with broader bandwidth FBGs. The results of a tradespace study involving (1, 3, and 5 nm) FBGs; silica versus germanosilicate fiber; as well as various cavity lengths will be presented.

9343-63, Session PTue

Improving the intensity of a focused laser beam

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Let us consider the family of symmetrical Laguerre-Gaus modes of zero azimuthal order which will be denoted as LGp0 . The later is made up of central lobe surrounded by p concentric rings of light. The fundamental mode LG00 is a Gaussian beam of width W. The focusing of a LGp0 beam of power P by a converging lens of focal length f produce a focal spot keeping the LGp0 -shape and having a central intensity I0=2P(W/(lambda.f))^2 whatever the value of the radial order p. Many applications of lasers (laser marking, laser ablation, ...) seek nowadays for a focal laser spot with the highest as possible intensity. For a given power P, increasing intensity I0 can be achieved by increasing W and reducing the focal length f. However, this way of doing is in fact limited because the ratio W/f cannot increase indefinitely at the risk of introducing a huge truncation upon the edge of the lens. In fact, it is possible to produce a single-lobed focal spot with a central intensity of about p times the intensity I0 . This result has been obtained by reshaping a LGp0 beam thanks to a proper Binary Diffractive Optical Element (BDOE). In addition, forcing a laser cavity to oscillate upon a LGp0 can improve the power extract due to a mode volume increasing with the mode order p. This could allow envisaging an economy of scale in term of laser pumping power for producing a given intensity I0 .

9343-64, Session PTue

Laser beam shape converter using spatially variable wave plate made by nanogratings inscription in fused silica

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In high energy and high intensity laser systems shaping of beam spatial profile is very important in aspect of active element fill factor maximization and nonlinear wave front distortions minimization. Many techniques for making flat-top beam spatial distribution were proposed. Some of these based on radiation absorption are not suitable for high mean power systems due to necessity to remove excessive heat. Some methods based on complex shape refractive optics are not flexible and difficult to align. Active shaping methods using spatial light modulators are sensitive to driving signals and limited in maximum laser beam power and individual pulse intensity.

In this work we present beam shaping technique based on variable phase retardation inscribed in fused silica using a femtosecond laser. Formation of self-assembled periodic nanostructures, known as “nanogratings”, was used to fabricate the converter. During the fabrication we control nanograting orientation and induced retardance. Combination of variable phase retardation plate and polarizer acts as spatially variable transmission filter. Using transmission profile which was calculated to transform an initially Gaussian beam to a super-Gaussian (flat-top) beam we converted more than 50% of initial laser power to flat-top beam power.

The efficiency of the proposed converter could be up to 70% theoretically. The proposed converter doesn’t have absorbing elements so its resistance to optical damage is similar to that of fused silica. Converter allows on-the-fly adjustment of beam shape from flat-top to beam with a dip in the middle. Shaped beam was tested in high power picosecond pulse amplifier.

9343-65, Session PTue

Role of geometry in optothermal response of toroidal ultra-high-Q cavities

Soheil Soltani, Andrea M. Armani, The Univ. of Southern California (United States)

Ultra-high quality factor (UHQ) resonant cavities are able to store light for long periods of time, resulting in high circulating intensities. As a result, numerous nonlinear optical phenomena appear, such as radiation pressure oscillations and lasing. However, deleterious behaviors also occur, such as optothermal broadening of the resonant linewidth. The degree of distortion is directly related to the circulating power in the cavity, the material absorption, and the thermo-optic coefficient of the cavity material. Specifically, a portion of the circulating power is absorbed by the material and converted to heat. This thermal energy is able to induce a refractive index change in the cavity which is experimentally observed as a resonant wavelength change. This behavior has been observed in numerous cavities, but one interesting case is the toroidal cavity, as it has a particularly complex geometry providing multiple thermal transport pathways. To accurately capture this complex behavior, we have developed a COMSOL Multiphysics model which combines the thermal and optical components. The model uses the non-uniform optical mode profile as the heat source. As such, changes in device geometry and wavelength are inherently captured. To verify the modeling, we characterize the optothermal threshold for a series of toroidal cavities across a range of wavelengths and device geometries. Additionally, the thermal time constant of the structure is explored. Of note, the membrane thickness is shown to play a critical role in the optothermal behavior.

9343-66, Session PTue

Whispering-gallery mode lasers for biosensing: a rationale for reducing the lasing threshold

Alexandre François, Nicolas Riesen, The Univ. of Adelaide (Australia); Hong Ji, The University of Adelaide (Australia); Shahraam Afshar Vahid, The University of Adelaide (Australia) and University of South Australia (Australia); Tanya M. Monro, The Univ. of Adelaide (Australia)

Whispering-gallery modes have been studied extensively for biosensing applications. Whilst the majority of work undertaken has focused on high Q factor resonators, with the main improvement being a reduction of the resonator size to improve sensitivity. This work chooses an alternative pathway exploiting resonators that exhibit extremely high refractive index sensitivity but low Q factor, such as small polystyrene microspheres. A way forward to overcome this Q factor limitation is to introduce a gain medium and operate the resonator above its lasing threshold. This has been shown to result on average in a 5-fold increase in the Q factor. However, the lasing threshold itself is dependent on the Q factor. Furthermore, reducing the resonator radius results in even lower Q factor, and so lasing has been impossible so far for microspheres in aqueous solution with diameter below 15 um. Nevertheless other parameters such as the gain medium concentration can be exploited to either reduce the lasing threshold or enable smaller resonators to be operated above their lasing threshold. As a demonstration we demonstrate a 10 um diameter polystyrene microsphere lasing in aqueous solution for refractive index sensing applications, which to the best of our knowledge is the smallest polystyrene microsphere Whispering-Gallery Modes laser ever demonstrated in these conditions.

9343-68, Session PTue

Self organization of multiple single emitters in an unstructured broad area diode laser using a spectral beam combining architecture

Christof Zink, Univ. Potsdam (Germany); Nils Werner, Univ. of Potsdam (Germany); Andreas Jechow, Axel Heuer, Ralf Menzel, Univ. Potsdam (Germany)

Multiple self organized single emitters are induced in a single unstructured broad area diode laser (BAL) utilizing an external cavity with a spectral beam combining architecture. The cavity consists of the BAL, a fast axis collimator, two cylindrical lenses in the slow axis, an optical grating, a slit aperture and an outcoupling mirror. The combination of a dispersive element, an aperture and the 4f self imaging lens setup inside the cavity leads to a wavelength gradient in the slow axis at the front facet of the BAL consisting of overlapping images of the slit aperture. After several round trips the gain competition between the overlapping feedback fields lead to the self organization of multiple single emitters in the active region of the BAL, although the BAL without any epitaxial sub-structuring. The self-organized emitters are equidistantly spaced across the slow axis and each lases at a distinct wavelength. Therefore mode competition is suppressed and crosstalk reduced. The self organization of the emitter during the start up process is analyzed with a streak camera. The emission of each emitter is multiplexed by the cavity into one spatial mode with near-diffraction limited beam quality. With this setup, multi-line emission of 31 individual spectral lines centered around 774 nm and a total spectral width of 3.6 nm is realized with a 1000 μm wide BAL.

9343-69, Session PTue

High-speed transient sensing using dielectric micro resonators

Amir R. Ali, Volkan Otugen, Tindaro Ioppolo, Southern Methodist Univ. (United States)

In this paper, we demonstrate the use of whispering gallery mode (WGM) resonators for high-speed transient sensing. In the typical WGM sensor, the micro-resonator modes are interrogated by coupling light from a tunable laser through a single mode optical fiber. The laser is tuned over a narrow range by thermo-optic effect, and mode shifts in the transmission spectrum through the fiber are observed. For high-speed applications, thermal inertia of the optical system impedes the proper tuning of the laser, limiting the WGM sensor applications to slow varying phenomena. In order to use the sensors for high-speed transient applications, we tune the DFB laser using a harmonic rather than a ramp waveform and calibrate the laser response at various input frequencies and amplitudes using a Fabry-Perot interferometer. WGM shifts are tracked using a fast cross-correlation algorithm on the transmission spectra. We demonstrate dynamic force measurements up to 10 kHz using this approach. We also present a simple lumped-heat capacity thermal model to predict the laser response.

9343-70, Session PTue

Short-and-long-term highly stable oscillation and amplification of linearly polarized passively mode-locked solitonic fiber laser resonators

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Pulsed optical sources with high repetition rates (tens of MHz to tens of GHz), ultrashort pulse widths (hundreds of fs to tens of ps) and high signal quality are being increasingly demanded in new generation optical and wireless communication networks and systems [1-3]. Passively mode-locked fiber lasers with linear Fabry-Pérot cavities have been demonstrated to be a reliable, compact and cost effective solution to generate femtosecond pulses with high repetition rates [4-6].

In this work, we present a short- and long-term operation and environmentally-stable, all-polarization-mantained, Fabry-Pérot resonator, passively mode-locked fiber laser operating in an all-anomalous-dispersion solitonic regime. Our results confirm that the highly stable operation of the laser oscillator is maintained after amplifying the laser output with a conventional EDFA. Such stability has been studied by a variety of measurements in the temporal and spectral -both optical and electrical- domains before and after amplification. Pulse durations of 540 fs, period-relative time jitters of ~0.015‰, and long-term uninterrumped operation with <3% variation of the individually photodetected pulse peak powers are obtained for the laser oscillator. After amplification, dispersion-induced pulse durations of ~244 fs, period-relative time jitters of ~0.019‰ and an average output power of 20 mW are obtained, while maintaining the 100 dB signal-to-noise ratio (SNR) measured at 500 Hz offset from the fundamental harmonic frequency of the photodetected signal. We have also carried out a theoretical validation of the emission properties of our laser oscillator based on solutions of the Nonlinear Schrödinger Equation (NLSE) that take into account wavelength and z-position dependence of the active medium gain.

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9343-71, Session PTue

Predicting the whispering gallery mode spectra of microresonators

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Whispering Gallery Modes (WGMs) of active optical resonators have prompted intense research efforts, due to their usefulness in the field of biological sensing and their employment of the Purcell effect. While much information is available in the literature on numerical modelling of WGMs in microspheres, it remains a challenging task to be able to predict the emitted spectra of active spherical microresonators.

Here, we establish a customisable Finite-Difference Time-Domain (FDTD)-based approach to investigate the WGM spectrum of active microspheres. The simulations are carried out in the vicinity of a dipole source, rather than a typical plane-wave beam excitation, thus providing an effective analogue of the fluorescent dye or nanoparticle coatings used in experiment to excite WGMs.

The analysis of a single dipole source at different positions on the surface or inside a microsphere, serves to assess the relative efficiency of nearby radiating TE/TM modes, which characterises the profile of the spectrum.

By changing the number, positions and alignments of the dipole sources, different excitation scenarios can be compared to analytic models, and to experimental results.

The energy flux is collected via a nearby disk-shaped region, which can measure the angular distribution of the energy flux of the fields, and the resultant spectral profile shows a dependence on the configuration of the dipole sources.

The power outcoupling can then be optimised for specific modes and wavelength regions. The development of such computational tool can aid the preparation of optical sensors prior to fabrication, by preselecting desired optical properties of the resonator.

9343-72, Session PTue

Manufacture of refractive and diffractive beam-shaping elements in higher quantities using glass molding technology

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Laser beam shaping components can improve the results of materials processing by transforming a Gaussian to a top hat profile having either a circular or a rectangular shape. Other frequently applied types of beam shaping are beam splitting or pattern generation which are used for the parallelization of materials processing or for image processing. Until today, most beam shaping devices are either produced by means of lithography (typically in fused silica) or in plastic using a hot embossing process. These elements bring along the disadvantage of high costs in the former case and restrictions with regard to the temperature range and applicable laser output in the latter case. A newly developed press molding process for glass along with an adjusted optical design facilitates the production of large quantities and the reduction of costs. The production of molds for refractive laser beam shaping components by grinding hard materials requires very high precision with form deviations of less than 100nm. We present measurements of the surface topography of freeform optics for gauss to top-hat beam shaping using white light interferometry as well as results of the optical measurement of reconstructed light distribution which display high efficiency and homogeneity. Diffractive molded optical components in glass were produced in continuous as well as in discrete fashion. The former by means of grinding the tools, the latter by employing lithography and ion beam etching. The continuous diffractive elements feature a typical grating constant of 100 μm and a height modulation in the range of 1 μm. We present the example of a 1x5 beam splitter which exhibits a high efficiency.

9343-73, Session PTue

Small refractive index, high performance: Magnesium fluoride whispering gallery mode resonators for refractometric sensing

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Chemical and biological sensing with Whispering Gallery Mode (WGM) resonators is a rapidly growing field. The evanescent field of the high quality Q, narrow linewidth modes interacts with the surrounding, providing high sensitivity to changes in the refractive index of the surrounding or the binding of particles and molecules. In the last years such resonators were used to detect nearly any kind of biological matter, even down to the single molecule level. The most established material used in this field thus far is fused silica in form of microspheres or toroids. We investigate for the first time single crystalline, birefringent magnesium fluoride (MgF2) resonators having a refractive index much closer to that of water than fused silica. The small index contrast with respect to water allows the evanescent field to penetrate deep into the surrounding, enhancing the interaction and therefore boost the sensitivity. Furthermore the birefringence amplifies the sensitivity difference between TE and TM modes significantly, which is advantageous for schemes that trace TE and TM modes simultaneously like temperature-drift compensating measurements. We present experimental results showing that the evanescent field decay length in such resonators is more than 50% larger compared to fused silica spheres and that millimeter sized MgF2 resonators provide a sensitivity that competes with that of ?m-sized fused silica spheres. Furthermore, we report on ultra-high Q factors well above 1x10^8 in water. We believe that our experimental results strongly indicate that MgF2 is a well suited candidate for future research regarding an application in WGM biosensing.

9343-74, Session PTue

High-speed tunable laser based on novel electro-optic effect

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Compact agile wavelength-tunable lasers are of great importance to many applications in telecommunications [1], biomedical imaging [2], display [3], spectral and remote sensing [4]. Among various types of miniaturized tunable lasers, external-cavity laser diodes with diffraction optics are promising due to its inherent potential for simple configuration, narrow spectral linewidth, continuous and wide tuning range. However, most of these lasers suffer from slow tuning speed and low output power.

We report the demonstration and fabrication of a high-speed electro-optic (EO) tunable laser with high output power and continuously wide wavelength tunability. We observe that the wavelength-swept speed exceeds 107 nm/s at center wavelength of 1550 nm. Moreover, the maximum output power is about 100 mW and the wavelength tuning range is near 100 nm with a FWHM (full width at half maximum) of less than 0.5 nm. The wavelength tuning mechanism is based on a high-speed EO Effect under low driving voltage. The EO tunable device allows rapid, accurate, and reproducible wavelength tuning with low power consumption, in comparison to other tunable devices such as the use of mechanical rotation mirrors [5], prisms or reflection gratings [6], piezoelectrically-tunable devices [7], Fabry–Perot filters [8] as well as acousto-optic tunable deflectors [9]. Our design combines the technical advantages of both the high speed of EO effect and the high gain of a semiconductor optical amplifier to realize a high-performance wavelength-tunable laser in a very compact size.

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9343-31, Session 9

Minimal-effort planning of active alignment processes for beam-shaping optics

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In science and industry, the alignment of beam-shaping optics is usually a manual procedure. Many industrial applications utilizing beam-shaping optical systems require more scalable production solutions and therefore effort has been invested in research regarding the automation of optics assembly. In previous works, the authors and other researchers have proven the feasibility of automated alignment of beam-shaping optics such as collimation lenses or homogenization optics. Nevertheless, the planning efforts as well as additional knowledge from the fields of automation and control required for such alignment processes are immense. This paper presents a novel approach of planning active alignment processes of beam-shaping optics with the focus of minimizing the planning efforts for active alignment. The approach utilizes optical simulation and the genetic programming paradigm from computer science for automatically extracting features from a simulated data basis with a high correlation coefficient regarding the individual degrees of freedom of alignment. The strategy is capable of finding active alignment strategies that can be executed by an automated assembly system. The paper presents a tool making the algorithm available to end-users and it discusses the results of planning the active alignment of the well-known assembly of a fast-axis collimator. The paper concludes with an outlook on the transferability to other use cases such as application specific intensity distributions which will benefit from reduced planning efforts.

9343-32, Session 9

Latest developments and experimental results of adaptive optics for ultra intense lasers

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Adaptive optics for high power and ultra intense lasers is an application that drives new developments in order to fulfill the specific needs of the laser end users. Mechanical deformable mirror technology has been developed for high power lasers, as well as specific correction strategies in order to correct for the focal spot directly in the interaction chamber.

Along with the various projects for the next generation of ultra intense laser facilities, new constraints and requirements appears and have to be fulfilled in order to cope with the challenges associated with these high end facilities. For instance, topics like the integration of the whole adaptive optics system in the control command system of the facility becomes more and more important.

We will present the latest adaptive optics systems as well as experimental results obtained in actual ultra intense laser facilities. The prospects of developments of adaptive optics systems, hardware for diagnostics, correction software, custom control strategies, integration of adaptive optics in the control command system, and specific sensors will be discussed.

9343-33, Session 9

FPGA-accelerated adaptive optics wavefront control part II

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We present progressive work based on a novel self- developed rapid control prototyping system that was introduced in 2014 for the design of high-performance adaptive optics control algorithms using a continuous deformable mirror. One focus is put on the assets, e.g. of recently developed algorithms for Shack-Hartmann wavefront sensor evaluation on an Field Programmable Gate Array. Furthermore, we are presenting recently attained results which are far superior to the former ones. Through experiments we demonstrate the effective performance, i.e. the maximum manageable complexity in the controller design that is achievable without performance losses of the overall controller.We give detailed studies on hidden latencies and show that they could be reduced drastically. The closed-loop interaction between integrated heater and the piezo actuators integrated in the DM is exemplary investigated.

9343-34, Session 9

New concepts of electro-optical light deflection: EO-slab and phased EO-array

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Deflection and modulation of a laser beam for Q-switching or material processing can be realized in many ways. Today, one task is still the speed of these components. Especially for spatial pulse separation in UKP-Laser applications the deflection must be faster (MHz).

In this report, we focus on two different innovative electro-optic (EO) deflector concepts. Both concepts use μ-Slab MgO:LiNbO3 crystals of 0.5mm thickness, for getting sufficient high electric fields at moderate voltages (≤200V). In the first refractive concept, the linear polarized light is focused in a single μ-Slab with four prism electrodes. The μ-Slab is sandwiched in between two Peltier elements for temperature control and electric isolation. We achieved a deflection angle of ±0.4mrad @ ±200V. This implies 6 resolvable angle states for a laser spot of 5mm diameter. The compact design makes integration of the deflector easy. The second diffractive concept is based on a phased array of 11 μ-Slabs. A linear polarized top-hat laser beam radiates through the array and its wave front is phase modulated by a set of voltages applied on the μ-Slabs. After cylindrical lens arrays and Fourier lenses this phase modulation leads to a deflection of the laser beam. We will achieve a deflection angle of ±10.3mrad @ set of voltages in between ±200V and 11 discrete resolvable angle states. A complete scan of the angle states will be executed in 2 μs (0.5 MHz) with developed electronics.

Both concepts are suitable for combination with other scan technologies like galvo-scanners.

9343-35, Session 10

Femtosecond laser direct writing of high-Q microresonators in glass and crystals *(Invited Paper)*

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Recently, femtosecond laser direct writing has emerged as a straightforward approach for fabrication of three-dimensional (3D) functional microstructures, such as microfluidics, microoptics, optical waveguides, and microelectrodes, in various kinds of transparent materials with great flexibility. Here, we extend this capability to fabrication of 3D microresonators of high quality (high-Q) factors in glass and crystalline materials. When glass materials such as fused silica and Nd:YAG glass are used as the substrates, the microtoroid resonators can be fabricated by first forming a thin microdisk on top of a glass stem using femtosecond laser direct writing, followed by a surface reflow process with a CO2 laser. In addition, high-Q microresonators can also be fabricated in crystalline materials, such as lithium niobate, by femtosecond laser micromachining. To smooth the edge of the microdisk resonator (i.e., reducing the boundary scattering), we employ focused ion beam (FIB) polishing and thermal treatment. Integration of a microresonator into a microfluidic system for refractive index sensing has been achieved by simultaneous fabrication of all the functional components in fused silica substrate. In addition, a microlaser fabricated in Nd:YAG glass has been demonstrated in which lasing action can be initiated at a pump power as low as 69 microwatts. Lastly, we demonstrate generation of second harmonic wave in the high-Q lithium niobate microresonator.

9343-36, Session 10

Nanowire-induced nanocavities in nanophotonics platform *(Invited Paper)*

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It had been demonstrated that one can create a high-Q wavelength-sized nanocavity by introducing a certain local modulation into a line defect of a photonic crystal slab, which is called a “modulated modegap cavity”. We are currently exploiting this cavity formation mechanism into a variety of systems. First, we embedded a InGaAsP wire-like structure into a InP photonic crystal by MOVPE overgrowth. This particular structure leads to very efficient nanolasers and optical RAMs. Recently, we have further extended this method, and placed a self-organized InP-based nanowire grown by VLS method on a Si photonic crystal to form a nanocavity. In the talk, we describe how this works, and what application will arise. In addition, we will describe a combination of nanowires and plasmonic systems.

9343-37, Session 10

Hybrid silicon unidirectional-emission microspiral disk lasers for optical interconnect applications *(Invited Paper)*

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We report our recent progress in hybrid silicon unidirectional-emission microspiral disk lasers for optical interconnect applications. Our hybrid silicon lasers comprise an InAlGaAs/InP multiple-quantum-well (MQW) gain medium shaped into a microdisk bonded on top of a silicon microspiral disk cavity acting as the laser cavity on a silicon-on-insulator (SOI) substrate. We employ the conventional die-to-die polymer-based bonding technique. The laser cavity is directly butt-coupled to a silicon waveguide for unidirectional output coupling. We employ spatially selective injection into the MQW gain medium by using a ring-shaped p-contact on top of the III-V microdisk rim region in order to selectively inject current to the whispering-gallery-like modes of the microspiral cavity. Such a design potentially lowers the lasing threshold, reduces the device capacitance and avoids excessive heat being generated at the central region of the microdisk laser. In order to improve the thermal property of the bonded hybrid silicon lasers, we design and numerically model different thermal shunts to carry the heat from the gain region to the silicon substrate.

Our on-going experiments focusing on III-V microspiral disk lasers reveal a directional emission from the butt-coupled waveguide above the injection lasing threshold, according to top- and side-view imaging of the scattering light. In the case of optically pumping the III-V microspiral disk lasers, our experiments with different donut-shaped pump patterns after an axicon lens and overlapping with the microdisk rim indicate that we can further optimize the microspiral disk lasing threshold and directional emission properties by shaping the spatially selective pumping.

9343-38, Session 10

Propagation of polariton condensate in a one-dimensional microcavity at room temperature *(Invited Paper)*

Yanjing Ling, Wei Xie, Yao Yao, Xuechu Shen, Zhanghai Chen, Fudan Univ. (China)

Excitonic polariton condensate, a coherent state of half light half matter, allows quantum manipulation of the macroscopic wavefunction by optical means in semiconductor. So far, the motion of polariton condensate has been achieved well below liquid N2 temperature, a room temperature operation is highly desirable for practical device application. In this work, we choose a ZnO microwire which provides two-dimensional confinement in the cross section and forms perfect whispering gallery microcavity. The polariton condensate propagating along the microwire is clearly demonstrated at room temperature under non-resonant excitation. This sustained flow of polariton fluid reaches dynamically equilibrium and is steady in real space. Thus, we study the k-space dispersion evolution of the condensed fluid and the non-dispersive transport for propagating distance as long as 40 ?m is observed. Unlike the waveguide behavior below the condensate threshold that the momentum distribution of propagating polaritons depends on the propagating distance, here above threshold, the condensed polariton fluid with given momentum do not suffer from obvious perturbation in k-space during propagation. By measuring the 2D Fourier plane image, the distinct intensity distribution pattern is observed, manifesting the extended spontaneous coherence in our system. Moreover, since the microwire acts as not only waveguide structure but also a gain medium, this makes it suitable for fabricating light emitting devices and appealing for room temperature polariton-based optical integrated circuits.

9343-39, Session 10

PDMS quasi-droplet microbubble resonator

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Composite or multi-layered whispering gallery resonators (WGR) have interesting optical effects that can be used for various sensing applications. A thin-walled microbubble WGR was fabricated and filled with a polymer

(PDMS) to form a polymer quasi-droplet optical cavity. The microbubble had a wall with a thickness around 1 um. The thin- walled microbubble supported WGMs and the higher order radial modes extended far into the polymer core. These modes are in the quasi-droplet regime and the optical properties of the polymer are dominant for them. The optical Q factor of these quasi-droplet modes remained high, with some modes in excess of 10^6 at a wavelength of 780 nm. PDMS has a thermo-optic coefficient that is much larger and negative compared to that for glass; it also has a larger thermal expansion coefficient. Therefore, the optical modes were very sensitive to changes in temperature. For the uncured polymer, the higher order WGMs experienced a significant blue shift with increasing temperature, whereas the sign of the shift changed when the polymer was cured. Different modes shifted in opposite directions and at different rates depending on the wall thickness and mode order. This created a complex mode spectrum and interferences, resulting in EIT and Fano-type resonances, which could be controlled by changing the temperature and polarization. The time response of the optical modes to changes in temperature was also compared for empty and polymer-filled bubbles.

9343-40, Session 11

Optimal coupling to high-Q whispering gallery modes with a sub-wavelength metallic grating coupler *(Invited Paper)*

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Gold grating patterned on the end-face of an optical fiber is able to excite whispering gallery mode (WGM) in a silica microsphere. With a direct pathway of the metal reflection, the coupled WGM is able to superimpose and create an asymmetric Fano resonance. With multiple resonances at play – the WGM, grating reflection, and a weak Fabry-Perot resonance along the diameter of the sphere – it is difficult to evaluate the power efficiency by simply looking at the reflection spectrum. Using temporal coupled-mode theory, a general model is constructed for the end-fire coupling from a grating to a WGM resonator. Both transmission and reflection spectra of the coupled resonator are obtained and they agree well with our experimental observations. The model confirms our intuitive understanding that a high coupling efficiency comes from a strong conversion ratio of the input light and the grating's first diffraction orders. The peak-to-dip intensity difference of the Fano resonance in the reflection/transmission spectrum, though not a true numerical coupling efficiency, is a qualitative indication of the coupling strength. When the reflectivity of the grating is low, the system can be approximated as one that gives symmetric resonance and the peak-to-dip difference reveals the approximate coupling efficiency. In this case, it is found out that optimal coupling is shifted to the deep over-coupling region that might never happen. The model serves as an optimization tool for the single port WGM coupling system which is uniquely useful in applications such as sensing, filtering switching and lasing.

9343-41, Session 11

Strong localization of whispering gallery modes in an optical fiber via asymmetric perturbation of the translation symmetry *(Invited Paper)*

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It is known that a weak nanometer-scale local deformation of the optical fiber shape can cause strong localization of whispering gallery modes (WGMs) launched along the transverse direction. This effect is explored in Surface Nanoscale Axial Photonics (SNAP), the new technology for fabrication of high Q-factor resonant circuits at the surface of an optical fiber. Usually, the fiber deformation is introduced by directional heating with a CO2 laser. For this reason, the deformation is azimuthally asymmetric. This paper presents the theory of WGMs in an asymmetrically perturbed optical fiber and determines the conditions of their strong localization.

9343-42, Session 11

Manipulating high-order scattering processes in ultrasmall optical resonators to control far-field emission *(Invited Paper)*

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Optical microcavities have a broad range of applications from coherent light sources in integrated photonics, to cavity quantum electrodynamics, and biochemical sensing. Directional emission is desired for many applications such as microlasers and single-photon emitters. There have been extensive studies on the emission directionality of microcavities defined by a variety of known cavity shapes, e.g. ellipse, quadruple, stadium, spiral, or limacon. The inverse problem, i.e. to design a cavity shape to obtain a desired emission pattern, is much more challenging and remains an open question. In this work, we show that we can manipulate the far-field emission pattern of a deformed microdisk by imposing a set of harmonic perturbations to the cavity boundary. These perturbations induce conversion and mixing of the orbital angular momentum of light via surface scattering. Multiple scattering paths are available due to high-order scattering, which can be greatly enhanced by quasi-degenerate resonances. By manipulating the relative strengths of these scattering processes, we theoretically synthesize the angular momentum spectra of individual modes so as to control their far-field patterns. We demonstrate experimentally that in wavelength-scale cavities of a fixed shape, the neighboring modes can have dramatically different emission directionality. This phenomenon is robust against slight shape deviations and surface roughness, and provides a general mechanism to control and switch the emission direction of ultrasmall resonators.

9343-43, Session 11

Cladding modes fiber coupling to silica micro-resonators based on long period gratings

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There is a large variety of applications for high-Q whispering gallery mode (WGM) resonators ranging from fundamental studies to commercial devices. A critical point is the implementation of the proper coupling system of the light to the cavity modes. Silica fiber tapers are widely used as they are excellent and easy-to-align coupling tools, which offer great flexibility for an ideal phase and mode-matching to the resonator modes. However they are inherently fragile because the tapered region can be very thin, down to less than one micron. We propose a new method based on long period gratings

(LPG) for improved robustness of fiber coupling to silica microresonators. An LPG is characterized by a series of periodic refractive index change in the core of a single-mode optical fiber and it allows coupling between the fundamental core mode and co-propagating LP cladding modes. One or more attenuation bands characterize the transmission spectrum with the minimum of each band related to the coupling with a selective cladding mode. After the LPG we make an adiabatic taper of the proper size so that the excited cladding mode increases its evanescent part but it is still not radiating. These tapers are up to one order of magnitude thicker than the 'standard' fiber tapers used for coupling light to WGM resonators, and therefore they are much more robust for practical applications. By scanning around the selected LPG transmission dip we successfully observed resonances both in silica microspheres and microbubbles.

9343-44, Session 11

Polymer waveguide couplers for ultra-high-Q low index open crystalline cavities

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We report on the development and testing of polymer waveguides suitable for planar integration of ultra-high-Q crystalline whispering gallery mode (WGM) resonators. Feasibility of the waveguides for coupling with lithium niobate and calcium fluoride WGM resonators is proven theoretically. Coupling efficiency on the order of 80% is demonstrated experimentally with calcium fluorite conical WGM resonators having a Q-factor exceeding a billion.

9343-45, Session 12

Uncovering the physical origin of self phasing in coupled fiber lasers *(Invited Paper)*

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No Abstract Available

9343-46, Session 12

Dynamics of passively phased regenerative high power fiber amplifier arrays

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We present a numerical solution of the equations describing the dynamics of regenerative high power fiber amplifier arrays that are globally coupled through an external cavity. The intra-cavity fields are described by bi-directional signal waves that are coupled to the population inversion and mutually coupled by boundary conditions at the interface with the external cavity. Since the solution of the discretized time-space dependent equations is a formidable computational task, we employ a multi-core CPU and multi-GPU (Graphic Processing Unit) acceleration technique that takes advantage of the inherent parallel nature of GPUs to achieve speedup factors exceeding two orders of magnitudes over the corresponding CPU implementations (2 fibers that are both approximately 20cm with about 1cm long external cavity, 500 round trips, CPU (Core 2 Extreme QX6800 2.93GHz, 2GB RAM) ~ 35 hours, GPU (GeForce GTX 680, 1536 CUDA Cores) ~ 19.7 minutes). Due to absence of published results and to compare the performance of various computational approaches, we devised several numerical tools, namely, finite-difference time-domain, the method of characteristics, and the predictor-corrector method. Through our numerics, we estimate the performance of the array as measured by phase quality and the output power as related, for example, to fiber length disorder (OPD), pump level, internal reflection, cavity loss and Kramer-Kronig and Kerr nonlinearities. Our preliminary results indicate that Kerr nonlinearity results in some instability in certain cases whereas the effect of KK nonlinearity is mostly minute at normal power levels. Additionally, by accurate prediction of instabilities and their causing factors, guidelines are offered for optimum design of passively phased arrays. To our knowledge, this is the first computational effort that allows for real time analysis of such arrays in reasonable computing time.

9343-47, Session 12

Dynamics of high power fiber laser arrays with active phase control

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We are studying an extended version of the active phase control system for fiber lasers first discussed generically by O'Meara (1976) and for fiber lasers by Shay (2006). Our analysis is an extension of that by Shay, by including the effects of laser line-width and phase jitter, in addition to that of optical path errors. At input, each beam is dithered by an RF phase modulator at a unique tag frequency. The output far-field intensity of the overlapped beams is converted to a photocurrent by a detector. This is demodulated by averaging the product of the photocurrent with an RF signal at a tag frequency over a time large compared to the RF beat intervals, yielding a corresponding phase-error signal, which is applied to adjust the phase at a photorefractive phase adjuster at the input of each amplifier.

It is found that for parallel polarization the closed-loop applied phase corrections satisfy differential equations of a generalized Kuramoto type, in which the coupling constants are functions of optical path differences, laser line width and the imposed phase jitter and noise terms represent internal thermo-mechanical noise and possible atmospheric turbulence. The performance of this system depends on the stability and nature of the N+1 stationary solutions given by 0 or pi . For example, in the absence of OPD the in-phase solution is the only one that is stable, but if there is significant OPD then this result is adversely affected. We will report on further results of a stability analysis of this system as affected by OPD, line width, phase jitter and noise.

9343-48, Session 12

Coupled mode description of external cavity-coupled laser array dynamics

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States) and Univ. of Tennessee (United States)

We address the problem of modeling the passive phasing dynamics of large laser arrays using a coupled mode approach with novel features. Passive phasing of large laser arrays is experimentally difficult mainly because of the variation in free-running frequencies. A challenge to the description of the temporal dynamics of large systems is their complexity, and for this reason coupled mode approaches seem to have greatest potential for providing insight and yielding reliable results.

A novel feature of our theory is that we employ the modes of the complete resonator as basis set. This description is necessary for arrays with strong out-coupling, since individual emitter modes fail by not satisfying the boundary conditions. This makes our approach applicable to semiconductor and fiber laser arrays with anti-reflection coated output facets. The array performance, measured in terms of phasing efficiency, stability, power output, etc., is characterized with respect to array size, cavity length disorder, external coupling, the magnitude of nonlinearities and other features.

In contrast to the traditional approach in which individual cavities have their own mode structures and are coupled by mutual injection, ours is based on rigorous expansion of the optical fields in transverse and longitudinal whole-resonator modes (i.e. modes of the compound cavity considered as a single unit). The use of Maxwell's equations couples the fields to the gain media, yielding nonlinear ordinary differential equations for the time-dependent expansion coefficients, which are supplemented with rate equations for the medium to complete the description.

9343-49, Session 13

Time-resolved deformation measurement of Yb:YAG thin disk using wavefront sensor

Michal Chyla, Siva S. Nagisetty, Patricie Severová, Taisuke Miura, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Klaus Mann, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Laser-Lab. Göttingen e.V. (Germany); Akira Endo, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Since fairly homogeneous temperature distribution in the large pumped area is a key issue of single transverse mode operation, thin disk medium mounted on a diamond substrate is generally used for high average power operation.

Even with Yb:YAG thin disk soldered to a copper-tungsten heatsink, we found that the pulsed pumping, of which duration was shorter than the upper-state-lifetime of Yb:YAG, could improve both the optical-to-optical (O-O) efficiency and the beam quality (Opt. Lett., Vol. 39, pp. 1441-1444 (2014)). We are expecting that the increase of O-O efficiency is caused by the suppression of ASE. However, the mechanism of beam quality improvement is not clear. Investigating thin disk dynamics under the pulsed pumping can help to greatly improve the mode matching to obtain higher output energy.

We developed a precise measurement system of thin disk deformation based on a Hartmann-Shack wavefront sensor. A fiber-pigtailed laser diode is used as a probe beam, illuminating whole area of the thin disk. The deformations of thin disk can be evaluated by analyzing the wavefront of the probe beam. We obtained the temporal deformation of thin disk with 100-us resolution by triggering the wavefront sensor, and found a pulsating deformation of thin disk at 1-kHz pulse pumping operation. We obtained the thin disk deformation under the pumping phase and amplification (energy extraction) phase independently. We are improving the time resolution of wavefront measurement by applying a sub microsecond pulsed probe light. Details of experimental results with comprehensive study of the thin-disk deformations will be presented.

9343-50, Session 13

Single shot M2 measurement for near infrared high energy laser pulses

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Since the principle of M2 measurement is to scan the beam discretely along with propagation direction, measurement time of several minutes is required which is not suitable for pulsed lasers. Several single-shot techniques have been proposed to measure M2 by using diffraction gratings and wavefront sensor, but were shown to be more complex and yield inaccurate results for multimode beams. Another approach to measure the M2 uses Rayleigh scattering from gas or liquid-filled cell. The scattered image by laser light in the cell, however, contains lots of speckle patterns which degrade the accuracy of M2 measurement.

We developed a single shot M2 measurement based on a photosensitive glass. The measurement system consists of the photosensitive glass plate and the imaging camera with macro lens. When the pulsed laser beam focused into the cross-sectional direction of photosensitive glass plate, the visible fluorescence of the glass plate indicates the focusing property of laser beam. Then the visualized beam propagation in the glass is imaged precisely to measure the beam diameters around beam waist. Since the coherent laser beam is converted to the incoherent fluorescence, the beam propagation image is free from speckle patterns. The M2 can be calculated from the image within less than a second. This simple technique allows the possibility of the real time monitoring of the beam quality. We obtained M2=1.2 from a Yb:YAG thin disk laser that is close to the actual value of M2=1.1 using the standard scanning method. Further improvement of measurement accuracy will be presented.

9343-51, Session 13

Characterization of vorticity in fluids by a spatially shaped laser beam

Anton Ryabtsev, Shahram Pouya, Manoochehr Koochesfahani, Marcos M. Dantus, Michigan State Univ. (United States)

Measuring the speed and direction of vortices is of great importance in fluid dynamics, especially for aerodynamic design and control of air flight. Presently, vortex characterization involves acquiring multiple measurements, from which the fluid velocity vectors are determined in space and used to calculate vorticity through vector product. We report on the use of a CW laser beam with a composition of Laguerre-Gaussian (LG) modes generated by a phase mask imprinted on a two-dimensional spatial light modulator. The shaped beam is then guided and scattered of a sample which is rotated at frequency ?. A back-reflected signal collected by a photodiode has a maximum at frequency n*?, where n is the number of bright features in the laser mode, therefore allowing the rotational frequency to be extracted from spectral analysis. Accuracy of this measurement depends on detection parameters, such as duration of a time series, sampling rate and averaging, and is limited by stability of rotational dynamics. Calibration of this method is performed on a solid rough surface. For practical measurements of fluid dynamics a container with spinning liquid is used. This method allows for virtually real-time determination of information required for characterizing vorticity in a fluid and can be further extended to gases.

9343-52, Session 14

Direct generation of radially polarized beams from a Nd:YVO4 laser chip with a gold ring pattern

Takeshi Sumi, Yuichi Kozawa, Shunichi Sato, Tohoku Univ. (Japan)

Radially polarized beams have been extensively studied due to the unique properties such as strong longitudinal field generation and smaller focal spot formation under tight focusing conditions. We have recently demonstrated that the focal spot size can be further decreased by focusing higher-order radially polarized (HRP) beams, which have a multi-ring-shaped intensity distribution. These features are quite advantageous to many applications including optical trapping, high-resolution laser microscopy, and particle acceleration. In order to apply an HRP beam to these applications, simple and reliable method to generate HRP beams with high beam quality is essential.

Here, we report the direct generation of a higher-order radially polarized beam from a c-cut Nd:YVO4 laser (oscillation wavelength: 1.06 microns). We fabricated two concentric gold rings (outer and inner rings), whose diameters are 50 and 20 microns with widths of 500 and 100 nm, respectively, on one surface of the laser crystal with a thickness of 1 mm. Additionally, both surfaces of the crystal were coated by dielectric multilayers to form a laser cavity. By adjusting a pump beam spot to the position of the gold pattern, a double-ring-shaped radially polarized beam whose node almost coincided with the outer gold ring was generated. The generation of radial polarization can be attributed to the inner gold ring due to the polarization selective transmission/reflection behavior of the thin ring structure. This result can be applied for further development of a simple and compact laser chip to directly generate an HRP beam.

9343-54, Session 14

Analysis of thermal depolarization compensation using full vectorial beam propagation method in laser amplifiers

Rainer Hartmann, Christoph Pflaum, Thomas Graupeter, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

In the case of isotropic materials, such as laser, Nd: YAG, the thermally-induced birefringence is one of the main sources of aberrations in cylindrical laser rods. Common assumptions in geometric optics cannot be used to describe aberrations of Gaussian beams analytically.

We developed a complex physical model for simulating laser amplifiers to numerically analyze the birefringence effects. This model includes pump configuration, thermal lensing effects, birefringence, and beam propagation in the laser amplifier. Temperature, deformation and stress inside the laser crystal were calculated by a three-dimensional finite element analysis (FEA). The pump configuration is simulated using a complete three-dimensional ray tracing or by an approximation based on super-Gaussian functions.

Our simulations show the depolarization of a linearly polarized electromagnetic wave in a cylindrical laser crystal. These simulations were performed using a complete three-dimensional vectorial beam propagation method (VBPM). This method is important when the birefringence obtained by the photo-elastic effect inside the laser crystal is considered. We also analyze the influence of the crystal cut.

Simulations results show that the shape and polarization of the amplified beam depends on the rotation of the crystal. This property holds not only for special cut directions like [100]-cut but also for standard [111]-cut crystals.

9343-55, Session 14

Lasing mode selection by active transformation optics

Li Ge, College of Staten Island (United States)

Selective pumping in lasers and other photonic light sources has attracted considerable interests in the past two decades. Typically the spatial profile of the pump is shaped to overlap strongly with the highest-Q mode(s), which leads to a reduced laser threshold. It can also be applied to the optimally outcoupled mode in a given laser cavity to enhance the output power, potentially by orders of magnitude, or to target different modes for directional output and frequency selection. If the cavity modes are weakly overlapping in space, such as in a deformed microcavity supporting distinct short periodic orbits or in a localized random laser, the general practice is again enhancing the overlap of the spatial pump profile with the desired mode. If there exist multiple spatially overlapping modes however, this procedure often fails to select modes with large cavity decay rates (i.e., ``higher-order" modes), because the tailored spatial pump profile still has a significant overlap with the non-targeted, lower-order modes and the latter lase before the target mode. In this regime brutal-force optimizations can be performed (such as the generic algorithm), but it requires many iterations of trial and error and becomes computationally intense in complicated geometries. In this talk I will show that a general method for spatial mode selection, especially for the higher-order ones, can be found in this regime by what I will refer to as "active transformation optics," which transforms a nonlinear lasing solution to a linear one, and by introducing/reducing fictitious mode competitions.

9343-57, Session 14

1600W monolithic CW single mode fiber laser oscillator at 1080 nm

Wei Shi, Tianjin Univ. (China); Qiang Fang, Qihang Zhang, HFB Photonics Co., Ltd. (China)

We have implemented a monolithic, CW ytterbium-doped fiber laser oscillator at ~ 1080 nm, producing 1630 W CW laser power with single mode beam quality (M2<1.1). The power fluctuation is < 1% when the laser kept running for one hour. The optical to optical efficiency with respect to the launched pump power is > 75.46%. The all fiber construction of the laser oscillator enables compact size, maintenance-free, robust operation and thus allows various practical applications in industry material processing, such as laser cutting, laser drilling, etc.

9343-58, Session 15

Controlling light's handedness inside laser resonators *(Invited Paper)*

Andrew Forbes, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa) and Univ. of KwaZulu-Natal (South Africa); Darryl Naidoo, CSIR National Laser Ctr. (South Africa) and Stellenbosch Univ. (South Africa); Filippus S. Roux, CSIR National Laser Ctr. (South Africa); Lorenzo Marrucci, Univ. degli Studi di Napoli Federico II (Italy) and CNR-SPIN (Italy); Igor A. Litvin, Angela Dudley, CSIR National Laser Ctr. (South Africa)

In this talk we consider the generation, in a controlled manner, of orbital angular momentum (OAM) carrying beams from a laser resonator. We first review previous observations of Laguerre-Gaussian modes and their superpositions from laser resonators. We show how amplitude masks, phase masks and gain shaping can be used to create superpositions of azimuthal modes up to very high order in the azimuthal index, which we demonstrate experimentally in a diode pumped solid state laser. Further, we show how to create single azimuthal modes through the use of intra-cavity non-homogeneous polarization optics that exploit the geometric phase of the light. In such a resonator the mode can be tuned from a vector field carrying OAM to a scalar field with a specific handedness.

9343-59, Session 15

Red-emitting external cavity diode laser with high slope efficiency and narrow bandwidth

Jiyeon Park, Hong Joo Song, Hong Man Na, Jun Ho Lee, Korea Electronics Technology Institute (Korea, Republic of); Ilgu Yun, Yonsei Univ. (Korea, Republic of)

To improve the narrow bandwidth and simultaneously the high output power, one of the most promising methods is to use an external cavity. Key element in this configuration is a grating section acting as the wavelength selection and feed-back into laser diode for a resonance behavior in a specific wavelength.

In this work, optical properties of red-emitting external-cavity diode laser(ECDL) have demonstrated by the dependence on grating types. For this purpose, the ECDL consists of these four parts: a gain-guided Broad Area Laser (BAL) diode, two collimators lens and a diffraction grating in a Littrow configuration. BAL diode has an emitting size of 100 ?m in the slow axis and 1 ?m in the fast axis and a chip length of 2000 ?m. A fast axis collimator (FAC) and a slow axis collimator (SAC) was used a cylindrical aspheric lens with a focal length of 10 mm and a cylindrical lens with a focal length of 50 mm, respectively. To compare spectral band width and slope efficiency, a diffraction grating was divided to four types according to the number of grooves and the diffraction efficiency (p- or s-polarization).

The output power-current characteristics in ECDL showed a significant dependence of slop efficiency on grating types. The high slop efficiency, which is comparable to the solitary laser diode of BAL, could be achieved with narrow spectral width in the optimized condition. The spectral behaviors revealed that the wavelength dispersion along the fast axis of a solitary LD takes advantage of a further narrow spectral linewidth. And the effect of the polarization in ECDL-operation was investigated in details.

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9343-60, Session 15

Wavefront control in high average-power multi-slab laser system

Jan Pilar, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Stefano Bonora, IFN-CNR LUXOR Lab. (Italy) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); Paul J. Phillips, Jodie M. Smith, John L. Collier, Rutherford Appleton Lab. (United Kingdom); Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Antonio Lucianetti, Tomás Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

In the frame of Hilase project a high average power cryogenically-cooled diode-pumped solid-state laser system is being developed in collaboration with Central Laser Facility at Rutherford Appleton Laboratory, England. The system will deliver pulses with energy of 100 J at 10 Hz repetition rate and will find applications in industry. The laser medium and other elements of the system are subject to heavy thermal loading which causes serious optical aberrations and degrade the output beam quality. To meet the industrial requirements it is necessary to implement adaptive optics system, which will correct for these aberrations. During our research the sources of aberrations have been identified and analyzed and based on this analysis a suitable adaptive optics system was proposed. After finalizing numerical models, simulations and optimizations, the adaptive optics system was developed, characterized and installed in a cryogenically-cooled multi-slab laser system running up to 6 J and 10 Hz. The adaptive optics system consists of 6x6 actuator bimorph deformable mirror and wavefront sensor based on quadriwave lateral shearing interferometry operated in closed loop. The functionality of the system was demonstrated at full power.

9343-61, Session 15

Ultra stable carbon fibre high power CO2 laser with high quality laser beam and AOM implementation

Markus Bohrer, Dr. Bohrer Lasertec GmbH (Austria) and Vienna Technical Univ. (Austria)

CO2 lasers celebrated their 50ieth anniversary and are seen as a mature technology. But there are still applications which are hungrily seeking improvements - especially when it comes to ultra high beam quality and stability. These applications comprise the high security and high quality printing industry and other niches, which are rapidly growing.

The answer is to design a resonator from the root with due respect to all elements. To calculate every single part (thermo-mechnaical FEM) and to use state of the art materials - especially carbon fibre with a special layer winding - is a must. Upon this state of the art numeric resonator design has been used to achieve a Gaussian beam. Additional measures have been taken to optimize power fluctuations to less than one percent.

The resulting beam is guided to a huge carbon fibre optical bench for automated evaluation and optimization of the complete beam path with optical elements arranged up to a length of 10 meters. A high speed rise and fall time detector shows the pulse behavior close to 1 MHz. Synchronously operating PyroCams give immediate information about the complete beam path, including non-linear elements such as AOMs. The difference of the laser mode - before and after the AOM - is calculated with up to 48 pictures per seconds, thus helping enormously to optimize translational and rotational position of the AOM as well as adjustment of the collimators.

This papers shows the resonator design as well as its impact and optimization for the external path and its use for high speed engraving applications.

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9344-1, Session 1

Large mode area Yb-doped photonic bandgap fiber lasers *(Invited Paper)*

Liang Dong, ECE/COMSET, Clemson Univ. (United States); Fanting Kong, Guancheng Gu, Thomas W. Hawkins, Joshua Parsons, Maxwell Jones, Christopher D. Dunn, Monica T. Kalichevsky-Dong, Clemson Univ. (United States); Kunimasa Saitoh, Hokkaido Univ. (Japan); Benjamin Pulford, Iyad Dajani, Air Force Research Lab. (United States)

Fiber lasers are in the process of revolutionizing modern manufacturing. Further power scaling is still much desired to increase throughput and to break new frontiers in science and defense. It has become very clear now that highly single-mode fibers with large effective mode areas are required to overcome both nonlinear effects and mode instability. We have been studying all-solid photonic bandgap fibers (ASPBF), which have open and highly dispersive cladding, making them ideal for higher-order-mode controls in large-mode-area fibers. I will review our recent progress in this area and, especially in ytterbium-doped ASPBF lasers and amplifiers.

9344-2, Session 1

Polarizing 50μm core Yb-doped photonic bandgap fiber

Fanting Kong, Guancheng Gu, Thomas W. Hawkins, Joshua Parsons, Maxwell Jones, Christopher D. Dunn, Monica T. Kalichevsky-Dong, Clemson Univ. Research Foundation (United States); Benjamin Pulford, Iyad Dajani, Air Force Research Lab. (United States); Kunimasa Saitoh, Hokkaido Univ. (Japan); Stephen P. Palese, Eric Cheung, Northrop Grumman Aerospace Systems (United States); Liang Dong, Clemson Univ (United States)

Polarizing optical fibers are important components for building compact fiber lasers with linearly polarized laser output. Conventional single-mode optical fibers with birefringence can only preserve the polarization when the incident beam is launched properly. Recent reports demonstrate that the birefringence in photonic bandgap fibers (PBFs) can provide single-polarization operation near the edge of transmission band by shifting the transmission band for the light with orthogonal polarizations. Here, we demonstrate a 50μm core Yb-doped polarizing photonic bandgap fiber (PBF) for single-polarization operation throughout the entire transmission band from 1010nm to 1170nm with a polarization extinction ratio (PER) of >5dB/m, which is >15dB/m near the short wavelength edge of the transmission band. The polarizing effect is due to the differential polarization transmission loss presented in this fiber, which is benefited from the fiber birefringence of 3.2x10-4, obtained by incorporating low-index boron-doped rods on either side of the core. The achievement is based on the fact that light at fast axis has lower effective mode index which is closer to the modes in the photonic cladding and thus to be easily coupled into cladding. A 2.6m long straight fiber was tested in a laser configuration without any polarizers to achieve single polarized laser output with a PER value of 21dB at 1026nm lasing wavelength.

9344-3, Session 1

Yb-doped large mode area fibers with reduced cladding symmetry

Federica Poli, Enrico Coscelli, Annamaria Cucinotta, Stefano Selleri, Univ. degli Studi di Parma (Italy); François Salin, EOLITE Systems (France)

Recently, a lot of research efforts have been devoted to the development of fiber lasers operating in the ultrashort pulse regime, with the aim to deliver mJ pulse energy and MW or even GW peak power. In order to reach such extreme performances, short fibers with very large core need to be used to grant efficient pump absorption and tolerance to nonlinear effects. The current bottleneck to further power scaling of fiber lasers is mainly determined by the onset of mode instabilities, which appear beyond a certain power threshold due to the thermally-induced power transfer between guided modes. Innovative fiber designs, capable of providing robust single-mode guiding under severe heat load, together with large mode area are thereby needed to push forward the current limits of fiber laser systems. In this work three different designs of double-cladding Yb-doped rod-type PCFs with reduced cladding symmetry and ~80 μm core diameter are numerically compared through simulations, carried out by means of a full-vector modal solver based on the finite-element method with integrated thermal model. The fundamental and most detrimental high-order modes have been calculated for each fiber design for coupled pump power values up to 300 W. The results have shown that the proposed designs can achieve a state-of-art modal discrimination even under significant heat load.

9344-4, Session 1

Assymptotically single mode hybrid fiber with a high anomalous dispersion in the 1μm wavelength region

Svetlana S. Aleshkina, Mikhail E. Likhachev, Andrei K. Senatorov, Mikhail M. Bubnov, Fiber Optics Research Ctr. (Russian Federation); Mikhail V. Yashkov, Institute of Chemistry of High-Purity Substances (Russian Federation) and N.I. Lobachevsky State Univ. of Nizhni Novgorod (Russian Federation); Mikhail Y. Salaganskii, Alexei N. Guryanov, Institute of Chemistry of High-Purity Substances (Russian Federation)

Cylindrically symmetric hybrid fiber proposed by our group recently allow one to achieve high anomalous dispersion (13-100 ps/nm/km) in the 1 μm spectral range. Refractive index of such fibers consists of one or two high index ring layer surrounding the core and depressed layer placed outside the ring layer. The drawback of the realized designs was presence of modes, localized in high-index rings, which tails nevertheless spread over the hybrid fiber core. Excitation of the operating hybrid mode LP03 in the two high-index ring design (or LP02 in the one high-index layer design) was accompanied by weak excitation (10-20% of total propagating power) of the modes, located in the high-index rings, that has non-zero electric field at fiber axis (mainly LP02 mode for two high-index-layers design and LP01 for one high-index layer design).

In the present work we have experimentally demonstrated possibility to suppress all the propagating mode except the operated hybrid one (LP03 for two high-index-layer design). The main idea is based on introduction a thin ring layer with an extremely high optical loss to the position of

electrical field minimum of the operating hybrid mode. Analysis of the mode composition carried out by off-center hybrid mode excitation confirm the asymptotically single-mode propagation regime.

9344-5, Session 2

High-power narrow-linewidth large mode area photonic bandgap fiber amplifier

Benjamin Pulford, Iyad Dajani, Thomas Ehrenreich, Roger H. Holten, Christopher L. Vergien, Air Force Research Lab. (United States); Guancheng Gu, Fanting Kong, Thomas W. Hawkins, Liang Dong, Clemson Univ. (United States)

All-solid photonic bandgap fibers (PBGF) can be spectrally tailored to suppress amplified spontaneous emission (ASE) and stimulated Raman scattering (SRS). Furthermore, this type of fiber is attractive for realizing high-power narrow-linewidth amplifiers as large mode areas can be attained while maintaining single-mode operation. Notably, an Yb-doped PBGF with a core diameter of ~50µm was fabricated using the stack and draw technique. The microstructures in the cladding are comprised of germanium-doped silica. A low refractive index polymer coating provides a numerical aperture of 0.46 for pumping purposes. The absorption was estimated to be 1 dB/m at a pump wavelength of 976nm. Approximately 11m of this fiber was mounted on a cold spool possessing a diameter of 53cm. The PBGF was pumped in a counter-propagating configuration using 976nm diodes.

The master oscillator was a non-planar-ring oscillator (NPRO) operating at

1064nm. The output of the NPRO was then coupled into a phase modulator for stimulated Brillouin scattering (SBS) suppression and then amplified using a multi-stage amplifier system. The phase modulation frequency was set at 400 MHz and the modulation depth was chosen such that three equal peaks corresponding to the carrier frequency and the two adjacent sidebands were generated. As much as 20W were used to seed the PBGF. The output signal power obtained was 587W; which represents to the best of our knowledge the highest power reported to date for a PBGF amplifier. The slope efficiency for this amplifier was ~70%. At the highest output power there was little sign of SBS.

9344-6, Session 2

158W core-pumped single-frequency amplifier at kHz linewidth using a standard ytterbium-doped single-mode fiber

Thomas Theeg, Christoph Ottenhues, Hakan Sayinc, Jörg Neumann, Dietmar Kracht, Laser Zentrum Hannover e.V. (Germany)

Single frequency amplifiers are important for applications such as interferometric gravitational wave detection and coherent beam combining. The common approach for power scaling of single frequency fiber amplifiers is the employment of double-clad fibers (DCF) with large mode field diameters and short fiber lengths in combination with counter-propagation pumping. The output power is limited by stimulated Brillouin scattering (SBS) and/or transversal mode instabilities in spite of all mitigation strategies. We present a concept for fiber-based single-frequency amplification by employing a standard (single-clad) single-mode Yb doped fiber. The advantage of core pumping results primarily from a short active fiber length and the elimination of the temperature limitation due to the acrylate coating, which is typically used for DCF. Hence, strong temperature-induced broadening of the Brillouin gain spectra can be obtained. An in-house developed single-mode fiber oscillator with an output power of 180 W at a wavelength of 1018 nm was used for core-pumping of a 1.25 m long Yb-doped fiber. The continuous wave seed signal of a nonplanar ring-oscillator (NPRO) with an output power of 2 W at a wavelength of 1064 nm (1 kHz spectral linewidth) was amplified up to an output power of 158 W without any indication of SBS. The amplifier output power was limited by the available pump power. In summary, we presented a monolithic concept for fiber-based amplification of single-frequency sources, which has the potential for further power scaling up to several hundred watts by employing standard Yb-doped single-mode fibers.

9344-7, Session 2

Record peak power single frequency erbium-doped fiber amplifiers

Leonid V. Kotov, Fiber Optics Research Ctr. (Russian Federation) and Moscow Institute of Physics and Technology (Russian Federation); Mikhail E. Likhachev, Mikhail M. Bubnov, Vladimir M. Paramonov, Mikhail I. Belovolov, Fiber Optics Research Ctr. (Russian Federation); Denis S. Lipatov, Institute of Chemistry of High-Purity Substances (Russian Federation) and N.I. Lobachevsky State Univ. of Nizhni Novgorod (Russian Federation); Aleksei N. Guryanov, Institute of Chemistry of High-Purity Substances (Russian Federation)

In this work we present results on the amplification of narrow-linewidth nanosecond pulses in a recently developed ytterbium-free erbium-doped large mode area fiber cladding pumped at 980 nm. At first, a co-propagating all-fiber amplifier scheme was used. Using 1 m of active fiber length in such configuration a peak power of 4 kW limited by instabilities caused by stimulated Brillouin scattering (SBS) was achieved. To the best of our knowledge this is the highest peak power ever reported for single-frequency single-mode silica-based fiber sources near 1550 nm.

Then all-fiber counter-pumped configuration with 6 m of active fiber was used and peak power of 900 W was obtained. In this case peak power was limited by SBS generation in a passive fiber at the laser output. Slope electrical-to-optical conversion efficiency of 8 % demonstrated in such scheme is a record value for kW-level single-mode single-frequency Er-doped nanosecond fiber lasers.

9344-8, Session 2

High-power single-frequency fiber MOPA at 1178 nm

Mingchen Chen, Akira Shirakawa, The Univ. of Electro-Communications (Japan); Christina B. Olausson, Thomas Tanggaard Alkeskjold, NKT Photonics A/S (Denmark)

Since a narrow linewidth and high power source is required for laser guide star (LGS) application, the main question is how to mitigate the stimulated Brillouin scattering (SBS). Typically the linewidth of fiber lasers is too broad in comparison with the Doppler broadened absorption spectrum of sodium atoms (~1.0 GHz). Therefore a master-oscillator and power amplifier (MOPA) setup with a single-frequency seed is preferred. However the linewidth of single-frequency sources are usually too narrow for the application which causes lower SBS threshold. In this paper, a MOPA configuration composed of an external-cavity laser diode (ECLD) and a dual stage amplifier by a fiber Raman amplifier (FRA) and an Yb-doped photonic bandgap fiber (PBGF) amplifier is presented. The single-frequency seed was obtained from an in-house ECLD. The linewidth of the seed was optimized for LGS via the subsequent electro-optic modulator (EOM) on which a white Gaussian noise was applied. It was obtained to be 780 MHz (FWHM) by a delayed self-heterodyne interferometer. The Raman fiber was core pumped by an in-house Yb fiber laser at 1120 nm. The 32 m PBGF was cladding pumped at 976 nm. The maximum output power of 87 W was obtained from the PBGF amplifier without the onset of SBS. No significant spectral degradation was obtained in the amplification due to the single-frequency amplification and

spectral filtering property of the PBGF. The polarization extinction ratio of 11 dB and the gain of as high as 13 dB were obtained.

9344-9, Session 3

Fiber based stimulated Raman scattering spectroscopy *(Invited Paper)*

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Stimulated Raman Scattering (SRS) microscopy allows label-free chemical imaging and has enabled exciting applications in biology, material science, and medicine. It provides a major advantage in imaging speed over spontaneous Raman scattering. Wider adoption of the technique has, however, been hindered by the need for a costly and environmentally sensitive tunable ultra-fast dual-wavelength source. We present the development of an optimized all-fiber laser system based on the optical synchronization of two picosecond power amplifiers. To circumvent the high-frequency laser noise intrinsic to amplified fiber laser, we have further developed a high-speed noise cancelation system based on auto-balanced detection. We demonstrate high-speed and shot-noise limited SRS imaging with our novel fiber-based SRS.

9344-10, Session 3

High stability single-frequency Yb fiber amplifier for next generation gravity missions

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In scope of the ESA funded “High stability Laser” activity, a laser source with extremely high frequency and power stability for satellite based gravity measurement via satellite-to satellite heterodyne interferometry, is developed as an elegant breadboard (EBB). The laser source is based on a master oscillator-fibre power amplifier and an ultra-stable Fabry-Perot reference cavity for frequency stabilisation.

The amplifier consists of an NPRO as master oscillator seed source with a linewidth below 10 kHz and a polarization maintaining Yb-fibre amplifier which is stabilized in power via pump diode modulation to a RIN performance of < 0.001/sqrt(Hz)xNSF(f) in the range from 10-4 Hz to 1 Hz and a PER of >30 dB. The achieved output power is > 500 mW at a wavelength of 1064 nm and no significant stimulated brillouin scattering (SBS) can be observed. Stabilizing the seed frequency by an external high finesse reference cavity the amplified output achieved a frequency stability of <40 Hz/sqrt(Hz)xNSF(f) in the range from 10-4 Hz to 1 Hz

The design of the amplifier has been analysed and optimised by structural and transient thermal analyses assuming a GOCE like environment. Off-the-shell components have been tested and pre-selected with respect to their thermal behaviour to achieve the required RIN and frequency-LSD performance. Additionally we have performed radiation tests of active as well as passive fibres to determine the radiation induced absorption in such a fibre amplifier.

9344-11, Session 3

High-intensity nanosecond all-fiber-coiled laser and extreme ultraviolet generation

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High power fiber laser retains the advantages of beam quality near diffraction limit, excellent thermal optical property, high gain or efficiency with continuous diode pumping, and the potential to be alignment-free, compact, reliable, robust in a harsh environment. It becomes a promising candidate of all kinds of practical strong-field laser plasma photonic devices. In this paper, we report a high efficiency laser-produced-plasma extreme ultraviolet driver in mirror-free configuration. The driver is based on a nanosecond ytterbium coiled all-fiber laser system in diode-seeded master oscillator power amplification. The maximum repetition rate of 20 kHz is determined by the periodic droplet target generation. With an optical efficiency up to 66%, it can produce 1064-nm, 6.1-ns laser pulses with 10 nm in FWHM linewidth, 1.16 mJ in energy and 117 kW in peak power which is close to damage criterion. After the laser pulse of M2=1.55 entered the vacuum, it was focused to a spot size of ~11 ?m in FWHM diameter with a f-number~ 4.2 for interacting with a solution droplet doped by tin oxide of 11% in concentration at a proper flow rate. With a calibrated intensity of 6.4?1010 W/cm2 the signal within 10~20 nm in wavelength was confirmed with a Si/Zr-coated x-ray photodiode by changing the numbers of Beryllium foil filters. For a numerical benchmark, the ionization model of collisional-radiative equilibrium instead of Saha model was coupled into an one-dimensional hydrodynamic code (MED103) to estimate EUV emission according to the weighted oscillator strengths of Sn8+ to Sn+13 ions.

9344-12, Session 3

Fiber lasers for directed energy *(Invited Paper)*

Don D. Seeley, High Energy Laser Joint Technology Office (United States); John M. Slater, LeAnn D. Brasure, Schafer Corp. (United States)

No Abstract Available

9344-13, Session 4

Femtosecond inscribed mode modulators in large mode area fibers: Experimental and theoretical analysis

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We present the experimental and theoretical analysis of a mode modulator in a few mode LMA fiber. The mode modulator consists of a section with a modified refractive index alongside the fiber core in the cladding, disturbing the guidance of the modes in the core. The extent of excitation of these disturbed modes depends on the overlap of the excited undisturbed and disturbed modes. At the end of the modulator, undisturbed modes will be excited again in the fiber core, in dependency of the spatial field distribution of the disturbed modes at the boundary. In the mode modulator disturbed higher order modes lead to modal interference, causing a dependency

of the spatial distribution of the light in the mode modulator on the propagation length of the disturbed modes. Hence, the modal output field depends on the length of the mode modulator. For the experiments, the mode modulator was inscribed directly into the LMA fiber with ultrashort laser pulses. During the inscription process the modal content at the end of the fiber was measured using a computer generated hologram as a correlation filter. In dependency of the length of the modulator strong oscillations between the content of the fundamental and the higher order modes are observable. In the case of an initially excited fundamental mode, its content could be reduced to below 5%, whereat the content of the LP11 modes was up to 90%. While measurement and simulation show qualitative agreement, differences are caused by inhomogeneities of the refractive index modifications.

9344-14, Session 4

High power cladding mode stripper

Lalitkumar Bansal, V. R. Supradeepa, Sean P. Sullivan, Clifford Headley III, OFS Fitel LLC (United States)

Despite significant advances in multi kW double-clad fiber lasers and amplifiers over the past decade, there still remain reliability and beam quality challenges, due to light in cladding modes. Thermal issues arise in cladding mode strippers due to heat generation in the small surface area imposed by the fiber dimensions. In this work, we describe a novel approach for stripping cladding light from double clad fibers that overcomes this limitation. This is achieved by index matching the cladding of the fiber with a glass capillary collapsed onto the fiber, allowing the cladding modes to expand in a larger volume of the capillary before they are dissipated through a high-index heat sink material into a metal package. This allows heat to be dissipated over a much larger surface area, allowing for a more reliable device. We minimize the signal quality degradation by using a lower melting point capillary glass. The cladding mode stripper is tested up to 100W using 915nm pump diodes. The input consists of four 0.14 NA, 25 W diodes, spliced to a (18+1) x 1 pump signal combiner with a 0.45 NA, 200?m diameter double clad output fiber. We demonstrate a device with 100W cladding power removed with a 99% (20dB) extinction. The thermal slope measurement is performed using an IR thermal camera on the surface of the capillary and is measured to be 0.75 C/W. The packaged device was tested for one hour for stable operation without degradation of performance or power.

9344-15, Session 4

Electrically tunable fiber-integrated Yb-doped laser covering 74 nm based on a fiber Bragg grating array

Tobias Tiess, Manfred Rothhardt, Leibniz-Institut für Photonische Technologien e.V. (Germany); Christoph Chojetzki, FBGS Technologies GmbH (Germany); Matthias Jäger, Leibniz-Institut für Photonische Technologien e.V. (Germany); Hartmut Bartelt, Leibniz-Institut für Photonische Technologien e.V. (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

Besides the highly appreciated advantages of an excellent beam quality and high efficiency, fiber lasers relying on an all-fiber geometry provide also the basis for compact and robust setups with low-maintenance requirements. Accordingly, the applications of such systems are spreading to various fields including both, the research as well as the industrial area. Based on the broad spectral gain regions of rare-earth-doped fibers, fiber lasers are increasingly desired to be wavelength tunable over large wavelength ranges in order to further adapt those systems for new applications especially arising in spectroscopy. However, common approaches for adjusting the emission wavelength either rely on free-space coupled spectral filters preventing fiber integrated designs, or are restricted to small tuning ranges of a few nanometers.

In this work, we present a new concept to electrically tune the emission wavelength of pulsed fiber lasers based on an array of fiber Bragg gratings as spectral filter. This dispersive element not only provides a fiber integrated structure, but also offers great design freedom for individual tuning characteristics including large spectral ranges as well as discrete emission lines. A modulator, which also sets the laser in pulsed mode, is used to switch the emission wavelength according to the feedback of the incorporated fiber Bragg gratings. The potential of this tuning method is demonstrated based on a ytterbium-doped fiber laser. Besides excellent spectral properties including narrow emission line width and high signal contrast, an enormous tuning range of more than 70nm has been realized.

9344-16, Session 4

Fiber laser pumping devices based on directional coupling via fused silica ridge waveguide arrays

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A new transversal pumping scheme of fiber lasers based on an array of large scale ridge waveguides and their application as directional couplers interacting with a double clad optical active fiber is presented. This new approach overcomes some disadvantages of conventional pumping schemes such as end side pumping or fused fiber bundling. Those pumping schemes suffer in general from expensive multiplexing arrangements, which are quite sensitive to misalignment, or rather expensive fiber pigtailed diode lasers as in the case of fiber bundling schemes. We made use of 12 cm long fused silica ridge waveguides with edge lengths of 400 μm and nearly 90° steep sidewalls produced by a high precision wafer dicing saw. An octagonally shaped laser active double clad fiber accurately fits into the created 400 μm wide trenches between the ridge waveguides. Conventional broad area emitters without slow axis collimation (SAC) can be used to couple light (wavelength ?p = 976 nm) via one or several prisms into the waveguide array. A uniform distribution of pump light over the cross section of the waveguide array, including multiple turns of the fiber, results in equivalent input coupling into the fiber and the ridge waveguides. The ytterbium doped core of the double clad fiber is optically pumped by the pump light, directly coupled into the fiber as well as the interaction of pump light fields, guided in the ridge waveguides and the fiber (directional coupling). Laser operation at wavelength ?s = 1075 nm is realized.

9344-17, Session 4

Superluminescent diode versus Fabry-Perot laser diode seeding in pulsed MOPA fiber laser systems for SBS suppression

Miguel Melo, MWTechnologies, Lda (Portugal) and Univ. of Porto (Portugal) and Multiwave Photonics, S.A. (Portugal); João M. Sousa, Datalogic Automation S.r.l. (Italy); José R. Salcedo, Multiwave Photonics, S.A. (Portugal)

We demonstrate the use of a pulsed superluminescent diode (SLD) through direct current injection modulation as seeding source in a master oscillator power amplifier (MOPA) configuration when compared to a Fabry-Perot (FP) laser diode in the same system. The performance limitations imposed by the use of the Fabry-Perot lasers, caused by the backward high peak power pulses triggered due to stimulated Brillouin scattering (SBS) are not

observed in the case of the SLD. Compared to conventional Fabry–Perot laser diodes, the SLD provides a smooth and broad output spectrum which is independent of the input pulse parameters. Moreover, the spectrum can be sliced and tailored to the application. Therefore, free SBS operation is shown when using the SLD seeder in the same system, allowing for a significant increase on the extractable power and energy.

9344-18, Session 5

Recent progress in the understanding of mode instabilities *(Invited Paper)*

Cesar Jauregui-Misas, Friedrich-Schiller-Univ. Jena (Germany)

No Abstract Available

9344-20, Session 5

Spectral analysis of SRS suppression in photonic bandgap fibers

Malte Karow, Yuta Suzuki, Henrik Tünnermann, Akira Shirakawa, The Univ. of Electro-Communications (Japan)

Pulsed fiber amplifiers operating in the ns regime are usually limited by stimulated Raman scattering (SRS). A promising concept to reduce the impact of SRS is the use of photonic bandgap fibers (PBGF), where the Stokes shifted light is in the stop band. We have characterized the a PBGF-based fiber amplifier in the spectral domain and show that compared to the performance of a standard fiber the spectral broadening due to SRS and four wave mixing (FWM) can be significantly reduced.

Using a random polarized seed source at 1064 nm, strong cross phase modulation (XPM) and FWM occurred in the PLMA-fiber. At 26 W of average output power only 42% of the output power were contained in the signal spectral region around 1064 nm, while it was 79% for the PBGF. The PBGF performance was independent of the input polarization. The spectral signal broadening was asymmetric with a dominant fraction on the long wavelength side of the main signal. This asymmetry indicates Raman amplification of the parametrically generated Stokes light, which was the dominating nonlinear process in this fiber. Its power fraction was much larger than the amount of power contained in the directly Raman scattered wavelength region beyond 1083.9 nm (5 %). For the PLMA fiber on the other hand, the spectrum strongly depended on the input polarization. In this case, the broadening due to FWM was symmetric and direct Raman scattering distributed 12 % of the power beyond 1084 nm, with a bump around 1120 nm.

9344-21, Session 5

Influence of signal bandwidth on mode instability threshold of fiber amplifiers

Jesse J. Smith, Arlee V. Smith, AS-Photonics, LLC (United States)

We show how signal bandwidth affects the gain of stimulated thermal Rayleigh scattering (STRS) which is responsible for a transverse mode instability in fiber amplifiers. The gain is reduced if the coherence time of the signal is less than the group-velocity-induced walk off between the two interacting modes, usually LP_01 and LP_11 . We derive expressions for the bandwidth required to suppress gain for short pulses, for periodically chirped continuous waves, and for general periodically modulated cases.

9344-22, Session 5

Impact of coupling strength on self-focusing in multicore fibers

Henrik Tünnermann, Akira Shirakawa, The Univ. of Electro-Communications (Japan)

Self-focusing is the ultimate power limit of single mode fiber amplifiers. Multicore fibers present an opportunity to scale this limit. At first glance the self-focusing limit seems to scale with the number of cores. However, this is only the trivial if the cores are uncoupled and the fiber behaves like multiple amplifiers.

We analyzed different modes and fiber designs by calculating the mode profiles in COMSOL (6 ?m core diameter, 15 ?m core to core distance, NA=0.076). We then used a split step Fourier propagation algorithm to simulate the self focusing. We assumed a signal at 1064 nm and a nonlinear refractive index of n2=2.2*10-20m2/W. Particularly interesting are the in-phase and out-of-phase mode of circular designs lacking the center core. For this design the intensity pattern of the in-phase and out-of-phase mode are quite similar. In neither case the beam would collapse to the center position, as there is low field intensity and no core in the center. However, our simulations have shown that the in-phase mode becomes unstable during propagation, which leads a decrease in mode area at quite low power levels. Using the out-of-phase mode even coupled cores scale with the number of active cores. Therefore we analyze the impact of coupling strength on the in-phase mode in a two-core design (same NA and core diameter). We observed a sudden mode shrinking at quite low power levels. This effect decreases with increased core-to-core distance, which corresponds to reduced coupling.

9344-23, Session 6

Supercontinuum, solitons, and instabilities *(Invited Paper)*

Goëry Genty, Tampere Univ. of Technology (Finland)

No Abstract Available

9344-24, Session 6

Fiber supercontinuum generation: Innovation through blue sky research *(Invited Paper)*

Jinendra K. Ranka, Intelligence Advanced Research Projects Activity (United States)

No Abstract Available

9344-25, Session 6

Fibre based supercontinua: Past, present, and future *(Invited Paper)*

James R. Taylor, Imperial College London (United Kingdom)

No Abstract Available

9344-26, Session 7

Novel hollow core fibers *(Invited Paper)*

Jonathan C. Knight, Univ. of Bath (United Kingdom)

No Abstract Available

9344-27, Session 7

Picosecond Yb-doped single-trench fiber amplifier with diffraction limited output

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We propose a novel fiber design single-trench fiber (STF) for large mode area fiber laser and amplifier. Fiber offers cylindrical symmetry and also offer higher refractive index of core compared to cladding. This avoids the need of stack and draw process and refractive index compensation of core doped with index raising rare-earth and co-dopants ions, which are an indispensable condition in case of LCF and 2D-ASPBGF. That is why, this fiber design can be fabricated with conventional MCVD process in conjunction with solution doping process, which can dramatically reduce the fabrication cost, hence suitable for mass production. Fiber offers very high loss (>10dB/m) and low power fraction in core (<50%) to the higher order modes for low loss of FM (<0.1dB/m) and high power fraction in core (>80%) thanks to the resonant coupling between core and ring modes. We fabricated a preform for 30μm core STF using MCVD process in conjunction with solution doping process in a single step, without using any micro-structuration and pixilation of core. Meticulous experiments ensure the robust single mode behaviour irrespective of launching condition of input beam.

Furthermore, this fiber used in three stages MOPA provides 80kW peak pulses with repetition rate of 500 kHz, average power up to 10W, with M2 ~ 1.14. Moreover, all solid structure ensures easy cleaving and splicing. In nutshell, an Ultra-low cost, Monolithic, Compact, and an effective Single mode fiber amplifier device can be achieved using Single trench fiber.

9344-28, Session 7

Monolithic sub-MW peak power tapered ytterbium-doped fiber amplifier

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In this study, we present a novel monolithic ytterbium-doped fiber amplifier with more than 0.5 MW peak power output power. The amplifier is based on a 2.1 m long tapered fiber with core/cladding diameters changing from 10/80 μm (at the signal input end) to 50/430 μm (signal output, pump input). The fiber has all-glass polarization-maintaining design, that make possible utilization of conventional FC adapter and standard angle polishing to 7° for thick end. Pump absorption was measured to be 8 dB at 915 nm for the whole fiber length. Despite a very large mode area (~30 μm) the tapered fiber demonstrates a low bend sensitivity (it is possible to coil tapered fiber with 18 cm diameter) and a diffraction limited beam quality.

In the amplifier the pump power was coupled through the thick end by means of collimating and focusing lenses. Dichroic mirror employed to separate output signal and counter-propagating pump power. We obtained 3.5 W of average output power for a 5 mW seed signal (coupled by usual fusion splicing through a thin end) corresponding to a 28 dB gain. The amplified pulses have duration of about 5 ps and energy of about 3.3 μJ that corresponding to over 0.5 MW peak power. The spectral width was 28 nm operating with center wavelength of 1057 nm. Due to observed linear chirp of the output pulses we expect compression of these pulses down to sub-100 fs duration (corresponding to the Fourier-transform-limited pulses with such spectra).

9344-29, Session 7

High peak power amplification in large-core all-solid triple-clad Yb fibers with an index-elevated pump clad and a low numerical aperture core

Martin Leich, Wenbin He, Matthias Jäger, Stephan Grimm, Jens Kobelke, Jörg Bierlich, Yuan Zhu, Hartmut Bartelt, Leibniz-Institut für Photonische Technologien e.V. (Germany)

We report on large-core Yb-doped triple-clad fibers with up to 100 μm core diameter for high peak power amplification. Using a high Al concentration we achieved a numerical aperture (NA) of 0.21 of the pump cladding and a low core NA < 0.1. The material for core and pump cladding was fabricated by Powder Sinter Technology. The fabricated fiber has a high pump absorption. Using a 0.55 m short fiber sample as the main amplifier in a 3-stage ns pulsed fiber Master Oscillator Power Amplifier system we achieved 3 ns output pulses with 360 kW peak power and 2 mJ pulse energy. We observed relatively low Stimulated Raman Scattering, which offers the possibility of further power scaling of such fiber amplifier systems.

9344-30, Session 8

Power scaling of Raman fiber lasers *(Invited Paper)*

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

Raman fiber laser is an efficient way to expand the spectral coverage of fiber lasers. In recent years, output power of Raman fiber laser has been scaled quickly. There is a great potential in further power scaling, technical innovations, and scientific applications. An integrated ytterbium-Raman fiber amplifier architecture was proposed, which allows power scaling of Raman fiber laser to over kilowatt and more. Hundred watt level single frequency Raman fiber amplifier was achieved, which allows the generation of high power sodium guide star laser. New scheme of cladding pumped Raman fiber laser is studied in order to improve the brightness enhancement.

9344-31, Session 8

Four-wave mixing based optical parametric oscillator producing high energy, tunable, chirped femtosecond pulses

Thomas Gottschall, Jens Limpert, Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

A novel concept for an optical parametric oscillator based on four-wave mixing (FOPO) producing energetic chirped femtosecond pulses is presented. The emission wavelength is given by phase matching conditions and can cover a wavelength range from 600 to 2500nm (1μm wavelength range pumping), i.e. extremely wide and gap-free tuneability can be realized. The cavity is based on a short piece of endlessly single mode fiber for signal conversion and a 250 m piece of single mode step index fiber resulting in a high positive net dispersion. The principle is demonstrated experimentally at a fixed pump wavelength of 1040 nm generating signal and idler wavelengths between 867 to 918 nm and 1200 to 1300 nm by altering solely the cavity length. With peak powers >20 kW and a repetition rate of only 780 kHz, this source provides tunable intense ultra-short pulses at moderate average powers.

9344-32, Session 8

Optical system design of a speckle-free ultrafast Red-Green-Blue (RGB) source based on angularly multiplexed second harmonic generation from a TZDW source

Yuhong Yao, Wayne H. Knox, Univ. of Rochester (United States)

We demonstrate a novel fiber based ultrafast RGB laser source based on single-pass simultaneous second harmonic generation from the efficiently generated Stokes and anti-Stkoes pulses from a commercially available photonic crystal fiber (PCF) with two zero dispersion wavelengths (TZDW). With an 1.3 W, 1035 nm, 240 fs, 40 MHz Yb:fiber chirped pulse amplifier as the pump source, we excite dual narrow-band pulses with peak wavelengths at 850 nm, 1260 nm and spectral bandwidths of 23 nm, 26 nm, respectively within 12 cm of TZDW PCF at 44% and 33% conversion efficiency. Due to the optimized fiber length, the dual pulses preserve their ultrashort pulse width (with measured autocorrelation traces of 200 fs and 227 fs) which eliminates the need of post-compression for subsequent harmonic generation. With proper displacements of folding mirrors for simultaneous phase matching, we achieve milli-Watts red, green and blue pulses at 630 nm, 517 nm and 425 nm. Although having much broader bandwidths compared to picosecond RGB laser sources, photometry calculation shows >99.4% excitation purities of the three primaries, leading to the coverage of 192% NTSC color gamut (CIE 1976) and the source is inherently speckle free due to the ultra-short coherence length (<37 μm). The reported fiber based RGB laser source features a very simple system geometry, its potential of significant power scaling is discussed with currently available technologies

9344-33, Session 8

White light 50 W supercontinuum roadmap to kW truly white lasers

Lucy E. Hooper, Mridu P. Kalita, Adam L. Devine, Ana Orec-Archer, John R. Clowes, Fianium Ltd. (United Kingdom)

One of the most spectacular inventions over the last two decades - white light supercontinuum (SC) fibre lasers - have become widely used due to their unique properties and broadly varying applications. These lasers are used in academia and industry for many purposes including bio-medical imaging such as fluorescence lifetime microscopy and optical coherence tomography, lamp replacement, machining, fundamental studies of light, display technologies, and defence applications. The demand for higher power SC fibre lasers is growing, because higher power would add further capability to existing applications, and will also open up new applications never before possible.

In this paper we study and discuss the various avenues to optimise high power SC lasers, report on their long-term stability, and the hurdles to overcome in development of these very high power yet practical sources of extremely broadband radiation covering the 410 nm to 2650 nm spectral band. We report the state of the art in high power SC fibre lasers, with the first truly white light SC with over 50 W total average power and > 20 mW/nm in the visible part of the spectrum. We also present experimental data to demonstrate a cost effective and practical route towards even higher powers by spatially combining the outputs from multiple single-mode SC fibres into a single multi-mode delivery fibre, which we envisage could lead to total visible powers in excess of 150 W or more. This paves the way towards practical kilowatt level truly white light sources.

9344-34, Session 8

Ultraviolet enhanced supercontinuum generation in uniform photonic crystal fiber pumped by giant-chirped fiber lasers

Shoufei Gao, Yingying Wang, Ruoyu Sun, Cuiping Tian, Dongchen Jin, Huihui Li, Pu Wang, Beijing Univ. of Technology (China)

We report on an ultraviolet-enhanced supercontinuum generation in a uniform photonic crystal fiber pumped by a giant chirp mode-locked Yb-doped fiber laser. We find experimentally the initial pluses with giant chirp leads more initial energy, which is transferred to the UV dispersive waves. The process is understood in terms of using giant chirp to enhance short-wavelength generation. The supercontinuum generation system consists of a giant-chirp oscillator, two stages fiber amplifiers and a PCF. The giant-chirp oscillator is mode-locked through nonlinear polarization rotation (NPR) to generate pulse width of 232 ps and spectral bandwidth of 2.4 nm at a repetition-rate of 198 kHz in a long ring cavity. The preamplifier followed 0.32 mW seed laser boosts up the output power to 28 mW under 480 mW preamplifier pump power. Through the second-stage power amplifier, the average power of giant chirp pulse is amplified to 1.4 W at pump power of 4.6 W. When the amplified giant-chirped pulse launch into the PCF, an extremely wide spectrum spanning from 370 nm to beyond 2400 nm with broad spectral bandwidth 560 nm (3 dB) is obtained. The power of visible spectral from 370 nm to 850 nm was 350 mW, high about 36% energy of total SC power. To the best of our knowledge, it is the widest SC and the highest conversion efficiency into the visible spectral ranges generated in a uniform PCF in the picoseconds pump regime using a 1060 nm fiber laser.

9344-35, Session 8

High power mid-infrared supercontinuum generation in a single-mode ZBLAN fiber pumped by amplified picosecond pulses and noise-like pulses at 2 ?m

Kun Liu, Jiang Liu, Hongxing Shi, Fangzhou Tan, Yijian Jiang, Pu Wang, Beijing Univ. of Technology (China)

We have demonstrated high power mid-infrared (mid-IR) supercontinuun (SC) generation in a single-mode ZBLAN fiber pumped by amplified picosecond pulses from single-mode thulium-doped fiber amplifier (TDFA). Firstly, a mode-locked fiber oscillator with pulse width of ~16ps and repetition rate of 42MHz at 1963 nm is used as a seed source of the TDFA.

A mid-IR SC from 1.9 to beyond 3.6?m with average output power of 8W is generated in the ZBLAN fiber. Then, in order to increase the SC average output power from ZBLAN fiber, the pulse width and repetition rate of the fiber oscillator are raised to ~24ps and 93.6MHz. At last, a mid-IR SC with up to 21.8W and an octave spanning from 1.9 to beyond 3.8?m is generated in the ZBLAN fiber with 17% optical-optical conversion efficiency without any damage observed in total system. It is, to the best of our knowledge, the highest average power mid-IR SC generation in a ZBLAN fiber. In addition, a noise-like fiber oscillator based on NOLM with wavepacket width of ~1.4 ns and repetition rate of 3.36MHz at 1966nm is also used as a seed source of the TDFA. At last, a mid-IR SC from 1.9 to beyond 3.6?m with average output power of 14.3W is generated in the ZBLAN fiber with 14.9% optical-optical conversion efficiency.

9344-36, Session 8

Yellow laser light generation by frequency doubling of the output from a master oscillator fiber power amplifier system

Manuel Ryser, Univ. Bern (Switzerland); Carlos A. F. Marques, Rogério N. Nogueira, Instituto de Telecomunicações (Portugal); Valerio Romano, Univ. of Bern (Switzerland)

Laser sources with light-emission in the yellow spectral range are of great interest for many applications such as sodium guidestar laser, quantum computing, and medical applications.

Here we present an approach for yellow laser-light emission that is based on an all-in fiber master oscillator fiber power amplifier (MOFA) configuration with a subsequent single pass frequency doubling stage. We generate radiation around 1154 nm within a fiber Bragg grating cavity that seeds the subsequent fiber power amplifier. To achieve lasing around 1154 nm special measures were taken to fulfill lasing condition and to suppress amplified spontaneous emission. To force the cavity to operate at 1154 nm the right choice of FBGs and heating of the Yb-doped fiber is crucial for suppressing unwanted amplified spontaneous emission. With our optimized MOFA system we got slope efficiencies of more than 40% inside the cavity and also within the fiber power amplifier. The output of the MOFA system around 1154 nm is efficiently frequency doubled in a single pass configuration by using a PPLN crystal to 577 nm.

This MOFA approach is scalable by using multi-stage amplifiers and large mode-area fibers. This approach is very promising for building a high power yellow laser-light source.

9344-68, Session PTue

The influence of photodarkening on the mode instability threshold of high-power fiber laser systems

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It has been repeatedly reported that the mode instability threshold of high-power fiber laser systems degrades with the operating time. Such degradation is able to significantly reduce the stable output power range of a fiber system. This degradation has been previously loosely linked to photodarkening, but no detailed analysis has been carried out in the topic to date. In this work we have modified our simulation models to take into account the spatially resolved contribution of photodarkening to the overall heat-load of the fiber system. This allows getting a deep insight in the relation of photodarkening with the behavior of the mode instability threshold observed in the experiments. Our detailed simulations reveal that photodarkening can rapidly become the main source of heat-load even in active fibers which are considered "photodarkening-free" from the practical point of view, i.e. those exhibiting just a few percent degradation of the output power. In particular, our model shows that in a rod-type fiber amplifier system showing as little as 7% loss in the output power the heat-load will be doubled due to photodarkening. Moreover, our simulation tools show a discrepancy between the theoretical predictions of the wavelength dependence of the mode instability threshold considering only quantum defect heating and those obtained taking into account the extra photodarkening-induced heating. Furthermore, these last predictions show a good agreement with experimental measurements. Thus, it is shown that the impact of photodarkening can be so strong that it modifies the expected behavior of the mode instability threshold.

9344-69, Session PTue

Wavelength dependence of maximal diffraction-limited output power of fiber lasers

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Fiber lasers have reached a performance level in terms of average output power where thermal effects become observable for the first time. The consequence of high thermal load in fiber lasers is the onset of mode instabilities (MI). Hereby, a former stable beam profile starts abruptly to fluctuate once a certain threshold power is reached. Additionally the beam quality degrades. The most straight forward mitigation strategy for MI is to reduce the thermal load by reducing the quantum defect induced heat.. It has been predicted that a significant increase of the MI threshold can be expected by shifting the seed and pump wavelength towards each other. In this contribution we experimentally investigate the influence of shifting the seed wavelength on the MI threshold. We utilize a Yb3+ based MOPA fiber laser system capable of shifting the operation wavelength from 1010 nm to 1060 nm, covering the emission cross-section of Yb3+:silica. It is shown, that the MI-threshold significantly drops for shorter wavelengths which contradicts the theoretical predictions. This surprising result leads to the conclusion that besides the QD a second, equally important heat source is involved. It is found experimentally and by advanced simulations that photodarkening is the second heat source which is actually underestimated. Even fibers where PD has a negligible influence on the laser efficiency, the MI threshold can be reduced by a factor of 2. Thus, the presented finding will lead to rethinking the design concepts of current state-of-the-art fiber-lasers.

9344-70, Session PTue

Sb2Te3 topological insulator based saturable absorber for Er-doped mode-locked fiber lasers

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Growing number of applications using mode-locked fiber lasers cause that the research on new materials used as a saturable absorbers (SA) has been intensified, recently. The ultrashort pulse generation has been reported in fiber lasers using carbon nanotubes and graphene. In last two year the new class of materials called topological insulators is extensively investigated.

We present the Er-doped fiber mode-locked laser based on evanescent field interaction with Sb2Te3 topological insulator. The SA consist of a bulk piece of Sb2Te3 material placed on the side-polished fiber in the presence of UV curable polymer. The measured SA optical parameters like: liniar absorption, modulation and non-saturable loses were of 50%, 6% and 43%, respectively. The SA was spliced into the ring cavity with all-anomalous dispersion, all-normal dispersion and dispersion managed. Such laser resonators allow to optical solitons, dissipative solitons and Gaussian pulses generation with 3dB bandwidth of 10.3 nm, 30 nm and 18 nm, respectively.

9344-71, Session PTue

Polarization-maintaining amplifier based on 3C fiber structures

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Chirally-Coupled-Core (3C) fiber structure can preserve a single mode quality and even a linear polarization for a large core size. A principal advantage of fiber laser is its compatibility with monolithic integration and robust system. But so far, devices such as a combiner using the 3C fibers have not been reported. Here we report the first demonstration of such monolithic amplifier structure which contains an active fiber and a combiner based on 3C fibers.

A single-stage amplifier is seeded by an EO Q-switched micro-laser and pumped by two high power fiber pigtailed 976-nm laser diodes via an in-house fabricated (2 + 1) ? 1 pump signal combiner. The active fiber is based on a 3-m-long, 3C Yb-doped fiber (33 ?m/250 ?m core/cladding diameter with 0.06/0.46 NA). The amplifier demonstrates scaling up to 30W average power and 150 kW peak power in 0.3mJ, 2ns pulses. The beam profiles and beam qualities were characterized as its output power was varied up to 30W. The beam profile was maintained at a high beam quality of around M2=1.2. The spectral properties of the 3C fiber were also characterized as its output peak power was varied.

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9344-72, Session PTue

Impact of chromatic dispersion and spectral filtering in an all fiber mode locked ytterbium laser

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In this study, a polarization maintaining (PM) all-fiber laser oscillator passively mode-locked at 1.03 µm is presented. The mode-locking is achieved by nonlinear polarization evolution occurring along a long span of standard PM fiber (26 m) spliced between an off-axis polarizer and a Faraday rotator mirror. The influence of the total chromatic dispersion and intra-cavity spectral filtering on pulsed operation is studied. Two experimental configurations have been tested. The first configuration is an all-normal dispersion cavity using a looped fibered circulator combined to a 1.5 nm filter used as an end cavity mirror. The second configuration used highly reflective chirped Fiber Bragg Grating (FBG) exhibiting different bandwidths (0.7 nm and 1.83 nm). The chromatic dispersion induced is +7.2 ps/nm for each FBG. Stable single-pulse mode-locked operation has been demonstrated for each configuration. The study highlights however different mode-locking operations according to the intra-cavity spectral filtering and total chromatic dispersion of the cavity. For the first configuration, pulse duration is about 7 ps. According to the optical spectrum which has a FWHM of 2.2 nm, pulses may be compressed to subpicosecond durations with the help of a suited compressor like bulk gratings. Shortest pulses of 2.2 ps have been obtained at a repetition rate of 3.3 MHz with the second experimental configuration. To our knowledge, this is the smallest pulse duration delivered by a fully-fibered mode-locked laser operating at a repetition rate lower than 10 MHz without any external pulse compressor.

9344-73, Session PTue

100w femtosecond fiber amplifier and harmonic generation from IR to UV

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Many industrial applications such as glass or battery foil cutting and ceramic micro-machining require sub-picosecond pulses. The main limitation for the expansion of the femtosecond market is the cost of high power laser sources, which is due to the complexity of the CPA architecture used for femtosecond pulse amplification.

In this demonstration, initially narrow linedwidth pulses, in the tens of picoseconds pulse duration range, can be amplified, accumulate well controlled nonlinearities and then be compressed 50 times shorter than the initial pulse duration. The use of passive fiber to temporally shape pulses is straightforward and constitutes the key element that ensures nonlinear effects control in the amplifier.

We used pulse shaping of a transform-limited 27ps passively modelocked fiber oscillator that produces 60mW at 30MHz and 1030nm in order to control nonlinear effects in the fiber amplifier. The pulse-picked output is then directly amplified with a double stage amplifier using DMF Rod-Type fibers to achieve 60µJ and 120W with 65ps pulses. Using a pair of transmission gratings, we finally obtained very good temporal quality 900fs pulses with an energy of 45µJ, leading to 50MW Peak Power. This laser source was then frequency converted with LBO Crystals and we obtained 30W at 1MHz and 57W at 3MHz at 515nm. We also demonstrated Third Harmonic Generation and got 14.7W at 1MHz and 28.5W at 3MHz at 343nm.

9344-74, Session PTue

Transient-fiber-Bragg grating spectra in self-swept Fabry-Perot fiber lasers

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Fiber laser instabilities may significantly influence fiber laser performance and in some case they may lead to damage of the components and devices. Particularly, self-Q-switched regimes may have catastrophic consequences. The self-pulsing regimes have been attributed, e.g., to reabsorption in an unpumped part of the active fiber, Raman and Brillouin scattering processes and ion pairs formation. Recently, we have shown that the self-Q-switching instability mode can evolve from the so-called self-induced laser line sweeping (SLLS). The SLLS effect is characterized by quasiperiodic laser line drift in a relatively broad range that can exceed 10 nm. Earliest published observations of this effect were about Yb-doped fiber-ring and Fabry-Perot lasers and later also about erbium-doped fiber lasers at around 1560 nm and thulium-doped fiber laser around 2 micrometers. The SLLS can be explained by a spatial-hole burning (SHB) in the active medium caused by standing-wave in the laser cavity. Since the standing wave is rather regular and has lifetime of the order of tens to hundreds microsecond, it may create not only the grating in the fiber gain but also significant reflection grating through resonant index change of the rare-earth doped core.

In this paper we provide analysis of such transient fiber-Bragg gratings and also experimental results in the rare-earth doped fiber laser with SLLS. We show that the transient gratings created in the cavity may easily achieve reflections above 20 %. Their spectral characteristics are narrow bandwidth typically <2 pm and asymmetric shape. As the longitudinal modes may overlap in time, effect of superimposed dumped gratings is shown.

9344-75, Session PTue

A high energy green fiber laser in the ns regime for advanced material processing applications

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The growing demand to reduce size, weight, and material cost in the production of electronic devices has led to an increasing demand for industrial laser tools for high precision, superior edge quality, and high throughput applications.

The choice of laser wavelength is primarily determined by the processed material, machined feature size, and the surface-quality requirements. While the use of UV lasers has met the need for creating smaller features with high quality in processing of various materials, high performance 532nm wavelength laser frequently provide sufficiently high quality at lower cost. Pulsed green DPSS lasers operating in the nanosecond regime are widely used as micromachining tools. These lasers, however, have characteristics that limit the extent to which process speed can be enhanced and manufacturing costs reduced. Pulsed fiber lasers, on the other hand, are reliable and cost effective solutions, but in contrast to IR lasers, frequency-doubled fiber lasers pose a technological challenge due to low pulse-energies and difficulties in achieving efficient wavelength conversion to green.

In this paper, we report the development of an advanced narrow linewidth, linearly polarized, Yb-doped fiber laser engine based on standard LMA fibers for high peak power and pulse energy capabilities, while maintaining excellent beam quality characteristics. The engine enables frequency-doubling in a single pass configuration with over 70% efficiency, achieving selectable 1-20ns pulses with up to 200uJ pulse energy with 20kW peak power at 532nm. The source is used to demonstrate high quality and throughput PCB cutting, glass cutting, and ceramic scribing.

9344-76, Session PTue

Measuring bend losses in large-mode-area fibers

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Large-mode-area (LMA) fibers, which typically have a core diameter of 20-30μm and a core NA of 0.06-0.08, can provide relatively high nonlinear thresholds and power handling capabilities while maintaining good beam quality, thus, are widely used in high power fiber lasers and amplifiers.

The bend loss, or more specifically the bend loss of the LP01 mode, is a basic but important parameter, when using the LMA fibers in compact packages. The measurement of the bend loss seems to be trivial, by taking the transmitted power at a series of bend diameters and processing/fitting the data. However, we found that some factors can significantly affect the measurement results. In this paper, we investigate the measurement of bend losses in few-mode large-mode-area fibers. The influence of the light source spectral characteristics, modal power content and cladding light on the measurement accuracy and precision is studied experimentally. Monte-Carlo simulations are performed to understand the distribution of the variations. This study provides practical guidelines for bend loss measurements.

9344-77, Session PTue

Continuously one-dimensional steering of coherently combined beam utilizing phased array of liquid crystal optical phased arrays (PALCOPA)

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Non-mechanical steering of coherently combined beam can make the coherent beam combining (CBC) technique be applicable to optical application areas which require random-access pointing. However, current research on CBC focuses mainly on combining coherent beams at a fixed point and little attention has been paid to the continuously steering of coherently combined beam. Here, we put forward a method to realize continuously one-dimensional steering of coherently combined beam via utilizing phased array of liquid crystal optical phased arrays (PALCOPA). More specifically, we first introduce the CBC system based on PALCOPA and the principle of directing the combined beam to arbitrary angle in PALCOPA field of regard. All the coherently incident lasers are directed to the assigned deflection angle of the combined output. In order to make the peak intensity in the far-field occur at the assigned angle, extra phase modulations, set by the assigned angle and the parameters of beam combining system, should be applied to the incident lasers. Then, the analytical expressions of the far-field intensity distribution of the combined beam, being employed to exploit the deflection angle, mainlobe width and combining gain, are derived by using the Fraunhofer propagation principle. Finally, computer simulations and experiments are carried out to evaluate the proposed technique. Theoretical analysis and experimental results show that the proposed technique is reasonable and efficient. The research results in this paper can also be extended to coherently combined beam steering of CBC system based on other optical phased arrays.

9344-78, Session PTue

Pulse shaping in fiber lasers for high energy micromachining applications

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High power pulsed fiber lasers are known for their ability in achieving high peak powers while preserving near diffraction limited beam quality. Achieving high energy pulses, however, is challenging as long pulses in high gain suffer from gain saturation that impedes the scalability of pulse energy, and causes inhomogeneity in the power during the pulse. In turn, larger core fibers, which enable power scalability, yield lower beam quality. While pulse shaping has been previously reported as a method of suppressing gain saturation effects in long pulses, the combination of long pulse duration and slowly rising pulse shape provides an ideal condition for the development of SBS. In fiber lasers, which often have narrow line-width, the threshold for SBS is, in essence, the limiting factor of peak-power scalability, thus overcoming this barrier can assist in producing higher power pulses.

In this work we demonstrate a broadband ASE source used as a seeder in a MOPA fiber laser. This seeder source, after being spectrally filtered, is then temporally shaped to produce the appropriate form for further amplification. Amplifying the designed pulses in a chain of Yb doped fiber amplifiers yields up to 1mJ pulses with more than 10kW of peak power and a 100-300 ns non gain saturated pulse shape. In comparison, a similar design with a narrowband seeder source exhibits a 400W SBS peak power threshold, 25 times lower than that achieved with the broadband seeder. This technique proves useful for various micromachining applications which require both high energy pulses in addition to good beam quality.

9344-79, Session PTue

High-average-output power mode-locked figure-eight all fiber Yb master oscillator

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The present work has for the first time demonstrated a record-high average output radiation power exceeding 1 W directly at the output of a mode-locked figure-eight all-fibre Yb master oscillator using a non-linear amplifying loop mirror. Generated double-scale pulse trains following at 25-MHz repetition rate had intensity envelope with duration of 20–25 ps filled with 200-fs sub-pulses. We have detailed parameters of two typical generation regimes of this laser, in which output pulses have fundamentally different spectra. Spectral evolution dynamics generated in these regimes at different values of output radiation power covering a wide range is also substantially different as is illustrated by included dependences. Several laser configurations are experimentally studied with and without polarisation controllers, as well as with a birefringent fibre spectral filter. It is relevant to note that the laser's output power in the proposed configuration is only limited by power damage threshold of the used fibre beam splitters. Consequently, the developed and proposed master oscillator configuration can is capable of substantially higher average output power if more power resistant fibre components are installed. The active medium of the laser was a GTWave fibre pumped with 7.4 W at 975 nm. The generated unique powerful clusters of femtosecond pulses will find applications in laser-induced breakdown spectroscopy, as well as in many other fields of research and technology.

9344-80, Session PTue

Binary phase shaping for mitigating self-phase modulation

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Self-phase modulation (SPM) leads to spectral broadening of optical pulses. This nonlinear effect can occur in any optical medium because of the intensity-dependent nature of index of refraction. For example, in the pulse amplification SPM is an unwanted effect which needs to be minimized otherwise it leads to pulse distortions and breakup. In fiber amplifiers, chirped pulse amplification leads to spectral and temporal changes. Here we report on the use of binary phase shaping which serve as an alternative method to mitigate SPM. The principle is based on the idea that each spectral component of the field is given a phase value of zero or Pi. The goal is creating interference in the high-order power spectrum of the pulse. We use pseudo-random binary phase sequences which are then introduced using a 4-f pulse shaper. We demonstrate that even when reaching of SPM threshold power 2.5x10^6 W the spectrum stays unchanged when the binary phase is applied. Compression of the pulses to their transform limited value involves an additional application of the same binary phase mask. Thus, the spectral regions with Pi retardation acquire 2*Pi retardation, which is the same as zero.

9344-81, Session PTue

MW-level, kHz-repetition rate femtosecond fiber-CPA system operating at 1555 nm

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Large-energy, high-peak power femtosecond sources of infrared radiation are currently on demand of many industrial, military and medical applications. Currently, the mainstream of high-power constructions based on the chirped pulse amplification (CPA) scheme is dominated by Yb-doped fiber-based systems, emitting extremely high powers in the 1 ?m wavelength range. However, there are several niche applications where 1 ?m systems are outperformed by lasers operating in the 1.55 ?m wavelength range, e.g. corneal surgery, processing of non-typical materials (e.g. solar cells), nonlinear parametric generation or supercontinuum generation. Here, we demonstrate a fully fiberized (except of the bulk compressor), CPA setup operating at 1555 nm wavelength, based on Er and Er/Yb-doped fibers, utilizing an acousto-optical pulse-picker. The repetition frequency of the system can be easily tuned and reduced to the kHz-range, which enables generation of sub-600 pulses with energies reaching the ?J level and peak power exceeding 1 MW.

The CPA system is seeded by a dispersion-managed, stretched-pulse Er-doped laser mode-locked by carbon nanotubes. It provides 200 fs pulses with 40 MHz repetition rate. The pulses from the seed laser are stretched in a segment of normal-dispersion. Afterwards, the pulses are boosted in two pre-amplifiers and directed to the pulse-picker. The final amplification stage is based on an Er/Yb co-doped LMA fiber with 25 ?m core. The pulses are compressed in a grating-based Treacy-type compressor. The system is capable of generating 590 fs pulses at 200 kHz repetition rate with 300 mW average power. Thus, the pulse energy reaches 1.5 ?J.

9344-82, Session PTue

Self-injection locking of the DFB laser through ring fiber optic resonator

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As well known, optical injection locking and self-injection locking of DFB lasers has drawn attention especially for optical communication application as an efficient technique to improve the spectral and polarization performance of semiconductor lasers.

In this work we study self-injection locking of DFB laser through ring fiber optic resonator in the different regimes. Experimentally measured transmitted and reflected from fiber cavity powers at undercoupled, critically coupled, and overcoupled regimes are properly coincide with the calculated values.

When the laser frequency is matched with ring resonance the power which is passing the resonator increases and provides powerful optical feedback which is enough for stable self-injection locking of the DFB laser. Now any change of the resonance frequency of the ring cavity due to, for example, temperature variation forces the matching-change of the locked laser frequency inside a locking interval. As result locked DFB laser adjusts its frequency equal to a resonance frequency of the ring cavity. However, the stable resonance regime is observed only during some intervals which are interrupted by short-time jumping-intervals. Significant reduction of locked laser linewidth was observed. For the free running laser, the full-width at half-maximum linewidth was equal to 2.6 MHz assuming that line shape is Lorentzian. Meanwhile the self-injection locked DFB laser demonstrates linewidth equal to 3.5 KHz for overcoupled and critically coupled regimes and about two times more (6.7 KHz) for undercoupled regime.

9344-83, Session PTue

Characterization of mode locking in an all fiber, all normal dispersion ytterbium based fiber oscillator

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An ytterbium based all-fiber, all normal dispersion fiber oscillator with integrated SESAM can have several operation modes like mode-locked, noisy and noise-like. To know and to control the quality of the mode-locking is essential for the application of such laser oscillators, otherwise the whole laser setup can be damaged or the expected operation characteristics of the oscillator driven systems cannot be achieved. Usually the two-photon signal generated by the short pulses is used to indicate the mode-locked operation, however such detection can be misleading in certain cases and not always able to predict the forthcoming degradation or vanishing of the mode-locking. The characterization method that we propose uses only the radio frequency spectrum of the oscillator output and can identify the different operation regimes of our laser setup. The optical spectra measured simultaneously with the RF signals proves the reliability of our method. Stable mode-locking can be initiated and maintained during the laser operation applying the proposed characterization process. The developed oscillator reported here with its compact setup and self alignment ability can be a reliable coherent light source with long term error free operation, without the need of expensive monitoring tools. The method combined with the ability to align the polarization states automatically in the laser cavity leads to the possibility to record a polarization map where the stability domains can be identified and classified. With such map the region where the mode-locking is self starting and stable with zero or minimal alignment can be selected.

9344-84, Session PTue

2 μm actively Q-switched all fiber laser based on Tm-doped silica fiber

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An actively Q-switched all-fiber laser operating at the wavelength of 1920 nm is experimentally demonstrated. Different to the highly Tm-doped germinate and silicate fiber used in reported paper, a commercial Tm-doped silica fiber has been used here. The laser cavity consists of an 8.5 cm long Tm-doped fiber which is cleaved and spliced between a pair of fiber Bragg gratings (FBGs). The HR FBG with a reflectivity >99% is imprinted in a SMF-28 fiber. Another one with a reflectivity of ~50% is imprinted in a polarization maintaining fiber (PM-1550). This makes the laser cavity polarization-dependent and only one polarization direction can get feedback in the cavity, which is the key element for the Q-switching method applied in this experiment. The Q-switching is achieved by polarization modulation through the stress-induced birefringence using a 3 mm long piezoelectric transducer (PZT) as the Q-switcher.

The output power characteristics of the laser in both the continuous-wave (CW) and the Q-switched regime have been investigated. The maximum output power of 18 mW can be achieved in CW regime when the launched pump power was nearly 300 mW. The repetition rate of the stable Q-switched laser can be tuned from 25 kHz to 175 kHz. The relationship between the pulse width and the pump power as well as the repetition rates was also researched. The shortest pulse duration of 413.2 ns has been achieved under the pump power of 145 mW and the repetition rate of 25 kHz.

9344-85, Session PTue

Phase stabilization of an actively mode-locked ring laser

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A phase resolved system based on swept source optical coherence tomography (SS-OCT) has to incorporate a phase-stabilized swept laser source. The phase instability is induced by fluctuation of the beginning swept optical frequency. The emitting wavelength of the actively mode-locked ring laser (AMLL) is tuned arbitrarily by changing its electrical modulation frequency. Using a properly frequency-modulated signal with the AMLL allows one to obtain the desired temporal waveform of the wavelength. Since we employ a saw-tooth like signal for wavelength sweeping, the beginning swept optical frequency is fluctuated by the abrupt frequency transition from the end of one sweep to the beginning of the successive sweep.

To suppress the fluctuation of the beginning wavelength in the AMLL, the sweeping signal is constant at the leading slope of the signal. However, the temporal phase response, which calculated from complex FFT of interferogram, has a standard deviation of several tens mrad. To compensate the phase variation, we employ the auxiliary reference in the sample arm. The phase variations, which are obtained by the auxiliary reference, are subtracted by the averaged phase variation during measurement. The individual interferogram is shifted to compensate the phase variation.

In this research, we have proposed the phase stabilization method that has nanometer sensitivity with millisecond response. In addition, the method has successfully suppress the depth dependence of phase instability.

9344-86, Session PTue

Genetic algorithm based optimization of pulse profile for MOPA based high power fiber lasers

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Although the Master Oscillator Power-Amplifier (MOPA) based fiber laser has received much attention for laser marking process due to its large tunabilty of pulse duration (from 10ns to 1ms), repetition rate (100Hz to 500kHz), high peak power and extraordinary heat dissipating capability, the output pulse deformation due to the saturation effect of fiber amplifier is detrimental for many applications. We proposed and demonstrated that, by utilizing Genetic algorithm (GA) based optimization technique, the input pulse profile from the master oscillator (current-driven laser diode) could be conveniently optimized to achieve targeted output pulse shape according to real parameters' constraints.

In this work, an Yb-doped high power fiber amplifier is considered and a 200ns square shaped pulse profile is the optimization target. Since the input pulse with longer leading edge and shorter trailing edge can compensate the saturation effect, linear, quadratic and cubic polynomial functions are used to describe the input pulse with limited number of unknowns(<5). Coefficients of the polynomial functions are the optimization objects. With reasonable cost and hardware limitations, the cubic input pulse with 4 coefficients is found to be the best as the output amplified pulse can achieve excellent flatness within the square shape. Considering the bandwidth constraint of practical electronics, we examined high-frequency component cut-off effect of input pulses and found that the optimized cubic input pulses with 300MHz bandwidth is still quite acceptable to satisfy the requirement for the amplified output pulse and it is feasible to establish such a pulse generator in real applications.

9344-87, Session PTue

Bi-directional pump configuration for increasing thermal modal instabilities threshold in high power fiber amplifiers

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We present a time dependent computer model for modal instabilities in high power fiber amplifiers based on a beam propagation approach which combines local rate equations with a time-dependent temperature solver and a quantum defect heating source. Three regimes of temporal dynamics that are characteristic of the transfer of energy between the fundamental mode and higher order mode are captured and applied to predicting the threshold of these instabilities in absence of any frequency offset between the interfering modes. Simulation results show an increase of the instabilities threshold by a factor of approximately 30% for bi-directional pump scheme with respect to the forward pump configuration without any additional adjustment of other amplifier parameters. It is shown that saturation effects are responsible for the higher obtained threshold in the case of bidirectional pumping. Furthermore, taking gain saturation effect into account, we apply a coupled-mode model of transverse mode instability to estimate the modal instability threshold for the bidirectional pumping case. The simulation results show that the bi-directional pump scheme provides a mode instability threshold increase of ~35% with respect to the forward pumping case, which is in good agreement with the beam propagation results.

9344-88, Session PTue

1.3μm optical amplification with double-clad Bi doped silica fiber

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1.3 um optical amplifiers for the long distance up-stream networks for a future increase of fiber access network in telecommunications are attractive. A bismuth-doped silica glass has a potential of the broadband spectrum as laser and amplifier applications at 1.3 um. The bismuth-doped fiber lasers and amplifiers were developed by the Dianov group fabricating by the MOCVD method. In this report optical amplification characteristics at 1.3 um are presented with the double-clad bismuth-doped silica fiber (DC-BDSF) made by the VAD method. The bismuth and aluminum ions were solution-doped into a porous germanosilicate layer. The concentration of Bi in the core glass was measured as 0.37~1.2 wt % by EDX spectroscopy. Refractive index difference between the core and the first cladding in the preform was measured as 0.52 % by the optical fiber preform analyzer. The D-shape preform was drawn into the fiber where the core and the first cladding diameters were measured as 8.4um and 125 um in the shorter and 140 um in the longer diameters, respectively. The polymer second-cladding diameter is 243 um and the index difference between the polymer index of 1.407 and the silica first cladding is 3.6%. Cladding pumping into the DC-BDSF was performed by using the focusing lens with the multimode fiber pigtail of the pumping LD. In the case of the D-shape fiber it is not so easy to realize a perfect splicing because of asymmetric structure on the cross section. The 1 dB/m amplification in 1310 nm was measured with 4 m long DC-BDSF. An off-focusing pumping was useful for avoiding a gain saturation in the DC-BDSF.

9344-89, Session PTue

Optimized mode-field adaptor for low-loss fused fiber bundle signal and pump combiners

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High power fiber lasers are typically based on double clad fibers (DCF). Several approaches were developed for pump and signal coupling into DCF. For practical applications are most suitable fused tapered fiber bundle combiners. Problem arises in signal branch of such a combiner when the input is required to be single-mode and also the active core is required to be single-mode. Because of tapering, mode field diameter changes in signal fiber along the taper and it is difficult to match it simultaneously on input and output. Several approaches addressing this problem were proposed. First technique is fattening of signal fiber core before bundling and tapering achieved by heating and subsequent dopant diffusion. Second approach is based on vanishing core technology when special double clad fiber is used as signal fiber inside the combiner. By tapering the field expands from core to first cladding which is matched to output fiber core at the end of taper. Third approach consists in etched taper conserving core diameter along the taper.

In our contribution we report on best to our knowledge novel mode field adapter incorporated inside bundled tapered pump and signal combiner. Proposed combiner allows simultaneous matching to single mode core on input and output. Losses of combiner signal branch are thus significantly reduced. Our numerical simulations estimates losses of 0.12 dB in signal branch for SMF28 input fiber and SMF28 matched output double clad fiber for the wavelength of 2 um. Preliminary experimental results showed the losses of 0.18 dB.

9344-90, Session PTue

A loss-compensated fiber loop available for short-pulse lasers and its application in water detection

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The concentration of trace sample can be determined by, and therefore an indicator of, the absorption property in fiber-loop ring-down spectroscopy. The aim of this study was to investigate the use of an ultrashort-pulse laser as a source of the fiber-loop ring-down spectroscopy and its applicability for loss-compensated fiber loops. A composite-type carbon-nanotube saturable absorber (CNT-SA) mode-locked fiber laser was built to be used as a source of experimental setup. The simulation has been done to check dispersion effects on ring-down signals, and it was found that the initial pulse duration affected ring-down information. To avoid this limitation, we just used the chirped pulses without any compensation process in the experiment. A loss-compensated fiber loop was constructed to measure the concentration of water in water/acetone mixture samples. The measurements were shown to lead to an accurate determination of the ring-down time. The result indicates that it is possible to measure the sample-induced absorption with the ultrashort-pulse laser source and loss-compensated fiber loop to determine the concentration of the sample.

9344-91, Session PTue

Double looped Mach-Zehnder interferometry for achieving simultaneous spectral ring down information

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We demonstrated an acquisition method of ring-down interferograms using double loops having slightly different lengths. Two cavities have slightly different lengths, and each group of pulses from sample and reference cavities builds each ring-down train with equal temporal intervals. Because the sample cavity is slightly longer than the reference cavity, the time delays Δ? of the two pulses from each loop increase in multiples of Δ?. If two trains would be overlapped successively with sufficient time delay in one arm, the multiple ring-down interferograms can be obtained. This configuration of two cavities plays a key role for obtaining ring-down interferograms with a remarkably short delay line and slow detector. For verifying the proposed method, we developed an experimental setup, which was made up of two fiber-loops having 0.6 mm differences. The two loops were kept stable and free of sharp bends. Experiment was performed with an erbium-doped fiber laser (EDFL), which is passively mode-locked by a carbon-nanotube saturable absorber (CNT-SA). Continuous multiple ring-down interferograms were successively obtained with a few mm delay line instead of complicated components such as optical switching mechanisms. Finally, this proposed method was used to estimate the total losses of two loops, and the difference was only 0.15 dB from the result of the conventional ring-down method.

9344-92, Session PTue

Thermal stability of multi-longitudinal mode laser beating frequencies in hybrid semiconductor-fiber ring lasers

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Fiber laser is a basic building block in many applications including fiber-laser frequency combs, environmental change measurements and rotation sensing. Their main advantage with respect to semiconductor lasers is their narrow linewidth and their high signal-to-noise ratio in sensing. The ring configuration has the advantage of allowing bidirectional operation and larger free spectral range, with respect to a Fabry-Perot configuration with the same length of the ring. In this work, the thermal stability of the beating frequencies is studied theoretically and experimentally for a multi-longitudinal mode fiber ring laser comprising traveling-wave semiconductor optical amplifier (SOA) as a gain medium. The SOA has central wavelength of 1530 nm and gain 3dB bandwidth of 36 nm. The effect of temperature variations in the SOA is found to be negligible as long as the fiber cavity is long enough. The variation of the beating frequency with temperature was found to be small for larger cavity length and smaller beating order. A measured frequency variation as low as -0.24 Hz/oC is obtained for ring cavity length of 2.7 km corresponding to a free spectral range of about 75 kHz . The stability of the frequency is evaluated by means of the Allan variance technique. The measurement is carried out for beating frequencies with different orders in a controlled environment within ±0.1oC temperature variations. The lowest order beating frequency has about 20x better long-term frequency stability than the beating frequency of the 100th order. The results indicate that there is a non-linear dependence of the long-term stability on the beating order.

9344-93, Session PTue

Bidirectional single-longitudinal mode SOA-fiber ring laser based on optical filter assisted gain starvation

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Generation of a single-longitudinal mode (SLM) in bidirectional ring lasers has a direct impact on the laser linewidth and the dynamic range of operation when used in rotation sensing applications. Besides, operating at a specific wavelength helps in optimizing the performance of the system components. Production of SLM in bidirectional fiber ring lasers was reported based on narrow-bandwidth fiber Bragg grating filters. The usage of relaxed filter specification was also reported based on the combined effect of the filter response and the nonlinearities of gain medium; yet in a unidirectional case only, where an isolator is inserted in the laser ring. In this work, we report a novel method for generating SLM in bidirectional SOA-fiber ring laser using a mechanically-tunable Fabry-Perot filter with 1-nm bandwidth. The method is based on gain starvation by tuning the central wavelength of the filter in the blue edge of the gain-wavelength response. By adjusting the SOA driving current, the oscillation condition is satisfied for only one mode and SLM bidirectional operation can be achieved. The SLM operation is identified by measuring the laser spectrum on an optical spectrum analyzer and monitoring the beating signal between the modes on an RF spectrum analyzer. Using an SOA with a small-signal gain of 23 dB at 300 mA pumping current and a gain bandwidth of 40 nm centered around 1534 nm; the central wavelength of the ring laser could be tuned from 1440 nm to 1480 nm with a side-mode suppression ratio of 25 dB.

9344-94, Session PTue

Synchronization of a programmable laser and Ti:Sapphire laser using an optical feedback

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We have built a dispersion-tuned actively mode-locked laser, or programmable laser, that can be synchronized to any passively mode-locked laser, which acts like the master laser. The synchronization of the programmable laser is done through a clock-recovery module that monitors a fraction of the optical power coming out of the master laser and then generates an electrical signal at the same repetition rate but with an adjustable phase. This signal is then used to drive the programmable laser and the phased adjusted to reach synchronization.

One of the challenges of synchronizing two different lasers is to have both laser cavities operating at the same length. The programmable laser can be synchronized to lasers with different repetition rates using two mechanisms. The first is using a highly dispersive fiber Bragg grating in the cavity so the programmable laser can operate over a range of repetition rates. The second is using harmonic mode-locking to operate the programmable laser at integer multipliers of its fundamental repetition rate.

Two schemes were used to validate the synchronization. First, two 25 ps programmable lasers, one at 1585 nm, the other adjustable from 1020-1050 nm were synchronized. The synchronization was within 2 ps over 8 hours. Second, the programmable laser at 1585 nm was doubled to 792.5 nm and synchronized to a Tsunami Ti :Sapphire laser. The synchronization was maintained for over 5 hours.

9344-95, Session PTue

Compression of chirp pulses from a femtosecond fiber based amplifier

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We demonstrated femtoseconds chirped pulse generation with an all fiber master oscillator power amplifier, and pulse compression of the chirped pulses using the transmission holographic gratings (800 line/mm). This grating has a high diffraction efficiency of 90 % at the Bragg condition, which makes easier the alignment procedure. We have built a passive mode-locked polarization maintaining Yb doped fiber laser based on a semiconductor saturable absorber mirror and a chirped fiber Bragg grating as a seed source. The output power was 73 mW at the center wavelength was 1065 nm. The pulse width was 2.0 ps (Sech^2) at a repetition rate of 42 MHz, and the spectral width (2?) was 6.3 nm. In fiber-based amplifiers, the self-phase modulation occurs due to the nonlinearity of fiber, and spreads the spectral widths of amplified optical pulses. The output power was amplified to 0.97 W from 73 mW in the amplifier, the slope efficiency was 44 %, and the peak power was 17 kW. The nonlinear phase shift and dispersion of active fiber create the chirped pulses that have the spectral width (2?) of 8.5 nm, and the pulse width of 1.4 ps (Sech^2). The compressed pulse width was 490 fs on dispersion rate -730,000 fs^2 .

9344-96, Session PTue

Group velocity dispersion analysis of large mode-area doped fibers implemented in a laser cavity during operation

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Developments in the field of high-power fiber lasers require extensive knowledge of the fiber structure parameters in various operating states. In an effort to gather such knowledge, this paper presents the results of dispersion characterization measurements using ytterbium-doped large mode area double-clad fibers implemented in the cavity of a high power fiber laser in operation as a case study. The laser cavity is part of a Michelson interferometer. Using dichroic mirrors the radiation of a supercontinuum light source is coupled into the fiber sample. Various types of LMA fibers were examined under different operating conditions of the Laser setup.

Group-velocity dispersion characteristics of several LMA double-clad fiber amplifiers with various launching laser power levels were systematically analyzed. The dispersion parameters for different fiber designs and various doping levels are investigated over a broad spectral range of about 1.3 µm for controlled sets of operating parameters. The experiment utilizes a supercontinuum source developed within this laboratory as well as a Michelson-Interferometer with a dual-channel spectral-detection system sensitive to wavelengths from 0.4 ?m to 1.7 ?m. Temporally resolved spectrograms recorded at distinct delay positions enable the detection of interference fringes for the equalization-wavelength. By applying a Sellmeier polynomial fit to the wavelength dependent differential group-delay function, the group-velocity dispersion can be derived. The measured Yb-doped LMA fibers show a variation of the doping concentration between 0.69 mass percent to 3 mass percent of ytterbium.

9344-97, Session PTue

All-PM-fiber normal dispersion femtosecond optical parametric oscillator pumped by Yb-doped fiber laser

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We report the development of a widely tunable all-PM-fiber normal dispersion femtosecond optical parametric oscillator pumped by Yb-doped femtosecond fiber laser. Operating in the normal dispersion regime allows significant output power scaling while avoiding pulse breakup. The output signal or idler pulses are high chirped but can be compressed to close to transform limit ensuring high peak power. We achieve over 300nm total tuning range (850-950nm and 1100-1300nm) with the output pulse energy above 1nJ. The laser source will be useful for many applications including multiphoton imaging.

9344-98, Session PTue

Low-threshold supercontinuum generation for a gain-switched 1126nm fiber laser

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In the past decade, highly nonlinear photonic crystal fibers (PhCF) have been recognized as a powerful and versatile tool for laser spectral broadening. These fibers propagate light along a small solid core surrounded by an array of larger air holes. The nonlinear optical properties of these structures are very much akin those of a rod of glass surrounded by air, stemming from strong confinement of the light within the structure and correspondingly a large nonlinearity to arise. The modulation instability, four-wave mixing, Raman scattering, and coupling with dispersive waves are the main effects responsible for the ultra-wide spectral broadening or supercontinuum generation (SCG) in highly nonlinear PCF when a narrow pump laser line spans up to an octave.

In the present paper, we investigate the properties of SCG in a PCF, where the SC is generated through the cascade of those nonlinear processes initiated inside the fiber by a sub-microsecond 1126-nm gain-switched fiber laser. Analyzing how the whole set of SC characteristics such as spectrum span, threshold, and spatial profile depend on the fiber length and pump power, we arrive to the conclusion that a proper choice of the pump light – fiber sample coupling arrangement is the key point for highly efficient SCG in the fiber.

In conclusion, gain-switched 1126-nm Yb-fiber laser is fabricated and its pulsed output provides a smooth half-octave generation. Since a low power fiber laser is used as a pump source, the entire configuration is convenient for the implementation of extremely compact monolithically integrated pulsed SC-sources. The SCG originates from Kerr-like nonlinearity of the silica secondary cores that is enhanced by the Raman scattering. Tight focusing into a single core is the prerequisite of the SCG and, along with the core width, offers the possibility for coupling of different-color lasers into the fiber. The presented SC source can be used for a variety of applications, e.g., broad-band pumping for Ho-lasers, Al/Hg atomic clocks, and medical imaging.

9344-99, Session PTue

Generation of stable high order harmonic noise-like pulses in a passively mode-locked double clad fiber ring laser

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In this work we study a passively mode-locked double-clad Erbium-Ytterbium fiber ring laser producing noise-like pulse through nonlinear polarization evolution and polarization selection. The fiber laser is composed by 4 m of double-clad Er3+/Yb3+ fiber pumped at 980 nm, a fiber bench containing a free-space single-polarization isolator which also acts as polarizer, and a 1-km spool of SMF-28 fiber. The configuration also includes two fiber polarization controllers and three output couplers for monitoring and signal measurement. We observed the single noise-like pulsing only at moderate pump power, pulse energies as high as 120 nJ are reached in this regime. As pump power is increased, and through polarization controllers adjustments, harmonic mode locking of growing order were successively appearing. For higher pump power, the experimental results show that the pulse splits into several noise-like pulses, which then rearrange into a stable and periodic pulse train. Harmonic mode locking from the 2nd to the 48th orders is readily obtained. At pump powers close to the damage threshold of the setup, much denser noise-like pulse trains are demonstrated, reaching harmonic orders beyond 1200 and repetition frequencies in excess of a quarter of a GHz. Besides providing insight into the noise-like pulse dynamics in long fiber lasers, these results could be useful in the quest for higher pulse energies and higher repetition rates that is currently going on in passively mode-locked fiber lasers. Finally, the mechanisms leading to noise-like pulse breaking and stable high-order harmonic mode locking are discussed.

9344-100, Session PTue

Experimental study of backscattering pulses and broadband generation in a Q-switched MOPA

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Experimental study of backscattered pulses and broadband generation in a Q-switched pulse seeded MOPA is presented. The backscattering pulses initially show 'delay' and 'broadening' relative to the forward pulse followed by pulse breaking phenomena and generated broadband light with increase of pump power. Q-switched seed pulse of 108ns width at 1064nm is fed through an isolator to power amplifier circuit which consists 8m long double clad Yb-doped fiber (CorActive: DCF-YB-15/128). A 90/10 coupler is used before the amplifier. The 10% port acts as a backward tap to characterize the backscattered pulse and spectrum by Tektronix DPO7254C oscilloscope and Yokogaowa AQ6319 OSA. After a certain threshold pump power (above 5W) to amplifier, the backscattered pulse showed delay and broadening relative to the forward pulse while the forward pulse retained the same temporal characteristics as the seed pulse. We observed that backscattered pulse was delayed by 30ns and seed pulse of width 108ns was broadened to 140ns at 20KHz repetition rate at pump power of 8.6W. The delay and broadening generated due to SBS effect in the amplifier active fiber. When the delay and broadening started, the backscattered power showed fluctuations and the forward output power slope was decreased slightly. With further increase in pump power (above 8.6W) both the forward and backward output showed instability with random fluctuations and unwanted pulse breaking was observed in the oscilloscope. In the frequency domain we observed the broad-band generation from 1050nm to 1650nm. In this regime, high peak power short pulses caused catastrophic damage sometimes.

9344-101, Session PTue

Reduction of self-phase-modulation induced phase jitter in multiplexing repetition rate of actively mode-locked laser for photonic analog-to-digital converters

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Analog-to-digital converters (ADCs) transforms analog signals into digital ones that can be processed easily with digital signal processor (DSP). Electronic ADC (EADC) suffers difficulty in satisfying the increasing requirements of sampling rate and precision due to electronic bottleneck. Photonic ADC (PADC) employing mode-locked fiber laser (MLL) as sampling clock can provide favorable effective number of bits (ENOB) at ultrahigh sampling rate and is expected to have important applications in many areas such as communications, radar, medical imaging, etc. Both passively MLL and actively MLL (AMLL) can be used as the sampling clock of PADC. By contrast, the repetition rate of AMLL output pulses is around GHz and is relatively easy to be multiplied to tens even hundreds of GHz. Its own time jitter has also been improved to the order of femtoseconds due to progress in microwave generator.

In this work, we propose a novel method to multiply the pulse repetition rate of AMLL by spectrum-slicing and time-division-multiplexing. We employed self-phase modulation (SPM) to broaden the spectrum of AMLL so as to obtain enough number of channels. The SPM induces additional phase jitter to the broadened optical spectrum, which degrades PADC's performance. It was theoretically and experimentally found that we can effectively reduce the SPM-induced phase jitter by precise control of the relative true-time delays among parallel channels. Sampling clock up to 80 GHz with low phase jitter can be achieved based on 10-GHz AMLL. PADC based on this clock with more than 6 ENOB at 80 GS/s is highly expectable.

9344-102, Session PTue

CW seed with no mode structure for high power Yb-doped fiber amplifier

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Stimulated Brillouin Scattering (SBS) is one of the main mechanisms limiting high power operation of fiber amplifiers. In order to overcome SBS limitation, the linewidth of the amplified signal should be considerably broader than the Brillouin linewidth which is on the order of 50-100 MHz. A conventional way to broaden out a spectral width of a signal to the level exceeding 10 GHz, while avoiding multiple modes interference, is the use of single frequency seed lasers with high speed phase or amplitude modulators. We propose to utilize an amplified spontaneous emission (ASE) from single-mode double clad active fibers with desirable spectral width

provided by narrow band Volume Bragg gratings (VBGs). This approach enables generation of seed radiation with dramatic broadening of spectral width with no mode structure. The proposed approach was demonstrated by pumping the Nd-doped fiber below lasing threshold with further filtering narrow lines from the broadband ASE by means of VBGs with diffraction efficiency exceeding 95% and spectral widths of 50 and 200 pm (13.5 and 54 GHz) in the wavelength range of 1057-1063 nm. The corresponding output power was measured to be ~1 mW and ~4 mW for 50-pm and 200-pm lines respectively. In order to maximize signal to noise ratio (SNR) of the selected lines, we used double reflection from VBG. It allowed increasing SNR from 20 dB after the first reflection up to 45 dB after the second one.

9344-104, Session PTue

Linear cavity all fiber dual wavelength actively Q-switched fiber laser with a Sagnac interferometer

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We report an all-fiber dual-wavelength actively Q-switched pulsed laser. The linear cavity is limited by two fiber Bragg gratings with central wavelengths of 1538.3 nm and 1548nm respectively in one side and Sagnac interferometer (SI) in the other side. A 3m length Er3+/Yb3+ double-clad fiber used as gain medium is pumped by a 978nm high power laser diode. The Er3+/Yb3+ fiber has a core diameter of 10 ?m and numerical aperture of 0.18. The pump power is coupled into the doped fiber through a beam combiner. The SI used as a tunable periodical spectrum wide band mirror to equalize generated laser lines competition by cavity losses adjustment is formed by high birefringence (Hi-Bi) fiber in the loop. The SI spectrum wavelength displacement adjustment is performed by temperature variations applied on the Hi-Bi fiber loop with a temperature controller. Pump power application is limited to a maximum power of 2W to avoid acousto-optical modulator damage with a maximal signal permitted average power of 1W. The Q-switch operation is achieved at pulse repetition rate of 75kHz with average pulsed output power of 60mW and pulse duration of 280 ns.

9344-105, Session PTue

Theoretical treatment of modal instability in high-power cladding-pumped Raman amplifiers

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Cladding-pumped Raman oscillators and amplifiers have been proposed as gain media to achieve power scaling in fiber-based laser systems. It is well-known that the modal instability is a limiting factor in achieving high power. We present an analytical approach to the investigation of the modal instability phenomenon in high-power, cladding-pumped Raman fiber amplifiers. The coupled-mode theory approach is used to formulate the governing amplitude equations. Quantum defect heating induces the coupling between the transverse modes and may lead to significant transfer of optical power among the various modes under the right conditions. The heat equation is solved in the frequency domain using the appropriate boundary conditions. By utilizing the conservation of the number of photons and the conservation of energy in the absence of loss, the nonlinear equations for the propagation of the pump power and the total signal power can be decoupled from one another. This decoupling leads to exact solutions for the pump power and the two transverse mode signal powers. Assuming consistent pump absorption, the analytical solutions show that the coupling to the higher-order mode is unchanged as the seed power increases. As the higher-order mode is given a larger fraction of the seed power, the energy coupling between the modes increases.

9344-37, Session 9

Photodarkening resistive optical fibers for high power application *(Invited Paper)*

Ji Wang, Corning Incorporated (United States)

No Abstract Available

9344-38, Session 9

Erbium nanoparticle doped fibers for efficient, resonantly-pumped Er-doped fiber lasers

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Erbium-doped fiber lasers (EDFLs) are attractive for directed energy weapons applications because they operate in a wavelength region that is both eye-safer and a window of high atmospheric transmission. For cladding pumped high energy laser applications it is necessary to have a relatively high Er core absorption because of the areal dilution of the pump intensity in the large pump cladding. However, it is well-known that Er ions tend to cluster in silica glass. The common solution-doping technique for making EDFs provides no mechanism for controlling the atomic environment of the Er, and in spite of the presence of Al to increase Er solubility and reduce clustering, clustering still occurs. Concentration quenching and cross-relaxation upconversion, which shorten the fluorescence lifetime, typically increase with increasing Er concentration.

Nanoparticle (NP) doping is a new technique for making EDFs where the Er ions are surrounded by a cage of aluminum and oxygen ions, thereby substantially reducing ion-ion energy exchange and its deleterious effects on laser performance. Er-doped a-Al2O3 NPs have been synthesized and doped in-situ into the silica soot core of the preform core.

We report the first known measurements of NP-doped EDFs in a resonantly-core pumped MOPA configuration; the optical-to-optical slope efficiency was 79%, which we believe is a record for this type of fiber and which compares well with the record efficiency of 84.3% measured on a commercial solution-doped fiber.

9344-39, Session 9

Fabrication of transparent polycrystalline ceramic fibers for optical applications

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Since the initial demonstration of lasing in polycrystalline YAG (Yttrium-Aluminum Garnet), considerable effort has been invested to improve this gain media for high-energy lasers. This is motivated by the low production costs, processing flexibility, and higher dopant concentrations of polycrystalline YAG compared to single-crystals. Fiber gain media are attractive because they are compact, vibration-resistant, require less cooling, and reduce or eliminate free-space optics. However, the performance of state-of-the-art silica glass fiber is limited by low thermal conductivity, high thermo-optic coefficients, and high optical losses beyond ~ 1900 nm. To use the advantages of both fibers and polycrystalline YAG, we have developed an extrusion process for Nd and Yb-doped YAG fibers with diameters from 25 to 50 µm. Process development for polycrystalline ceramic core-clad fibers will be discussed, and optical and microstructural characterization will be presented.

9344-40, Session 9

A double clad ytterbium fibre laser operating at 280°C

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We look at the effects of extended operating temperature on an all-glass cladding-pumped fibre laser. Traditional cladding pumped fibre laser designs utilise a low index fluoro-polymer cladding for pump guidance. These fluoro-polymer claddings must be maintained at temperatures below 80-100°C. Above this temperature the onset of polymer degradation leads to increased pump absorption and eventually catastrophic failure. By using an all-glass clad optical fibre design we can significantly increase the fibre operating range before thermal effects lead to fibre damage. In the case of passive fibres, all glass fibre structures have been demonstrated to remain functional at temperatures in excess of 800°C (albeit with increased background losses).

By removing the limitation of conventional polymers it is possible to operate fibre lasers over a much wider temperature range. This allows for both weight savings and reduced energy usage as large heat sinks and active cooling are no longer required. By actively heating the laser gain material we can also exploit the three level nature of the rare earth dopant to shift the fibre gain band towards longer wavelengths. In ytterbium this can enable high power operation at 1178 nm. The ability to operate the active fibre over a very large temperature range is also beneficial for the suppression of non-linear effects such as stimulated Brillouin scattering (SBS). In this submission we present the results of operating a ytterbium fibre laser at temperatures in excess of 280°C whilst showing only small reductions in output power. The ASE emission spectrum of this source is also presented at tempertures of up to 400°C.

9344-41, Session 9

Long-term optical reliability and lifetime predictability of double clad fibers

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With the use of fiber lasers pervading diverse applications and environmental conditions, the long-term reliability of low index (LI) polymer coated double-clad (DC) fibers used for this purpose is significant. While optical reliability of DC fibers under accelerated temperature and humidity aging are a helpful reference in providing a figure of merit, it becomes important to decouple the effects of temperature and moisture in order to understand the underlying degradation mechanisms of LI coatings. This paper evaluates and shows the superior optical reliability of LI coated 125um DC fibers with a specially engineering coating in both accelerated "damp-heat" (60°C 85% relative humidity) and "dry-heat" (85°C 1% relative humidity). Multiple lots of the specially engineered coatings are tested and compared to various lots of commercially available coatings indicating consistency of superior reliability performance. The specially engineered coating is capable of achieving <10 dB/km optical attenuation at 1095nm after 2000hrs of exposure to damp-heat and <7 dB/km attenuation at 1095nm after 2000hrs of exposure to 85°C dry-heat. Further for the first time, percentage change in transmittance in DC fibers after prolonged damp heat exposure measured with a 0.42NA launch is reported. The data shows that DC fibers with the specially engineered coating are capable of <5% change in transmission after 1000hrs of damp heat exposure. In addition to the above dry and damp heat conditions tested, ongoing work is being conducted to measure Arrhenius data for a range of temperature and moisture exposure levels enabling the generation of a lifetime predictability curve for safe operation of these DC fibers in various conditions of operation and storage.

9344-202, Session Plen

Coherent Combination of Ultrafast Laser Pulses: A Route to Joule-Class High Repetition Rate Femtosecond Lasers

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The quality of any laser application crucially depends on the quality of the driving light source, i.e. the laser itself. Hence, it is not surprising that novel laser output parameters reveal new aspects of applications, or even open up novel opportunities. There are emerging applications, e.g. laser particle acceleration, asking for a laser architecture that efficiently allows for the combination of Petawatt (PW) peak powers with Megawatt (MW) average powers.

The fundamentals and the potential of coherent combination of a larger number of ultrafast fiber amplifiers, i.e. a fiber–based amplifying interferometer, will be reviewed.

9344-42, Session 10

Divided-pulse techniques in short-pulse generation *(Invited Paper)*

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Coherent division and recombination of short pulses has recently been introduced as a way to control nonlinear phase accumulation, which typically limits short-pulse generation. Divided-pulse techniques complement, and can be combined with, techniques based on dispersion management. Applications of divided-pulse techniques to lasers, amplifiers, and pulse compression will be reviewed, and limitations will be discussed.

9344-43, Session 10

Sub-8fs, 353µj pulses with 53W average power by nonlinear compression of a fiber chirped pulse amplifier

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We present two-stage nonlinear compression of a high average power fiber chirped pulse amplifier that incorporates coherent combination. The laser system is operated at 150 kHz and emits 1 mJ, 210 fs pulses at an average power of 150 W. These pulses are first coupled to a 1 m long hollow core fiber with an inner diameter of 250 µm, which is filled with 2 bar of argon. The nonlinear interaction with the gas leads to spectral broadening via self-phase modulation. A chirped mirror compressor reduces the pulse duration to 30 fs. The overall transmission of this first stage is 55% resulting in 550 µJ pulse energy (83 W of average power). A second compression stages again uses a 250 µm inner diameter capillary with a length of 0.5 m, which is filled with 6 bar of neon gas. The spectrum after the second stage extends from 800 nm to 1200 nm. Temporal compression in a second chirped mirror compressor results in 7.8 fs pulses that have a pulse energy of 353 µJ resulting in a peak power of 25 GW. Consequently, the average power of the few-cycle pulses is as high as 53 W, which is the highest reported so far. The concept is power scalable and currently only limited by heating of the metallic mirrors. Improved optical components, advances in coherent combination and the application of spatial and temporal multiplexing techniques will make multi-100W, multi-mJ few-cycle pulses available in the near future.

9344-44, Session 10

Experimental demonstration of multidimensional amplification of ultrashort pulses

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Peak-power-scaling of femtosecond fiber-laser systems while maintaining high beam quality is restricted by nonlinear effects and material damage. Besides state-of-the-art techniques that reduce the peak intensity during amplification, spatially and temporally separated amplification, known as coherent beam combination and divided-pulse amplification, are promising approaches reducing the peak intensity further. For coherent beam combination the beam is divided onto a certain number of amplifier channels, being amplified, and finally coherently recombined. Using divided-pulse amplification a certain number of delayed pulse replicas is generated by splitting the pulse in time domain prior to the amplification and recombining them afterwards. Since saturation effects accompanied by nonlinear-phase differences within the pulse train cannot be compensated using the passive approach, actively stabilized divided-pulse amplification can be employed to allow for shaping of the input pulse train.

In this contribution we demonstrate for the first time a scalable multidimensional amplification scheme of ultrashort pulses combining both spatial and temporal multiplexing with complete active stabilization. Applying a proof-of-principle setup, the efficient pulse recombination at high pulse energies and large accumulated nonlinear phase has been achieved. Particularly, up to four pulse replicas have been amplified in two single-mode fiber-amplifier channels with core diameters of 6 µm using stretched femtosecond pulses. With this, a total output pulse energy of 32 µJ has been achieved which is far beyond the damage threshold of the single fiber using a single pulse. Applying advanced fiber designs such as large-pitch fibers will scale the achievable pulse energy to the multi-mJ range.

9344-45, Session 11

5.7mJ fiber-CPA system delivering 23.5 gW of peak power

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High average powers have been a major advantage for fiber-based laser amplifiers, where powers approaching the kW-regime have been reached. But the peak-power of the emitted pulses has been limited due to the confinement of the propagating light in the relatively small fiber core. Here, we present one approach to overcome these limitations by using coherent combination of multiple fibers, which basically makes it possible to increase the total mode-field diameter while preserving the high quality of the output beam and, therefore, achieving a reduction of nonlinear effects.

The experimental setup starts with a mode-locked oscillator, whose pulses are stretched to a duration of 2 ns in a grating stretcher. Three pre-amplifiers and two acousto-optic modulators are used to generate 50 µJ pulses at a repetition rate of 31.8 kHz for the main amplification stage. The signal is split into equal parts with polarization dependent beam-splitter cubes to seed four parallel large-pitch fiber amplifiers. The output beams of those amplifiers are coherently recombined again into a single beam using thin-film polarizers, their phases are locked with an active stabilization system and the combined pulses are finally recompressed in a grating compressor.

The combined and compressed pulses have an energy of 5.7 mJ and a pulse duration of 200 fs with a resulting peak-power of 23.5 GW. At the given repetition rate, this corresponds to an average power of 182 W. The combination process of the three amplifiers could be realized with a high efficiency of 88%, despite already occurring nonlinearities.

9344-46, Session 11

Coherent pulse stacking in fiber chirped-pulse amplification systems

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We demonstrate a new technique of coherent pulse stacking (CPS) for increasing pulse energies from femtosecond chirped-pulse fiber amplifier systems based on time-domain combining of a sequence of amplified chirped input pulses into a single chirped output pulse. Coherent pulse stacking is achieved by tailoring the amplitudes and phases of a burst of pulses which are launched into a Gires-Tournois interferometer (GTI) traveling-wave cavity, so that they destructively interfere at the partially-reflecting front mirror and are stored as a single pulse inside the cavity, until the final pulse in the burst constructively interferes with the intra-cavity pulse at the front mirror and thus extracts all the stored energy from the cavity into a single output pulse. With several GTI cavities more than 100 pulses can be stacked.

In a proof-of-principle experiment, a five-pulse sequence of ~500ps

stretched pulses is coherently stacked in a GTI cavity, yielding a theoretically predicted 2.56 times peak-power enhancement factor. Properly tailored five-pulse bursts are produced from a 122-MHz repetition-rate mode-locked pulse train using an amplitude modulator and a phase modulator positioned after the pulse stretcher. These pulse bursts are amplified into microjoule-millijoule range prior to stacking using an amplification chain with a final 55-?m Chirally-Coupled-Core (CCC) fiber amplifier. Comparison between measured autocorrelation traces of compressed stacked and unstacked pulses shows no observable pulse distortions.

CPS opens a path to extracting all stored energy from a fiber CPA with negligible nonlinear distortions. This can enable much higher pulse energies from FCPA and coherently-combined FCPA array systems.

9344-47, Session 11

Chirped and divided-pulse Sagnac fiber amplifier

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Femtosecond fiber chirped pulse amplifiers have numerous advantages, but are limited in energy because of the small interaction area with the fiber core. In this contribution, we create two orthogonally-polarized stretched pulse replicas in the time domain, following the divided-pulse amplification (DPA) principle. This beam is subsequently separated into two counter-propagating beams in a Sagnac interferometer to finally generate four pulse replicas. These pulses are amplified in two state-of-the-art large mode area rod-type fiber amplifiers in series, before final coherent combination and compression.

Because the stretched-pulse duration is of the order of hundreds of picoseconds, the DPA delay is induced using a freespace interferometer with reasonable arm lengths of few tens of centimeters. The use of a common interferometer to divide and recombine temporal pulse replicas, together with the Sagnac geometry, results in an identical optical path for all four replicas. Therefore, the whole spatio-temporal combining architecture is passive, avoiding the need for active electronic stabilization systems. Because we only use two temporal replicas, the system is immune to differential saturation levels or B-integrals between successive pulses: this is compensated by controlling the amplitude of both pulses at the input of the amplifying setup.

This setup allows the generation of 1.1 mJ, 330 fs compressed pulses at 50 kHz repetition rate, corresponding to 50 W output average power, with a combining efficiency above 90% at all power levels.

9344-48, Session 11

Phase stabilization of multidimensional amplification architectures for ultrashort pulses

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Today, high-power femtosecond laser systems enable demanding industrial and scientific applications. The occurrence of nonlinear effects up to optically induced damage limit performance scaling, even after applying elaborate methods such as chirped-pulse amplification. Coherent beam combination and divided-pulse amplification are promising techniques to exceed the current limitations by temporally increasing the beam area and the pulse duration, respectively. Actively stabilized implementations achieved the highest combining efficiencies even for strong amplifier saturation and large nonlinear phase accumulation.

In this contribution a combining scheme utilizing two amplifier channels and four divided-pulse replicas is applied, which is stabilized using LOCSET. A bistable behavior is observed for this system. The additional stable state yields a temporally uncombined pulse train. Simulations prove that mutual influence of the optical error signals is the reason. Different approaches to mitigate the issue are proposed. It was found in the simulations that gating of the raw error signal with a time window for the desired output pulse suppresses the second stable state. Optical methods utilizing a peak intensity dependent effect such as Raman scattering or second harmonic generation in the error signal generation are currently under investigation based on the reduced pulse peak power of the undesired state.

The stability issue of LOCSET for the active temporal and spatial beam combining approach may be solved by either method. Moreover the analysis of the stability at higher channel counts and more delay lines is in progress.

9344-49, Session 11

Erbium:ytterbium fiber-laser system delivering watt-level femtosecond pulses using divided pulse amplification

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Investigations into a Divided-Pulses-Amplification (DPA) fiber-amplifier system at a wavelength of 1550 nm are presented. Pulses from a saturable-absorber mode-locked polarization-maintaining fiber oscillator are amplified in a polarization-maintaining normal-dispersion fiber. The pulses after this stage are positively chirped and have a duration of 700 fs at an average power of 21 mW. Birefringent Yttrium-Vanadate crystals divide these pulses 32 times. We amplify these pulses using a double-clad Erbium:Ytterbium fiber pumped by a multimode fiber combiner. The pulses double pass the amplifier and recombine in the crystals using non-reciprocal polarization rotation by a Faraday rotator. Pulses with a duration of 290 fs are generated after separation from the input beam using a polarizing beam splitter cube. These pulses have an average power of 1.6 W at a repetition rate of 80 MHz. They are nearly transform limited with a time-bandwidth product of 0.47. The generation of femtosecond pulses directly from the amplifier was enabled by a positively chirped seed pulse, normally dispersive Yttrium-Vanadate crystals, and anomalously dispersive amplifier fibers. Efficient frequency doubling to 775 nm with an average power of 610 mW and a pulse duration of 260 fs is demonstrated. In summary we show a DPA setup that enables the generation of femtosecond pulses at watt-level at 1550 nm without the need for further external dechirping and demonstrate a good pulse quality by efficient frequency doubling. Due to the use of polarization-maintaining fiber components and a Faraday rotator the setup is environmentally stable.

9344-50, Session 12

High power performance limits of fiber components *(Invited Paper)*

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High power combiners are essential for practical fiber lasers, recent developments in pump technology has increased the available brightness and power of pumps significantly, enabling multi kW lasers and pushing

combiner designs to new limits. I will present the challenges, measurements and some solutions to these issues. Traditional calculations for combiners underestimate the issues associated with the 'tails' of the pump NA distribution, losses in fully filled combiners increase rapidly as pump NA blooms, and subsequent heating effects dominate the combiner's power handling. Acrylate coated pump fibers are reaching their limits and devices and measurements on double clad pump combiners with losses <0.05dB, will be presented enabling multi kW operation, The use of triple clad fibers in the gain section will discussed as a solution for multi kW applications. Results on ultra-low background loss FBG's will be presented, along with developed measurement techniques.

9344-51, Session 12

2.1 kW single mode continuous wave monolithic fiber laser

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A robust, alignment-free, all-fiber 2.1 kW single-mode continuous wave fiber laser, operating at 1083 nm is demonstrated. The laser is pumped with commercial fiber pigtailed multimode diodes through all-fiber pump-signal power combiners in a MOPA architecture. The oscillator was formed with a high reflector and output coupler fiber Bragg gratings written in 11/200 µm (mode field/cladding diameter) single-mode fiber. The gain medium was a 19m OFS commercial 11/200 µm double clad Yb-doped fiber (DCY). Pump light was coupled to the oscillator using two 11/200 µm pump-signal power combiners (PSC). A total of 20 commercially available 58W pump diodes at 915 nm were used to generate 800W of signal, as measured before the amplifier. The Raman power after the oscillator was more than 60 dB below the signal power. The amplifier was built using 13 m of 14/200 µm DCY and two (18+1)x1 PSC combiners with more than 95% pump and signal light transmission. A total of 2 kW of power was used to bi-directionally pump the amplifier. The output was measured after 3 m 14/200 µm fiber, and 10 m 100/360 µm delivery cable. Total signal output power was 2.1 kW, corresponding to an amplifier slope efficiency of 77%. The Raman power is more than 30 dB below signal power. At maximum power, no modal instabilities, thermal effects, nor power rollover were observed. With higher power pumps, it is predicted that a power level of 2.6 kW can be achieved with the Raman level below 20 dB.

9344-52, Session 12

6.8kW peak power quasi-continuous wave tandem-pumped ytterbium amplifier at 1071nm

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The scalability of Ytterbium doped high-power fiber laser amplifiers is limited by several effects, e.?g. optical nonlinearities and mode instabilities which are fractionally caused by thermal loads. In order to reduce the quantum defect and therefore the induced heat, tandem-pumping operation of laser amplifiers is an appropriate approach. To investigate the suitability of an optical fiber for high power operation and to decrease the average load it is an advantage to operate the amplifier in quasi-continuous wave mode. We demonstrate an output peak power of 6.8?kW from a quasi-continuous wave fiber amplifier pumped by an industrial thin-disk laser at 1030?nm. A high slope efficiency of 84.0?% has been obtained within a duty cycle of 10?% at a wavelength of 1071?nm. 1?ms pump pulses were used at a repetition frequency of 100?Hz and a continuous wave seed power of 10?W. The amplifier setup was also operated in continuous wave mode and an output power of 985?W could be achieved, while the output power was limited by thermal destruction of the fiber. In this context, a slope efficiency of 83.4?% could be obtained. The used Ytterbium-doped double-clad fiber has a doped core diameter of 45µm, an air-clad diameter of 120?µm and a doping concentration of approximately 1.3?1026 ytterbium ions per cubic meter. A signal to ASE peak ratio of 48?dB could be determined. A beam quality of M2 = 6 was obtained. The quasi-cw results show the power scalability of the used fiber design for continuous wave operation.

9344-53, Session 12

High power 1018nm continuous wave ytterbium- doped fiber lasers and amplifiers

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Ytterbium-doped fiber lasers (YDFLs) that operate from 1.0 to 1.2?m are well known for their outstanding characteristics, which include excellent power conversion efficiency and the broad gain bandwidth. With the development of high-power laser diode (LD) sources and advances in double-clad fiber (DCF) design and fabrication, kilowatt level fiber lasers and amplifiers pumped by 975 nm LDs have been successfully demonstrated. 1018 nm YDFLs have attracted many attentions for the use of tandem pumping, which is regarded and preliminarily demonstrated to be an ideal scheme for power scaling beyond multi-kilowatt level. So far as we know, the most powerful YDFL is pumped by 1018 nm YDFL arrays. We have demonstrated a 1018 nm continuous wave fiber oscillator pumped by LDs operating at 976 nm. Two kinds of Ytterbium-doped dual-clad fibers, 15/130?m fiber and 30/250?m fiber, are employed separately in the experiments. We have achieved 67 W total output power of an oscillator with the 15/130?m fiber for 100 W of pump power with an efficiency of 67%. And with the 30/250?m fiber, 300 W total output power of a fiber oscillator is generated for 372 W of pump power with an efficiency of 81%; 400W total output power of a fiber amplifier is generated with an efficiency of 70%. To the best of our knowledge, this is the highest output ever reached by a dual-clad fiber at this wavelength that reported in open detail.

9344-54, Session 12

200W single mode monolithic fibre laser at a wavelength of 1018 nm

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Transversal mode instabilities, nonlinear effects and thermal stress in high power cladding-pumped Ytterbium-doped fibre amplifiers are the main limitations for further power scaling. To achieve higher amplifier output power levels we developed an Ytterbium-doped monolithic fibre laser at a wavelength of 1018 nm with an output power of 200 W in continuous wave operation. This fibre laser can directly be used for core-pumping of Ytterbium-doped amplifier systems. Previously, the active fibre length and the reflectivity of the Fibre Bragg Grating (FBG) on the out-coupling

(OC) side for the fibre laser were simulated and investigated to achieve optimum output power. The active fibre length was determined to a value of 2 m and the reflectivity of the OC-FBG was 28.9 %. The used active fibre was an Ytterbium-doped Large Mode Area fibre with a core diameter of 10 µm (NA 0.075) and a cladding diameter of 130 µm (NA 0.46). To realize a monolithic combination of the fibre laser with an amplifier system in the future, we tested an in-house developed pump light stripper to remove the unabsorbed pump power in the cladding of the fibre laser. The attenuation of the pump light was higher than 35 dB. Also an in-house developed Wavelength Division Multiplexer (WDM) was tested. Our in-house developed WDM with a wavelength set of 1018 / 1064 nm can handle a total power of 210 W. The insertion loss of both ports is lower than 0.2 dB while the isolation is higher than 16 dB.

9344-55, Session 13

Sub-700fs pulses at 152W average power from a Tm-doped fiber CPA system

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Laser sources with an emission wavelength in the 2 µm region are interesting for applications such as spectroscopy, material processing and medical surgery. Additionally they could be very beneficial for high-harmonic generation, since a longer driving laser wavelength allows for a higher energy transfer into the accelerated electrons and, consequently, for higher photon energies up into the X-ray region. Thulium-based fiber lasers are ideally suited to develop high average-power ultrafast laser systems around the 2 µm wavelength. The current performance records of Tm-based ultrafast fiber laser systems have been limited by the use of common step-index fibers with core diameters ranging between 10 µm and 25 µm which lead to the onset of detrimental nonlinear effects like pulse-to-pulse instabilities (modulation instability) and spectral broadening. In this work we utilize a Tm-doped photonic-crystal fiber (PCF) with a mode field diameter of 36 µm and high slope efficiency of up to 55%. For the first time a Tm-doped PCF amplifier allows for a pump-power limited average output power of 241 W with a slope efficiency above 50%, high beam quality and linear polarization. A record compressed average power of 152 W and a pulse peak power of more than 4 MW at sub-700 fs pulse duration are enabled by dielectric gratings with diffraction efficiencies higher than 98% leading to high compression efficiencies of more than 70%. A further increase of pulse peak power towards the GW-level is planned by employing Tm-doped LPFs with mode field diameters well above 50 µm.

9344-56, Session 13

Sub-100 fs passively mode-locked holmium-doped fiber oscillator operating at 2.06 ?m

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Here we demonstrate a simple and compact Holmium-doped fiber (HDF) femtosecond oscillator with 35 MHz repetition rate. The pump light from a commercial Tm-doped fiber laser operating at 1.95 ?m is coupled into the cavity via a wavelength-division multiplexer. A dispersion compensating fiber was utilized to set the intra-cavity net dispersion to zero at 2.06 ?m. Taking into account the spectral broadening via self-phase modulation (SPM), this corresponds to a slightly normal effective net dispersion for the oscillating pulse. Mode-locking was initiated and stabilized by nonlinear polarization evolution (NPE) and the rejection port of the polarizing beam splitter was used as the output port. Above a pump power of 650 mW, self-starting mode-locked operation was obtained. Limited by double pulsing due to an overdriven NPE, the maximum output power was 40 mW (> 1 nJ pulse energy). Without additional pulse compression we obtained 160 fs pulses at a Fourier-limit of 145 fs. To further shorten the pulse duration, we implemented a nonlinear compressor consisting of a solid core highly nonlinear fiber (HNLF) for SPM broadening and single mode fiber (SMF) for pulse compression. The spectrum was broadened to 105 nm and the pulses could be recompressed to sub-100 fs at a Fourier-limit of 95 fs. This constitutes a 20-fold improvement in spectral bandwidth and 8-fold improvement in pulse duration compared to previously reported Ho-doped fiber as well as Ho-doped solid-state oscillators.

9344-57, Session 13

High-power linearly polarized thulium-doped all fiber picosecond master oscillator power amplifier

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We have demonstrated a high-power all-polarization-maintaining thulium-doped all-fiber picosecond-pulsed master-oscillator power-amplifier. The thulium-doped all-fiber oscillator was mode-locked by a SESAM to generate average output power of 100 mW at a repetition-rate of 611.5 MHz in a short linear cavity. The first PM thulium-doped fiber preamplifier produced 4.5 W average output power for 17 W incident pump power, and the pulse width was measured to be 18 ps. In the second PM thulium-doped fiber preamplifier and the final PM thulium-doped fiber power amplifier, a segment of 4.5 m LMA PM thulium-doped double-clad fiber were used as the gain medium. Both the thulium-doped active fiber has a core diameter of 25 µm, a core NA of 0.09, inner cladding diameter of 400 µm and a NA of 0.46. The second PM fiber preamplifier produced 73 W average output power for 135 W incident pump power. In the final PM fiber power amplifier, the maximum average output power was up to 203 W at the maximum available pump power of 300 W, the slope efficiency for the final PM fiber power amplifier was 50.7%. The PER at the highest average output power was measured to be >15 dB. The pulse width was 15 ps and the central wavelength was 1985 nm, which corresponds to peak power 22 kW. To the best of our knowledge, this is the highest average output power ever reported for an all-fiber ultrashort-pulsed laser at 2 ?m wavelength region.

9344-58, Session 13

Peak power scaling of thulium-doped ultrafast fiber laser systems

Martin Gebhardt, Christian Gaida, Fabian Stutzki, Cesar

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In this work we investigate challenges for scaling the output peak powers of thulium-doped fiber chirped-pulse amplification systems (FCPA) towards the GW-level. An oscillator delivering 220 fs pulses with 1.1 nJ pulse energy at 24 MHz repetition rate was developed as a seed source which is suitable for subsequent amplification. The center wavelength of the oscillator at 1915 nm was chosen with respect to the available gain from short fibers with large mode field areas, which are required to prevent nonlinear effects during amplification. Following this approach, we have demonstrated output pulse energies of 60 µJ. However, the compressed peak power was limited to 30 MW due to a significant degradation of the pulse quality which can be associated with the relatively long free-space propagation that is required in a FCPA system. The output of the oscillator was used to show that the degradation in pulse quality and peak power is due to water absorptions which are strongly pronounced in the covered spectral region and transfer into a nonlinear phase across the spectrum upon propagation. It was found in experiment and simulation that the peak power decreased by approximately 60% after 11.5 m free space propagation at 50% relative humidity and was almost restored when decreasing the relative humidity to 10%. Thus, it can be expected that reducing the relative humidity in the free space sections of the FCPA below 10% and utilizing Tm-doped large-pitch fibers will ultimately lead to a further increase of pulse peak power towards the GW-level.

9344-59, Session 14

160W average power single-polarization, nanosecond pulses generation from diode-seeded thulium-doped all fiber MOPA system

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We demonstrate high pulse energy, 160 W output power Tm-doped nanosecond laser based on all-fiber master-oscillator power-amplifier (MOPA) configuration. The seed source employed is a directly modulated discrete-mode (DM) diode at 2 ?m with pulse width 15.8 ns. The pulse width changes shorter to 6 ns as the gain reshaping during amplification. The system is capable of operating at repetition rate in the range of 400 KHz to 4 MHz without change of configuration. Polarization maintaining (PM) large mode area (LMA) fiber with core diameter 25 ?m and cladding diameter 400 ?m was employed as gain medium. The MOPA yielded 160 W maximum average power of single polarization output at 4 MHz repetition rate with 6 ns pulse width. The single pulse energy and peak-power were 40 ?J and 6.7 KW respectively. The slope efficiency for the PM fiber power amplifier was 48.8% with respect to launched pump power. The polarization extinction ratio (PER) of system measured at 160 W output power was beyond 15 dB. This kind of fiber laser can be widely used for nonlinear wavelength conversion, such as optical parametric oscillator (OPO), optical parametric amplification (OPA) applications.

9344-60, Session 14

Polarized picosecond pulses amplification in a Tm-doped large mode-area photonic crystal fiber amplifier

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High power picosecond sources within the emission band of Thulium-doped fibers (1.7 – 2.1 µm) are useful for spectroscopic, medical as well as military applications and are very well suited for precise processing of polymers and semiconductors. Furthermore, a 2 µm source providing multi-kWs peak powers can be used for nonlinear frequency conversion into the mid-IR.

Seed source was a commercially available laser diode operated in gain-switched. Resulting pulses were 100 ps long and average output power levels were between 3 µW and 24 µW for repetition rates between 2.5 MHz and 40 MHz respectively. Due to very low output power emitted from GSLD two pre-amplifier stages are needed prior to Tm-doped large mode-area photonic crystal amplifier (LMA-PCF). Pre-amplification is realized with standard step-index Tm-doped fibers. To obtain higher energetic pulses we have picked, with an acousto-optic modulator (AOM), the fundamental pulse-train down to 50 kHz, 100 kHz and 250 and then launched it to a counter-pumped Tm-doped polarizing LMA-PCF amplifier. Fiber used was approx. 1.7 meter long and both fiber ends were collapsed, angle-cleaved and was counter-pumped with 793 nm fiber-coupled laser diode. For all repetition rates we were able to reach 100 kW peak power levels what corresponds to 10 µJ pulse energy with good optical signal-to-noise ratio (50 kHz – 14 dB OSNR, 100 kHz – 16 dB OSNR, 250 kHz 19 dB OSNR) with minimal nonlinear spectral degradation.

9344-61, Session 14

Self-efficiency improvement and cooling in thulium-doped fibers

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Thulium fibers operate around ~2µm, which confers them many interesting advantages. For example, for the same numerical aperture the core area of the fiber can be four times larger than that used at 1µm while preserving the same modal characteristics. Furthermore, the strength of most non-linear effects is inversely proportional to the operating wavelength and, in particular, the critical power of self-focusing scales with the square of the wavelength. Thus, Thulium doped pulsed fiber laser systems can potentially outperform their Yb-doped counterparts. Unfortunately thermal problems plague Thulium-doped fibers to the extent that they limit the power scalability of high-pulse energy high-average power fiber systems. These thermal problems come from the large quantum defect present in Thulium-doped systems pumped at 793nm and emitting around ~2µm, and by the inability to efficiently exploit cross-relaxation mechanisms in most silica based fibers. Moreover, the large quantum defect also results in a relatively low efficiency of the amplification process.

A way to increase the efficiency of Thulium-doped fiber systems and simultaneously prevent the generation of heat by pumping the excited state around 1470nm has been recently proposed by the authors. This technique seems very promising, but it has the drawback that high-power high-brightness laser sources around 1470nm are not easy to obtain. In this contribution we further refine this technique and demonstrate that a Thulium-doped fiber amplifier can lase around 1470nm which brings all the benefits of higher efficiency and lower operating temperatures while making an external pump around 1470nm redundant.

9344-62, Session 14

Resonantly pumped amplification in a Tm-doped large mode-area photonic crystal fiber

Alex M. Sincore, Lawrence Shah, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Mateusz Wysmolek, Laser Zentrum Hannover e.V. (Germany); Robert Ryan, Ali Abdulfattah, Martin C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

The high average power performance of ytterbium doped fiber lasers has largely been enabled by their high optical-to-optical efficiency. By comparison, while thulium-doped fiber lasers have demonstrated >1 kW output power, efficiency has been limited to <60% whether pumped at ~1550 nm or ~795 nm. Efficiency has been a particular limitation in thulium-doped photonic crystal fiber due to difficulties in achieving effective cross-relaxation.

One recently demonstrated alternative pumping method is resonant pumping, which significantly reduces quantum defect by using Tm:fiber as both the pump at ~1.9 μm and the gain medium for amplification at wavelengths >1.95 μm. In this work, we demonstrate resonant pumping for amplification in Tm:PCF for the first time. Tm:PCF amplification has enabled >100 kW peak power for nanosecond and picosecond pulse amplification, and in this work we compare resonant pumping to pumping at 795 nm to scale average power in nanosecond amplification to simultaneously achieve high peak power and high average power for use as a pump for nonlinear mid-IR generation and materials processing applications.

9344-63, Session 15

Coherent combining of fiber-laser-pumped frequency converters using all fiber electro-optic modulator for active phase control

Pierre Bourdon, Anne Durécu, Guillaume Canat, Julien Le Gouët, Didier Goular, Laurent Lombard, ONERA (France)

Coherent beam combining (CBC) by active phase control could be useful for power scaling fiber-laser-pumped optical frequency converters like OPOs. However, a phase modulator operating at the frequency-converted wavelength is needed, which is non standard component.

Fortunately, nonlinear conversion processes rely on a phase-matching condition correlating, not only the wavevectors of the coupled waves, but also their phases. This paper demonstrates that, using this phase correlation for indirect control of the phase, coherent combining of optical frequency converters is feasible using standard all-fibered electro-optic modulators.

For the sake of demonstration, this new technique is experimentally applied twice for continuous wave second-harmonic-generator (SHG) combination: i) combining 2 SHG of 1.55-μm erbium-doped fiber amplifiers in PPLN crystals generating 775-nm beams; ii) combining 2 SHG of 1.064-μm ytterbium-doped fiber amplifiers in LBO crystals generating 532-nm beams.

Excellent CBC efficiency is achieved on the harmonic waves in both these experiments, with lambda/20 and lambda/30 residual phase error respectively.

In the second experiment, I/Q phase detection is added on fundamental and harmonic waves to measure their phase variations simultaneously. These measurements confirm the theoretical expectations and formulae of correlation between the phases of the fundamental and harmonic waves.

Unexpectedly, in both experiments, when harmonic waves are phase-locked, a residual phase difference remains between the fundamental waves. Measurements of the spectrum of these residual phase differences locate them above 50 Hz, revealing that they most probably originate in fast-varying optical path differences induced by turbulence and acoustic-waves on the experimental breadboard.

9344-64, Session 15

Interferometric phase measurement techniques for coherent beam combining

Marie Antier, Jérôme Bourderionnet, Christian Larat, Eric Lallier, Thales Research & Technology (France); Jérôme Primot, ONERA (France); Arnaud Brignon, Thales Research & Technology (France)

Coherent beam combining of fiber amplifiers provides an attractive mean of reaching high power laser. In an interferometric phase measurement the beams issued for each fiber combined are imaged onto a sensor and interfere with a reference plane wave. This recording of interference patterns allows the measurement of the exact phase error of each fiber beam in a single shot. Therefore, this method is a promising candidate toward very large number of combined fibers. Based on this technique, several architectures can be proposed to combine a high number of fibers. The first one based on digital holography transfers directly the image of the camera to spatial light modulator. The generated hologram is used to compensate the phase errors induced by the amplifiers. This architecture has therefore a collective phase measurement and correction. Unlike previous digital holography technique, the probe beams measuring the phase errors between the fibers are co-propagating with the phase-locked signal beams. This architecture is compatible with the use of multi-stage isolated amplifying fibers. In that case, only 20 pixels per fiber are needed to obtain a residual phase shift error below ?/10rms. The second proposed architecture calculates the correction applied to each fiber channel by tracking the relative position of the interference fringes. In this case, a phase modulator is placed on each channel. In that configuration, only 8 pixels per fiber on the camera is required for a stable close loop operation with a residual phase error of ?/20rms, which demonstrates the scalability of this concept.

9344-65, Session 15

Beam combining and SBS suppression in white noise and pseudo-random modulated amplifiers

Brian E. Anderson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); Angel Flores, Iyad Dajani, Air Force Research Lab. (United States)

Power scaling of narrow linewidth high-power fiber amplifiers is limited due to the onset of the nonlinear phenomenon known as stimulated Brillouin scattering (SBS). White noise source (WNS) phase modulation and pseudo-random bit sequence (PRBS) phase modulation are techniques capable of broadening a single frequency source, and increasing the SBS threshold allowing for high power amplifiers to be constructed. Theoretical models exist to predict the enhancement factor, but detailed experimental studies comparing their effects and the coherent combining performance have not been completed.

We present a detailed cutback experiment to compare the performance of PRBS and WNS phase modulation in ytterbium doped fiber amplifiers. Based on previous theoretical models, the enhancement factor was studied as a function of gain fiber length ranging from 8m to 30m, modulation frequencies ranging from 250MHz to 3GHz, and pattern lengths of 27-1 and 215-1. Furthermore, comparisons are made in the coherent beam combining performance of 2 phase modulated lasers to show how the PRBS and WNS phase modulated signals result in different coherent lengths. The PRBS

signal exhibits periodic coherence due to the discrete nature of the phase modulated signal, while the WNS signal does not.

9344-66, Session 15

A higher-order mode fiber amplifier with an axicon for output mode conversion

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Fiber amplifiers designed to operate specifically in a single higher-order mode (HOM) are capable of scaling to effective areas of several thousand square microns, in a format that can be fusion spliced and coiled. A UV-written long-period grating (LPG) converts the input fundamental mode to the desired HOM. Amplification takes place in the HOM, and at the output, reconversion to a diffraction limited beam is achieved with a second LPG matched to the input The ultra-large area of the HOM fiber enables the generation of record peak powers with low nonlinearity in all-fiber fusion spliced amplifiers. However, in high peak power pulsed systems, even if the fiber is terminated immediately after the LPG and the beam subsequently enters free space, requiring reconversion to the fundamental mode before exiting the fiber can add substantially to the nonlinearity in the amplifier. Consequently, a low-nonlinearity, bulk-optic approach to beam conversion at the output of an HOM fiber amplifier would be advantageous for high peak power systems.

In this work we propose and demonstrate for the first time mode conversion at the output of an HOM fiber amplifier using an axicon. An axicon is a conical lens that produces in its focus a J0 Bessel beam. Here we effectively operate the axicon in the reverse of its typical direction, entering the axicon with a beam that is approximately a Bessel beam to achieve diffraction limited output at its exit. Using an axicon for the first time, we reconvert the output LP0,14 mode of 6000 um2 effecitve area, erbium-doped HOM amplifier. An M2 of 1.25 is achieved for 82% conversion efficiency.

9344-67, Session 15

Brightness enhancement of a multi-mode ribbon fiber laser using transmitting Bragg gratings

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Recently, there has been an interest in the design of high power fiber resonators using large core sizes and rectangular geometry to overcome various nonlinear effects, such as stimulated Brillouin scattering and thermal lensing. However, the design of such fibers is currently limited in brightness due to the multiple transverse modes which are guided within the structure. Many methods exist to improve the brightness of such fibers. We present an additional method to improve the beam quality using the narrow angular selectivity of a transmitting Bragg grating (TBG) in an external cavity laser resonator. While previous work has been done using the TBGs as a mode selecting element in solid state resonators, this work enhances that work by demonstrating the applicability of this method to the design of fiber lasers. Both modeling and experimental results are presented, demonstrating that in an external cavity resonator the brightness of a multi-mode fiber can be improved by 5.1 times to an M2 of 1.45 with an absorbed slope efficiency of 54%.

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9345-18, Session PTue

COMBINE*: An integrated opto-mechanical tool for LASER performance modeling

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Accurate modeling of thermal, mechanical and optical processes is important for achieving reliable, high-performance with high energy lasers such as the National Ignition Facility (NIF). The need for this capability is even more critical for high average power, high repetition rate applications. Modeling the effects of stresses and temperature fields on optical properties allows for optimal design of optical components and more generally of the architecture of the laser system itself. We present a modern, integrated analysis tool that efficiently produces reliable results that are used in our laser propagation tools. COMBINE is built on and supplants the existing legacy tools developed for the previous generations of lasers at LLNL but also uses commercially available mechanical finite element codes ANSYS or COMSOL (including computational fluid dynamics). The COMBINE code computes birefringence and wave front distortions due to mechanical stresses on lenses and slabs or arbitrary geometry. The stresses calculated typically originate from mounting support, vacuum load, gravity, heat absorption and/or attending cooling. Of particular importance are the depolarization and detuning effects due to thermal loading. Results are given in the form of Jones matrices, depolarization maps and wave front distributions. The suite is validated, user friendly, supported, documented and amenable to collaborative development.

* COMBINE stands for Code for Opto-Mechanical Birefringence Integrated Numerical Evaluations

9345-19, Session PTue

Centroid stabilization in alignment of FOA Corner Cube: designing of a match filter

Abdul A. S. Awwal, Karl Wilhelmsen, Randy S. Roberts, Richard R. Leach Jr., Roger R. Lowe-Webb, Tony Huu Nguyen Ngo, Lawrence Livermore National Lab. (United States)

No Abstract Available

9345-20, Session PTue

The virtual beamline (VBL) laser simulation code

Richard A. Sacks, Kathleen P. McCandless, Eyal Feigenbaum, Jean-Michel G. Di Nicola, Lawrence Livermore National Lab. (United States); Kevin J. Luke, Columbia Univ. (United States); William Riedel, Apple, Inc. (United States); Benjamin J. Kraines, Rochester Institute of Technology (United States)

Design, activation, and operation of large laser systems rely on accurate, efficient, user-friendly simulation of laser performance. The VBL code was developed to predict energetics, wavefront, near- and far-field beam profiles, and damage risk in the 192-beam, 1.8 MJ NIF laser. Its capabilities include diffractive propagation; focusing with a Talanov transformation to maintain resolution, astigmatic effects, and a through-focus option allowing examination of and interaction with the beam inside the Rayleigh region; image relaying and spatial filtering effects; saturated amplification, including lower-level lifetime; Seidel and numerically-described aberrations; frequency conversion, including alternating-z configurations, spatial walk-off, spatially-varying crystal axis orientation, harmonic-dependent bulk absorption, and beam amplitude modulation; probabilistic damage initiation; and a robust pulse-solver to determine the input P(t) required to generate a user-specified output P(t). Graphical output in the form of lineouts, 2D contour plots, 3D surface plots, and temporal traces is presented through a problem-specific generated website, enabling real-time inspection of results and interactivity. VBL's front end is a simple text input format enabling other tools to easily generate setups. A GUI capability aids in compiling, viewing, and editing these files and also streamlines the viewing of numeric and graphic output.

With increasing interest in high-average-power and high-peak-power lasers, VBL is expanding to include new physics. We now have a chirped-pulse-amplification model that includes chromatic aberration and dispersion, and are actively implementing birefringence effects based on a Jones Matrix approach, a broadband capability to include group velocity dispersion, grating models, and a frequency conversion model that includes non-uniform thermal effects.

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9345-21, Session PTue

FM-to-AM conversion in angular filtering with transmitting volume Bragg gratings

Xiao Yuan, Xiang Zhang, Dengsheng Wu, Jiansheng Feng, Kuaisheng Zou, Fan Gao, Soochow Univ. (China)

Issue of frequency-to-amplitude modulation (FM-to-AM) conversion is one of the key scientific problems in the development of high power laser systems, especially in fusion laser drivers. In large aperture and high power lasers, the sinusoidal phase modulated pulses is used to avoid stimulated Brillouin scattering and to obtain spatially-averaged focal spot on the target. Propagation through different components in the laser chains is not optimal and slightly filters the optical spectrum. Therefore, the FM is partly converted into the AM, and this AM leads to higher-order nonlinear effects or causes damages to optical elements due to instantaneous ultrahigh intensity in process.

Transmitting volume Bragg gratings (TBGs) with programmable angular selectivity from 0.1mrad to 10mrad and high efficiency of 99 % is an effective filtering element to clean up the spatial modulations in laser beams. Our previous work have shown that the angular filtering can suppress the medium and high frequency modulation and improve the spatial distribution, but it works at the continuous wave or the no modulation pulses.

FM-to-AM conversion in near-field angular filtering based on TBG is discussed. A sinusoidal phase modulation pulse with the bandwidth of 0.31nm is used to study the FM-to-AM conversion. The dependence of angular selectivity and wavelength selectivity for TBGs with different structural parameters of the gratings is studied. It is noted that the wide wavelength selectivity with constant angular selectivity of TBGs is achieved with increasing the grating thickness and period, and the FM-to-AM conversion level can be reduced to less than 5%.

9345-22, Session PTue

Stretching of ultrashort laser pulses with chirped volume Bragg gratings

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Ultrashort laser pulses with high peak power and short pulse width have been widely used in various fields of science, medicine and engineering such as spectroscopy, optoelectronics, communication techniques and material processing. Chirped pulse amplification (CPA) has been the most effective approach to compress or stretch laser pulses. The most widely used dispersion element is the surface grating of which the laser damage threshold is not ideal, and improving the laser beam power requires the increase of the grating size. Chirped volume Bragg gratings (CVBGs) may be an alternative dispersion element due to the high laser damage threshold, simple configuration and easy alignment.

In this paper, we describe the stretching or compression of ultrashort laser pulse with CVBGs. The beam propagation in CVBGs is characterized with an F-matrix method, and the stretching and compression of ultrashort laser pulse is numerically studied. It is noted that the well-designed CVBGs can compress a linear chirped pulse into a Fourier-Transform-Limited (FTL) one and stretch a FTL pulse into a pulse of arbitrary duration. A fiber laser with the wavelength of 1030 nm, pulse width of 25 ps and bandwidth of 4.5 nm as the source beam and the CVBG with the length of 37 mm, group velocity dispersion of 26 ps/nm and bandwidth of 13nm are used to demonstrate the pulse stretching. The output pulse of 953 ps is obtained with 4 passes and the stretching ratio is up to 38, which may has potential applications in high power lasers.

9345-23, Session PTue

Impact of FM-AM conversion on smoothing by spectral dispersion

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In order to set the shape of the focal spot, high power lasers for inertial confinement fusion have a phase plate at the end of the chain. This produces hot spots that can be avoided by the use of optical smoothing. Smoothing consists either in reducing the number of high-energy hot spots by splitting the focal spot energy on two orthogonal states of polarization or in moving the speckle pattern sufficiently fast so that the focal spot seems more homogeneous over time. In the latter case, the spectrum is broadened by a temporal phase modulation and dispersed with a grating. However, because of propagation impairments (filtering functions, chromatic dispersion, frequency conversion,…), part of the frequency modulation is converted into detrimental amplitude modulation. This is called FM-AM conversion. Its impact on smoothing performance is considered here. Three main parameters may be affected: power fluctuations of the focal spot, size of the speckle hot spots (autocorrelation function) and dynamic of the evolution of the spatial contrast of the focal spot versus time. We show that depending on the features of the FM-AM conversion (frequency content of AM, type of filtering function) either one or more of these parameters may be affected. As a matter of fact, a low frequency AM induces power fluctuations while higher frequency AM induces variation of the autocorrelation function. Moreover, as opposed to an amplitude-filtering function, chromatic dispersion will not change the power spectral density of the pulse and thus the dynamic of the contrast.

9345-24, Session PTue

A robust in-situ warp-correction algorithm for VISAR streak camera data at the National Ignition Facility

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The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is a 192-beam pulsed laser system for high energy density physics experiments.

Sophisticated diagnostics have been designed around key performance metrics to achieve ignition. The Velocity Interferometer System for Any Reflector (VISAR) is the primary diagnostic for measuring the timing of shocks induced into an ignition capsule.

The VISAR system utilizes three streak cameras; these streak cameras are inherently nonlinear and require warp corrections to remove these nonlinear effects. A detailed calibration procedure has been developed with National Security Technologies (NSTec) and applied to the camera correction analysis in production. However, the camera nonlinearities drift over time affecting the performance of this method. An in-situ fiberarray is used to inject a comb of pulses to generate a calibration correction in order to meet the timing accuracy requirements of VISAR. We develop a robust algorithm for the analysis of the comb calibration images to generate the warp correction that is then applied to the data images. Our algorithm utilizes the method of thin-plate splines to model the complex nonlinear distortions in the streak camera data and is modified to be sufficiently robust in order to be used in automated production software. In this paper, we focus on the theory and implementation of the warp-correction algorithm for the use in a production environment.

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9345-25, Session PTue

Diagnostics of pulse contrast for petewatt laser in SGII

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Pulse contrast is an important parameter for ultrafast pulses. It shall be 108 or higher in order to avoid effect from noise before main pulse. Diagnostics with cross-correlation can achieve high temporal resolution such as ~7fs. Cross-correlation has advantage in pulse contrast measurement than autocorrelation because it can distinguish noise before or after main pulse. High dynamic range is also essential in pulse contrast measurement. Cross-correlation signal from a single shot is converted into a signal series through fiber array, which can be analyzed by a set of a PMT and an oscilloscope. Noise from nonlinear crystal and scatter needs decrease to improve dynamic range. And pulse power is also discussed in pulse contrast experiments. Time delay ? is generated by travel stage in measurement for repetition pulses. Then energy instability will generate error in this measurement. In measurement for single shot pulse, time delay ? is generated by slant angle of beams. The scanning procession is completed with thousands parts of beam section within a single shot, and error will generated from no uniformity in near field. Performance test of pulse contrast measurement is introduced in subsequent sections. Temporal resolution is testified by self-calibration. Dynamic range is judged by a parallel flat. At last pulse contrast of petawatt laser is diagnosed by a single shot cross-correlator with high

confidence. The ratio is 10-6 at 50ps before main pulse, and 10-4 at 10ps before main pulse.

9345-1, Session 1

The LMJ: Overview of recent advancements and very first experiments

Pierre A. Vivini, Marc G. Nicolaizeau, Commissariat à l'Énergie Atomique (France)

The Laser Megajoule (LMJ) is one of the most important tools of the French Simulation Program managed by the Military Applications Division of the French Alternative Energies and Atomic Energy Commission (CEA). The LMJ is a Nd-glass laser facility, designed to focus up to 44 group of 4 beam lines (176 UV beam lines) on a micro-target located at the center of a 10 meters diameter spherical target chamber.

These past years have been devoted to assembly and integrate the main structures in the target bay and in the 4 laser bays.The year 2014 saw the progressive commissioning of the equipment in order to the first experiments. The first part of the process involved the front-end commissioning, the measurement of the amplifying gain, the test of the wave front control system, the alignment of the laser beampath from the front end to the final optics assembly, the tuning of the KDP crystals to optimize the frequency conversion efficiency. In the target bay, the main part of the work was to align the different equipment near the chamber center: the micro-target, the plasma diagnostic inserter and the plasma diagnostic itself and finally to measure the pointing performance on target. The communication between the equipment through the integrated control system and the ajustment of the integrated timing system in charge of the triggers signal for all the equipment were also a great challenge.

The presentation gives more details on these steps and illustrates the results obtained recently.

9345-2, Session 1

High peak power diode stacks for high energy lasers

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High Power Diode Laser systems are well established as optical pumps for TRUMPF "TruDisk" series of Thin Disk Lasers as well as the beam source in "TruDiode" Direct Diode systems. In most of these systems the Diode Lasers are able to operate in both CW and pulsed regime, where the peak power when pulsed is at the same level as the CW power.

We have developed a new compact laser stack which is able to operate in QCW regime with peak current intensity several times higher than those in CW regime. Peak power exceeds 12.5 kW per stack with an emission area of 10x30 mm^2. The duty cycle is on the order of 1-2%, with a pulse duration of several ms. New designs are being developed to extend the pulse duration to 10 ms. The electro-optical efficiency is on the order of 60%, even though the peak power and peak current is several times higher than in the CW operation regime of similar laser bars. At the same time, we achieve a manufacturing cost below the $1/W level, which makes these stacks a very attractive candidate for optical pumping in many industrial as well as research applications.

9345-3, Session 1

The laser infrastructure of the ELI attosecond light pulse source *(Invited Paper)*

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The research infrastructure of the Attosecond Light Pulse Source of the ELI project (ELI-ALPS) is based on four main laser sources operating in the 100 W average power regime at NIR, and a mid-IR laser (MIR) at 10W. The systems with different repetition rates and peak powers are designed for stable and reliable operation, yet to deliver pulses with unique parameters, especially with unmatched fluxes and extreme bandwidths.

The high repetition rate (HR) system implements optical parametric amplification offering 1TW peak power, sub-5fs pulses at 100kHz. The system will feed the gas high order harmonic sources with CEP controlled laser pulses at 1mJ and sub-7fs from mid 2016. The ultimate specifications will be available for the users by 2018.

The 1kHz repetition rate single cycle (SYLOS) system will drive the high-photon energy attosecond pulse sources generated via surface high harmonics and the high photon flux gas harmonics with 4.5TW, sub-10fs pulses from early 2016. Over the following 1.5 years the performance will be boosted up to 20TW peak power at sub-5fs, keeping the CEP stability better than 250 mrad.

The petawatt power class arm of the high field (HF PW) laser delivers sub-20fs optical pulses of 2PW peak power with ultra-high temporal contrast (C~1011) at 10Hz onto a target by early 2017. The other arm (HF 100) provides reduced peak power (40TW) pulses but at 100 Hz repetition rate. The HF laser drives novel attosecond source researches beyond keV, based on surface harmonics as well as Thomson scattering, and would also provide regional radiobiological researches with ions.

9345-4, Session 1

Inertial fusion power plant concept of operations and maintenance

Brad Knutson, Parsons Corp. (United States); Mike Dunne, Lawrence Livermore National Lab. (United States); Jack Kasper, Timothy Sheehan, Parsons Corp. (United States); Dwight Lang, Tom Anklam, Valerie Roberts, Lawrence Livermore National Lab. (United States); Derek Mau, Parsons Corp. (United States)

Parsons and LLNL scientists and engineers performed design and engineering work for power plant conceptual designs based on the anticipated laser fusion demonstrations at the National Ignition Facility (NIF). Work included identifying concepts of operations and maintenance (O&M) and associated requirements relevant to fusion power plant systems analysis.

A laser fusion power plant would incorporate a large process and power conversion facility with a laser system and fusion engine serving as the heat source, based in part on some of the systems and technologies advanced at NIF. Process operations would be similar in scope to those used in chemical, oil refinery, and nuclear waste processing facilities, while power conversion operations would be similar to those used in commercial thermal power plants. While some aspects of the tritium fuel cycle can be based on existing technologies, many aspects of a laser fusion power plant presents several important and unique O&M requirements that demand new solutions. For example, on-site recovery of tritium; unique remote material handling systems for use in areas with high radiation, radioactive materials, or high temperatures; a five-year fusion engine target chamber replacement cycle with other annual and multi-year cycles anticipated for major maintenance of other systems, structures, and components (SSC); and unique SSC for fusion target waste recycling streams.

This paper describes fusion power plant O&M concepts and requirements, how O&M requirements could be met in design, and how basic organizational and planning issues can be addressed for a safe, reliable, economic, and feasible fusion power plant.

9345-5, Session 1

DiPOLE: The development of combined high average and high peak power lasers at RAL *(Invited Paper)*

John L. Collier, Rutherford Appleton Lab. (United Kingdom)

Over the last few decades the cost reductions and performance increase of diode laser technology has advanced to the point that it has now become a very attractive and generic means of driving laser systems. Diode pumped technology has found widespread uptake in the industrial sector - multi kW CW powers are routine and a wide variety of low energy pulsed systems have been reported – many are commercially available. However the development of pulsed diode pumped systems capable of operating at mutli kW and higher average power levels with very high pulse energy (100'sJ – kJ's) has been very limited.

In this presentation I will report on the development of a new diode pumped high energy laser concept at the Rutherford Appleton Laboratory (RAL). Known as "DiPOLE", it has been developed to be an intrinsically scalable system, providing a high average power basis for energetic pulse production from Joules to kiloJoules.

Based on large aperture ceramic Yb:YAG configured in a novel geometry and operated at cryogenic temperatures it is a concept that is, in principle, scalable from the Joule level to the multi kiloJoule level at high average power. A prototype system, operating at close to 10 J / 10 Hz has been constructed, and two 100 J / 10 Hz version are under construction for the Czech Reublic's Hilase project and the European X-Ray Free Electron Laser in Hamburg, Germany.

The DiPOLE architecture is being developed, in part, to capitalize on the applications potential of high peak power (~PW+ level) lasers but operating high average power levels (multi kW). This offers a truly exciting opportunity for both new scientific advance and, possibly of more relevance in today's climate, of new, emergent commercial and industrial applications. Today's generally flashlamp pumped high peak power lasers can be unique, super bright, super fast sources of very energetic electrons, protons, neutrons, X-Rays, g-Rays, THz radiation etc. and thus offer a significant applications potential. In some areas it's fair to say they offer a possible capability that cannot be achieved with conventional non-laser based source technology, for example RF accelerators. Certainly, driving high peak powers lasers with diode technology offers an efficient, compact and reliable route for such an applications environment to develop.

Consequently, I will also discuss some of the downstream applications opportunities we are working on where the potential availability of combined high peak power and high average power technologies could provide transformative capability, as well as of course underpinning long term endeavours such as the future development of inertial fusion as a potential energy source.

9345-26, Session 1

Status of NIF laser

Peter J. Wisoff, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) was commissioned in 2009, then invested several years of integrating diagnostics and capabilities for yield shots. Since then we have gained operational experience as a national user facility. Recent enhancements to meet the needs of the growing user base will be described, including increasing experiment time on NIF, reducing shot cycle duration, expanding experimental capabilities, and improving the usability of the facility.

9345-6, Session 2

Laser damage resistance qualification of large optics for high power laser *(Invited Paper)*

Laurent Lamaignère, Maxime Chambonneau, Romain Diaz, Roger Courchinoux, Thierry Donval, Stéphane Reyné, Commissariat à l'Énergie Atomique (France)

The rasterscan procedure, developed to test large components, is an efficient method that allows measuring extremely low surface damage density (until 0.01 site/cm? for large optics). This procedure was improved in terms of accuracy. The equipment, test procedure and data analysis to perform this damage test of large aperture optics are described. The originality of the refined procedure is that a shot to shot correlation is performed between the damage occurrence and the corresponding fluence by recording beam parameters of hundreds of thousands of shots during the qualification. Because tests are realized with small Gaussian beams (about 1mm @ 1/e), beam overlap and beam shape are key parameters which have to be taken into account in order to determine damage density. After complete data analysis and treatment, a repeatable metrology has been reached. The measurement is destructive for the sample. However the consideration of error bars on defects distributions allows us to compare data obtained on a same batch of optical components. This will permit to reach reproducible metrology. Then this procedure provides a straightforward means of comparing the experimental results obtained from several facilities using different lasers. Recently, an additional step has been added to the procedure, a growth step that permits considering only growing damage sites. To the end the lifetime of large optics on high power laser can be predicted.

9345-8, Session 2

Optical damage performance measurements of multilayer dielectric gratings for high energy short pulse lasers

David A. Alessi, Christopher W. Carr, Raluca A. Negres, Richard P. Hackel, Kenneth A. Stanion, David A. Cross, Gabriel M. Guss, James D. Nissen, Ronald L. Luthi, James E. Fair, Jerald A. Britten, Constantin L. Haefner, Lawrence Livermore National Lab. (United States)

Predicting the damage resistivity of multilayer dielectric (MLD) pulse compression gratings in the environment and arrangement consistent with the configuration in the full laser system is key to establishing laser output performance parameters. We have developed a damage test capability for examining witness samples using picosecond duration pulses from a ?o=1053nm short pulse laser system. Tests were performed in a vacuum environment (~10-5torr) where the level of vapor-phase organic contamination (VOC) is measured and adjustable. We have used the standard R-on-1 test method to compare the laser induced damage threshold in air, "clean" vacuum, and vacuum exposed to VOCs. Damage initiation is defined as laser-induced modification in the sample surface at the microscopic level. Different damage site morphologies are observed with varying pulse duration (1-30ps) and chamber pressure. Preliminary tests confirm improved laser induced damage performance in a clean vacuum environment as compared to air.

For estimating the full size optic performance we have developed a multi-step damage testing procedure using both R-on-1 and raster scanning methods to probe the effects of the test area on the damage onset and determine whether or not damage with picosecond pulses is defect driven in nature, as is the case with nanosecond pulse durations. Additional R-on-1 tests were performed on the initiated damage sites to determine the probability of damage growth upon subsequent laser exposure. Results indicate that sparse defects present in the optical surface lead to damage initiation at laser fluences below the damage threshold indicated on the R-on-1 test and subsequent damage growth at even lower fluences.

This work was performed under the auspices of the U.S. Department of Energy (DOE) by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

9345-9, Session 2

In-situ investigation of damage processes on fused silica induced by a pulsed 355nm laser with high repetition rate

Jian Chen, Jingtao Dong, Zhouling Wu, ZC Optoelectronic Technologies, Ltd. (China)

Pulsed lasers with high repetition rate have attracted more and more attention in recent years, due to the increased demand in many fields, including industrial applications such as laser processing and micromachining. However, the damage thresholds of optics exposed to high repetitive laser pulses, especially at the 355 nm wavelength, remain a major concern.

Previous work about laser damage in optics was performed mainly by using pulsed lasers with 1-on-1 test or N-on-1test but with very low pulse repetition rate (for example, from several Hz to hundreds of Hz). The results obtained, however, cannot be directly extended to analyze and understand the damage processes induced by high repetitive laser pulses.

In this paper, we present our recent progress on investigation of damage processes on fused silica induced by a pulsed 355 nm laser with high repetition rate. By using a system based on photothermal effect, we have realized in-situ monitoring of laser-material-interaction dynamics through measuring the laser-induced absorption evolution. The results demonstrate that the initiation of laser-induced damage process occur far before any physical damage observable using high-resolution optical microscopes. The damage processes typically are long term accumulation effects of laser-induced increase in absorption, that itself is depending on both the irradiation fluence and repetition rate.

The photothermally measured results are also compared with results obtained by using light scattering technique and photoluminescence technique. The results show that such a photothermal technique is a very useful tool for in-situ studies of the damage process induced by high repetitive laser pulses at 355 nm wavelength.

9345-27, Session 2

Roughness reduction on aspheric surfaces

Sven R. Kiontke, Sebastian Kokot, asphericon GmbH (Germany)

For a lot of applications like spectrometer and high power laser roughness as an important parameter has been discussed over and over again. Especially for high power systems the surface quality is crucial for determining the damage threshold and therefore the field of application. Above that, it has often been difficult to compare roughness measurements because of different measurement methods and the usage of filters and surface fits. Measurement results differ significantly depending on filters and especially on the measured surface size. Insights will be given how values behave depending on the quality of surface and the size of measured area.

Many applications require a high quality of roughness in order to reduce scattering. Some of them in order to prevent from damage like high power laser applications. Others like spectrometers seek to increase the signal-to-noise ratio. Most of them have already been built with spherical surfaces. With higher demands on efficiency and more sophisticated versions aspherical surfaces need to be employed. Therefore, the high requirement in roughness known from spherical surfaces is also needed on aspherical surfaces. For one thing, the constant change of curvature of an aspherical surface accounts for the superior performance, for another thing, it prevents from using classical polishing technics, which guarantied this low roughness. New methods need to be qualified. In addition, also results of a new manufacturing process will be shown allowing low roughness on aspheric even with remarkable departure from the best fit sphere.

9345-10, Session 3

Dynamics of molecular clouds: Observations, simulations, and NIF experiments *(Invited Paper)*

Jave Kane, David A. Martinez, Lawrence Livermore National Lab. (United States); Marc W. Pound, Univ. of Maryland, College Park (United States); Robert F. Heeter, Lawrence Livermore National Lab. (United States); Alexis Casner, Commissariat à l'Énergie Atomique (France); Roberto C. Mancini, Univ. of Nevada, Reno (United States)

Astronomers at the University of Maryland and scientists at LLNL will test the cometary model for the formation of the famous Pillars of the Eagle Nebula using scaled laboratory astrophysics experiments at the National Ignition Facility (NIF). Because these experiments require the evolution of deeply nonlinear ablative hydrodynamics, the NIF shots will feature a new long-duration source in which multiple hohlraums are driven with UV laser light in series to create an extended x-ray pulse. The source will be used to illuminate two science packages with directional radiation mimicking a cluster of stars.

* Prepared by LLNL under Contract DE-AC52-07NA27344.

9345-11, Session 3

Near field intensity trends of main laser alignment images

Richard R. Leach Jr., Roger Lowe-Webb, Ilona Beltsar, Victoria J. Miller-Kamm, Karl Wilhelmsen, Scott C. Burkhart, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) utilizes 192 high-energy laser beams focused with enough power and precision on a hydrogen-filled spherical, cryogenic target for initiating a fusion reaction. NIF has been operational for four years and during that time, more than 1100 successful firings or shots have occurred.

Critical instrument measurements and camera images carefully recorded for each shot. The result is a massive and complex database or 'big data' archive that can be used to understand the state of the laser system at any point in its history or to locate and track trends in the laser operation over time.

In one such study, the optical light throughput for each of the 192 beams was measured over a 3 year period in order to verify that any change in transmission rate of the optics performed within design expectations. Differences between average intensity from images recorded before the input sensor package (ISP) and after the output sensor package (OSP) in the NIF beamline were examined.

We discuss the metric for quantifying the change in transmission rate and the resulting trends. Results are presented that illustrate the change in light transmission through the lens over a 3 year timeframe.

9345-12, Session 3

Laser performance operations model (LPOM): The computational system that automates the setup and performance analysis of the National Ignition Facility *(Invited Paper)*

Michael J. Shaw, Ronald House, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) is a stadium-sized facility containing a 192 beam, 1.8 MJ, 500-TW, 351-nm laser system together with a 10-m diameter target chamber with room for many target diagnostics. NIF is the world's largest laser experimental system, providing a national center to study inertial confinement fusion and the physics of matter at extreme energy densities and pressures. A computational system, the Laser Performance Operations Model (LPOM) has been developed that automates the laser setup process, and accurately predict laser energetics. LPOM uses diagnostic feedback from previous NIF shots to maintain accurate energetics models (gains and losses), as well as links to operational databases to provide 'as currently installed' optical layouts for each of the 192 NIF beamlines. LPOM deploys a fully integrated laser physics model, the Virtual Beamline (VBL), in its predictive calculations in order to meet the accuracy requirements of NIF experiments, and to provide the ability to determine the damage risk to optical elements throughout the laser chain. LPOM determines the settings of the injection laser system required to achieve the desired laser output, provides equipment protection, and determines the diagnostic setup. Additionally, LPOM provides real-time post shot data analysis and reporting for each NIF shot. The LPOM computation system is designed as a multi-host computational cluster (with 200 compute nodes, providing the capability to run full NIF simulations fully parallel) to meet the demands of both the controls systems within a shot cycle, and the NIF user community outside of a shot cycle.

9345-13, Session 3

Advanced scheme for high-yield laser driven proton-boron fusion reaction

Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Antonino Picciotto, Fondazione Bruno Kessler (Italy); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

A low contrast nanosecond laser pulse with relatively low intensity (3 ? 10^16 W/cm2) was used to enhance the yield of induced nuclear reactions in advanced solid targets. In particular the "ultraclean" proton-boron fusion reaction, producing energetic alpha-particles without neutron generation, was chosen. A spatially well-defined layer of boron dopants in a hydrogen-enriched silicon substrate was used as target. The combination of the specific target geometry and the laser pulse temporal shape allowed enhancing the yield of alpha-particles up to 10^9 per steradian, i.e 100 times higher than previous experimental achievements. Moreover the alpha particle stream presented a clearly peaked angular and energy distribution, which make this secondary source attractive for potential applications. This result can be ascribed to the interaction of the long laser pre-pulse with the target and to the optimal target geometry and composition.

9345-14, Session 4

High bandwidth measurement and control of FM-AM modulation

Sebastien Montant, Vanessa Moreau, Jacques Luce, Commissariat à l'Énergie Atomique (France)

Spectral broadening is required on high power lasers like the NIF or the LMJ to avoid Stimulated Brillouin Scattering in the laser chains and to smooth the focal spot. Spectral broadening is obtained by sinusoidal temporal phase modulation. However the spectral broadening is high and non-homogenous. But the spectral bandwidth of the laser chain is limited by the third harmonic conversion and by the limited spectral bandwidth of the Nd laser amplifier. Hence the spectral bandwidth reduction induced in the laser chain leads to temporal shape distortion through the so-called FM to AM conversion. As the frequency modulation is at high frequency, the temporal modulation induced by the FM-AM conversion can be at frequency more than 100 GHz.

So the temporal diagnostics needs to characterize the FM-AM conversion must have a bandwidth as high as possible. To obtain a precise measurement of the temporal profile of laser pulse, we perform a precise characterisation of spectral response of the temporal diagnostic setup. In the presentation we presented this characterisation of the 33GHz bandwidth temporal diagnostic setup.

Many effects may contribute to FM-AM conversion. Hopefully, for the LMJ a significant number of effects are simply due to linear spectral filters and thus they can be compensated thanks to inverse transfer functions. In this talk we will present the different spectral filter used and the performance obtained. These filters have been used on LIL high power chain, the prototype of the LMJ. The amplitude and stability performance of the FM-AM compensation is evaluated.

9345-15, Session 4

The multiple-pulse driver line on the OMEGA laser

Tanya Z. Kosc, John H. Kelly, Elizabeth M. Hill, Leon J. Waxer, Univ. of Rochester (United States)

The multiple-pulse driver line (MPD) provides on-shot co-propagation of two separate pulse shapes in all 60 OMEGA beams at the Laboratory for Laser Energetics (LLE). The two co-propagating pulse shapes would typically be (1) a series of 100-ps, "picket" pulses followed by (2) a longer square or shaped "drive" pulse. Smoothing by spectral dispersion (SSD), which increases the laser bandwidth, can be applied to either one of the two pulse shapes. Therefore, MPD allows for dynamic bandwidth reduction, where bandwidth is applied only to the picket portion of a pulse shape. The use of SSD decreases the efficiency of frequency conversion from the IR to the UV so that dynamic bandwidth reduction provides for an increase in the drive-pulse energy. MPD also provides for the future possibility of propagating different spatial profiles for each pulse shape, such as a smaller beam diameter on the drive pulse, which in conjunction with a special phase plate, can lead to a reduced focal spot size. The design of the MPD required careful consideration of beam combination as well as the minimum pulse separation for two pulses generated by two separate seed sources. A new combined-pulse–shape diagnostic needed to be designed and installed after the last grating used for SSD. This new driver-line flexibility was built into the OMEGA front end as one component of the initiative to mitigate cross-beam energy transfer on target and to demonstrate hydro-equivalent ignition on the OMEGA laser at LLE.

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9345-16, Session 4

The commissioning of the advanced radiographic capability laser system: Experimental and modeling results at the main laser output

Jean-Michel G. Di Nicola, Steven T. Yang, Charles D. Boley, John K. Crane, John E. Heebner, Phillip A. Arnold, Christopher P. J. Barty, Mark W. Bowers, Tracy S. Budge, Kim Christensen, Jay W. Dawson, Gaylen Erbert, Eyal Feigenbaum, Gabriel M. Guss, Constantin L. Haefner, Mark R. Hermann, Doug Homoelle, Jeffrey A. Jarboe, Janice K. Lawson, Kathleen P. McCandless, Brent McHale, Lawrence J. Pelz, Phil P. Pham, Matthew A. Prantil, Matthew A. Rever, Michael C. Rushford, Richard A. Sacks, Michael J. Shaw, David A. Smauley, Larry K. Smith, Thomas M. Spinka, Gregory L. Tietbohl, Paul J. Wegner, Clay C. Widmayer, Lawrence Livermore National Lab. (United States)

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is the first of a kind megajoule-class laser with 192 beams capable of delivering over 1.8 MJ and 500TW of 351nm light [1]. It has been designed and operated since 2009 to support the study of inertial confinement fusion, high energy density physics, material science, laboratory astrophysics, etc...

In order to advance our understanding, and enable radiographic experiment of denser cores and material, the generation of very hard X-rays above 50 keV is necessary. X-rays with such characteristics can be efficiently generated with high intensity laser pulses above 10^17 W/cm2. The Advanced Radiographic Capability (ARC) [2] currently commissioned on the NIF will provide eight 1 ps to 50 ps adjustable pulses with up to 1.7 kJ each to create x-ray point sources enabling dynamic, multi-frame x-ray backlighting.

In this talk, we will provide an overview of the ARC system and report on the laser performance tests conducted with a stretched-pulse up to the main laser output and their comparison with our laser propagation codes.

9345-17, Session 4

Freeform beam shaping in optical systems of high-power lasers

Alexander V. Laskin, Vadim V. Laskin, AdlOptica Optical Systems GmbH (Germany); Aleksei Ostrun, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Control of irradiance distribution in complex optical systems of modern high-power lasers is of great importance to increase efficiency of optical techniques used to reach high power levels. For example, flat-top or super-Gaussian irradiance profiles are optimum for amplification in MOPA lasers and for reduction of thermal effects in crystals of solid-state ultra-short pulse lasers when pumping by an external multimode laser. Specific requirements to beam shaping optics in these laser systems are providing variable irradiance distributions, saving of beam consistency and flatness of phase front, capability to work with TEM00 and multimode lasers, resistance to high peak power radiation. Among various refractive and diffractive beam shaping techniques only refractive field mapping beam shapers like piShaper meet these requirements. The operational principle of these devices presumes almost lossless transformation of laser beam irradiance from Gaussian to flat-top, super-Gauss or inverse-Gauss through controlled wavefront manipulation inside a beam shaper using lenses with smooth optical surfaces.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying in optical systems of high-power lasers. Examples of real implementations and experimental results will be presented as well.

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9346-1, Session 1

Beam vignetting effect in micro-optic collimation and transmission for high power diode laser arrays

Martin Forrer, Hansruedi Moser, Dzelal Kura, Hans Forrer, FISBA OPTIK AG (Switzerland)

Huge improvements in power and beam quality the field of high power diode lasers in direct diode applications make it necessary to improve the microscopic collimation, beamshaping and focusing for high power diode laser arrays. A known and established solution makes use of cylindrical micro- optics for fast axis collimation and subsequent individual twisting of each emitter beamlet by a microoptic cylindrical telescope array in order to achieve a symmetric beam parameter product. A crucial factor for the overall performance is the achievable transmission to collimation and to a focused spot for fibercoupling. We present an optical analysis of vignetting effects on this transmission in the beam twisting setup and show a optimization which can be achieved by advanced micro-optic production technologies.

The optical analysis is based on a given but scalable diode array pitch of the diode laser arrays. It makes use of high index of the optical material and aspheric coefficients of the microoptics in order to optimize for the transmission of the diode laser power through the beam twisting element. The results of the analysis show that the vignettting in the telescope array is a determining factor for the achievable transmission and that by selection of the materials and the optical design of the telescope array the transmission can be raised to values above 95%. The results in micro-optic elements show a good correlation to the the optical analysis.

9346-2, Session 1

High-brightness power delivery for fiber laser pumping: Simulation and measurement of low-NA fiber guiding

Dan Yanson, Moshe Levi, Ophir Peleg, Noam Rappaport, Moshe Shamay, Yuri Berk, Nir Dahan, Genadi Klumel, Ilya Baskin, SCD SemiConductor Devices (Israel)

Fiber laser manufacturers demand high-brightness laser diode pumps delivering optical pump energy in both a compact fiber core and narrow angular content. A pump delivery fiber of a 105 μm core and 0.22 numerical aperture (NA) is typically used, where the fiber NA is under-filled to ease the launch of laser diode emission into the fiber and make the fiber tolerant to bending. At SCD, we have developed ultra-bright NEON multi-emitter fiber-coupled pump modules that deliver 50 W output from a 105 μm, 0.15 NA fiber at 915, 950 and 976 nm wavelengths enabling low-NA power delivery to a customer's fiber laser network.

We present simulations of light propagation inside the low-NA multimode fiber for different launch conditions and fiber bend radii using a raytracing tool and demonstrate how these affect the injection of light into cladding-bounded modes. The mode filling at launch and source NA directly limit the bend radius at which the fiber can be coiled. Experimentally, we measure the fiber bend loss and fiber heating using our 50 W fiber-coupled module and establish a critical bend radius in agreement with our simulation results.

The low mode filling of the 0.15 NA fiber by our brightness-enhanced laser diodes allows it be coiled with radii down to 32 mm at full operating power despite the low NA and further eliminates the need for mode-stripping at fiber combiners and splices downstream from our pump modules.

9346-3, Session 1

High power diode laser stack development using gold-tin bonding technology

Dong Hou, Jingwei Wang, Xi'an Focuslight Technologies Co., Ltd. (China); Pu Zhang, Xi'an Institute of Optics and Precision Mechanics (China); Ye Dai, Yingjie Li, Xingsheng Liu, Xi'an Focuslight Technologies Co., Ltd. (China)

As the application of high power diode lasers is keep increasing in many fields, including scientific research, aerospace, display, industrial surface treatment and medical applications etc, the diode lasers with high electrical-optical conversion efficiency, high output power, compact size, long lifetime and high reliability are desired. The conduction cooled stack diode lasers have been widely used for pumping, illumination and medical for years, however the typical output power and lifetime are limited due to the restriction of solder interface failure, especially in on-off mode operations. Traditionally soft solder of indium is used to bond laser diode bar onto copper heatsink, however, the repeated on-off current-cycling with long pulse width in laser operations can cause mechanical stress, which leads to various failures, such as material cracking, migration and thermal fatigue.

In this work, a sophisticated high power and high performance conduction cooled diode laser stack have been developed. The CTE-matched submount and types of hard solders are used for bonding the laser diode bar to achieve higher reliability. By means of numerical simulation, the transient thermal behavior of a 5-bars laser diode stack module has been investigated to find out the optimized pitch in the diode stack. Guided by the numerical simulation and analytical results, conduction cooled diode laser stack with high power under the condition of high duty cycle and long pulse duration are designed and fabricated. Compared with the conventional diode laser stack products, the new design is a cost effective approach to obtain improved performance with higher output power density .

9346-4, Session 2

Advances in bonding technology for high power diode laser bars *(Invited Paper)*

Jingwei Wang, Xingsheng Liu, Xi'an Focuslight Technologies Co., Ltd. (China)

Due to their high electrical-optical conversion efficiency, compact size and long lifetime, high power diode lasers have found increased applications in pumping of solid state lasers and fiber lasers, as well as direct applications such as material surface treatment, illumination, medical and display etc.. As the improvement of device technology and the increase of optical output power, high power diode laser bars with output power of multiple tens or hundreds watts have been commercially available. Currently, high power diode laser bars are manufactured by indium bonding technology and gold-tin bonding technology. For diode laser bars packaged by indium bonding technology can easily cause the decrease of lifetime and reliability because of the electro-migration and thermal fatigue. With the increment of high current and output power, the reliability and lifetime of high power diode laser bars becomes a challenge, especially for the harsh working conditions which is the on and off current-cycling with long pulse duration such as millisecond even a few seconds. As a result, bonding technologies for high power diode laser bars have been become critical.

In this article, we review and describe the advances in bonding technology for high power diode laser bars, including conduction cooled diode laser bars, micro-channel water cooled diode laser bars, and horizontal array diode laser bars. Additionally, different bonding technologies and packaged structures for high power diode laser bars presented. We will also discuss the challenges and issues in bonding technology for high power diode laser bars.

9346-5, Session 2

Innovative hybride heat sink materials with high thermal conductivities and tailored CTE

Michael Kitzmantel, Technische Univ. Wien (Austria); Erich Neubauer, RHP-Technology GmbH & Co. KG (Austria)

Combining the extremely high thermal conductivity of synthetic diamond particles (typically 2000W/mK) with the one of metals like aluminum, silver or copper is challenging due to the different physical mechanism of thermal conductivity in both materials. On the one hand phonons conduct the heat, on the other hand electrons. Thermal coupling can be significantly enhanced by introducing carbide interlayers on the diamonds, but all effects are not fully understood today.

This study focuses besides manufacturing on testing of copper-diamond materials embedded in copper or other cladding materials to realize a machineable surface, which is essential to commercial applications. The challenging task is to maintain the excellent thermal properties of the core material throughout the manufacturing process, including soldering or brazing and in-application thermal cycling.

Hybride structures like heat sinks for laser diodes, realized in this study, do not need the use of CTE-matched submounts any more. The tailored thermal expansion is already realized in the heat sink itself and the laser diode bar can be directly brazed to the (plated) heat sink surface. The used cladding also takes the needed surface and edge quality into account. The paper includes an overview on advantages, draw backs and challenges using these advanced hybride materials.

9346-6, Session 2

Effect of interface layer on the performance of high power diode laser arrays

Pu Zhang, Xi'an Institute of Optics and Precision Mechanics (China); Jingwei Wang, Xi'an Focuslight Technologies Co., Ltd. (China); Xiaoning Li, Dong Hou, Focuslight Technologies Co., LTD (China); Lingling Xiong, Xi'an Institute of Optics and Precision Mechanics (China) and Chinese Academy of Sciences (China); Xingsheng Liu, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences (China) and Focuslight Technologies Co., LTD (China)

High power diode lasers have found increased applications in industry, advanced manufacturing, scientific research, aerospace and medical therapy, etc. In the packaging structure of high power diode laser array, the properties of interface layers have significant effect on the thermal behavior of high power diode laser. The junction temperature rise of diode laser affects output power, spectrum, slope efficiency, threshold current and the reliability, etc. Most degradations and failures in high power diode laser packages are directly related to interface layer. In this work, a conduction-cooled diode laser array packaged with indium solder was studied. Effect of voids in the solder layer on the temperature increase in active region was conducted. The local temperature rise of diode laser array with voids in the solder layer and the correlation between temperature rise and voids sizes was analyzed. The effect of solder interface on the performances of high power diode laser array was also studied. According to the simulation results, it is found that the local temperature rise of active layer originated from the voids in the solder layer will lead to wavelength shift of some emitters. Hence, the spectrum shape of 'right shoulder' or 'double peaks' can appear in diode laser arrays. The local junction temperature rise also leads to the decrease of output power, efficiency and lifetime of semiconductor laser array. In conclusion, we discuss the thermal behavior related to the solder interface of high power diode laser array. This study will contribute to improve the packaging techniques, e.g., die bonding and refluxing, which could efficiently improve the performances of high power diode laser array.

9346-7, Session 2

760nm: A new laser diode wavelength for hair removal modules

Martin Wölz, Martin Zorn, Agnieszka Pietrzak, JENOPTIK Diode Lab GmbH (Germany); Alex Kindsvater, Jens Meusel, JENOPTIK Laser GmbH (Germany); Ralf Hülsewede, Jürgen Sebastian, JENOPTIK Diode Lab GmbH (Germany)

Introducing a new high-power semiconductor laser diode module, emitting at 760 nm. This wavelength permits optimum treatment results for fair skin individuals, as demonstrated by the use of Alexandrite lasers in dermatology. Hair removal applications also benefit from this industry-standard diode laser design utilizing highly efficient, portable and light-weight construction.

We show the performance of a tap-water-cooled encapsulated laser diode stack with a window for direct use in dermatological hand-pieces. The stack design takes into account the pulse lengths required for selectivity in heating the hair follicle vs. the skin. Super-long pulse durations place the hair removal laser between industry-standard CW and QCW applications. We lay out the rationale for package selection with the help of 500 ms pulse data from 808 nm diodes.

The new 760 nm laser diode bars are 30% fill factor devices with 1.5 mm long resonator cavities. These units provide 40 W of optical power at 43 A with wall-plug-efficiency greater than 50%. The maximum output power before COMD is 100 W. Lifetime measurements at 40 W show less than a 6% degradation after 1600 h continuous operation. Configurations available of the hair removal stacks are 1x3, 1x8 and 2x8 bars.

9346-8, Session 3

Universal solders for direct bonding and packaging of optical devices *(Invited Paper)*

Sungho Jin, Univ. of California, San Diego (United States); Anthony W. Yu, NASA Goddard Space Flight Ctr. (United States)

For optical packaging, there is a need to directly bond non-solderable materials such as functional optical crystals, optical fibers, laser materials made of oxides, nitrides, borides and fluorides to various types of substrates including ceramics, substrates/heat sinks made of metallic materials, Al, AlN or diamond, or another functional optical materials/devices. These materials are all very difficult to wet/bond with low melting point solders, for example, at ~150oC or below. In this presentation, we will describe new Pb-free universal solders doped with a small amount of rare-earth elements, especially inexpensive mischmetals, which allow direct and powerful bonding onto the surfaces of various optical and electronic devices. Optical components require accurate dimensional stability, especially for alignment purposes. Therefore, in addition to reliability in terms of mechanical/physical durability, creep-resistant behavior is highly desirable. The microstructure and mechanical behavior of the new universal solder bonds will be described, and their potential applications for passive and active optical components assembly will be discussed.

9346-9, Session 3

PQ:PMMA-based volume Bragg grating for external cavity diode laser

Te-Yuan Chung, Yu-Hua Hsieh, Long-Chi Du, National Central Univ. (Taiwan)

PQ:PMMA (phenanthrenquinone-doped poly methyl methacrylate) is a photopolymer which has been suggested as a material for optical storage and holography. Therefore, a two-beam interference scheme was utilized to write a transmitting phase volume Bragg grating (VBG) in a PQ:PMMA sample with thickness of 2 mm. The Bragg wavelength of this PQ:PMMA VBG is 3010 nm. By rotating the sample by about 28 deg, the diffraction wavelength is centered at 976 nm. The diffraction efficiency spectrum was measured with FWHM about 1 nm and the peak diffraction efficiency is about 0.4. Diode laser and tapered amplifier with center emission wavelengths at 808 nm and 976 nm was utilized as the gain medium. V-shaped cavities were constructed with the PQ:PMMA VBG placed at the corner the V-shaped cavity. The light incident angle to PQ:PMMA VBG was tuned to match the gain media wavelength to ensure high diffraction efficiency. The light diffracted by the PQ:PMMA VBG was reflected back along the same path by a highly reflective dielectric coated mirror which serves as the end mirror of the V-shaped cavity. The laser output reaches hundreds of mW without damaging the PQ:PMMA. The laser output spectral widths were less then 60 pm and the laser output wavelength can be tuned over 10 nm.

9346-10, Session 3

Multiwavelength diode laser source based on multiplexed volume Bragg grating notch filters

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Thick reflecting volume Bragg gratings recorded in photo-thermo-refractive (PTR) glass have been used in laser development due to their excellent spectral filtering capabilities. Recent work in multiplexing volume Bragg gratings has demonstrated the benefits for applications such as high power beam combining. In this paper we present new work in increasing the number of multiplexed gratings within the volume of PTR glass to scale previous work and then create a multichannel laser source. Notch filters can be useful for applications such as spectroscopy or astronomy where there are unwanted atmospheric noise. At the same time, it is very useful to have a multiwavelength source which will be able to simultaneously probe or excite and interrogate many user defined wavelengths. In order to create this source, an 18 channel multiplexed notch filter was recorded to produce spectral filtering of 18 spectral lines in the vicinity of 1064 nm, each separated by 0.5 nm. The rejection ratio was greater than 10 dB with respect to the out of band transmitted light and each channel bandwidth was around 50 pm. Then, this filter was coupled with a broad band laser diode in order to create 18 distinctive laser channels operating simultaneously. We will also present different setups and channel configurations. Such laser source could be used for absorption, fluorescence, or a combination of excitation/probing spectroscopies.

9346-11, Session 3

Effects of packaging on the performances of high brightness 9xx nm CW mini-bar diode lasers

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High brightness and high reliable 9xx nm CW mini-bar diode lasers and stacks are desired for pumping fiber lasers and direct fiber coupling applications. For traditional 10mm bar with 1mm-2mm cavity, it can provide CW output power up to 80W-100W and high reliability, whereas the brightness is relatively low. In comparison, mini-bar based diode lasers with 4mm cavity offer a unique combination of power, brightness, and reliability. Mini-bar diode laser is the development trend of the high bright diode lasers. However, geometrical limitation of mini-bar diode laser renders its sensitivity towards thermal stress formed in packaging process. The thermal stress significantly influences device polarization, wavelength, and even results in bar cracking. In this work, the thermal stress correlating with package structure and packaging process were compared and analyzed. An optimized package structure of CW 60W 9xx nm mini-bar diode lasers and thermal stress relieving process was designed and developed. The output power 60 W at 61.49 amps was obtained. The Full Width at Half Maximum (FWHM) spectrum width is 3.78nm, and 90% energy width is 4.93 nm. From the test results, it can be seen that average degree of polarization of mini-bar diode laser packaged using the optimized structure were 97.6%, which is about 5% higher than that of conventional structure. It was also found that the degree of polarization is correlated with the spectrum and smile effect in our experiments. A better the spectrum shape offers a higher the degree of polarization.

9346-12, Session 4

Rugged laser and component packaging challenges and strategies *(Invited Paper)*

Thomas L. Haslett, Joseph L. Dallas, Avo Photonics, Inc. (United States)

Optical technology applications continue to push further from the relatively benign environment of laboratory and clinic into uncontrolled environments, in some cases being exposed to harsh and inaccessible conditions. Along with the expansion of application space is the drive for higher powers, smaller packaging and lower costs all while maintaining a high reliability and stable operation. Engineering challenges to meeting these conflicting requirements and mitigating packaging strategies will be discussed.

9346-13, Session 4

Strategies for precision adhesive bonding of micro-optical systems

Tobias Müller, Sebastian Haag, Daniel Zontar, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

Today's piezo-based micromanipulator technology allows for highly precise manipulation of optical components. In principle, the positioning process is limited by the measurement equipment's resolution. A crucial question for the quality of optical assemblies is the misalignment after curing. The challenge of statistical deviations in the curing process requires a sophisticated knowledge on the relevant process parameters. An approach to meet these requirements is the empirical analysis such as characterization of shrinkage. Gaining sophisticated knowledge about the statistical process of adhesive bonding advances the quality of related production steps like FAC lens or Beam Twister assembly, mounting of turning mirrors for fiber coupling or building resonators evaluating power, mode characteristics and beamshape. Maximizing the precision of these single assembly steps fosters the scope of improving the overall efficiency of the entire laser system. At Fraunhofer IPT research activities on the identification of relevant parameters for improved adhesive bonding precision have been undertaken and are ongoing. The influence of the volumetric repeatability of different automatic and manual dispensing methods play an important role. Also, the evaluation of UV-light sources and the relating illumination properties have a significant influence on the bonding result. Furthermore, common UV-curing adhesives are being examined on their performance and reliability for both highest precision prototyping, as well as their application as robust bonding medium in automated optics assembly cells. This paper sums up the parameters of most influence. Overall goal of these activities is the development of a prediction model for optimized shrinkage compensation and thus improved assembly quality.

9346-14, Session 4

Airborne molecular contamination: Quality criterion for laser and optical components

Michael Otto, M+W Group GmbH (Germany)

Airborne molecular contaminations (AMCs) have been recognized as a major problem in semiconductor fabrication. Enormous technical and financial efforts are made to remove or at least reduce these contaminations in production environments to increase yield and process stability. It can be shown that AMCs from various sources in laser devices have a negative impact on quality and lifetime of lasers and optical systems. Outgassing of organic compounds, especially condensable compounds were identified as the main source for deterioration of optics. These compounds can lead to hazing on surfaces of optics, degradation of coating, reducing the signal transmission or the laser signal itself and can enhance the probability of laser failure and damage. Sources of organic outgassing can be molding materials, resins, seals, circuit boards, cable insulation, coatings, paints and others. Critical compounds are siloxanes, aromatic amines and high boiling aromatic hydrocarbons like phthalates which are used as softeners in plastic materials. Nowadays all sensitive assembly steps are performed in controlled cleanroom environments to reduce risks of contamination. We will demonstrate a high efficient air filter concept to remove AMCs for production environments with special AMC filters and methods for the qualification and monitoring of these environments. Additionally, we show modern techniques and examples for the pre-qualification of materials. For assembled components, we provide sampling concepts for a routine measurement for process, component and product qualification. A careful selection of previously tested and certified materials and components is essential to guarantee the quality of lasers and optical devices.

9346-15, Session 4

Autofly: Highly flexible assembly solution for photonic applications

Moritz Seyfried, Achim Weber, Detlef Rose, Frederik Truter, Torsten Vahrenkamp, ficonTEC Service GmbH (Germany); Friedemann Scholz, Georgios Tsianos, Hendrick Thiem, Eagleyard Photonics GmbH (Germany); Gunnar Böttger, Henning Schröder, Sebastian Marx, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany)

Assembly processes for photonic devices become more and more demanding in terms of precision, number and complexity of parts and component variety. For large quantities of the same device especially suited automation machines can be designed and hence the assembly costs per part can be reduced to a moderate level. However, technically specialized small and medium sized Photonic companies often have a highly diversified portfolio with a limited number of assembled devices ranging from less than ten up to several hundred parts per year. For these companies high cost of available automation solutions for each product type is a burden to employ such systems.

The project AutoFly is addressing this topic and combines the view of an assembly subcontractor, a laser manufacturer and an automation solution provider. As a result a highly flexible automation solution is developed which allows the use of the same assembly machine for various product types even though the form factor or the assembly process may be completely different. One key aspect is to ensure a fast and easy switching of the device assembly from one product type to another and hence to keep the machine-off time below one hour. To allow for this the programming software also needs to reflect a high flexibility and allow for a device sensitive programming which is easy to learn and can be programmed offline. Such a type of machine considerably reduces the design-to-assembly time. In this presentation the interim results of the two years project will be shown.

9346-16, Session 5

Space qualification of the optical filter assemblies for the ICESat-2/ATLAS instrument

Elisavet Troupaki, Stewart T. Wu, NASA Goddard Space Flight Ctr. (United States); Zachary H. Denny, Sigma Space Corp. (United States); Luis A. Ramos-Izquierdo, William B. Cook, NASA Goddard Space Flight Ctr. (United States)

The Advanced Topographic Laser Altimeter System (ATLAS) will be the only instrument on the Ice, Cloud, and Land Elevation Satellite -2 (ICESat-2). ICESat-2 is the 2nd-generation of the orbiting laser altimeter ICESat, which will continue polar ice topography measurements with improved precision laser-ranging techniques. In contrast to the original ICESat design, ICESat-2 will use a micro-pulse, multi-beam approach that provides dense cross-track sampling to help scientists determine a surface's slope with each pass of the satellite. The ATLAS laser will emit visible, green laser pulses at a wavelength of 532 nm and a rate of 10 kHz and will be split into 6 beams. A set of six identical, thermally tuned optical filter assemblies (OFA) will be used to remove background solar radiation from the collected signal while transmitting the laser light to the detectors. A seventh assembly will be used to monitor the laser center wavelength during the mission. In this paper, we present the design and optical performance measurements of the ATLAS OFA in air and in vacuum prior to their integration on the ATLAS instrument.

9346-17, Session 5

Virtual commissioning of automated micro-optical assembly

Christian Schlette, Daniel Losch, RWTH Aachen Univ. (Germany); Sebastian Haag, Daniel Zontar, Fraunhofer-Institut für Produktionstechnologie (Germany); Jürgen Rossmann, RWTH Aachen Univ. (Germany); Christian Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

In this contribution, we present a novel approach to enable Virtual Commissioning for process developers in micro-optical assembly. Our approach aims at supporting micro-optics experts to effectively develop assisted or fully automated assembly solutions without detailed prior experience in robot programming -- while at the same time enabling them to easily implement their own libraries of expert schemes and algorithms for handling optical components. The Virtual Commissioning is enabled by a 3D simulation and visualization system in which the functionalities and properties automated systems are modeled, simulated and controlled based on multi-agent systems. For process development, our approach supports event-, state- and time-based visual programming techniques for the agents and allows for their kinematic motion simulation in combination with looped-in simulation results for the optical components. After successful process implementation and validation in the virtual environment, the agents are then switched to command the real hardware setup for program execution. The core of the underlying 3D simulation system is an active, object-oriented database to manage generic nodes and graph structures.

For Virtual Commissioning, the nodes were extended with robot, gripper and sensors functionalities that have been developed to address manifold applications in industrial and research robotics. Here, we combined and furtherly extended our system to meet the requirements set by industrial partners – laser manufacturers as well as manufacturers of stations for micro-optical assembly. The concept is applied to the automated assembly of optical components for optically pumped semiconductor lasers (OPSL) as well as for beam-shaping systems for high-power diode lasers.

9346-18, Session 5

Review of polarization techniques for optimal performance of one and two color wavelength laser range finders and designators

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Laser range finders (LRF) and target designators (TD) for military applications usually have stringent environment requirements for optimal performance. Current technology and system architectures are in need of such LRF and TD lasers to function in more than one color (near IR and eye safe wavelengths) for multiple ground and airborne applications. Key performance requirements usually include parameters such as stable energy and pulse-widths over a broad temperature, and insensitivity to shock/ vibrations. In addition, these kind of lasers need to be packaged inside a small volume for portability. It is for these reasons that a folded crossed porro-polarization- out coupled resonators is usually the chosen geometry. This presentation will explore polarization techniques to design a laser resonator cavity that works perfectly for more than one color, sometimes without the need of actual birefringence components (i.e waveplates) to achieve the goal of a stable laser resonator. Examples of a polarization analysis package created in Mathematica will be highlighted.

9346-19, Session 5

Adjustable mounting device for high-volume production of beam-shaping systems for high-power diode lasers

Sebastian Haag, Henning Bernhardt, Fraunhofer-Institut für Produktionstechnologie (Germany); Volker R. Sinhoff, INGENERIC GmbH (Germany); Tobias Müller, Daniel Zontar, Christian Brecher, Fraunhofer-Institut für Produktionstechnologie (Germany)

In many applications for high-power diode lasers, the production of beam-shaping and homogenizing optical systems experience rising volumes and dynamical market demands. The automation of assembly processes on flexible and reconfigurable machines can contribute to a more responsive and scalable production. The paper presents a flexible mounting device designed for the challenging assembly of side-tab based optical systems. It provides design elements for precisely referencing and fixating two optical elements in a well-defined geometric relation. Side tabs are presented to the machine allowing the application of glue and a mechanism allows the attachment to the optical elements. The device can be adjusted to fit different form factors and it can be used in high-volume assembly machines. The paper shows the utilization of the device for a collimation module consisting of a fast-axis and a slow-axis collimation lens as well as for a beam-tilting module consisting of a fast-axis collimation lens and a cylinder array. Results regarding the repeatability of bonding side-tab-assemblies as well as overall performance indicators achieved such as cycle time and throughput will be discussed. The paper concludes with an outlook to further optimization potential regarding throughput such as improved feeding technology for optical components.

9346-41, Session PTue

Building beam shaping optics for micromachining

Alexander V. Laskin, AdlOptica Optical Systems GmbH (Germany); Valdemaras Juzumas, Aivaras Urniezius, Altechna R&D (Lithuania); Vadim V. Laskin, AdlOptica Optical Systems GmbH (Germany); Gintas Slekys, Altechna R&D (Lithuania); Aleksei Ostrun, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Applying beam shaping optical components is important in various modern laser micromachining technologies like drilling holes, scribing, patterning. Typically micromachining systems contain such components like F-theta lenses, beam expanding and scanning optics like 2- and 3-axis galvo mirror scanners, therefore using of beam shapers require building of special optical systems combining all optical components. As the beam shaping optics it is suggested to apply field mapping refractive beam shapers like piShaper having some important features: low output divergence, high transmittance, extended depth of field, capability to work with TEM00 and multimode lasers, as result providing a freedom in building various optical systems. De-magnifying of flattop laser beam is realized with using imaging technique; the imaging optical system to be composed from F-theta lens of scanning head and additional collimating system to be used right after a piShaper. One of technical tasks in this approach is implementation of compact design of the collimating part, another task – simple switching between final spot sizes. As a solution it is suggested to apply a specially designed Beam Shaping Unit, which is based on a piShaper and combination of mirrors, locating between a laser and a scanning head; the functions of that combined system are: conversion from Gaussian to flattop laser beam irradiance profile, compact design, alignment features, easy adaptation to a laser and a scanning head used in particular equipment, stepwise switching between resulting spot sizes.

There will be considered design features of refractive beam shapers and Beam Shaping Unit, examples of optical layouts to generate flattop laser spots, which sizes span from several tens of microns to millimetres. Examples of real implementations and results of material processing will be presented as well.

9346-42, Session PTue

Modeling laser beam propagation through components with internal multiple reflections

Site Zhang, Zongzhao Wang, Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

Fabry-Pérot-Interferometers belong to an important group of optical components also in laser technology. If the boundaries of the component are not parallel we obtain a wedge type Fabry-Pérot-Interferometer. In addition, one or both surfaces can be also curved, with the special case of the appearance of Newton's rings. In all cases, the optical functionality is based on a multiple reflection and interference effect inside the component. The lateral and frequency distribution of the transmitted and reflected field drastically depends on the layer structure of the component and the parameters of the incident light. We introduce an electromagnetic concept that allows the modeling of such components for general incident light, e.g. Gaussian beams. It is based on an iterative field tracing approach through and inside the component. We will present the details and demonstrate various examples. We will also discuss sampling issues related to the modeling. Due to the internal, multiple reflections the resulting field may require a quite high sampling effort. The physical reasons for that are discussed.

9346-43, Session PTue

Packaging of 4mm full-bar high power diode laser on micro-channel cooler using a complete AuSn bonding technology

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High power diode lasers have been widely used in many fields, including industry, scientific research, and bio-medical system etc. For traditional standard 2mm fullbar, a single bar diode laser with tens of Watts have been commercially available. It's known that higher optical output power demands the fullbar with the longer cavity. To obtain higher power, the development of a single diode laser bar with longer cavity length (e.g. 4mm) becomes a trend. However, it is difficult to package the bar with such longer cavity length, as the heat dissipation and thermal stress induced by its large cavity dimension become more serious compared with the 2mm fullbar. In this work, high power diode lasers with 4mm fullbar were presented. The packaging process and structure using a complete AuSn bonding technology were designed and optimized. The details of packaging process were described as follow: the flipchip approach is applied to bond the fullbar, a CuW submount, which was used as a CTE-matched substrate to GaAs material, was sandwiched between a fullbar and MCC heatsink using a complete AuSn bonding technology. Gold wire bonding process was employed to n-contact connection. Compared with indium bonded fullbar, the reliability of the complete AuSn bonded fullbar was significantly improved. Therefore, it's a very promising alternative to achieve higher optical power with a 4mm-full bar packaged using a complete AuSn bonding technology in the future.

9346-44, Session PTue

Optical components for improved normal-incidence optically-pumped VECSELs

Kelly R. Farner, Stephen M. Misak, Paul O. Leisher, Rose-Hulman Institute of Technology (United States)

Vertical external cavity surface emitting laser (VECSEL) arrays are attractive as high optical output, diffraction limited laser sources. In optically-pumped configurations, VECSELs offer a high degree of scalability. Traditional cavity designs have relied on the formation of a stable optical cavity by means of curved output coupler mirrors and the pump light is introduced off-normal incidence. This paper departs from the established approach by presenting results on normal-incidence pumping configurations. The optical components which enable high operating power and efficiency in this configuration are discussed. In this work we report on our efforts to improve the power efficiency achieved in a single element 980 nm VECSEL. A pareto of the sources of loss in the cavity is presented and optical component requirements for improved efficiency are discussed.

9346-45, Session PTue

Integrated RGB laser light module for autostereoscopic outdoor displays

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We have developed highly compact RGB laser light modules to be used as light sources in multi-view autostereoscopic outdoor displays and projection devices. Each light module consists of an AlGaInP red laser diode, a GaInN blue laser diode, a GaInN green laser diode, as well as a common cylindrical microlens. The plano-convex microlens is a so-called "fast axis collimator", which is widely used for collimating light beams emitted from high-power laser diode bars has been optimized for polychromatic RGB laser diodes. The three light beams emitted from the red, green, and blue laser diodes are collimated in only one transverse direction, the so-called "fast axis", and in the orthogonal direction, the so-called "slow axis", the beams pass the microlens uncollimated. In the far field of the integrated RGB light module this produces Gaussian beams with a large ellipticity which are required, e.g., for the application in autostereoscopic outdoor displays. For this application only very low optical output powers of a few milliwatts per laser diode are required and therefore we have developed tailored low-power laser diode chips with short cavity lengths of 250 μm for red and 300 μm for green and blue. We have developed an ASIC with three integrated photodiodes and closed-loop driver electronics for all three colors. Our RGB laser light module including the three laser diode chips, the driver ASIC with integrated monitor photodiodes, the common microlens, as well as the hermetically sealed package has a total volume of only 0.43 cm?, which to our knowledge is the smallest RGB laser light source to date.

9346-46, Session PTue

Characterization of far field of diode laser by three dimensional measurement

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Far field, which characterizes the divergence angle of the light and intensity distribution, is an important parameter of diode laser. Accurate measurement of the far field of diode laser is significant for beam shaping and optical coupling. There are several methods to measure the far field, such as knife-edge test and optical imaging. Some of these methods can only provide divergence angle measurement and can not offer intensity distribution measurement, and some of the approaches can not reach high measurement accuracy. For most of the common far field measurement methods, the measurement is conducted along the fast and slow axis of the diode laser device with the original at the center of the front facet. However, the scans performed in the orthogonal directions do not provide sufficient information for improving the beam shaping and performance analysis. To overcome the existing limitations in far-field measurement, a new measurement approach is developed and an instrument based on this approach is built. This approach offers three dimensional measurement of the far field of diode laser beam. Both the divergence angle and intensity distribution can be extracted and analyzed from the measurement results. The instrument provides high resolution and fast measurement.

The far field measurement system offers the intensity measurement I(?, ?) of the diode laser, with high angular sampling resolution 0.01° and a wide measurement field-of-view up to nearly 180°. The scanning scope for the spatial intensity distribution covers the far field spatial irradiance. The far field measurement system is applied in the characterization of the far field of diode laser, and the results and discussion are also demonstrated in paper in detail.

9346-20, Session 6

Part I: Growth and characterization of highly doped Nd:YAG crystal; Part II: Sensitive saturable absorption response of Bi2Te3 and application in low-threshold solid-state pulsed lasers *(Invited Paper)*

Mitch M. C. Chou, Chao-Kuei Lee, National Sun Yat-Sen Univ. (Taiwan)

Two topics will be covered in our presentation. A highly doped Nd (3%) :Y3Al5O12 (YAG) is grown by Czochralski (Cz) pulling method. The dimensions are cylindrical length: 100mm with an average diameter 50mm. CW and Q-switched laser systems were built up to measure the efficiency, lifetime and output power.

Recently, the nonlinear saturable absorption rate and femtosecond excited spectra of topological insulator Bi2Te3 were studied. But very few reports on its saturable absorption under low pumping power. Especially, on the comparisons of different bulk and surface state. Vertical Bridgmen method was to grow Bi2Te3 single crystal. The sample for measuring its saturable absorption response is prepared by hydrothermal intercalation method to obtain its corresponding bulk and surface state. Its nonlinear saturable absorption is measured under the different wavelengths. Benefiting from its sensitive response, the threshold absorbed pump power is only 31 mW, which is the lowest in passively Q-switched solid-state lasers. It also shows the shortest duration 93ns. More details will be presented in the conference.

9346-21, Session 6

Lithium niobate Q-switch to prevent pre-lasing of high gain lasers operating over a wide temperature range

Dieter H. Jundt, Gooch & Housego, Palo Alto (United States); Peter E. MacKay, Gooch & Housego plc (United Kingdom)

Because of its ease of growth and large electro-optic effect, lithium niobate is the preferred choice for Q-switching mobile lasers. Temperature-induced pyro-electric charges degrade the performance of Q-switch and may lead to premature lasing. This problem is particularly acute for high gain lasers as the temperature drops, e.g. during flight. While the alpha-emitter americium can be used to bleed off the charges, better approaches to improve cold-performance are needed.

We describe the manufacturing process and characterization for temperature-stable LN Q-switch. A thermo-chemical anneal was performed that renders the optical Z-faces slightly conductive. The treatment is performed at temperatures below 500°C and creates a conductive material layer of about 0.5mm thickness. While this process also increases the optical insertion loss by a few percent, that magnitude of loss is tolerable in high gain laser systems where pre-lasing is problematic. We present technical details of the treatment method, the surface charge creation and dissipation mechanism and the setup used to asses the cold-performance used to demonstrate improved charge dissipation when compared to untreated crystals.

9346-22, Session 6

Rigorous modeling of laser light propagation through uniaxial and biaxial crystals

Site Zhang, Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany); Daniel Asoubar, LightTrans VirtualLab UG (Germany) and Friedrich Schiller University Jena (Germany)

Crystals are widely applied in laser systems and they play important roles as polarization manipulators. A simple uniaxial crystal plate with a certain thickness may serve as a linear/circular polarizer. A uni/biaxial crystal with a proper orientation may work as a polarization beam splitter/combiner. A biaxial crystal at conical refraction may be used to generate radially polarized light or help form a Bessel beam. To design a laser system including crystal component(s), or to optimize the performance of such a system, simulation techniques which models the light propagation through crystals is required. We present a full-vectorial and electromagnetic method that enables the modeling of crystal components with general laser fields, based on the angular spectrum of plane waves. Propagation of general field within anisotropic media and the reflection and transmission at a planar interface between isotropic/anisotropic and anisotropic/anisotropic media are discussed. We also demonstrate examples on how crystals are used to manipulate the polarization state of laser beams.

9346-23, Session 6

Optical isolators for 2-micron fibre lasers

Gary Stevens, Thomas H. Legg, Gooch & Housego Systems Technology Group (United Kingdom); Peter Shardlow, Optoelectronics Research Ctr. (United Kingdom) and Univ. of Southampton (United Kingdom)

We report on the development and testing of optical isolators for use in 2-micron fibre laser systems. A variety of potential Faraday rotator materials were characterised to identify the most suitable materials for use in the 1700-2100nm wavelength range, including making measurements of the Verdet constant over 1200-2400nm using a supercontinuum source. Isolators based on the three best performing materials were then developed and packaged as fibre-in, fibre-out and fibre-in, beam-out devices. The isolators were then tested in CW, pulsed and ultrafast laser systems, including high average power systems to determine maximum operating powers and to measure temperature dependent losses, including thermal lensing. The three different designs produced different performance characteristics, but all designs demonstrated isolation >25dB and insertion losses of <1dB. Novel magnet systems producing large field strengths were also investigated, which could produce field strengths double that currently used. This could reduce the length of Faraday rotator material significantly, leading to a lower insertion loss and smaller thermal lensing effect. Modelling was also carried out to predict the performance of the isolators at CW powers >100W.

9346-24, Session 7

Beam delivery components for industrial laser systems *(Invited Paper)*

Magnus Pålsson, Stuart Campbell, Ola I. Blomster, Optoskand AB (Sweden)

Beam delivery components are as critical for an industrial laser system as the laser it self. Not only for delivering the laser beam to the application but also for internal delivery of for example the pump power to the laser engine. For laser systems operating at around 1μm wavelength fiber optic based beam delivery components are today the baseline. With a wide spectrum of laser systems and laser designs there is also a need for a wide spectrum of beam delivery components. Not only fiber optic cables but also fiber to fiber switches to convert the single output from, for example, a fiber laser to a multiple output system. The Optoskand beam delivery technology is today used by a major part of the industrial laser system manufacturers and the mechanical interfaces have become industrial standards. But the most critical design is on the inside and with >20-years know how and a broad patent portfolio Optoskand offer today state of the art technology. This presentation will describe the available beam delivery components including technology and latest results.

Our safe and reliable high technology products have only one goal: to optimize your laser.

9346-25, Session 7

Achromatic phase elements based on a combination of surface and volume diffractive gratings

Ivan B. Divliansky, Evan R. Hale, Marc SeGall, Daniel Ott, Boris Y. Zeldovich, Bahaa E. A. Saleh, Leonid B. Glebov, The College of Optics and Photonics, Univ. of Central Florida (United States)

Phase masks are important optical elements that have been utilized for several decades in a large variety of applications from imaging and astronomy to encryption. While traditional methods of producing phase masks create elements which are inherently monochromatic, it was previously found that the use of birefringence in subwavelength diffraction gratings enables their partial achromatization. Here, we present a new method of achromatization by encoding phase profiles into volume Bragg gratings, allowing these holographic elements to be used as phase masks at any wavelength capable of satisfying the Bragg condition of the hologram. Such holographic phase masks (HPMs) utilize the diffraction characteristics of transmission Bragg gratings, which can diffract up to 100% of a beam into a single order, and can diffract over a broad range of wavelengths by changing the angle of incidence (with the diffraction efficiency depending on the wavelength and strength of the grating). In order to remove this need for angle tuning, we combine this HPM approach with a pair of surface diffraction gratings to achieve true phase mask achromatization. This approach also enables other completely new capabilities, as several encoded phase masks may be multiplexed into a single holographic element without cross-talk while maintaining high diffraction efficiency. As examples, we demonstrate laser mode conversion with near-theoretical conversion efficiency over a broad wavelength spectrum, as well as simultaneous mode conversion and beam combining at wavelengths far from the original hologram recording wavelength.

9346-26, Session 7

Refractive beam shapers for optical systems of lasers

Alexander V. Laskin, Vadim V. Laskin, AdlOptica Optical Systems GmbH (Germany); Aleksei Ostrun, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Performance of modern high-power lasers can be strongly improved by control of irradiance distribution in laser optical systems: flat-top or super-Gaussian irradiance profiles are optimum for amplification in MOPA lasers and for reduction of thermal effects in crystals of solid-state ultra-short pulse lasers; variable profiles are also important in irradiating of photocathode of Free Electron lasers (FEL). This task can be easily solved with using beam shaping optics, for example, the field mapping refractive beam shapers like piShaper. The operational principle of these devices presumes transformation of laser beam intensity from Gaussian to flattop one with high flatness of output wavefront, saving of beam consistency, providing collimated output beam of low divergence, high transmittance, extended depth of field, negligible residual wave aberration, and achromatic design provides capability to work with ultra-short pulse lasers having broad spectrum. With using the same piShaper it is possible to realize various beam profiles like flattop, inverse Gauss or super Gauss by simple variation of input beam diameter.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying in optical systems of high-power lasers. Examples of real implementations and experimental results will be presented as well.

9346-27, Session 7

Monolithic lens arrays as homogenizers for ultra-uniform field illumination

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Micro optics are well-suited for beam shaping of almost all kinds of lasers. Collimation or etendue matching is one major field of application, homogenizing and field or line generation is another one.

This paper focusses on monolithic lens arrays as homogenizers for ultra-uniform field illumination. Such approaches are relevant for lithography, annealing with long and narrow line foci, laser-lift-off processes, powerful eye-safe diode laser lines for metrology and many other applications. All these applications need ultra-uniform and highly efficient beam shaping with low diffraction and a high damage threshold of optics.

Monolithic lens arrays as homogenizers have very good parallelism and very low pitch errors due to the production process. Obviously no gluing or clamping of single lenses is necessary for monolithic lens arrays.

Basic principles and examples of specific designs for annealing and small homogeneous lines for multimode DPSSLs are presented. The influence of surface tolerances, design and size of the optics on field parameters is discussed. Measurement results of such highly homogenous line or field arrangements are shown.

Beam homogenization by means of monolithic micro optics lens arrays is a very efficient and comfortable approach to match the beam properties of laser sources to the requirements of various applications.

9346-28, Session 8

Diamond optical components for high-power and high-energy laser applications

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High-power and high-energy laser systems have firmly established their presence and continue finding new applications in a wide variety of fields, such as materials processing, high – precision and high – throughput manufacturing, semiconductors, defense. Multi-kilowatt laser systems are now shipped to customers globally. Along with high average power CO2 lasers operating at ~ 10 micron wavelength, solid state lasers and fiber lasers operating at ~ 1 micron wavelength are now being increasingly used, both in the high average power and high energy pulse regimes.

In recent years, diamond has become the material of choice when it comes to making optical components for multi-kilowatt CO2 lasers at 10 micron, outperforming ZnSe due to diamond's superior thermo-mechanical characteristics. For 1 micron laser systems, fused silica has been the most popular optical material owing to its outstanding optical properties. This report evaluates high-power / high-energy performance of anti-reflection coated optical windows made of different grades of diamond (single crystal, polycrystalline) and of fused silica. Thermo-mechanical modeling results are presented for mounted optical windows. Laser – induced damage threshold tests are performed and analyzed. Conclusions and recommendations are

made for choosing the optimal material and component mounting design to be used in high power / high energy laser systems.

9346-29, Session 8

BBO sapphire compound for high-power frequency conversion

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Lasers used for diverse applications from industry to fundamental science tend to increasing output powers. Some applications require frequency conversion via nonlinear optical crystals, which suffer from the formation of temperature gradients at high power operation which causes thermal lensing or destruction of the crystal due to tensile stress. To avoid these unwanted effects we joined a beta barium borate (BBO) crystal with sapphire disks serving as effective heat spreaders due to their high thermal conductivity (thermal conductivity = 42 W/Km). Therefor smooth and flat crystal surfaces without intermediate layer were joined by plasma-activated bonding.

The fundamental bases for stable links between the different substrates are strong covalent bonds, which are formed via a polycondensation reaction of the polar molecules at the surfaces of both components. The cleaned surfaces are activated by plasma and brought into close contact, pressed together and heat treated at a temperature of about 100°C. Special attention has been paid to the cleaning of the surfaces. Therefor the surfaces have been evaluated before and after treatment by means of atomic force microscopy. A stable bond has been formed successfully, which has been tested in a proof of principle experiment and demonstrated efficient second harmonic generation at up to253 W of output power. Compared to a bare single BBO crystal it is shown that the temperature within the crystal compound is reduced by a factor of 2.4. The investigated sandwich structures pave the way for frequency conversion at kilowatts of average power for future high power lasers.

9346-30, Session 8

Solid-state laser source of narrowband ultraviolet B light for skin disease care with advanced performance

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In [1] we reported about the development of laser source, which generates ultraviolet light at 310.6 nm. This wavelength is optimum for light treatment of psoriasis and vitiligo. The source is based on third harmonic generation of pulsed Ti: Sapphire laser at 932 nm, pumped by Nd: YAG laser second harmonic at 532 nm.

Laser source operated at 50 Hz, producing pulse energy up to 17 mJ at 932 nm and up to 7 mJ at 310.6 nm before the input of beam profile smoothing system, based on solarization resistant multimode fiber. Laser damage of input end and relatively low fiber transmission restricted available output energy of the source at 4 mJ and average power at 200 mW.

Serious disadvantage of the source was large size of laser head, which resulted from large (94 cm) cavity length of Ti: Sapphire laser. As notified at [1], the main reason, why we had to increase cavity length, was laser damage of volume Bragg grating (VBG), used as spectral selective output mirror of Ti: Sapphire laser.

Here we report about the improvement of laser source performance: increase of average power by more than 50% and reduction of device size. This improvement was realized due to 2 diffraction optical components, used in the device: fused silica transmission grating [2] instead VBG for laser wavelength selection, and diffraction diffuser [3] for beam profile smoothing.

Using transmission grating as spectral selector, when laser cavity length was reduced to 40 cm, we were able to obtain up to 16 mJ pulse energy at 932 nm, at increased to 100 Hz pulse repetition rate, with linewidth less than 0.05 nm. Maximum energy was restricted by available pump energy at 532 nm. No damages of grating were found. For VBG, used at equivalent cavity configuration (same spot size at the both gratings), grating damage begins, when pulse energy exceeded 12.5 mJ.

According to our knowledge, Ti: Sapphire laser generation with such type of grating was obtained for the first time; whereas extracavity laser applications of these gratings (for pulse compression of femtolasers) are well known.

In comparison with other types of Gaussian to flat-top beam profile transformers, diffraction diffuser has important advantage - insensitivity to input beam lateral shift. So, for beam delivery we can use articulated arm with handpiece at the output end, which include diffraction diffuser. We describe 2 handpiece schemes: one – with variable spot size and another – with fixed spot size but increased energetic efficiency.

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9346-31, Session 8

Demonstration of >5kW emissions with good beam quality from two different 7:1 all-glass fiber coupler-types

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From the physical point of view, the rise of the fiber laser is based on its remarkable high power capability paired with an inherently supreme beam quality. On the other hand, engineers recognize the ease of handling fibers

and fiber-optical devices by means of technologies introduced in the heyday of fiber-based telecommunication. Both, the physical and the technological aspects led to the development of environmentally stable kW-laser systems. Contrary to the general scientific movement towards brightness enhancement, some applications do not need fundamental beam quality but enough power on a defined spot size. By geometrical combination of a number of kW single-mode emitters the superb beam quality can be abandoned in favor of sheer power scaling while keeping over-all brightness.

In this contribution, two different types of 7:1 single-mode to multi-mode fiber coupler are described and compared to each other. Both use the same single-mode input fibers (MFD=13μm) which will be arranged as a bundle and then adiabatically tapered down in two different approaches (with and w/o intermediate fiber) as well as by two different glass machining technologies (filament and CO2-laser technology). In both cases the taper is spliced to a 50μm multi-mode beam delivery fiber with a nominal NA of 0.2. While coupler (A) reaches an output power of 5.1kW with M2=6.8 and a heat load of ~12 K/kW, coupler (B) reaches 5.7kW at M2=4.6 with a heat load of 8 K/kW. Both coupler where limited in output power just by experimental restrictions making further improvement almost certain.

9346-32, Session 8

Photothermal studies of the radiation effects on weakly absorptive optical thin film coatings induced by high repetitive laser pulses

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In this paper a commercial photothermal instrument is used to study the radiation effects on weakly absorptive optical thin film coatings induced by high repetitive laser pulses. Through in-situ measuring of the coatings'absorption under irradiation of high repetitive laser pulses, the dynamic information of laser-material-interaction process is obtained, which is very useful for understanding and analyzing of laser damage mechanism of the coatings.In addition, absorption defects on the coatings are clearly determined through the photothermal imaging instrument. The radiation effects on defect and in the "defect-free" area were studied and compared. The lasers used for the study are at 1064nm, 532 nm and 355 nm wavelengths, and repetitive frequencies are in the range of 50 KHz – 300 KHz. The results are presented with discussions on the laser interaction mechanisms.

9346-33, Session 9

Integrated femtosecond lasers *(Invited Paper)*

Clemens Hönninger, Martin Delaigue, Florent Guichard, Amélie Letan, Guillaume Machinet, Franck Morin, Julien Pouysegur, Birgit Weichelt, Yoann Zaouter, Eric P. Mottay, Amplitude Systèmes (France)

Femtosecond lasers have performed an important move from refined scientific tools to the laser source of choice in a growing number of industrial laser applications. A key enabler of this achievement was the intense development work and innovation in the recent years towards compactness and integration both, on the laser technology side and on the components and packaging side. We will present recent achievements on compact and powerful industrial femtosecond lasers allowing industrial and scientific users to exploit the full benefits of laser sources with extremely short pulse duration and ultra-high peak power.

9346-34, Session 9

Kagome-type hollow-core photonic-crystal fibers for beam delivery and pulse compression of high-power ultrafast lasers *(Invited Paper)*

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Tremendous progress has been achieved in the last years in the field of ultrafast high-power sources. Among the different laser technologies driving this progress, thin-disk lasers (TDLs) have gained significant ground, both from amplifiers and modelocked oscillators. Modelocked TDLs are particularly attractive, as they allow for unprecedented high energy and average powers directly from an oscillator.

The exponential progress in the performance of these sources drives growing needs for efficient means of beam delivery and pulse compression at high average power (> 100 W) and high peak power (> 10 MW). This remains a challenging regime for standard components: microstructured large-mode-area silica photonic-crystal fibers (PCFs) are good candidates, but peak powers are limited to ≈4-6 MW by self-focusing. Hollow-core (HC) capillaries are adapted for higher peak powers, but exhibit high losses and are not suitable for compact beam delivery. Kagome-type HC-PCFs are excellent candidates: their intrinsic guiding properties allow for extremely high damage thresholds and low losses over wide transmission windows.

We present most recent results of pulse compression in the hundred-watt average power regime using Kagome-type HC-PCFs. We launch 127-W, 18-μJ, 740-fs pulses from our modelocked TDL into an Ar-filled fiber (13 bar), reaching 93% transmission. The resulting spectral broadening allows us to compress the pulses to 88 fs at 112 W of average power, reaching 105 MW of peak power, at 88% compression efficiency. These results demonstrate the outstanding suitability of Kagome HC-PCFs for compression and beam delivery of state-of-the-art kilowatt-class ultrafast systems.

9346-35, Session 9

Efficient chirped Bragg gratings for stretching and compression of high power ultra short laser pulses

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Chirped Bragg Gratings (CBGs) recorded in photo-thermo-refractive (PTR) glass have been successfully used as ultrashort pulse stretchers and compressors in Ultra Short Pulse Lasers (USPLs). Compared to traditional pairs of surface gratings, CBGs offer significant advantage in compactness and robustness. In a single pass configuration, CBGs provide up to 100 nm spectral bandwidth, up to 500 ps of stretching time, and stretching rates from few ps/nm to > 500 ps/nm. It was shown that usage of a matched grating pair for stretching and compression results in a transform limited pulse durations. All above make this technology preferable for manufacturing of industrial grade USPL systems.

In order to widen applicability of CBGs and to enhance the achievable parameters of USPL systems, an innovative design of stretcher and compressor is proposed. This design is based on usage of CBGs in a double pass configuration that results in doubling its dispersion compared to that

in a single pass. Gratings with thickness ranged from few to 50 mm where successfully applied for this geometry. Maximum dispersion of 1 nsec has been achieved when 50 mm thick gratings were used in a double pass arrangement. Distortion free gratings with diffraction efficiency above 90% were fabricated for spectral region ranging from 1000 nm up to 2500 nm. Efficiency of stretching and compressing with 1 nsec dispersion above 80% was demonstrated. Large aperture of chirped gratings allows their usage for stretching and compressing high energy (several mJ) and high average power (tens of Watts) pulses.

9346-36, Session 9

Adaptive optics for ultra short pulsed lasers in UHV environment

François Deneuville, Laurent Ropert, Sébastien Theis, Paul Sauvageot, ISP System (France)

Adaptive optics for ultra short pulsed lasers in UHV environment

ISP SYSTEM has developed a deformable mirror compatible with UHV environment, suitable for ultra short pulsed lasers. The aim of the development was to bring to the market an UHV-compatible deformable mirror with a very good resistance to electro-magnetic pulses, with a very good linearity and a very low hysteresis and which avoid any print through effect.

The design of the deformable mirror is based on force application on numerous locations. μ-AME actuators are driven by stepper motors, and their patented special design allows controlling the force with a very high accuracy.

Optical aberrations up to Zernike order 4 (excluding piston) can be corrected. Hysteresis is lower than 0.1% and linearity better than 99%. Contrary to piezo-electric actuators, the μ-AME actuators avoid any print through effects and they permit to keep the mirror shape stable even unpowered, improving significantly the resistance to electro-magnetic pulses.

The deformable mirror design allows changing easily an actuator or even the membrane if needed. Maintenance tools have been developed so that the end-user can himself replace the membrane by another spare paired membrane, in order to improve the system availability.

They are designed for circular, square or elliptical aperture from 30mm up to 500mm or more, with incidence angle from 0° to 45°. They can be equipped with passive or active cooling for high power lasers with high repetition rate.

MD-AME mirrors are compatible with all dielectric or metallic coatings.

9346-37, Session 10

Components for beam combination in high power fiber systems *(Invited Paper)*

Joshua E. Rothenberg, Northrop Grumman Aerospace Systems (United States)

There has been rapid and significant progress in recent development of high power fiber systems for both industrial and military applications. Multiple commercial suppliers now offer fiber lasers and amplifiers with near diffraction limited output and kW power. For applications requiring much higher power (10's kW – MW's), it is valuable to combine individual fiber outputs while preserving beam quality. A number of spectral and coherent beam combination approaches have been pursued to this goal. Here we discuss the progress, challenge, and promise of beam combination techniques and key components required for high power fiber laser systems.

9346-38, Session 10

New generation of VBGs for efficient spectral beam combination of high power diode lasers

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The brightness of laser diodes (LDs) is one of the most critical parameter when LDS used for pumping or direct high power laser applications. Recently significant development has been accomplished towards improvement of LDs beam quality. Nowadays the brightness of commercial LDs is close to theoretical limits imposed by semiconductor technology. Despite of improvements still this is a major factor limiting its applications. Nowadays spectral beam combining (SBC) is considered as a major technique for further brightness enhancement. It can increase the brightness of LDs by more than 10 times. One of the most advanced techniques for SBC is based upon reflecting Bragg Gratings (RBGs). This approach has demonstrated the combination of fiber lasers to multi kilowatt level without degradation of the combined beam quality. Serious obstacle though for using this method for efficient combining of LDs is wide divergence. The recent developments in the technology of volume Bragg gratings in Photo-Thermo-Refractive (PTR) glass results in increased refractive index modulations well above 1000 ppm accompanied by small losses. All above allows manufacturing of high efficient RBGs with enhanced angular acceptance. Input beams having divergence above 10 mrad can be combined by such gratings with efficiency about 95%. We demonstrated efficient combining of three high power LD modules with more than 90% efficiency.

9346-40, Session 10

Beam combining techniques for high-power high-brightness diode lasers

Ralf Koch, Haro Fritsche, Bastian Kruschke, Holger Kern, Ulrich Pahl, Thomas Hagen, Andreas Grohe, Wolfgang Gries, DirectPhotonics Industries GmbH (Germany)

Laser diodes are efficient and compact devices operating in a wide range of wavelengths. Boosting power by beam combining while maintaining good beam quality has been a long-standing challenge.

We discuss various approaches for beam combining with emphasis on solutions pursued at DirectPhotonics. Our design employs single emitter diodes as they exhibit highest brightness and excellent reliability. In a first step, after fast axis collimation, all single emitter diodes on one subunit are stacked side-by-side by a monolithic slow-axis-collimator thus scaling the power without enhancing the brightness.

The emission of all diodes on a subunit is locked by a common volume Bragg grating (VBG), resulting in a bandwidth < 0.5nm and high wavelength stability. Second, two subunits with identical wavelength are polarization coupled forming one wavelength channel with doubled power and brightness. Third, up to five channels are serially spectrally combined using dichroic filters. The stabilized wavelengths enable dense spectral combining, i.e. narrow channel spacing. This module features 500W output power within 20nm bandwidth and a beam parameter product better than 3.5mm*mrad x 5mm*mrad (FA x SA) allowing for a 100?m, 0.15NA delivery fiber. The brightness ex-fiber exceeds100 GW m-2 sr-1.

The small bandwidth of a 500-W-module enables subsequent coarse spectral combining by dichroic filters, thus further enhancing the brightness.

This potential can only be fully utilized by automated manufacturing ensuring reproducibility and high yield. A precision robotic system handles and aligns the individual fast axis lenses. Similar technologies are deployed for aligning the VBGs and dichroic filters.

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9347-1, Session 1

Broadband 2.5-6μm frequency comb source for dual-comb molecular spectroscopy

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Absorption spectroscopy with frequency combs in the molecular fingerprint portion of the spectrum (2-10 ?m) has great potential for trace molecular detection and in particular for such applications as monitoring of the atmosphere and medical breath analysis. Especially attractive is dual-comb Fourier transform spectroscopy where full advantage is taken of temporal and spatial coherence of frequency combs as well as of their broadband nature. The promise is high speed, broad spectral coverage, superior sensitivity, high spectral resolution, and the possibility of absolute frequency calibration of molecular resonances. Here we report a dual-comb system based on a pair of doubly-resonant near-degenerate optical parametric oscillators (OPOs) based on orientation-patterned GaAs (OP-GaAs) pumped by two mutually phase- and frequency-locked femtosecond Tm-fiber lasers at 2-μm wavelength. Low pump threshold (7 mW), high coherence, and broad instantaneous spectral coverage (2.5 - 6 μm) make this system promising for spectroscopic studies.

9347-2, Session 2

Ultrafast nonlinear Si optics *(Invited Paper)*

Alexander L. Gaeta, Cornell Univ. (United States)

No Abstract Available

9347-3, Session 3

CW, single-frequency 229nm laser source for Cd-cooling by harmonic conversion

Yushi Kaneda, J. Michael Yarborough, Yevgeny A. Merzlyak, College of Optical Sciences, The Univ. of Arizona (United States) and KATORI Innovative Space-Time Project, ERATO (Japan)

With the application in cadmium optical lattice clock in mind, cooling laser is developed. An InGaAs-based optically pumped semiconductor laser is tuned to 915nm with a quartz birefringent filter, and single-frequency operation is enforced by an etalon. Two independent resonant harmonic conversion stages are used to convert the IR emission to 458nm and subsequently to 229nm. LBO crystal is used in the first SHG, and Brewster-cut, 10mm long BBO is used in the second resonator. With 650mW of 458nm input, 216mW of 229nm power was observed. Conversion efficiency from 458nm to 229nm is more than 33%. Considering the 23% reflection loss at the output facet of the BBO crystal, the generated 229nm power is 277mW, giving the gross conversion efficiency of more than 43%. More than 100mW of output power was maintained for more than 4 hours of unattended operation, showing the potential as the cooling laser for cadmium atoms.

To the best of our knowledge, we believe this is the shortest wavelength demonstrated by a phasematched SHG in CW mode with output power in excess of 100mW.

9347-4, Session 3

Second harmonic 266nm generation by PP-LBGO device

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Second harmonic deep UV (266nm) generation was demonstrated by periodically poled LaBGeO5 (PP-LBGO) from nano second pulsed 532 nm laser. LBGO crystal was grown by Czochralski pulling method successively with 18mm in diameter with 40mm in length. Grown axis was c-axis. Fan-out PP structures with periodicity from 5.9 to 6.5 micron were fabricated by electric field poling method on LBGO with 11mm in length and 0.5mm in thickness. The duty ratio of the periodically poled structure was 50% +/- 5% in whole poled area. Although most of nonlinear optical materials for deep UV have problems in hygroscopy, PP-LBGO does not show any hygroscopy. Therefore input and output surfaces was optically polished based on conventional mechanochemical polishing method without special treatment. Pulsed 532 nm laser with 10 kHz repetition rate and 7.5ns was focused into the fabricated device. Generation of 266nm was confirmed at around 6.4 micron in periodicity as 3rd order QPM condition. Since the calculated periodicity of 1st order based on reported Sellmeier equation is 2.17 micron, the phase matched periodicity was slightly narrower than the calculated value. Non-walk-off circular beam profile of 266nm was obtained. Since nonlinear coefficient of 3rd order QPM is 0.12 pm/V, the 1st or 2nd order QPM structures are prospective for achieving much higher conversion efficiency.

9347-5, Session 3

High brightness 188nm light source with low temporal jitter

James J. Jacob, Actinix (United States)

This paper describes a hybrid fiber/solid-state laser system that generates multi-millijoule scale light pulses in the vacuum ultraviolet at 188 nm. Pulse durations of 2ns and a temporal jitter on the order of 50ps are realized via a sum-frequency generation process where light at 1599nm is mixed with light at 213nm in the non-linear crystal CLBO. A wavelength-stabilized, seed pulse at 1599nm is derived from a pulse-modulated, single-frequency distributed feedback laser diode that is subsequently boosted to the micro-joule scale with erbium fiber L-band amplifiers. A two-stage optical parametric amplifier (OPA) is then utilized to increase the 1599nm pulse energy to greater than twenty millijoules. The main advantages of this approach over an OPO configuration are the low temporal jitter of the resulting amplified pulse and the preservation of the short pulse duration and narrow bandwidth of seed laser. The OPA first stage is a high-gain green pumped KTP crystal followed by an IR pumped second stage consisting of tandem KTP crystals. The 213nm light is generated as the fifth harmonic of the system pump laser. The gain and temporal characteristics of the OPA will be discussed as well as the performance of CLBO running in the 188nm wavelength region

9347-6, Session 3

Ten deep blue to cyan emission lines from an intracavity frequency converted Raman laser

Dimitri Geskus, Ctr. de Lasers e Aplicações (Brazil); Jonas Jakutis Neto, Instituto de Estudos Avançados (Brazil); Helen M. Pask, Macquarie Univ. (Australia); Niklaus U. Wetter, Instituto de Pesquisas Energéticas e Nucleares (Brazil)

Solid-state intracavity frequency converted Raman lasers are able to efficiently deliver many “hard to reach” wavelengths in the near-infrared and visible spectral regions. The small stimulated Raman Scattering cross-section requires high intensity laser fields and extremely low loss cavities to enable resonant build-up of intracavity Stokes shifted laser fields. The currently commercially available high quality optical components such as crystals and dielectric coatings with complex spectral characteristics and durability, enable the development of such intracavity Raman lasers, allowing continuous wave (cw) stimulated Raman scattering (SRS) laser operation. In addition, intracavity sum frequency generation (SFG) and second harmonic generation (SHG) has been reported resulting in highly efficient laser emission in the yellow-orange-red spectral region. Here we exploit the 4F3/2-4I9/2 three level laser transition of Nd:YLiF4 (Nd:YLF) and demonstrate intracavity SRS conversion using a KGW Raman crystal, providing laser oscillation in the 9XX nm wavelength regime. Via SHG and SFG using a LBO crystal inside the cavity we demonstrate emission of ten spectral lines ranging from deep-blue to cyan (451-495 nm). Quasi continuous wave (qcw) laser operation has been characterized, reaching watt level output powers in the visible spectral range. These results highlight the wavelength agile character of the new generation intravavity frequency converted Raman laser sources, providing a suitable replacement for many other lasers in this field such as the Argon ion lasers and frequency doubled optically pumped semiconductor lasers (OPSLs).

9347-7, Session 3

Frequency doubling of near-infrared radiation enhanced by a multi-pass cavity for the second-harmonic wave

Daniel Jedrzejczyk, Reiner Güther, Katrin Paschke, Götz Erbert, Ferdinand-Braun-Institut (Germany)

High-power laser light sources in the green spectral region with a good beam quality are required for medical applications such as, e.g., laser coagulation. Frequency doubling of near-infrared (NIR) diode lasers in nonlinear bulk crystals in a single-pass configuration enables the realization of such devices in a compact manner, but it is characterized by a relatively low nonlinear conversion efficiency.

The nonlinear interaction in a bulk crystal can be enhanced by an external cavity, which is resonant, e.g., for the fundamental wave. This can result in a considerably higher conversion efficiency, but requires active or passive frequency locking, which makes the setup complicated and expensive.

In this work, we demonstrate frequency doubling in a nonlinear bulk crystal of near-infrared radiation (1064 nm) of a DBR tapered diode laser enhanced by a multi-pass cavity resonant for the second-harmonic wave (532 nm). The introduced concept requires no frequency locking, since the relatively low reflectivity of the rear cavity mirror leads to wide resonances in the wavelength distribution, which can be matched with the diode laser and the nonlinear crystal parameters. In addition, no impedance matching in the cavity is required, since the cavity is resonant only for the second harmonic wave.

At the conference, the results reached by means of the introduced concept will be presented in comparison with the results of a single-pass configuration. In particular, through the application of SH cavity the nonlinear conversion efficiency in a 20 mm long periodically poled MgO doped LiNbO3 crystal was nearly doubled. Up to date, a maximum visible power of 1 W at a conversion efficiency of 20 % was reached in this configuration.

9347-70, Session 3

High average power quasi-CW single-mode green and UV fiber lasers *(Invited Paper)*

Alexey Avdokhin, Valentin P. Gapontsev, Pankaj Kadwani, Andreas Vaupel, Igor Samartsev, IPG Photonics Corp. (United States)

The narrow-linewidth single-mode ytterbium fiber laser operating in quasi-continuous-wave (QCW) regime with pulse repetition rate of 150 MHz and providing 1 kW of average output power was used to obtain 700 W of average power at 532 nm with single-mode beam quality and wall-plug efficiency of over 23 % via employing single-pass SHG in LBO crystal. To the best of our knowledge, our laser provides about 60 % more output power than the previously reported single-mode green lasers based on non-fiber platforms, while featuring significantly more efficient, simple, robust and compact design. We also experimentally proved that the same type of QCW ytterbium fiber laser can be used for generating of world-record levels of power at other wavelengths of visible and UV spectral ranges by employing cascaded non-linear frequency conversion. Thus, operating ytterbium laser at average power of 630 W and repetition rate of 50 MHz, and using single-pass frequency tripling in 2 LBO crystals, we achieved over 160 W of average power of nearly single-mode UV emission at 355 nm with THG efficiency of more than 25 %. As far as we know, this is the highest output power ever reported for UV laser with nearly diffraction limited beam quality. Our ongoing experiments are targeted at improving this result via utilizing of full available power level of ytterbium laser by increasing pulse repetition rate while maintaining the same peak power. With this approach, we plan to reach over 250 W power level in ultraviolet before the presentation.

9347-8, Session 4

Whispering gallery resonator from lithium tetraborate for nonlinear optics

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The guiding of light in whispering gallery resonators is based on the principle of continuous total internal reflection. This guiding principle leads to outstanding quality factors of these resonators, limited only by absorption of the material, they are made of. Due to this, conversion efficiencies in the percent regime have already been achieved for pump powers on the microwatts level for frequency conversion in the visible and infrared spectrum. This makes them attractive devices for nonlinear optics also in the ultraviolet regime, where the nonlinear coefficients of suitable materials tend to decrease. Lithium tetraborate is a suitable material for ultraviolet applications. First of all, it exhibits collinear phase-matching for second harmonic generation for 488 nm. The transmission window starts at 180 nm and covers the whole visible and near infrared regime. Thus, the participating wavelengths for collinear phase matching are well within the transmission window, allowing for large quality factors for each of them. We report on the successful fabrication of a whispering gallery resonator made of lithium tetraborate. Quality factors on the order of 10^8 are observed from the ultraviolet to the infrared spectrum. These values match well with the material absorption. On this basis, we will present first results on nonlinear optics experiments with lithium tetraborate.

9347-9, Session 4

Fiber-integrated second harmonic generation modules for visible and near-visible picosecond pulse generation

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Second harmonic generation (SHG) is a ubiquitous technique for extending the spectral coverage of laser sources into regions that would otherwise be technologically challenging to access. SHG schemes however, typically rely on the use of bulk optical components, resulting in systems with larger footprints requiring precise optical alignment. Integration of the SHG components into a single unit facilitates the implementation of compact, robust and turn-key sources, suitable for applications in bio-photonic imaging.

We report on the development of fiber-coupled frequency doubling modules and their application to novel fiber-integrated picosecond pulse sources in the visible region. The modules employ a simple, single-pass configuration using a periodically-poled lithium niobate (PPLN) crystal as the nonlinear conversion medium. They are readily adaptable for different fiber pump laser configurations and are configurable with either fibre-coupled or collimated free-space outputs.

Two sources using the modules are presented, operating at 780 nm and 560 nm. The 780 nm source utilises an erbium master oscillator power fiber amplifier (MOPFA) scheme. SHG was performed in a 35 mm long crystal, generating 4 W of 780 nm radiation with a pulse duration of 300 ps at 50 MHz and conversion efficiencies exceeding 40%. Results from this source being used for nonlinear-parametric wavelength conversion in photonic crystal fibre will be discussed. The 560 nm source was based on SHG of a Raman amplified CW diode pumped by a pulsed ytterbium-fiber MOPFA. This source generated 450 mW of average power with conversion efficiencies greater than 20%.

9347-10, Session 4

0.5W CW single frequency blue at 486 nm via SHG with net conversion of 81.5% from the NIR using a 30 mm PPMgO:SLT crystal in a resonant cavity

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In this experiment a FBG stabilized single frequency laser at 972 nm is used as a convenient fundamental NIR source. The optical doubling cavity has a 91% input coupler, a 30 mm long Brewster cut PPMgO:SLT crystal (Oxide Corp., Japan) and a high reflector. Due to the Brewster cut, the beam inside crystal has an elliptical waist of 79X49 ?m. The cavity has a FSR of 2.2 GHz and optical length of 138 mm. We measured a round trip loss of 0.63%, a buildup 37 and 18.8 W at 972 nm circulating inside the cavity. Our measured single pass conversion efficiency of 1.28 %/W^2 is near the theoretical value of 1.47 %/W^2. The IR cavity mode matching of 95% at low power decreased to 90% at high power due to wavefront distortion. Reflection from the crystal poling boundaries and crystal polarization rotation caused 0.1% and 0.23% out of the 0.63% total round trip loss. The cavity is monitored using a photodiode and stabilized with piezo translation of the high reflector under control of the output of a single chip mixed signal processor (MSP). The laser package (IR laser source, cavity and MSP) is 8X8X2 inches. With 572 mW of power from the IR laser, a maximum blue power of 466 mW is obtained, giving a conversion efficiency of 81.5%. The blue beam (96% Gaussian fitted beam profile) is separated from the IR beam by refraction at the crystal's Brewster surface with negligible loss and without the need for dichroic optics.

9347-11, Session 4

517nm - 538nm tunable second harmonic generation in a diode-pumped PPKTP waveguide crystal

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Compact continuous wave (CW) tunable laser sources in the visible spectral region are currently very attractive for a number of cutting-edge applications ranging from photomedicine and biophotonics to confocal fluorescence microscopy. The most promising approach to develop a compact, efficient and broadly tunable visible laser source is second harmonic generation (SHG) in a periodically poled nonlinear crystal containing a waveguide, which not only allows highly efficient frequency conversion even at low pump power levels but also offers an order-of-magnitude increase of wavelength range for efficient SHG. In this respect, semiconductor lasers with their small size, high efficiency, reliability, low cost and a wide spectral range coverage are very promising for realization of tunable visible laser sources.

In this work, we show a compact all-room-temperature laser source generating tunable green light in the wavelength range between 517 nm and 538 nm by frequency doubling in a periodically poled potassium titanyl phosphate (PPKTP) waveguide using a broadly tunable quantum well external-cavity diode laser (QW-ECDL) coupled into a single mode fiber. Maximum output power of 12.88 mW and conversion efficiency of 14.8% was obtained at 530 nm using a non-antireflective (AR) coated 15-mm long PPKTP waveguide with a cross-sectional area of 3x5 μm2. Second harmonic tunability in PPKTP waveguides with cross-sectional areas of 4x4 μm2 and 2x6 μm2 was also investigated. The demonstrated laser source represents an important step towards a compact tunable green light source operating at room temperature, which could be extremely valuable in a wide range of cutting-edge applications.

9347-12, Session 4

A novel collinear LiNbO3 acousto optical tunable filter with the improved range of transmission and spectral resolution

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This investigation represents a deep and advanced analysis of exploiting lithium niobate (LiNbO3) crystals for the collinear acousto-optical tunable filter (AOTF) in violet and near ultraviolet ranges. The selection of this material is motivated by its high birefringence, which is a key parameter for improving the resolution of AOTF. For this matter, we take into account all the important factors that can deteriorate the resolution in order to find

extreme conditions for the best performances. In concrete, we analyze the well- known photorefraction effect accompanied by the light induced absorption in those ranges for the LiNbO3 crystals doped by selected materials. The best observed results have been obtained with 4% of magnesium (Mg) dopant in the congruent melt of LiNbO3, which also shifts the absorption edge far into the middle UV-range. This analysis had made it possible to formulate the physical criterion determining the enlarged practical limitations of the incident light power density.

Together with previously studied non-uniformity and dispersion of the birefringence along the length of acousto-optical interaction in a crystal, we exploit the recently discovered and experimentally confirmed acousto-optical nonlinearity, which can improve the transmission function inherent in the collinear interaction via applying the acoustic waves of finite amplitude in the AOTF. As a result, the obtained spectral resolution is the best available for any collinear AOTF to our knowledge.

9347-13, Session 5

Sub-cycle control of multi-THz high-harmonic generation and all-coherent charge transport in bulk semiconductors *(Invited Paper)*

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Ultrafast charge transport in strongly biased semiconductors lies at the heart of high-speed electronics, electro-optics and fundamental solid-state physics. Intense phase-locked terahertz (THz) pulses at photon energies far below electronic interband resonances may serve as a precisely adjustable alternating bias, far exceeding dc breakdown voltages. Here, we use controlled (multi-)terahertz transients centered at 30 THz with peak fields of 72 MV/cm to drive coherent interband polarization and dynamical Bloch oscillations of electrons in the conduction band of undoped, semiconducting gallium selenide, on femtosecond timescales. The dynamics encompass the generation of absolutely phase-stable high-harmonic transients containing up to the 22nd order of the fundamental and thus spanning over 12 octaves of the entire terahertz-to-visible spectral domain between 0.1 and 675 THz, in a single pulse. Phase and amplitude of high-harmonic components can be adjusted via the carrier envelope phase of the driving pulse which controls the interference of multiple ionization channels, as supported by our microscopic calculations. Our experiments establish a new field of light-wave electronics exploring coherent charge transport at optical clock rates. Furthermore, first experiments at 1 THz exploiting the near-field enhancement in metamaterials demonstrate how atomically-strong THz pulses drive massive interband carrier generation in gallium arsenide through Zener tunneling, which leads to strong, THz-induced electroluminescence at up to 500 times the THz photon energy. Within the 1.5-ps duration of the THz pulse, more than 10^19/cm^3 carriers tunnel, sufficient for transistor operation. Our experiments bring picosecond-scale electric circuitry at the interface of THz optics and electronics into reach.

9347-14, Session 5

Intense THz pulses for condensed matter physics *(Invited Paper)*

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Sources of intense THz sources using difference frequency generation and optical rectification of femtosecond laser pulses have undergone rapid development in recent years. New materials, conversion techniques and pump laser sources have enabled pulse energies and field strengths that rival accelerator-based methods. These sources have enabled novel experiments that take advantage of the high electromagnetic fields that can exceed 1 MV/cm at the sample. It is possible to use these fields to manipulate and control complex quantum material systems such as high temperature superconductors and multiferroic materials and then probe the nonequilibrim properties on the subpicosecond time scale. We will briefly review current state-of-the-art sources of high-field THz pulses and then discuss a number of examples of applications in condensed matter physics. We will highlight the combination of THz pump techniques with femtosecond X-ray probe pulses to investigate the structural dynamics of matter on the ultrafast time scale.

9347-15, Session 5

Ultrafast photo-response in superconductive isotropic radiators for microwave generation

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The discovery of high temperature superconductors (HTS) and the expected applications in the field of ultrafast opto-electronics has created a unique circumstance where the technology has the potential to bridge the frequency gap from infrared to microwave. Many HTS materials such as yttrium barium copper oxide (YBCO) contain the inherent electrical and optical properties such that in a thin film form their response to a pulsed ultrafast laser can be used to generate radiation that spans frequencies from the terahertz to the microwave regime.

The electromagnetic radiation phenomenon was demonstrated by transient photo-excitation measurements of an ultrafast laser induced non-equilibrium quasi-particle relaxation. The photo-response from a laser of an average power of 1 W and a pulse duration greater than 120 fs (808 nm wavelength) incident on a charged YBa_2 Cu_2 O_(7-?) (YBCO) Corbino disk thin film at superconductive temperatures was measured using a series of microwave antennas. From the observed nanosecond response time of the transient pulse, we extract frequency band structure in the GHz regime that was dependent on the incident beam diameter, pulse duration, power, and the physical structure of the YBCO thin film.

The electron-phonon energy relaxation time is known to be on the order of a picosecond. However, by manipulating the resistive and kinetic inductive response of the material we demonstrate the ability to generate wideband microwave frequencies with a transient response in the nanosecond time scale. Quasi-particle dynamics and the temporal response were analyzed using the Rothwarf-Taylor rate equations and the radiating low frequency circuit equation.

9347-16, Session 5

High efficiency, wide bandwidth THz generation in organic crystals OH1 and DSTMS

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Organic electro-optic crystals are efficient THz-wave generators using optical rectification (OR) or difference-frequency generation (DFG) of various fs–ns pump laser sources in the infrared, which is due to their higher

second-order susceptibilities compared to inorganics, combined with phase-matching possibilities. We investigate THz interactions using recently developed new materials, stilbazolium salt DSTMS*, which is an organic material similar to DAST*, but with better damage threshold and THz figures of merit, as well as phenolic polyene OH1*, which is a hydrogen bonded crystal developed at ETH and an important alternative for stilbazolium salts due to the low THz absorption and the best figure of merit for THz wave generation.

Best phase-matching properties of these materials for pump optical wavelengths in the range of 800–1600 nm and for THz frequencies in the range of 0.1–16 THz have been determined. We demonstrate efficient generation and coherent detection of very broadband THz pulses (0.1–12 THz) using these materials, pumped by fs fiber lasers at telecommunication wavelengths, and show its use for THz time-domain spectroscopy, imaging and material testing. In another set-up, tunable THz waves for remote sensing have been realized using difference frequency generation of the signal and idler wavelengths of a BBO based optical parametric oscillator. THz pulses with frequencies 1–20 THz and a bandwidth of less than 100 GHz are produced via a difference frequency generation (DFG) process by mixing two infrared waves in OH1 and DSTMS.

* DSTMS (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate); DAST (4-N,N-dimethylamino-4'-N'-methyl-stilbazolium tosylate); OH1 (2-(3-(4-hydroxystyryl)-5,5-dimethylcyclohex-2-enylidene)malononitrile)

9347-17, Session 6

Optical parametric oscillation in quasi-phase-matched GaP *(Invited Paper)*

Peter G. Schunemann, Leonard A. Pomeranz, Daniel J. Magarrell, BAE Systems (United States)

Orientation patterned gallium phosphide (OP-GaP) is a new quasi-phase-matched (QPM) nonlinear optical (NLO) semiconductor for mid-infrared frequency generation. It overcomes several limitations of ZGP, the current NLO crystal of choice for 2-um-pumped optical parametric oscillators (OPOs): OP-GaP exhibits 4X lower 2-um absorption loss, 3X higher thermal conductivity, noncritical phasematching via quasi-phasematching (QPM), and a larger band gap that allows for pumping at 1064 nm without two-photon absorption.

Here we report the first OPO based on bulk OP-GaP. Multi-grating OP-GaP QPM structures were grown by polar-on-nonpolar molecular beam epitaxy (MBE), lithographically patterned, reactive ion etched, and regrown by MBE to yield templates for subsequent bulk growth by low-pressure hydride vapor phase epitaxy (LP-HVPE). A Tm-fiber-pumped Ho:YAG pump (2090nm, 20W, 20kHz, 12 ns) was linearly polarized along the <100> orientation of the AR-coated 16.5 x 6.3 x 1.1 mm3 OP-GaP crystal (QPM layer = 800 um thick, grating period = 92.7 um) mounted on a copper blocked maintained at 20°C by a thermo-electric cooler. The OPO cavity was a linear resonator with 10-cm ROC mirrors coated for DRO operation (85%R at signal, 55%R at idler). The pump spot size at the crystal face was 250 um. The observed OPO threshold was 2.6 W (44 MW/cm2) with a slope efficiency of 16% and a maximum output power of 350 mW until surface damage occurred at 1.25 to 1.5 J/cm2. The signal (3.54 um) and idler (5.1 um) output wavelengths agreed well with Sellmeier predictions.

9347-18, Session 6

1-micron-pumped OPO based on orientation-patterned GaP

Leonard A. Pomeranz, Peter G. Schunemann, Daniel J. Magarrell, John C. McCarthy, Kevin T. Zawilski, BAE Systems (United States)

Orientation patterned gallium phosphide (OP-GaP) is a new nonlinear optical (NLO) crystal which exhibits the highest nonlinear coefficient (d36=70.6 pm/V) and the longest infrared cut-off (12.5 um) of any quasi-phase-matched (QPM) material that can be pumped at 1-um without two-photon absorption.

Here we report the first 1064 nm pumped OPO based on bulk OP-GaP. Multi-grating OP-GaP QPM structures were grown by producing an inverted GaP layer by polar-on-nonpolar molecular beam epitaxy (MBE), lithographically patterning, reactive ion etching, and regrowing by MBE to yield templates for subsequent bulk growth by low-pressure hydride vapor phase epitaxy (LP-HVPE). The OP-GaP OPO sample was 16.5 x 6.3 x 1.1 mm3. The crystal had an 800 um thick HVPE layer and a 20.8 um grating period (only 150 um thick). The crystal was mounted on a copper block controlled by thermo-electric cooling.

The pump was a Q-switched Nd:YVO4 laser (~1W, 3.3ns, 10KHz) polarized along the <100> orientation. The OPO was doubly resonant with variable output coupling dependent on temperature tuned wavelength. Initial 20°C data generated a signal at 1385 nm and idler at 4591 nm. Here the OPO produced 19mW output (15mW signal / 4mW idler) with a slope efficiency of 5% and threshold of 500mW. Orange parasitic output at 601.7 nm corresponded to 9th order QPM sum frequency mixing between the pump and signal. The OPO was temperature tuned from 20-100 C shifting the signal between 1385 and 1361 nm and the idler between 4591 and 4876 nm which agreed well with Sellmeier predictions.

9347-19, Session 6

Highly efficient double pass optical parametric generator for ultrashort pulses of tunable NIR radiation

Heiko Linnenbank, Stefan Linden, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

Tunable NIR frequency conversion systems with pulse lengths in the femtosecond range and high repetition rates are key components for e.g. time resolved optical spectroscopy or multi-photon fluorescence microscopy. The most widely used devices for these purposes are rather complex optical parametric oscillators (OPO) and optical parametric amplifiers (OPA). A much simpler approach is the optical parametric generator (OPG), which is like the OPO seeded by vacuum fluctuations, but works like the OPA without a synchronized cavity.

In the case of ultrashort pulses at high repetition rates the crystal length and the usable pump power are strongly limited. To overcome this issues we demonstrate a double pass OPG based on MgO:PPLN. In this configuration the signal and the residual pump light are separated after the first pass through the crystal to compensate temporal walk-off effects and are afterwards focused back into the crystal. This allows us to generate more than two watts of tunable NIR radiation with a saturated

pump-to-signal conversion efficiency of nearly 55%, by directly pumping the system with 550 fs pulses from a 42 MHz repetition rate passively mode-locked Yb:KGW oscillator. We achieved pulse durations below 200 fs, without further compression techniques or damaging the crystal during long term operation. Due to saturation of the conversion efficiency we obtained a good pulse-to-pulse stability and a suppression of the long term signal fluctuations below 2% rms. Our system is compact, cost effective and easy to operate and therefore presents an alternative to OPO or OPA systems.

9347-20, Session 6

Tunable continuous-wave midwave infrared generation using an orientation patterned GaAs crystal with a fan-out grating design

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Tunable mid-wave infrared (MWIR) generation by frequency doubling continuous-wave (CW) carbon dioxide lasers with power levels of about 30 W and operating in the 9 to 11 um wavelength has been demonstrated using orientation patterned GaAs (OP-GaAs) as the nonlinear optical medium [1]. To obtain optimum efficiency at different laser lines, the temperature of the OP-GaAs crystal needed to be set at different values. Use of a crystal with a fan-out grating structure allows the frequency conversion of the different lines to take place at the same temperature, thereby reducing experimental complication. We present here to our knowledge the first demonstration of tunable second-harmonic generation (SHG) of a CW CO2 laser using OP-GaAs crystal with a fan-out grating structure.

The crystal used was 4 cm x 1.5 cm by 3.5 mm in dimension, with grating periods ranging from 212.5 um to 220 um. From the measured refractive index values for GaAs [2], these periods correspond to pump wavelengths of 9.2 um to 9.6 um for optimum quasi-phase matched SHG at 22 C. Using a CW CO2 laser with power level of ~ 10 W at 9.2 um to 9.6 um, we obtained tunable SHG at room temperature with approximately constant power level in the few milliwatt regime. With optimum focusing this SHG power is expected to increase.

9347-21, Session 6

Temperature-tuned 90° phase-matched SHG and DFG in BaGa4S7

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In a recent paper [K. Kato et al., Proc. SPIE, 8604, 860416/1-5 (2013)], we have reported the high-accuracy Sellmeier equations for BaGa4S7 that provide a good reproduction of the phase-matching angles for type-1 SHG and SFG observed at 0.7584-7.560?m in the three principal planes and the temperature-tuned 90° phase-matching condition for type-1 SHG of a frequency-doubled CO2 laser at 5.2955?m along the z(=b) axis.

We next attempted to measure the temperature-tuned 90° phase-matching conditions for type-1 DFG between the outputs of a Nd:YAG laser-pumped KTP/OPO and its pump source along the z axis, and have obtained the DFG outputs ranging from 5.341 to 7.477?m by heating the BaGa4S7 crystal from 25? to 180? and simultaneously tuning the OPO wavelength from 1.3290 to 1.2408?m. This range is very close to the value observed in the previous experiments carried out with the angle-tuned OPO pumped by a 100 Hz Nd:YAG laser [E. A. Tyazhev et al., Opt. Lett. 37, 4146 (2012)].

Although no attempt was made to use the present crystal for the temperature-tuned 90° phase-matched OPO owing to its internal damage, this scheme might provide the much higher conversion efficiencies compared to the above-mentioned angle tuning.

Finally, we note that the present experimental results agree well with the theoretical values calculated with our Sellmeier equations and thermo-optic dispersion formula constructed from our own data of dnx/dT, dny/dT, and dnz/dT.

9347-53, Session PTue

Tunable two-color soliton pulse generation through soliton self-frequency shift

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Tunable optical solitons due to intra-pulse stimulated Raman scattering are well-known for their ultrashort pulse width, superb pulse quality and broadband tunability. Consequently they are suitable for a variety of applications, especially multi-photon microscopy (MPM). Recent progress in MPM demands two- or multi-color excitation to match the absorption peaks of multiple fluorophores. Here we propose a new scheme to generate two-color solitons with each wavelength individually tunable. The wavelength of the most energetic soliton can be easily tuned through energy tuning, while qualitative analysis indicates that stretching the input pulse width raises soliton order and narrows the wavelength separation between the most and the second most energetic solitons. Numerical simulations show that under realistic experimental conditions, wavelength separation tuning of hundreds of nanometers can be achieved through prechirping the input pulse. This tunable two-color source may find application in various modalities of MPM.

9347-54, Session PTue

Chemical synthesis and crystal growth of AgGaGeS4, a material for mid-IR nonlinear laser applications

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Mid infrared laser sources have attracted a particularly attention due to their potential applications in different fields such as infrared counter-measures and remote chemical sensing (e.g: LIDAR) [1]. Nowadays, there is a strong need for nonlinear materials able to convert efficiently a 1.064 μm wavelength (Nd:YAG) to wavelengths higher than 4 μm. Consequently, we are particularly interested in the AgGaGeS4 compound (AGGS) which is a promising nonlinear material for mid-IR applications [2]. In the present work, the different steps of this material's processing will be described. The chemical synthesis of polycrystals and the single crystal growth process will be presented. Otherwise, we will discuss about the key parameters related to this material preparation and elaboration. Particularly, we will focus on compounds volatility which can induce stoichiometry deviation and reduce the quality of obtained single crystals. Currently, a 28 mm diameter and 70 mm length single crystals have been grown by the Bridgman-Stockbarger method. The crystal has good homogeneity and an absorption coefficient as low as 0.04 cm-1 in the 0.5-11.5 μm range which make it usable in nonlinear optical devices. Difference frequency generation (DFG) experiments are currently in progress to characterize the nonlinear properties of the material.

9347-55, Session PTue

Nonlinearity improvement in rubidium vapor by means of additional optical pumping

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The nonlinear polarization self-rotation experienced by an elliptically polarized beam propagating in rubidium vapor is a well known phenomenon. One of its applications is the generation of squeezed light. In this and other applications the ratio R of nonlinearity to absorption is the parameter that should be enhanced. Recently, it was shown theoretically and experimentally that it is possible to increase the value of R in a signal beam tuned to Fg=1 87Rb D2 line by using an additional pump beam tuned at Fg=2, Fe=2 transition. In this article, we show experimentally that R can also be enhanced when the pump is tuned at Fg=1, Fe=0 transition. Configurations with a co- and counter-propagating pump beam are considered. An increment of 2 times in R (with respect to the case without pump), is obtained in the co-propagating case for a pump beam intensity of 0.55mW/mm2. For the counter-propagating case a saturation pump intensity is found after which the value of R decreases. This saturation intensity was predicted by the theory for a pump beam tuned at Fg=2.

The polarization of the pump beam can be changed from perpendicular to parallel with respect to that of the signal beam. The results of this pump polarization change for absorption and nonlinearity curves are shown.

9347-56, Session PTue

Surface characterization studies of orientation patterned ZnSe doped with Cr2+

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ZnSe was grown on top of orientation patterned GaAs. Cr2+ was thermally diffused into ZnSe after it was separated from GaAs. SEM and XPS analyses revealed the surface concentration of Cr2+ to be at least 2% or higher. Elemental analysis revealed the presence of unintentional dopants such as Ti, Ga, Ta etc. SEM analysis did not reveal any variation in Cr2+ concentration on the sample surface. We, in particular, looked for concentration change at the domain boundaries but found none. UV excited photoluminescence revealed band edge luminescence as well as charge transfer bands. Micro Raman studies were performed on the sample surface which revealed some interesting information. Micro-Raman study revealed the LO, TO and 2TA modes at 252, 205 and 140 cm-1. Under 488 or 514.5 nm excitation background luminescence was predominant due to excitation of Cr2+ electrons into the conduction band. However, 632.8 nm laser excitation revealed strong Raman signals superimposed on weak background luminescence. At room temperature phonon coupled transitions excite electrons from the valence band to the Cr2+. As expected background emission decreased when the sample was cooled to 90 K. Raman data were acquired by exciting the sample on the grain boundary and inside the domain, for comparison. LO mode intensity was always stronger. However TO mode intensity acquired from the grain boundary was stronger than that obtained from inside the grain, indicating that the polarizability tensor was distorted on the grain boundary due to inhomogeneity. Raman spectral measurements revealed the presence of local modes in the sample. When Raman data were acquired from different points (in a group of spots) on the sample surface for comparison, it revealed that the LO mode was distorted as well as broadened whereas the TO mode intensity increased. This was due to the presence of local modes induced by the sample inhomogeneity and the interaction of the holes with the LO mode.

9347-57, Session PTue

Double-pump-pass singly resonant optical parametric oscillator for efficient generation of infrared light at 2300 nm based on PPMgSLT

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The pump laser was a cw-diode-pumped, acousto-optically Q-switched Nd:YAG laser operating at 1064 nm. The laser had a pulse width of ~100 ns when operating at 10 kHz repetition rates. For infrared output of 2300 nm, we used 35-mm-long PPMgSLT which has a grating period of 32.7 m for the first-order quasi-phase matching, resulting in the signal wavelength of 1980 nm at the crystal temperature of 76oC.

Our optical parametric oscillator (OPO) was of a simple linear extra-cavity structure, formed by two flat dichroic mirrors with a separation of ~50 mm. The input coupling mirror had a high transmission of 98% for the pump, high reflectance of 98% for the signal and idler, whereas the output coupler had a high reflectance of 98% and high transmission of 80% for the pump and idler. Hence, the OPO can be considered as singly resonant with double-pass pumping. In order to find an optimum reflectance for the efficient generation of infrared radiation of 2300 nm, we used the three different output mirrors whose reflectivity are ranging from 90% to 38% at the signal wavelength. We measured the signal and idler power as a function of the pumping power of Nd:YAG laser for three different output couplers. A maximum extraction efficiency with an optimum reflectance of output mirror was 23% for the idler, corresponding to ~5 W of average output power. The fluctuations in the idler rms output power were measured to be below 1.5%. Our result is comparable with the recent one based on PPLT even with a simple cavity.

9347-58, Session PTue

Generation of third harmonic picosecond pulses at 355 nm by sum frequency mixing in periodically poled MgSLT crystal

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Laser pulses from diode based laser systems in the UV range are of great interest in the fields of microscopy and spectroscopy. Providing UV wavelength pulses at variable repetition frequencies or on demand requires nonlinear frequency conversion in single pass arrangement with a crystal featuring a high effective nonlinear coefficient.

We will show results on high efficient third harmonic generation by sum frequency mixing in a periodically poled magnesium doped stoichiometric lithium tantalate (PPMgSLT) crystal. The generation of third harmonic picosecond pulses at 355 nm is based on the 1062 nm radiation of a gain-switched distributed feedback laser diode which is amplified by a two-stage fiber amplifier. The laser diode is freely triggerable at variable repetition rates up to 80 MHz and provides optical pulses of 65 ps FWHM duration and pulse energies in the range of 5 pJ. The 355 nm third harmonic generation is done in a two-step conversion process. First, the 1062 nm fundamental radiation is frequency-doubled to 531 nm, afterwards both frequencies are mixed in the PPMgSLT crystal to 355 nm. The UV-radiation shows a pulse width of 60 ps FWHM, a good beam profile and stable pulse energy over a wide range of repetition rates by proprietary pump power management. At 355 nm a pulse peak power of 0.26 W was achieved with 30 W and 26 W pulse peak power of the fundamental and second harmonic, respectively.

Because of its good conversion efficiency and beam charakteristcs PPMgSLT is a good choice for generating UV wavelengths by sum frequency mixing.

9347-59, Session PTue

Chalcogenide suspended-core fibers for supercontinuum generation in the mid-infrared

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Recently, chalcogenide optical fibers have gathered great interest because the excellent glass transmission and nonlinear properties in the near- and mid-infrared can be successfully exploited for practical applications. Among

them, the possibility to obtain supercontinuum generation extending up to 10 μm - 12 μm, by choosing a proper glass composition, is particularly attractive. The main drawback of chalcogenide glasses is their very long zero-dispersion wavelength, typically beyond 4.5 μm, which needs to be significantly blue-shifted, through a proper engineering of the fiber waveguide properties to allow efficient pumping with available sources. Suspended-core microstructured optical fibers are ideal candidates for this task, since they provide light guidance in a very small high-NA core, with widely tunable dispersion.

In this work the dispersion and nonlinear properties of chalcogenide suspended-core fibers are deeply investigated by means of simulations carried out with a full-vector modal solver based on the finite-element method. The effects of all the structural parameters, that is the core diameter, the number and thickness of the struts, as well as of different bulk materials are taken into account.

The results show that a proper design of the struts and of the shape of the core can be exploited to significantly shift the zero-dispersion wavelength over a range of several hundreds of nm. Optimization of the fiber parameters will be carried out to provide designs suitable for wide-band supercontinuum generation in the mid-infrared, whose spectral properties will be numerically evaluated.

9347-60, Session PTue

Characterizing germania concentration and structure in fiber soot using multiphoton microscopy and spectroscopy technology

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Ge doping in the core is used to make low loss optical fibers due to its advantages compared to other materials such as superior transparency in near-infrared telecommunication wavelength region. During fiber preform manufacturing using the outside vapor deposition (OVD) process, Ge is doped into silica soot preform by chemical vapor deposition. Since the Ge doping concentration profile is directly correlated with fiber refractive index profile, its characterization is critical for the fiber industry. Electron probe micro-analyzer (EPMA) is a conventional analysis method for characterizing Ge concentration profile, which however requires significant sample preparation and measurement time.

In this paper, multiphoton microscopy techniques are utilized to measure multiphoton fluorescence intensity of soot layers to characterize Ge doping profile. Two samples, one with ramped and another with stepped Ge doping profiles were prepared for measurements. Measured results show that the technique is capable of distinguishing ramped and stepped Ge doping profiles with good accuracy. In the ramped soot sample, a sharp increment of doping level was observed in about 2 mm range from soot edge followed by a relative slow gradient doping accretion. As for the stepped doping sample, stepped sizes ranging from around 1 mm (at soot edge) to 3 mm (at soot center) were observed. All the measured profiles were quantitatively agreed with regular EPMA measurements. In addition, multiphoton spectroscopy was also studied. Both multiphoton fluorescence (around 420 nm) and sharp second harmonic generations (at 532 nm) were observed, which indicates the co-existence of crystal and amorphous Germania.

9347-61, Session PTue

Dissipative collinear weakly coupled acousto-optical states

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We investigate the components of dissipative multi-wave solitons in the form of three-wave weakly coupled states originating within the collinear acousto-optical interaction due to acoustic waves of finite amplitude. This investigation is carried out in a square-law nonlinear birefringent medium with linear optical losses, theoretically and experimentally. Theoretically, we study the three-wave collinear acousto-optical interaction using several acoustic pulse profiles, with the cases of infinite support (when the acoustic pulse envelope is gradually vanishing on the boundaries) and compact support (when acoustic pulse envelope is cut down on the boundaries), and consider the appropriate boundary conditions in a quasi-stationary regime with the phase mismatch. As a theoretical result, one has found that the system can be described; in particular, by the cnoidal Jacobi elliptic functions whose limiting cases lead to hyperbolic and trigonometric solutions.

The experiments dedicated to examine these theoretical results have been done with a X-ray irradiated ?-quartz crystalline cell enabling the collinear acousto-optical interaction. The cell used the pure longitudinal acoustic wave with the frequency mismatch along the 6 cm interaction length. Two types of acoustic pulses had been generated, namely, hyperbolic-secant pulse (infinite support) and a bounded rectangular pulse (compact support). During these experiments one had observed the optical components peculiar to the mismatched weakly coupled states. Rather well agreement between the theoretical model, simulated numerically, and the obtained data of measurements for the frequency detuning, acoustic power density, and efficiency of the coupled states localization have been achieved.

9347-62, Session PTue

Temperature-dependent phase-matching properties with oo-e and oo-o interactions in 5mol% MgO doped congruent LiNbO3

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Although we have reported the Sellmeier and thermo-optic dispersion formulas for the extraordinary ray of a 5mol% MgO doped congruent LiNbO3 (MgO:CLN), there are no accurate temperature-dependent Sellmeier equations for the ordinary ray in this material. For example, the temperature-dependent Sellmeier equations of Gayer et al. [Appl. Phys. B 91, 343 (2008)] give the 90º phase-matching temperature of 53.2? for type-1 SHG of a Nd:YAG laser at 1.0642?m, which is significantly different from our experimental values of 114-118? in the several MgO:CLN crystals supplied by the different companies.

In order to predict the temperature-dependent birefringent (BPM) and quasi phase-matching (QPM) conditions with oo-e and oo-o interactions precisely, we attempted to construct the new Sellmeier and thermo-optic dispersion formulas. Since the crystal to crystal variations of the phase-matching properties have been observed in a MgO:CLN crystal, we measured the temperature-dependent phase-matching wavelengths for type-1 90º phase-matched SHG and SFG, and quasi phase-matched SHG with oo-e (first, third, fifth, and minus first-orders) and oo-o interactions (third-order) by using the MgO:PPLN crystal (?=29.0?m) used in our previous experiment.

From our experimental results, we obtained the Sellmeier and thermo-optic dispersion formulas for the ordinary ray, which provide a good reproduction of our experimental data for BPM and QPM in the 0.41-2.0?m range within an accuracy of less than ±1.5nm.

We will report the temperature sensitivity for the phase-matching conditions with oo-o and oo-e interactions in detail.

9347-63, Session PTue

Temperature-dependent phase-matching properties of 1.3mol% MgO doped stoichiometric LiNbO3

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Although the Sellmeier equations of 1.3mol% MgO doped stoichiometric LiNbO3 (1.3mol%MgO:SLN) have been reported by Nuki et al.[in Nonlinear Optics 2013, OSA, Hawaii, paper NW4A-28], there is no data for the temperature-dependent phase-matching conditions in this material. By using the Nd:YAG laser-pumped KTP/OPO as the pump source, we first measured the temperature-tuned 90°phase-matching SHG wavelengths at 20-120?. The experimental result obtained at 20? was ?1=0.9882?m, which agrees with the theoretical value calculated with our new Sellmeier equations. Our index formula was constructed by taking the refractive index given by Nuki et al. and by adjusting them to give the best fit to our experimental data for the phase-matching conditions in the 0.4155-2.0?m range.

While, the temperature variation of the fundamental wavelength for this process was d?1/dT=2.8?/?, which is also in good agreement with the theoretical value (d?1/dT=2.9?/?) calculated with our thermo-optic dispersion formula for a 5mol% MgO doped congruent LiNbO3 (5mol%MgO:CLN). This result indicates that our thermo-optic dispersion formula for a 5mol%MgO:CLN was highly useful for predicting the temperature phase-matching conditions of a stoichiometric LiNbO3. In order to confirm the validity of our thermo-optic dispersion formula in another LiNbO3 crystal, we made the same experiments in the undoped stoichiometric LiNbO3 fabricated by vapor transport equilibration (VTE:SLN). As a result, the temperature variation of the 90°phase-matching wavelengths for type-1 SHG was d?1/dT=2.86?/?, which agrees with the theoretical values calculated with the aforementioned thermo-optic dispersion formula in the VTE:SLN crystal.

In this presentation, we report the temperature-dependent phase-matching conditions of the 1.3mol%SLN and VTE:SLN together with the Sellmeier equations for these crystals.

9347-64, Session PTue

Polarization tunable spatial and angular Goos-Hänchen shift and Imbert-Fedorov shift using long range surface plasmon

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A new proposal towards the polarization tunable Goos-Hänchen (GH) and Imbert-Fedorov (IF) spatial and angular shifts is explored analytically in a four layer Kretschmann-Raether geometry comprising a ZnSe prism, a dielectric layer of PMMA-DR1 (Polymethylmthacryalate-Disperse red) and two metal layers of silver having thicknesses of 50 nm and 200 nm respectively. Observations from the different graphical representations reveal that in correspondence of the long range surface plasmon (LRSP) resonant angle both spatial and angular GH shifts get appreciably enhanced in case of p polarized light whereas negligible or very less amplification of spatial and angular GH shifts are obtained for s polarized light. With the switching of polarization of the incident light beam on the proposed configuration through the half wave plate, the spatial and angular GH shift is tuned from -17.35 ?m to 0.105 μm and -0.631 ?rad to 4.28 nrad respectively and the spatial and angular IF shift is tuned from 94.16 ?m to -53.58 ?m and about 7.774 ?rad to -11.17 ?rad respectively. To the best of our knowledge, several articles have been devoted for depicting the GH shift without considering the IF shift, whereas the exact beam position of the output beam can only be identified with the composite effect of GH and IF spatial and angular shifts. The above new proposal can be implemented in the field of fine tuning of optical switching at the ?m ranges with varying polarization, optical sensors applications and serves interesting opportunities to make atomic mirrors.

9347-65, Session PTue

Effect of surfactants on the emission properties of ZnO: Mn3O4 nanocomposites

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Nanocomposites of metal oxide semiconductors are multifunctional and one such nanocomposite ZnO: Mn3O4 (2:1) was synthesized by the coprecipitaion route. The prepared nanocomposites are coded as ZMA4 (ZnO: Mn3O4¬ using ammonia), ZMH4 (ZnO: Mn3O4¬ using hexamine) and are compared with pure ZnO (ZA and ZH). XRD reveals the crystal structure of ZnO (hexagonal) and Mn3O4 (tetragonal). By Scherrer formula, the average crystallite size is estimated as 43, 12, 42 and 18 nm for ZA, ZMA4, ZH and ZMH4 respectively. FTIR peaks at 440-490 cm-1 and 616-621cm-1 are due to Zn-O and Mn-O vibrational bands. Presence of manganese in ZnO nanocomposites is confirmed by EDS. SEM data indicate the formation of nanoparticles (ZA and ZMA4) and nanorods (ZH-98 nm length, 63 nm dia). Excitonic absorption peaks at 370 and 290 nm in UV-Vis spectra are attributed to ZnO and Mn3O4 nanocomposites. The bandgap is estimated as 2.7, 2.3, 2.6 and 3.0 eV for ZA, ZMA4, ZH and ZMH4 respectively. FL spectra of ZA, ZMA4 expose the emission at 366 and 396 nm owing to the near band edge (NBE) and zinc interstitial at 468 nm. ZH nanorods show the emission at 386, 468 and 558 nm which are attributed to NBE, zinc interstitial and oxygen vacancy respectively. The reduction of oxygen vacancy is observed in ZMH4 as manganese effectively changes the morphology from nanorod to nanoparticle. The second harmonic generation efficiency measured for ZA and ZH is 0.6 and 0.9 times KDP using Q - switched Nd: YAG laser (1064nm, 10 Hz, 9 ns).

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9347-66, Session PTue

Self-focusing effect on THG at interfaces of solvent-cuvette

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Third-harmonic generation (THG) has been widely explored for basic material characterization and for applied purpose such as in the THG microscopy. Recently, we have suggested the THG in a slab interface is strongly affected by the self-focusing effect at the output interface. In the present communication we report on new results on third harmonic (TH) generated at tightly focused condition in a quartz cell in order to investigate the self-focusing contribution in this arrangement. As it is well known, at such thick sample condition the THG occurs only at interfaces due to the Gouy phase shift. Then, TH is observed when there is a discontinuity in the nonlinearity that is the case of the interface of two different materials. Using a quartz cuvette filled with solvents we have four different interfaces which can be studied independently. We report here the TH intensity and beam waist radius behavior at function of input laser power and the results are interpreted in terms of THG theory and self-focusing effect contribution. By mean of TH signal and slope at function of pump intensity, we could estimate the solvents nonlinearity and we also observed that the beam waist

behavior is slightly different from one observed in slabs. As light source we have used pulses at 1300 nm, 1 kHz repetition rate with 120 fs-duration delivered by a commercial optical parametric amplifier pumped by an amplified 150-fs Ti:sapphire laser at 775 nm.

9347-67, Session PTue

Supercontinuum from single- and double-scale fiber laser pulses in long extra-cavity P2O5-doped silica fiber

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The present work has, for the first time, studied efficiency of non-linear transformation of single- and double-scale fibre laser pulses in the process of supercontinuum formation due to cascaded stimulated Raman scattering (SRS) in a 1.2-km extra-cavity fiber with a 6-μm core. It is demonstrated that 3-ps single-scale pulses and double-scale pulses with a 8-ps envelope generated in one fiber laser mode-locked due to non-linear polarisation evolution at different polarisation controller settings undergo substantially different SRS in a long fiber and, as a consequence, supercontinua initiated by these pulses differ in both spectral and temporal intensity distribution. Spectrally broader supercontinua (up to 300 nm wide) were produced by double-scale pulse pumping, which indicates better efficiency of non-linear transformation of these pulses compared to single-scale pulses and opens new opportunities for practical application of double-scale pulses. This work presents properties of temporal distributions of radiation intensity of single- and double-scale pulse-induced supercontinuum at different average input powers, topping at 840 mW. Examination of the temporal structure of SRS-induced supercontinuum pulses pumped with double-scale pulses demonstrated the presence in the temporal intensity profile of the output radiation of a relatively narrow (< 0.5 ns) pronounced peak shifting towards the rear edge of the pulse at higher pumping pulse power and corresponding to residual pump radiation.

9347-68, Session PTue

Flat mid-infrared supercontinuum generation in tapered fiber with thin coating of highly nonlinear glass

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The generation of supercontinuum (SC) mid-infrared light has attracted intense interest due to its numerous applications, in spectroscopy, sensing, optical frequency metrology, optical communications and optical coherence tomography. Research has been focused on the utilization of highly nonlinear characteristics of conventional lightwave mediums such as photonic crystal fibers and highly non linear fibers, where their operation is limited by the length of the fiber, the waveguide optical characteristics (e.g. dispersion profile) and the high input power which is necessary in order to turn on the corresponding non linear processes.

Here is proposed a simple and efficient platform based on SMF tapered fiber (by means of heating and stretching in a flame). Typical tapered fibers of 90mm uniform waist of 1 ?m diameter, exhibiting an effective area of ~1 ?m2 and the large effective-index between the silica and air, promotes the non linear characteristics of the taper, offering a desirable SC spectra when it is coupled with ultrashort pulse source. Enhancement of nonlinear processes of such small core fiber tapers is achieved through the deposition of thin layers made by high nonlinear glasses (HNG), on the taper surfaces, increasing further the effective index difference between the silica core and the covering layer. Furthermore the group velocity dispersion (GVD) of the fundamental guided mode is reduced or transferred in the anomalous region at mid - infrared wavelengths, expanding the SC capabilities of the proposed platform. The generation of a flat, octave spanning supercontinuum extending from 750 nm to 2750nm (at -20dB) has been theoretically demonstrated.

9347-69, Session PTue

High power narrow linewidth monolithic PM fiber lasers in 1μm region for nonlinear frequency conversion

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We report high power monolithic linearly polarized fiber laser in 1 ?m region. The dependence of the polarization extinction ratio (PER) on the laser power was theoretically and experimentally investigated. In CW regime, we achieved >500 W with narrow linewidth (< 0.2 nm) and near diffraction-limited beam quality. Also, we implemented the monolithic linearly polarized ns pulsed fiber laser with tens of kW peak power. These CW and pulsed fiber lasers can be used for nonlinear frequency conversion.

9347-22, Session 7

6.5W mid-infrared ZnGeP2 parametric oscillator directly pumped by a Q-switched Tm3+-doped single-oscillator fiber laser

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The direct pumping of nonlinear frequency converters like OP-GaAs or ZnGeP2 (ZGP) by pulsed 2 μm single oscillator fiber lasers is a very promising way to efficiently generate mid-IR radiation (3-5 μm) in a highly compact and robust manner. We have already demonstrated 2.2 W of average power from a OP-GaAs OPO directly pumped by a Q-switched Tm3+,Ho3+-codoped single-oscillator fiber laser. Using a polarization-maintaining (PM) Tm3+-doped fiber and PM components, we recently simplified and increased the efficiency of the whole pumping setup.

The Tm3+-fiber pump laser based on a silica polarization-maintaining double-clad fiber provided average powers of up to 23 W at pulse widths of 65 ns at 40 kHz repetition rate. The LP02 higher order transverse mode was supported by the fiber. TheTm3+:fiber laser beam propagation-factor, M2, was measured for 10 W of average output power at 40 kHz and yielded M2x = 1.7 and M2y = 1.7. At 40 kHz repetition rate, for 20 W of average pump power, up to 6.5 W of average power was generated between 3 and 5 ?m corresponding to a slope efficiency of 40% where up so far only 3 W have been reported elsewhere using complex MOPA architectures as the pump. The threshold corresponds to an average pump power of 2.4 W. The OPO (fiber laser) power stability measured over 6 minutes was better than 1% (0.35%).A 65 ns pump pulse generates a 45 ns mid-IR pulse. M? values around 2 and 2.5 were measured for the signal and the idler beams.

9347-23, Session 7

Cascaded OPGaAs OPO for increased longwave efficiency

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Optical parametric oscillators (OPOs) producing longwave output from a much shorter pump wavelength suffer from low conversion efficiency into the idler due to the large quantum defect compared with similar devices operating in the 3 – 5 μm regime. One method to increase pump to idler conversion efficiency is to recycle the undesired and higher energy signal photons into additional idler photons in a second nonlinear stage. We present numerical simulation results showing the improvement in efficiency that can be obtained in a linear, two stage, cascaded orientation patterned gallium arsenide (OPGaAs) nanosecond OPO. Here, the signal generated in the first crystal is used to pump a second crystal within the same OPO cavity, patterned to produce the same idler generated in the first crystal. The numerical model implements a split step integration method where, with small enough step size through the crystal, the linear propagation and nonlinear mixing steps can be calculated independently. It includes diffraction, crystal loss, phase mismatch, pump depletion, and backconversion; and it assumes monochromatic waves but it neglects group velocity dispersion. For a singly resonant oscillator (SRO) pumped by a 2.054 μm Tm:Ho,YLF laser with 45 ns pulse widths, the addition of the second crystal in the cavity increases idler generation by over a factor of two and exceeds the quantum defect limit. The model has been validated by comparison with SNLO for the case of a single-stage OPO, and suggests crystal and resonator parameters that will lead to an optimized cascaded OPO.

9347-24, Session 7

High average power difference-frequency generation of picosecond mid-IR pulses at 80MHz using an Yb-fiber laser pumped optical parametric oscillator

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We present an efficient coherent source widely tunable in the mid-infrared spectral range consisting of a commercial picosecond Yb-fiber laser operating at 80 MHz repetition rate, a synchronously-pumped OPO (SPOPO) and difference-frequency generation (DFG) in AgGaSe2. With an average input pump power of 7.8 W at 1032 nm, the SPOPO outputs are tunable from 1380 to 1980 nm (Signal) and from 2.1 to ~4 μm (Idler) with pulse durations between 2.1 and 2.6 ps over the entire tuning range. After temporally overlapping Signal and Idler through a delay line, the two beams are spatially recombined with a dichroic mirror (reflecting for the Signal in s-polarization and transmitting for the Idler in p-polarization), and focused by a 150 mm CaF2 lens to a common focus. For DFG we employ an AR-coated 10-mm thick AgGaSe2 nonlinear crystal cut for type-I interaction at ? =52°. The generated mid-infrared picosecond pulses are continuously tunable between 5 and 18 μm with average power at 80 MHz up to 140 mW at 6 μm and more than 1 mW at 18 μm. Their spectra and autocorrelation traces are measured up to 15 μm and 11 μm, respectively, and indicate that the input spectral bandwidth and pulse duration are maintained to a great extent in the nonlinear frequency conversion processes. The pulse duration slightly decreases from 2.1 to 1.8 ps at 7.2 μm while the spectral bandwidth supports ~1.5 ps durations across the entire mid-infrared tuning range. For the first time narrow-band mid-infrared pulses with energy exceeding 1nJ are generated at such high repetition rates.

9347-25, Session 7

Power scaling in a mid-IR OPO, pumped by high power Tm:fiber MOPA system

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In this work, we investigate the constraints that limit both average and peak power scaling in a doubly resonant OPO pumped by nanosecond thulium-doped fiber laser MOPA systems. Two different laser systems and two different OPO crystals are compared. One maximizes peak power, utilizing large mode area photonic crystal fiber with 50-μm core diameter capable of supporting peak powers >100 kW with minimal spectral distortion. Unfortunately, these PCFs have been limited by relatively poor efficiency and therefor have been generally limited to <10 W average power. The second system utilizes a step-index large mode area fiber with 25-μm core diameter. This system is capable of producing 100 W average power, but the nonlinear effects limit the peak power to ~25 kW.

In terms of nonlinear crystals, mid-IR OPOs based on ZnGeP (ZGP) are better suited for high energy applications as the crystal clear aperture can be scaled to relatively large area; however absorption for pump wavelengths ≤2000 nm leads to significant thermal lensing and therefor limits average power scalability. By comparison, OPOs based upon orientation patterned GaAs (OPGaAs) has higher thermal conductivity and lower absorption when pumped by Tm-based lasers operating at 1900-2000 nm wavelengths; however fabrication limits the clear aperture of these crystals to <600-μm thickness.

9347-26, Session 8

Second harmonic generation from metamaterials strongly coupled to intersubband transitions in quantum wells *(Invited Paper)*

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We theoretically and experimentally analyze the second harmonic generation capacity of two-dimensional periodic metamaterials comprising sub-wavelength resonators strongly coupled to intersubband transitions in quantum wells (QWs). The metamaterial is designed to support both a fundamental resonance and an orthogonally polarized resonance at the second harmonic frequency to provide beam-polarization manipulation flexibility. The asymmetric QW structure is designed to provide a large second order susceptibility. Due to the sub-wavelength extent of our QW structure, we are not limited by phase matching conditions as one would have for a conventional nonlinear crystal. Upon continuous wave illumination at the fundamental frequency we observe second harmonic signals in both the forward and backward directions. We achieve very efficient overall second harmonic generation given the deep sub-wavelength dimensions of the QW structure (at mid-infrared, about 1/15th of the free space wavelength of 10 μm). Such systems represent a viable strategy for designing easily fabricated sources across the entire infrared spectrum through proper choice of QW and resonator designs.

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Portions of this work were supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

9347-27, Session 8

Adiabatic nonlinear optical processes *(Invited Paper)*

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Recently, adiabatic methods have been used in order to control the evolution of nonlinear optical processes. In these methods, a system parameter is changed very slowly as compared to the system dynamics. Adiabatic schemes have been experimentally demonstrated to achieve very efficient (near 100% efficiency within the undepleted pump regime) and broadband frequency conversion of ultrashort pulse lasers.

In the last few years, we have extended the basic scheme to include multiple processes, resulting in novel phenomena, such as intensity-dependent phase-matching for three wave mixing and conversion through dark frequencies. The latter was also demonstrated experimentally, indicating that conversion through absorptive frequency bands is possible. Furthermore, we have experimentally achieved simultaneous control over multiple efficient and broadband conversion processes.

Most recently, we developed a generalized, comprehensive and rigorous Hamiltonian model, which removes the undepleted pump restriction from adiabatic evolution. Within the framework of this model, we established a scheme for adiabatic frequency conversion, in the most general three wave mixing interaction regime. The generality of this approach makes it applicable to any and all three wave mixing processes: sum frequency generation, difference frequency generation, second harmonic generation and optical parametric amplification. Consequently, the bandwidth and efficiency of ultrabroadband frequency conversion can reach new records, as has been shown experimentally by several groups in the past year.

9347-28, Session 8

Design and results of a dual-gas quasi-phase matching (QPM) foil target

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Quasi-phase matching (QPM) can be used to increase the conversion efficiency of the high harmonic generation (HHG) process [1,2,3]. An improved dual-gas quasi-phase matching (QPM) foil target for high harmonic generation has been developed. It can be setup with 12 individual gas jets separated by a minimum distance of 10 μm. The gas density profile was measured in three dimensions with a Mach-Zehnder Interferometer. This measurement demonstrates how the jets influence the density of gas in adjacent jets. The jet properties, such as size and density, were preserved up to 300 ?m from the target exit. With a 1kHz-10mJ-30fs-laser system an increased harmonic conversion efficiency in the 17-30 nm spectral range was observed. In particular, a strong enhancement factor of 6 was possible with neon and hydrogen for the 45th harmonic.

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9347-29, Session 8

Co-existence of harmonic generation and two-photon luminescence in selectively grown coaxial InGaN/GaN quantum wells on GaN pyramids

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We report the generation of tunable coherent light along with white light based on the nonlinear optical properties of hybrid GaN/InGaN and ZnO based wide bandgap semiconductors. Nonlinear optical properties of selectively grown coaxial InGaN/GaN multiple quantum well (MQWs) submicron hetero-structures were investigated using a tunable near-infrared femtosecond laser source at room temperature. Co-axial InGaN/GaN MQW hetero-structures were fabricated by depositing InGaN/GaN layers on GaN submicron tubes using selective growth of GaN submicron tubes on the top of GaN micro-pyramids. The GaN pyramids were fabricated using photolithography and epitaxial lateral overgrowth technique. ZnO submicron rods grown on GaN pyramids using vapor transport method were used as templates for the growth of GaN/InGaN MQWs. Excitation and signal collection from a single micro-structure was achieved using multi-photon microscopy/spectroscopy. Simultaneous generation of second harmonic signal (SHG) and multi-photon induced luminescence (MPL) were observed in InGaN/GaN co-axial MQW structures for off resonant excitations from 1.5 eV – 1.42 eV, whereas only MPL was observed for excitations close to resonance. The characteristics of the SHG photons at energies below the bandgap of ZnO/GaN are dependent on the excitation as well as the surface morphology of the orientation of GaN pyramids and the InGaN/GaN co-axial MQW structures. Broadband white light emission due to MPL or selective coherent SHG light generation can be controlled by selective spatial excitation of the MQWs on the pyramids.

9347-30, Session 8

Increased distributed sensing sensitivity using higher order stimulated Brillouin scattering

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Research groups have focused on increasing the spatial resolution and potential reach of distributed temperature and strain sensors (DTSS) based on Brillouin scattering (BS). A current reach of several 10's of kilometers with real-time data acquisition for a spatial resolution of a few cm's is possible with this technology. However, sensitivity of these types of sensors has remained more or less constant over the years. We recently proposed a new scheme [1] that could be potentially integrated into a DTSS Brillouin sensor to further improve the sensitivity, with a possibility of early fault detection. That first system for temperature sensing was demonstrated with an increase of 6 ? the standard sensitivity of currently available DTSS Brillouin based sensors. In this paper, we demonstrate a similar increase in strain sensitivity, and a fully distributed sensor for the first time. Typical DTSSs are capable of sensitivities to temperature and strain of ~1.3 MHz/°C and ~0.046MHz/μ?, respectively in standard fiber. We propose here this new technique using higher order Stokes shifts of SBS [2], to dramatically increase the sensitivity by the order of the Stokes shift, without significantly affecting the resolution of the sensor. Preliminary measurements show an increase in the Brillouin frequency shift's temperature and strain sensitivity as a function of the order of the higher Stokes wave. We propose a way to incorporate this device in a BOTDR DTSS system, giving the ability to detect temperature or strain change with a higher sensitivity than currently available commercially.

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9347-31, Session 9

Quantum optical arbitrary waveform manipulation and measurement in real time *(Invited Paper)*

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We present numerical and experimental evidence of a quantum optical technique capable of manipulating and measuring arbitrary optical waveforms in real time while, in principle, being lossless and free of background noise. In our design the signals are manipulated through quantum frequency conversion (QFC) processes tailored by shaped classical pump pulses, which are created by using optical arbitrary waveform generators (OAWGs). This allows to fine tune the QFC process for realizing coherent operations on individual or on superpositions of quantum modes in arbitrary waveforms. As examples, we first utilize the OAWG device to generate custom-tailored pump pulses for selectively upconverting optical quantum states in arbitrary temporal profiles. Then, by passing a quantum signal sequentially through multiple QFC stages each driven by pump pulses generated via OAWG, we numerically demonstrate mode-resolved photon counting of the signal. Moreover, we show that high-efficiency, essentially lossless reshaping of quantum optical waveforms is also possible, which represents an essential resource for interfacing disparate architectures in networked quantum applications. We emphasize that owing to the development of dynamic OAWG devices, those operations can be implemented in "real time," i.e., the converted modes can be updated at a GHz rate or higher. Finally, we report on experimental progress to distinguish two overlapping temporal modes of orthogonal shape, demonstrating an over 8 dB extinction between picosecond modes, which agrees well with our theory. Our technique could lead to exciting applications in ultra-efficient secure information processing, particularly quantum key distribution using high-dimensional temporal modes.

9347-32, Session 9

New nonlinear signal processing schemes based on photonic-phononic emitter-receivers in silicon *(Invited Paper)*

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Optical forces mediated phononic modes provide new ways to approach to optical signal processing technologies via photon-phonon interactions, and recent investigations in Nonlinear Optics and Optomechanics show greatly enhanced photon-phonon interactions in a variety of micro-and nano-scale systems. We will discuss optical forces and nonlinear effects including stimulated Brillouin scattering in micro- and nano-scale systems. We will present our recent first-ever demonstration of the photonic-phononic emitter-receiver (PPER) system in multi-port silicon Brillouin-active membrane waveguides. The new mechanism of photon-phonon emitting-receiving process yields at first the signal conversion from photon domain to phonon domain in the emitter port, then the shaping and transduction of coherent phononic information between two distinct optical waveguides, and at last the signal conversion back to optical domain in the receiver port. The theoretical and experimental research results show that the PPER systems have the second-order response function which is a powerful advantage for the potential applications including highly selective RF photonic filters. In addition, the traveling-wave scheme of the PPER systems yields high power handling and wavelength (frequency) insensitivity with unrivaled combination of high dynamic range, selectivity, and linewidth. Furthermore, the geometry of the PPER systems allows independent control of photonic and phononic modes, so that we can readily design PPER devices to have the desired performance with an unprecedented degree of tailorability. The controllable photon-phonon interaction in the PPER systems could provide a host of new optical signal processing technologies.

9347-33, Session 9

Second harmonic generation at oblique angles in photonic bandgap structures

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A generalization of the transfer matrix method is developed to analyze the phenomenon of second harmonic generation in multilayer nonlinear photonic bandgap (PBG) structures. The case of a monochromatic fundamental frequency plane wave incident on the multilayer, nonlinear PBG structure with arbitrary incidence angle is treated. The corresponding type 0 second-harmonic wave is generated through the nonlinear polarization induced by the fundamental wave with its specific angle. The proposed transfer matrix method takes into account reflections and interference between forward and backward propagation waves. The conversion efficiency is calculated as a function of the incident angle of the fundamental and the thickness of the nonlinear material. Specific incident angles and thicknesses may generate relatively high conversion efficiency inside of nonlinear material. Our analysis provides upper bounds on pump wave intensity for a given incidence angle and sample thickness where the undepleted pump approximation can be used to model such a 1-D nonlinear structure.

9347-34, Session 9

Second harmonic generation of a random fiber laser with Raman gain

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Random fiber lasers have attracted great deal of attention due to ultimate simplicity of their structure and unique features of the generated radiation. In contrast to conventional Raman fiber laser with linear cavity formed by point mirrors, e.g. fiber Bragg gratings (FBGs), random fiber lasers operate via distributed feedback provided by Rayleigh backscattering in cavity-free passive fibers with Raman gain that is also distributed along the fiber. Such random fiber lasers generate quasi-continuous spectrum (without mode structure) with relatively narrow bandwidth (~1 nm) without spectrally selective elements. Moreover, they are easily tunable within broad Raman gain peak (~50 nm) exhibiting very flat tuning curve. These features make random fiber lasers very attractive for applications such as bio-medical diagnostics, imaging or laser displays, but they usually require visible light, while fiber lasers operate in near infrared region.

Here we report on the first experimental demonstration of second harmonic generation (SHG) with random fiber laser as a pump source. We explore random lasing in a phosphosilicate fiber with Raman gain at 1308 nm. SHG

power of >100 mW at 654 nm has been obtained in PPLN pumped by ~7 W laser power. The SHG beam is stable, high-quality (M^2<1.3), herewith its spectrum has no mode structure within SHG bandwidth of ~0.5 nm that is quite different from conventional Raman fiber laser with FBG cavity. Direct comparison of two laser configurations (with and without cavity) demonstrates better parameters of the random fiber laser with great potential for applications requiring low-coherence visible light.

9347-35, Session 9

Mechanisms for forbidden hyper-Rayleigh scattering

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Hyper-Rayleigh scattering (HRS) is an incoherent variant of second harmonic generation. The theory involves terms of increasing order of optical nonlinearity: for molecules or unit cells that are centrosymmetric, and which accordingly lack even-order susceptibilities, HRS is often regarded as formally forbidden. However, for the three-photon interaction, theory based on the standard electric dipole approximation, represented as E13, does not include the detail required to describe what is observed experimentally, in the absence of a static field. New results emerge upon extending the theory to include E12E2 and E12M1, incorporating one electric quadrupolar or magnetic dipolar interaction respectively. Both additional interactions require the deployment of higher orders in the multipole expansion to govern these processes, with the E12E2 interaction analogous in rank and parity to a four-wave susceptibility. A key feature of the present work is its foundation upon a formal tensor derivation which does not oversimplify the molecular components, yet leads to results whose interpretation can be correlated with experimental observations. Results are summarised for the perpendicular detection of both parallel and perpendicular polarizations. Using such methods to investigate molecular systems that might have useful nonlinear characteristics, HRS therefore provides a route to data with direct physical interpretation, to enable more sophisticated design of molecules with sought optical properties.

9347-36, Session 10

Vacuum-UV to IR supercontinuum generated by impulsive Raman self-scattering in hydrogen-filled photonic crystal fibre *(Invited Paper)*

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Many areas of biology and physics would benefit greatly from the availability of compact and spectrally bright sources in deep UV (DUV; ~200 – 300 nm) and vacuum UV (VUV; 100 – 200 nm) spectral region [1–3]. Although supercontinuum sources are readily available for the visible and near-IR [4], and recently also for the mid-IR [5,6], they have not yet been demonstrated in the DUV or the VUV, mainly limited optical transparency and cumulative optical damage of the optical materials when delivering UV light. In my contribution I will report on our recent results in the generation of a bright supercontinuum spanning more than three octaves from 125 nm to beyond 1200 nm [7]. The technique involves launching few-μJ, 30 fs, 800 nm pulses into a hydrogen-filled, broadband-guiding hollow-core photonic crystal fibre, where they undergo Raman-enhanced self-compression. Modelling indicates that before reaching a minimum pulse duration of ~1 fs – much less than one period of molecular vibration (8 fs) – nonlinear reshaping of the pulse envelope, accentuated by self-steepening and shock formation, causes impulsive and "displacive" excitation of the vibrational Raman coherence. This strongly modulates the trailing edge of the pulse, resulting in dramatic spectral broadening.

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[2] J. C. Travers et al., "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers [Invited]," JOSA B 28, A11-A26 (2011).

[3] K. F. Mak et al., "Tunable vacuum-UV to visible ultrafast pulse source based on gas-filled Kagomé-PCF", Opt. Express 21, 10942 (2013).

[4] J. K. Ranka et al., "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," Opt. Lett. 25, 25-27 (2000).

[5] C. Xia et al., "Mid-Infrared supercontinuum generation to 4.5 ?m in ZBLAN fluoride fibers by nanosecond diode pumping," Opt. Lett. 31, 2553-2555 (2006).

[6] X. Jiang et al, "Close to three-octave-spanning supercontinuum generated in ZBLAN photonic crystal fiber [Post-deadline]," Mid-Infrared Coherent Sources (MICS), JTh5A.6, Paris (2013).

[7] F. Belli et al, "Vacuum UV to IR supercontinuum generation by impulsive Raman self-scattering in hydrogen-filled PCF [Invited]," Conference on Lasers and Electro-Optics (CLEO), FW1D.1, San Jose, CA (2014).

9347-37, Session 10

Analysis of a low-cost technique for the generation of broadband spectra with adjustable spectral width in optical fibers

Roberto Rojas-Laguna, Juan C. Hernández-Garcia, Julián Móises M. Estudillo-Ayala, Univ. de Guanajuato (Mexico); Baldemar Ibarra-Escamilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Olivier J. M. Pottiez, Ctr. de Investigaciones en Óptica, A.C. (Mexico); Everardo Vargas-Rodríguez, Alejandro Barrientos-Garcia, Univ. de Guanajuato (Mexico)

In this work we provide an experimental study of the nonlinear processes involved in the generation of a broadband spectrum with selectable spectral width. The wide spectrum source was generated in a relatively short length of SMF-28 fiber as a nonlinear medium pumped by a microchip Q-switched pulsed laser at 1064 nm (operating in ps regime). The proposed optical setup shows that is possible to control the spectral width based in filtering the broad spectrum through inducing a mechanical stress in the optical fiber. In this case, two different lengths of SMF-28, 30 m and 50 m, were considered in the setup for the generation of continuum spectra. Bending effects in the spectra were observed through wrapping the fibers on a cylindrical tube with different diameters. We demonstrated that the spectral characteristics of the broadband spectrum directly depend on the properties of the nonlinear medium and the excited nonlinear effects. In the experimental results we observe that it is possible increase or decrease the spectral width for a maximum selectable spectral above 892 nm (808 nm to over 1700 nm) for 50 m of fiber length, and 468 nm (1050 nm to 1518 nm) using 30 m of SMF-28 fiber obtaining a high spectral flatness. Finally, the main advantages of the proposed technique in this work are; obtaining the desired bandwidth for a supercontinuum light source through an easy and flexible control, and achieving low-cost configuration in which photonic crystal fibers are not used.

9347-38, Session 10

High sensitivity mid-infrared incoherent broadband cavity enhanced absorption spectroscopy with a supercontinuum source

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Broadband cavity enhanced absorption spectroscopy can be used to perform detection of gases with a very high sensitivity due to the very long optical path of the cavity. Compared to coherent methods, cavity enhanced absorption spectroscopy is simpler and more robust allowing to readily perform in-situ measurements. Supercontinuum sources on the other hand possess unique properties in terms of brightness and spatial coherence that make them particularly suitable for a wide range of applications ranging from spectroscopy and imaging to metrology and communications.

Here we demonstrate for the first time cavity enhanced absorption spectroscopy in the mid-IR wavelength range using a specifically developed supercontinuum source. The source is based on a gain-switched nanosecond fiber laser operating at 1545 nm and the combination of a silica-based dispersion shifted fiber and fluoride fiber that possesses low absorption in the mid-IR range. The result is an incoherent fiber-based broadband source that extends from c.a. 1 to 3.5 microns and with a total average power of 160 mW. Using a one meter-long near-confocal cavity with mirrors specifically designed with a 99.9% reflectivity at around 3.3 microns we measure the absorption spectrum of methane over the full 3.1-3-3 micron range with a high accuracy. Our technique has the potential to perform selective multi-component measurement with extreme sensitivity in the mid-IR spectral range.

9347-39, Session 10

Interferometric coherence measurement and radio frequency noise characterization of the 1.3 μm femtosecond intense Stokes continuum from a TZDW source

Yuhong Yao, Wayne H. Knox, Univ. of Rochester (United States)

Photonic crystal fiber (PCF) with two closely spaced zero dispersion wavelengths (TZDW) offers a unique route to efficient energy transfer to two spectrally localized continua beyond either side of the ZDWs, which we have employed in previous work for mid-IR difference frequency generation. In this manuscript, we report the full experimental characterization of amplitude noise and spectral coherence of the Stokes side TZDW component. With a custom-built 1.3 W, 1035 nm, 40 MHz, 240 fs Yb:fiber chirped pulse amplifier as the pump source, we use 12 cm of commercially available TZDW PCF to excite the dual narrow-band continua from which the Stokes pulse is filtered out with a 1180 nm long wave pass filter. We achieve 0.8 to 3 nJ of narrow-band pulses within the spectral range of 1200 – 1315 nm at an average power conversion efficiency of 33%. Its measured mutual spectral coherence is in excess of 0.76 with pump Soliton order as high as N ~70. Its measured RF noise spectrum at the first harmonic of the laser repetition rate shows less than 5 dBc/Hz higher RIN compared to that of the power amplifier, which is consistent with reported studies employing sub-100 fs pulses from relatively low noise oscillators. In contrast to the broadband continuum from a single ZDW PCF where severe noise amplification is found with pumping at high soliton order and longer pump pulse width, the reported TZDW fiber source shows preservation of intensity stability and phase coherence against variation in pump pulse parameters, which not only attests to the stability of our reported method for mid-IR generation, but also shows promising potential towards an all-fiber, efficient and low noise ultrafast source that can be helpful for applications such as biomedical deep-tissue imaging.

9347-40, Session 11

Passive noise suppression in cascaded Raman fiber lasers

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The next generation of gravitational wave detectors will most probably use lasers at 1.5μm to improve their sensitivity. Due to the requirements of such detectors, diffraction limited, single frequency, high power and low-noise laser sources are needed. Er-doped fiber amplifiers at 1.5μm are a promising candidate to fulfill these requirements, although additional external stabilization may be needed to reach the desired noise levels. High power cascaded Raman fiber lasers at 1.48μm can be used to pump Er-doped fiber amplifiers and by previous work we know that especially the low-frequency noise of the Raman laser will couple to the output power of the fiber amplifier at 1.5μm. In this contribution, we present a method to decrease the low-frequency noise of cascaded Raman fiber lasers by using a parasitic Stokes order. Above the threshold of the parasitic Stokes order the output power of the previous Stokes order is, in the best case, almost insensitive to any change of pump power. Thus, depending on the resonator design, the low-frequency noise coupled in from the pump laser is suppressed passively. We present experimentally obtained transfer functions in the range of 10Hz-100kHz that confirm this suppression. In addition, due to the fact that to the best of our knowledge no analytical solution of the problem exists, we also present numerically obtained results. By solving the time dependent boundary value problem some general relations between the resonator design and the most important parameters of the noise suppression, the strength and the cut-off frequency, can be found.

9347-41, Session 11

Femtosecond diamond Raman lasers

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We have demonstrated the first synchronously-pumped femtosecond Raman laser. A Ti:Sapphire laser that generated 3.5 W output power at 800 nm and 180 fs pulse duration was used as the pumping source. Raman-shifted in CVD-diamond to the first-Stokes at 895 nm, up to 800 mW output power was achieved for the first-Stokes, corresponding to a 33% slope efficiency. The bandwidth of the Stokes output was greatly broadened and chirped, and was subsequently compression to 67 fs using a prism pair.

The first-Stokes field can be cascaded to second-Stokes by using different sets of mirrors for the synchronous Raman cavity. Our preliminary experiments have obtained more than 600 mW output power for the second-Stokes field with a broad spectrum spanning from 992 – 1029nm.

Modelling results suggest that self-phase modulation drives the broadening of the Stokes spectrum in this highly transient Raman laser. The strong self-phase modulation in the Raman cavity could be exploited with anomalous-GVD to generate a Raman soliton laser, potentially providing shorter Stokes pulses in this regime.

Our results have demonstrated the potential for Raman conversion to extend the wavelength coverage and pulse shorten Ti:sapphire lasers. Raman shifting of a Ti:sapphire laser tunable from 700 to 950 nm would provide continuous coverage out to 1271 nm using a second-order-Stokes Raman laser, and to 1531 nm using the third order. Furthermore, cascaded Raman lasers generating femtosecond pulses at multiple wavelengths simultaneously enable some applications such as multi-colour, multi-photon imaging.

9347-42, Session 11

Diode side pumped, quasi-CW Nd:YVO4 self-Raman laser operating at 1176 nm

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Solid-state Raman lasers provide a practical way to shift the wavelength of the fundamental laser line to longer wavelengths. When combined with nonlinear conversion processes this techniques enables emission of hard to reach colors in the visible spectral range. The most compact, simple and low-cost Raman lasers are the self-Raman lasers, in which generation of the fundamental laser field and stimulated Raman scattering (SRS) processes occur in the same crystal. The tetragonal Nd:YVO4 crystal has been widely recognized as an excellent candidate for development of high power diode pumped lasers. The YVO4 host crystal is Raman active and allows for (cascaded) SRS to emit a wide range of wavelengths. Here the four-level Nd transition is exploited generating a fundamental laser field at 1064 nm. The 890 cm-1 Stokes shift of the YVO4 host crystal shifts the wavelength of the fundamental field via SRS to 1176 nm.

Because of the low SRS gain, intracavity Raman lasers have been operated so far in longitudinally pumped schemes that require expensive pump schemes such as fiber-coupled diodes and do not permit power scalability.

We plan to exploit nonlinear conversion processes to access the orange-yellow spectral region, for applications in the medical and biological research area and display technology.

9347-43, Session 11

Enhanced stimulated Brillouin scattering in chalcogenide elliptical photonic crystal fibres

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Stimulated Brillouin scattering (SBS) in optical fibres represents a versatile nonlinear effect for the realization of various applications such as slow light generation, sensing and signal processing techniques. SBS strength is dictated by intrinsic material nonlinearities and its dependence on waveguide geometry. SBS can be enhanced in chalcogenide photonic crystal fibres (PCF) thanks to the high nonlinearity of the material and the remarkable guiding properties for both optical and acoustic waves which these fibres exhibit [1]. SBS has been traditionally studied in PCFs with circular air holes. In this work, we show that the SBS is enhanced in PCF with elliptical air holes characterized by air hole ellipticity ? which is the ratio of major to minor axis of the elliptical hole [2].

The study of SBS in elliptical photonic crystal fibres (EPCF) is based on a full modal analysis of the optical and acoustic properties using the finite element method. We investigate the influence of the shape of the air holes on Brillouin gain spectrum. We find that the interaction between optical and acoustic modes is enhanced in EPCF with a multi-peak behavior of the Brillouin gain spectrum (BGS). We also find that by pressing the lattice of the air holes, the interaction between optical and acoustic waves is enhanced and the BGS is increased. For EPCF with ? = 3, ?x = 0.7 μm and ?y = 2.2 μm, a multi-peaked BGS is obtained and the main Brillouin peak component is shifted by 8.19 GHz with a gain of 4.107 10-9 m/W while the only peak in EPCF with ? = 3 and ?x = ?y = 2.2 μm is shifted by 8.21 GHz with a gain of 3.32 10-9 m/W at ??=1550 nm. SBS is enhanced by only modifying the x-pitch. Therefore, the flexibility that offer EPCF in the design of fibres gives us more SBS control.

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[2] Yang Yue et al, "Highly birefringent elliptical-hole photonic crystal fiber with squeezed hexagonal lattice," Opt. Lett 32, 469 471 (2007)

9347-44, Session 12

Frequency conversion for infrared generation in monolithic semiconductor waveguides *(Invited Paper)*

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Widely tunable mid infrared radiation achievable using quantum cascade lasers (QCLs) often requires external cavities and several QCL chips to cover a large bandwidth similar to the range reported here (~ 1000s nm). The cost and mechanical stability of these designs leaves room for alternative more rugged approaches, which require no cavities to achieve very broad band tunability. While difference frequency generation (DFG) will unlikely match the power levels achievable from QCLs, it can provide spectral brightness and extremely wide tunablity, which can be valuable for numerous applications.

Recently, we have demonstrated that dispersion engineering techniques can be used for phase matching of second order nonlinearities near the bandgap in monolithic waveguides.

In this work we demonstrate an extremely simple structure to grow and fabricate, which utilizes dispersion engineering not only to achieve phase matching but also to expand the tuning range of the frequency conversion achieved in a waveguide through difference frequency generation. Frequency conversion in monolithic AlGaAs single-sided Bragg reflection waveguides using c(2) nonlinearities produced widely tuneable, coherent infrared radiation between 2-3 μm and 7-9 μm. The broad tunability afforded by dispersion engineering and possible current injection, waveguide width chirping and temperature tuning makes it possible to produce a single multi-layer substrate to generate mid-IR signals that span μms in wavelength.

9347-45, Session 12

Calorimetric measurement of absorption loss in orientation-patterned GaP and GaAs

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Materials grown by vapor phase techniques such as chemical vapor deposition or hydride vapor phase epitaxy (HVPE) often exhibit very low losses which are difficult to quantify by simple transmission measurements. The measurement of extremely low absorption coefficients can be carried out by laser calorimetric or thermal rise techniques, which determine the absorption coefficients by measuring the temperature increase caused by the absorbed laser radiation. We report here on results of measuring absorption coefficients of bulk HVPE-grown orientation-patterned GaAs (OP-GaAs) and GaP (OP-GaP) crystals using one of the methods of laser calorimetry, called transient calorimetry. In our setup, the sample under test is attached to a high-conductivity copper holder and placed in a vacuum chamber. A 2-micron CW laser beam is transmitted through the sample and the temperature rise in the sample is measured and, through the calorimeter calibration process, related to the power absorbed in the sample. The absorbed power, Pa, is a function of the total attenuation coefficient atot , the length of the sample, and the laser power Po, defined as Pa = Po exp (-atot l), where total attenuation atot is the sum of absorption and scattering: atot = aabs + ascat. Since scattered light does not cause heating, the calorimetric technique is only applicable to determining aabs. By this technique we have measured 2-micron absorption coefficients in OP-GaAs and OP-GaP as low as 0.007 cm-1.

9347-46, Session 12

Lithium niobate: Wavelength and temperature dependence of the thermo-optic coefficient in the visible and near infrared

Stephan Fieberg, Streit Levin, Jens Kiessling, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Petra Becker, Univ. zu Köln (Germany); Frank Kühnemann, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Karsten Buse, Fraunhofer-Institut für Physikalische Messtechnik (Germany) and Univ. of Freiburg (Germany)

Lithium niobate ($LiNbO_3$) is one of the most important materials for nonlinear frequency conversion with a wide range of applications because of large nonlinear-optical coefficients, excellent availability, and a vast knowledge accumulated to treat this material, e.g. for periodic poling. However, a severe problem of the material is that thermal lensing limits the power that can be handled. Despite this fact, the thermo-optic coefficient for $LiNbO_3$ is not well known. The literature data obtained by different experimental methods show considerable deviations, especially for ordinarily polarized light.

In this work we present the results of measurements of the thermo-optic coefficient of lithium niobate over a wide temperature and wavelength range using an interferometric setup. Undoped, iron-doped and magnesium-doped congruently melting $LiNbO_3$ crystals and undoped stoichiometric $LiNbO_3$ crystals are studied in a temperature range from 0 to 150 °C. In addition to standard measurements using a helium-neon laser, data has been collected in the visible (450 – 650 nm) and near-infrared wavelength ranges (900 – 1300 nm) using a frequency-doubled cw optical parametric oscillator. The results show a good agreement with a deviation smaller than 10 % for ordinarily and smaller than 5 % for extraordinarily polarized light.

9347-47, Session 12

Highly sensitive absorption measurements in lithium niobate using whispering gallery resonators

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The absorption coefficient of a material is a parameter being of key relevance for applications in optics. Especially in nonlinear optics absorption is harmful since it causes heating and therefore inhibits phase matching or may even damage the material.

The standard methods to measure the absorption such as Fourier-transform spectroscopy or grating spectroscopy require absorption losses of at least 1 %. With whispering gallery resonators (WGR), monolithic cavities that guide light by total internal reflection, one can detect smaller light absorption.

Lithium niobate combines large second-order nonlinear-optical coefficients and low light absorption in a wide spectral window, making it an important material for nonlinear-optical processes. Although lithium niobate is well-established, its absorption coefficient in its highly transparent window is still not known.

Applying WGRs we measure the absorption coefficient of undoped, congruently grown lithium niobate using a tunable Ti:sapphire laser without an with frequency doubling as well as an optical parametric oscillator covering the whole transparent region of the material. The lowest measured value is 0.0001 1/cm at 1700 nm.

9347-48, Session 13

Peter Powers' inspirational collaborative style

Joseph W. Haus, Univ. of Dayton (United States)

No Abstract Available

9347-49, Session 13

Polarization meets nonlinear optics

Qiwen Zhan, Univ. of Dayton (United States)

No Abstract Available

9347-50, Session 13

Peter Powers: A long-lasting impact on nonlinear optics

Majid Ebrahim-Zadeh, ICFO - Institut de Ciències Fotòniques (Spain)

No Abstract Available

9347-51, Session 13

Physics works! The teaching style of Professor Peter Powers

Kenneth L. Schepler, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

No Abstract Available

9347-52, Session 13

Peter Powers: His unique contributions to laser physics and nonlinear optics

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No Abstract Available

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9348-1, Session 1

Scaling brightness and power of diode laser arrays *(Invited Paper)*

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There is continuing interest in increasing the power and improving the beam quality of laser sources for a variety of applications including materials processing, pumping, power transmission, and illumination. One approach is to continue to develop improved lasers with higher power and good beam quality. Another approach, particularly relevant to semiconductor and fiber lasers, is to beam combine large arrays of lasers. Beam combining has become increasing viable over the past decade as the community has developed a better understanding of the requirements imposed by beam combining, and various implementations have been successfully demonstrated in the laboratory. These implementations are beginning to see commercial application.

Key metrics for high-power arrays include the output power, the brightness, and the spectral width. To achieve high brightness, both high power and good beam quality are required. High-power diode arrays currently are composed of large numbers of emitters tiled side-by-side with the emitters being mutually incoherent with respect to each other. As the number of array elements increases, the beam quality decreases, and the brightness can be no better than that of an individual element. This is known as side-by-side beam combining. Polarization beam combining is often used to combine two arrays of orthogonal polarization. This can increase the brightness a factor of 2 at best.

There are two approaches, wavelength beam combining (WBC) and coherent beam combining (CBC), to scaling the brightness by large amounts, in principle by as much as the number of elements. In WBC, the array elements operate at different wavelengths and a dispersive optical system is used to overlap the different wavelengths spatially. Typical dispersive optical systems use gratings, prisms, or wavelength-selective reflectors. This is equivalent to what is done in wavelength division multiplexing for optical communications. The differences here are that the goal is higher power, and, therefore, the efficiency is more important. In CBC, the beams are interferometrically combined, or phased. If the beams are phased properly, then constructive interference occurs and the power can be combined into a single beam.

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9348-2, Session 1

A 40kW fiber-coupled diode laser for material processing

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In this paper we describe the next step on the roadmap “system scalability towards an output power > 100 kW”, first time presented in 2013 (SPIE 8965-10).

Therefore the fiber-coupled high-power diode laser has been improved up to an optical power of more than 42 kW and a laser head wall-plug efficiency larger than 40%. The laser contains modules at 4 different wavelengths (980nm, 1020nm, 1040nm, 1060nm) which are polarization multiplexed. After the slow-axis collimation these wavelengths are combined using dense wavelength coupling before focusing onto the fiber endface. The delivery-fiber is an uncoated fiber with a diameter of 2.0 mm and 0.22 NA corresponding a BPP of 220 mm mrad.

In a stability test the laser showed a constant maximum output power with less than ±0.5 % variation over 100h. Further results of the optical properties of the laser will be presented.

This new laser has been based on a turn-key industrial platform, allowing straight-forward integration into almost any industrial application, like welding or large area heat treatment. As an application example laser welding of thick sheet metal will be presented. The complete system has a footprint of less than 2.8 m? and a height of less than 1.8 m.

9348-3, Session 1

High brightness diodes and fiber-coupled modules

Manoj Kanskar, Ling Bao, Zhigang Chen, David Dawson, Mark DeVito, Weimin Dong, Mike P. Grimshaw, Xingguo Guan, David M. Hemenway, Keith Kennedy, Robert Martinsen, Wolfram Urbanek, Shiguo Zhang, nLIGHT Corp. (United States)

There is an increasing demand for high-power, high-brightness diode lasers from 8xx nm to 9xx nm for applications such as fiber laser pumping, materials processing, solid-state laser pumping, and consumer electronics manufacturing. The kilowatt CW fiber laser pumping (915 nm - 976 nm) particularly requires the diode lasers to have both high power and high brightness in order to achieve high-performance with reduced manufacturing cost. This paper presents our continued progress in the development of high power and high brightness fiber-coupled product platform, elementTM to address these applications. Recent improvements in fiber-coupled power has been enabled by significant advances in the slow-axis brightness of broad area lasers. We have demonstrated 30% improvement in slow-axis brightness resulting from reducing the number of allowed modes in the slow-axis direction. This new generation of reduced-mode diodes (REM-diodes) have two-times smaller slow-axis divergence at the same operating powers. As a result, we have achieved 75 watts from a 1?6 elementTM in the 9xx nm spectral range; and with further optimized REM-diodes, we expect over 160 watts from a 2?6 elementTM out of a 105 μm/0.14 NA beam. We will report on power scaling beyond 300 watts in 200 μm/0.18 NA beam as well as wavelength-stabilization and reliability assessment of these devices in fiber-coupled modules.

9348-4, Session 1

Narrow-line fiber-coupled modules for DPAL pumping

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Recent advances in high power diode laser technologies have enabled advanced research on diode pumped alkali metal vapor lasers (DPALs). Due to their low quantum defect, DPALs offer the promise of scalability to very high average power levels while maintaining excellent beam quality. Research is being conducted on a variety of gain media species, requiring different pump wavelengths: near 852 nm for cesium, 780 nm for rubidium, 766 nm for potassium, and 670 nm for lithium atoms. The biggest challenge in pumping these materials efficiently is the narrow gain media absorption band of approximately 0.01 nm.

Typical high power diode lasers achieve spectral widths around 3nm (FWHM) in the near infrared spectrum. Gratings may be used internal or external to the cavity to reduce the spectral width to 0.5 nm to 1 nm for high power diode laser modules. Recently, experimental results have shown narrower line widths ranging from picometers at very low power levels to sub-100 picometers for water cooled stacks around 1kW of output power.

The focus of this work is a further reduction in the spectral line width of high power diode laser bars emitting at 766nm, with full applicability to other wavelengths of interest. One factor limiting the reduction of the spectral line width is the optical absorption induced thermal gradient inside the VHG. Simulated profiles and demonstrated techniques to minimize thermal gradients will be presented. To enable the next stage of DPAL research, a new series of fiber coupled modules is being introduced featuring greater than 400W from a 600μm core fiber of 0.22NA. The modules achieve a spectral width of <<0.1 nm and wavelength tunability of +/- 0.15 nm.

9348-5, Session 1

Low-NA fiber laser pumps powered by high-brightness single emitters

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Fiber laser manufacturers demand high-brightness laser diode pumps delivering optical pump energy in both a compact fiber core and narrow angular content. A pump delivery fiber of a 105 μm core and 0.22 numerical aperture (NA) is typically used, where the fiber NA is under-filled to ease the launch of laser diode emission into the fiber and make the fiber tolerant to bending. At SCD, we have developed high-brightness NEON multi-emitter fiber-coupled pump modules that deliver 50 W output from a 105 μm, 0.15 NA fiber enabling low-NA power delivery to a customer's fiber laser network.

Brightness-enhanced single emitters are engineered with ultra-low divergence for compatibility with the low-NA delivery fiber. The slow-axis divergence is narrowed through an elongated emitter cavity and optimized epitaxial design, where we reduced the peak optical intensity to achieve both lower filamentation within the laser cavity and lowered the power density on the output facet thus increasing the emitter reliability.

The low mode filling of the fiber allows it be coiled with diameters down to 65 mm at full operating power despite the low NA and further eliminates the need for mode-stripping at fiber combiners and splices downstream from our pump modules. Product versions at 915, 950 and 976 nm wavelengths are presented, with an 808 nm prototype demonstrated in QCW mode.

9348-6, Session 2

Packaging of high power bars for optical pumping and direct applications

Stefan W. Heinemann, Haiyan An, Tobias Barnowski, Viorel C. Negoita, Robert Roff, Thilo Vethake, TRUMPF Photonics (United States); Sven-Silvius Schad, Hagen Zimer, TRUMPF Laser GmbH & Co. KG (Germany); Konstantin M. Boucke, Georg Treusch, TRUMPF Photonics (United States)

We report on the latest results for scaling the output power of bars for optical pumping and materials processing. The epitaxial design and geometric structures are specific for the application, while packaging with minimum thermal impedance, low stress and low smile are generic features. The bar is packaged on a custom heatsink with hard solder. For pumping applications, bars with a fill factor of about 50% are deployed emitting 260W of output power with an efficiency of about 55%. 8 bars are arranged into a compact pump module emitting 2 kW of collimated power suitable for pumping disk lasers. For direct applications we target coupling kilowatts of output powers into fibers of 100 um to 200 um diameter with 0.1 NA. Dense wavelength multiplexing is deployed that uses customized bar designs together with standard beam shaping optics and unique optics for wavelength stabilization. Based on 70W locked power per bar we expect about 600 W from a 100 um fiber, 0.1 NA for a single module with an efficiency of 45%. Optical stacking and polarization multiplexing allows scaling the power to multiple kilowatts sufficient for cutting and welding using direct diode lasers. We will further report on scaling the power of individual bars to more than 150 W through improved packaging.

9348-7, Session 2

Power scaling of kW-diode lasers optimized for material processing applications

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Cutting of metal sheets is a key application in material processing and high power diode lasers gain further importance in this field due to their exceptionally good current to light conversion efficiency. Both, power scaling and process optimization are under investigation to improve the performance of this application. We report first results of a laser system combining these approaches. The presented diode laser power scaling is realized by means of an asymmetric, noncircular beam shape. The beam parameter product of the laser light is manipulated accordingly. In addition, the power scaling of this approach allows the generation of spot geometries which inherently support the interaction processes of the laser light with materials as metals. The setup reaches today up to 8 kW of optical power. It is based on conventional, highly reliable and well tested principles and components, as they are passively cooled laser diode bars, coarse wavelengths coupling and fiber delivery.

First results of material processing are presented. The new laser configurations allow cutting of mild steel and stainless steel of thicknesses exceeding 8 mm with high quality of the cutting kerf.

9348-8, Session 2

Tailored bar concepts for 10mm-mrad fiber coupled modules scalable to kW-class direct diode lasers

Andreas Unger, Bernd Köhler, Ross Uthoff, Thomas Brand, Heiko Kissel, Jens Biesenbach, Michael Stoiber, DILAS Diodenlaser GmbH (Germany)

Direct diode lasers for materials processing in the kW power range are a highly active field of research and will potentially replace fiber lasers in applications like remote welding and sheet metal cutting. For these applications, beam parameter products below 20 mm-mrad are required. Over the last years DILAS developed and published the tailored bar concept for efficient fiber coupling into 20 mm-mrad together with the tooling for fully automated mass production of laser modules for pumping applications. In this paper, laser modules based on newly developed tailored bars are presented. The modules allow efficient fiber coupling of more than 320 W into 10 mm-mrad or 160 W into 6 mm-mrad at one single wavelength. For further power scaling dense wavelength coupling concepts are presented which enable kW-class lasers with a beam quality of 10 mm-mrad

9348-9, Session 2

Highly modular high brightness diode laser system design for a wide application range

Haro Fritsche, DirectPhotonics Industries GmbH (Germany) and Technische Univ. Berlin (Germany); Bastian Kruschke, Ulrich Pahl, Fabio Ferrario, Ralf Koch, Einar Ehm, Holger Kern, Andreas Grohe, Wolfgang Gries, DirectPhotonics Industries GmbH (Germany)

For an economic production it is important to provide as many applications as possible while keeping the product variations minimal. We present our modular laser design, which is based on single emitters and various combining techniques.

In a first step we accept a reduction of the originally very high brightness of the single emitters by vertical stacking. Those emitters can be wavelength-stabilized by an external resonator, providing the very same feedback to each of those laser diodes which leads to an output power of about 100W with BPP of < 3.5 mm*mrad x 5 mm*mrad (fast axis x slow axis). Further power scaling is accomplished by polarization and wavelength multiplexing yielding high optical efficiencies of more than 80% and results in about 500W launched into a 100µm fiber with 0.15NA.

Subsequently those building blocks may also be stacked by the very same dense spectral combing technique to up to multi-kW systems without changing the BPP.

These “500W building blocks” are consequently designed in a way that without any system change new wavelengths may be implemented by only exchanging parts but without change of the production process. This design principle offers the option to adapt the wavelength of those blocks to any application, from UV, visible into the far IR; from laser pumping and scientific applications to materials processing such as cutting and welding of copper aluminum or steel and also medical applications.

In addition, the built-in electronics are capable of very short µs pulses up to cw mode operation without change.

9348-10, Session 3

Brightness and average power as driver for advancements in diode lasers and their applications *(Invited Paper)*

Reinhart Poprawe, Hans-Dieter Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany)

Spatial and spectral emission characteristics and efficiency of high-power diode laser (HPDL) based pump sources enable and define the performance of the fundamental solid state laser concepts like disk, fiber and slab lasers.

HPDL are also established as a versatile tool for direct materials processing substituting other laser types like CO2 lasers and lamp pumped solid state lasers and are starting to compete with high brightness diode pumped solid state lasers. Further improvement of the brightness and control of the output spectrum of HPDL will be of benefit for both: pumping and direct applications.

While edge emitting diodes are already established, a new generation of vertical emitting diodes (VCSEL) made significant progress and provides easy scalable output power in the kW range. Beneficial properties are simplified beam shaping, flexible control of the temporal and spatial emission, compact design and low current operation. Other characteristics like efficiency and brightness of VCSEL are still lagging behind the edge emitter performance.

The main drivers of HPDL development for pumping will be presented. Examples of direct applications like surface treatment, soldering, welding, additive manufacturing, cutting and their requirements in HPDL performance will be shown. A diagram visualizing process requirements versus available and perspective parameter ranges of industrial HPDL is derived.

9348-11, Session 3

High reliability demonstrated on high power and high brightness diode lasers

Ling Bao, Manoj Kanskar, Mark DeVito, David M. Hemenway, Wolfram Urbanek, Mike P. Grimshaw, Weimin Dong, Xingguo Guan, Shiguo Zhang, David Dawson, Rob Martinsen, nLIGHT Corp. (United States)

In this paper we present nLight’s most recent reliability assessment of both the released and newly developed high power, high brightness single emitter laser diodes for fiber laser pumps. We report on the latest updates of lifetests performed on released 18W-rated diode lasers which have been successfully incorporated into nLight’s 210W 200 µm/0.16NA elementTM pump module. Two groups of step-stress lifetests with the initial current at 20A and final current at 26A in 2A increments have accumulated ~4200h and ~2600h of operation. In addition, a total of 212 units of 18W-rated single emitters in wavelength range of 915 to 980 nm, were assessed at 20A or 22A at a junction temperature, Tj~70ºC. Cumulatively, these devices have accrued ~ 1.7 million equivalent device hours. The initial reliability analysis based on these lifetest results support >99% module reliability for 1-year of continuous operation. We also report on the initial lifetest of the newly developed high brightness REM-diodes (Reduced Mode diodes) for new elementTM configuration that are underway. Several REM-diode designs that will enable ~15W of reliable power and improved operational efficiency are being evaluated. Initial highly accelerated lifetest on these REM-diodes accumulated over 2700h of operation time with only one sudden failure, while the control diode lasers under the same conditions exhibited two failures so far. Superior performance has already been demonstrated on the initial module builds with these new REM designs into elementTM. Module level reliability demonstration will also be presented.

9348-12, Session 3

Development of high power diode lasers with beam parameter product below 2 mm?mrad within the bridle project

Paul Crump, Jonathan Decker, Martin Winterfeldt, Jörg Fricke, Andre Maassdorf, Götz Erbert, Guenther Tränkle, Ferdinand-Braun-Institut (Germany)

High power broad-area diode lasers are the most efficient source of optical energy, but cannot directly address many applications due to their high lateral beam parameter product BPP=0.25?LFF95%?W95% (LFF95% and W95% are emission angle and aperture at 95% power content), with BPP>3mm?mrad for W95%~90µm. We review here progress within the BRIDLE project, that is developing diode lasers with BPP<2mm?mrad for use in direct metal cutting systems, where the highest efficiencies and powers are required. Two device concepts are compared: narrow-stripe broad-area (NBA) and tapered lasers (TPL), both with monolithically integrated gratings. NBAs use W95%~30µm to cut-off higher order lateral modes and reduce BPP. TPLs monolithically combine a single mode region at the rear facet with a tapered amplifier, restricting the device to one lateral mode for lowest BPP. TPLs fabricated using ELOD (Extremely LOw Divergence) epitaxial designs are shown to operate with BPP below 2mm?mrad, but at cost of low efficiency (<35%, due to high threshold current). In contrast, NBAs operate with BPP<2mm?mrad, but maintain efficiency >50% to output of >7W, so are currently the preferred design. In studies to further reduce BPP, lateral resonant anti-guiding structures have also been assessed. Optimized anti-guiding designs are shown to reduce BPP by 1mm?mrad in conventional 90µm stripe BA-lasers, without power penalty. In contrast, no BPP improvement is observed in NBA lasers, even though their spectrum indicates they are restricted to single mode operation. Mode filtering alone is therefore not sufficient, and further measures will be needed for reduced BPP.

9348-13, Session 3

Heading to 1kW levels with laser bars of high efficiency and emission wavelength around 880nm and 940nm

Agnieszka Pietrzak, Ralf Huelsewede, Martin Zorn, Martin Woelz, Olaf Hirsekorn, JENOPTIK Diode Lab GmbH (Germany); Jens Meusel, Alex Kindsvater, Matthias Schroeder, JENOPTIK Laser GmbH (Germany); Jürgen Sebastian, JENOPTIK Diode Lab GmbH (Germany)

High-power quasi-CW laser bars are of great interest as pump sources of solid-state lasers generating high energy ultrashort pulses for high energy projects. These applications require a continuous improvement of the laser diodes for reliable optical output powers and simultaneously high electrical-to-optical power efficiencies. An overview is presented of recent progress at JENOPTIK in the development of commercial quasi-CW laser bars emitting around 880nm and 940nm optimized for peak performance.

First performances of 1.5mm long laser bars with 75% fill-factor are presented. Both, 880nm and 940nm laser bars deliver reliable power of 500W with wall-plug-efficiencies (WPE) >55% within narrow beam divergence angles of 11° and 45° in slow-axis and fast-axis directions, respectively. The reliability tests at 500W power under application quasi-CW conditions are ongoing. Moreover, laser bars emitting at 880nm tested under 100µs current pulse duration deliver 1kW output power at 0.9kA with only a small degradation of the slope efficiency. The applications of 940nm laser bars require longer optical pulses and higher repetition rates (1-2ms, ~10Hz). In order to achieve output powers at the level of 1kW under such long pulse duration, heating of the laser crystal has to be minimized. Power-voltage-current characteristics of 4mm long cavity bars with 50% fill-factor based on an optimized laser structure against carrier leakage were measured. We report an output power of 0.8kW at 0.8A with >60% conversion efficiency (52% WPE). By increasing the fill-factor of the bars a further improvement of the WPE at high currents is expected.

9348-14, Session 4

915nm high power broad area laser diodes with ultra-small optical confinement based on asymmetric decoupled confinement heterostructure (ADCH)

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915nm high-power and high-reliability single emitter laser diodes based on Asymmetric Decoupled Confinement Heterostructure (ADCH) are demonstrated, aiming at applications to fiber laser pumping and other industrial use. Advantage of ADCH is that it can optimize active layer confinement (G) and confinement ratio of p- to n-doped layer (Gp/Gn), independently. Therefor it can manage large effective spot size (dwell/ G) and low internal loss required for high power operation, without any penalty in carrier confinement. 4mm-cavity, 100um wide stripe LDs designed with large effective spot size of 1.5um demonstrated record high Catastrophic Optical Damage (COD) free operation over output power of 42W under 50A pulsed drive condition. To assess long term reliability of the diodes, aging tests have been conducted under highly accelerated multi conditions. The aging data were accumulated 2,000-8,000 hours by 325 devices, corresponding to more than 1.6 million device hours under tested condition. Mean time to failure of random mode is estimated to be 1,200,000 hours for 12W operation at room temperature and these results prove high reliability of ADCH at high power.

9348-15, Session 4

29.5W continuous wave output from 100um wide laser diode

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Semiconductor lasers with high output optical power are of interest to many applications. Higher power could be achieved by making the laser chip bigger but there are limits in both length, which can reduce efficiency, and emission width, which can reduce brightness. Historically, increasing the cavity length combined with reduced internal losses improved power due to better heat dissipation and reduced current density of the larger area laser diode. However, for longer cavities, and with higher ratio between back and front facet reflectivities, photon and carrier inhomogeneties become significant at higher currents. Thus power improvement does not scale with cavity length increase mainly due to penalties related to these asymmetric features. In this paper, we report modeling and experimental results that demonstrate mechanisms limiting the output power of semiconductor lasers, and a method experimentally yielding a dramatic increase of the maximum continuous wave output power. Unfolded cavity is used to achieve higher power and efficiency by improving the alignment between the carrier and photon density profiles in a long cavity device. This method offers reduced longitudinal spatial hole burning (LSHB) and lower photon density inside the laser cavity; therefore, it decreases possible LSHB and non-linear effects that could limit the output power of a semiconductor laser. We have demonstrated 29.5W from 5.7mm long and 100um wide waveguide at 9xx nm. A semiconductor laser with an unfolded cavity allows scaling of the output power by increasing the cavity length.

9348-17, Session 4

High power operation of AlGaInP red laser diode for display applications

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A laser diode (LD) consisted of AlGaInP material system is widely used for a red color source. In this LD, one of the limiting factors for higher output power is thermal saturation which is caused by temperature rise at an emitting region. In order to suppress this temperature rise, a new LD structure with triple emitters was designed. The emitter width of 60um was also adopted to each emitter instead of 40um of our current single-emitter LD. In addition, this LD was assembled on a 9.0mm-diameter TO package instead of a 5.6mm diameter-TO package. The thermal resistance between the active layer and the LD holder estimated by thermal simulation was 4.0K/W.

The total emitter width of new LD was 180um (60um?3) which was 4.5 times wider than that of previous LD. This contributes to the reduction of optical density and would greatly expand the failure time of catastrophic optical mirror degradation (COMD) which is the main failure mode of this type of LD.

This newly developed LD could emit over 5.5W at 25°C and 3.8W at 45 °C under pulsed operation despite these temperatures were not that of the package but the LD holder. These values are about 2.7 times higher than that of our current product. This superior P-I characteristics of the new LD is due to temperature reduction at an active layer by applying the triple-emitter structure and a 9.0mm-diameter package.

9348-18, Session 4

Advancements in high power high brightness laser bars and single emitters for pumping and direct diode application

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High power and efficiency laser bars with high fill factor are used to build the pump sources for thin disc laser systems. We have continuously optimized bar and packaging design to increase power and efficiency for this application. The reliable output power per bar in a DCB based module configuration has been increased from 140W to 200W. On the other hand, low fill factor bars packaged on the same DCB cooling platform are used to build multi-kilowatt direct diode laser systems. To further advance these products in terms of increased brightness, laser structures incorporating optimized waveguide designs based on the control of the lateral index step and measures for higher order mode filters have been developed. Based on this technology, we have optimized the bar designs at 910-1030nm wavelengths for wavelength beam combining and single emitter designs for fiber laser pump applications.

In this paper, we will give an overview of our recent advances in high power and high brightness laser bars and single emitters for pumping and direct diode application. We will present 280W bar development results for TRUMPF's next generation thin disk laser pump source. We will also show recent improvements on slow axis beam quality of low fill factor bar and its application on performance improvement of 4-5 kW TruDiode laser system with a BPP of 30 mm*mrad from a 600 μm beam delivery fiber. In addition, performance and reliability results of single emitters for multi-emitter fiber laser pump source will be presented as well.

9348-19, Session 5

Reliability study of high brightness multiple single emitter diode lasers

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Fiber lasers and direct laser applications require diode laser of even higher power and brightness delivered via even smaller core multimode fiber. Among all diode laser types, multiple single emitter laser modules allow high power and high brightness to meet this demand sufficiently. Diode lasers for most applications are operated mainly in CW mode, and requested to be highly reliable.

In this study, we first optimized the chip bonding processes for various chips from various chip suppliers around the world, achieved the reliable chip on sub-mount processes for high performance and high manufacturing yields. These chip-on-submounts, for examples, include three types of 9xxnm 10W-20W AuSn bonded lasers and 1470 nm 6W Indium bonded lasers. Some detail Chip on Sub-mount (COS) reliability study will be presented in this paper.

These 9xx chips from various chip suppliers which were bonded on AIN sub-mounts then packaged into many multiple single emitter laser modules, using similar packaging techniques from 2 emitters per modules to up to 7 emitters per modules. A reliability study especially aging test had performed on those multiple single emitter laser modules, with our robust packaging design and techniques, precise optical and fiber alignment processes, and superior chip bonding capability, we have achieved a total MTTF exceeding 100,000 hours of life time with 60% confidence level. Furthermore, a separated reliability study on wavelength stabilized single emitter laser modules have shown our wavelength stabilized module packaging process is reliable as well.

9348-20, Session 5

Reliable single emitters and laser bars for efficient CW-operation in the near-infrared emission range

Martin Zorn, Ralf Huelsewede, Agnieszka Pietrzak, JENOPTIK Diode Lab GmbH (Germany); Jens Meusel, JENOPTIK Laser GmbH (Germany); Martin Woelz, Jürgen Sebastian, JENOPTIK Diode Lab GmbH (Germany)

Laser bars, laser arrays, and single emitters are highly-desired light sources e.g. for direct material processing, pump sources for solid state and fiber lasers or medical applications. These sources require high output power with optimal efficiency together with good reliability resulting in a long lifetime of the device. Desired wavelengths range from 760 nm as replacement for Alexandrite lasers in esthetic skin treatment over 940 nm and 976 nm to 1020 nm for direct material processing and pumping applications.

At 760 nm laser bars with 30 % filling factor and 1.5 mm resonator length mounted on active heat sinks show a maximal output power of 100 W with a wall-plug-efficiency of 56 % at 25°C. The spectral width is around 2 nm and up to now life time tests show reliable operation of 1600 h at 40 W with 5 % power degradation only.

At 940 nm and 976 nm single emitters were fabricated with 90 um and 200 um emitter width. At 20 W and 25°C they need currents of 20.4 A and 21.5 A resulting in wall plug efficiencies of 61.8 % and 61.0 %, respectively. Life time test show reliable operation for more than 3500 h. The divergence angle at 20W lies at 8° (FWHM). Comparable laser bars with 50% filling factor show life times over 7500 h. Finally, laser bars with 50 % filling factor, 23 emitters and 4 mm resonator emitting at 1020 nm length are currently under investigation. Reliable operation is shown for 700 h up to now.

9348-21, Session 5

Degradation mechanisms in high power multi-mode InGaAs-AlGaAs strained quantum well lasers for high reliability applications

Yongkun Sin, Nathan Presser, Erica DeIonno, Miles Brodie, Brendan Foran, Steven C. Moss, The Aerospace Corp. (United States)

Laser diode manufacturers perform accelerated multi-cell lifetests to estimate lifetimes of lasers using an empirical model. Since state-of-the-art laser diodes typically require a long period of latency before they degrade, significant amount of stress is applied to the lasers to generate failures in relatively short test durations. A drawback of this approach is the lack of mean-time-to-failure data under intermediate- and low-stress conditions, leading to uncertainty in model parameters and potential overestimation of lifetimes at usage conditions. A number of groups have studied reliability and degradation processes in GaAs-based lasers, but none of these studies have yielded a reliability model based on the physics of failure. Our present study addresses the aforementioned issues by performing long-term lifetests under low-stress conditions followed by failure-mode-analysis (FMA) and physics of failure investigation.

We performed low-stress lifetests on broad-area InGaAs-AlGaAs strained QW lasers under ACC mode to study low-stress degradation mechanisms. Our lifetests have accumulated over 30,000 test hours and FMA was performed on failures using our angle-polishing technique followed by EL.

We also investigated degradation mechanisms in broad-area lasers using various FMA techniques. Since it is a challenge to control defect densities during the growth of laser structures, we chose to control defect densities by introducing extrinsic point defects to the laser via proton irradiation. These lasers were subsequently lifetested to study degradation processes in the lasers with different defect densities and also to study precursor signatures of failures. Our long-term low-stress lifetest results and physics of failure investigation results will be presented.

9348-22, Session 5

High-power diode lasers under external optical feedback

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Within the last few years, intentional and unintentional external optical feedback has become more important in many high-power diode laser applications. It modifies the laser parameters in many ways, e.g. reducing the threshold current, influencing the optical output power or changing the emission kinetics. Intentional feedback is widely used for wavelength stabilization and tuning.

The optical near-field is an important parameter with high practical relevance, because its properties determine the coupling efficiency of a broad-area high-power laser into a fiber. Unintentional feedback from optical elements in fiber-coupled modules like micro-lenses or fiber ends can cause gradual or sudden degradation effects. We will discuss the impact of optical feedback to filamentation amplitudes of single emitters with different reflectivity of the front facet coatings at several wavelengths in the spectral range between 780nm and 980nm.

In addition to reversible modifications of external optical feedback to the device properties, we will consider irreversible impacts leading to gradual and sudden degradation including catastrophic optical damage (COD).

For GaAs-based laser diodes, the energy gap of GaAs makes a distinction at a wavelength of about 870nm. For shorter wavelengths, e.g. at 808nm, a substantial part of the feedback light is absorbed by the substrate and GaAs cap layers very close to the front facet leading to a significant heating of the outcoupling facet. For longer wavelengths, e.g. 976nm, this energy intrusion is not a local one at the front facet, but rather spreads along the whole cavity length.

9348-23, Session 5

Analysis of 980nm emitting single-spatial mode diode lasers at high power levels by complementary imaging techniques

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Standard 980-nm emitting single-spatial-mode high power diode lasers were operated with sub-μs pulses at multi-watt power levels. Primary emission, short wavelength infrared (SWIR) emission, as well as the mid-infrared thermal emission are separately monitored by appropriate infrared cameras. Moreover, the spatio-temporal evolution of the emission nearfield during the pulses is recorded with ns temporal resolution. This combined approach allows for the determination of the operation parameters (pulse length and operation current) during which single-spatial-mode operation is maintained. This gives limits for safe operation far beyond the original specification of the devices. While absolutely no sign of catastrophic front facet degradation is observed, at utmost high power levels, internal sudden degradation is discovered as a mechanism setting the ultimate limits. Corresponding signatures are tracked by SWIR- and thermo-cameras observing the scenario along the laser axis (side view). The data reveal the starting points of internal degradation, as well as the propagation of the defect front along the laser axis. It turns out that in the single-spatial-mode device, after interrupting the waveguide by the initial degradation event, further motion of the defect front is fed by amplified spontaneous emission. Experiments with a device set of long-term operated devices reveals gradual aging signatures within the SWIR emission. This includes a systematic reduction of this emission in device parts, which are affected by gradual degradation. Therefore, also for gradual degradation, the starting points of the relevant processes become detectable.

9348-24, Session 5

Mechanisms driving the catastrophic optical damage in high power laser diodes

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The catastrophic optical degradation (COD) of high power laser diodes is discussed in terms of the thermal transport properties of the laser structures. The origin of the degradation is associated with the thermal stresses induced by the local heating of the laser structure during the laser operation. The initial stage of local heating is produced by either non radiative recombination at point defects in a region of the active zone of the laser rich in point defects, and/or to local heating by Joule effect due to changes in the local electrical resistance of the laser structure due to the accumulation of point defects. This initial local heating produces self absorption of the optical field, which results in a further temperature increase, constituting a local heat source, which introduces thermal stresses. The thermomechanical analysis of the laser structure in the presence of this local heat source shows that dislocations can be generated for absorbed laser powers densities below the laser power density of operation. Once the plastic deformation of the laser structure is achieved dislocation networks mainly localized in the QW layer are formed, which can be observed by Cathodoluminescence (CL). The main defects observed are dark line defects (DLDs) oriented along the laser cavity, which suggests that they are propagated by the optical field of the laser. The role of the thermal conductivity of the laser structure in the COD is discussed.

9348-25, Session 6

Separate phase-locking and coherent combining of two laser diodes in a Michelson cavity

Guillaume Schimmel, Ioana Doyen, Sylvie Janicot, Lourdes Patricia R. Ramirez, Marc Hanna, Gaëlle Lucas-Leclin, Patrick Georges, Lab. Charles Fabry (France); Ville Vilokkinen, Petri Melanen, Petteri Uusimaa, Modulight, Inc. (Finland); Jonathan Decker, Paul Crump, Götz Erbert, Ferdinand-Braun-Institut (Germany); Stephen Bull, The Univ. of Nottingham (United Kingdom)

Coherent beam combining (CBC) is a powerful technique to scale up the brightness of arrays of diode lasers while maintaining a narrow spectral bandwidth. We investigate a new CBC architecture using a common external cavity on the back side of the lasers for the phase locking, while the coherent beam superposition of the phase-locked beams is realized on the front side. This technique leads to a separation of the phase-locking stage – which takes place in the common external cavity - and the beam combining

stage – which is achieved outside the cavity. Then the electrical-to-optical efficiency of the phase-locked laser array is increased, as the losses are minimized on the useful output.

We demonstrate the phase-locking and coherent beam combining of two semiconductor ridge-waveguide lasers using a common external Michelson cavity on the back facet. The external-cavity losses are about 20%, limited by the discrepancies between the beam profiles. On the front facet, the two lasers beams combine coherently on a beamsplitter with an efficiency above 90%; the relative phase stability between the two lasers is ≤ ?/250 RMS over 10 s. The passive phase-locking of the lasers is limited by slow drifts of the external cavity which change the relative phase between the lasers. Different low-bandwidth active-locking schemes have been compared to stabilize the phase-locked operation of the lasers. This experiment is a proof-of-principle of the separate phase-locking / coherent beam combining architecture, and is being implemented with two high-power tapered lasers.

9348-26, Session 6

Wavelength stabilized multi-kW diode laser systems

Bernd Köhler, Andreas Unger, Tobias Kindervater, Simon Drovs, Paul Wolf, Ralf Hubrich, Stefan Auch, Holger Müntz, Jens Biesenbach, DILAS Diodenlaser GmbH (Germany)

We report on wavelength stabilized high-power diode laser systems with enhanced spectral brightness by means of volume holographic gratings. Wavelength stabilization of high-power diode laser systems is an important method to increase the efficiency of diode pumped solid-state lasers. It also enables power scaling by dense wavelength multiplexing. To ensure a wide locking range and efficient wavelength stabilization the parameters of the volume holographic grating and the parameters of the diode laser bar have to be adapted carefully. Important parameters are the reflectivity of the volume holographic grating, the reflectivity of the diode laser bar as well as its angular and spectral emission characteristics.

We will present data on wavelength stabilized diode laser systems with and without fiber coupling in the spectral range from 630 nm up to 1540 nm. The maximum output power of 2.7 kW was measured for a fiber coupled system (1000 μm, NA 0.22), which was stabilized at a wavelength of 969 nm with a spectral width of only 0.6 nm (90% value). Another example is a narrow linewidth diode laser stack, which was stabilized at a wavelength of 1533 nm with a spectral bandwidth below 1 nm and an output power of 800 W.

9348-27, Session 6

High power external cavity CW red laser diode

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Although red emitting diode lasers have been used in a lot of applications due to their inherent advantages, their higher specification in output power, spectral behavior and beam quality has been constantly required for some fields such as a laser-based display, laser metrology and Raman spectroscopy.

To improve these properties, one of approaches is to append the tapered amplifier section to single frequency laser diode chips [1,2]. However, they showed the limitation of scale-up of optical power with the low slop efficiency or the unsuitable room temperature-operation. Furthermore, the internal grating in red-emitting diode lasers is technologically challenging as well as has the disadvantages of a complicated manufacturing process, high cost and a relatively poor reliability, originating from the inherent material properties.

Alternatively, the external cavity diode lasers(ECDLs) based on a narrow stripe or a tapered laser have been demonstrated[3,4]. However, their optical power was limited to under 200 mW with a low slop efficiency of below 0.3 W/A.

In this work, a broad-area laser(BAL) diode, which is more effective for high output power as compared to a narrow stripe or a tapered laser, was enhanced by an external cavity with a diffraction grating in order to achieve higher output power with narrow spectral width and good wavelength stability. At an injection current of 1.6 A, higher than 0.7 W of output power with a slop efficiency of 0.85 A/W, which is comparable to those of a solitary BAL diode, could be achieved with a spectral width of 120pm which is about 70 % narrower as compared to a solitary BAL diode. The center wavelength stability of below 20 pm was obtained for the wide range of injection current.

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[4] G. Blume et al., IET Optoelectron. 3, 320-325 (2009)

9348-28, Session 6

High power laser diodes using a large active core combined with mode control for high beam quality

David M. Pai, Bright Beam Technologies (United States)

This paper presents a high power laser diode method using a large core combined with mode control. The thrust of the method is on high power as well as high beam quality. Beam quality is accomplished by mode control in an external cavity. The advantage is that power can be simply scaled up by increasing the core size or by using multiple cores, with no negative impact on the beam quality. Wave analysis shows the method can control the output beam to near ideal diffraction limit.

9348-29, Session 7

New developments in diode lasers in Europe *(Invited Paper)*

Günther Tränkle, Ferdinand-Braun-Institut (Germany)

A review of recent progress and future perspectives for high-power GaAs-based diode lasers is presented, focusing on work at the FBH Berlin. There are three main topical areas. First, ongoing studies seek to enhance material properties and key building blocks, including optimized facet passivation and low-loss monolithic Bragg gratings. Second, higher performance is sought in industry-standard devices, such as 100μm single emitters and 1cm bars, where higher power, efficiency and beam quality are targeted. Finally, novel device concepts are studied, with potential for break-through performance in new or existing applications fields, such as monolithically integrated sources for spectral beam combination.

9348-30, Session 7

Progress in high-energy-class diode laser pump sources

Paul Crump, Carlo F. Frevert, Frank Bugge, Steffen Knigge, Götz Erbert, Guenther Tränkle, Ferdinand-Braun-Institut (Germany); Agnieszka Pietrzak, Ralf Hueslewede, Martin Zorn, Jürgen Sebastian, JENOPTIK Diode Lab GmbH (Germany); Jens Lotz, Wilhelm Fassbender, Joerg

Neukum, DILAS Diodenlaser GmbH (Germany); Joerg Körner, Joachim Hein, Thomas Toepfer, Lastronics GmbH (Germany)

A new generation of high-energy-class solid-state laser facilities is in development that deliver multi-joule pulse energies at around 10Hz. Commercial quasi-continuous-wave (QCW) diode lasers are used as pump sources, currently delivering pump powers of around 300W per bar. Increased power-per-bar helps reduce the system size, complexity and cost per Joule and the increased pumping brilliance also potentially enables more efficient operation of the solid state laser itself. In promising recent studies, it has been shown that optimized QCW diode laser bars operating at 940...980nm can operate with an output power of >1000W per bar, triple that of commercial sources. When operated at pulsed condition of 1ms, 10Hz, this corresponds to >1J/bar. We review here the status of these high-energy-class pump sources, showing how the highest powers are enabled by using long resonators (4...6mm) for improved cooling and robustly passivated output facets for high reliability. Results are presented for prototype passively-cooled single bar assemblies and monolithic stacked QCW arrays, both adapted for long resonators and high current operation. We confirm that 1J/bar is sustained for fast-axis collimated stacks with a bar pitch of 1.7mm, with narrow lateral far field angle (<12° with 95% power) and spectral width (<12nm with 90% power). Such stacks are anticipated to enable Joule/bar pump densities to be used near-term in real systems. Finally, we briefly summarize the latest status of research into bars with higher efficiencies, including studies into operation at sub-zero temperatures (-65°C), which also enables higher powers and narrower far field and spectra.

9348-31, Session 7

High brightness 9xxnm fiber coupled diode lasers

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Industrial application and fiber laser pumping have demonstrated an increasing demand for higher brightness fiber coupled diode lasers. Higher brightness pump sources enable higher power fiber lasers through the ability to spatially combine a greater number of pumps and more efficiently couple them into the fiber. Pulsed fiber lasers also require high brightness pump modules to reduce the active fiber length and corresponding fiber nonlinearities.

In this paper, we report on the development of a high brightness laser diode module capable of coupling 100W of output power with a 105?m 0.15NA fiber at 976nm with an electrical to optical efficiency greater than 44% and a 92% power enclosure at 0.12NA at the rated output power. Use of the volume Bragg gratings to narrow and stabilize wavelength is also available.

It is based on multiple single emitter coupling and polarization beam combining technique. With the similar technology, 150W/120W output power with a fiber 105?m NA0.22/0.15 at 915nm were also achieved, separately (>48% electrical to optical efficiency).

The reliability test data of similar designed multiple single emitter laser module under high optical load are also presented and analyzed using a reliability model with an emitting aperture optimized for coupling into 105?m core fiber. The total MTTF shows exceeding 100,000 hours within 60% confidence level. The packaging processes and optical design are ready for commercial volume production.

9348-32, Session 7

High power VCSEL systems and applications

Holger Moench, Ralf Conrads, Philips GmbH (Germany); Carsten Deppe, Guenther Derra, Philips GmbH Photonics (Germany); Stephan Gronenborn, Philips GmbH (Germany); Xi Gu, Philips GmbH Photonics (Germany); Gero Heusler, Johanna S. Kolb, Michael Miller, Pavel Pekarski, Jens Pollmann-Retsch, Armand Pruijmboom, Ulrich Weichmann, Philips GmbH (Germany)

High power VCSEL systems are made from many VCSEL chips each comprising thousands of low power VCSELs. Systems scalable in power from watts to multiple ten kilowatts and with various form factors utilize a common modular building block concept. This approach is not only most easy from a product design perspective but allows a simple understanding of the system performance which is determined by the properties of the single VCSEL and the thermal resistance of the total package. VCSELs have low power density and show excellent reliability. Designs for reliable high power VCSEL arrays and systems can be developed and tested on each building block level. Furthermore advanced assembly concepts aim to reduce the number of individual processes and components and make the whole system even more simple and reliable.

Three different examples will be presented in more detail to illustrate the wide scope of systems and applications: First, single chip modules are used for IR camera illumination enabling well defined and uniformly illuminated areas. Second, a very compact system of only 23mm diameter produces more than 500W QCW pump power for laser ignition applications in combustion engines. Third, an extendable system provides a uniform or locally and timely addressable illumination pattern along a line with about 500W laser power per cm line length and total power beyond 10 kilowatt. The compact form factor, the gentle optical properties and the addressability in combination with on-line diagnostics enable a new class of laser systems for material processing.

9348-33, Session 7

Watt-level continuous-wave diode lasers at 1180 nm with high spectral brightness

Katrin Paschke, Gunnar Blume, Olaf Brox, Frank Bugge, David Feise, Jörg Fricke, Julian Hofmann, Hans Wenzel, Götz Erbert, Ferdinand-Braun-Institut (Germany)

Diode lasers which emit at a wavelength of about 1180 nm are interesting for non-linear frequency conversion (SHG) to the yellow and orange spectral range. Laser sources at and around 590 nm are key components for many applications, e.g. laser cooling of sodium atoms, high resolution glucose content measurements as well as spectroscopy on rare earth elements. The advantages of single-pass SHG laser modules at 590 nm based on diode lasers are unprecedented degrees of miniaturization and efficiency, while allowing direct modulation.

Tapered diode lasers are well suited for applications, such as single-pass second harmonic generation, which require a high optical output power in combination with a good beam quality. Adding monolithic internal gratings to such devices led to the development of distributed Bragg-Reflector tapered diode lasers (DBR-TPLs).

At the conference we will show results concerning the development of DBR-TPLs emitting near 1180 nm. For this purpose, highly strained InGaAs quantum well laser structures were grown by metalorganic vapor-phase epitaxy. The wafers were processed into tapered lasers with integrated 3rd-order surface Bragg gratings. Coated lasers were mounted onto conductively cooled heat sinks for continuous-wave operation.

The mounted lasers feature an output power of more than 1 W, a conversion efficiency of more than 40% at heat-sink temperatures of 25°C and nearly diffraction limited emission into a single longitudinal mode at 1177 nm. These monolithic, high-brilliance diode lasers are suitable laser sources for efficient single-pass SHG and will allow the miniaturization of existing laser systems for bio-analytics and spectroscopy due to their compactness.

9348-34, Session 8

Copper-based micro-channel cooler reliably-operated using solutions of distilled-water and ethanol as a coolant

Aland Chin, Somerville Laser Technology, LLC (United States); Alan Nelson, Richard H. Chin, Science Research Lab., Inc. (United States); Rick K. Bertaska, New England Analytical, LLC (United States); Jonah H. Jacob, Science Research Lab., Inc. (United States)

Copper-based micro-channel coolers (MCC) are the lowest thermal-resistance heat-sinks for high-power laser-diode (LD) bars that operate at high electrical and thermal power densities. In commercial use, the coolant is water which has the highest, relative heat-transfer rate among common liquids. Up to now, the resistivity, CO2 content, and O2 content of water coolant must be carefully controlled to prevent corrosion and electro-corrosion of the copper. Additionally, the water must be constantly exposed to ultraviolet radiation to limit the growth of micro-organisms that may clog the micro-channels. Thus, water is not a suitable coolant for systems that must meet the storage requirements of Mil-Std 810G, e.g. exposure to a temperature as low as -51°C and no growth of micro-organisms during passive storage.

We report the first carefree-operation of copper-based MCCs using solutions of distilled water and ethanol. Solutions of water-ethanol containing more than 75% ethanol are antiseptic and have a freezing temperature below -51°C. We have performed life-tests of high-power laser-diode bars, attached to enhanced lateral-flow MCCs, cooled with water-ethanol solutions containing 0%, 40% and 100% ethanol. During the tests, the pressure coefficient was used to monitor the performance of the coolers. Aged coolers were analyzed using CAT (computerized axial-tomography) scans, SEM (scanning electron microscopy), and optical microscopy. No significant changes in the performance or mechanical structure of the MCCs were observed over test times as long as 2000hrs.

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9348-35, Session 8

Coupling of a high-power tapered diode laser beam into a single-mode-fiber within a compact module

Daniel Jedrzejczyk, Alexander Sahm, Ferdinand-Braun-Institut (Germany); Christian Carstens, Gerald A. Urban, C2GO inprocess solutions GmbH (Germany); Markus Pulka, FCC FibreCableConnect GmbH (Germany); Bernd Eppich, Ferdinand-Braun-Institut (Germany); Friedemann Scholz, Eagleyard Photonics GmbH (Germany); Katrin Paschke, Ferdinand-Braun-Institut (Germany)

Efficient high-power laser light sources in continuous-wave (CW) operation emitting spectrally narrow-band near-infrared radiation in spatial fundamental mode are desired for applications such as pumping of advanced solid-state lasers or frequency conversion.

In this work, we demonstrate coupling of a high-power distributed Bragg reflector (DBR) tapered diode laser around 1064 nm into a single-mode-fiber (SMF) within a butterfly module with a footprint < 10 cm2. The module comprises temperature stabilizing components, a brightness maintaining micro optical assembly mounted with sub-micrometer precision and a standard FC/APC output connector. The aim of the introduced concept is to improve the beam quality and to eliminate the current dependent beam astigmatism, and, thus, provide an efficient, multi-Watt laser light source characterized by a narrow-band spectrum and a stigmatic, nearly Gaussian laser beam independent of the operating point.

At the conference, the concept of the compact butterfly module and its electro-optical characteristics will be presented. In particular, the optical power ex SMF and the corresponding coupling efficiency, as well as the spectral and spatial laser beam properties are being investigated. Up to date, a maximum power ex SMF of 2.5 W at a coupling efficiency of nearly 60 % has been achieved with this compact module concept.

9348-36, Session 8

Maximizing coupling-efficiency of high-power diode lasers utilizing hybrid assembly technology

Daniel Zontar, Fraunhofer-Institut für Produktionstechnologie (Germany); Mehmet Dogan, Stephen F. Fulghum, Science Research Lab., Inc. (United States); Tobias Müller, Sebastian Haag, Fraunhofer-Institut für Produktionstechnologie (Germany); Christian Brecher, RWTH Aachen (Germany); Jonah H. Jacob, Science Research Lab., Inc. (United States)

In this paper, we present hybrid assembly technology to maximize coupling efficiency for spatially combined high-power diode laser systems. High quality components, such as center-turned focusing units, as well as suitable assembly strategies are necessary to obtain highest possible output ratios. Alignment strategies are challenging tasks due to their complexity and sensitivity. Especially in low-volume production fully automated systems are economically at a disadvantage, as operator experience is often expensive to translate. However reproducibility and quality of automated systems can be superior. Therefore automated and manual assembly techniques are combined to obtain high coupling efficiency while preserving maximum flexibility. The paper will describe necessary equipment and software to enable hybrid assembly processes. Micromanipulator technology with high step-resolutions and six degrees of freedom provide a large number of possible evaluation points. Automated algorithms are necessary to speed-up data gathering and alignment to efficiently utilize available granularity in manual assembly processes. Furthermore an engineering environment is presented to enable rapid prototyping of automation tasks with simultaneous data evaluation. Integration with simulation environments, e.g. Zemax, allows the verification of assembly strategies in advance. Data driven decision making ensures constant high quality, documents the assembly process and is basis for further improvement.

The hybrid assembly technology has been applied on several applications and will be discussed in this paper. Maximized coupling efficiency has been achieved with minimized assembly effort due to semi-automated alignment. Focus of the description will be on hybrid automation for optimizing and attaching turning mirrors and collimation lenses.

9348-16, Session PTue

Assessment of high-power kW-class single-diode bars for use in highly efficient pulsed solid-state laser systems

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Future high-energy-class diode laser pumped solid-state laser (HEC-DPSSL) systems operating at multi-J pulse energies and repetition rates of around 10 Hz, such as those in construction at the HiLASE and STFC facilities, require pump lasers with the very highest performance. Higher power diode lasers are of particular interest, as the increased power density potentially enables higher amplifier performance, as well as reducing cost in $/J. However, high powers are only of use provided lateral (in-plane) divergence remains narrow and conversion efficiency remains high. The efficiency-optimized diode laser bars with long resonators that are constructed with robustly passivated output facets have the potential to fulfil this need, as in development at the Ferdinand-Braun-Institut (FBH). We have therefore investigated in detail the performance of two prototype 940 nm QCW single-diode bars manufactured at the FBH, and have compared their performance to the requirements for HEC-DPSSL systems. The measurements were performed at room temperature on a test bench developed at HiLASE Centre, as a function of operating condition. The single-diode bars generated > 1.0 kW when tested with 1 ms pulses at 1-10Hz operating frequency, corresponding to > 1 J per pulse. The maximum electrical-to-optical efficiency was > 60 %, with operating efficiency at 1 kW of > 50%, limited by the ~ 200 μW resistance of the bar packaging. In addition, slow axis divergence at 1 kW is below 6° FWHM and spectral width at 1 kW is below 7 nm FWHM. We therefore confirm that such high power bars are potentially good candidates for use in future HEC-DPSSL systems. Further optimization of the design for operation at sub-zero temperatures (ca. -50°C) is anticipated to bring substantial increases in power and efficiency.

9348-37, Session PTue

In-volume heating using high-power laser diodes

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High-power lasers are useful instruments suitable for applications in various fields; the most common industrial applications include cutting and welding. We propose a new application of high-power laser diodes as in-bulk heating source for food industry. Current heating processes use surface heating with different approaches to make the heat distribution more uniform and the process more efficient. High-power lasers can in theory provide in-bulk heating which can sufficiently increase the uniformity of heat distribution thus making the process more efficient. We chose two media (vegetable fat and glucose) for feasibility experiments. First, we checked if the media have necessary absorption coefficients on the wavelengths of commercially available laser diodes (940-980 nm). This was done using spectrophotometer at 700-1100 nm which provided the dependences of transmission from the wavelength. The results indicate that vegetable fat has noticeable transmission dip around 925 nm and glucose has sufficient dip at 990 nm. Then, after the feasibility check, we did numerical simulation of the heat distribution in bulk using finite element analysis software. Based on the results, optimal laser wavelength and illuminator configuration were selected. Finally, we carried out several pilot experiments with high-power diodes heating the chosen media.

9348-38, Session PTue

Tapered laser diode with linearly effective-refractive-index variational waveguide

Duchang Heo, Korea Electrotechnology Research Institute (Korea, Republic of); Yun-Seok Kwak, Tae-kyung Kim, QSI Co., Ltd. (Korea, Republic of); Young-Wook Choi, Korea Electrotechnology Research Institute (Korea, Republic of)

Recently, high power laser diodes (HPLDs) have enlarge the field of applications from industry to medicine. There are two kinds of HPLDs; one is bread area LD and the other is tapered LD. Taperd LD has more stable beam profile by maintining the stable single mode profile from single mode ridge section [1]. The tapered LDs are categorized into gain-guided and index-guided tapered strcuture for from a few to a few decade W and ~ a few hundred mW respectively. In this work, We proposed a novel design concept of index-guided tapered laser diodes(LDs) to make a quality beam. In the index-guided tapered laser diode, the guided wave feels different effective index with increment of the taper width. We design the device on a point of view of effective-refractive-index not geometry. Therefore we vary the width of the tapered LD based on linearly effective-refractive-index variation which a propagation beam undergoes, instead of linearly geometrical variation. We fabricate the LDs using a standard ridge LD process. We measurement near-field-pattern and far-filed-pattern to investigate the beam quality. We can obtain spatial single-mode like laser diode with aperture size of 30, 50, 70 um at a operating current. The linearly effective-refractive-index variational waveguide is helpful to make more stable optical mode profile by desiging waveguide on a point of view of beam propagation.

Conference 9349: Vertical External Cavity Surface Emitting Lasers (VECSELs) V

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9349-1, Session 1

Ultrafast non-equilibrium carrier dynamics in semiconductor laser mode-locking *(Invited Paper)*

Jerome V. Moloney, Isak Kilen, Joerg Hader, College of Optical Sciences, The Univ. of Arizona (United States); Stephan W. Koch, Philipps-Univ. Marburg (Germany)

We present detailed simulations of microscopic many body effects in the VECSEL gain medium and in the saturable QW absorber by solving the 2-band Maxwell - Semiconductor Bloch equations (MSBE) in the Hartree-Fock limit using microscopically motivated carrier relaxation and dephasing times. Our simulations show that 100fs or sub 100fs pulse mode-locking is difficult to achieve in resonant-periodic-gain (RPG) active structures. In fact a nonuniform spacing of QWs was used recently in the low gain limit to broaden the linear net gain to achieve 107fs duration pulses. In higher gain situations unused carriers can destabilize the pulse by seeding amplification in spectral windows that exist outside the direct interacting nonequilibrium system. The implications of this are profound and show that it will be extremely difficult to avoid dynamical pulse breakup under strong pump conditions. In particular, we show that pulse molecules form with hundreds of femtosecond to picosecond overall duration that contain subpulses of 50-60fs duration. We show that these are due to a pulse splitting into two relatively clean and interfering time shifted longer duration pulses that feed off independent carrier reservoirs in the inverted system. We also identify a clear pulse separation in time at higher pump levels that is consistent with predictions from prior high average power mode-locking experiment with a graphene (GSAM) mode-locking element. The limitation on short pulse duration will be associated with the inability to efficiently utilize unused carriers in the inverted semiconductor chip.

9349-2, Session 1

Influence of non-equilibrium carrier dynamics on pulse amplification in semiconductor gain media

Christoph N. Boettge, Joerg Hader, Isak Kilen, College of Optical Sciences, The Univ. of Arizona (United States); Stephan W. Koch, College of Optical Sciences, The Univ. of Arizona (United States) and Philipps-Univ. Marburg (Germany); Jerome V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States)

A fully microscopic many-body model is coupled to a Maxwell solver to investigate the influence of non-equilibrium carrier dynamics on pulse propagation through inverted semiconductor gain media. The model allows us to investigate fully self-consistently the carrier dynamics, the optical response of the laser medium, and the modification of the light field through the resulting optical polarization. Under pulsed laser operation as, e.g., in mode-locked vertical external-cavity surface-emitting lasers, the stimulated carrier recombination strongly depletes electron--hole states resonant with the lasing wavelength leading to kinetic hole burning, i.e., non-equilibrium deviations from quasi-equilibrium Fermi--Dirac distributions. The depth and extent of these kinetic holes is ultimately determined by the balance between the stimulated carrier removal and the replenishing via carrier--carrier and carrier--phonon scattering. Intraband scattering can substantially refill the spectral holes on a sub-100 fs timescale. This can make additional carriers available for stimulated emission while the pulse is present and significantly enhance the pulse amplification. Ultimately, the carrier replenishing is limited by the much slower interband scatterings associated with pump injection. Thus, these dynamics set fundamental limits to the achievable pulse lengths and amplitudes. Here, the model is used to study the influence of the intra-pulse dynamics on the magnitude and spectral dependence of pulse amplification for single pulses passing through inverted quantum-well media. The dependence on pulse lengths and amplitudes is investigated. Pulses shorter than about 100 fs are found to be rather unaffected by the carrier dynamics. For pulses in the multi-picosecond range the pump-related dynamics become significant.

9349-3, Session 1

Pumping of VECSELs using high quantum defect and broadband sources *(Invited Paper)*

Adrian H. Quarterman, Univ. of Dundee (United Kingdom)

VECSEL slope efficiency can be expressed as a product of the quantum defect, the output coupling efficiency, and the quantum efficiency. This last factor represents the efficiency with which pump photons incident on the sample are converted into useful laser photons. Measurements of the quantum efficiency of a VECSEL sample using pump sources over a range of wavelengths and with a range of powers and areas on the sample can be used to characterise a sample and to inform decisions about the optimum pumping conditions to achieve maximum output power given a particular pump source and gain sample.

This paper will describe the results of lasing and quantum efficiency measurements of a resonant, 10 quantum well gain sample when pumped using 808 nm, 532 nm and broadband pump sources over a range of spot sizes and incident powers. Conclusions will be drawn regarding VECSEL power scaling, sample design, and the prospects for optical pumping of high power VECSELs using non-laser sources.

9349-4, Session 1

DBR-free optically pumped semiconductor disk lasers *(Invited Paper)*

Zhou Yang, Alexander R. Albrecht, The Univ. of New Mexico (United States); Jeffrey G. Cederberg, Sandia National Labs. (United States); Mansoor Sheik-Bahae, The Univ. of New Mexico (United States)

While maintaining the wavelength flexibility and high gain of edge-emitting semiconductor lasers, vertical external-cavity surface-emitting lasers (VECSELs) have the advantages of good beam quality with high CW output powers, and easy intra-cavity access for use of additional optical elements, like birefringent filters for wavelength tuning, non-linear crystals for wavelength conversion, or saturable absorbers for mode-locking. One design restraint is the need of a distributed Bragg reflector (DBR), typically monolithically integrated with the VECSEL active region. This can be a challenge, since not all material systems have lattice-matched material combinations of sufficient refractive index contrast. In addition, the DBR – by nature of the multilayer interfaces – suffers from low thermal conductivity, making heatsinking and power scaling more difficult. Here, we demonstrate a DBR-free vertically emitting semiconductor disk laser, which has been lifted off and van der Waals bonded to various transparent substrates. This allows us to achieve CW operation in a vertical geometry without the need for a semiconductor DBR. For two different quantum well

samples, we achieved 160mW output at 1037nm after bonding to a sapphire window and 2W at 1150nm with a single crystal diamond window. For a sample bonded on 45deg right angle fused silica prism, pulsed lasing has been achieved with total internal reflection. A few more explorations are still underway to improve the performance of the laser. We also present a few monolithic cavity geometries with ZnS cube and ZnSe equilateral prism by using only total internal reflection.

9349-5, Session 1

Recent advances in the field of vertical-external-cavity surface-emitting lasers *(Invited Paper)*

Arash Rahimi-Iman, Mahmoud Gaafar, Dalia Al Nakdali, Christoph Möller, Fan Zhang, Matthias Wichmann, Mohammad K. Shakfa, Philipps-Univ. Marburg (Germany); Ksenia A. Fedorova, Aston Univ. (United Kingdom); Wolfgang Stolz, Philipps-Univ. Marburg (Germany) and NAsP III/V GmbH (Germany); Edik U. Rafailov, Aston Univ. (United Kingdom); Martin Koch, Philipps-Univ. Marburg (Germany)

Owing to the vertical-external-cavity surface-emitting lasers' (VECSELs) design and features, these versatile lasers serve as an excellent platform for the realization of various emission schemes. These include high-power multi-mode or single-frequency continuous-wave operation, two-color as well as mode-locked emission. Moreover, their external resonator allows for intra-cavity frequency conversion via nonlinear elements. Particularly, VECSELs have become appealing sources of pulsed laser light. Much work has been performed in this field by the community to provide ever shorter pulses using resonator-integrated or even chip-integrated semiconductor saturable-absorber mirrors (SESAMs), while exploiting a high output power and outstanding beam quality that a VECSEL typically provides. However, the carefully designed and costly SESAMs naturally impose limitations on the performance of the device.

Here, light is shed on recent demonstrations of SESAM-free VECSELs which are operated under self-mode-locking (SML) conditions. It will be shown that the SML scheme is not only applicable to quantum-well VECSELs, but also to quantum-dot devices. Furthermore, SML can be used for passively harmonically mode-locked devices with sub-ps-pulsed operation demonstrated at discrete power levels up to the third harmonic. However, the mechanism of SML, which could once give access to an exhaustive utilization of the occurring effects, is not fully understood yet. Nevertheless, an optimization of the dispersion management and thermal management promises the achievement of shorter pulses in the fs-range and significantly higher peak powers exceeding the current values of up to 1kW.

9349-6, Session 2

Recent progress in wafer-fused VECSELs emitting in the 1310nm waveband *(Invited Paper)*

Alexei Sirbu, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Antti J. Rantamaki, Tampere Univ. of Technology (Finland); Vladimir Iakovlev, Alexandru Mereuta, Andrei Caliman, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Jari Lyytikäinen, Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland); Elyahou Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Wafer fusion has proved to be very successful in producing state-of-the-art optically pumped vertical external cavity surface emitting lasers (VECSELs) with InP-based active regions. The gain mirror structures in these VECSELs are formed by bonding of InAlGaAs/InP active cavities to AlGaAs/GaAs distributed Bragg reflectors (DBRs). Thanks to the excellent thermal properties of these gain mirrors, optically pumped VECSELs demonstrate multi-Watt level nearly diffraction limited beams in the full 1300 nm waveband, from 1250 nm to 1350 nm. Currently, this wafer-fusion fabrication approach is the only solution for high power lasers emitting in this wavelength range, which is becoming important for new fiber lasers and amplifiers, spectroscopy, frequency doubled lasers, etc.

Over the last years we have continuously improved the performance of 1300 nm band VECSELs with both intra-cavity diamond and flip-chip heat dissipation schemes.

In the talk we will present results on modeling and experiments for gain mirrors that implement both heat-dissipation schemes. We demonstrate record high output power levels of 7.1 W in the intra-cavity diamond heat-spreader configuration and 6 W with the flip-chip heat dissipation scheme. These improvements are achieved mainly due to optimized configurations of the InAlGaAs/InP multi-quantum wells gain region. The flip chip approach is also expected to eventually surpass the intracavity diamond heat spreader configuration in output power. This progress should be achievable upon further development of gain mirrors for a better power scaling by increasing the pump spot size on the gain element.

9349-7, Session 2

Towards high power flip-chip long-wavelength semiconductor disk lasers *(Invited Paper)*

Antti J. Rantamaki, Esa J. Saarinen, Jari Lyytikäinen, Juha M. Kontio, Juuso Heikkinen, Kimmo Lahtonen, Mika Valden, Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland)

We present optically pumped semiconductor disk lasers (SDLs) with emphasis on the integration of semiconductor structures grown on different substrates and reducing the number of layer pairs in the distributed Bragg reflector (DBR). The integration of disparate structures is essential when the optimal gain medium and distributed Bragg reflector (DBR) cannot be grown monolithically on the same substrate. Furthermore, a thin DBR section is preferable for flip-chip devices, because the excess heat in the active region is extracted through the DBR.

In particular, InP-based active regions are ideal for SDLs emitting in the range 1.2-1.6 μm. They are preferably wafer-bonded with GaAs-based DBRs that possess high refractive index contrast and thermal conductivity. Conventionally, a relaxed requirement for matching the coefficients of thermal expansion between disparate wafers is achieved using low temperature hydrophilic wafer bonding with reactive surface oxides. However, hydrophilic wafer bonding for III-IV materials is not straightforward, because the characteristics of surface oxides and the surface cleaning procedures are not as well studied when compared with ordinary the Si-based materials. We have resolved this issue by utilizing thin intermediate Si-based layers for bonding GaAs-based DBRs with InP-based active regions. Furthermore, placing a thin dielectric layer to between the semiconductor DBR and the highly reflecting backside metallization allows to reduce the number of DBR layer pairs significantly without compromising the reflectivity of the structure. Thus, the use of thin dielectric sections with a total thickness of ?100 nm in the SDL structure can improve the performance of flip-chip long-wavelength SDLs.

9349-8, Session 2

>8W GaInNAs VECSEL emitting at 615 nm

Tomi Leinonen, Jussi-Pekka Penttinen, Ville-Markus Korpijärvi, Emmi L. Kantola, Mircea Guina, Tampere Univ. of Technology (Finland)

Intra-cavity frequency-doubled Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) offer an attractive solution for generating light at the visible wavelength band via efficient intracavity frequency doubling. Amongst the visible wavelengths, the 610 – 630 nm range is one of the least explored. The reason for this is the high lattice strain associated with the mature GaInAs/GaAs quantum well technology, which ren-ders the fabrication of gain mirrors for the fundamental wavelength of 1220 – 1260 nm difficult. However, VECSELs emitting at 610 – 630 nm wavelengths would be attractive light sources for many applications, including biophotonics and in laser projec-tion.

To this end, we have developed dilute nitride (GaInNAs) – based gain mirrors to gener-ate fundamental light at around 1230 nm. The use of nitrogen in GaInAs decreases the band gap, and in addition, decreases the lattice strain by shortening the lattice constant. It is worth noting, however, that without careful control of the material growth, the point defects associated with nitrogen incorporation will hinder the luminous efficiency of the material. The gain chip of the laser was grown by plasma-assisted molecular beam epitaxy and it comprised 10 GaInNAs quantum wells. The VECSEL cavity had a V-shaped geometry. A bulk nonlinear crystal was located inside the laser cavity to ensure efficient second harmonic generation. Preliminary experiments show an output power of 8.5 W.

9349-9, Session 2

20W continuous wave output power from an GaSb-based VECSEL at 2μm emission wavelength *(Invited Paper)*

Marcel Rattunde, Peter B. Holl, Sebastian Kaspar, Steffen Adler, Andreas Bächle, Rolf Aidam, Wolfgang Bronner, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

In recent years, vertical-external-cavity surface-emitting laser (VECSEL) have attracted considerable interest due to their capability of simultaneously delivering high output powers and a high quality output beam. By using different material systems, VECSEL operating from the visible red (650 nm) all the way up to the mid-infrared (5μm) spectral range [1,2] have been realized.

In the 2-3μm wavelength range, high-performance VECSEL can be realized by using the (AlGaIn)(AsSb) material system. For thermal management, either the “thin disk” approach can be used for this material system by completely removing the substrate [3] or a transparent heatspeader can be bonded to the chip surface, with the latter technique still showing the higher output power in the multiple watt range [4] in this wavelength range.

Here we present a GaSb-based VECSEL with an optimized heat sinking technology by using a combination of the two approaches discussed above. Further on, the VECSEL was optimized for 1.5 μm diode pumping, yielding a reduced quantum defect of only 25%. With this combination we were able to achieve 20 W CW output power at 0°C heatsink temperature and still over 15 W at 10°C with a standard (single-chip) linear cavity. The optical to optical conversion efficiency, neglecting reflection losses of the pump beam, reaches 27% at 20 W output power.

We will compare the efficiency, threshold power density, thermal resistance and power level with results achieved in other material systems (e.g. GaAs-based VECSELs [5]) in order to identify and discuss dominant loss mechanisms. Further on, we will address different applications of these high power 2 μm laser sources.

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9349-10, Session 3

Direct blue laser emission from InGaN-based VECSEL *(Invited Paper)*

Thomas Wunderer, Palo Alto Research Center, Inc. (United States)

Vertical-external-cavity surface-emitting lasers (VECSELs) combine desirable features from several types of solid-state laser devices. Both high optical output power and a nearly diffraction limited beam quality can be simultaneously achieved. High-performance VECSELs with InGaAs or InGaAsP active zones are commercially available. However, until recently VECSEL emission in the near-UV and blue spectral regime has been only accessible through frequency multiplication. In this presentation, we demonstrate direct blue laser emission (? = 440 – 455nm) from an InGaN-based VECSEL. The laser heterostructures were grown on bulk GaN substrates by using MOVPE near atmospheric pressure. The active zone consisted of 20 InGaN quantum wells distributed in a resonant periodic gain configuration. High-reflectivity dielectric distributed Bragg-reflectors were used as mirrors. The concept of in-well pumping opens the possibility to use compact high-power GaN-based laser diodes as pump sources in future applications. The in-well absorption allows pumping through the GaN substrate and, therefore, the possibility to mount a heat sink close to the active zone. Furthermore, the approach reduces the thermal energy dissipation due to the low quantum deficit between the pump and lasing emission energies. Finally, homogeneous carrier generation throughout the distributed MQW region can be achieved, which is essential for high-performance VECSEL operation. An all-optical measurement technique was developed to determine the thermal resistance of the prototype VECSEL devices. The non-optimized thermal management could be identified as the limiting factor toward CW operation.

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9349-11, Session 3

Degradation studies and pump optimization of optically pumped red-emitting AlGaInP-VECSELs

Hermann Kahle, Univ. Stuttgart (Germany); Cherry M. N. Mateo, University of Stuttgart - IFSW (Germany); Maren Jäger, Caroline Weinspach, Stefan Baumgärtner, Univ. Stuttgart (Germany); Uwe Brauch, University of Stuttgart - IFSW (Germany); Roman Bek, Thomas Schwarzbäck, Michael Jetter, Univ. Stuttgart (Germany); Thomas Graf, University of Stuttgart - IFSW (Germany); Peter Michler, Univ. Stuttgart (Germany)

Optically pumped semiconductor (OPS) vertical external-cavity surface-emitting lasers (VECSELs) are an important category of power scalable lasers with a wide range of applications in biophotonics and medicine technologies, spectroscopy, projector technologies and lithography. The open laser resonator allows to insert frequency selective and converting intra-cavity elements. The possibility of bandgap engeneering, a laser emission in the fundamental Gaussian mode and the technical simplicity leads to ongoing growth of the area of applications for these tuneable laser sources.

We present degradation studies of metal-organic vapor-phase epitaxy (MOVPE) grown, optically pumped, red emitting AlGaInP-VECSELs with quantum-wells as active layers. Laser performance due to continuous operation at various operation modes, pumped with a 532 nm Nd:YAG laser, will be shown. Surface investigations of the gain structure via scanning electron microscopy, large-area photoluminescence maps and photoluminescence spectra show the possible consequences of optical pumping. A comparison of barrier-pumped performance data with the data of an in-well pumped VECSEL device is possible as well as power measurements at different operating temperatures up to values close to room temperature.

9349-12, Session 3

Monolithic GaInNAsSb/GaAs VECSEL emitting at 1550 nm

Ville-Markus Korpijärvi, Emmi L. Kantola, Tomi Leinonen, Mircea Guina, Tampere Univ. of Technology (Finland)

Different semiconductor heterostructures have enabled lasing of vertical external-cavity surface-emitting lasers (VECSELs) in a broad spectral range (from ultraviolet to mid-infrared). GaAs-based VECSELs emitting at 1.0–1.1 μm have attained the best performance in terms of power and efficiency. These achievements have been enabled by the high gain of InGaAs quantum wells (QWs) and outstanding properties of AlAs/GaAs distributed Bragg reflectors (DBRs), such as high refractive index contrast, low lattice mismatch and relatively high thermal conductance. However, at the telecom wavelength of 1.55 μm, the lattice mismatch between InGaAs and GaAs limits the use of InGaAs/GaAs QWs while the AlAs/GaAs DBRs retain their good characteristics. VECSELs with emission at 1.55 μm have been demonstrated based on monolithic InP-based gain mirrors, wafer-fused gain mirrors with AlAs/GaAs DBR and InP-based gain region, or gain mirrors with InP-based gain region and hybrid metal–metamorphic AlAs/GaAs mirror.

Here we report the first monolithic GaAs-based VECSEL operating at 1550 nm. The MBE-grown gain mirror comprised 8 GaInNAsSb/GaAs QWs, where both the nitrogen and antimony were used to increase the emission wavelength while nitrogen also decreases the lattice strain. The output power of the VECSEL was 80 mW for a mount temperature of 16 °C. The measurements were carried out in a straight cavity formed between the GaInNAsSb/GaAs gain mirror, pumped by 808 nm diode laser, and an output coupler with R>99.8%. By optimizing the gain mirror structure and its fabrication, and by modifying the cavity configuration, watt-level output powers should be attainable.

9349-13, Session 3

Power and wavelength scaling using semiconductor disk laser-bismuth fiber MOPA systems

Juuso Heikkinen, Regina Gumenyuk, Antti J. Rantamaki, Jari Lyytikäinen, Tomi Leinonen, Tampere Univ. of Technology (Finland); Igor O. Zolotovskii, Ulyanovsk State Univ. (Russian Federation); Mikhail A. Melkumov, Eugeny M. Dianov, Fiber Optics Research Ctr. (Russian Federation); Oleg G. Okhotnikov, Tampere Univ. of Technology (Finland)

Few decades of intensive implementations of semiconductor disk lasers (SDLs) allow to appoint the firm statement: semiconductor gain media placed in a disk cavity format represent a breakthrough solution primarily due to high power achievable in a fundamental mode regime. The extended wavelength range and high repetition rate mode-locking make SDLs very attractive for applications such as photonic switches, telecommunications and optical clocking. New opportunities for spectral and power scaling arise by combining the wafer bonding of disparate semiconductors and novel non-rare-earth doped fiber amplifiers. In particular, bismuth-doped fibers have emerged as a promising stage for master oscillator - power amplifier (MOPA) systems operating at the wavelength range 1.2-1.4 μm.

This study presents a mode-locked SDL emitting at 1.33 μm as a master source for the MOPA. The gain element was fabricated by wafer bonding an InP-based gain section with a GaAs-based distributed Bragg reflector (DBR). Both structures were grown by molecular beam epitaxy (MBE). The gain section of the SDL comprises 10 compressively strained AlGaInAs quantum wells (QWs) and the DBR 25.5 GaAs/AlAs layer pairs. Passive mode-locking was achieved using an AlGaInAs QW semiconductor saturable absorber mirror (SESAM) with the recovery time controlled by Ni ion irradiation. The output of the mode-locked SDL was coupled into a bismuth-doped fiber amplifier that was pumped by a continuous wave SDL emitting at 1.18 μm. The MOPA system produces 5.7 ps pulses with 520 mW of average output power at the repetition rate of 830 MHz.

9349-14, Session 4

Carrier-envelope-offset frequency detection of an ultrafast VECSEL *(Invited Paper)*

Mario Mangold, Christian A. Zaugg, Alexander Klenner, Aline S. Mayer, Sandro M. Link, Florian M. Emaury, Matthias Golling, Emilio Gini, ETH Zürich (Switzerland); Clara J. Saraceno, ETH Zürich (Switzerland) and Univ. de Neuchâtel (Switzerland); Bauke W. Tilma, Ursula Keller, ETH Zürich (Switzerland)

High power ultrafast VECSELs are of particular interest for gigahertz frequency combs, providing a high power per comb-line and large comb-tooth spacing. However, the detection and stabilization of the carrier-envelope-offset frequency (fCEO) with an f-to-2f detection scheme, crucial for many applications, requires pulse durations in the order of 100 fs and kilowatt peak power to generate a coherent octave-spanning supercontinuum.

Here, we present the first detection of the fCEO from an ultrafast semiconductor laser. We used a state-of-the-art SESAM-modelocked VECSEL, generating 231-fs pulses in 100-mW average output power at a repetition rate of 1.75 GHz at 1040 nm. To achieve the required peak power for coherent supercontinuum generation, the pulses were amplified in a commercial Yb-doped fiber amplifier and subsequently broadened by self-phase modulation in a large mode area fiber. After re-compression 85-fs pulses at 1.4 W of average output power were obtained. By launching this output into a highly nonlinear photonic crystal fiber, a coherent octave-spanning supercontinuum covering 680 nm to 1360 nm was generated, supporting the first fCEO detection from an ultrafast VECSEL with a SNR of ≈17 dB with a 3-dB-linewidth of ≈10 MHz using a standard f-to-2f interferometer.

New concepts potentially leading to even shorter pulses directly from the VECSEL oscillator will be presented. In combination with higher peak power this should allow for omitting the amplification in the future, enabling an all-passive fCEO detection scheme. Compact and inexpensive frequency combs based on ultrafast semiconductor lasers may pave the way for numerous scientific and industrial applications.

9349-15, Session 4

Quantum dot based mode-locked AlGaInP-VECSEL

Roman Bek, Grizelda Kersteen, Hermann Kahle, Thomas Schwarzbäck, Michael Jetter, Peter Michler, Univ. Stuttgart (Germany)

Vertical external-cavity surface-emitting lasers (VECSELs) with quantum dots (QDs) as gain material have shown to produce high output power with lower temperature sensitivity compared to quantum well (QW) based gain structures. Furthermore, using QDs in semiconductor saturable absorber mirrors (SESAMs) allows for a greater flexibility in wavelength range and SESAM parameters such as modulation depth and saturation fluence than with QWs.

We present a passively mode-locked AlGaInP-VECSEL fabricated by metal-organic vapor-phase epitaxy emitting at around 655 nm. This wavelength region is reached by using InP-QDs in the active zone of the gain structure and the SESAM. Both semiconductor structures have a near anti-resonant design with the QD layers embedded in Al0.10GaInP barriers and Al0.55GaInP cladding layers. We use a v-shaped cavity with a concave output coupler serving as a folding mirror to tightly focus onto the absorber. The repetition frequency of the emitted pulse train is about 850 MHz. Due to the intra-cavity use of a plane diamond heat spreader without anti-reflection coating, side pulses are observed with a pulse duration of the single pulses in the order of one picosecond. Further research is made toward single pulse operation by using a wedged, anti-reflection coated diamond heat spreader.

9349-16, Session 4

Ultrafast in-situ probing of passively mode-locked VECSEL dynamics

Maik Scheller, Caleb W. Baker, College of Optical Sciences, The Univ. of Arizona (United States); Stephan W. Koch, Philipps-Univ. Marburg (Germany); R. Jason Jones, Jerome V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States)

While Vertical-External-Cavity-Surface-Emitting-Lasers (VECSELs) have been successfully used as ultrafast laser sources with pulse durations in the hundreds of femtosecond regime, the dynamics within the semiconductor gain structure are not yet completely understood. With the high carrier densities inside the semiconductor, nonequilibrium effects such as kinetic-hole burning are expected to play a major role in pulse formation dynamics. Moreover, the nonlinear phase change by the intense light field can induce a complex dispersion, which may potentially limit the achievable pulse durations.

To shed light on such nonequilibrium dynamics, we perform in-situ characterization of mode-locked VECSELs. We probe the gain media as well as the intracavity absorber with a sub-100fs fiber laser source. For measuring temporal characteristics, we employ an asynchronous optical sampling technique by phase-locking the repetition rate of the VECSEL to a multiple of the probe laser with an adjustable offset frequency. This allows for probing dynamics from femtosecond to nanosecond time scales with scan rates up to hundreds of Hertz without compromise of measurement precision that can be introduced by mechanical delays covering such large temporal windows. With a resolution in the femtosecond range, we characterize gain depletion by the intracavity pulse as well as the gain recovery timescales for different power levels and operation regimes. We also study the effect of the absorber recovery time and the resulting stability and duration of the emitted pulses. . Finally, we characterize the intracavity nonlinear lensing of the VECSEL chip and show its significance for the resulting operation mode.

9349-17, Session 4

Spectrally resolved pulse evolution in a mode-locked vertical-external-cavity surface-emitting laser from lasing onset measurements

Andrew P. Turnbull, Christopher R. Head, Edward A. Shaw, Theo Chen-Sverre, Anne C. Tropper, Univ. of Southampton (United Kingdom)

Here we present an extension to the saturated gain spectrum and CW-lasing onset measurements in VECSELs reported last year [1] to passively mode-locked VECSELs to investigate the effect of laser parameters on the pulse formation.

An intra-cavity chopper is used to block and unblock the laser mode allowing for the observation of the intra-cavity power build-up transient. For passive mode-locking a semiconductor saturable absorber mirror (SESAM) is included in the cavity, generating a VECSEL emitting transform-limited femtosecond pulses with GHz repetition rates.

The output of the laser is split into two components: the first is incident on a 1-GHz photodiode which can measure the fundamental power rise; the second is passed through a non-linear crystal to generate the second harmonic, which is subsequently recorded. By observing the second harmonic rise with respect to the fundamental power transient we can determine the mode-locking onset time and the pulse-shortening per round trip.

Furthermore a monochromator has been used to separate the spectral components of the fundamental power transient, to observe the spectral evolution during lasing and mode-locking onset with a high temporal and spectral resolution until the final steady state output is reached. This is, to our knowledge, the first attempt to spectrally resolve the formation of a pulse in a mode-locked semiconductor laser.

Combining both measurements we can provide a comprehensive description of pulse formation in VECSELs enabling further characterisation and optimisation of laser structures.

[1] Opt. Express 22, 6919-6924 (2014)

9349-18, Session 5

Development of next generation OPS laser products *(Invited Paper)*

Juan L. Chilla, Coherent, Inc. (United States)

Starting with the first commercially available solid state laser at 488 nm in 2001, we have translated the advantages of the OPS technology into products. These advantages include wavelength flexibility, broad pump tolerance, efficient spectral and spatial brightness conversion and high power scaling. Examples of the first generation of commercial lasers based on OPS technology are being used in a wide range of applications, including scientific, bio-instrumentation, medical, military and entertainment.

An active development program is required in order to compete favorably and displace alternative laser technologies in this broad array of markets. Our group is embarked in several programs to develop OPS technology in different directions, including: high power scaling, both at the single chip level and aggregation efforts; expansion of the spectral coverage, novel cavity designs and packaging techniques, smaller and more efficient lasers to facilitate integration and adoption in different applications.

We will present a summary of our latest developments, taking examples and results from all these programs.

9349-19, Session 5

Development and commercialization of mode-locked VECSELs *(Invited Paper)*

Nils Hempler, Craig J. Hamilton, Gareth T. Maker, Graeme P. A. Malcolm, M Squared Lasers Ltd. (United Kingdom); Bartlomiej Bialkowski, M Squared Lasers Ltd (United Kingdom)

In launching the Dragonfly, M Squared Lasers has successfully commercialised recent advances in mode-locked semiconductor disk laser (SDL or VECSEL) technologies. For end users in a range of ultrafast laser applications, there are now compelling reasons to adopt SDLs in place of sources based on more established laser technologies, which can often be overspecified for typical usage scenarios. The Dragonfly system has been engineered to utilise low-cost semiconductor gain media and integrated diode pumping, whilst exhibiting minimal footprint, high average powers, diffraction limited beam quality and low intrinsic noise. With a robust design philosophy, practical user-interface and compact form factor, opportunities arise to utilise these sources in established ultrafast laser applications, where low-cost, reliable and user-friendly sources can have a disruptive effect by providing previously unobtainable specification options. Multiphoton microscopy in particular has the potential for increased adoption and utility where specific fluorophores can be targeted through engineering of the semiconductor properties. In this presentation, we will describe the current state-of-the-art in commercial mode-locked SDLs and demonstrate their efficacy in key applications. In addition, the development challenges that have been overcome to bring this promising technology to market will be discussed. These include: thermal management challenges, repetition rate and pulse duration optimisation, electronic control system development and robust mechanical design requirements. Different approaches to the mode-locking of these lasers will be discussed with reference to advances in SESAM-free operation and also in saturable Bragg reflector-assisted modes of operation.

9349-20, Session 5

Latest achievements of NECSEL visible extended cavity surface emitting lasers *(Invited Paper)*

Gregory T. Niven, Simon J. Field, Michael J. Finander, Necsel (United States)

High power, frequency-doubled, extended cavity surface emitting lasers built by Necsel have now been commercialized in the green wavelengths to enable the launch of dual-RGB primary 3D cinema projectors in premium cinemas around the world. This is the first use of lasers in the cinema market, and is the result of many years of technical challenges being solved. Technical hurdles overcome were mass production of the three key elements of the laser: (1.) the use of periodically-poled Lithium Niobate, (2) volume Bragg gratings with flat surfaces for easy alignments, and (3) the semiconductor laser arrays that are broad area surface emitters. All of these were done with a plurality of wavelengths to enable the key cinema application.

9349-21, Session 5

21.2% wall-plug efficiency green laser based on an electrically pumped VECSEL through intracavity second harmonic generation

Pu Zhao, Bing Xu, Robert Van Leeuwen, Tong Chen, Laurence S. Watkins, Delai Zhou, Jean-Francois Seurin, Peng Gao, Guoyang Xu, Qing Wang, Chuni Ghosh, Princeton Optronics, Inc. (United States)

Nowadays, there is increasing demand for laser displays in television, mobile phone and movie theatre projector applications. The laser source for this application is realized through mixing red, blue and green laser beams. The green laser still remains a bottleneck in achieving efficient high power laser displays. Through frequency doubling, vertical external-cavity surface emitting laser (VECSEL) provides an effective way of generating green light.

While VECSEL can be optically pumped or electrically pumped (EP), the electrical pumping method is more attractive since it is a less complex pumping scheme. Moreover, EP-VECSEL can easily be designed as a two-dimensional array with multiple lasing elements, dramatically scaling up the output power.

In this work, we have successfully demonstrated a 20.3% wall-plug efficiency, continuous-wave 4.47 W green laser at 531.5nm based on EP-VECSEL through intracavity second harmonic generation. To the best of our knowledge, this efficiency is the highest value that has been reported to date from an intracavity frequency doubled EP-VECSEL. At the highest output power, the M2 beam quality parameter was measured to be around 13.

9349-22, Session 5

Simultaneous power and beam-shape optimization of an OPSL resonator *(Invited Paper)*

Sebastian Haag, Sebastian Sauer, Fraunhofer-Institut für Produktionstechnologie (Germany); Torsten Garlich, Wolf R. Seelert, Coherent Lubeck GmbH (Germany); Christian Brecher, Tobias Müller, Daniel Zontar, Fraunhofer-Institut für Produktionstechnologie (Germany)

As published in former works, the highly reflective resonator end mirror is the most crucial component in the resonator assembly of an optically pumped semiconductor laser (OPSL) as all manufacturing tolerances add up in this step. In previous cooperation, the Coherent GmbH and the Fraunhofer Institute for Production Technology IPT had developed a robust active alignment strategy to optimize the output power of the OPSL resonator using search strategies for finding the laser threshold as well as hill-climbing algorithms for maximizing the output power. As a result of manufacturing tolerances of the optical components and previous assembly steps no prediction of the beam shape or laser mode are possible. Both, beam shape and laser mode, have major influence on the quality and the duration of subsequent beam-shaping and fiber-coupling steps of the laser system. Therefore, the alignment algorithm has been extended recently by simultaneous image processing for ensuring a Gaussian beam as the result of alignment. The paper describes the enhanced approach of automated alignment by additionally scanning for plateaus of maximum power along the optical resonator and subsequently evaluating and optimizing the roundness of the beam as well as minimizing the beam radius through twisting and tilting of the mirror. A quality metric combining these measures is defined. The results are evaluated through M? measurements of the collimated beam and they are documented in the paper. The paper also describes the setup for alignment including measuring and micromanipulation devices.

9349-23, Session 6

Time-gated detection and VECSELs: A grand unison towards the wide dissemination of STED microscopy *(Invited Paper)*

Ivàn Coto Hernàndez, Marco Castello, Paolo Bianchini, Alberto Diaspro, Giuseppe Vicidomini, Istituto Italiano di Tecnologia (Italy)

Stimulated emission depletion (STED) microscopy is a prominent approach of super-resolution fluorescence microscopy, which allows cellular imaging with sub-diffraction spatial resolution. But the complexity and cost of the early STED microscopy implementations, together with the need of high-intensity illumination, have limited its wide dissemination. The combination of time-gated detection with STED microscopy significantly helped to overcome these limitations: A cheap, easy-to-implement and efficient implementation of STED microscopy which works at low-intensity illumination is obtained using continuous-wave (CW) lasers, the so-called gated CW-STED implementation.

Here we show that the performance of this system can be further improved

by using a low-intensity noise laser: Weak intensity fluctuations reduce the average intensity needed for obtaining a certain resolution, which is a key condition to reduce photodamage effects on the sample. We took advantage of the low-noise characteristic of an optically pumped VECSEL to built a gated CW-STED microscope which provides ~40 nm resolution in biological samples at moderate (peak) intensity illumination, well below the values used by more complex and expensive STED microscopy implementations.

Finally, we discuss the future research directions of gated STED microscopy with respect to the properties of the laser sources.

9349-24, Session 6

Optically pumped semiconductor lasers for atomic and molecular physics *(Invited Paper)*

Shaun C. Burd, Dietrich Leibfried, Andrew C. Wilson, David J. Wineland, National Institute of Standards and Technology (United States)

Experiments on atomic and molecular physics require laser sources at many different wavelengths and with varying requirements on spectral linewidth, output power and intensity stability. Optically pumped semiconductor lasers (OPSLs) when combined with nonlinear frequency conversion, can potentially replace many of the laser systems currently in use. We are developing a source for laser cooling and spectroscopy of Mg+ ions at 280 nm, based on a frequency quadrupled OPSL with a gain chip fabricated at the ORC at Tampere Univ. of Technology. The target specifications of the system are approximately 100 mW of output power at 280 nm in a single longitudinal mode, mode-hop-free tunability exceeding 1 GHz, less than 1 MHz linewidth in 1 second of averaging and relative intensity stability below 1%. An OPSL system with such specifications could serve as a prototype for many other sources used in atomic and molecular physics.

9349-25, Session 6

Dual-comb MIXSEL

Sandro M. Link, Christian A. Zaugg, Alexander Klenner, Mario Mangold, Matthias Golling, Bauke W. Tilma, Ursula Keller, ETH Zürich (Switzerland)

We present the first semiconductor disk laser simultaneously emitting two different GHz modelocked pulse trains from a single gain chip. The modelocked integrated external-cavity surface-emitting laser (MIXSEL) combines the gain of a VECSEL and the saturable absorber of a SESAM in a single semiconductor structure. This allows for modelocking in a simple straight cavity, only comprising the MIXSEL chip and a curved output-coupler. For the dual-output operation, we insert a birefringent CaCO3 crystal into the cavity to separate the one cavity beam into two spatially separated beams with perpendicular polarizations on the MIXSEL chip. By pumping both cavity spots on the MIXSEL with a single fiber-coupled laser-diode, we achieve two collinear orthogonally-polarized modelocked pulse trains with slightly different repetition rates of 1.824 GHz and 1.828 GHz respectively. The pulse durations are 18.3 ps and 15.5 ps at an average output power of 50 mW and 65 mW, respectively. An intracavity fused silica etalon centers the wavelengths to 968.32 nm and 968.19 nm. Outside the cavity both beams are superimposed on a photodetector to generate beat signals in the microwave spectrum. A radiofrequency comb between DC and half the repetition rate with comb-lines separated by the repetition rate difference of the two laser beams is produced. This represents a strikingly simple setup to down-convert the terahertz optical frequencies into the electronically accessible gigahertz microwave regime. The high compactness and simplicity, the low costs and the gigahertz repetition rates make the dual-comb MIXSEL scheme a very interesting candidate for dual-comb spectroscopy applications.

9349-26, Session 6

Coherent spectral broadening and compression of the output of a mode-locked VECSEL

Edward A. Shaw, Univ. of Southampton (United Kingdom); Adrian H. Quarterman, Univ. of Dundee (United Kingdom); Lucy E. Hooper, Peter J. Mosley, Univ. of Bath (United Kingdom); Keith G. Wilcox, Univ. of Dundee (United Kingdom)

We report our recent advances on using coherent spectral broadening in normal dispersion photonic crystal fibre, followed by subsequent compression using a high efficiency transmission grating compressor to reduce the pulse duration of the pulse train generated by our mode-locked VECSELs from 400 fs, to close to 100 fs, where coherent supercontinuum generation becomes feasible. Using this approach we have, to date, generated pulses of duration 150 fs, and achieved average powers of > 0.5 W at repetition rates around 1.5 GHz, from the compressed output [1].

Since the work reported in [1], we have reduced the repetition rate of our VECSEL to ~1 GHz and improved the power handling of the photonic crystal fibre, through reducing beam distortion in the relay optics before launch, collapsing the photonic crystal fibre tip and using a more effective passive mount to cool the fibre tip. Further, we have tested all normal dispersion photonic crystal fibre with less dispersion at the dispersion minimum, increasing the non-linear interaction length, as well as increasing the interaction length in a commercial photonic crystal fibre, pumped in the normal dispersion regime, close to the zero dispersion wavelength.

[1] A.H. Quarterman, L. E. Hooper, P. J. Mosely, K. G. Wilcox, Optics Express 22, 12096-12101 (2014)

9349-27, Session PTue

Evaluation of the noise properties of a dual-frequency VECSEL for compact Cs atomic clocks

Paul Dumont, Lab. Charles Fabry (France) and LNE-SYRTE, CNRS, Observatoire de Paris (France); Gaëlle Lucas-Leclin, Patrick Georges, Lab. Charles Fabry (France); Jean-Marie Danet, David Holleville, Stéphane Guerandel, LNE-SYRTE, CNRS, Observatoire de Paris (France); Ghaya Baili, Grégoire Pillet, Loïc Morvan, Daniel Dolfi, Thales Research & Technology (France); Iryna Gozhyk, Lab. de Photonique et de Nanostructures (France) and Lab. Charles Fabry (France); Grégoire Beaudoin, Isabelle Sagnes, Lab. de Photonique et de Nanostructures (France)

Coherent population trapping (CPT) is a common technique used in compact atomic clocks which requires two-phase coherent laser modes with a frequency difference in the GHz range for alkali atoms. To improve the performance vs size trade-off of Cs atomic clocks, we develop a laser source generating two cross-polarized coherent laser fields at 852 nm. It relies on the dual-frequency and dual-polarization operation of an optically-pumped vertical external-cavity semiconductor laser. Independent control of the wavelength of emission and of the frequency difference between the laser modes is achieved using birefringent intracavity elements. One laser line is stabilized onto a Cs transition at 852.14 nm while the frequency difference is locked to a low noise RF oscillator at 9.2 GHz, equal to the ground state hyperfine splitting. As the laser noise deteriorates the clock stability during the light/atom interaction, we thoroughly investigate the laser intensity and frequency noise. Experimental results show that laser noise is pump-limited: the pump-intensity noise is transferred to the laser intensity noise through carrier fluctuations and to frequency noise through thermal effects.

Different solutions are studied to reduce the impact of the pump intensity noise on the clock stability, including power stabilization loops. With those improvements, a relative frequency stability for the clock of 3 ? 10-13 at 1 second is a realistic target, corresponding to the current state-of-art for compact CPT atomic clocks.

9349-28, Session PTue

Optimisation of fundamental transverse mode output in electrically pumped vertical external cavity surface emitting lasers

Xiao Jin, Pavlo Ivanov, David T. Childs, Nasser Babazadeh, Jonathan R. Orchard, Ben J. Stevens, Richard A. Hogg, The Univ. of Sheffield (United Kingdom)

Electrically pumped vertical external cavity surface emitting lasers (EP-VECSELs) are suitable for generating high quality fundamental transverse mode with high output power. It is important to maintain the fundamental transverse mode operation as the devices diameter increased. This requires the design of the EP-VECSEL with homogeneous transverse carrier distribution, and a range of design optimizations have already been discussed with regard to the thickness and doping of current spreading layers. In this work we report on the simulation of EP-VECSELs, paying particular attention to the effect of an etched mesa structure, and the details of the DBR design on the carrier distribution within the active element. This simulation is compared to sub-threshold near-field images of the emission from fabricated devices.

We study 980 nm InGaAs/AlGaAs/GaAs substrate-emitting EP-VECSELs grown on n-doped substrates. A circular trench was applied in the p-DBRs region to provide transverse electrical confinement. We investigate the role of this etched structure on the current and optical confinement. We go on to study the effect of details of the DBR design on current distribution and differential resistance.

To validate the simulation, we have measured the near field emission intensity of the devices and compared these results to the calculated electron and hole populations. These results show a good agreement between modelling with the experimental data. The results indicate that a shallower trench and modified DBR design should give a more homogeneous carrier distribution, as compared to the device studied. Results of the optimization of those parameters will be presented.

9349-29, Session PTue

1180nm VECSEL with 40 W output power

Emmi L. Kantola, Tomi Leinonen, Sanna Ranta, Miki Tavast, Jussi-Pekka Penttinen, Mircea Guina, Tampere Univ. of Technology (Finland)

Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) operating in the 1160-1200 nm range have recently gained increased attention owing to their ability to emit yellow-orange radiation via second harmonic generation. At short infrared wavelengths, i.e. 1000-1120 nm range, VECSELs based on GaInAs/GaAs/GaAsP gain chips have produced output powers reaching a 100 W level. However, for longer wavelengths the high lattice strain related to the high indium composition of the quantum wells has limited the output power to much lower levels.

We report on the recent development regarding a MBE-grown gain chip capable of emitting high output power in the 1180 nm range. The gain chip incorporated 10 GaInAs/GaAs/GaAsP quantum wells and it was cooled using an intra-cavity diamond heat spreader attached to a TEC-cooled copper mount. The VECSEL was built to form an I-cavity defined by the gain chip and a curved dielectric mirror (RoC=150 mm). The length of the cavity was ~110 mm. The maximum output power of 40 W was reached with a 97 % reflective output coupler. Current work is focused on optimizing the cavity for achieving high power single frequency operation.

9349-30, Session PTue

Super resolution photophysics probed by VECSEL and DPSS lasers

Angus J. Bain, Richard J. Marsh, Siân Culley, Univ. College London (United Kingdom); Emmi L. Kantola, Mircea Guina, Tampere Univ. of Technology (Finland)

Continuous wave (CW) stimulated emission depletion dynamics of fluorescent probes are investigated using VECSEL and DPSS lasers in conjunction with time correlated single photon counting following single and two-photon excitation in a confocal fluorescence microscope. Time resolved intensity and anisotropy measurements reveal significant orientational hole-burning in slowly rotating systems leading to decreased depletion efficiency (saturation). The existence of orientation independent saturation of the CW depletion process is also observed, mechanisms involving triplet formation and reverse intersystem crossing are suggested. The implications of these observations for super resolution techniques where high levels of depletion are essential are discussed.

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9350-1, Session 2

Fabrication of periodic metal nanowire grating and dotted structures on silica substrate by femtosecond laser irradiation

Yasutaka Nakajima, Mitsuhiro Terakawa, Keio Univ. (Japan)

Periodically arranged metal nanoscale structures play key roles to realize novel optical devices. Various methods for fabrication of these structures including chemical methods and lithography techniques have been developed, however, these methods require multiple process steps. In this study, we propose and demonstrate a simple method for high-throughput fabrication of periodically arranged metal nanoscale structures utilizing femtosecond laser. The linearly polarized 430 fs laser pulses at 800 nm central wavelength were used. By irradiating laser pulses on platinum thin films deposited on a silica substrate, nanowire grating and dotted structures were fabricated which can be controlled by changing the number of pulses. Elemental analysis on the fabricated nanowire grating by Energy Dispersion X-ray Spectroscopy (EDX) revealed that platinum and silicon were detected alternately in the direction across grating of the fabricated structure, which is different from well-known laser-induced periodic surface structure (LIPSS). This method provides simple and high-throughput fabrication of periodically arranged metal nanoscale structures which may contribute to realize novel optical devices such as optical sensors and metamaterials.

9350-2, Session 2

Direct laser beam interference patterning technique for fast high aspect ratio surface structuring

Simonas Indrisiunas, Bogdan Voisiat, Airidas Zukauskas, Gediminas Raciukaitis, Ctr. for Physical Sciences and Technology (Lithuania)

Direct laser beam ablation is a very flexible method for the surface structuring. Periodical structures with various shapes and depths are possible to produce using this method by just simply controlling the laser scanning path and the equipment parameters. The key drawback of this process is the low speed performance on large areas when fine structures should be produced, because the process requires pixel by pixel scanning of the whole area. This process has the limitation of the structure aspect ratio, which is limited by numerical aperture of the focusing optics and the laser beam quality. To overcome these drawbacks, the Direct Laser Interference Patterning (DLIP) technique is presented in this work. The technique uses the interference of several beams to directly ablate the material. It was shown that DLIP method is capable of producing sub-wavelength features not limited by a beam spot size and is an effective method in production of two-dimensional periodic structures on relatively large area with just a single laser shot, which can increase the laser surface patterning speed up to hundred times. A novel method of DLIP sub-period scanning technique for formation of the complex shape of the periodic structures was d investigated in this work. A new method of laser scanning of the diffractive optical element was also tested for fabrication of periodic structures on the area up to 300 mm2 without any visible stitching sings between laser irradiation spots.

9350-3, Session 2

F2 laser induced micro/nanostructuring and surface modification of iron thin film

Masayuki Okoshi, National Defense Academy (Japan) and Kanto Gakuin Univ. (Japan)

Nano-swellings on the average of 60 nm in height and 700 nm in diameter of the iron thin film deposited on silica glass substrate at a regular interval of 2.5 micron were fabricated by the irradiation of 157 nm F2 laser. The F2 laser was focused on iron thin film by each microsphere made of silica glass 2.5 micron in diameter which covered whole surface of the iron thin film; surface of silica glass substrate underneath the F2 laser irradiated iron thin film was selectively swelled to push up the iron thin film. After the laser induced micro/nanostructuring, afresh the F2 laser irradiated whole surface of the periodic micro/nanostructured iron thin film to form approximately 2 nm thick Fe3O4 modified layer. As a result, the samples revealed successfully hydrophobic property and high corrosion resistance to 3 wt% NaCl aqueous solution, quasi-seawater. No rust was observed on the samples after the immersion test in quasi-seawater for 24 h.

9350-4, Session 2

Femtosecond laser induced extraordinary relief surface microstructures on thin Cr films

Jianxiong Zhou, Institute of Modern Optics (China); Jianjun Yang, Nankai Univ. (China); Bo Zhao, Institute of Modern Optics (China) and Nankai Univ. (China); Xianfan Xu, Purdue Univ. (United States)

In this work, we report an observation of extraordinary periodic relief surface microstructures on chromium (Cr) films that are deposited silicon substrate by scanning 1 kHz linearly polarized 800 nm femtosecond lasers at the normal incident angle. In contrast to the ordinary ablative ripple patterns, highly uniform grating-like structures on Cr films are organized in relief with the orientation parallel to the incident laser polarization, which is called as relief type-c structures. Film thickness dependence of these structures is studied, in which the uniformity in both grating number and the tooth length for the relief type-c structure becomes degraded with increasing the film thickness. Upon considering the modification of physical properties of thin Cr film under multipulse femtosecond laser action, the observed relief type-c structures could be attributed to the interference between the transmitted and the scattered laser irradiation on the substrate interface. Moreover, we also carried out a second-step scanning after rotating the incident laser linear polarization. If the laser polarizations during the two steps are perpendicular each other, periodic microdot arrays can be formed in the valleys of relief type-c structures, resulting in two-dimensional hybrid relief surface microstructures on thin Cr films. On the other hand, if the two-step laser pulses have the same polarization direction, no microdot arrays can be generated on the films. This method could paved a way for the design of metallic micro/nano-gratings and other plasmonic devices.

9350-5, Session 3

Optical vortices pioneer chiral nano-structures *(Invited Paper)*

Takashige Omatsu, Chiba Univ. (Japan)

Optical vortices, carrying a annular intensity profile and an orbital angular momentum owing to a phase singularity, have been widely attracting in many applications, such as optical tweezers, fluorescence microscopes with a spatial resolution beyond the diffraction limit, spatial multiplexing in optical communication, and quantum information technology.

Recently, we have discovered that the optical vortices allow us to force materials to form chiral nano-structures, of being difficult to create even by utilizing advanced chemical techniques, at atmospheric pressure and room temperature. The chirality of the fabricated nano-structures can be also determined selectively merely by the sign of the orbital angular momentum of the optical vortices. This phenomenon is originated by orbital angular momentum transfer effects to the melted (or vapolarized) matter by the irradiation of the optical vortices, and it will potentially open the door to develop a variety of novel photonic devices, such as chiral plasmonics, chiral meta-materials, and ultra-highly efficient solar energy devices. Such research study, including chiral nano-structures fabrication based on the optical vortices, is termed 'chiral photonics'.

In this presentation, we review a state-of the art of the 'chiral photonics'. We also address the development of a variety of the vortex lasers in a frequnecy range of deep ultraviolet ~ terahertz.

9350-6, Session 3

Material properties and applications of blended organic thin films with nanoscale domains deposited by RIR-MAPLE *(Invited Paper)*

Adrienne Stiff-Roberts, Ryan D. McCormick, Wangyao Ge, Duke Univ. (United States)

Resonant infrared, matrix-assisted pulsed laser evaporation (RIR-MAPLE) has been used to deposit blended, organic thin-films with nanoscale domain sizes of constituent polymers, small molecules, or colloidal nanoparticles. RIR-MAPLE is a vacuum-based technique in which an organic thin film is deposited, without significant damage, by resonant infrared laser absorption in the target. Our unique approach is to use host emulsion matrices in the target. In this emulsion-based RIR-MAPLE process, the target contains a nonpolar, organic solvent phase (to dissolve guest organic materials) and a polar, water phase (to provide hydroxyl bonds with resonant infrared vibrational modes). The emulsion properties have a direct impact on the nanoscale morphology of single-component organic thin films, while the morphology of blended, organic thin films also depends on the RIR-MAPLE deposition mode.

In addition to these fundamental aspects, different applications of blended organic films deposited by emulsion-based RIR-MAPLE will be presented. For organic photovoltaics, bulk heterojunction solar cells featuring small molecule or colloidal quantum dot acceptors have been deposited. For anti-reflection coatings, RIR-MAPLE deposition of porous organic films (blends of scaffold and sacrificial polymers) that behave as effective media for optical transmission, as well as porous films featuring varying porosity with film thickness and a gradient refractive index profile, have been demonstrated. For reusable antimicrobial surfaces, RIR-MAPLE has been used to co-deposit multi-functional films that feature biocidal activity (oligomer that generates reactive oxygen species) and release functionality (stimuli-responsive polymer). Importantly, for each application, the domain sizes of the constituent materials are critical to thin-film functionality.

9350-7, Session 3

Quantifying forces of levitated graphite particles in air with a diverging hollow Bessel beam

Niko O. Eckerskorn, Avinash Upadhya, Steve Lee, Andrei V. Rode, The Australian National Univ. (Australia)

We use this effect to levitate micron-size graphite particles in a diverging hollow-core quasi-Bessel beam. The beam was generated from a phase-only spatial light modulator, and the hologram was designed by superposing the phase factor of a lens and an axicon. The axial equilibrium position of a suspended particle with known mass, in the diverging beam with known intensity distribution, immediately provides the axial force acting on the particle. By measuring the size of the levitating particles in the upward propagating beam and the position of the particle relative to the beam size we performed a quantitative evaluation of the photophoretic force in vertical direction and the trapping stiffness in the horizontal plane. Changing the beam power changes the irradiation intensity on the particle surface, which in turn force the particle to find a new equilibrium position. By repeating such experiments with different particle sizes and at different pressure we map the force acting on the particle in the beam. The measurements were compared with light pressure forces evaluated for known intensity illuminating the particle. The results provide grounds to link the position and size of a spherical particle in an arbitrary intensity distribution to the value of photophoretic and light pressure forces under various irradiation conditions.

9350-8, Session 3

Surface modification using shaped laser pulses as optimal control reagents

Ali O. Er, Western Kentucky Univ. (United States) and Princeton Univ. (United States)

Using shaped laser pulses as optimal control reagents, a number of gas phase and condensed phase chemical reactions have been examined in recent years. Feedback optimal control of surface constrained reactions have not been frequently studied. We report the use of shaped laser pulses as optimal control reagents to selectively promote the breaking of O-H or N-H terminal functional groups on well characterized self-assembled organophosphonate monolayers (SAMPs). These SAMPs are formed from 4-hydroxybenzylphosphonic acid and -aminobenzylphosphonic acid assembled on oxidized silicon single crystal substrates. Evidence for selective reaction and optimal control feedback information is provided by sum frequency generation probing of the SAMP monolayer surface.

9350-9, Session 4

3D micro-printing of optical temperature probes

Andreas Wickberg, Jonathan B. Mueller, Karlsruher Institut für Technologie (Germany); Yatin J. Mange, Thomas Nann, Univ. of South Australia (Australia); Martin Wegener, Karlsruher Institut für Technologie (Germany)

We present printable optical temperature probes to monitor the temperature with a spatial precision on the micrometer scale. Our approach is based on the temperature-dependent upconversion fluorescence from $NaYF_4:Yb^{3+}, Er^{3+}$ co-doped nanocrystals. These nanoparticles are dispersed in a standard photoresist for direct laser writing, allowing for spatially resolved micro-printing of single or multiple probe spots. For demonstration, we decapsulate a fully operational integrated circuit and print temperature probes directly on the semiconductor chip to monitor its local heating. The printability of the probes facilitates an easy integration into diverse systems, especially when aiming at integrated optics or lab-on-a-chip systems.

For our experiments, we use an inverted microscope and excite the temperature probes with a 980 nm diode laser. The fluorescence is collected using a low NA objective lens and dispersed by a grating spectrometer. The intensity ratio of the fluorescence peaks at around 525 nm and 550 nm wavelength is a measure for the local temperature at each probe spot. Even though the particles have been used as temperature probes directly, the integration of the particles into the specific system is an issue that has to be solved for each application individually. Therefore, our approach offers huge advantages with respect to easy adaptation to future applications. The polymerized photoresist can easily be attached to a variety of substrates and has a high chemical and thermal resistance. Furthermore, the probes can be directly coupled to fibers printed by the same printing setup, allowing for excitation and luminescence detection without far-field alignment.

9350-10, Session 4

Trans-wafer removal of metallization using a nanosecond Tm:fiber laser

Ilya Mingareev, Sascha Berger, Thomas Tetz, Ali Abdulfattah, Alex M. Sincore, Lawrence Shah, Martin C. Richardson, The College of Optics and Photonics, Univ. of Central Florida (United States)

The study of laser-semiconductor interaction and its applications has been a subject of immense academic and practical interest in the last two decades. However fabrication of next-generation, high-performance electronic and photonic devices requires further advancements in laser-based wafer processing technologies. Recent progress in the development of infrared fiber lasers established a new processing regime of semiconductor materials used in photovoltaic and microelectronics applications. By utilizing photon energies considerably smaller than the semiconductors' energy band gap, space-selective modifications can be induced far beyond the laser-incident surface. Previously, we demonstrated that back surface modifications could be produced in 500-600 μm thin Si and GaAs wafers independently without affecting the front surface.

In this paper, we present our latest studies on trans-wafer processing of semiconductors using a self-developed nanosecond-pulsed thulium fiber laser operating at the wavelength 2 μm. A qualitative study of underlying physical mechanisms responsible for material modification by modeling and infrared imaging of focused beam propagation was performed. We explored experimental conditions that will enable many potential applications of this processing regime, including trans-wafer metallization removal, e.g. for PV cell edge isolation, selective surface annealing and wafer scribing. These processes were investigated by studying the influence of process parameters, such as the incident pulse energy, the pulse duration and the focusing conditions, on the resulting surface morphology, microstructure and electric properties. This unique processing regime has the potential to facilitate novel applications such as semiconductor joining and space-selective doping for many applications in integrated circuits technology, photovoltaics and consumer electronics.

9350-11, Session 4

Bragg grating fabrication in microfiber by femtosecond pulse filamentation induced periodic refractive index modification

Farid Ahmed, Martin B. G. Jun, Univ. of Victoria (Canada)

Fabrication of fiber Bragg grating (FBG) in single mode micron fiber (core diameter: 3.75 ?m, cladding diameter: 40 ?m) by femtosecond laser pulse radiation is presented. Femtosecond pulse filamentation technique is employed to inscribe single shot periodic index modification in the core of the microfiber. Prior to writing gratings, a short length (~10 mm) of microfiber is fusion spliced between two standard single mode fibers (SMF) in order to improve handling and ease fabrication process. The kilohertz femtosecond laser used to carry out the experiment operates at 800 nm with pulse duration of 120 fs. Ultra-short pulses are focused with an objective lens (40X/ NA=0.75) to confine the pulses into a very tiny focal volume and spatially control index modification. Then the fiber is scanned along its axis with pulse energy of 5 μJ at the speed of 0.540 mm/sec to write submicron periodic filamentary voids in the core. For the specified feed rate, the partial overlapping of void structures produces a periodic index modification in the core with a period of 540 nm and constructs the Bragg reflection spectrum centered at 1558 nm. For a laser scanning speed of 0.540 mm/sec, the fabrication of a 6 mm long FBG takes only 11 seconds. The spectral position of Bragg reflection spectrum can easily be tailored simply by changing pulse scanning speed. The performance analysis of the FBG is examined for temperature and axial strain sensitivity. The grating sensor exhibits a temperature and strain sensitivity of 11.5 pm/ 0C and 1.15 pm/ micro-strain respectively.

9350-12, Session 4

Augmentation of degree of conversion in resins via Thiol-ene chemistry in microstructures fabricated by two-photon polymerization

Lijia Jiang, Yunshen Zhou, Wei Xiong, Univ. of Nebraska-Lincoln (United States); Tommaso Baldacchini, Newport Corp. (United States); Yongfeng Lu, Univ. of Nebraska-Lincoln (United States)

This study focused on the modification of acrylic-based resins by thiol molecules to enhance the degree of conversion (DC) of the resins used in two-photon polymerization (TPP). Six resins containing different amount of polythiols ranging from 0 to 10 wt% were prepared. Characterization of the resins' DC upon UV polymerization was performed using Raman microspectroscopy. TPP dosimetry experiments were conducted to investigate the polymerization threshold and feature size. The augment of DC via thiol-ene polymerization was verified via Raman microspectroscopy. It is proved that the small concentration of polythiols significantly improves the DC and varies the cross-linking status in TPP microstructures.

9350-13, Session 5

Quantized structuring of transparent films with femtosecond laser interference

Stephen Ho, Kenneth K. C. Lee, Jianzhao Li, Peter R. Herman, Univ. of Toronto (Canada)

Femtosecond laser interactions are presented for highly resolved internal structuring inside transparent dielectric films. Strong nonlinear interactions are found to be confined over the bright Fabry-Perot interference fringes as formed by thin film interference, generating narrow nano-length scale plasma zones of 20 to 45 nm thickness. Micro-disk explosions are shown to cleave open the film into sub-wavelength internal cavities at single or multiple periodic depths at low laser exposure, while higher exposure will eject fractional film segments at various controllable depths. This spatially localized laser interaction follows the predicted lambda/2nfilm fringe spacing for 522, 800, and 1045 nm laser wavelengths. The threshold for laser cleaving further lines up with a calculated plasma density becoming opaque at critical density. The process window is examined around the limiting effects of pulse duration in terms of fringe blurring at ultrashort pulse duration through to thermal diffusion blurring at picosecond pulse duration.

This new form of high-resolution patterning is presented for SiNx film, where Fresnel reflection supports sufficient fringe contrast to isolate the laser dissipation into nano-length scale zones. The process opens sub-wavelength internal cavities and forms thin membranes (~100 nm) at single or multiple film depths from which follows a new lab-in-film direction of writing multilevel micro- or nano-fluidic channels inside dielectric film as well as ejecting nano-disks at quantized film depths. The process window on laser wavelength, pulse duration and coherence are presented together with time-resolved microscopic imaging of the quantized film ejections. New directions are explored in film coloring, printing, 3D surface patterning, nanofluidics, capacitor trimming, and nano-optic fabrication. This new opportunity holds a promise to further improve the functionality of CMOS microelectronics and photonics, photovoltaics, MEMS, LED, lab-on-a-chip devices where thin films are widely deployed during their manufacture.

9350-14, Session 6

Ship-in-a-bottle integration by hybrid femtosecond laser technology for fabrication of true 3D biochips

Felix Sima, Dong Wu, Jian Xu, Katsumi Midorikawa, Koji Sugioka, RIKEN (Japan)

Femtosecond laser is a promising tool for fabrication of biochips since it can modify the interior of glass in a spatially selective manner due to multiphoton absorption and thereby to directly form three-dimensional (3D) microfluidic structures inside substrates. We developed a technique fabricating true 3D microfluidic structures inside photosensitive glass by femtosecond laser direct writing followed by thermal treatment and successive chemical wet etching. This technique can also integrate some functional microcomponents such as microoptical components and micromechanical components. Then, functional microfluidics and optofluidics were successfully fabricated by this technique for biological analysis. To further enhance functionalities of biochips, in this paper, we propose a new strategy (hybrid femtosecond laser processing), in which subtractive manufacturing and additive manufacturing based on femtosecond laser are combined. In this process, 3D microfluidic structures are first formed in the photosensitive glass by femtosecond laser 3D glass micromachining, and then functional micro and nano components are integrated in the 3D microfluidics by either femtosecond laser selective metallization or two-photon polymerization. We term such glass microfluidics afterwards integrated with functional microcomponents a ship-in-a-bottle biochip This technique is successfully applied to fabricate true 3D, functional biochips to demonstrate efficiently mixing fluids in microfluidics, detecting and counting living cells, flexibly manipulating microorganisms, and so on.

9350-15, Session 6

Formation of nanogratings in a porous glass immersed in water by femtosecond laser irradiation

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Formation of nanogratings inside transparent materials by femtosecond laser irradiation has attracted broad attention because of its sub-diffraction-limit nature and its potential for optical, polarization sensitive and fluidic applications. In fused silica, the nanogratings formed by femtosecond laser irradiation emerge as a succession of variable density layers oriented perpendicular to the laser polarization, which can be revealed by scanning electronic microscopy (SEM) examination after etching with hydrofluoric acid. Until now, although great effort has been made on investigating the mechanism behind this phenomenon, a clear picture is still lacking. Recently, it has been found that nanogratings can also be formed in a porous glass immersed in water by irradiation with femtosecond laser pulses of carefully selected pulse energies. In particular, a single nanocrack can be induced in the central area of the focal volume when the laser intensity is close to the threshold value, which has been applied to fabrication of three-dimensional (3D) nanofluidic channels for DNA analysis. Due to the unique property of the porous glass, the technique has enabled direct formation of hollow nanostructures as small as a few tens of nanometers, which can immediately be observed using a scanning electron microscope (SEM). In this contribution, we systematically examine the evolution of femtosecond laser-induced nanostructures as a function of the number of pulses. Our results reveal that the processes of formation of a single nanocrack and an array of nanocracks that form the nanograting are significantly different.

9350-16, Session 6

Laser induced structural modifications in fused silica within the microexplosion regime evidenced by Raman spectroscopy

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Femtosecond lasers are now widespread and used for industrial and scientific applications, giving a way to achieve warm dense matter conditions [1]. In such conditions, surface nano-fibers with extremely high aspect ratios could be produced [2, 3]. We examine here the conditions under which those nano-fibers may appear. We present Raman spectroscopy studies of laser (350 fs pulse @ 1030 nm) - wide-bandgap material modifications in the warm-dense matter conditions. Three-dimensional Raman mapping of the interaction volume allows the localization of the laser-induced cavity and density variations inside fused silica. Here we put in evidence the matter displacement under the action of accumulated laser pulses when their number increases and which further leads to subsurface cavity creation and piercing with nano-fiber formation. We analyse the structural reorganization mechanisms of fused silica under high-temperature and pressure conditions induced by femtosecond pulses. Thus we outline the presence of a fused silica phase, which globally shows low density but meanwhile a very high degree of dense constraints resulting from an initial densification in the central part of the cavity. In addition, we demonstrate the presence of molecular oxygen inside the cavity at the early stage of the interaction, confirming the spatial separation of silicon and oxygen ions in hot plasma. The molecular oxygen formation may be linked to the formation of silica nano-pores, which could have extreme density properties [4].

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9350-17, Session 7

High-resolution printing of functional microdots by double-pulse laser-induced forward transfer *(Invited Paper)*

Aiko Narazaki, Ryozo Kurosaki, Tadatake Sato, Hiroyuki Niino, National Institute of Advanced Industrial Science and Technology (Japan)

For higher-resolution printing, we have developed a novel way of functional microdots deposition based on laser-induced forward transfer, which is referred to laser-induced dot transfer (LIDT). LIDT is one of promising additive manufacturing techniques because it can realize flexible patterning of micron and submicron-sized dots at atmospheric room-temperature conditions. In the LIDT process, a laser pulse is tightly focused onto a source film, leading to a transient melting of the film followed by sub-spot transfer using one-to-one microdot deposition with laser-illuminated area. High-resolution printing of functional microdots is promising for future optoelectronic integrations. Recently, we have achieved printing of functional oxide microdots using a double-pulse LIDT. The first ns pulse was irradiated onto a transparent support / source film interface through the support to preheat the film. After adequate time delay, the second ns pulse was more tightly focused on the same position for microdot transfer. As a result, the double-pulse LIDT can control laser-induced high-temperature and resultant thermal-stress even in a fragile oxide source film more precisely. Temporal temperature distributions during the transfer process have also been investigated using a Finite Element Method (FEM) approach.

9350-18, Session 7

Advances and future directions in laser-induced forward transfer (LIFT)

Alberto Piqué, Heungsoo Kim, Nicholas A. Charipar, Raymond C. Y. Auyeung, Kristin M. Charipar, Scott A. Mathews, U.S. Naval Research Lab. (United States)

Laser direct-write (LDW) techniques based on laser induced forward transfer (LIFT) of functional materials offer unique advantages and capabilities for the rapid prototyping of electronic, optical and sensor elements as opposed to other digital printing processes such as inkjet. LIFT processes have been applied to the fabrication of a wide variety of microelectronic elements such as interconnects, passive components, antennas, sensors, power sources and embedded circuits. An example of these processes is the congruent laser transfer of high viscosity metallic nano-inks to generate thin film-like structures non-lithographically. This technique, known as Laser Decal Transfer is capable of printing patterns with excellent lateral resolution and thickness uniformity such as 3-dimensional stacked assemblies, MEMS-like structures and free-standing interconnects. Overall, LDW techniques are highly adaptable digital microfabrication processes in terms of materials versatility, substrate compatibility and range of writing speed, scale and resolution. This talk will describe the unique advantages and capabilities of LIFT-based processes, discuss their applications and explore their role in the future of printed microelectronics.

This work was funded by the Office of Naval Research (ONR) through the Naval Research Laboratory Basic Research Program.

9350-19, Session 7

All-printed reduced graphene oxide gas sensors

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In recent years graphene based materials have gained considerable attention as candidates for gas–sensing elements due to their unique and catalytic properties (e.g., extremely high surface–to–volume ratio) that potentially can lead to novel sensors with exceptional performance.

The aim of this work is the fabrication of Laser printed gas sensors consisting of reduced graphene oxide as sensing element, metallic nanoparticle electrodes (silver, copper) on flexible (PI) and conventional (SiO_2/Si) receiver substrates, by means of Laser Induced Forward Transfer process (LIFT). The LIFT experiments were carried out using a pulsed ns Nd:YAG laser combined with a high power imaging micromachining system.

Using the all-LIFT approach, metallic NPs inks were printed on receiver substrates followed by curing and sintering steps, in order to form the electrodes with a distance between them smaller than 80 ?m. The donor substrates were prepared by spin coating the metallic NPs inks on Ti/quartz substrates. Subsequently, by printing graphene oxide on top of the pre-deposited electrodes and employing a thermal reduction step, so as to restore the electrical conductivity of GO, gas sensors are formed. These sensors will be used for the detection of various gases under atmospheric pressure at room temperature.

The printed devices were characterized by Optical microscopy, Scanning Electron Microscopy, electrical measurements and Raman Spectroscopy. Finally, the sensors response has been evaluated, by measuring the electrical resistance variations upon exposure to different gas analytes (humidity vapors, NH_3) concentrations.

9350-20, Session 8

Laser-assisted conductive silver ink printing with inkjet and laser-induced forward transfer techniques for organic transistor fabrication

Dimitris Karnakis, Riccardo Geremia, Oxford Lasers Ltd. (United Kingdom); Lee Winchester, Simon Ogier, Ctr. for Process Innovation Ltd. (United Kingdom); Roger Artigas, Sensofar-Tech, S.L. (Spain); C. Florian, F. Caballero-Lucas, Juan Marcos Fernández-Pradas, Pere Serra Coromina, Univ. de Barcelona (Spain)

Digital fabrication of organic electronics devices on rigid or flexible substrates is quite attractive [1]. It can facilitate low cost mass customization of electronics for a wide range of applications. But high-speed printing of electronic devices is not trivial. Currently, it is mostly limited by materials' performance and lifetime, but also manufacturing issues such as the printing resolution without the need for lithographic steps. In this work, we will demonstrate that lasers can be employed both to (i) tailor surface wetting or the ablated topology profile of the substrate and (ii) print silver conductive inks by laser induced forward transfer (LIFT) mainly for defect repair. LIFT printing is a versatile non-contact technique that offers several advantages in terms of achievable resolution and clogging-free printing. It is also compatible with a wide range of ink viscosities and will be compared to inkjet printing. Additionally in this paper, laser surface modification or substrate ablation to form guide channels for subsequent printing of the conductive inks will be compared to dry reactive ion etching (DRIE) as a means to prepare the receiving substrate.

UV picosecond and NIR femtosecond DPSS lasers were used in a maskless direct write setup delivered on target with fast scanning optics. A custom-made strongly hydrophobic transparent planarisation layer on glass was used as the receiving substrate. High speed LIFT and inkjet printing were tested for bulging free continuous line printing and several strategies were devised to achieve that goal.

This work is part of EU-funded project Digiprint (2012-2014).

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9350-21, Session 8

Laser-assisted transfer and bonding for MEMS and microelectronics *(Invited Paper)*

Andrew S. Holmes, Imperial College London (United Kingdom)

This paper will discuss the use of pulsed lasers for transfer and bonding of micro-scale parts. In earlier work we investigated the assembly of hybrid MEMS devices by laser-assisted transfer of micromachined components fabricated on transparent carriers with polymer release layers. More recently we have extended this technique to the transfer of functional films (e.g. ferroelectrics) from high-temperature growth substrates, providing a route for the integration of such materials into MEMS devices fabricated at lower temperatures. Transferred components generally need to be bonded to a final substrate, and currently we are exploring the idea of using confined ablation as a source of ultrasonic energy for direct metal-metal thermosonic bonding. A key feature of this approach is that it allows targeted and controlled delivery of ultrasonic energy to the bonding site which is not possible in conventional thermosonic bonding. The results of initial experiments using nanosecond pulsed lasers to deliver ultrasonic energy to a bonding interface will be reported. The long term aim is to develop an integrated technology in which both the transfer and bonding processes are laser-driven. A key target application area for such a technology would be the integration of thin silicon dies with plastic electronics.

9350-43, Session PTue

Mobile laser lithography station for microscopic two-photon polymerization

Frank Leinenbach, Hans G. Breunig, Karsten König, Univ. des Saarlandes (Germany)

We present a mobile laser lithography station for microscopic two-photon polymerization. For structuring the Coherent Vitarra UBB titanium:sapphire femtosecond laser is used, which has a power output of 500mW and a fix central wavelength of 810nm. This laser has a tunable bandwidth from 50nm to 250nm. The pulses are compressed using chirped mirrors to a pulse duration of less than 15fs at the sample. The laser power can be motionless controlled by a combination of liquid crystal retarder and a polarizer within milliseconds. The sample is placed onto a microscope stage with a movement range in the X, Y and Z direction of 300 microns with an accuracy of 2nm. Simultaneous structuring and sample imaging is possible with a microscope camera. The beam is focused by a 40X microscope objective (1.3NA) on the sample. To operate the lithography station, we developed a LabVIEW-based software which controls the sample position, laser power and objective height and as well as a camera. Furthermore, CAD data can be read and converted into sample position data.

By combining all these components, a fully automatic structuring of a sample with submicron precision is possible. We present the results on nano- and microstructuring in dependence on the spectral bandwidth using resists with various absorption behaviour.

9350-46, Session PTue

Effect of different properties of Cu(in1-xGax)Se2 thin films synthesized by femtosecond and nanosecond pulsed laser deposition

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Two kinds of pulsed laser sources, femtosecond laser (fs laser) and nanosecond laser (ns laser), were used in the pulsed laser deposition (PLD) system to synthesize copper indium gallium selenium (CIGS) thin films at the substrate temperature from room temperature (RT) to 500oC. Different surface morphology, crystallinity, and stoichiometric ratio were observed on CIGS thin films deposited by femtosecond pulsed laser deposition (fs-PLD) and nanosecond pulsed laser deposition (ns-PLD) respectively, that resulted in different optical and electrical properties. It is proposed that the laser absorption of CIGS target with different laser wavelength caused the difference in laser penetration depths into the target, so that the stoichiometric ratio of the evaporated materials splashing from the target were different between fs-PLD and ns-PLD processes.

9350-47, Session PTue

The effect of femtosecond laser processing conditions on the properties of a polarization imaging filter inside a silica glass

Yuya Yamada, Hitachi Zosen Corp. (Japan); Takafumi Ohfuchi, Naoaki Fukuda, Masaaki Sakakura, Yasuhiko Shimotsuma, Kiyotaka Miura, Kyoto Univ. (Japan); Toshio Takiya, Hitachi Zosen Corp. (Japan)

A polarization imaging filter is an optical device which can acquire the spatial distribution of polarization of an incident light. The filter can be applied to recognition of the three- dimensional form of objects and detection of stress distributions inside transparent materials. Such filter can be produced by making a two-dimensional array of birefringent regions inside a silica glass using a femtosecond (fs) laser. Birefringent regions can be generated inside a silica glass by focusing fs laser pulses and the azimuth of the birefringence can be controlled by the polarization of the laser pulses. To improve the performance of the filter made by fs laser, it is important to investigate how to control the laser-induced birefringent structure inside a silica glass to obtain larger birefringence with maintaining the uniformity and the transmittance as possible.

In this paper, we investigated fs laser induced birefringent structures inside a silica glass under the various processing conditions. For the process of writing birefringent structures, a parallel laser processing system with a spatial light modulator was used to induce photoexcitation at multiple spots simultaneously inside a silica glass. We found that parallel writing of birefringent lines can make more uniform birefringent area than those wrote one by one. In addition, the transmittance and retardance in the processed area were measured and the relationships between them and processing conditions were investigated.

9350-48, Session PTue

Laser micromachining of transparent glass and quartz dielectrics using nano short pulsed Nd:YVO4 laser harmonics

Shiva P. Gadag, Southern Methodist Univ. (United States)

Laser micromachining of transparent dielectric materials like glass and qaurtz is quite challenging using nanosecond pulses of infrared laser. The dielectric materials like glass are >92% transparent to 1064 nm IR laser. However using black ink and beam shaping, manipulation or tight focusing and 2nd or 4th harmonics of the fundamental wavelength, this can be overcome to some extent. The micromachining of the 1-2 mm glass and quartz are accomplished using relatively inexpensive nano short pulsed 1064 nm Nd:YVO4 laser. The nanosecond pulses of IR laser often results in variety of cracks or defects due to annealing of the transparent dielectrics. In order to determine the suitable wavelength of the nano short pulsed laser, threshold and usable limits of the laser power, a calibration of absorption coefficient at various wavelength and power levels are performed. A systematic classification of various types of cracks, morphology and manifestation of micro-cracks encountered during the micro processing by nano short pulsed laser and failure analysis of laser induced defects of dielectrics are distinguished diagnosed. Optimum power and suitable wavelength of the IR laser are established from power calibration of the absorption coefficient for various wavelengths of the Nd: YVO4 laser. Finally micromachining of the transparent dielectrics is successfully achieved based on optimal power limit and wavelength of the laser.

9350-49, Session PTue

Experimental and calculative estimation of femtosecond laser induced-impulsive force in culture medium solution with motion analysis of polymer micro-beads

Takeshi Yamakawa, Akihiro Maruyama, Hirohisa Uedan, Takanori Iino, Yoichiroh Hosokawa, Nara Institute of Science and Technology (Japan)

When an intense femtosecond laser is focused in aqueous solution through objective lens, explosive morphological change is induced at the laser focal point. Then, shock and stress waves propagate and act to an object at the vicinity of the laser focal point as an impulsive force. The impulsive force can be utilized for laser cell manipulation, laser peening, and laser cleaning. Our group has applied it not only to cell manipulation and but also to measurement of mechanical properties of cells. To establish the measurement method, it is indispensable to quantify the impulsive force. Recently we have developed a new methodology to calibrate it from motion of micro beads. In this study, the experimental data of the beads motion was analyzed by kinetic simulations utilizing Monte Carlo least square method.

The micro polymer beads as a model of animal cells were dispersed in cell culture medium solution. Single—shot femtosecond single pulse was focused into the medium. The displacement of the beads by the force loading was observed and evaluated as a function of the initial position of the beads. The measurement result was fitted on a simulation based on a motion equation, in which intensity and time duration of the impulsive force were treated as a fitting parameter.

The parameters determined from the random estimation method were nearly in agreement with values predicted in the high speed imaging. These results suggest reliability of our experimental and calculative method to estimate the impulsive force.

9350-50, Session PTue

High speed laser transfer (LIFT), thin-film patterning and selective sintering of printed Ag nanoparticle inks for electronic device integration on flexible substrates

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LIFT (Laser-induced forward transfer) is a versatile, non-contact and high-resolution laser printing technique which represents a promising approach for the deposition of electrical connections with high throughput. We used a fast picosecond laser (30ps; 0.2-2MHz) with a galvanometric mirror, and we investigated the interactions between the jets by means of fast imaging [1]. The transfer of silver nanoparticle ink leads to the printing of 18um width lines at velocities up to 4m/s [2]. After sintering these lines have been used as electrodes for gas sensors on flexible substrate.

Selective laser sintering of deposited metal nanoparticle (NP) inks has been explored over the past few years as an alternative to conventional micro-patterning of fully coated metal layers. . The sintering potential of nanosecond pulsed lasers has been previously demonstrated [3]. In this work a Nd:YVO4 pulsed DPSS laser, (532 nm, 8 ns) was employed for selective sintering of spin coated Ag NPs ink, on PEN substrates (Tg =120 oC). This specific wavelength has been chosen due to the high absorbance of Ag NPs at this regime. The measured electrical characteristics of the sintered structures are very close to bulk Ag (resistivity of 6x10-6 ?.cm). Laser sintering is combined with laser ablation to constitute a fully autonomous micro-patterning technique of homogeneous metallic features to fabricate devices like waveguides or electrodes, with minimum feature size of 50?m. The characteristics and the underlying mechanisms of the process are discussed. The novel aspects of this technological approach may have significant implications in the field of flexible electronics and optics.

9350-51, Session PTue

Glass drilling by longitudinally excited CO2 laser with short laser pulse

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

Recently, glass is used by some devises. Glass absorbs CO2 laser light well. Short-pulse CO2 lasers are able to mark clearly on glass without cracks. Marking some informations is useful for the security and the assuring traceability. Although there are many generation methods of short-pulse CO2 lasers, we focus on a longitudinally excitation scheme.

We have developed a longitudinally excited CO2 laser with short laser pulse. The laser consisted of a 60-cm-long laser tube, a pulse-power supply, a spark gap, a transformer, and a capacitor. This scheme does not require a strong preionization or a fast gas flow system. Therefore, the laser devise is compact and inexpensive. This devise produced a short laser pulse like a TEA-CO2 laser pulse (Type-A) and a tail-free short laser pulse like a Q-swiched CO2 laser (Type-B). Type-A had a spike pulse width of 166 ns and a pulse tail length of 58.2 ?s. The output energy was 17.2 mJ and the spike pulse energy was 4.6 mJ. Type-B had a pulse width of 60 ns. The output energy was 14.7 mJ.

Laser pulses were irradiated onto a quartz glass plate. In the laser pulse with a pulse tail (Type-A) at a fluence of 5.3 J/cm^2, cracks were not produced. The 60 shots (1 Hz) produced a drilling depth of 240 nm, and the 300 shots (1 Hz) produced a 330 nm-depth. In this presentation, we will report about the CO2 laser with short laser pulse and glass drilling in detail.

9350-52, Session PTue

On the transmission of sub-wavelength annular apertures based on periodic structure

Kuan-Ming Chen, Chun-Hung Weng, Ming-Han Chung, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

Extraordinary light transmission effect on a metal surface, also known as surface plasmon resonance, has been widely discussed in recent years. Extending from this line of research, surface plasmons generated by subwavelength annular apertures (SAA) on metallic film has been identified to have the ability to create sub-wavelength Bessel-like beams. It has also been found that this type of Bessel beam can be used to produce high-aspect ratio microstructures when adopted in laser micromachining. However, the drawback is that the Bessel beams produced by the SAA structure is often characterized as having a low transmission rate and high side lobes. In order to improve these shortcomings, an improved SAA-like structure is proposed in this paper. A new photon-sieve replaces the annular aperture by an array of holes which can lower the side lobes of the emitted Bessel beams. More specifically, the original ring-shaped holes are now replaced by a series of smaller holes arranged in a circular shape to mimic a ring. We show by FDTD (Finite-Difference Time-Domain) simulation that a glass substrate removed from this newly created SAA-like structure can increase transmission efficiency by 27.5%. Considering the absorption of the glass substrate is only in the range of 4%-5%, the additional efficiency can actually be attributed to the surface plasmon effect involved in the symmetric nano-structures. Our simulation results were verified by experimental results. The high aspect ratio microstructures fabricated will also be detailed.

9350-53, Session PTue

Modelling and analysis of image degradation due to birefringence created by UV laser on optical specimen

Achyut Adhikari, Nanyang Technological Univ. (Singapore)

Birefringence obtained during Ultraviolet (UV) laser on optical specimen was investigated through phase shift polariscope. Temperature gradient obtained during UV laser was carefully studied to analyze its effects on birefringence. UV laser employed was solid state Q switched laser of 355 nm wavelength at average power of 1 watt with optimal frequency of 60kHz. Power, frequency and scanning speed are varied to characterize the birefringence induced in the material and their further effects in image degradation. Mathematical modelling of Birefringence in the optical specimen was done relating to its magnitude and fast axis direction. Modelling of birefringence is done by denoting polarization sate of optical element by a Jones vector. Image intensity distribution is calculated by using fourier transform of object wave amplitude and its direction. The contrast, wavefront aberration and modulation transfer function was thoroughly studied to examine the image degradation created by the laser spot. The optical plates like sodalime glass,BK7,PMMA and many others were studied to analyze the birefringence properties of different optical specimen. Optical design, opto-mechanical software and mathematical tools with appropriate algorithm were used for modelling, simulation and comparison with real experiment. The results deliver useful information about the spatial distribution and orientation of the birefringent element and its effects on image degradation. Methods have been devised for making low birefringence elements and its precise measurement and effects on imaging. Moreover, damage detection by analyzing image degradation due to birefringence created due to UV laser spot is examined through the experiment which will be the further scope on carrying this experiment.

9350-54, Session PTue

Experimental study on early stage of LIPSS formation on SiC by using double pulses of femtosecond laser

Taira Enami, Shuhei Yada, Yasutaka Nakajima, Mitsuhiro Terakawa, Keio Univ. (Japan)

Laser-induced periodic surface structure (LIPSS) has been of interest due to its simplicity of fabrication process by using femtosecond laser. The formation mechanism of LIPSS, however, remains to be fully elucidated and many researchers have been discussing the mechanism. We have been investigating the contribution of defects on early stage of LIPSS formation. In this study, we have conducted the double-pulse experiments in order to consider the effect of defects on early stages of LIPSS formation. The double-pulses of 800 nm femtosecond laser were irradiated on the surface of SiC crystal at normal incidence in air. With changing the double-pulse delay from 0 ps to 2 ns, we observed the surface morphology of SiC. We first investigated at the irradiation condition in which no nano-voids are formed at 1 kHz repetition rate. With this laser fluence, we then carried out the experiments with varied double-pulse delay. When the two pulses were overlapped, LIPSS was observed over wide area in the laser spot. When double-pulse delay was 3 ps, voids were scattered randomly within the spot. These voids are considered to be the origin of LIPSS formation. By increasing double-pulse delay, the number of voids decreased. The detailed results of SEM observation with changing double-pulse delay will be presented as well as the discussion of the underlying physics on LIPSS formation from the point of view of defect levels.

9350-55, Session PTue

Molybdenum thin film ablation on glass substrate by ultra-short laser

Pinaki Das Gupta, Gerard M. O'Connor, National Univ. of Ireland, Galway (Ireland)

Molybdenum (Mo) is widely used in solar cell industry, OLED devices among other photovoltaic research. Laser processing on Mo is very interesting matter of research because of its d-electron configuration. A repetitively pulsed femtosecond laser source with wavelengths 1030 nm, 515 nm and 343 nm each of pulse duration 500 fs was used to ablate ultra-thin molybdenum films on glass substrate. The laser beam was Gaussian both spatially and temporally. A beam scanning system was used to direct the beam over surfaces. After laser beam irradiation, optical and electron microscopes were used to analyse the results.

The threshold fluence of films was calculated by Liu's method by plotting a graph between square diameter verses log (applied fluence). Initially, threshold fluence was estimated using different laser wavelengths and initial results shows threshold fluence changes with molybdenum bulk sample and different types of glass substrate. It was found that applied threshold fluence for bulk molybdenum ablation by 1030, 515 and 343 nm laser ablation are (0.454±0.02), (0.351±0.02) and (0.272±0.02) Jcm-2. A variation of threshold fluence was observed with decreasing film thickness.

A full analysis and demonstration of Molybdenum ablation by femtosecond laser and the dependence of wavelength and absorbed laser fluence will be presented.

9350-56, Session PTue

Controlling depth and distance of the hole formations at the bottom of laser-scribed trenches in silicon using fs-pulses

Matthias Domke, Bernadette Egle, Giovanni Piredda, FH Vorarlberg (Austria)

The application of ultrashort pulsed lasers for silicon scribing enables precise control of the ablation depth and generally reduces thermal side effects compared to ns-pulses. However, the formation of periodic holes with a depth of several µm can be usually observed at the bottom of the scribed trenches. The goal of this study is to investigate the influence of the pulse energy and the pulse to pulse distance on the depth and periodicity of these holes.

For this purpose, a simple model was developed to calculate the number of overscans to achieve a specific cutting depth for different pulse energies and scan speeds. Then, wafers with a thickness of 525 µm were scribed to a depth of 50 µm using a fs-laser at a pulse duration of 400 fs and a wavelength of 520 nm. The pulse energy was increased from the minimum pulse energy of 3 µJ to achieve a scribing depth of 50 µm up to 8 µJ. In addition, the scan speed was varied between 20 mm/s and 2000 mm/s. Finally, the wafers were broken along the cut and the side walls were investigated with scanning electron microscopy.

It was found that the periodicity of the holes decreases and the depth of the holes increases with the pulse energy. These findings suggest that the roughness at the trench bottom can be minimized by reducing the pulse energy to the minimum value necessary to achieve the desired cutting depth and by increasing the number of overscans.

9350-57, Session PTue

Fabrication of 4, 5, or 6-fold symmetric 3D photonic structures using single beam and single reflective optical element based holographic lithography

David George, Jeffrey R. Lutkenhaus, David Lowell, Usha Philipose, Hualiang Zhang, Univ. of North Texas (United States); Zsolt L. Poole, Kevin P. Chen, Univ. of Pittsburgh (United States); Yuankun Lin, Univ. of North Texas (United States)

Here we present the holographic fabrication of large area 3D photonic structures using a single reflective optical element (ROE) with a single beam, single exposure process. The ROE consists of a 3D printed plastic support that houses 4, 5, or 6-fold symmetrically arranged reflecting surfaces which redirect a central beam into multiple side beams in an umbrella configuration to be used in multi-beam holography. With a circular polarized beam incident to silicon wafer reflecting surfaces at the Brewster angle, multiple linearly s-polarized side beams are generated. 3D photonic crystal structures of woodpile, Penrose quasi-crystal, and hexagonal symmetry were produced with ROEs that have 4+1, 5+1 and 6+1 beam configurations, respectively. By changing the material of one of the reflecting surfaces from silicon wafer to a fused silica slide and blocking one other silicon wafer on the ROE with 6+1 beam configuration, spiral-step 3D crystals can be fabricated. Since the ROE design can be readily changed and implemented for different photonic crystal structures, this fabrication method is more versatile and cost effective than currently comparable single optical methods like prisms and phase masks.

9350-58, Session PTue

Synthesis of Sb-doped ZnO microspheres by pulsed laser ablation and their photoluminescence properties

Toshinobu Tanaka, Tetsuya Shimogaki, Mitsuhiro Higashihata, Daisuke Nakamura, Tatsuo Okada, Kyushu Univ. (Japan)

ZnO is a significant II-VI semiconductor material which has a wide band-gap energy of 3.37 eV and a large exciton binding energy of 60 meV. Besides, doped-ZnO nano/microstructures have attracted considerable research interest. We succeeded in synthesizing Antimony (Sb) doped ZnO microspheres by ablating a Sb-doped ZnO sintered target with focused pulsed laser at a fluence of 25 J/cm2. Room-temperature photoluminescence properties of the microsphere were investigated under cw He-Cd laser and UV 355 nm pulsed laser excitations. An UV emission, which corresponds to near-band-edge emission and lasing in whispering gallery mode were observed from optically-pumped ZnO microsphere.

9350-22, Session 9

Laser-driven surface and interface nanotechnology *(Invited Paper)*

Jan J. Dubowski, Univ. de Sherbrooke (Canada)

No Abstract Available

9350-23, Session 9

Advances in ultrafast laser processing in the last two decades and the future *(Invited Paper)*

Koji Sugioka, RIKEN (Japan)

No Abstract Available

9350-24, Session 9

Adjusting material properties locally via phase change using controlled laser processing schemes *(Invited Paper)*

Henry Helvajian, The Aerospace Corp. (United States)

No Abstract Available

9350-25, Session 10

Laser patterning for reel-to-reel production of organic photovoltaic (OPV) devices

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The EU funded project Smartonics main objective is to develop pilot

production lines to combine smart processing technologies with new nanomaterials for the precision synthesis of organic photovoltaic (OPV) devices. These devices are attracting increasing commercial interest due to their low weight/size and flexibility, which allows them to be used on the exterior windows of cars, backpacks & clothing. The direct write and non-contact nature of laser patterning is highly desirable for the P1, P2 & P3 serial interconnection and isolation structures, since it is compatible with integration in reel-to-reel production lines. However, detrimental effects such as layer edge delamination or laser debris redeposition can effect OPV performance and represent real technological problems hindering the adoption of laser schemes to production lines. Since, OPVs consist of highly sensitive, thin (<0.2 μm) layers of novel organic & inorganic materials, the reduced thermal effects of ultrafast lasers along with intelligent beam delivery schemes are key to produce selective removal of individual thin film layers. P1 & P2 scribes made using picosecond and femtosecond lasers are characterized to identify the laser parameters and conditions required to produce working solar cells.

9350-26, Session 10

Laser “lift-off” observation of zinc oxide and copper-indium-diselenide thin-films on molybdenum initiated by sub-ns-laser pulses

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To minimize interconnection area of the monolithic interconnection in CIS (copper-indium-diselenide) thin-film solar cells, ultra-short laser pulses have been applied successfully. It is important to optimize the galvanic isolation of the zinc oxide (ZnO) layer. For this confined laser ablation should be used, also referred to as laser “lift-off”. The energy per ablated volume of the confined laser ablation (<10 J/mm?) is much more efficient than direct laser ablation (~100 J/mm?). It has been shown that confined laser ablation can be created up to pulse durations of about 10 ps.

In this work the selective laser structuring by confined laser ablation of a ZnO/CIS/Mo (mo-lybdenum) layer-system is investigated, using 800 ps (FWHM) pulses (wavelength 1064 nm).

The structured thin-films are transparent (ZnO) and partly transparent (CIS) for the used la-ser wavelength. Thus the majority of the laser pulse is absorbed in the CIS-layer. The absorp-tion leads to heating and heat diffusion inside and from the CIS-layer. As a consequence heat expansion and the creation of a high stress in the ZnO/CIS/Mo layer system takes place. The stress causes bulging of the ZnO/CIS layers resulting in a “lift-off” under well-defined process parameters. With that confined laser ablation ZnO/CIS layers are selectively structured by single laser pulses (energy per ablated volume ~ 2.5 J/mm?).

These measurements are compared with the laser “lift-off” experiments performed with 460 fs, 10 ps and 6 ns, to show the relation between the pulse duration and the selectiveness of confined laser ablation.

9350-27, Session 10

Evaluation of electrical shunt resistance in laser scribed thin-films for CIGS solar cells on flexible substrates

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Formation of serial interconnections in thin-film solar cells is an important step for upscaling their production over large areas. Laser scribing is a promising tool for that however evaluation of alterations in electrical properties of the cells during the technology development and validation is not a trivial task, especially for flexible substrates when production is based on roll-to-roll processes. We applied the technique of nested circular scribes proposed by K. Zimmer et. al. for in-line quality evaluation of the P2 and P3 scribing processes in CIGS solar cells on polyimide. Scribing experiments were performed using picosecond (10 ps) laser working at 532 nm wavelength. Validation of the measurement technique was performed and adopted to both scribing steps. Data on formation of interconnection by melting of the CIGS layer in P2 process and shunting the isolating P3 scribe by modified surface of the absorber were extracted analyzing I-V characteristics and equivalent scheme of the cell. Integration of laser scribing experiments with electrical characterization facilitates optimization of the laser processes and increases reliability of the selected regimes.

9350-28, Session 11

Towards an understanding of laser ablation efficiency: Comparison of pico- and femtosecond pulse durations *(Invited Paper)*

Juergen Sotrop, Jan Winter, Heinz P. Huber, Hochschule für Angewandte Wissenschaften München (Germany)

Ultra-short laser pulses are widely used in industrial applications. The cost per photon is strongly depending on the pulse duration of the laser source. Investigations show the existance of an optimum pulse duration for different materials, where the ablation efficiency (irradiated energy per removed volume) achieves a maximum value. For nanosecond laser pulses the behavior is well known by thermal diffusion, where the heat penetration depth is proportional to the square root of the pulse duration. However, the mechanisms for ultra-short laser pulses are not completely understood so far. For studying the dependency of ablation efficiency with pulse duration an improved numerical model for single pulse laser ablation is created. It includes a Lorentz-Drude sub-model for the absorption, electron-phonon-coupling and heat diffusion of electrons and lattice and a phase change sub-model for the ablation. The results show, that the reflectivity and therefore the deposited energy, are changing during the irradiation time. The ablation process is driven by non-equilibrium effects like spallation and phase explosion. This talk will give an overview of the current state of research.

9350-29, Session 11

Burst mode with ps- and fs-pulses: Influence on the removal rate, surface quality, and heat accumulation

Beat Neuenschwander, Beat Jäggi, Thorsten Kramer, Berner Fachhochschule Technik und Informatik (Switzerland)

In the application of ultra-short pulses, pulse bursts denote the situation where every pulse, emitted with the repetition rate of the laser system, is replaced by a series of n pulses emitted with the much higher repetition rate of the seed oscillator. Therefore the burst mode allows to distribute the energy of a single pulse onto the n pulses in the burst sequence, e.g. for laser systems with a maximum repetition of 1 MHz and a 8 pulse burst, the single pulses in the burst have the same energy as the pulses from a 8 MHz system with the same average power. The reported removal rates were often much higher when the burst mode was used. This can be explained with the lower energy per pulse and therefore with the reduced pulse fluence which is nearer the optimum value going with highest removal rates.

But there is a difference between the high repetition rate and the burst operation. Even the removal rate should not significantly change, the thermal management is completely different as the pulses within a burst see a surface at a much higher temperature (which can even be above the melting temperature). For some materials this can reduce the surface roughness due to controlled melting but it can also increase oxidation effects. We will present a systematic study of burst experiments with ps and fs laser systems together with a numerical model to simulate the local temperature raise in burst and high repetition rate mode as well.

9350-30, Session 11

Experimental investigation of CFRP cutting with nano second laser under air and Ar gas ambience

Yuji Sato, Masahiro Tsukamoto, Fumihiro Matsuoka, Osaka Univ. (Japan); Kensuke Yamashita, Osaka Univ (Japan); Kenjiro Takahashi, Shinichiro Masuno, Osaka Univ. (Japan)

A carbon fiber reinforced plastic (CFRP) plates were cut with a nanosecond laser under air and Ar gas ambience. Ambient gas is an important factor for reduction of heat affected zone (HAZ) since formation of HAZ might be related to the oxidization of carbon fibers and resin.

The CFRP plates were put on a XYstage in processing chamber to evacuate to pressure of less than 10 Pa and then fill with air or Ar gas at 0.1 MPa. Under these conditions, the CFRP plate was irradiated and scanned with a Q-switch Nd:YAG laser whose pulse width, wavelength and repetition rate were 6 ns, 1064 nm and 10 Hz, respectively. In order to investigate the HAZ after laser irradiation, a scanning electron microscope and a Raman spectrometer were conducted. In order to evaluate the oxidization, spectroscopic analysis was carried out to investigate an ablation plume under air and Ar gas. Furthermore, a surface on CFRP plate was observed with a scanning electron microscope (SEM) and a Raman spectrometer. As the results, it was found that the HAZ on the CFRP surface under Ar is one-ninth as small as that under air. The results revealed that an oxidization of carbon fiber and resin was caused to expand the HAZ by the laser irradiation.

9350-31, Session 11

Ultrafast pump-probe studies of the complex refractive index in metals

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Ultra-short pulsed lasers offer a great potential in precise and efficient material processing. Thus, intensive research is needed to obtain a fundamental understanding of the physical ablation mechanisms and to answer still open questions. For example, it is not yet understood why significant variations are observed for the ablation efficiency using laser pulses between several hundred femtoseconds and a few picoseconds pulse duration. An explanation could be found in ultra-fast changes of the material absorption on a time scale shorter than the pulse duration. This would influence the laser pulse energy input into the material and thus the ablation efficiency. To investigate the transient absorption, a unique pump-probe ellipsometry microscope is presented in this work. A laser at a wavelength of 1053 nm and a pulse duration of 650 fs (FWHM) is used as laser source. This setup allows the determination of the complex refractive index, describing the material absorption, with a sub-ps temporal resolution. First measurement series on platinum and molybdenum samples are presented. They show the change of the real part (n) as well as the imaginary part (k) of the complex refractive index. These measurements are set in relation to the ablation efficiency. The correlation between ablation efficiency and transient absorption is investigated.

9350-32, Session 11

Dynamics of ZnO nanoparticles formed in the high-pressure phase during growth of ZnO nanocrystals

Daisuke Nakamura, Tetsuya Shimogaki, Shuhei Takao, Shihomi Nakao, Kosuke Harada, Mitsuhiro Higashihata, Tatsuo Okada, Kyushu Univ. (Japan)

ZnO nanocrystals have attracted a great attention as building blocks for the optoelectronic devices in ultraviolet region. We have been succeeded in growing nanocrystals by a newly developed nanoparticle-assisted pulsed-laser deposition (NAPLD). In NAPLD, ZnO nanoparticles formed in the high gas pressure phase play an important role in the ZnO nanocrystals growth. However, temporal and spatial dynamics of the nanoparticles during the growth of the nanocrystals have not been investigated. In this presentation, the dynamics of the ZnO nanoparticles measured by a scattering imaging technique will be discussed.

9350-33, Session 12

Femtoseconds to microseconds: Multi-scalar response during liquid spallation of metal films *(Invited Paper)*

Steven M. Yalisove, Keegan J. Schrider, Michael J. Abere, Ben R. Torralva, Univ. of Michigan (United States)

The dynamics of femtosecond laser ablation of 20 nm thick Ni films very close to the ablation threshold reveal multiple mechanisms that occur on many different time scales. Experimental and theoretical results will be presented which show how two liquid layers are ejected ~ 600 picoseconds apart. The hot liquid that is expelled in the first spallation event, and the hot liquid that initially stays attached to the substrate, both undergo cooling which results in a phase separation at two distinct times. Results will also be shown which suggest that this hot underdense liquid breaks up into small droplets which can be deposited on a thin C membrane that is positioned 140 microns away from the original metal film. The particles are very small and form nanoparticles with a variety of size distributions. Data will be presented to explain the role of thickness, and spallation mechanism, on the size distributions which are observed. If the film thickness is reduced to 10 nm, then the small ejected droplets are deposited on the thin membrane on 0.1 microsecond time scales, are quenched, react with Oxygen from the ambient, and form a very narrow distribution of NiO nano particles with size 2nm +-1nm.

9350-34, Session 12

Ablation depth control on ITO thin film using a beam shaped femtosecond laser

Hoon-Young Kim, Ji-Wook Yoon, Won-Suk Choi, Sung-Hak Cho, Korea Institute of Machinery & Materials (Korea, Republic of) and Univ. of Science & Technology (Korea, Republic of)

We report on the ablation depth control with the resolution of 40 nm on indium tin oxide (ITO) thin film using pulse numbers of a square beam shaped femtosecond (190 fs) laser (?p = 1030 nm). The slit is employed to make the square, flat-top beam shaped from the Gaussian beam profile of femtosecond laser. The depth of flat shaped ablation is approximately 40 nm by the single pulse irradiation at the peak-intensity of 2.8 TW/cm2. The morphologies of the ablated area were characterized using an optical microscope, atomic force microscope (AFM), and energy dispersive X-ray spectroscopy (EDS). Ablations with square, rectangular types of several sizes were demonstrated on ITO thin film using the slit with varying x-y axises. The stereo structure of ablation with the depth resolution of approximated 40 nm was also fabricated using the control of single pulse with varying square size of beam shaped femtosecond laser.

9350-35, Session 12

The role of under-dense liquids in the ultrafast laser ablation dynamics of thin Ni films on glass: A theoretical study

Ben R. Torralva, Keegan J. Schrider, Steven M. Yalisove, Univ. of Michigan (United States)

The ultrafast laser ablation of thin Ni films on glass results in two distinct ablation thresholds -- one for intra-film removal (7 nm of a 20 nm film), and one at higher fluence that results in removal at the interface. Our recent time-resolved experimental results show that intra-film and interface removal are separated in time by ~600 ps for a single laser pulse of sufficient fluence. In this presentation, we build on our recent radiation hydrodynamic results of the ablation dynamics by further investigating the state of the material at crucial points along the dynamical pathway, and the fluctuation dynamics that lead to interface removal. Particular attention is given to the superheated liquid-like nickel that remains on the substrate for ~600 ps even though simple calculations and our hydrodynamic results indicate that the material should be sufficiently heated to nucleate vapor at the interface. Additionally, the hydrodynamic results indicate that the material is well below normal liquid density, and molecular dynamics simulations give results inconsistent with the experiments, necessitating the need to pay proper attention to the state of the material during the ablation process. Results will be presented from both classical molecular dynamics and density functional based methods, along with radiation hydrodynamic simulations for various initial conditions.

9350-36, Session 12

Ultrafast laser irradiation of thin films as a route to the formation of very small nanoparticles with controllable size distributions

Keegan J. Schrider, Ben R. Torralva, Steven M. Yalisove, Univ. of Michigan (United States)

Ultrafast laser ablation of thin Ni films on glass substrates is a promising technique for the production of nano particles with controllable size distribution. This talk will describe our experiments with 10 and 20 nm thick Ni films on glass that are irradiated from the back side to enable an ultrafast Laser Induced Forward Transfer (LIFT) route to printing nanoparicles. Our group has previously shown that ablation of thin Ni films shows a sharp transition from partial to complete removal depending on the local fluence, these are referred to as intrafilm and interface ablation respectively. Recent pump probe results currently being submitted for publication show that intrafilm ablation occurs as voids nucleate homogeneously within the film while interface ablation occurs as Ni vapor nucleates heterogeneously at the Ni-glass interface. We will build on our previous results to show how the size distribution of nanoparticles produced during LIFT is dependent on the ablation mechanism. To further understand the mechanism of interface ablation, new pump probe data will show how local fluence affects the delay for interface ablation relative to intrafilm ablation. If time permits we will present pump probe of Ni thin films irradiated with multiple pulses, how the composition of the film affects intrafilm and interface ablation, and how composition of the film influences nano particle formation by each ablation mechanism.

9350-37, Session 13

Efficient processing of CFRP with a picosecond laser with up to 1.4 kW average power *(Invited Paper)*

Volkher Onuseit, Margit Wiedenmann, Christian Freitag, Jan-Philipp Negel, André Löscher, Marwan Abdou Ahmed, Rudolf Weber, Thomas Graf, Univ. Stuttgart (Germany)

Laser processing of carbon fiber reinforce plastic (CFRP) is a very promising method to solve challenges for lightweight constructions in automotive and airplane industries especially for large-volume production. Unfortunately the laser process is actually limited by two main issues: First the quality is reduced due to thermal damage. Second very high process energy is needed for sublimation of the carbon fibers requiring laser sources with high average power for productive processing. To achieve thermal damage of the CFRP below 10 µm intensities above 108 W/cm? are needed. To reach this high intensities in the processing area ultra-short pulse laser systems are favored. Today the average power of such laser systems is limited to a few hundred Watt. To sublimate the carbon fibers the volume specific enthalpy of 85 J/mm? is necessary. As an example this means for cutting of 2 mm thick material with a kerf width of 0.2 mm with industry-typical 100 mm/sec, several kilowatts of average power are required. At the IFSW a thin-disk multipass amplifier yielding a maximum average output power of 1400 W (300 kHz, 8 ps, 4.7 mJ) allowed for the first time to process CFRP at this average power and pulse energy level. With this unique laser system cutting of CFRP with a thickness of 2 mm an effective average cutting speed of 150 mm/sec was demonstrated. Optimized thermal management avoiding heat accumulation effects allowed achieving thermal damage below 10 µm.

9350-38, Session 13

Modification of flow of glass melt and elemental distributions by parallel irradiation with femtosecond laser pulses

Masaaki Sakakura, Torataro Kurita, Kouhei Yoshimura, Naoaki Fukuda, Yasuhiko Shimotsuma, Kiyotaka Miura, Kyoto Univ. (Japan)

Local melting can be induced inside a glass by focusing femtosecond (fs) laser pulses at high repetition rate (>100kH). As the results, the spatial distributions of glass elements are modified in the molten region. Because various propertied of glasses depends on the composition of elements, the modification of spatial distribution of glass elements using fs laser will make it possible to control glass properties in three dimensional manner. The important point of the control of elemental distribution is how to control the flow of molten glass during laser irradiation. However, only an ellipsoidal-shaped elemental distribution is possible by fs laser irradiation of a single beam, because the temperature distribution, which can induce flow of glass melt, is always symmetric about the beam axis. In this presentation, we demonstrated that the elemental distributions inside a sodalime glass and alumino-borosilicate glass can be modified by simultaneous irradiation with 1 kHz fs laser pulses at four points and 250 kHz fs laser pulses at the center. The in-situ observation by an optical microscope during laser irradiation showed that the flow of glass melt could play an important role in modifying the elemental distributions. Therefore, for fine control of elemental distribution, we investigated the relationship between the flow of glass melt and various irradiation parameters, such as focal depth, numerical aperture and spherical aberration, based on in-sites observation of flow of glass melt using an interference microscope.

9350-39, Session 13

Material processing with ultra-short pulse lasers working in 2μm wavelength range

Bogdan Voisiat, Ctr. for Physical Sciences and Technology (Lithuania); Dmitry A. Gaponov, NOVAE (France); Paulius Gecys, Ctr. for Physical Sciences and Technology (Lithuania); Laure Lavoute, Manuel Silva, NOVAE (France); Ammar Hideur, CORIA CNRS UMR6614, Université de Rouen (France); Nicolas Ducros, NOVAE (France); Gediminas Raciukaitis, Ctr. for Physical Sciences and Technology (Lithuania)

New wavelengths of laser radiation are of interest for material processing. Results of application of the all-fiber ultra-short pulsed laser emitting in 2 μm range, manufactured by Novae, are presented. Average output power was 4.35 W in a single-spatial-mode beam centered at the 1950 nm wavelength. Pulse duration was 40 ps, and laser operated at 4.2 MHz pulse repetition rate. This performance corresponded to 23 kW of pulse peak power and almost 1 μJ in pulse energy. Material processing was performed using three different focusing lenses (100, 30 and 18 mm) and mechanical stages for the workpiece translation.

2 μm laser radiation is strongly absorbed by some polymers. Swelling of PMMA surface was observed for scanning speed above 5 mm/s using the average power of 3.45 W focused with the 30 mm lens. When scanning speed was reduced below 4 mm/s, ablation of PMMA took place. The swelling of PMMA is consequence of its melting due to absorbed laser power. Therefore, experiments on butt welding of PMMA and overlapping welding of PMMA with other polymers were performed. Stable joint was achieved for the butt weld of two PMMA blocks with thickness of 5 mm.

The laser was used to cut a Kapton film on a paper carrier with the same set-up as previous. Cut width depended on the cut speed and focusing optics. A perfect cut width of 11 μm was achieved at a 60 mm/s speed.

9350-41, Session 14

Machine technology for 3D microprocessing of complex curved surfaces *(Invited Paper)*

Max Groenendijk, Lightmotif B.V. (Netherlands)

Ultrashort pulsed lasers have proven to be excellent tools to fabricate micro and nanotextures for the generation of functional surfaces. Especially interesting is to apply the negative of such textures to injection molds, which enables mass production of polymer parts with new functionalities. This presentation shows the technology that Lightmotif develops to enable accurate microprocessing of large complex curved surfaces, and examples of applications such as soft-touch surfaces.

A highly accurate 5-axis machine was integrated together with a picosecond pulsed laser and a galvo-scanner. The machine works according to the step-and-scan principle where the surface is divided into small segments (tiles) that are textured one after anther. Specifically developed control software is used to generate the complex machining programs and control the machine.

The problem that needed to be solved is the accurate positioning of each individual tile on a large complex curved surface, which needs to be maintained over long machining cycles of up to several days. For this the machine alignment, pointing stability and scan field calibration need to be well controlled.

The presentation shows our approach of these issues and the results. Early results of an automated calibration sensor are presented. This device automatically ensures scan field calibration over long periods and can also compensate for pointing errors and drift. Other machine automations that are under development include an automated power calibration, which makes it possible to program the machine by only specifying the needed pulse energies. All power measurements and calibrations are performed automatically.

9350-42, Session 14

Improvements in ultra-high precision surface structuring using synchronized galvo or polygon scanner with a laser system in MOPA arrangement

Markus Zimmermann, Beat Jäggi, Beat Neuenschwander, Berner Fachhochschule Technik und Informatik (Switzerland)

In earlier works the capabilities of synchronizing a galvo scanner or a polygon scanner with a picosecond laser system in MOPA arrangement were presented. Both scanner solutions provide excellent positioning of laser pulses relatively to each other. But in combination with other mechanical axes or in an industrial micromachining process the precision of the absolute positions of the craters is essential. Therefore recent research efforts were focused on enhancing the precision of absolute positioning and to improve the overall machining efficiency.

The classic way to assess positioning precision is to measure the positions on a test sample with an optical microscope. This procedure is intricate when measuring positions in the micrometer range is demanded. In order to avoid optical measurements a simple method to determine the laser pulse position directly on the scanner setup was developed. With an optimized scanner control on the fly markings with micrometer resolution become possible. This augmented precision enables machining in both scanning directions. In combination with the latest pulse on demand devices the machining speed of the synchronized galvo scanner has been increased by a factor of six in the last two years.

To address a 2D-area which exceeds the working area of the galvo scanner it is necessary to combine the galvo scanner with mechanical axes. The aforementioned position measurement enables precise tuning between the mechanical axes and the scanner which enables new machining strategies such as arranging multiple scan areas side by side.

9350-44, Session 14

Efficient processing of brittle industrial materials by hybrid-fiber UV laser

James M. Bovatsek, Rajesh S. Patel, Ashwini Tamhankar, Spectra-Physics, a Newport Corp. Brand (United States)

Various brittle dielectric materials are increasingly incorporated in modern devices. From smart phones and tablets to advanced IC packages and the latest high-brightness LED, materials such as chemically-strengthened glass, ceramics, and sapphire crystals are finding increased use. Their unique properties include superior scratch resistance, high mechanical hardness and, in some cases, high thermal but low electrical conductivity. Their brittleness and heat sensitivity makes these materials difficult and costly to machine, requiring gentle handling and low mechanical processing speeds. Creating micro-features with high-throughput is especially challenging, since this generally requires high power levels concentrated in small material volumes. For such tasks, the laser industry's latest technological innovations are required. Spectra-Physics® offers a new-generation Quasar® 355-nm hybrid-fiber laser with TimeShift™ pulse-shaping technology built-in. The laser offers 60-W output power which means high-throughput processing is possible. For high-quality processing, we have shown that pulse widths down to <2 nanoseconds offer significant improvement compared to longer pulse widths. Even at this short pulse width the laser maintains 60-W power for megahertz-level pulse repetition frequencies, which means high-throughput can also be achieved. Larger features in thicker materials are also possible with the >300 microJoule output pulse energy that is available. For some cutting and drilling processes, we have demonstrated that there is a trade-off between speed and quality which is determined by, for example, high-versus-low PRF or short-versus-long pulse duration. With the variable pulse width output, and with the unique TimeShift™ pulse intensity tailoring capability, Quasar allows "dialing-in" the ideal combination of quality and throughput.

Conference 9351: Laser-based Micro- and Nanoprocessing IX

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9351-1, Session 1

Smart laser micro-welding of difficult-to-weld materials for electronic industry *(Invited Paper)*

Yasuhiro Okamoto, Okayama Univ. (Japan); Norio Nishi, Shin-ichi Nakashiba, Tomokazu Sakagawa, KATAOKA Corp. (Japan); Akira Okada, Okayama Univ. (Japan)

It has been known that the wavelength, power density, interaction time and material properties have great influence on processing characteristics in laser material processing, in which materials with higher reflectivity classify into difficult-to-weld materials. In electronic industry, aluminum alloy is widely used as structural components due to its high specific strength, and copper became an important material because of its excellent electrical conductivity. These materials have high reflectivity and high thermal conductivity, which results in instability of energy absorption and processing results. Therefore, welding defects might be noticed in the micro-joining of aluminum alloy and copper. In this paper, the smart laser micro-welding of difficult-to-weld materials such as aluminum alloy and copper were discussed.

The combination of a pulsed Nd:YAG laser and a continuous diode laser could perform the high-performance micro-welding of aluminum alloy. A pulsed Nd:YAG laser was absorbed effectively from the beginning of laser scanning by pre-heating Nd:YAG laser pulse with the superposition of continuous LD, and wide and deep weld bead could be obtained with better surface integrity.

As for micro-welding of copper material, the stable absorption state could be achieved by using a pulsed green Nd:YAG laser, since its absorptivity showed almost constant values with change of power density. A longer pulse duration is effective to achieve not only high absorptivity but also low deviation of absorptivity. The pulse waveform with maximum peak at the early period and a long pulse duration led to stabilizing the penetration depth with less porosity.

9351-2, Session 1

Picosecond laser fabrication of micro cutting tool geometries on polycrystalline diamond composites using a high-numerical aperture micro scanning system

Gregory Eberle, ETH Zürich (Switzerland); Claus A. Dold, EWAG (Switzerland); Konrad Wegener, ETH Zürich (Switzerland)

The generation of microsized components found in LEDs, watches, molds as well as other types of micromechanics and microelectronics require a corresponding microcutting tool in order to be manufactured, typically by milling or turning. Microcutting tools are made of cemented tungsten carbide and are conventionally fabricated either by electrical discharge machining or by grinding. An alternative method is proposed through a laser-based solution operating in the picosecond pulse duration whereby the beam is deflected using a modified galvanometer-driven microscanning system exhibiting a high numerical aperture. A microcutting tool material which cannot be easily processed using conventional methods is investigated, which is a fine grain polycrystalline diamond composite. The generation of various microcutting tool relevant geometries, such as chip breakers and cutting edges, are demonstrated. The generated geometries are subsequently evaluated using scanning electronic microscopy and quality is measured in terms of surface roughness and cutting edge sharpness. Additionally, two processing strategies in which the laser beam processes tangentially and radially are compared in terms of quality.

9351-3, Session 1

Experimental and modelling investigations into the laser ablation with picosecond pulses at second harmonics

Paul Börner, ETH Zürich (Switzerland); Germana Zandonadi, ETH Zürich (Switzerland) and Univ. Federal de Santa Catarina (Brazil); Gregory Eberle, Konrad Wegener, ETH Zürich (Switzerland)

Ablation threshold experiments on various materials are carried out using a picosecond laser generating second harmonic radiation in air at atmospheric pressure. Various materials are investigated which vary according to their electronic band gap structure and include: silicon, fine grain polycrystalline diamond, copper, steel and tungsten carbide. Through the use of scanning electron microscopy and 3D confocal microscopy, the crater depth and diameter are determined and a trend is correlated. The damage and ablation threshold are given for the aforementioned materials and compared with past literature results. Picosecond laser-material interactions are modelled using the two-temperature model, simulated and compared with experimental results for metallic materials. An extension of the two-temperature model is discussed in terms of how it can be extended to semiconducting and insulating materials. This alternative model uses multiple rate equations to describe the transient free electron density. Additionally, a set of coupled ordinary differential equations describes the processes of multiphoton excitation, inverse bremsstrahlung, and collisional excitation. The resulting electron density distribution can be used as an input for an electron density dependent two-temperature model. This multiple rate equation model is a generic and fast model, which provides important information like ablation threshold, ablation depth and optical properties.

9351-4, Session 1

Generating embedded 3D optical functions in ultrafast laser processed bulk chalcogenide glasses for photonic applications in the mid-IR domain

Ciro D'Amico, Lab. Hubert Curien (France); Guanghua Cheng, Xi'an Institute of Optics and Precision Mechanics (China); Cyril Mauclair, Lab. Hubert Curien (France); Johann Trolès, Laurent Calvez, Virginie Nazabal, Céline Caillaud, Univ. de Rennes 1 (France); Guillermo Martin, Brahim Arezki, Etienne P. Le Coarer, Pierre Kern, Institut de Planétologie et d'Astrophysique de Grenoble (France); Stefano Minardi, Friedrich-Schiller-Univ. Jena (Germany); Razvan Stoian, Lab. Hubert Curien (France)

Efficient light transport in ultrafast laser 3D photoinscribed embedded systems, in the visible and the near-IR domains, was demonstrated in several optical materials, and the applications range from embedded waveguide laser prototypes to new concepts in mode selection and conversion in astrophotonics. Applications in the mid-IR domain require upscaling of the

waveguides cross-section diameter and index contrasts for large area mode transport. i.e. waveguide dimensions allowing light transport and mode filtering in the L, M, N astronomy bands for remote sensing and imaging.

Chalcogenide glasses (ChGs) are ideal materials for creating and testing new integrated optical functions in the mid-IR domain due to their transparency up to 14 µm, and their nonlinear strength.

Here, firstly we study the photoinscription process in As40S60 (As2S3) and Ge15As15S70 glasses, showing that Ge insertion in As2S3 significantly enhances the processing window for positive refractive index changes, via gap engineering. Then we demonstrate laser photoinscribed large mode area guiding in several concepts (slit-shaping, multicore, multistrip waveguides), and the implementation of 3D optical functions (beam splitters, beam combiners, ...), putting forward interesting new applications in the mid-IR integrated photonics domain. Furthermore, we demonstrate the feasibility of embedded nonlinear optical (NLO) functions in GLS, such as for example saturable absorber waveguides, and band-gap effects in type II photonic crystal waveguides, in the multicore configuration.

9351-5, Session 1

Femtosecond fiber laser welding of PMMA

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Ultrashort-pulsed laser welding of transparent materials on a micrometer scale is a versatile tool for the fabrication of electronic, electromechanical, and medical micro-devices. Recently, direct fs-laser welding of fused silica borosilicate glass and dissimilar glasses without any intermediate absorbing layer, has been successfully demonstrated at repetition rates ranging from several hundred kHz up to a few MHz. This fs-laser joining technique could potentially be exploited also in case of transparent polymers. Currently, laser welding of transparent polymeric materials is only possible by interposing an absorbing medium between the two transparent layers or using on an opaque substrate to the laser wavelength. In this work, we report on fs-laser microwelding of two transparent layers of PMMA using an ultrafast CPA fiber laser system with a wavelength of 1030 nm in the MHz regime. PMMA (polymethyl methacrylate) is a very attractive material for fabricating low costly bio-medical devices such as Lab-on-Chips We aim at exploiting localized heat accumulation to weld two PMMA layers without any preprocessing of the sample and/or any intermediate absorbing media, by focusing fs-laser pulses at high repetition rate at the interface.

We have firstly investigated the modifications produced by the focused laser beam into a 3-mm-thick bulk PMMA sample in a wide range of working parameters (average power, repetition rate, scan speed) aiming to find a process window producing continuous melting of the material. Results have been evaluated based on heat accumulation models presents in literature

Finally, fs-laser welding of two 1-mm-thick PMMA layers have been successfully demonstrated and some static and dynamic leakage tests have been performed to check the sealing, up to 1 bar of liquid pressure.

9351-7, Session 2

Laser processing of carbon based nanomaterials *(Invited Paper)*

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No Abstract Available

9351-8, Session 2

Laser direct written silicon nanowires for field effect transistors and p-n junction diodes

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Silicon nanowires are promising building blocks for high-performance electronics and biomedical diagnostic devices due to their ultra-small body and high surface-to-volume ratios. However, the lack of the ability to assemble and position nanowires in a highly controlled manner still remains an obstacle to fully exploiting the substantial potential of nanowires. Here we demonstrate a single-step laser manufacturing method to synthesize silicon nanowires for electronic device applications. Boron- and phosphorus-doped nanowires are deposited using laser direct writing in combination with chemical vapor deposition. The interference effect between incident laser and surface-scattered light creates nanowires as thin as 60 nm, which is far below the diffraction limit of the 400 nm laser light. In addition, our approach features in-situ doping, catalyst-free growth, and excellent control of the position, orientation, and length of nanowires. The direct deposition of semiconductor nanowires on an insulating surface provides a platform ready for subsequent device fabrication. Furthermore, by switching dopant gases during nanowire growth, modulation-doped nanowires are synthesized. Field effect transistors and p-n junction diodes are demonstrated. Schottky barrier field effect transistors are fabricated using both p- and n-type nanowires, and the effect of annealing conditions and doping concentration will be discussed. P-n junction diodes are fabricated using modulation-doped nanowires, demonstrating the versatileness of our method. We expect that our approach could be a promising alternative for fabrication of many kinds of silicon devices.

9351-9, Session 2

Two-color double-pulse experiments studying the dynamics of femtosecond laser-induced periodic surface structures (LIPSS) on metals, semiconductors, and dielectrics

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The dynamics of the formation of laser-induced periodic surface structures (LIPSS) on Titanium (Ti), Silicon (Si), and Fused Silica (FuSi) upon irradiation with linearly polarized fs-laser pulses (pulse duration: 50 fs) is studied experimentally. In order to reveal the underlying physical mechanisms, the relevance of temporally distributed energy deposition on LIPSS formation is investigated. A Mach-Zehnder interferometer generated double-pulse sequences at two different wavelengths (400 nm & 800 nm), with varying inter-pulse delays up to a few picoseconds and allowed a selective polarization control (parallel or cross-polarized pulses). Multiple of these two-colour double-pulse sequences were focused by a spherical mirror to the surface of the samples. The corresponding surface areas were characterized by scanning electron microscopy and the LIPSS periods were determined by Fourier transform. The latter ones along with the orientation of the LIPSS allow a clear identification of the pulse which dominates the energy coupling to the material. In dielectrics (FuSi) the first pulse dominates the energy deposition. In contrast, for strong absorbing materials (Si, Ti), a plasmonic mechanism can explain the delay-dependence of the LIPSS appearance. These two-color experiments confirm the importance of the ultrafast energy deposition stage for LIPSS formation.

9351-10, Session 2

A point defect injection and diffusion mechanism for the origin of high spatial frequency laser induced periodic surface structures

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High spatial frequency (HSF) laser induced periodic surface structures (LIPSS) are commonly observed after ultrafast laser irradiation. The structures have period less than 0.3 times the laser wavelength and cannot be explained with previously existing models for LIPSS formation. We demonstrate that HSF-LIPSS formation is related to the accumulation of laser injected point defects and subsequent diffusion of the vacancy-interstital pairs. Here, we focus on irradiation of GaAs with a linearly polarized, 150 fs, 1 kHz repetition rate, ?=780 nm laser. The observed LIPSS have period 180 ± 30 nm and align perpendicular to the laser polarization. HSF-LIPSS only form below the material melt threshold. Hundreds of exposures are required for sufficient defect accumulation to initiate HSF-LIPSS formation. The injected defects can contribute to HSF-LIPSS formation on a timescale that suggests they have a lifetime on the order of hours. We then connect the LIPSS bifurcation to an insolubility of the accumulated vacancies in the semiconductor lattice that drives diffusion. Tensile strain from the vacancy-rich lattice is observable as a redshift in the longitudinal optical mode in Raman Spectroscopy.

9351-11, Session 3

High volume transfer of high viscosity silver pastes using laser direct-write processing for screen printing of c-Si cells

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INTRODUCTION

Laser Induced Forward Techniques (LIFT) can be an alternative to traditional screen printing of c-Si cells. The morphology of the fingers (the aspect ratio) is a critical factor in the performance of c-Si solar cells.

The main objective of this work is to adapt the LIFT process to define metallic contacts (fingers and busbars) onto c-Si cells and to obtain the dependence of the height and width of the deposited lines on the process parameters.

EXPERIMENTAL PROCEDURE

A silver paste with high viscosity (280-400 Pa·s) is applied over a glass substrate using a coater. The thickness of the paste layer (30-80 um) can be controlled with the deposit parameters. The glass with the silver paste is set at a controlled gap (in our case 50-150 um) to the substrate.

A DPSS (Diode Pumped Solid State laser (532 nm) is focused at the glass/silver interface producing a droplet of silver that it is transferred. A scanner can be used to print lines at very high speeds.

The process parameters (silver paste thickness, gap and laser parameters -spot size, pulse energy and overlapping of pulses) are modified and the morphology of the lines is studied using confocal microscopy.

Long lines, of several centimeters, are printed and the uniformity and repeteability (in thickness and height) of the process is analyzed.

RESULTS

With an appropriate process parameterization (laser pulse energies around 30 μJ) it is possible to transfer volumes around 30 pL per pulse and lines with a height of 40 μm and a width of 100 μm.

The laser power, the paste thickness and the paste-substrate gap are identified as key variables in the process.

Acknowledgements

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9351-12, Session 3

Multilayer based lab-on-chip-systems for substance testing

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Introduction

Realization of complex 3D tissue cultures on a chip requires the implementation of closed circulation systems. These consist of several cell culture segments, storage chambers and micro-pumps. So far the fabrication was accomplished by casting a silicone flow cell to a connector plate. This process is complicated, expensive and difficult to automate. It also limits the microfluidic system to be designed in a single layer [1, 2 and 3].

Setup

We are developing a closed process chain to manufacture automatically cost effectively inexpensive chips. The novel system is a multilayer design based on laser micro structured foils. The first step is to slice the microfluidic system design into individual layers so that each layer can be fabricated on a separate foil. The next step is to select the desired properties (e.g. hydrophilic, transparent …) for each foil, which depends on the functional requirements. In the third step these foils are laser processed on both sides, i.e. they are micro structured and functionalized. The final fourth step is laminating these individual foils into a multilayered system via adhesive or plasma bonding. The multilayer technology is also applied to fabricate pneumatically powered pumps and valves. For this purpose the design of these elements has to be adapted.

Results

Microfluidic structures can be placed at different levels in the multilayer design, which results in greater functionality per chip area. Surface properties can be tailored by using foils with different properties (hydrophilic, hydrophobic) in combination with laser structuring and laser functionalization. This enables the implementation of new functions such as capillary stop valves and the tailored occupation of areas with cells. Foils can also be used to integrate thin film electrodes.

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9351-13, Session 3

Enhancing vapor generation at a liquid-solid interface using micro/nanoscale surface structures fabricated by femtosecond laser surface processing

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Femtosecond Laser Surface Processing (FLSP) is a versatile technique for the fabrication of a wide variety of micro/nanostructured surfaces with tailored physical and chemical properties. Through control over processing conditions such as laser fluence, incident pulse count, polarization, and incident angle, the size and density of both micrometer and nanometer-scale surface features can be tailored. Furthermore, the composition and pressure of the environment both during and after laser-processing have a substantial impact on the final surface chemistry of the target material. FLSP is therefore a powerful tool for optimizing interfacial phenomena such as wetting, wicking, and phase-transitions associated with a vapor/liquid/solid interface. In the present study, we utilize a series of multiscale FLSP-generated surfaces to improve the efficiency of vapor generation on a structured surface. Specifically, we demonstrate that FLSP of a stainless steel 316 electrode surface in an alkaline electrolysis cell results in increased efficiency of the water-splitting reaction used to generate hydrogen as an alternative energy source. The electrodes are fabricated to be superhydrophilic (the contact angle of a water droplet on the surface is less than 5 degrees). The overpotential of both the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) are measured using a 3-electrode configuration with a structured electrode as the working electrode. The enhancement is attributed to several factors including increased surface area, increased wettability, and the impact of micro/nanostructures on the bubble formation and release. Special emphasis is placed on the identifying and isolating the relative impacts of the various contributions.

9351-14, Session 3

Fundamental investigations of ps-laser burst-mode on common metals for an enhanced ablation process

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During the last decade laser micro machining became an indispensable tool for scientific and industrial applications. Many efforts are done to speed up the micromachining process and to improve the surface quality. One promising approach is the so-called burst-mode, where one burst consists of two or more succeeding pulses with a temporal separation on the ns time scale. Up to now burst-machining has been optimized for selected applications with an increase in processing speed in the order of several magnitudes as well as an improved surface quality. However, the exact ablation mechanism is not fully understood yet to apply this technique to other applications. Several publications predict that the first laser pulse causes a preconditioning of the surface by changing the thermo-physical and optical properties of the material for the subsequent pulses. For a systematic understanding of these predominant effects, however, they have to be investigated by detailed experiments. Therefore, we investigated single pulse, multiple pulse and burst-mode machining of different metals like copper, aluminum, titanium, tungsten and tin. All these metals strongly differ in their optical and thermal properties. The experiments were carried out for 1064nm, 532nm and 355nm wavelengths, respectively, which are widely used in industrial applications. The laser induced morphologies were investigated by SEM evaluation. Furthermore these experiments were accompanied by an analytical model that considers the heat conduction mechanism between consecutive pulses.

9351-15, Session 3

Vibration assisted femtosecond laser hole drilling on fine metal mask for AMOLED application

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The current trend of display panel is high resolution that increasing Pixel per Inch. Fine Metal Mask (FMM) is using in RGB (Red, Green, Blue) evaporation process for AMOLED (Active Matrix Organic Light Emitting Diode) manufacturing. It is necessary to decrease pattern size of FMM. In evaporation process for RGB deposition using FMM, lower taper angle of pattern is important. Ti:sapphire femtosecond laser, optics for beam delivery, objective lens, coaxial illuminator, and vision system was used in experiment. Vibration module was adapted to objective lens for taper angle control. For study of effect of moving focusing point in hole drilling, we controlled the frequency and amplitude of vibration in drilling process. Femtosecond laser pulse was irradiated on Invar alloy with 30 ?m thickness through vibration module. Compared to laser machining without vibration assistance, smaller taper angle obtained when vibration was assisted. In conclusion, we have demonstrated the effect of vibration of objective lens for taper angle control on FMM for AMOLED manufacturing. Vibration assisted taper angle control can be useful technic not only the Fine Metal Mask, but also other application such as micro nozzle, fluidic micro channel, and bio micro needle etc.

9351-16, Session 4

fs-Laser based production of 3D micro- and nano-devices in transparent substrate displays with fs lasers *(Invited Paper)*

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No Abstract Available

9351-17, Session 4

Dynamics of optically excited Tungsten and Silicon for ripples formation

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We measured the dielectric constant of strongly excited Tungsten, Stainless Steel and Zr based Bulk Metallic Glass using a dual-angle femtosecond reflectivity pump-probe technique, in the fluence regime which allows the formation of laser-induced periodic surface structures (LIPSS). The energy deposition in ripples formation is then investigated by simulating the laser pulse interaction with an initially random distributed rough surface using 3D Finite Difference Time Domain (FDTD) method, with the measured dielectric constant as a material input. We found in the FDTD simulation periodic

energy depositions both perpendicular and parallel to the laser polarization. The origin of them are discussed for originally plasmonic and non-plasmonic metals.

9351-18, Session 4

Process and parameter optimisation for micro structuring of 3D freeform metallic surfaces: A comparative study of shortpulse (ns) and ultrafast laser (ps, fs) ablation

Steffen G. Scholz, Melanie Mangang, Wilhelm Pfleging, Karlsruher Institut für Technologie (Germany)

Layer-based laser ablation of three dimensional micro structured freeform surfaces has become of significant importance for technical applications such as bio mimetic surfaces in recent years. In order to identify the optimum set of process parameters for a complex laser ablation operation a design of experience (DoE) study has been carried out with laser sources covering pulse durations from the femtosecond (fs) up to the nanosecond (ns) regime. The aim was to identify the optimum parameter set for achieving best surface roughness and, as a second criteria, for the optimisation machining time to be reduced to a minimum. In a first step, rectangular pockets have been machined and a DoE based parameter variation was performed. In particular, the parameters wavelength (1030 nm, 515 nm, 343 nm), machining speed, laser power, and laser pulse duration (fs, ps, ns) have been modified. Surface roughness was measured and an optimum set of parameters was calculated. Finally, with this parameter set a shark skin like micro structured test structure covering a macroscopic freeform surface was ablated in a layer based manner utilising a full CAD/CAM approach. The results show, that the ultrafast laser radiation has the best performance to achieve lowest surface roughness and best ablation efficiency. Whereas scanning speed and pulse duration have a linear influence on achievable roughness, laser power has a quadratic influence with a global maximum on the surface roughness result.

9351-19, Session 4

Superhydrophobic metallic surfaces functionalized via femtosecond laser surface processing for long term air film retention when submerged in liquid

Craig A. Zuhlke, Troy P. Anderson, Pengbo Li, Michael Lucis, Nick Roth, Jeffrey E. Shield, Benjamin Terry, Dennis R. Alexander, Univ. of Nebraska-Lincoln (United States)

Femtosecond laser surface processing (FLSP) is a powerful technique that can be used for surface texturing metals on the micro- and nano-scales and can be utilized to modify the wetting properties of a surface. Through FLSP we have demonstrated the ability to change the wetting properties of various metals, including titanium and stainless steel, creating surfaces that range from superhydrophobic to superhydrophilic depending on the processing conditions. Using FLSP, a superhydrophobic surface has been demonstrated that can retain an air film between the surface and a surrounding liquid when completely submerged. Surfaces that can retain an air film when submerged have many promising applications ranging from drag reduction to antibiofouling by creating a boundary between fouling agents and the sample surface. One of the greatest challenges to the application of superhydrophobic surfaces for biofouling applications is the limited lifetime of the generated air film. Air films on insects submerged in water have been observed by other research groups to be stable for several months, but engineered surfaces have resulted in much shorter lifetimes. However, we have demonstrated stability of an air film when submerged in water for an extraordinary 44 days on stainless steel 430 functionalized using FLSP. We have also demonstrated short term stability of an air film when submerged in synthetic stomach acid. Through early studies, we have shown that the air film lifetime is critically dependent on the specific degree of surface micro- and nano-roughness, which can be tuned by controlling various parameters used during FLSP.

9351-20, Session 4

Influence of pulsed Nd3+: YAG laser beam profile and wavelength on micro-scribing of copper and aluminum thin films

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Evenly spaced conductive grids of copper and aluminum thin films on polyamide substrate are used for parabolic reflector-antennas, aboard telecommunications satellite. In the present paper, laser micro scribing of thin films using a flat-top and Gaussian laser beam profile are analyzed with 95% overlapping of the diameter of the laser spot. Laser scribing is performed using the Q-switched Nd3+: YAG (532, 355 nm) laser. The influence of laser irradiation and beam shape are experimentally analyzed using non-contact optical profilometer, scanning electron microscope and Energy dispersive X-Ray analysis. Optical profilometer studies show that the depth of ablation increased by 40% for flat-top compared to Gaussian profile for 532 nm. By increasing laser irradiation, material removal rate increases for flat-top profile as the preliminary contact area is more. Using Gaussian profile the probability of melting is greater than vaporization; this melt pool absorbs the laser energy, preventing it from reaching the next layer thus re-solidification also plays a prominent role. The response of aluminum and copper for high fluences is also studied. Theoretical modeling of the laser-material interaction using Comsol mulitphysics software will be discussed. Similar analysis is being studied for 355nm under different ambient conditions.

9351-21, Session 4

Effects of burst mode on transparent materials processing

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In order to induce non-linear effects in transparent materials multi photon processes are required to bridge the photonic bandgap of dielectrics. Therefore femtosecond lasers providing pulse energies up to 50µJ and pulse durations well below 500fs are preferred for this application. However due to the poor absorption the major part of photons pass the dielectrics without interaction. In order to enhance energy deposition and thus process efficiency the time between consecutive laser pulses needs to be shorter than the electron relaxation time in the lattice. With high repetition rate fiber lasers burst mode operation with inter pulse durations below 20 ns are possible. Within the current investigation we study the influence of bust mode operation of up to 10 pulses within a burst on the absorption and ablation behavior of selected materials like fused silica, optical grade glass and sapphire. We will characterize the ablation efficiency as well as the obtained surface quality on line scribe protocol. We will further determine the influence of the repetition rate on process quality.

9351-22, Session 4

Laser processing of glass fiber reinforced thermoplastics with different wavelengths and pulse durations

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Fiber reinforced plastics offer a high lightweight construction potential to a wide range of applications because of their specific strength. For high volume applications fiber reinforced compounds with thermoplastic matrix are interesting because of the usability of inkjet molding for production.

The presented work addresses the processing of glass fiber reinforced thermoplastics with different laser sources. In the work the ablation behavior of laser systems with ps- and ns- pulse duration at infrared and green wavelength will be compared with CO2 processing with µs- pulse duration, which is classically used for polymer structuring. As matrix systems polypropylene and polyamide with natural and black color will be compared. For ultra-short laser processing a Fuego system with a fix pulse width of 10 ps is used. Maximum pulse energy at infrared is 150 µJ. The second system is a Datalogic laser MW-20DY from the "Multiwave" series. The pulse duration can be adjusted from 10 ns to 200 ns by an maximum pulse energy of 500 µJ. The CO2-laser is a SCx20 from Rofin Sinar with 400 µs pulse duration and up to 190 mJ pulse energy.

In the experiments the influence of energy intensity, pulse duration and wavelength on the processing characteristic of fiber reinforced materials is investigated. With this it is possible to identify the process conditions where selective matrix removal can be reached without ablating the reinforcing fibers and conditions where matrix and fibers are ablated in the same way. Outgoing from these results first applications will be presented.

9351-57, Session PTue

Extreme ultraviolet surface modification of biomaterials: A novel technique for biocompatibility control

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Micro- and nano-texturing on the surfaces of polymeric biomaterials influence the wetting and adhesive forces, that can be used to control the material biocompatibility for a given application. The conventional excimer laser and plasma-based surface modification techniques are prone to undesirable effects such as bulk alteration and unsustainability. In this study, a laser-plasma extreme ultraviolet (EUV) source based on a double-stream gas-puff target, irradiated with the 3 ns/0.8J Nd:YAG laser pulse at 10Hz is used for surface modification of polytetrafluoroethylene (PTFE) and polyvinyl fluoride (PVF). The source is able to irradiate large amount of energy (60 mJ/cm2 at the focal spot) in a spatially confined area at the upper layer surface due to limited penetration depth of EUV photons. Polymers can be irradiated in the presence or absence of an additional gas (such as nitrogen or argon) to get functional groups at the surface. The EUV modified surfaces have been characterized by Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), X-ray photoelectron spectroscopy (XPS) and water contact angle (WCA) measurement. The EUV irradiation resulted in formation of micro- and nano-patterning on the polymer surfaces. Such patterns provide sites for focal adhesion and increased the surface roughness up to many folds. The contact angle is increased up to 20 degrees making the surface more hydrophobic. Initial biocompatibility tests have been performed by in-vitro cell culture studies. L929 fibroblasts demonstrated strong cell adhesion and high viability on EUV modified polymer surfaces as compared to control samples.

9351-58, Session PTue

Research on femtosecond laser processing by using patterned vector optical fields

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On account of the growing interest in laser micromachining in insulators, semiconductors and metalsfor applications in nanoelectronic and micro devices, ultrashort pulsed laser ablation offers a superior means due to the minimization of the thermal effects and collateral damage. To improve the micromachining efficiency, multi-beam interference has been used to fabricate multi-microholes, two- and three-dimensional microstructures. However, this multi-beam interference is less flexibleand all the beams are still scalar fields which have spatially homogeneous distribution of polarization. Polarization, as an intrinsic and fundamental nature of light, provides more degrees of freedom and means to manipulate optical fields. So we present an approach for fabricating the multi-microholes, by using femtosecond (fs) patterned vector optical field (PVOF) composed of multiple vector optical fields (VOFs). In as much as the multiple VOFs could have arbitrary spatial arrangement and any individual vector optical field (VOF) could also have arbitrary spatial polarization distribution, such two degrees of freedom make the PVOF have the diversity. Consequently, the resultant diversity of the focal field patterns of the focused PVOFs is possible to fabricate various multi-microholes patterns.

9351-59, Session PTue

Laser micro-engineering of functionalised cyclic olefin polymers for microfluidic applications

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Direct-write laser processing has been demonstrated to be capable of both surface patterning of micro/nanoscale structures on polymer surfaces and the alteration of the surfaces' physical and chemical properties [1–3]. These alterations allow for control of surface wettability and optical transmission. Recently, liquid-phase pulsed laser ablation (LP-PLA) has been reported as a fast and adaptable method of nanoparticle production [4] while nanoparticle coatings have emerged as promising substrates for potential applications in biochemical separations and micro-total analysis systems [5]. When employed in conjunction with laser micro-fabricated polymer substrates, these nanoparticle coatings have the potential for functionalization of laser-engineered microfluidic devices.

In this work, 188 µm thin cyclic olefin polymer (COP) substrates were textured to create microchannels using a diode-pumped solid state (DPSS) Q-switched 1064nm Nd:YAG laser. The same laser was used to produce carbon nanoparticles in liquid suspension via LP-PLA. The viscosity of these suspensions was investigated to determine their suitability for spin coating and inkjet printing onto laser-textured COP substrates. Post-texturing surface characterisation was performed on the substrates using scanning electron microscopy (SEM) to examine the effects of laser-induced changes in surface morphology. Uniformity and repeatability of substrates post-coating was also examined using SEM. Changes in composition and optical properties as a result of both the laser-texturing and carbon nanoparticle coating were investigated using Fourier-transform infrared spectroscopy, UV-Vis and florescence spectroscopy. These results are discussed in the context of achieving surfaces optimised for microfluidic-based separations with optical detection.

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9351-60, Session PTue

Generation of laser-induced periodic surface structures in indium-tin-oxide thin films and two-photon lithography of ma-N photoresist by sub-15 femtosecond laser microscopy for liquid crystal cell application

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Indium-tin-oxide (ITO) is a widely used electrode material for liquid crystal cell applications because of its transparency in the visible spectral range and its high electrical conductivity. Important examples of applications are displays and optical phase modulators. We report on subwavelength periodic structuring and precise laser cutting of 150 nm thick indium-tin-oxide films on glass substrates, which were deposited by magnetron reactive DC-sputtering from an indium-tin target in a low-pressure oxygen atmosphere [1]. In order to obtain nanostructured electrodes laser-induced periodic surface structures with a period of approximately 100 nm were generated using tightly focused high-repetition rate sub-15 femtosecond pulsed Ti:sapphire laser light, which was scanned across the sample by galvanometric mirrors [2]. Three-dimensional spacers were produced by multiphoton photopolymerization [3] in ma-N 2410 negative-tone photoresist spin-coated on top of the ITO layers. The nanostructured electrodes were aligned in parallel to set up an electrically switchable nematic liquid crystal cell. The optical and electrical properties of the cell as well as its performance as a polarization rotator were characterized.

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9351-61, Session PTue

Tribological performance of near- and sub-wavelength femtosecond laser-induced periodic surface structures on titanium

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Laser-induced periodic surface structures (LIPSS) were generated by irradiation of titanium with linear polarized femtosecond laser pulses (30fs, 790nm, 1kHz). The conditions were optimized for the generation of two different types of nanostructures with periods of ~600 nm (LSFL) and of ~100 nm (HSFL). The tribological performance of the LSFL/HSFL-covered surfaces was characterized under reciprocating sliding condition in different lubricants. The corresponding wear tracks were characterized by optical and electron microscopy. For specific conditions, a reduction of the friction coefficient was observed and the LIPSS endured the treatment, indicating the benefit of laser surface structuring for tribological applications.

9351-62, Session PTue

Investigation of double-pulse femtosecond laser induced breakdown spectroscopy of polymethyl methacrylate (PMMA)

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The emission properties of double-pulse (DP) over single-pulse (SP) femtosecond laser breakdown spectroscopy (FLIBS) of polymethyl methacrylate (PMMA) were investigated. The signal enhancements in the DP-FLIBS strongly depend on the DP delay and influenced by the type of emission particles. Intensity enhancement of emission lines decreases in sequence of ions, neutral atoms, and molecules. Electron density and temperature were reported to describe the plasma. They exhibit similar variation trajectories with respect to the DP delay and show a distinct increase of electron density and plasma temperature at an optimal DP delay of ~80 ps, indicating reheating of pre-plume is responsible for the emission enhancement. The effect of laser energy on the signal enhancement was also studied, showing higher energy produces higher enhancement factor and further revealing the reheating mechanism behind signal enhancement.

9351-63, Session PTue

High performance light trapping structures for Si-based photoelectronics fabricated by hybrid picosecond laser irradiation and chemical corrosion

Lingfei Ji, Xiaozhan Lv, Yan Wu, Zhenyuan Lin, Yijian Jiang, Beijing Univ. of Technology (China)

Light collection efficiency is an important factor that affects the performance of many optical and optoelectronic devices. We propose the fabrication of various high performance texturized antireflective structures on crystalline (100) silicon (c-Si) surface by hybrid picosecond laser scanning irradiation followed by chemical corrosion. The design and the fabrication with high controllable performance were studied. The hybrid method includes 1064nm picosecond (ps) laser scanning to form micro-hole array and subsequently short-time alkaline corrosion. After ps laser processing, there is no reconsolidation and heat affect zone on the silicon surface, which is beneficial to achieve the precise chemical corrosion effect. Depending on the laser scanning intervals, scanning times and chemical corrosion time, a variety of surface texture morphologies, even a special micro-nano hierarchical structure in which finer nano-structures formed in the micro units of the texture, were achieved. Observing with SEM, the average diameter of the micro-holes in the micro-nano hierarchica is 25~30 ? m, while the average size of the nano-level ladder-like structures on the micro-hole wall is from dozens to hundreds of nanometers. Comparing to the traditional laser texturing techniques for c-Si solar cell, the whole laser processing was carried out in an open air ambient without the use of etch mask and SF6/O2 plasma. The results show the reflectance value of the c-Si surfaces with the hybrid laser-chemical fabrication can reach as low as 8%?350 nm~1000 nm?of incident light without any antireflective

coating. This is a potential method for economical antireflective structures fabrication which is ideal for using in the high-efficiency silicon-based photoelectronic devices.

9351-64, Session PTue

Laser-induced controlled crystallization of heavy metal oxide glass

Juliana M. P. Almeida, Paulo Henrique D. Ferreira, Antonio C. Hernandes, Cleber R. Mendonça, Univ. de São Paulo (Brazil)

Glass-ceramics are glassy materials that experienced devitrification, usually achieved by a heating process in the presence of nucleating agents. Due to its good thermomechanical properties and biocompatibility, the application of glass-ceramics has been focused on cookware and bone implants. However, new functionalities can be reached if the devitrification was spatially controlled. In this sense, femtosecond laser micromachining has been a powerful technique, since materials properties can be changed with high spatial precision. Fs-laser pulses affect mainly the refractive index of glass, and phase transformation has been barely exploited. In this study, we have used fs-laser micromachining to induce surface crystallization of heavy metal oxide glass for the development of microdevices. Such technique enables controlling not only the phase transformation at micrometer scale, but also its kinetics of crystallization.

We have first studied the third order optical nonlinearities of 50B2O3-50PbO (mol %). Its glass transition temperature is 318 °C and no crystalline phase was observed over the heating up to 600 °C. The glass was micromachined with a Ti: Sapphire laser, operating at 5 MHz with pulses of 50 fs at 800 nm. The laser pulses were focused on the sample surface through a microscope objective, while the sample was moved by a xyz stage at constant speed. After a chemical etching in aqueous solution of KOH, crystals of PbO were observed only in the irradiated regions. Depending on the experimental conditions, ?- or ?-PbO can be preferentially grown on the glass surface. In addition, by changing the number of incident laser pulses it is possible to write a polycrystalline structure or obtain a single crystal. The control of the crystalline phases as well as its crystallization kinetics using direct laser writing has enabled new applications for glass-ceramics, as the development of photonic crystals.

9351-65, Session PTue

Electrochemical and kinetic studies of ultrafast laser structured LiFePO4 electrodes

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Due to a growing demand of cost-efficient lithium-ion batteries with an increased energy and power density as well as an increased life-time, the focus is set on intercalation cathode materials like LiFePO4. It has a high practical capacity, is environmentally friendly and has low material costs. However, its low electrical conductivity and low ionic diffusivity are major drawbacks for its use in electrochemical storage devices or electric vehicles.

By adding conductive agents, the electrical conductivity can be enhanced. By increasing the surface of the cathode material which is in direct contact with the liquid electrolyte the lithium-ion diffusion kinetics can be improved. Nevertheless, a decrease of the active material particle size leads to a decrease of the active particle packing density. Furthermore, a higher amount of carbon black is needed to ensure a proper electrical conductivity in the electrode layer.

A new approach to increase the surface of the active material without changing the active particle packing density or the weight proportion of carbon black is the laser-assisted generation of 3D surface structures in electrode materials.

In this work, ultrafast laser radiation was used to create a defined surface structure in LiFePO4 electrodes. It was shown that by using ultrashort laser pulses instead of ns laser pulses, the ablation efficiency could be significantly increased. Furthermore, melting and debris formation were reduced.

To investigate the diffusion kinetics, electrochemical methods such as cyclic voltammetry and galvanostatic intermittent titration technique were applied. It could be shown that due to a laser generated 3D structure, the lithium-ion diffusion kinetic, the capacity retention and cell life-time can be significantly improved.

9351-66, Session PTue

Nanosecond laser-induced nanostructuring of thin metal layers and dielectric surfaces

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Nanostructures have a widespread field of application. Here, the nanosecond laser-induced nanostructuring of thin metal layers on dielectric surfaces as well as the fabrication of nanostructures into dielectric surfaces using a laser-induced self-organised molten metal layer deformation process are considered. A low laser fluence irradiation of a thin metal layer on dielectric surfaces results in a melting and nanostructuring process of the metal layer and partially of the dielectric surface. The resultant structures can be controlled by the used laser parameters (laser fluence, number of laser pulses, lateral laser beam profile). This allows inter alia the fabrication of well-defined circular ring structures into the dielectric surface. Applying lateral modulated laser beam profiles allows the fabrication of periodic structures assisted by a guided molten layer deformation process. Furthermore, a subsequent high laser fluence treatment of the metal nanostructures allows the transfer of the lateral geometry of the metal nanostructures into the dielectric surface. The resultant structures, dependent on the metal layer thickness and the laser parameters, were investigated by atomic force (AFM) and scanning electron microscopy (SEM). This method allows the easy, large-scale, fast, and cost-effective production of randomly distributed and periodic metal nanostructures as well as dielectric surface nanostructures with a lateral dimension down to 10 nm. However, for an optimization of this process a profound physical understanding is necessary. For this the process was simulated and the simulation results were compared with experimental ones.

9351-67, Session PTue

Structural dependence and mechanisms of LIPSS formation at a step edge due to single-pulsed femtosecond laser irradiation

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The origin of laser induced periodic surface structures (LIPSS) is still a developing research topic due to the complexity of its mechanisms. We fabricated gold mesas on silicon substrates to serve as a controllable environment for the generation of surface plasmon polaritons (SPP) and near-field diffraction by femtosecond laser irradiation. The steep discontinuity at the mesas' edge produces well-defined LIPSS on gold and silicon surfaces with a single pulse. We observed LIPSS with wave vector perpendicular to the step-edge regardless of polarization orientation.

Two mechanisms of LIPSS formation are proposed: For beam polarization perpendicular to the mesas' edge, LIPSS formation is driven by excitation of SPP. For beam polarization parallel to the mesas' edge, the LIPSS pattern is weaker and has a larger frequency distribution. We believe the periodic electromagnetic fields on the surface responsible for the resulting structures are caused by near-field diffraction.

Electromagnetic finite-element calculations will be presented that show surface plasmons coupling to the gold mesas for perpendicularly polarized light. The plasmons intensity varies depending on mesas' height, which is weakest at multiples of half the beam wavelength due to phase matching conditions at the step discontinuity. We will present experimental results of gold mesa irradiation of various heights that support the model. For parallel polarization, the periodic electromagnetic field amplitude on silicon increases for taller mesas, which is confirmed by stronger LIPSS in the experiments. The results provide further evidence for the occurrence of both mechanisms during LIPSS formation.

9351-68, Session PTue

Laser based microstructuring of polymer optical fibers for sensors optimization

Loukas Athanasekos, National Hellenic Research Foundation (Greece); Miltiadis Vasileiadis, Univ. of Patras (Greece); Alexandros El Sachat, National Hellenic Research Foundation (Greece) and Catalan Institute of Nanoscience and Nanotechnology (Spain); Nikolaos A. Vainos, Univ. of Patras (Greece); Christos Riziotis, National Hellenic Research Foundation (Greece)

A detailed study on Polymer Optical Fibers' -POFs' material interaction with ArF excimer laser at 193 nm was performed revealing interesting results in the engineering of sensors' development. Laser parameters, such as fluence, power, and repetition rate were evaluated and optimized for their effect on ablation characteristics. The difference in fluorinated polymer, i.e. cladding material, and pure PMMA, i.e. the core material, upon laser illumination was investigated and also the laser irradiation effects were dynamically studied by on-line monitoring of the induced guiding losses. Study of SEM images of fabricated structures revealed the mechanism and also the threshold where the cladding is separated or ejected from the core allowing thus controllable access to fibers' core. The observed single-pulse ablation fluence thresholds were found to be 121 mJ/cm2 for the cladding and 101 mJ/cm2 for the core. Furthermore, the behavior of created microcavities on POF surface as material receptors for photonic sensors was studied towards ammonia and humidity sensing drawing useful conclusions correlating the ablation induced loss and sensor's sensitivity. Furthermore it was found that the transverse -to the fiber axis- grooves were found to be more effective in humidity sensing, as they induce a more drastic perturbation in optical propagation allowing thus the interaction of more propagating and cladding/radiation modes with the environment. The rapid prototyping of POFs with the use of relatively low cost -as compared to femtosecond laser units- and compact table top excimer laser units with remarkable operational stability make them a cost-efficient rapid prototyping tool for the development of POF based customized sensors.

9351-70, Session PTue

The development of enhanced flexible PET substrate using picosecond laser scribing

Min Gi Kang, Seung Sik Ham, Tae Dong Kim, Sung Yeol Kim, Yong Joong Lee, Ho Lee, Kyungpook National Univ. (Korea, Republic of)

No Abstract Available

9351-23, Session 5

Ultrafast laser processing for mobile display *(Invited Paper)*

Eric P. Mottay, Amplitude Systèmes (France); Jiyeon Choi, Korea Institute of Machinery & Materials (Korea, Republic of); Rainer Kling, ALPhANOV (France)

Displays are key components of many of today's mobile electronic devices such as smartphones, digital cameras, mp3 players, etc. As the market for mobile electronics expands, displays are required to fulfil more and more challenging requirements for power consumption, image quality and definition, as well as robustness. The development of new display technologies, such as organic LEDs and flexible displays, put stringent requirements in terms of manufacturing processes. Ultrafast lasers allow non-thermal ablation of materials, which accounts for high precision interaction. We report on new results aiming at improving processing quality and yield.

Femtosecond lasers allow non-thermal ablation of materials, owing to the extremely short interaction time of the laser-matter interaction. We will report on two crucial processes in display manufacturing: i) selective removal of multi-layer organic materials and ii) ultra-precision drilling and cutting.

9351-24, Session 5

Dynamic optics in laser fabrication *(Invited Paper)*

Patrick S. Salter, Martin J. Booth, Univ. of Oxford (United Kingdom)

Laser material processing with short pulsed laser beams has been widely used for the fabrication of devices such as artificial bandgap materials, microfluidic devices, metal nanostructures and photonic devices based upon embedded waveguides. Structures are created by focusing the laser into the material where multi-photon absorption and/or avalanche effects cause permanent material changes in the focal region. We present advances using dynamic optical elements (DOEs) – deformable mirrors and liquid crystal spatial light modulators – to bring extra degrees of control to the laser fabrication system. The methods include aberration correction, parallelization and spatial control over the temporal intensity profile of the pulse. The fidelity of fabrication in laser processing depends strongly on the focal spot quality, which in many cases is impaired by aberrations. Aberrations lead to a deviation from the desired focal energy distribution, in particular an elongation along the optic axis, and a reduction in its intensity. DOEs are useful in removing aberrations and restoring diffraction limited performance. We explore experimentally and theoretically the range of aberration that can be realistically compensated by a particular DOE. Often, it is possible to correct aberrations up to the working distance of the objective, at which point the remaining dynamic range of the DOE can be employed for parallelisation of the fabrication process. We also examine how DOEs not only modify the phase front of the incident light, but for ultrashort pulses can additionally influence the temporal intensity profile of the pulse with spatial resolution.

9351-25, Session 5

Metal deep engraving with high average power femtosecond lasers

Rainer Kling, Marc Faucon, Girolamo Mincuzzi, ALPhANOV (France); Franck Morin, Clemens Hönninger, Eric P. Mottay, Amplitude Systèmes (France)

Deep engraving of 3d textures is a very demanding process for the creation of master tools e. g molds, forming tools or coining dies. As theses masters are uses for reproduction of 3D patters the materials for the tools are typically hard and brittle and thus difficult to machine. The new generation of industrial femtosecond lasers provides both high accuracy engraving results and high ablation rates at the same time. Operation at pulse energies of typically 40 μJ and repetition rates in the Mhz range the detrimental effect of heat accumulation has to be avoided. Therefore high scanning speeds are required to reduce the pulse overlap below 90%. As a consequence scan speeds in the range of 30-50 m/s a needed, which is beyond the capability of galvo scanners. In this paper we present results using a combination of a polygon scanner with a high average power femtosecond laser and compare this to results with conventional scanners. The effects of pulse energy, repetition rate and scan speed of the head on geometrical accuracy are discussed. The quality of the obtained structures is analyzed by means of 3D surface metrology microscope as well as SEM images.

9351-26, Session 5

Bessel filamentation in glass

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Glass processing is an important technological problem since this class of material generates an increasing number of applications (solar calls, flat panel displays, microfluidics, optofluidics). In this context, the ability of femtosecond laser pulses to deposit energy in the bulk of transparent material is an important benefit for drilling, cleaving or index writing. At high intensities, femtosecond pulses in glass undergo Kerr self-focusing and interact with laser-generated free-electron plasma. Gaussian beams usually undergo strong spatio-temporal distortions during propagation in dielectrics.

We investigate the propagation dynamics of Bessel filaments. They exhibit a regime that is distortion-free even at high intensity. To develop applications, it requires thorough comparisons between experiments and simulations. We have developed a novel 3D beam imaging technique allowing for direct and quantitative comparison between numerical and experimental beam fluence distributions in glass. We also report on the domain of existence of stationary femtosecond Bessel beams in dielectrics and the emergence of instabilities from studies both in near and far field. Applications to femtosecond laser processing will be reported.

9351-27, Session 5

Metal mirrors with metal-dielectric HR-coating for ultrashort lasers pulses applied in scanner applications

Mark Schuermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Christian Franke, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany); Sandra Müller, Stefan Risse, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Helena Kaemmer, Felix Dreisow, Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany); Ramona Eberhardt, Norbert Kaiser, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Metal mirrors with excellent optical, mechanical and thermal properties are applied for a broad spectrum of modern optical systems like telescopes, spectrometers or scanners. An important advantage in comparison with glass-, glass-ceramics and ceramic-mirrors is the easy and cost-efficient manufacturing technology.

Ultraprecise metal mirrors are therefore an attractive solution for opto-mechanical high-performance components for scanners working with ultrashortpuls lasers. Each ultrashort laserpuls has to be matched very precisely to the correct spot. In order to achieve very fast and precise positioning small mechanical inertia and a small mirror mass are required. The mirrors have to be very stiff and a high quality optical surface has to be provided. It will be shown that this can be achieved with ultraprecise machined lightweight AlSi-based mirrors with diamond-turned NiP polishable plating. The polishing results in a surface roughness lower than 1 nm rms, the amorphous NiP is thermal matched with the AlSi alloy better than 0.5 ppm.

Different coating options were evaluated in order to provide the necessary high reflectivity and a satisfactory laser damage threshold for ultrashort laser pulses in the few ps to fs regime at lambda = 1030 nm. It was found that metal-dielectric coatings exhibit similar or even higher laser damage thresholds than pure dielectric coatings and offer at the same time the advantage to be thinner than pure dielectric coatings. The coatings were deposited by magnetron sputtering. High-reflective metal layers enhanced by dielectric HfO_2/SiO_2-stacks were found to be the most advantageous coating option due to their comparably small thickness and measured damage thresholds above 1 J/cm2@10ps. These coatings are suitable for the deposition onto mirrors for scanner applications.

9351-28, Session 6

Ultrashort pulse laser processing of glass: From cutting to welding *(Invited Paper)*

Stefan Nolte, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer Institute for Applied Optics and Precision Engineering (Germany)

Ultrashort laser pulses have shown a tremendous potential for precise microstructuring. Especially, the possibility to realize three-dimensionally localized modifications within the bulk of transparent materials has attracted increasing interest in the past years. When intense ultrashort pulses are tightly focused into the transparent material, the intensity in the focal volume can become high enough to initiate nonlinear absorption processes. This localized energy deposition results in permanent structural changes inside the sample without affecting the surface. However, apart from the focusing conditions especially nonlinear propagation effects as well as incubation and accumulation effects are responsible for the size and shape of the interaction volume. Tailoring the energy deposition allows to realize various applications.

In this presentation a short overview on the fundamentals of ultrashort pulse volume structuring will be given. Special attention is paid to the cutting of (hardened) glass. Here, elongated modifications are induced inside the bulk material to define the contour for glass separation. An analysis of the temporal and spatial evolution of the absorption profile will be given based on pump-probe measurements.

A completely different kind of modification can be obtained, when ultrashort laser pulses at high repetition rates are applied. In this case heat accumulation from successive pulses leads to localized melting. If the focal spot is placed directly at the interface of two transparent substrates, this local point heat source can be used to weld even different glasses with dissimilar thermal expansion coefficients together. The parameters influencing the bond stability will be discussed.

9351-29, Session 6

Design and fabrication of sub-wavelength annular apertures for femtosecond laser machining

Kuan Yu Hsu, Yen Chun Tung, Ming-Han Chung, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

Optical micromachining technology is gaining popularity over the years. In laser micromachining, focal spot sizes and depth of focus (DOF) are two of the most important parameters for micromachining outcomes. The focal spot size determines the minimum features can be fabricated. However, in traditional optical systems, focal spot size is inversely proportional to DOF. That is, if the focal spot size gets smaller, the DOF is shorter. This situation got worse for sub-micrometer spot size as the DOF of the emitted light beam will be limited to tens of nanometers in most cases, which is difficult for most of the mechanical alignment. Furthermore, it was identified that hot work of traditional laser machining has disadvantages such as formation of burrs and surface roughness. These disadvantages will seriously influence accuracy of micromachining. This is the main reason that 780 nm femtosecond laser is adopted in our experiments. The sub-wavelength annular aperture (SAA) is adopted due to its potential to generate Bessel light beam when illuminated by laser beam. To optimize the system performance, the parameters associated with the transmittance efficiency associated with the SAA structure for 780 nm femtosecond laser was optimized by using finite difference time domain simulations method. A lateral microscope modified from traditional microscope was developed to facilitate the optical energy distribution of the emitted light beam to be used for laser machining. The results obtained from performing the processes on silicon, PCB board, and 80% transmittance glass were demonstrated to examine the suitability of using femtosecond laser and SAA to create high aspect ratio structures.

9351-30, Session 6

Enhancing direct laser patterning of Si wafers by polystyrene films

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Interferential irradiation of high power laser pulses can produce arrays of periodic nanostructures on surfaces. Patterning Si wafers directly by high power laser pulses indicates that the trench depth is limited to the laser pulse intensity. Thin polymer films can enhance the laser ablation selectively at the interference maxima area because the enhanced absorption of light due to the polymer capping layer. We present our recent studies on direct laser patterning of polystyrene coated Si wafers, which are irradiated interferentially by high power laser pulses Polystyrene films were formed on silicon wafers with thickness controlled based on a previously developed method. Interferential irradiations of laser pulses are applied on the polystyrene coated Si wafer. The laser pulse intensities are varied along with other interferential parameters such as interference angle and laser wavelengths of 532, 355, and 266nm. The polystyrene film is dissolved to expose the patterned Si surfaces. Atomic force microscopy (AFM) images from the patterned Si surfaces indicate that the area covered with the films has trenches deeper than those on bare Si wafers patterned at the same laser intensity. Furthermore, studies of AFM images suggest that the polystyrene films can be used to modify the surface morphologies of the laser patterned strips. The impact of polystyrene film thickness will be discussed along with the other interferential parameters. The enhancement and modification due to polymer films may enhance the security features by enhancing the quality of holograms.

9351-31, Session 7

Present status and future outlook of selective metallization for electronics industry by laser irradiation to metal nanoparticles *(Invited Paper)*

Akira Watanabe, Tohoku Univ. (Japan)

Recently an alternative to conventional methods based on vacuum processes such as evaporation or sputtering is desired to reduce the energy consumption and the environmental impact. Printed electronics has been developed as a one of the candidates, which is based on wet processes using soluble functional materials such as organic semiconductors, inorganic nanomaterilas, organic-inorganic hybrids, and so on. Although inkjet printing has been studied widely as a core technology of printed electronics, the limitation of resolution is around 20 micrometer. Other selective metallization process is necessary because the resolution of several micrometers is required in some optical and electrical devices. The laser processing has emerged as an attractive technique in microelectronics because of the fascinating features such as high resolution, high degree of flexibility to control the resolution and size of the micro-patterns, high speed, and a little environmental pollution. In this paper, the present status and future outlook of selective metallization for interconnection, the alternative of metal plating, and formation transparent conductive film based on the laser processing using metal nanoparticles are presented. The laser beam irradiation to metal nanoparticles causes the fast and efficient sintering by plasmon resonance of metal nanoparticle, where the absorbed energy is confined in a nanoparticle and the nanoparticle acts as a nano-heater. The laser irradiation to metal nanoparticles were applied to the laser direct writing of metal wiring, selective gold coating on a copper substrate, and micropatterning of a transparent conductive film such as an indium thin oxide.

9351-32, Session 7

Laser nanofabrication for functional devices *(Invited Paper)*

Hong-Bo Sun, Jilin Univ. (China)

Femtosecond laser direct writing (FsLDW) has been established as a nano-enabler to solve problems that are otherwise not possible in diversified scientific and industrial fields, because of its unique three-dimensional processing capability, arbitrary-shape designability, and high fabricating accuracy up to tens of nanometers, far beyond the optical diffraction limit. This talk will introduce novel laser nanofabrication technologies and their applications on fabrication of functional devices in microelectronics, micromechanics, microoptics and microfluidics.

9351-33, Session 7

Laser forward transfer of solder paste for microelectronics fabrication

Scott A. Mathews, Heungsoo Kim, Nicholas A. Charipar, Alberto Piqué, U.S. Naval Research Lab. (United States)

The progressive miniaturization of electronic devices requires an ever-increasing density of interconnects attached via solder joints. As a consequence, the overall size and spacing (or pitch) of these solder joint interconnects keeps shrinking. When the pitch between interconnects decreases below 200 μm, current technologies, such as stencil printing, find themselves reaching their resolution limit. Despite the benefits of miniaturization strategies such as Chip Scale Packaging (CSP) that aim to achieve assembly at the wafer level, small dimension printing of solder paste has forced semiconductor manufacturers to investigate other techniques beyond stenciling. However, all the techniques considered so far, such as electroplating, evaporation, solder jetting and drop-on-demand, tend to be more expensive, take more time and struggle with the accurate placement of reduced volumes of solder paste over a small interconnect pad. Laser direct-write (LDW) techniques based on laser-induced forward transfer (LIFT) of functional materials offer unique advantages and capabilities for the printing of solder pastes. At NRL, LIFT processes have been applied to the transfer of solder paste voxels with diameters under 100 μm with high precision over various types of substrates and interconnect pads. The LIFT process works best with small particle size solder pastes, such as the ones developed for Ultra-Fine Pitch (UFP) applications with 5 – 15 μm particle size distribution, known as Type 6 in the microelectronics industry. Higher resolutions are expected with smaller particle size solder pastes such as Type 7 (2 – 11 μm). This paper will show the results obtained with LDW of solder pastes and describe how this highly adaptable digital microfabrication processes is ideal for UFP printing of solder paste for CSP applications. Examples of results obtained so far together with specific applications will be discussed.

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9351-34, Session 7

Local nitrogen doping in 4H-SiC by laser irradiation in atmospheric-pressure plasma

Ryota Kojima, Hiroshi Ikenoue, Yousuke Watanabe, Akihiro Ikeda, Daisuke Nakamura, Tanemasa Asano, Tatsuo Okada, Kyushu Univ. (Japan)

We have proposed a novel method of nitrogen doping into 4H-SiC(0001) induced by KrF excimer laser irradiation in nitrogen plasma at atmospheric pressure. The 4H-SiC sample was a p-type epitaxial layer/n+-type 4H-SiC(0001) substrate. The laser with pulse duration of 55 ns was used as a local heating source on the SiC surfaces. Wavelength of the laser was 248 nm, and beam size on the SiC surface was 350 um*150 um. Irradiation fluence was 3.5 J/cm^2-4.6 J/cm^2, and the number of shots was from 1 shot to 5 shots. The nitrogen plasma was produced by applying AC voltage of 8.5 kV to plasma electrodes, and flow rate of nitrogen gas was 5 L/min.

After laser irradiation at the irradiation condition of 3.2 J/cm^2 and 1 shot, pn-junction diode characteristics were clearly observed in IV curve, which was measured between the laser irradiation region and a p-type epitaxial layer region (non-irradiation region). The diode had a large on/off ratio of over 7 orders of magnitude and long reverse recovery time of 100 ns. In addition, the ideal factor n of the diode was n=1.2. It is known that ideal factor reflects recombination of electron-hole pair at pn-junction. An ideal diode without recombination vacancies shows n=1, and ideal factor increases up to n=2 with increase of recombination sites at pn junction. Therefore, we conclude that local n-type doping into 4H-SiC substrate can be successfully achieved by KrF excimer laser irradiation in nitrogen plasma at atmospheric pressure.

9351-35, Session 7

Diffractive beam shaping for enhanced laser polymer welding

Jens Rauschenberger, Daniel Vogler, Christoph Raab, Ulrich Gubler, Leister Technologies AG (Switzerland)

Laser welding of polymers increasingly finds application in a large number of industries such as medical technology, automotive, consumer electronics, textiles or packaging. More and more, it replaces other welding technologies for polymers, e. g. hot-plate, vibration or ultrasonic welding. At the same rate, demands on the quality of the weld, the flexibility of the production system and on processing speed have increased.

Traditionally, diode lasers were employed for plastic welding with flat-top beam profiles. With the advent of fiber lasers with excellent beam, quality, the possibility to modify and optimize the beam profile by beam-shaping elements has opened.

Diffractive optical elements (DOE) can play a crucial role in optimizing the laser intensity profile towards the optimal M-shape beam for enhanced weld seam quality. We present results on significantly improved weld seam width constancy and enlarged process windows compared to Gaussian or flat-top beam profiles. Configurations in which the laser beam diameter and shape can be adapted and optimized without changing or aligning the laser, fiber-optic cable or optical head are shown. Besides the fixed DOEs etched into glass substrates, a quickly variable DOE based on a liquid crystal phase modulator array are presented for beam-shaping in laser polymer welding.

In addition, DOEs allow for customized contour shaping for one-shot welding processes. Any 2D contour can be welded in a mass production setting in a simultaneous process with short welding time and high flexibility. We present examples of 2D contour simultaneous welding suited for mass production with reduced welding times.

9351-36, Session 7

Laser sintering of silver nano-particle inks printed on paper substrates

Enkeleda Balliu, Henrik Andersson, Magnus Engholm, Mid Sweden Univ. (Sweden)

Printed electronics is an emerging field with a rapid development of applications. There is an increasing interest for using paper based substrates as it offers several benefits; e.g. it can be combined with the existing production processes within for example the packaging industry.

Sintering of metal nano-particle inks can be performed by using various methods such as e.g. heating, flash lamp, microwave, chemical, electrical and laser sintering.

In the present work we have investigated the use of laser sintering of ink-jet printed nano-particle inks (NPI) on paper substrates. Using paper substrates requires a sintering method that gives a low resistivity and at the same time leaves the paper substrate without damage. By optimizing the laser parameters, laser based sintering could offer a fast and non-destructive way to produce paper based electronics on a large scale. Several different laser sources (CW and pulsed) in combination with a galvo-scanning mirror system have been used and evaluated. The resulting resistivity of the laser sintered silver NPI structures is in the order of ~2.7*10-8 Ωm corresponding to ~60% conductivity to that of bulk silver. This can be compared to 4.7*10-7 Ωm when heated in a convection oven at 150 °C, the highest temperature the paper substrate can tolerate, and 3.1*10-8 Ωm for electrically sintered samples. Laser sintering is shown to be a promising method to sinter NPI on paper based substrates to a low resistivity and at a high speed suited for roll-to-roll (R2R) production processes.

9351-37, Session 8

Surface structuring of metals and non-metals for printing tools and embossing dies with an ultrafast ps-laser machining system *(Invited Paper)*

Stephan Brüning, Schepers GmbH (Germany); Guido Hennig, Daetwyler Graphics AG (Switzerland)

With roll-to-roll processes, millions of reproductions (e.g. RFID-antennas or Fresnel-lenses) can be produced in a fast and economical way. The processing of replica tools for such printing and embossing applications requires in many cases sub-µm and µm-structures. Ultra-short pulse lasers with ps- and fs-pulse durations and in single pulse or burst mode operation are appropriate tools to generate this micro- or nanostructures. In recent years the ongoing development of this laser sources and of fast beam delivery optics allows higher ablation rates combined with a superior quality for several materials like copper and brass as well as glass and dielectrics.

A 10 ps laser system at 1064 nm with a pulse repetition rate up to 8 MHz and pulse energies up to 50 µJ (at lower repetition rate) has been used in a cylinder micro processing system. This setup allows the micro structuring of cylinder surfaces as well as the processing of thin film substrate sheets up to a thickness of approximately 300 µm. Dimensions up to 7 m face length and circumferences up to 1,3 m could be processed with an accuracy of about 1µm. A variety of metals have been investigated by structuring 2D and 3D elements. The process is nearly melt-free, but the surface structure of the ablated zone depends on the sort of metal. The high fluencies enable the engraving of transparent materials which allow a much faster micro processing speed compared to metals. This work shows examples of micro-structuring melamine-resin and transparent acrylate coated cylinder surfaces.

9351-38, Session 8

Towards 3D laser nano patterning in polymer optical materials *(Invited Paper)*

Patricia J. Scully, The Univ. of Manchester (United Kingdom); Walter Perrie, Univ. of Liverpool (United Kingdom)

Progress towards 3-D subsurface structuring of polymers using femtosecond lasers, is presented. Highly localised refractive index changes can be generated deep in this transparent optical polymer, without pre doping for photo-sensitisation or post processing by annealing. Understanding the writing conditions surpasses the limitations of materials, dimensions and chemistry, to facilitate unique structures entirely formed by laser-polymeric interactions to overcome common materials, dimensional, refractive index and wavelength constraints.

Structuring, at low energies, since the low glass transition temperature, T¬g¬ of PMMA and low damage threshold intensity Ith, (10-1 of that of glass), enables creative use of the Energy Balance available per pulse, spatially confined to within the focal volume and temporally confined by the pulse length, rep rate and writing speed and accumulated number of overwrites into the same focal volume. This facilitates time and temperature dependent chemical reactions such as depolymerisation and chain scission. Micro-scanning Raman spectroscopy has been used to map chemical bond changes in photonic structures in PMMA, up to 500µm below the surface. Inscription at UV and IR wavelengths (775nm, 387nm) exploits different bandgaps and photochemistries.

Writing conditions change as a function of depth due to non-linear optical interactions. Chromatic aberration, self focusing and filamentation, cause written structures become elongated in the direction of beam propagation creating asymmetric structures such as elliptical cross-section waveguides. Control and correction of these effects using a spatial light modulator (SLM) is demonstrated. Non-linear aspects of multiphoton absorption and plasma generation and effects of SLM beam polarisation on writing conditions will be presented.

9351-39, Session 8

Direct laser interference patterning (DLIP) technique applied to the development of optical biosensors based on biophotonic sensing cells (bicells)

Francisco J. Sanza, Univ. Politécnica de Madrid (Spain) and Bio Optical Detection (Spain); Denise Langheinrich, Jana Berger, Fraunhofer IWS Dresden (Germany); Ana L. Hernández, Univ. Politécnica de Madrid (Spain); Ines Dani, Fraunhofer IWS Dresden (Germany); Rafael Casquel del Campo, Álvaro Lavin, Univ. Politécnica de Madrid (Spain); Álvaro Otón, Univ. Politécnica de Madrid (Spain) and Bio Optical Detection (Spain); Betxu Santamaría, María-Fe Laguna, Univ. Politécnica de Madrid (Spain); Andres F. Lasagni , Fraunhofer IWS Dresden (Germany); Miguel Holgado Bolaños, Univ. Politécnica de Madrid (Spain)

Biophotonic sensing cells (BICELLs) are transducers for optical biosensing based on photonic structures, mainly on periodic lattices of structures, e.g. pillars. It has been demonstrated in previous works, that the use of pillars of high aspect ratio, with dimensions in the order of hundreds of nanometers, can improve the sensitivity in the recognition of a concrete biomolecule.

Different fabrication techniques have been tested to produce these transducers. Though lithographic processes can produce structures of high quality, high resolution and scalable up to wafer scale, they involve the use of several fabrication steps that increase the complexity and cost of the final structure. Therefore, use of large area patterning using one fabrication step is preferred in order to develop cost-effective biosensors. Direct laser interference patterning (DLIP) technique, based on the interference of two high power laser beams, has demonstrated its capability to pattern large areas on different materials.

In this work, it has been investigated the feasibility of this technique to produce periodic lattices of pillars on crosslinked SU-8 for optical biosensing. Different geometries and substrates (Si, glass) have been used. Finally, it has been tested its capability as biosensor performing a standard BSA/aBSA immunoassay, comparing experimental results with simulated data.

9351-40, Session 8

To use or not to use (direct laser interference patterning), that is the question

Andres F. Lasagni, Teja Roch, Fraunhofer IWS Dresden (Germany) and Technische Univ. Dresden (Germany); Jana Berger, Technische Univ. Dresden (Germany) and Fraunhofer IWS Dresden (Germany); Tim Kunze, Fraunhofer IWS Dresden (Germany); Valentin Lang, Technische Univ. Dresden (Germany); Eckhardt Beyer, Fraunhofer IWS Dresden (Germany) and Technische Univ. Dresden (Germany)

Direct Laser Interference Patterning has shown to be a fabrication technology capable of producing large area periodic surface patterns on almost any kind of material. The produced periodic structures have been used in the past to provide surfaces with new advanced properties that can

be used to enhance their functions in applications such in photonics and sensor systems, tribology and biomaterials between others.

On the other hand, the industrial use of this technology is still at the beginning due to the lack of appropriate and affordable systems, especially for small and medium enterprises. Furthermore, depending on the application, several challenges concerning the quality or homogeneity of the produced patterns (e.g. overlap of structured area per laser pulse) have still to be addressed.

In this paper, the use of Direct Laser Interference Patterning (DLIP) for the fabrication of periodic surface structures using different structuring strategies as well as new developed optical concepts is discussed. Both, economic and technological challenges are addressed, showing the perspective of the DLIP Method for the next years. The analysis also includes the use of different laser systems (continuous wave or pulsed nanosecond, picosecond and femtosecond operating at different wavelengths) denoting their advantages and disadvantages. Finally, some application examples are described.

9351-41, Session 8

Fabrication of highly efficient transparent metal thin film electrodes using Direct Laser Interference Patterning

Sebastian Eckhardt, Fraunhofer IWS Dresden (Germany) and Technische Univ. Dresden (Germany); Lars Müller-Meskamp, Technische Universität Dresden (Germany); Markus Loeser, Mathias Siebold, Helmholtz-Zentrum Dresden-Rossendorf (Germany); Andres F. Lasagni, Fraunhofer IWS Dresden (Germany) and Technische Univ. Dresden (Germany)

The demand of highly efficient transparent electrodes without the use of rare earth materials such as indium requires a new generation of thin metallic films. For this purpose, Direct Laser interference Patterning was used to fabricate periodic hole-like surface patterns on thin metallic films in order to improve their optical transparency by selective laser ablation of the material at the interference maxima positions, and at the same time keeping the electrical properties at an acceptable level.

Metallic films consisting of Al, Cu, Cr and Ag with film thicknesses ranging between 5 and 40 nm were deposited on glass substrates using Physical Vapor Deposition (PVD).

In order to analyze the processability of the films, the laser ablation threshold for each material as function of the layer thickness was firstly determined. After analyzing these initial experiments, the samples were structured with µm-scaled holes using three beam direct laser interference patterning. The quality of the fabricated structures was analyzed as function of the spatial periods (from 1.5 to 5.0 µm) and the laser energy density (laser fluence).

Finally, the structured samples went through optical, topographical and electrical analysis processes using optical spectroscopy, atom force microscopy (AFM) as well as surface impedance measurements. A concept for large area surface structuring of metallic electrodes will be also introduced.

9351-42, Session 8

Role of the surface plasma density on the formation of laser induced periodic surface structures (LIPSS) on Ti upon double fs pulse irradiation

Laura Gemini, HiLASE Ctr. (Czech Republic); Masaki Hashida, Yasuhiro Miyasaka, Shunsuke Inoue, Kyoto Univ. (Japan); Jiri Limpouch, Czech Technical Univ. in Prague (Czech Republic); Tomas Mocek, HiLASE Ctr. (Czech Republic); Shuji Sakabe, Kyoto Univ. (Japan)

Laser induced periodic surface structures are nowadays of considerable interest in many application fields thanks to the current availability of large scale laser processing. Consequently, the possibility to readily foresee LIPSS interspaces from key process laser parameters, such as the laser fluence, is of great relevance. A parametric decay model has been proposed by Sakabe et al. and experimental results for several materials are in reasonable agreement with the model's predictions. According to the model's assumptions, the pre-formed plasma (PF-P) has a key role in the LIPSS formation mechanism. However, it is technically difficult to measure the composition of PF-P because its thickness is small and its density is also quite low. To confirm the possibility of PF-P generation in such a short time scale, we irradiated Ti surfaces with a femtosecond laser beam composed by double fs pulses. The fluence of the first pulse (FPP), responsible for surface plasma formation, and the fluence of the delayed pulse (FLP), responsible for LIPSS formation, were varied and always kept below and above the LIPSS formation threshold fluence, respectively. Regardless the specific fluence FLP, the LIPSS interspace increases with the increase of FPP. This tendency suggests that a variation of the surface plasma density actually leads to a modification of the grating features. The results confirm the possibility of surface plasma formation during the ultra-short interaction between the laser beam and the material and support the validity of the model as a handy tool for LIPSS features estimation.

9351-43, Session 9

Ultrafast laser processing and metrology for consumer applications *(Invited Paper)*

Naoki Murazawa, Kunimitsu Takahashi, DISCO Corp. (Japan)

No Abstract Available

9351-44, Session 9

Nanosecond laser-induced ablation and laser-induced shockwave structuring of polymer foils down to sub-µm patterns

Pierre Lorenz, Lukas Bayer, Martin Ehrhardt, Klaus-Peter Zimmer, Leibniz-Institut für Oberflächenmodifizierung e.V. (Germany); Lutz Engisch, Hochschule für Technik, Wirtschaft und Kultur Leipzig (Germany)

Micro- and nanostructures exhibit a growing commercial interest where a fast, cost-effective, and large-area production is attainable. Laser methods have a great potential for the easy fabrication of surface structures into flexible polymere foils like polyimide (PI) and polyethylene terephthalate (PET). In this study two different concepts for the structuring of polymere foils using a KrF excimer laser were tested and compared: the laser-induced ablation and the laser-induced shockwave structuring.

The direct front side laser irradiation of these polymers allows the fabrication of different surface structures. For example: The low laser fluence treatment of PI result in nano-sized cone structures where the cone density can be controlled by the laser parameter. This allows inter alia the laser fabrication of microscopic QR - code and high resolution grey-tone images. Furthermore the direct irradiation of PET results in the formation of periodic patterns. Due to the statistic nature of the both surface structure can be used for security application.

Furthermore, the laser treatment of the back side of the polymer foil allows the front side structuring due to a laser-induced shockwave where a mask-assisted laser embossing and a mask-less free forming can be applied.

The resultant surface structures was analyzed by optical and scanning electron microscopy (SEM) as well as white light interferometry (WLI).

9351-45, Session 9

Laser direct patterning of graphene on SiC(0001) surfaces by KrF excimer laser irradiation

Masakazu Hattori, Kyushu Univ. (Japan); Kazuaki Furukawa, Makoto Takamura, Hiroki Hibino, NTT Basic Research Labs. (Japan); Hiroshi Ikenoue, Kyushu Univ. (Japan)

We have proposed a novel direct patterning method of graphene on SiC(0001) surfaces by KrF excimer laser irradiation. In this method, Si atoms are locally sublimated from the SiC surface in the laser irradiation area, and graphene growth is induced by the rearrangement of surplus carbon on the SiC surface. The KrF excimer laser with a wavelength of 248 nm was used as a local heating source on the SiC surfaces. Pulse duration of the laser was 55 ns, and repetition rate was 1000 Hz. The laser shape was 6 um*300 um, and line-and-space (L&S) patterns were formed by step-and-repeat operation of scan and irradiation at scan pitch from 8 um to 20 um. From measurement results of Raman spectra, G and 2D band peaks of graphene were clearly seen in the spectrum in the irradiation area. Therefore, we conclude that micro-size L&S patterns of graphene can be successfully formed by KrF excimer laser irradiation. It is known that the intensity ratio of D and G bands (ID/IG) in Raman spectra reflects grain size of graphene. The ID/IG ratio was 0.6 at the irradiation condition of 1.2 J/cm2 and 10000 shots in the ambient Ar of 500 Pa. The grain size of graphene estimated from the ID/IG ratio was 23.7 nm. Thus, it is concluded that we found out possibility of micro-size direct patterning for high quality graphene formation.

9351-47, Session 10

Laser-printed lithium-sulphur micro-electrodes for Li/S batteries *(Invited Paper)*

Andreas Hintennach, Sarah Rosenberg, CGS (Germany)

A novel path for the preparation of electrodes for lithium-sulphur cells was developed using a very fast laser-printing setup for the direct and dry i.e., solvent-free transfer of electrode materials onto the current collectors. Model electrodes could be prepared at very small dimensions enabling these batteries to be used even in portable small devices. The initial specific charge was remarkably high at about 1300 Ah kg 1 (relating to the active material content of the electrode) with a loss of specific charge of about 75 % after about 400 cycles at 1C. In addition, the dry transfer technique has highly beneficial effects on the environmental sustainability and, therefore, supports the concept of the use of “green” power storage.

9351-48, Session 10

Analytical model of the laser ablation mechanism of lithium-Ion battery electrode coatings *(Invited Paper)*

Benjamin Schmieder, Manz AG (Germany)

In Lithium-Ion battery production many different active material coatings are used to serve the individual needs of the final product. Furthermore laser processing becomes the method of choice in the production to allow a maximum degree of freedom and reduce tooling costs. The used electrode coatings and its different components highly influence the laser process and its results in terms of quality and efficiency. To achieve a better understanding of the ablation mechanism high speed video recording was used to allow a more detailed observation of the cutting and ablation mechanism, respectively. Based on these insights an analytical model was created and verified by time resolved shadowgraph imaging and experimental determined laser ablation thresholds.

9351-49, Session 10

Laser-induced breakdown spectroscopy for chemical characterization of laser structured Li(NiMnCo)O2 electrodes for lithium-ion batteries

Peter Smyrek, Johannes Pröll, Hans J. Seifert, Karlsruher Institut für Technologie (Germany); Wilhelm Pfleging, Karlsruher Institut für Technologie (Germany) and Karlsruhe Nano Micro Facility (Germany)

Lithium-ion batteries require an increase in cell life-time as well as an improvement in cycle stability in order to be used as energy storage systems, e.g. for stationary devices or electric vehicles. Nowadays, several cathode materials such as Li(NiMnCo)O2 (NMC) are under intense investigation to enhance cell cycling behavior by simultaneously providing reasonable costs. Previous studies have shown that processing of three dimensional (3D) micro-features in electrodes using nanosecond and femtosecond laser radiation further increases the active surface area and therefore, the lithium-ion diffusion cell kinetics. Within this study, the lateral and bulk element distributions of unstructured and laser structured NMC cathodes were analyzed by Laser-Induced Breakdown Spectroscopy (LIBS). The main goal was to investigate the lithium distribution in laser structured NMC electrodes at different state-of-charges to develop an optimal 3D cell design with enhanced electrochemical cell properties. The results will be discussed with respect to debris formation and laser-induced material modification by using pulse durations ranging from 350fs up to 200ns. Variations in chemical composition of electrodes with different active material proportions (85wt.%-95wt.%) and thicknesses (75μm-130μm) were investigated. Experiments were carried out using a LIBS workstation (SNO13, SECOPTA, Germany) equipped with a diode-pumped solid-state laser (DPSS, ?=1064nm). The element distribution was investigated by using two different methods: element mapping at the structured electrode surface and element depth profiling down to the substrate. The lithium-ion cells were assembled in an argon-filled glove box using the Swagelok® design. The electrolyte was a mixture composed of ethylene carbonate and dimethyl carbonate (EC:DMC 1:1) with 1 M lithium hexafluorophosphate (LiPF6) as conducting salt. Battery tests were carried out and different state-of-charges within voltage windows of 3.0-5.0V were applied in order to determine the element distribution of unstructured electrodes as well as within 3D micro-features. Therefore, the lithium-ion cells were transferred into argon-filled glove-box after cycling for disassembling process. All cathodes were washed in DMC and dried under vacuum for subsequent LIBS studies.

9351-50, Session 10

Surface micro-structuring of intercalation cathode materials for lithium-ion batteries: A study of laser-assisted cone formation

Wilhelm Pfleging, Johannes Pröll, Peter Smyrek, Thomas Bergfeldt, Robert Kohler, Karlsruher Institut für Technologie (Germany)

Currently, strong efforts are undertaken in order to further improve the electrochemical performance of high energy lithium-ion batteries incorporating thick composite electrode materials. The properties of these

electrode materials such as active surface area, film thickness and film porosity strongly impact the cell life-time and cycling stability. A rather new approach is to generate hierarchical architectures in cathode materials by laser direct ablation as well as by laser-assisted formation of self-organized structures. It could be shown that appropriate surface structures can lead to a significant improvement of lithium-ion diffusion kinetics leading in turn to higher specific capacities at high charging and discharging currents.

In this paper, the formation of self-organized conical structures in intercalation materials such as $LiCoO2$ and $Li(NiMnCo)O2$ is investigated in detail. For this purpose, the cathode materials are exposed to excimer laser radiation with wavelengths of 248 nm and 193 nm leading to cone structures with outer dimensions in the micrometer range. The process of cone formation is investigated using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) and laser-induced breakdown spectroscopy (LIBS). Cone formation can be initiated for laser fluences up to 2 J/cm2 and a selective removal of lithium could be detected during the cone formation process. It could be shown that material re-deposition supports the cone-growth process leading to a low loss of active material. Besides the cone formation process, laser-induced chemical surface modifications will be discussed.

9351-51, Session 10

Femtosecond laser patterning of lithium-ion battery separator materials: Impact on liquid electrolyte wetting and cell performance

Johannes Pröll, Karlsruher Institut für Technologie (Germany); Bertram Schmitz, Treofan Germany GmbH & Co. KG (Germany); Axel Niemoeller, Bernd Robertz, Manfred Schäfer, Sihl GmbH (Germany); Maika Torge, Peter Smyrek, Hans J. Seifert, Karlsruher Institut für Technologie (Germany); Wilhelm Pfleging, Karlsruher Institut für Technologie (Germany) and Karlsruhe Nano Micro Facility (Germany)

High capacity lithium-ion batteries are composed of alternating stacked cathode and anode layers with thin separator membranes in between for preventing internal shorting. Such batteries can suffer from insufficient cell reliability, safety and electrochemical performance due to poor liquid electrolyte wetting properties. Within the electrolyte filling process, homogeneous wetting of cathode, separator and anode layers is strongly requested due to the fact that insufficient electrolyte wetting of battery components can cause limited capacity under challenging operation or even battery failure. The capacity of the battery is known to be limited by the quantity of wetting of the electrode and separator layers. Therefore, laser structuring processes have recently been developed for forming capillary micro-structures into cathode and anode layers leading to improved wetting properties. Additionally, many efforts have been undertaken to enhance the wettability and safety issues of separator layers, e.g. by applying thin coatings to polymeric base materials. In this paper, we present a rather new approach for ultrafast femtosecond laser patterning of surface coated separator layers. Laser patterning allows the formation of micro-vias and channel structures into thin separator membranes. Liquid electrolyte wetting properties were investigated before and after laser treatment. The electrochemical cyclability of batteries with unstructured and laser-structured separators was tested in order to determine an optimal combination with respect to separator material, functional coating and laser-induced surface topography.

9351-52, Session 11

Magnetic field-assisted laser micro machining

Hamid Farrokhi, Nanyang Technological Univ. (Singapore) and SysteMED Pte Ltd. (Singapore); Wei Zhou, Nanyang Technological Univ. (Singapore); HongYu Zheng, Singapore Institute of Manufacturing Technology (Singapore)

Applying a magnetic field on laser produced plasma (LPP) has broad applications in both basic and applied research due to its effect on the plasma dynamics. Beside the basic research, most of attempts in applied research have been conducted in the field of pulsed laser deposition (PLD) and laser welding, but hardly any studies can be found on magnetized laser micromachining of materials. We showed that an axial magnetic field (B ? target surface) slows down expansion of the LPP and prevents rapid decrease in the plasma electron/ion density and temperature. It can be used as a versatile tool to confine the LPP and to increase laser ablation depth, significantly. Using Si wafer as an instance, we increased ablation depth via laser irradiation (20ns, 112µJ, 30pulses) from 40µm in absence of magnetic field to around 90µm in the presence of 0.192T. This unprecedented improvement can make a breakthrough in the laser processing of hard-to-ablate materials, laser cutting and laser welding.

The laser used was UV laser system (? = 355 nm, f=1 kHz, and ? ≈ 20 ns). The magnetic field for this experiment was produced by a 385-turn copper coil, with a current passing through it. This coil system can produce a uniform magnetic field of 0.05 - 0.4 T along its axis. Si surface was irradiated by various laser pulses, without and with magnetic field. Morphological studies of ablated region were carried out by scanning electron microscope (SEM) and confocal microscope.

9351-53, Session 11

Nano-pulsed-CO2-laser drilling for glass and its absorption change during laser processing

Yosuke Watanabe, Hiroshi Ikenoue, Kota Yamasaki, Daisuke Nakamura, Tatsuo Okada, Kyushu Univ. (Japan)

We have developed the glass processing for micromachining by ns pulsed CO2 laser (Wavelength: 10.6 um, pulse duration: 13ns). In this report, firstly we mention the sucess at forming through hole with diameter phi60 ?m in 300 um thickness alkali-free thin glass and hole depth 200um with diameter phi40 ?m in quarz. Secondarily, we report increase of the absorption coefficient ? of quartz with the increase of average temperature during laser processing for micromachining. In order to keep averaged power, we changed fluence by controlling the repetition rate. So we considered heat-accumulation constant at the each averaged power and then calculated ? with respect to each averaged power. Number of shots was controlled by a mechanical shutter. The observation of ablated holes was performed by optical microscope measurement from side view. Target materials were quartz or PMMA. As for quartz, we noticed the trend that ? increases 2500[cm-1] to 20000[cm-1] with the power increasing 0.6W to 1.8W. As for PMMA, ? was approximately constant 2000[cm-1]. By comparison with PMMA, it was confirmed that ? of quartz changes significantly with changing the averaged power.

9351-54, Session 11

Investigation on the effect of ambient and beam profile in annealing and texturing of amorphous silicon thin films by pulsed Nd3+:YAG laser

Esther Blesso Vidhya Yesudasan, Nilesh J. Vasa, Sriram R., Indian Institute of Technology Madras (India)

Thin film solar cells are becoming important because of formation of tandem junctions and large scale manufacturability. Amorphous silicon (a-Si) thin films possess a larger band gap (1.7 eV) than crystalline silicon (1.1 eV). Hence, they absorb the visible part of the solar spectrum effectively and offer material saving. Laser annealing is used to modify a-Si and to induce crystallization to produce poly silicon films and improve photovoltaic efficiency. Simultaneous formation of texture reduces reflection and improves absorption by light trapping. A Q switched Nd3+: YAG laser, with the wavelength 532 nm and pulse duration 6 ns FWHM is considered. Laser annealing is performed with a Gaussian beam and flat-top beam profile on 400 nm and 1000 nm thick a-Si films deposited on c-Si. In order to induce annealing along with texturing of surface, laser beam overlap technique with a 95% spot overlapping is used. Experiments are perfomed in air and in water ambience. XRD peaks corresponding to poly-silicon thin film are observed with the Nd3+:YAG laser treatment. Surface profile with the treatment in the water medium shows increase in texture height. Currently, a-Si films with a wide area annealing and texturing are being studied. In theoretical simulation, thermal modeling is used and nanosecond laser induced annealing at a longer wavelength has been found to be suitable for crystallization of thick amorphous silicon films but results in heating the substrate also.

9351-55, Session 11

Reflectivity enhancement underwater caused by super hydrophobic polytetrafluoroethylene surface

Yijian Jiang, Wenshen Cao, Yan Zhao, Lingfei Ji, Beijing Univ. of Technology (China)

Micro-groove array structure on PTFE surface farbricated by optimal processing parameters and 25?m Scan interval, makes the static contact angle up to 156 °, induced a super-hydrophobic modification. Micro-column array structure PTFE farbricated by optimal processing parameters and 50?m scan interval, makes the static contact angle up to 153 °, induced a super-hydrophobic modification.For the micro-groove PTFE surface, if the groove wall thickness is 25 ?m, PTFE surface contact angle will get the maximum value of the optimal processing parameters. For the micro-column PTFE surface, if the column's length of side is 20.5 ?m, PTFE surface contact angle will get the maximum value of the optimal processing parameters.

It is fouund that If the superhydrophobic PTFE processed by picosecond laser is put into the water, the bright reflective light will be observed. We conclude that this phenomenon is caused by superhydrophobic surface enhancing visible light reflection underwater. The contrast experiments that we designed to prove super-hydrophobic PTFE underwater indeed produce visible light reflection enhancement.Because of the Cassie model that exists the air layer beneath the water ,it concludes phenomenon of visible light enhancement comes from the total reflection. Thermodynamic formula obtained the water cross-section in the micro-structure is an arc. And when the micro-groove slit width is 25 ?m, the depth h ≤ 57 cm, three-phase contact state can exist stable underwater, highly reflective phenomenon can be observed. Because the normal direction is differnent on each point of the arc, the incidence angle is less than the critical angle of total reflection can still be seen underwater.

9351-56, Session 11

Comparison of laser structuring of thin dielectrics using multiple laser sources

Adam R. Collins, National Univ. of Ireland, Galway (Ireland); David Milne, Camilo Prieto, M-Solv Ltd (United Kingdom); Gerard M. O'Connor, National Univ. of Ireland, Galway (Ireland)

Accurately structuring thin glass is of significant industrial interest due to the growing popularity of touch screen displays, microfluidic ,microoptic and photovoltaic applications. Glass has a good chemical resistance, high optical transparency and moderate flexibility for thicknesses below 200 ?m. The flexibility of thin glass offers an opportunity to substitute sheet-fed processing with a fully reel-to-reel process decreasing processing time significantly.

Lasers potentially offer a reconfigurable and versatile solution for structuring thin glass. Glass is a challenging material to laser process due to its transparency and brittleness. A clear understanding of the laser cut zone is lacking. Structuring thin glass with a 500fs IR laser source was investigated by the author previously. High quality scribes were produced in glass and a standard ablation rate (SAR) of 6.1 nl/J was found for a 50?m deep scribe. The orientation of the laser polarisation was shown to have a significant effect on the SAR (30%) and feature quality. This effect was attributed to the reduction in transmission through the scribe walls for S polarised light.

We propose a parametric study of laser SAR and feature quality for three laser sources, the previously mentioned 500fs IR laser, a 20ns UV laser and a 10?s CO2 laser. The standard ablation rate and feature quality for each laser will be examined, giving an insight into absorption and thermalisation mechanisms of the various lasers. Characterisation will be carried out using SEM, AFM and real time diagnostic techniques, with particular attention paid to the effect of laser polarisation.

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9352-1, Session 1

Laser-based synthesis of nanomaterials for heterogeneous catalysis and energy research *(Invited Paper)*

Philipp Wagener, Galina Marzun, Stephan Barcikowski, Univ. Duisburg-Essen (Germany)

Pure inorganic nanoparticles without ligands or stabilizers fabricated by laser ablation in liquid are promising materials for energy converting materials like heterogeneous catalysts or hydrogen storage materials. Especially in case of heterogeneous catalysts, common preparation techniques like impregnation or colloidal deposition are usually accompanied by extensive use of chemical precursors, stabilizers and ligands that may result in catalysts poising. In our recent work, we showed how to laser-fabricate colloidal stable and size-controlled nanoparticles made of catalytic active materials (e.g. Pt, Pd, Ni). These particles are supported to carrier structures like metal oxides and carbon allotropes for synthesis of heterogeneous catalysts. Using the model system of platinum nanoparticles and titania support, we demonstrate that the nanoparticle adsorption is dominantly controlled by electrostatic interactions. This attractive electrostatic interaction even overcompensates steric repulsion by various ligands attached to nanoparticle surface. In addition to electrostatic interactions, colloidal stability given by moderate ionic strengths and pH above isoelectric point of nanoparticles is a prerequisite for colloidal deposition. First tests of laser-generated nanomaterials proved its catalytic activity and application potential.

9352-2, Session 1

Laser-activated nanoparticles for biomedical applications *(Invited Paper)*

Roberto Pini, Fulvio Ratto, Francesca Rossi, Paolo Matteini, Francesca Tatini, Marella de Angelis, Lucia Cavigli, Sonia Centi, Istituto di Fisica Applicata Nello Carrara (Italy)

Laser-assisted tissue repair or laser welding has been proposed to close chronic accidental and surgical wounds. An exemplary application is in micro-vascular surgery for the repair of arterial wounds. To this aim we have recently engineered a hybrid bioadhesive consisting in a chitosan film doped with gold nanorods (GNRs) that can be activated by NIR laser light to induce a well-localized photothermal effect leading to the adhesion of the film with the arterial wall. The effectiveness of the patches to close arterial wounds, has been tested in vivo in preclinical studies in rabbits. Moreover, the combination of pulsed and CW near-infrared laser light with plasmonic particles is gaining relevance for the photoacoustic imaging and photothermal ablation of cancer. Selective targeting of malignant cells with these contrast agents may rely on complementary biochemical and biological strategies, including the use of specific probes or the exploitation of cellular vehicles. Here we moved from a platform of PEGylated GNRs with plasmonic NIR bands and we implemented different approaches for active delivery by functionalization with (i) antibodies against cancer antigen 125 (CA125), which is a common biomarker for ovarian lesions; (ii) inhibitors of carbonic anhydrase 9 (CAIX), which are expressed by hypoxic cells such as those found in solid tumors; and (iii) by introducing macrophages as a versatile model of cellular vehicles that would phagocytose the particles and home to inflammatory lesions. In vitro studies on cell cultures on those different approaches will be presented and discussed.

9352-3, Session 1

Catalytic Rh-based alloy nanoparticles by femtosecond laser irradiation of aqueous solution

Takahiro Nakamura, Tohoku Univ. (Japan); Md. Samiul I. Sarker, Univ. of Rajshahi (Bangladesh); Shunichi Sato, Tohoku Univ. (Japan)

Catalytic Rh-based alloy nanoparticles (NPs) were fabricated by femtosecond laser irradiation of aqueous solution of mixed ions. Local structure of fabricated NPs was characterized by means of X-ray diffraction and STEM-EDS techniques. The XRD patterns of fabricated NPs in the solutions with different feeding ratios were typical of fcc-structured crystal, and the peak positions were in the range of those of pure Rh, Pd and Pt. In addition, the elemental compositions of NPs measured by EDS were comparable to the initial feeding ratio of the metal ions in the solutions. Namely, all-proportional solid-solution Rh-based alloy NPs with fully tunable composition were successfully fabricated only by tightly-focused femtosecond laser irradiation of a mixed aqueous solution of metal ions. It should be noted that this is difficult to attain by conventional methods due to the immiscible property in the system. The fabricated NPs were supported on aluminum oxide (g-phase, 99.97 %, metal basis, surface area of 80-120 m2/g, Alfa Aesar) as a matrix, and then catalytic activity of the NPs was evaluated through CO oxidation reaction. Although the catalytic stability was much improved by alloying, the catalytic activity was not so much enhanced in comparison with that of pure metal NPs probably due to a uniform local structure of the alloy NPs. Actually, the catalytic activity of the NPs was improved by introducing some defect sites and/or phase segregated structure through a proper heat treatment process to the as-prepared alloy NP. The detailed results will be described in the presentation.

9352-4, Session 1

Laser-ablative synthesis of functional nanomaterials for biomedical applications

Andrei V. Kabashin, Aix-Marseille Univ. (France)

Pulsed laser ablation in liquids has recently emerged as a novel “green” tool for synthesis of ultrapure colloidal nanomaterials. In this method, laser radiation is used to ablate a solid target in liquid ambience to form nanoclusters, which are then released into the liquid forming a colloidal nanoparticle solution. A huge advantage of this “physical” synthesis route consists in the possibility of avoiding toxic substances or by-products during the synthesis. This presentation will review our last results on laser ablative synthesis of colloidal nanomaterials and their testing in biological systems. Our approach consists in the employment of ultra-short (ps, fs) laser radiation for ablation from a solid target or from already formed water-suspended colloids, which makes possible an efficient physical control of size characteristics of synthesised nanomaterials. Exhibiting exceptional purity in the absence of any trace of contaminant, the synthesized nanomaterials present unique objects for biomedical tasks.

9352-5, Session 2

Nondestructive analysis of nanomaterials using optofluidic assisted Raman spectroscopy *(Invited Paper)*

Amr S. Helmy, Siu Wai Mak, Univ. of Toronto (Canada); Steven A Rutledge, Univ of Toronto (Canada); Janahan Ramanan, Univ. of Toronto (Canada)

Raman spectroscopy has witnessed significant advances in its applicability since the discovery of the Raman effect in 1928. Since molecular vibrations are specific to the molecular bonds and their symmetries, they are unique to every type of material at the molecular level and can also be described as the 'fingerprint' of materials. The Raman effect is also an extremely weak process in which only 1 in 10 million photons are scattered. This low probability is responsible for the low sensitivity of Raman spectroscopy.

This talk will review and compare the different optofluidic techniques for enhancing the retrieved Raman signal of nanomaterials in liquids and aerosols. Recent progress on this front utilizing optofluidics such as photonic crystal waveguides will be discussed. Techniques and applications to combine surface enhanced with optofluidic-assisted Raman spectroscopy will be also reviewed. Challenges and future opportunities to advance optofluidics-assisted Raman spectroscopy that are carried out using portable Raman spectrometers and controlled using handheld controllers such as mobile phones will be presented.

As an example, a detailed, non-destructive characterization of CdTe nanoparticles using Raman spectroscopy using concentrations of 2 mg/mL, will be highlighted. Our platform allows clear vibrational modes corresponding to the structure and interactions of the QDs to be observed. These vibrational modes include those of the CdTe core, Te defects, CdSTe interface, thiol agent and carboxylate-metal complexes. These modes are correlated with the crystallinity of the QD core, interfacial structure formed upon stabilization, QD-thiol interaction mechanisms, water solubility of the QDs and their potential bio-conjugation abilities.

9352-6, Session 2

Persistent all-optical memory effect in a nanostructured metamaterial

Kannatassen Appavoo, Vanderbilt Univ. (United States); Dangyuan Lei, The Hong Kong Polytechnic Univ. (China); Filip Ligmajer, Yannick Sonnefraud, Imperial College London (United Kingdom); Richard F. Haglund Jr., Vanderbilt Univ. (United States); Stefan A. Maier, Imperial College London (United Kingdom)

Nanoscale active optical devices, such as modulators and electro-optical transducers, can be constructed by integrating plasmonic nanostructures with functional materials. Vanadium dioxide (VO2), a strongly-correlated electron material, is appealing for active plasmonic applications because its reversible insulator-to-metal transition (IMT) is accompanied by large changes in its electronic and optical properties. Here we exhibit a persistent all-optical memory effect in the localized surface plasmon resonance (LSPR) of Au nanoparticles lithographically patterned in an array on a thin VO2 film. Periodic arrays of Au nanodisks of varying diameters were fabricated lithographically on a 50 nm thick VO2 thin-film made by pulsed laser deposition. The Au nanoparticles were arranged in a square lattice with a nominal period much shorter than the wavelength of the pump light in order to avoid diffraction effects in transmission measurements. Extinction spectra were acquired using an inverted optical microscope integrated with a Fourier-transform infrared spectrometer. By heating or cooling the VO2 film, the Au plasmon response to ultraviolet light pulses during the IMT was effectively pinned to a strongly correlated state of the VO2. Persistent, non-volatile blue-shifting and optical tuning of the LSPR was observed when the array was illuminated by successive ultraviolet-light pulses throughout the temperature range corresponding to the hysteresis of the film. Control experiments at temperatures above and below the region of strong correlation in the VO2, on the other hand, showed no memory effect. The blue-shifted, persistent response of the LSPR is an all-optical analog of memory capacitance and the memristive response of VO2 in electronic circuits.

9352-7, Session 2

Nanoplasmonics of particles over thin films: Quantum and magnetic effects

Reuven Gordon, Ghazal Hajisalem, Reza N. Sanadgol, Haitian Xu, Byoung-Chul Choi, Univ. of Victoria (Canada)

In this presentation, I will discuss our recent work on the physics and applications of metal nanoparticles over thin films. Applications to probing the ultimate quantum tunneling limits to third harmonic generation will be shown, using both experiments and a quantum corrected model theory. In addition applications to heat-assisted magnetic recording will be shown, where local plasmonic heating increases the demagnetization signal through increased local heating.

9352-8, Session 2

Low frequency shear and breathing modes in few-layer MoSe2 with different stacking

Alexander A. Puretzky, Bobby G. Sumpter, Oak Ridge National Lab. (United States); Liangbo Liang, Vincent Meunier, Rensselaer Polytechnic Institute (United States); Kai Wang, Masoud Mahjouri-Samani, Xufan Li, Kai Xiao, Juan Idrobo, David B. Geohegan, Oak Ridge National Lab. (United States)

Raman spectroscopy is widely used to characterize few-layer 2D crystalline materials, however typically intralayer vibrations with frequencies >100 cm-1 are probed, principally and practically determined by the cut-on edges of existing notch filters used for these measurements. Here we report measurements and ab initio calculations of low frequency (<50 cm-1) Raman shear and breathing modes in few trilayer MoSe2 that we synthesized by chemical vapor deposition with a variety of different layer stackings. In the case of two layer (2L) MoSe2 measurements of 50 different 2D crystals showed only two types of low frequency Raman spectra, i.e., 1) a strong narrow peak at 19.5 cm-1 (~ 1 cm-1 FWHM) and a very weak broad peak at ~ 34 cm-1 and 2) much weaker, slightly shifted peak at 19.0 cm-1 and similar broad feature at 34 cm-1. Using ab initio calculations of the Raman frequencies and intensities these two types of Raman spectra were attributed to the most stable stacking patterns of the MoSe2 layers, 2H and 3R. Similarly, three distinct low frequency Raman spectra were observed in the case of 3L MoSe2 and assigned to different stacking patterns of the corresponding MoSe2 trilayers. The low frequency modes in transition metal dichalcogenides (TMDs) provide a powerful tool for understanding interlayer interactions and designing heterostuctures based on stacking of different TMD layers.

Research sponsored by the U.S. Dept. of Energy, Basic Energy Sciences, Materials Science and Engineering Div. (synthesis science) and Scientific User Facilities Div. (characterization and computational science).

9352-9, Session 3

Hot electron photodetectors based on metamaterial perfect absorbers *(Invited Paper)*

Jason G. Valentine, Wei Li, Vanderbilt Univ. (United States)

While the non-radiative decay of surface plasmons was once thought to be only a parasitic process which limits the performance of plasmonic devices, it has recently been shown that it can be harnessed in the form of hot electrons for use in photocatalysis, photovoltaics, and photodetectors. Unfortunately, the quantum efficiency of hot electron devices remains low due to poor electron injection, and in some cases, low optical absorption. Here, we demonstrate how metamaterial perfect absorbers can be used to achieve near-unity optical absorption using ultrathin plasmonic nanostructures with thicknesses of 15 nm, smaller than the hot electron diffusion length. The metamaterial is integrated with a silicon substrate forming a Schottky barrier with a height that is smaller than the silicon band gap, allowing electrons with sub-band gap energy to be collected. This configuration was used to experimentally demonstrate a broadband and omnidirectional hot electron photodetector with a photoresponsivity >3mA/W at wavelengths >1200 nm. We also show how the spectral bandwidth can be increased to ~800 nm and a polarization-independent response can be achieved through engineering the geometry of the metamaterial unit cell. These perfect absorber photodetectors could open a pathway for enhancing hot electron based photovoltaic, sensing, and photocatalysis systems.

9352-10, Session 3

Surface plasmon amplification and active nonreciprocal gratings *(Invited Paper)*

Elham Karami Keshmarzi, R. Niall Tait, Carleton Univ. (Canada); Pierre Berini, Univ. of Ottawa (Canada)

Stimulated emission and amplification of surface plasmon polaritons (SPPs) on planar metallic waveguides can be achieved by allowing SPPs to propagate through an adjacent optical gain medium, usually dipolar and optically-pumped. Structures based on the single metal-dielectric interface and on thin metal films and stripes in a symmetric dielectric, supporting long-range SPPs, are reviewed. The conditions required to achieve complete SPP loss compensation at visible and infrared wavelengths are discussed, along with designs for single-mode SPP lasers. Nonreciprocal Bragg gratings, based on an asymmetric step-in-width long-range SPP waveguide and a periodically-modulated gain medium, are described and discussed. Such structures are capable of very strong reflection when excited from one end, and produce nearly no reflection when excited from the other end at the same wavelength.

9352-11, Session 3

3D terahertz metamaterials with asymmetric transmission

Aggelos Xomalis, George Kenanakis, Alexandros Selimis, Maria Vamvakaki, Maria Kafesaki, Maria Farsari, Foundation for Research and Technology-Hellas (Greece)

We present our latest research into the design and fabrication of 3D nanostructures by direct laser writing and selective electroless plating. Direct laser writing is a nonlinear optical technique which allows the fabrication of three-dimensional structures with a resolution beyond the diffraction limit. The polymerization process is initiated when the beam of an ultra-fast infrared laser is tightly focused into the volume of a transparent, photosensitive material. Multi-photon absorption takes place within the focal volume, where polymerization occurs. By moving the focused laser beam in a three-dimensional manner within the resin, 3D structures can be fabricated. The technique has been employed successfully in the fabrication of nanophotonic structures and devices.

Here, we talk about our latest results into the design and fabrication of 3D devices that exhibit asymmetric polarization transmission in the THz spectral region. Simulation and experimental results demonstrate that the suggested metamaterials offer great polarization possibilities by simply changing their geometrical features.

9352-12, Session 3

Response of zinc-oxide core-shell nanowires to gamma irradiation

Richard F. Haglund Jr., Daniel C. Mayo, Claire Marvinney, Vanderbilt Univ. (United States); Richard Mu, Fisk Univ. (United States)

Zinc oxide (ZnO), a II-VI semiconductor with a direct bandgap of 3.37 eV and exciton binding energy of 60 meV, is a promising optoelectronic materials for a wide variety of applications. Room temperature photoluminescence (PL) spectra for ZnO exhibit a band-edge exciton-recombination peak at 3.37 eV and a broad visible emission peak centered near 2.3 eV that is usually described as superposition of donor-acceptor-pair (DAP) recombination lines. A range of zinc-oxide optoelectronic devices are being developed, including light-emitting diodes, lasers and sensors. On the other hand, relatively little attention has been paid to ZnO as a possible scintillator material, even though it has many desirable properties – including the possibility of efficient scintillator response in the ultraviolet without the addition of dopants and an efficient unidirectional light output that is easily captured in a linear array geometry.

In this paper, we describe experimental studies in which the photoluminescence (PL) of ZnO/MgO core-shell nanowire (NW) arrays was measured before and after gamma irradiation (662 keV) to a level of as much as 20 kGray. The most noticeable effect is an increased, dose-dependent level of visible PL, indicating the production of radiation-induced defects. Annealing studies suggest that some, though not all, of the defects can be annealed by heating in an oxygen-rich ambient. As in previous experiments, we find that the band-edge PL can be enhanced by decorating the NWs with plasmonic-metal nanoparticles, apparently due to the Purcell mechanism. We compare the scintillation response to conventional strontium-iodide-based bulk crystals to benchmark the efficiency of this material, and describe routes to nanofabrication of efficient arrays for space and other applications.

9352-13, Session 4

Nanophotonic designs for photovoltaics *(Invited Paper)*

Vivian Ferry, Univ. of Minnesota, Twin Cities (United States)

The integration of nanostructures into photovoltaics offers the ability to control, concentrate, and spectrally tune light in subwavelength dimensions, leading to enhanced absorption in thin volumes of semiconductor. Increased absorption in semiconductor films has both fundamental and practical benefits, leading to improved photovoltaic performance while decreasing the cost of production.

The first portion of my talk will focus on light trapping in ultrathin silicon solar cells by metallic and resonant semiconductor nanostructures. Integrating metallic nanostructures into the back electrode of ultrathin film amorphous silicon solar cells couples incident sunlight into guided and localized modes of the device, which enhances absorption relative to both unstructured and randomly textured solar cells. Through control of the spatial frequencies, pseudo-random nanostructure patterns are designed which exhibit broadband and isotropic photocurrent enhancement. We then consider the effects of resonant semiconductor nanostructures in comparison to plasmonic nanostructures, identifying benefits and drawbacks to each with the aid of a coupled optical-electrical model.

The second part will discuss luminescent concentrators and the benefits of combining engineered quantum dot heterostructures and photonic reflectors for efficient concentration and downshifting of sunlight. CdSe/CdS seeded nanorods are used as tunable lumophores in a luminescent concentrator, combined with photonic design to efficiently trap the luminesced light. Experiments show that increased nanocrystal volume leads to longer propagation lengths, and with the aid of a theoretical model, that narrow emission line widths can lead to efficient concentration.

9352-14, Session 4

Photo-refractive polymers for ophthalmic applications *(Invited Paper)*

Norbert A. Hampp, Philipps-Univ. Marburg (Germany)

Cataract treatment to date requires replacement of the eye lens by an artificial polymeric lens, a surgery done several millions of times every per year. It is not possible to ensure that the intraocular lens (IOL) implanted fully restores vision because wound healing etc. are not fully predictable. Photo-refractive polymers suitable for IOLs may enable the postoperative tuning of the refractive properties of implanted IOLs. Due to the absorptive properties of the cornea two-photon-absorption controlled refractive index changes of the IOL material is the tool to accomplish this task. We developed a series of polymers based on coumarin derivatives with good two-photon-absorption cross sections which enable photo reversible optical tuning of implanted IOLs by 2 diopters.

9352-15, Session 4

Laser synthesis of group IV semiconductors nanoparticles for bio-labelling applications

Marina Rodio, Alberto Diaspro, Romuald Intartaglia, Istituto Italiano di Tecnologia (Italy)

Nanoparticles (NPs) of group IV semiconductors such as silicon (Si) and germanium (Ge) have wide applications in optics and electronic devices, as well as in biological fluorescence imaging, because of their size-dependent optical properties and relatively low toxicity.[1] Ge is particularly attractive due to its narrow bulk bandgap (0.67 eV) as infrared biolabels at tissue-transparent wavelengths (700-1100nm). However, NPs of group IV have been proven to be much more difficult to synthesize colloidally, which has been attributed to the high crystallization temperatures of these materials due to strong covalent bonding.[1] The conventional synthetic routes are less effective and may cause health issues. In order to overcome these limitations, pulsed laser ablation in liquid method has emerged as an alternative approach to generate semiconductor NPs in a simple route, free of contaminants [2-7]. Here we will report on Si NPs prepared by pulsed laser ablation in liquid and the synthesis of Ge NPs by picosecond laser ablation of Ge bulk in liquids as function of laser wavelength (1064 nm, 532 nm, 355 nm). Results on the crystalline structure, optical properties and stability of the colloidal solutions are assessed by the means of transmission electron microscopy, Raman spectroscopy, UV-visible and infrared spectroscopy. The colloidal solutions display tunable photoemission properties in the visible range from 350 nm to 650 nm in correlation with the laser wavelength. The mechanism of NPs generation is attributed to an in situ photo-fragmentation effect [5].

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9352-16, Session 4

Metallic nanoholes and nanogaps for plasmonic biosensing and spectroscopy *(Invited Paper)*

Sang-Hyun Oh, Univ. of Minnesota, Twin Cities (United States)

Unlike conventional diffractive optical devices, realization of high-performance optical nanostructures based on metals presents daunting challenges for both fabrication and modeling.

Extreme squeezing of optical energy in metallic nanostructures such as subwavelength gaps and apertures is possible via surface plasmon waves, yet they are highly susceptible to defects and nanometric surface roughness. This presentation will focus on two nanofabrication techniques that our team has developed to overcome these challenges, namely, template stripping for making ultra-smooth patterned metals and atomic layer lithography for wafer-scale production of sub-nanometer-wide gaps. Applications of ultra-flat and ultra-small optical structures produced via these methods will be presented, focusing on surface plasmon resonance biosensing and surface-enhanced spectroscopies.

9352-17, Session 4

Photocorrosion metrology of photoluminescence emitting nano-heterostructures

Srivatsa Aithal, Jan J. Dubowski, Univ. de Sherbrooke (Canada)

Photocorrosion of semiconductors is typically considered a parasitic effect in functioning of electronic devices, such as field effect transistors, memory chips, light emitting diodes or electrochemical solar cells. The photocorrosion process depends on the concentration of impurities, energy and intensity of photons irradiating semiconductor microstructures, and on the nature of surrounding environment. A typical defence against photocorrosion could include surface passivation with atoms of a material capable to neutralize chemical reactivity of the semiconductor surface, coating with hole scavenging compounds, or with oxide/nitride films to create a physical barrier between the semiconductor surface and a corrosion inducing environment. Under constant irradiation conditions and a continuously refreshing environment, the photocorrosion of semiconductors becomes a well reproducible effect that could be monitored in situ with, e.g., photoluminescence (PL) or Raman spectroscopies. We have investigated photocorrosion of GaAs/AlGaAs microstructures immersed in deionized water or NH4OH solution and, by employing PL emitting GaAs layers or quantum wells, we were able to monitor the process of photocorrosion with an in-depth nanometer-scale precision. We discuss some potential applications this super-slow photocorrosion brings to the metrology of stacked nano-heterostructures and to the analysis of surface and interface states/traps.

9352-18, Session 5

Pulsed laser deposition of calcium barium niobate thin films for electro-optical devices *(Invited Paper)*

Mohamed Chaker, Nadir Hossain, Institut National de la Recherche Scientifique (Canada)

To overcome the present limitations of the electro-optical (EO) modulators technology, one main issue is to develop new thermally stable materials with high EO coefficient that also provide the ability of being integrated on silicon. We have shown that calcium barium niobate ($Ca_xBa_{1-x}Nb_2O_6$) in the form of thin film is a promising material for integrated EO devices applications, due to its unique EO properties (EO coefficient of 130 pm/V) and high Curie temperature (above 250°C). The systematic investigation of the influence of the physical properties of the CBN thin films on their optical characteristics together with the development of a well-controlled CBN plasma etching process are prerequisites for the fabrication of high-performance large-bandwidth integrated EO modulators. We successfully used Pulsed Laser Deposition to grow high quality CBN epitaxial thin films on various substrates. In this work, we investigated the synthesis of CBN thin films on magnesium oxide (MgO), platinum coated MgO and silicon substrates in view of optimizing their optical characteristics. An advanced patterning method using a nickel hard mask and a chlorine plasma was developed. Finally, waveguides were fabricated (as building block of EO device) and promising EO material properties were demonstrated towards the development of high performance novel CBN based EO devices

9352-19, Session 5

Controlled growth of 2D metal chalcogenides from pulsed laser deposited nanoparticles

Masoud Mahjouri-Samani, Ryan Gresback, Oak Ridge National Lab. (United States); Mengkun Tian, The Univ. of Tennessee (United States); Kai Wang, Abledaziz Boulesbaa, Alexander A. Puretzky, Christopher M. Rouleau, Gyula Eres, Ilia N. Ivanov, Kai Xiao, Michael A. McGuire, Oak Ridge National Lab. (United States); Gerd J. Duscher, The Univ. of Tennessee (United States); David B. Geohegan, Oak Ridge National Lab. (United States)

Pulsed laser deposition (PLD) of as-synthesized nanoparticles is used to grow metal chalcogenide (GaSe) and dichalcogenide ($MoSe_2$) 2D crystals in either nanosheet networks (200 nm domain sizes) or large single crystalline domains (100 μm lateral sizes) with controlled stoichiometry, number of layers, crystallite size, and growth location. Small-domain nanosheet networks are formed by direct deposition of stoichiometric nanoparticles onto heated substrates formed by laser vaporization into 1 Torr argon background. Tuning the digital delivery of the precursor flux can easily control the thickness of the nanosheets or change in-plane growth to out-of-plane orientation. Time-resolved in situ diagnostics are used to characterize the deposition conditions. To understand the growth of 2D crystals from laser-deposited nanoparticles, room temperature-deposited nanoparticles were sandwiched between two substrates and annealed to form a confined vapor transport growth system. By simply heating the source substrate in an inert background gas, a natural temperature gradient is formed that evaporates the confined nanoparticles to grow large, crystalline 2D nanosheets by digital transfer in pre-patterned locations onto the cooler receiver substrate. This novel PLD-based synthesis and processing method offers a unique approach for the controlled growth of large-area, metal chalcogenides with a controlled number of layers and sizes in patterned growth locations for optoelectronics and energy related applications.

Research sponsored by the U.S. Dept. of Energy, Basic Energy Sciences, Materials Science and Engineering Div. (synthesis science) and Scientific User Facilities Div. (characterization science).

9352-20, Session 5

Growth of nanostructures and mesoscale architectures by pulsed laser synthesis, deposition, and integration of ultrasmall nanoparticle "building blocks"

David B. Geohegan, Masoud Mahjouri-Samani, Kai Wang, Alexander A. Puretzky, Christopher M. Rouleau, Oak Ridge National Lab. (United States); Mengkun Tian, Gerd J. Duscher, The Univ. of Tennessee (United States); Mina Yoon, Gyula Eres, Miaofang Chi, Oak Ridge National Lab. (United States)

Here we investigate ultrasmall nanoparticles (UNPs, < 3 nm) formed in the gas phase by pulsed laser vaporization as reactive "building blocks" in the catalyst-free growth of hyperbranched mesoporous nanoparticle architectures, crystalline nanorods, 2D nanosheets, and thin films by pulsed laser deposition (PLD). Nanoparticles synthesized during typical PLD conditions in background gases (typically >30 mTorr) preserve target stoichiometry, but their integration in films or nanostructures remains poorly understood due to the lack of in situ diagnostics. Temporally- and spatially-resolved gated-ICCD imaging, spectroscopy and ion probes are employed as in situ diagnostics to understand and control the plume expansion conditions in order to synthesize UNPs of primarily oxides. We first focus on the synthesis conditions, size and optical properties, and atomic structure of loose 'amorphous' UNPs of TiO_2 that do not conform to a known TiO_2 bulk phase. These UNPs serve as "building blocks" for the assembly of hyperbranched 3D mesoporous architectures at room temperature, but with increasing substrate temperature they become integrated into vertically-oriented crystalline nanorods, sometimes with unusual phases (e.g., TiO_2 (B)). Similar results will be shown for other oxides (e.g., SnO_2, MgO, $PbZr_{(x)}Ti_{(1-x)}O_3$). Atomic-resolution Z-contrast scanning TEM and EELS are described to characterize the stoichiometry, atomic structure, and electronic structure (band gap) of individual UNPs., These findings are crucial to understand stoichiometry transfer and film growth modes in PLD, catalyst-assisted nanotube and nanowire growth in PLV, and catalyst-free nanorod synthesis in NA-PLD.

Research sponsored by the U.S. Dept. of Energy, Basic Energy Sciences, Materials Science and Engineering Div. (synthesis science) and Scientific User Facilities Div. (characterization science).

9352-21, Session 5

Study on generation process of nanofibers from back surface of thin glass substrate using pulsed UV 355nm laser

Sho Itoh, Nippon Electric Glass Co., Ltd. (Japan); Masaaki Sakakura, Yasuhiko Shimotsuma, Kiyotaka Miura, Kyoto Univ. Graduate School of Engineering (Japan)

Glass nanofibers are prospective material, because they have the potential to function as biomedical tissues, optical components, or catalysts. Now, precise control of synthesis method is necessary for a variety of glass nanofiber applications. We found that glass nanofibers were generated from the back surface of a substrate during a drilling experiment using a nanosecond pulsed UV laser. In this report, we investigated the generation process. To understand the process, we set up an optical system for generating nanofibers, which is capable of moving a sample linearly using an X-Y stage, and monitored around the laser spot using a CCD camera. A non-alkaline, thin glass substrate was irradiated with a laser beam of

wavelength 355 nm and pulse width 40 ns. As a result, when the scanning speed and focusing position were favorable, glass nanofibers were generated. According to the in-situ observation, microparticles were found on the tip of the nanofibers. Also, the glass substrate was modified in a wider range compared with the laser spot size. Thus, we considered that glass nanofibers were generated when the particles were ejected resulting from local heating. Additionally, glass nanofibers could be generated in combination with a galvano scanning system. The generation of glass nanofibers from the back surface of a substrate is advantageous in terms of their collection owing to the reduced interaction with the laser beam.

9352-22, Session 5

Rapid fabrication of graphene on dielectric substrates via solid-phase processes

Wei Xiong, Yunshen Zhou, Wenjia Hou, Yongfeng Lu, Univ. of Nebraska-Lincoln (United States)

To unleash the full potential of graphene in functional devices, high-quality graphene sheets and patterns are frequently required to be deposited on dielectric substrates. However, it generally calls for post-growth catalyst etching and graphene transfer steps in currently existing approaches, which are very time consuming and costly for fabricating functional graphene devices. We developed a rapid and cost-effective growth method to achieve the graphene formation directly on various kinds of dielectric substrates via a novel solid-phase transformation mechanism based on Ni/C thin films. High-quality graphene was obtained uniformly on whole surface of wafers with a controlled number of graphene layers. The monolayer graphene, as obtained, exhibits a low sheet resistance of about 50 Ω/sq (close to the theoretical limit) and a high optical transmittance of 95.8% at 550 nm. Graphene patterns were successfully fabricated simply by either conventional photolithography or laser direct writing techniques. Various graphene patterns, including texts, spirals, line arrays, and even large-scale integrated circuit patterns, with a feature line width of 800 nm and a low sheet resistance of 205 ohm/sq, were achieved. The developed method provides a facile and cost-effective way to fabricate complex and high-quality graphene patterns directly on target substrates, which opens a door for fabricating various advanced optoelectronic devices.

9352-23, Session PTue

Vertical silver nanorod growth as a surface-enhanced Raman scattering

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There have been increasing demands for alternative methods with simple and cost effectiveness of fabrication of nanometer scale structures as surface-enhanced Raman scattering (SERS) materials. The enhancements of SERS signal strongly depend on the shape and size of their materials due to the change of absorption and scattering rates on the surface. The major problem with the sensitivity scaling-up was in the development of fabrication technology for stability and reproducibility of SERS substrates. We have developed the method to fabricate arrays of vertically grown nanometer scaled silver rod using micro-, or nanosphere lift-off (polystyrene) on silicon wafer as a SERS substrate by thermal evaporation technology. Closed packed microsphere produced 2-D array of periodic structure on SiO2 substrate, then the size of sphere was reduced to nano-sized sphere by O2 plasma treatment (plasma cleaner, PDC-32G). Silver nanorod arranged in a vertical position was grown around the sphere up to ~70 nm in diameter and ~800 nm in height via thermal evaporation using resistively heated tungsten filament sources. Using the scotch tape, the spheres were removed from a substrate, resulting in Stonehenge like Fisher patterns. We report an optimization of sphere size dependence of SERS signal enhancement as well as 1-porpanethiol coated Ag nanorod on SiO2 substrate in order to detect real time vapor phase chloroform by the radiation of fiber optic coupled 785nm diode laser and spectrograph. Raman peak at 668.2 cm-1 for chloroform was compared to 1026.9 cm-1 of 1-propanethiol as a function of vapor phase ratio, resulting in detectable range at 1-900 ppm.

9352-24, Session PTue

Direct laser fabrication of GaAs nanostructures on GaAs(001) in MBE reactor in-situ

Haeyeon Yang, Anahita Haghi Zadeh, South Dakota School of Mines and Technology (United States)

The so-called Stranski-Krastanov (S-K) growth technique is useful to fabricate quantum dots (QDs) while it is limited to hetero-epitaxial systems because the S-K growth method generally requires a lattice mismatch larger than 2% such as in InGaAs quantum nanostructures. We present a laser direct fabrication of a strain-free GaAs nanostructures including nanodots and nanowires produced in-situ on GaAs(001) surfaces in a molecular beam epitaxy growth reactor by applying interferential irradiations of high power laser pulses on the surfaces. The morphologies of the GaAs nanodots and nanowires are characterized by atomic force microscopy and field emission scanning electron microscopy (FESEM) while their stoichiometry is characterized by energy dispersive X-ray spectroscopy that is coupled with FESEM. The morphological study indicates that the width and length of nanodots are a few tens of nanometers while their height is around ten nanometers. The nanodot dimensions are much smaller than the interferential period and the wavelength of laser used but comparable to findings in our recent reports of QDs produced by direct laser annealing. Low electron voltages less than 5 kilovolts have been used in order to enhance the surface sensitivity of the resulting X-ray fluorescence due to the small inelastic mean free path of electron (~ 4 nm at 3 kV) in GaAs. The stoichiometric analysis indicates that the arsenic content and the relative Ga composition reaches to those of GaAs substrate when the dot size becomes smaller than 100 nm. The chemical analysis suggests a novel route of strain-free semiconductor nanodots.

9352-25, Session PTue

Comparison of the critical dimensions of one dimensional diffraction gratings extracted from the different scatterometric measurements

Kyongseok Kim, Chang Hyun Park, Daeyeon Kim, Seung-Han Park, Yonsei Univ. (Korea, Republic of)

We have constructed a scanning-angle phase modulation ellipsometer, which can measure ellipsometric angles (EAs) by varying the angle of incidence (AOI). The goniometer was automatized with high-precision motorized stages for ?-2? rotations. Therefore, we can get the repeatability of AOI within 0.01˚ with precise alignment process. In addition, we have modified our system to have the functionality as a reflectometer by making a detour for the incident beam, putting a beamsplitter, and monitoring the incident beam intensity. With this extended setup, we can measure the EAs and the reflectance while scanning AOIs. Diffraction gratings are employed as a sample to measure EAs and reflectances with the same AOIs. The measured EAs and reflectance data were analyzed by RCWA algorithms with parametrized nonlinear regression process. By comparing the CDs extracted from our analysis with the one from scanning electron microscopy(SEM), we can demonstrate the traceability of the optical critical dimension of nanostructures by using our a scanning-angle phase modulation ellipsometer.

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9353-1, Session 1

2D/3D laser cutting of carbon fiber reinforced plastic (CFRP) by fiber laser irradiation

Hiroyuki Niino, Yoshihisa Harada, National Institute of Advanced Industrial Science and Technology (Japan) and Advanced Laser and Process Technology Research Association (Japan); Kenji Anzai, Mitsuaki Aoyama, Miyachi Corp. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Masafumi Matsushita, Koichi Furukawa, Shin Nippon Koki Co. Ltd. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Michiteru Nishino, Mitsubishi Chemical Corp. (Japan) and Advanced Laser and Process Technology Research Association (Japan); Akira Fujisaki, Taizo Miyato, Takashi Kayahara, Furukawa Electric Co., Ltd. (Japan) and Advanced Laser and Process Technology Research Association (Japan)

We have developed a new 3D-scanning system based on galvanometer scanning. This work was supported in part by the national project of “Advanced Laser and Processing Technology for Next-generation Materials Project” was launched in 2010FY (period: 5 years) in Industrial Technology Center of NEDO.

9353-2, Session 1

Additive manufacturing in production: Challenges and opportunities *(Invited Paper)*

Michael Schmidt, BLZ Bayerisches Laserzentrum GmbH (Germany)

Additive manufacturing, characterized by its inherent layer by layer fabrication methodology has been coined by many as the latest revolution in the manufacturing industry. Due to its diversification of Materials, processes, system technology and applications, Additive Manufacturing has been synonymized with terminology such as Rapid prototyping, 3D printing, free-form fabrication, Additive Layer Manufacturing, etc. A huge media and public interest in the technology has led to an innovative attempt of exploring the technology for applications beyond the scope of the traditional engineering industry. Nevertheless, it is believed that a critical factor for the long-term success of Additive Manufacturing would be its ability to fulfil the requirements defined by the traditional manufacturing industry. A parallel development in market trends and product requirements has also lead to a wider scope of opportunities for Additive Manufacturing. The presented talk discusses some of the key challenges which are critical to ensure that Additive Manufacturing is truly accepted as a production process in the industry. These challenges would highlight on various aspects of production such as product requirements, process management, data management, intellectual property, work flow management, quality assurance, resource planning, etc. In Addition, changing market trends such as product life cycle, mass customization, sustainability, environmental impact and localized production will form the foundation for the follow up discussion on the current technical limitations in the process and corresponding research opportunities. A discussion on ongoing research to address these challenges would include topics like process monitoring, design complexity, process standardization, multi-material and hybrid fabrication, new material development, etc.

9353-3, Session 2

Laser printing of nanoparticles and living cells *(Invited Paper)*

Boris Chichkov, Laser Zentrum Hannover e.V. (Germany)

I will report on our progress in the development of 2D and 3D laser printing technologies for applications in photonics and biomedicine. Realization of photonic and plasmonic components, sensors, biomedical implants, and tissue engineering constructs will be discussed.

9353-4, Session 2

Laser sintering of metal nano-ink tracks embedded into 3D structure

Abraham Rotnemer, Orbotech Ltd. (Israel); Michael Zenou, Orbotech Ltd. (Israel) and Hebrew Univ. (Israel) and Ricah Institute of Physics (Israel); Jonathan Ankri, Zvi Kotler, Orbotech Ltd. (Israel)

Embeding electronic components in 3D printed structures involves integration of electrical circuits as part of the automatic fabrication of complete functional devices. One can obtain high conductivity of such printed electrical circuits by photonic sintering of the deposited metal ink. This method benefits from the large difference in absorption between a metal ink and the underlying, transparent substrate. Previously such high quality photonic sintering was shown also on sensitive substrates such asPET, PEN, ABS. However a large difference in absorption also involves considerable thermal gradients which depend on the specifics of the printed track geometry, the illumination beam profile and the specific thermal properties of the substrate (heat capacity, thermal conductivity). Therefore, photonic sintering, unlike oven sintering where heating is uniform, poses special challenges when complex printed track geometries are present.

We present an experimental investigation of such geometrical dependencies of the photonic sintering process. We use a scanning laser source (CW IR source) to sinter ink tracks of varying geometries. The line tracks were defined by laser ablation of a spin coated nanoparticle metal ink film. We provide a theoretical validation of the experimental findings using 3D-FEM thermal simulations. Finally we conclude by providing guidelines to robust photonic sintering for varying ink track geometries on various, sensitive substrates.

9353-5, Session 2

Monolithic hybrid optics for broadband focusing and beam shaping

Ulrike Fuchs, asphericon GmbH (Germany)

Almost any application that involves more than one wavelength going through an optical system has same need for color correction. Thus, the common approach is to add more surfaces and balance the optical glass in order to achieve this goal. For some applications, especially when ultrashort laser pulses (pulse durations way below 100fs) are involved, it is quite important to reduce the amount of higher order dispersion in an optical system because it is basically impossible to compensate for them afterwards. Therefore, we pursue a different approach.

We present two different specially designed monolithic hybrid optics comprising refraction and diffraction effects for tight spatial and temporal focusing of ultrashort laser pulses. Both aims can be put into practice by having a high numerical aperture (NA=0.5 and 0.7) and low internal

dispersion at the same time. The focusing properties of the first example are very promising, due to a design, which provides diffraction limited focusing for 80nm bandwidth at 780nm center wavelength. Thus, pulses with durations as short as 25fs can be focused without pulse front distortion. The outstanding performance of this optics is shown in theory and experimentally. The approach for the second focusing optics goes even further beyond common designs. It not only combines refraction with diffraction, but also involves total internal reflection for beam shaping and therefore improving focusing quality even further while reducing the spot size. This optics is especially interesting for nonlinear material processing.

9353-40, Session PTue

Two-photon microfabrication using azo dyes as polymerization initiator

Adriano J. G. Otuka, Vinicius Tribuzi, Univ. de São Paulo (Brazil); Daniel S. Correa, Embrapa Instrumentação Agropecuária (Brazil); Leonardo De Boni, Cleber R. Mendonca, Univ. de São Paulo (Brazil)

Two-photon polymerization has been the leading fabrication method used in the production of functional microstructures because of its versatility and its advantages over other fabrication techniques. Several groups have worked towards improving fabrication resolution. Inhibition of the initiating species is one of the most successful methods studied. This is done either chemically, by adding an inhibitor compound, or optically, by laser irradiation and saturation of the photoinitiator.

Here we present the production of microstructures by two-photon polymerization using, as photoinitiator, a series of different azo dyes. In our experiment a Ti:Sapphire laser is focused through a microscope objective into the volume of a liquid resin. The liquid resin is mixed to a solution of an organic dye and, upon laser pulse irradiation, we observe localized polymerization. Under irradiation, the dye undergoes two-photon absorption and its molecule is cleaved, yielding radicals that will start the polymerization process. The use of different organic dyes as photoinitiators can be explored to improve fabrication resolution. By changing the dye used, laser irradiation will produce different radicals and their properties like, initiation efficiency and diffusion in the resin, will be different, yielding voxels that have different sizes. Aiming at improving fabrication resolution we have tested several azo dyes. For each of them we have produced 3D microstructures after measuring their two-photon absorption cross-section and polymerization threshold.

In addition to improving fabrication resolution, this method also represents a simple way of producing dye doped microstructures, which have great potential in the development of active photonic devices.

9353-41, Session PTue

Evaluation of laser ultrasonic testing for inspection of metal additive manufacturing

Sarah K. Everton, The Univ. of Nottingham (United Kingdom) and The Manufacturing Technology Ctr. (United Kingdom); Phill Dickens, Christopher Tuck, The Univ. of Nottingham (United Kingdom); Ben Dutton, The Manufacturing Technology Ctr. (United Kingdom)

Additive Manufacturing (AM) is often termed a “revolutionary” technology, showing great potential to be implemented over a wide range of industries. Production by AM offers a number of benefits over conventional processes, such as increased design freedom leading to weight reduction or the integration of multiple components. However, in order for these benefits to be realised, further development of suitable monitoring techniques and closed loop control systems is needed.

Laser Ultrasonic Testing (LUT) is an inspection technology which shows great promise for in-situ monitoring of AM processes. Non-contact measurements can be performed on curved surfaces and in difficult to reach areas, even at elevated temperatures. Interrogation of each build layer generates defect information which can be used to highlight processing errors and allow for real-time modification of processing parameters, enabling improved component quality and yield.

This paper evaluates the use of LUT for detection of seeded defects within AM components using laser-generated surface waves in metallic samples produced by Laser Powder Bed Fusion. The effect of “as-built” surface finish on detection has also been investigated.

The trials undertaken utilise the latest LUT equipment which is capable of being controlled remotely, allowing the system to optimise or adapt “on-the-fly”, simplifying the integration of the system within an AM machine. The high power generation and detection lasers allow faster scanning of rough surface samples and the telescopic optical arrangement allows smaller, AM process representative defects to be detected at greater depths, progressing beyond the state of the art in this field.

9353-42, Session PTue

Two photon polymerization (2PP) technique optimization study using a green femtosecond oscillator

Areti Mourka, Amplitude Systèmes (France); Vasileia Melissinaki, Foundation for Research and Technology-Hellas (Greece) and Univ. of Crete (Greece); Maria Farsari, Foundation for Research and Technology-Hellas (Greece); Antoine Courjaud, Eric P. Mottay, Amplitude Systèmes (France)

Research into 3D fabrication by two photon polymerization (2PP) technique using ultrashort laser pulses has seen immense growth over the past two decades. The 2PP is a direct laser writing (DLW) technique, based on highly localized polymerization which is achieved by tightly focusing an ultrafast laser beam into a photosensitive material. The phenomena of simultaneous absorption of two photons lead to the polymerization reaction in the volume of the material. However, as for many ultrafast applications, different strategies of energy deposition are possible, depending on pulse energy, repetition rate, scanning speed, wavelength, etc. Here, we report on 3D fabrication by 2PP of the hydrid sol-gel based resist SZ2080 using a compact green ultrafast laser. The resist consists of 20% of zirconia and 80% of polymer forming methacryloxypropyltrimethoxysilane (MAPTMS) and methacrylic acid (MAA) both having photo-polymerizable methacrylate moieties. The green ultrafast laser is based on an air-cooled high average power oscillator delivering 1W at 1030nm, 50MHz repetition rate and 200fs pulse duration. A frequency doubler allows reaching 500mW at 515nm, and an acousto-optic modulator permits the adjustment of the repetition rate of the pulse train. Therefore, we report on the study of the effect of pulse energy and repetition rate on the incubation effects occurring in 2PP process, particularly when using SZ2080 photoresist.

9353-43, Session PTue

Contributions for the next generation of 3D metal printing machines

Milton Pereira, Instituto Federal de Santa Catarina (Brazil); Ulrich Thombansen, Fraunhofer-Institut für Lasertechnik (Germany)

The 3D metal printing processes are key technologies for the new industry manufacturing requirements, as low volume production associated with design complexity and flexibility are needed towards personalization and customization. The main challenges for these processes are associated to increasing printing volumes, lowering the relative accuracy level and reducing the global manufacturing time.

This paper presents some design solutions created to overcome these challenges. As SLM and SLS processes are based on laser scanning, to increase the printing volume and keep the printing accuracy it is necessary to synchronize the scanning movement with some other kind of macro displacement system with compatible global accuracy, as coordinate displacement tables or free form displacement devices. Doing this will proportionality increase the manufacturing time, as only one laser source will be responsible for building the entire work piece. The paper presents solutions using multiple laser sources.

Another concern is related to the weight level reached by large work pieces. Greater is the work piece weight, more difficult will be to cause small and uniform displacements between the laser apparatus and powder work bed. The paper presents solutions for this problem and for the elimination of fumes produced during the process, which interfere in the process performance.

9353-44, Session PTue

Fabrication of perfluoropolyether atomic force microscopy tips with two-photon polymerization

Tommaso Zandrini, Raffaella Suriano, Carmela De Marco, Politecnico di Milano (Italy); Roberto Osellame, Istituto di Fotonica e Nanotecnologie (Italy) and Politecnico di Milano (Italy); Stefano Turri, Politecnico di Milano (Italy); Francesca Bragheri, Istituto di Fotonica e Nanotecnologie (Italy)

Two-photon polymerization (2PP) is a fabrication technique that allows the production of polymeric three-dimensional structures with a submicron resolution. It relies on non-linear two or multi-photon absorption of infrared photons in UV photopolymerizable materials, triggered in the focus of a femtosecond pulsed laser beam. By moving the beam focal spot with respect to the photoresist a complex polymeric structure can be fabricated. The unpolymerized resist is then removed with a development solution. A very promising application for this technique is the realization of atomic force microscopy (AFM) tips directly on the top of commercial cantilevers. In particular, we are fabricating AFM tips with a zirconium-based solgel hybrid resist (SZ2080) and with a new highly hydrophobic perfluoropolyether based photoresist (PFPE), being the latter suitable for indentation measurements on biological samples, since it overcomes the problems of adhesion forces between the tip and the sample. This photoresist proved to have better chemical resistance and hydrophobicity than previously exploited acrylic and epoxy polymers.

Our fabrication setup consists in a femtosecond erbium fiber laser (FemtoFiber pro, Toptica Photonics) focused through a 100x 1.4 NA oil-immersion objective (Plan-Apochromat, Zeiss), a power control unit, a mechanical shutter and a piezoelectric stage (Physik Instrumente) for sample traslation.

We produced conical and cylindrical structures, the latter with a hemisphere on top, with both photoresists first on glass coverslips, to find the suitable irradiation parameters, then on cantilevers. Preliminary results let us envisage the possibility to validate these tips in an AFM indentation experiment on known samples.

9353-7, Session 3

Selective laser melting process fundamental and 3D printing of rocket engine *(Invited Paper)*

Youping Gao, John S. Malinzak, Aerojet (United States)

Metallic materials additive manufacturing has taken the traditional manufacturing industry by storm not only because it offers significant savings in cost and schedule but it also provides the ability to produce geometrically complex monolithic parts that are unattainable or extremely difficult to produce through conventional manufacturing processes. The most prominent process among all metallic additive manufacturing is the powder bed laser layer-build additive process - Selective Laser Melting (SLM). SLM, at its core, is a precision laser welding/cladding process. Instead of joining two solid pieces together as in traditional laser welding, the SLM process overlays metal powder to its underlying solid or support structures to build the solid object. In this process, the melting of the metal powder, liquid metal solidification, microstructure structure evolution includes solid state phase transformation, alloying elements interaction, defects formation and elimination, the thermal mechanical stress issues that are all related to the transient heat source and how it is being applied. Therefore, typical welding defects such as porosity, lack of penetration, lack of fusion, undercutting, spattering, and cracking all contribute to the quality of the additively built objects. In this work, typical defects of SLM are investigated, and methods of eliminating defects are established through controlling of the process inputs: pre-build powder treatments, laser power, scanning speed, laser-scan synchronization, offsets, and processing environmental controls. Laser-powder metal interaction, material melting and solidification, as well as microstructure evolution are studied. Support structure to facilitate the additive build process is evaluated. Dimensional tolerance and precision of additively build object are characterized. The result of optimized pre and post process sequences and properties are presented. Process robustness, failure mode, interruption, restart and rebuild are assessed. As the industrial infrastructure for the additive manufacturing evolves, supply chain including system OEM, powder producer, and process supplier develops, the cost of additive manufacturing will become very competitive. As nature has demonstrated where all structures are grown additively, additively produced metallic structure will no doubt be a significant path in how future hardware is produced.

9353-8, Session 3

Effect of heat treatment on properties of inconel 718 superalloy manufactured by 3D metal printing

Joung Soo Kim, Korea Atomic Energy Research Institute (Korea, Republic of) and Hoseo Univ. (Korea, Republic of); Chang-Kyu Rhee, Korea Atomic Energy Research Institute (Korea, Republic of); Jeong-Hun Suh, InssTek Co., Ltd. (Korea, Republic of)

Microstructures and mechanical properties of Inconel 718 superalloy manufactured using the 3D metal printing (or additive manufacturing) technology (DMT*) were investigated at 5 different heat treatment conditions. Additively manufactured rectangular shapes of Inconel 718 superalloy were cut using an electric discharge machine and heat treated (solution annealing, aging), followed by microstructure observation and analysis using OM, SEM/EDX, and TEM/EDX, and tensile tests. According to the experimental results, the microstructure, and tensile strength and elongation of as-deposited Inconel 718 superalloy were fine cellular dendrites, and 962 MPa and 28%, respectively. However, the tensile strength and elongation of the heat treated specimen were obtained to be 1422 MPa and 15%, respectively, which are superior to those of a wrought 718 alloy specified by the Aerospace Material Specification. Porosity of the as-deposited specimen was measured to be 0.07%. The dependence of the mechanical properties on heat treatment conditions were analyzed with the microstructure changes.

9353-9, Session 3

Femtosecond fiber laser welding and additive manufacturing for 3D manufacturing *(Invited Paper)*

Huan Huang, Bai Nie, Peng Wan, PolarOnyx, Inc. (United States); Lih-Mei Yang, PolarOnyx Laser Inc. (United States); Shuang Bai, PolarOnyx, Inc. (United States)

3D printing is revolutionizing the world of manufacturing, allowing to produce freeform parts with complex structures with a range of logistical, economic and technical advantages. Though 3D printing by using continuous-wave (CW) or long-pulsed lasers has achieved some developments, there are still some challenges hard to overcome, such as limited materials range and accuracy. Due to the unique ultra-short pulse duration and high peak power, femtosecond (fs) laser has emerged as a powerful tool for many applications but has rarely been studied for 3D printing. In this paper, welding of both bulk and powder materials is demonstrated for the first time by using high energy and high repetition rate fs fiber lasers. It opens up new scenarios and opportunities for 3D printing with the following advantages - greater range of materials especially with high melting temperature, greater-than-ever level of precision (sub-micron) and less heat-affected-zone (HAZ). Mechanical properties (strength and hardness) and micro-structures (grain size) of the fabricated parts are investigated. For dissimilar materials bulk welding, good welding quality with over 210 MPa tensile strength is obtained. Also full melting of the micron-sized refractory powders with high melting temperature (above 3000°C) is achieved for the first time. Millimeter-scale resolidified parts is obtained with grain size smaller than 1 μm. 3D micro parts with complex internal structure are demonstrated with limited HAZ. Not only does this study explore the melting feasibility of dissimilar and high melting temperature materials using fs lasers, but it also lays out a solid foundation for 3D printing of complex structure with designed compositions, microstructures and properties. This can greatly benefit the applications in automobile, aerospace and biomedical industries, by producing parts like nozzles, engines and miniaturized biomedical devices.

9353-10, Session 3

Microstructural evolution and mechanical behavior of nickel-based superalloy 625 made by selective laser melting

David B. Witkin, Paul M. Adams, Thomas V. Albright, The Aerospace Corp. (United States)

The mechanical properties and microstructures of Selective Laser Melted (SLM) alloy 625 procured from different suppliers were compared. The post-SLM process of hot isostatic pressing (HIP) led to a relatively coarse recrystallized gamma matrix phase that was similar in all the suppliers' materials, resulting in nearly identical tensile properties. These similarities obscure significant differences between them with respect to the population of second phase particles, which consisted of carbides or Laves-type silicides. During solidification, the final liquid phase is concentrated in Nb, Mo, Si and C, and leads to L ? ? + carbide/Laves eutectic reactions. Secondary particles are limited to these are nearly non-detectable in the fine-grained eutectic regions of the material prior to HIP. During HIP the gamma phase recrystallizes to remove the original as-solidified SLM microstructure, but secondary particles nucleate and grow where their elemental constituents first solidified, leading to non-homogeneous distribution. Quasi-static tensile properties do not appear to be sensitive to these differences, but it is likely that other mechanical properties will be affected, especially fatigue and fracture behavior. Surface roughness, large grain size, and pores and voids left unhealed by the HIP cycle will also influence fatigue and fracture. Surface roughness and porosity in particular are features that could be improved by implementing novel approaches to laser processing in SLM.

9353-11, Session 3

Composition analysis using laser induced plasma for metal additive manufacturing

Lijun Song, Wenkang Huang, Ting Tan, Hunan Univ. (China)

"Certify as you build" as a new manufacturing paradigm caters to the request of intelligent manufacturing, which requires sophisticated science based in-situ diagnostic techniques to produce defect free parts suitable for their service performances. During laser aided metal additive manufacturing process, composition losses due to evaporation effect by high powder laser may cause the performance failure of the manufactured parts. In this paper, laser induced plasma during laser aided metal additive manufacturing is characterized by plasma temperature and electron density. Composition prediction is implemented using both calibration curve method and support vector machine method, which extract useful information from plasma signals. Both methods provide suitable in-situ composition prediction to fulfill as part of "certify as you build" manufacturing paradigm.

9353-203, Session Plen

Laser 3D Printing of Metallic Components and its Industrial Applications: Technical Breakthroughs and Opportunities

Xiaoyan Zeng, Wuhan National Lab. for Optoelectronics (China)

Laser melting deposition (LMD) with powder feeding and selective laser melting (SLM) with powder bedding are two typical methods of laser 3D printing to fabricate metallic components directly from designed 3D data with high performance, net-shape, short cycle, and almost 100% density. In this talk, the current status and main technical breakthroughs in both LMD and SLM in China will be introduced and compared from different aspects, including: compositions, microstructures, performances, and dimensional precisions of components. Laser 3D printing promises a revolutionary progress to shorten production cycles and costs, and to improve the component quality in aeronautics, astronautics, and other industrial fields in the coming years.

9353-12, Session 4

Development of high-strength and light-weight hierarchical materials based on 3D direct laser writing *(Invited Paper)*

Jens Bauer, Almut Schroer, Ruth Schwaiger, Oliver Kraft, Karlsruher Institut für Technologie (Germany)

We have developed cellular materials with the aim to combine high strength with light weight. This is achieved by designing specific micro-architectures, which are fabricated by applying 3D direct laser writing [1]. The structures consist of polymeric trusses with typical diameters of 0.5-1.0 μm. The structures are coated with various ceramic films by atomic layer deposition with thicknesses in the range of 10 to 100 nm. The approach takes advantage of a mechanical size effect as the strength of such thin films exceeds the one of the bulk counterpart. With respect to their mechanical properties, the truss structures are characterized using nanomechanical testing methods. We demonstrate that the specific strength of these artificial cellular materials is higher compared to all other engineering foams with a density below 1 g/cm?. It is also found that the elastic deformation behavior as well as the failure of the structure depends sensitively on details of the truss architecture. Currently, two approaches are pursued to further increase the strength of the materials. First, the aspect ratio of the trusses is reduced and, second, other ceramic coating materials are examined.

[1] J. Bauer, S. Hengsbach, I. Tesari, R. Schwaiger, and O. Kraft "High-strength cellular ceramic composites with 3D microarchitecture" PNAS (2014)

9353-13, Session 4

On the influence of atmospheric oxygen on 2D and 3D direct laser writing

Michael Adams, Jonathan B. Mueller, Joachim Fischer, Martin Wegener, Karlsruher Institut für Technologie (Germany)

Oxygen is known to be an effective inhibitor for radical polymerization reactions. However, little attention has been paid to the impact of atmospheric oxygen on direct laser writing by multi-photon polymerization. We present our recent experimental results, indicating that oxygen quenching is the dominating termination reaction for polymerization in this case, if - as usual - no special attention is paid to provide an oxygen-free environment. As the polymerization reaction is spatially confined, oxygen diffusion is shown to enhance this effect, both in 2D and 3D lithography.

For 3D lithography, oxygen leads to an increase of the polymerization threshold power by factors of two to four. This effect is the most prominent if the exposure time is longer than typical diffusion time constants, as oxygen diffusion then occurs during polymerization from the surrounding (unexposed) photoresist. We also take a close look at laser lithography in photoresist films. Here, we find that writing in thin films of less than approx. 100 nm is not even possible under oxygen-containing atmosphere. The reason is that in this case, diffusion from the photoresist-air-interface is dominating. When using a blue diode laser for one-photon absorption, polymerization threshold powers as low as 100 pW are achieved under nitrogen atmosphere. This corresponds to a reduction in required laser power by about four orders of magnitude. Therefore, highly parallel laser lithography appears to be in reach even with relatively inexpensive sources.

9353-14, Session 4

Advantages and drawbacks of Thiol-ene based resins for 3D-printing

Holger Leonards, Sascha Engelhardt, Andreas Hoffmann, Fraunhofer-Institut für Lasertechnik (Germany); Ludwig Pongratz, Sascha Schriever, Jana Bläsius, Fraunofer ILT (Germany); Martin M. Wehner, Arnold Gillner, Fraunhofer-Institut für Lasertechnik (Germany)

The technology of 3D printing is conquering the world and awakens the interest of many users in the most varying of applications. New formulation approaches for photo-sensitive thiol-ene resins in combination with various printing technologies, like micro-stereolithography, projection based printing or multiphoton polymerization are presented. Thiol-ene polymerizations are known for its fast and quantitative reaction and to form highly homogeneous polymer networks. As the resins are locally and temporally photo-curable the polymerization type is very promising for 3D-printing. By using suitable wavelengths, photoinitiator-free fabrication is feasible for single- and two photon induced polymerization. Vinyl esters of polyethylene glycols in combination with star-shaped thiols were used to design a simple test-system for photo-curable resins. In order to control and improve curing depth and lateral resolution in 3D-polymerization processes, either additives in chemical formulation or process parameters can be changed. The achieved curing depth and resolution limits depend on the applied fabrication method. While multiphoton induced lithography offers the possibility of micron- to sub-micron resolution it lacks in built-up speed. Hence singlephoton polymerization is a fast alternative with optimization potential in sub-10-micron resolution. Absorber- and initiator free compositions were developed in order to avoid aging, yellowing and toxicity of resulting products. They can be cured with UV-laser radiation below 300 nm. The development at Fraunhofer ILT is focusing on new applications in the field of medical products and implants, technical products with respect to mechanical properties or optical properties of 3D-printed objects. Recent results with advantages, drawbacks and prospects are presented.

9353-15, Session 4

Direct laser writing of 3D nanostructures using a 405nm laser diode

Patrick Mueller, Karlsruher Institut für Technologie (Germany) and Nanoscribe GmbH (Germany); Michael Thiel, Nanoscribe GmbH (Germany); Martin Wegener, Karlsruher Institut für Technologie (Germany)

Direct laser writing (DLW) is a well-known and established technology for fabricating 3D micro- and nanostructures. Usually, red femtosecond laser sources with wavelengths around 800 nm are used. Here, we use a laser diode with a wavelength of 405 nm as the exciting laser source and thus improve structures in terms of decreasing feature size and line distance by exploiting the linear wavelength dependence of the Sparrow resolution limit. A nonlinear multi-photon polymerization process is necessary for manufacturing true 3D structures. We investigate different photoresists and measure their nonlinearities by variation of the electronic pulse scheme of the laser. We observe an adequately high nonlinearity in a resist system based on the monomer pentaerythritol triacrylate. To benefit from the improved theoretical resolution of the smaller wavelength, it is necessary to achieve a close to diffraction-limited focal spot which we have confirmed by measuring the point spread function of the objective lens and comparing it to numerical simulations. In order to prove the performance of the system, we fabricate benchmark structures and characterize them with different experimental methods. Line gratings and point arrays are written to investigate 2D resolution and feature sizes. To characterize the capabilities in 3D, we fabricate woodpile photonic crystals that show a photonic stop band in the visible. The achievable lattice constants in both 2D and 3D are considerably smaller than in previous work with red femtosecond lasers, proving the success of the wavelength-reduction approach. Previous work using the conceptually diffraction-unlimited STED technology is also outperformed.

9353-16, Session 5

Polymer microframes by interference lithography and 3D direct write *(Invited Paper)*

Edwin L. Thomas, Rice Univ. (United States)

Periodic polymers can be made by photolithography. Such materials provide a versatile platform for 1, 2 and 3D periodic nano-micro scale composites with either dielectric or impedance contrast or both, and these can serve for example, as photonic and or phononic crystals for electromagnetic and elastic waves as well as mechanical frames/trusses. Current interest is in our group focuses using design - modeling, fabrication and measurement of polymer-based periodic materials for applications as tunable optics and control of phonon flow. We employ mulitbeam interference lithography, phase mask lithography and 2 photon direct write techniques to make 200nm - micron scale periodic structures. Several examples will be described including the design of structures for multispectral band gaps for elastic waves, the creation of carbon nano frames for templates for block copolymers and robust bicontinuous ballistic resistant structures and quasi-crystalline solid/fluid structures that can steer shock waves.

9353-17, Session 5

Tailored multiphoton polymerization with abruptly autofocusing beams

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Cylindrically symmetric Airy beams[1] (ring-Airy beams) can abruptly autofocus, along their propagation, delivering high intensity contrast at the focus position. It is also quite interesting the fact that such beams present long working distances, tight focusing and small focal volumes[2], while nonlinear propagation effects can be very exciting[3]. Here we demonstrate experimentally generated ring-Airy beams using a Fourier Transform (FT) approach[2] and a simple method to spatially control their autofocus position. The generated ring Airy beams have a high aspect ratio focal voxel that can be positioned at different working distances keeping almost invariant its dimensions and shape. These remarkable abilities of ring Airy beams make them ideal candidates for direct laser writing by multiphoton polymerization. The controllable, long working distance and the high aspect ratio focal volume, surpass the restrictions set to the overall height of a 3D structure when using Gaussian beams and small working distance, high NA objective lenses. We present 3D structures made using ring-Airy beams that were set to autofocus inside the volume of a photoresist while the sample was moved only on the x-y plane. Finally, we report on parametric results of such ring Airy beams and also compare with Bessel beams.

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9353-18, Session 5

Hierarchical 3D nano-architectures for photonics, biomimetics, and lightweight structural materials *(Invited Paper)*

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Creation of extremely strong yet ultra-light materials can be achieved by capitalizing on the hierarchical design of 3-dimensional nano-architectures. Such structural meta-materials exhibit superior thermo-mechanical properties at extremely low mass densities (lighter than aerogels), making these solid foams ideal for many scientific and technological applications. The dominant deformation mechanisms in such "meta-materials", where individual constituent size (nanometers to microns) is comparable to the characteristic microstructural length scale of the constituent solid, are essentially unknown. To harness the lucrative properties of 3-dimensional hierarchical nanostructures, it is critical to assess mechanical properties at each relevant scale while capturing the overall structural complexity.

We present the fabrication of 3-dimensional nano-lattices whose constituents vary in size from several nanometers to tens of microns to millimeters. We discuss the deformation and mechanical properties of a range of nano-sized solids with different microstructures deformed in an in-situ nanomechanical instrument. Attention is focused on the interplay between the internal critical microstructural length scale of materials and their external limitations in revealing the physical mechanisms which govern the mechanical deformation, where competing material- and structure-induced size effects drive overall properties.

We focus on the deformation and failure in metallic, ceramic, and glassy nano structures and discuss size effects in nanomaterials in the framework of mechanics and physics of defects. Specific discussion topics include: fabrication and characterization of hierarchical 3-dimensional architected meta-materials for applications in biomedical devices, ultra lightweight batteries, and damage-tolerant cellular solids, nano-mechanical experiments, flaw sensitivity in fracture of nano structures.

9353-19, Session 5

Two-photon polymerization of hybrid polymers for applications in micro-optics

Sönke Steenhusen, Fraunhofer-Institut für Silicatforschung (Germany); Frank Burmeister, Hans-Christoph Eckstein, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Ruth Houbertz, Fraunhofer-Institut für Silicatforschung (Germany) and Multiphoton Optics GmbH (Germany)

Miniaturization and higher integration of opto-electronic components require highly sophisticated optical designs and materials. Especially, light guiding, light steering or – in general – light management is a key factor for the functionality and performance of devices. However, classical fabrication technologies for micro-optical structures rely on 2.5-dimensional processes, which limit assembly designs strongly.

Freeform technologies such as Two-photon polymerization (2PP) are considered as versatile tools to enable new designs for future components, since arbitrarily shaped functional structures can be created in 3D. In 2PP, the polymerization reaction is triggered by tightly focused femtosecond laser pulses. The solidification of the photopolymer is confined spatially as light intensities only exceed the polymerization threshold in the focal volume. 3D scanning enables true 3D lithography.

The application of hybrid polymers in 2PP is beneficial in multiple ways, because they combine the advantages of organic photodefinable polymers and glass-like materials. They can, for example, be processed like conventional negative tone resists, and offer outstanding chemical, mechanical, and thermal stability. In addition, their optical properties such as refractive index and absorption can be widely tailored to the application requirements.

We present our recent progress in the fabrication of micro-optical structures using 2PP and specially designed hybrid polymers (ORMOCER®s). Among the structures are freeform and aberration-optimized micro-lenses, and multilevel diffractive optical elements. These components are discussed with respect to the fabrication process and their resulting optical performance. Furthermore, 2PP-initiated refractive index modification, offering high potential for energy-efficient fabrication of 3D optical interconnects, is discussed.

9353-20, Session 5

Parallel optical micro/nanofabrication using desktop digital projection micro-stereolithography *(Invited Paper)*

Nicholas X. Fang, Massachusetts Institute of Technology (United States)

We are at the threshold of exploring an entirely new world of functional micro and nanosystems: the emergence of hierarchical 3D networks of nano-electronics, nano-photonics, nano-electromechanical systems (NEMS)

and nano-biomedical devices necessitate developments of cost-effective and high throughput 3D nano manufacturing techniques. However, due to the planar nature of current fabrication technology, the geometry and functionality of the nanodevices are severely limited. Several additive manufacturing options have been limited by either speed or the ability to fabricate true three-dimensional structures.

We present here an innovative Projection micro-stereolithography (PuSL) technology that promises mass production of truly complex 3D micro/nanosystems with CAD/CAM capability. The core of our PuSL technology is the use of a digital light display as the dynamic mask for solid freeforming simultaneously with million pixels of better than 400nm resolution. Our homebuilt prototype system can readily reproduce 3D microstructure of thousands of layers of excellent alignment fidelity within a couple of hours. This invited talk discusses the critical process parameters that influence polymerization depth and structure quality. Experimental characterization and performance of the LED-based P?SL system for fabricating highly complex three-dimensional structures for a large range of applications, such as ultra-lightweight and ultra-stiff cellular materials and acoustic absorbers, will also be discussed.

9353-21, Session 5

Three-dimensional two-photon laser fabrication for metals, polymers, and magneto-optical materials *(Invited Paper)*

Takuo Tanaka, RIKEN (Japan); Atsushi Ishikawa, Okayama Univ. (Japan); Tomohiro Amemiya, Tokyo Institute of Technology (Japan)

We present the three-dimensional (3D) two-photon laser fabrication techniques for metal, polymer, and magneto-optical structures. Two-photon-induced reduction of metal complex ions was developed to create 3D metal micro/nano structures. Owing to the inhibition of unwanted growth of metal nano crystals using surfactant molecules, we have successfully improved the spatial resolution of fabricated metal structures down to 100 nm in linewidth. Arbitrary shaped 3D silver structures with high electric conductivity were fabricated. Two-photon-induced photopolymerization technique has been applied for the photonic wire bonding. We have demonstrated the optical interconnection of III-V based DFB lasers and photo detectors by polymer wires with optical coupling loss less than 0.3dB. We also applied two-photon laser irradiation technique for the modification of the magnetic properties of cerium-substituted yttrium iron garnet crystal (CexY3-xFe5O12: Ce:YIG). A Ce:YIG layer was epitaxially-grown on a monomagnetic garnet (<111>-SGGG) substrate. 3D fs laser scanning in the Ce:YIG layer creates the micrometer patterns of both refractive index and magnetic properties change of the crystal. The magnetic pattern was observed as the magneto-optical polar Kerr effect (MOKE) images. When the external magnetic field was applied to the crystal, the laser irradiated regions easily changed their magnetization while the non-irradiated ones tended to maintain their magnetization. From the result, we demonstrated the micro/nanometer scale patterning of both optical and magnetic properties in the Ce:YIG crystal.

9353-22, Session 6

Additive manufacturing of optical elements from inorganic materials *(Invited Paper)*

Augustine M. Urbas, Jonathan T. Goldstein, Christopher E. Tabor, Air Force Research Lab. (United States); Ed C. Kinzel, Missouri Univ. of Science and Technology (United States)

3D Printing of lenses and waveguide structures offers the potential to incorporate gradients of optical properties and complex optical surfaces to dramatically increase the design space of optical systems. Direct printing of optical components and systems can be enabled by the development of printable high quality dielectric materials. Dielectric materials are one of the basic components of electronic and optical systems and polymer materials are flexible and capable and can serve both in electronic and optical systems. Research on printed optical components has been conducted using polymer based materials with promising results for visible and NIR wavelengths. In optics, polymers and organics have substantial losses at infrared wavelengths because of absorption in the material. Ceramics and glasses are the materials of choice in this wavelength range, but precursors and processes compatible with 3D printing of optical quality components from these materials are not readily available. We will overview efforts to develop material and process combinations which can enable 3D printing or additive manufacturing of optical quality materials and components. We will review current work in this area to explore materials processing of ceramics and glasses that could lead to printing of optical quality materials and address topics such as precursor materials, process methods (including laser sintering and laser assisted melting), bulk material properties and surface quality which will present key challenges for identifying viable paths to print complex optical components.

9353-24, Session 6

High resolution Laser Micro Sintering / Melting using q-switched and high brilliant laser radiation *(Invited Paper)*

Horst Exner, Andrè Streek, Hochschule Mittweida (Germany)

Since its invention by Carl Deckard & colleagues [1] selective laser sintering has been upgraded continuously to meet the requirements for the production of functional components [2]. A considerable contribution to the improvement of resolution was the modification and optimization of the already established technology in 2001 by Laserinstitut der Hochschule Mittweida. It resulted in a technology termed laser micro sintering. The main features are the employment of q-switched laser pulses and the use of powder with particle sizes in the μm-range. Resolutions have been achieved that approximate the focal diameter (25 μm). A great disadvantage was the limited powder bed density of the applied fine grained powders. Therefore, the recoil forces of the expanding plasma generated by the high intensive q-switched pulses were necessary as a powder condensing mechanism. Because of limited intensities of commonly available laser sources in the past a technique for laser sintering of fine grained powders with a cw-Laser was never accomplished. Applying new high power laser sources with highest brilliance coupled with a powder compacting mechanism allows for laser micro sintering with cw-radiation, which is commonly denoted as laser melting, but in our case in the micro scale dimension.

The new developed powder densification equipment will be shown. Powder densities before laser sintering of above 50% are demonstrated. The applicability for the laser sinter process with layer thicknesses below 10 μm is shown. The deflection speed of the applied brilliant laser beam could be increased by a new developed polygon scanning system up to 1000 m/s. Laser sintering/melting results up to 500 m/s are shown. Simultaneously the build rate is increasing dramatically by a factor of about 50. The Laser Micro Melting (LMM) is born.

9353-25, Session 6

Mechanisms of 3D nanoparticles formation using direct laser writing and thermal annealing in a phosphate glass

Nicolas Marquestaut, Lab. Ondes et Matière d'Aquitaine (France); Yannick G. Petit, Institut de Chimie de la Matière

Condensée de Bordeaux (France); Patrick Mounaix, Lab. Ondes et Matière d'Aquitaine (France); Thierry Cardinal, Institut de Chimie de la Matière Condensée de Bordeaux (France); Lionel Canioni, Lab. Ondes et Matière d'Aquitaine (France)

In this paper, we demonstrate the first true 3D-patterning of metal-dielectric composites at the sub-micrometer scale in glass. A high silver-content zinc-phosphate optical transparent glass is structured by means of a near-infrared femtosecond laser via nonlinear absorption processes. The silver ions embedded in glass photo-chemically react under controlled laser irradiation, inducing ions clustering and formation of nucleation centers. A subsequent thermal development allows silver reduction and growth into metallic nanoparticles. A very strong surface plasmon resonance is measured, revealing the very high concentration of metallic particles. Our direct laser writing process enables inscriptions of silver nanoparticles domains well below the diffraction limit (~100 nm). A very detailed parametric study is given, leading to the first thorough understanding of the ultrafast laser-induced photochemistry in silver-containing glass materials.

The reported results demonstrate an entirely new capability to address the problem of controlling nano-assembly processes of three-dimensional metal disconnected nanoparticles patterns in fully inorganic and stable hard materials. It allows the synthesis of homogeneously-dispersed, encapsulated nanoparticles, paving the way to the direct 3D-patterning of nano-composites for (i) sensing via plasmonics, (ii) photonics or even (iii) metamaterials applications.

9353-26, Session 6

Mesoscale pentamode metamaterial elasto-mechanical cloak by 3D galvo-scanner dip-in direct laser writing *(Invited Paper)*

Tiemo K. Bückmann, Karlsruhe Institute of Technology (Germany); Michael Thiel, Karlsruhe Institute of Technology (Germany) and Nanoscribe GmbH (Germany); Muamer Kadic, Robert Schittny, Karlsruhe Institute of Technology (Germany); Martin Wegener, Karlsruhe Institute of Technology (Germany) and Nanoscribe GmbH (Germany)

3D galvo-scanner dip-in direct-laser-writing optical lithography allows for the fabrication of mechanical metamateral architectures with deep submicron features yet cubic millimeter overall volumes at the same time. Here we focus on 3D pentamode metamaterials, which can be seen as meta-liquids. For example, we have designed, fabricated and characterized polymeric core-shell elastostatic unfeelability cloaks composed of as many as 1024 extended fcc unit cells. As another example, aiming at the dynamic case, we present modified pentamode architectures allowing for independently tailoring bulk modulus and mass density, hence phase velocity and wave impedance.

In more detail, regarding the static unfeelability cloak, we have optically imaged the metamaterial structure while pushing onto it from the top. Using an image autocorrelation analysis, we measure the displacement vector field for reference, obstacle, and cloaking samples. In agreement with microscopic calculations, good cloaking is obtained in the quasi-static case.

With respect to the dynamic case, we suggest and realize a design in which a first structure parameter mainly determines the bulk modulus and a second structure parameters mainly determines the mass density. We show that this blueprint, which contains fine features and large elements in the unit cell at the same time, can be fabricated by 3D galvo-scanner dip-in direct-laser-writing optical lithography. We also show that laminates of such modified pentamode metamaterials with equal bulk modulus yet different mass density allow for effectively anisotropic dynamic mass density tensors.

9353-45, Session 6

Pulsed laser ultrasonic excitation and heterodyne detection for in situ process control in additive metal manufacturing

Anthony J. Manzo, Henry Helvajian, The Aerospace Corp. (United States)

No Abstract Available

9353-27, Session 7

Insights into cellular contact guidance through 3D nanofabrication *(Invited Paper)*

Wolfgang Losert, Univ. of Maryland, College Park (United States)

Guided cell migration is essential for many living organisms for development, wound healing or immune response. In addition to chemical cues, cells are able to sense and follow the texture of their surrounding environment in the natural world. In this presentation I will illustrate the use of 3D nanofabrication techniques to create topographies that are recognized by the cells and guide cell motion. Sensing of nanotopography is based on control of intracellular waves that allow cells to follow topographical features on the 100s of nm scale, raising the possibility of control of cell behavior through nanofabrication of finetuned topographies.

9353-28, Session 7

Additive laser-based techniques for surface structuring of 3D micro-replication tools

Nerea O. Otero, Pablo M. Romero, Ivette Coto, Cristina Leira, AIMEN - Asociación de Investigación Metalúrgica del Noroeste (Spain)

Additive laser manufacturing in combination with micromachining is a powerful means for generating microfeatures on moulds for micro-injection moulding of polymeric medical devices. Laser microcladding is the technique of surfacing by melting of additive material on the substrate, when the produced features are micron-sized.

This paper explores the application of laser-based additive technologies for the surface structuring of metallic moulding tools. Pre-placed layer of powder on the substrate surface and an automated technique using a powder feeding combined with a micro-cladding head are used to produce the microstructures on already machined moulds. The need for producing features of a few tens of microns implies certain stringent requirements on the laser sources, powder feeding equipment and powder characteristics. Microcladding has been developed for micro-features production, precision repairing, and direct manufacturing. The limits of the methods are being expanded thanks to new processing regimes, new laser sources and feeding concepts. The tool materials are different tool steels and heat treatable aluminium alloys. Initial results are presented in novel glass-based microrreplication tools.

The laser source used in this work is a diffraction limited single mode fibre laser (Trufibre 400), with a fibre core diameter of 11 microns and a maximum power of 400 W. This equipment is representative of the new generation of high brilliance industrial lasers, able to produce high energy densities for fast and accurate processing. The advanced power modulation of this laser is exploited in this work to produce high geometrical quality, low dilution and low heat input cladding tracks by controlling the temporal profile of the energy deposited.

Different materials were used in microcladding generation, in order to

test the potential of the technology, as well as the dependence of results on the nature of the workpiece material. Powder melting with low power, highly focused laser is a stable process at scanning speeds over 1000 mm/s and power densities about 10 MW/cm2. High scanning speeds also avoids excessive dilution and heat effects. The geometrical quality, accuracy, stability and minimum track size are discussed in relation with the laser parameters, but also with their dependency on the powder size distribution, size and powder placement procedure.

9353-29, Session 7

Cellular scanning strategy for selective laser melting: Generating reliable, optimized scanning paths, and processing parameters

Sankhya Mohanty, Jesper H. Hattel, Technical Univ. of Denmark (Denmark)

Selective laser melting is yet to become a standardized industrial manufacturing technique. The process continues to suffer from defects such as distortions, residual stresses, localized deformations and warpage caused primarily due to the localized heating, rapid cooling and high temperature gradients that occur during the process. While process monitoring and control of selective laser melting is an active area of research, establishing the reliability and robustness of the process still remains a challenge.

In this paper, a methodology for generating reliable, optimized scanning paths and process parameters for selective laser melting of a standard sample is introduced. The processing of the sample is simulated by sequentially coupling a calibrated 3D pseudo-analytical thermal model with a 3D finite element mechanical model. A customized genetic algorithm is used along with the simulation model to generate optimized cellular scanning paths and processing parameters, with an objective of reducing thermal asymmetries and mechanical deformations.

The optimized processing parameters are then subjected to a Monte Carlo method based uncertainty and reliability analysis. Confidence intervals are evaluated for history outputs such as maximum temperature, maximum Von-Misses stress, etc. The reliability of the process is established using cumulative probability distribution functions for process output criteria such as final sample density, maximum deformation, etc. The optimized scanning strategy is used for selective laser melting of the standard samples, and experimental and numerical results are compared.

9353-30, Session 7

Certify as you build: A challenge for additive manufacturing *(Invited Paper)*

Jyoti Mazumder, Univ. of Michigan (United States)

Additive Manufacturing (AM) has been hailed as the “third industrial revolution” by The Economist magazine [April-2012], although the first patent on Stereo-lithography was awarded in 1986. An enabling technology which can build, repair or reconfigure components layer by layer or even pixel by pixel with appropriate materials to match the performance will enhance the productivity and thus reduce energy consumption. The capability to form a three dimensional object directly form digital data reduces many intermediate steps in manufacturing and thus potentially an attractive and economic fabrication method. This is very suitable for low volume manufacturing.

Quality assurance for any low volume manufacturing is a challenge. Statistical quality control is not applicable due to low volume. In-situ optical diagnostics and its capability to integrate with the process control is a prudent alternative. The two main groups of AM are powder bed (e.g. Laser Sintering) and pneumatically delivered powder (e.g. Direct Metal Deposition [DMD]) to fabricate components. DMD enables one to deposit different material at different pixels with a given height directly from a CAD drawing. The feed back loop also controls the thermal cycle. New optical Sensors are being developed to control geometry using imaging, cooling rate by monitoring temperature, microstructure, temperature and composition using optical spectra. Ultimately these sensors will enable one to “Certify as you Build”. Flexibility of the process is enormous and essentially it is an enabling technology to materialize many a design. Conceptually one can seat in Detroit and fabricate in Dusseldorf.

9353-31, Session 8

Microfabrication of three-dimensional filters for liposome extrusion *(Invited Paper)*

Tommaso Baldacchini, Newport Corp. (United States); Vicente Nunez, Univ. of California, Riverside (United States); Ruben Zadoyan, Newport Corp. (United States)

Liposomes play a relevant role in the biomedical field of drug delivery. The ability of these lipid vesicles to encapsulate and to transport a variety of bioactive molecules has fostered their use in several therapeutic applications, from cancer treatments to the administration of drugs with antiviral activities. Size and size distribution are key parameters to take into consideration when preparing liposomes; these factors greatly influence their effectiveness in both in vitro and in vivo experiments. A popular technique employed to achieve the appropriate liposomes dimension (around 100 nm in diameter) and uniform size distribution is repetitive extrusion through a polycarbonate filter. We present a methodology whereby two-photon polymerization (TPP) is used to fabricate three-dimensional filters within a microfluidics chip for liposomes extrusion. We take advantage of the unique capabilities of TPP to create intricate three-dimensional microstructures for studying the effect of the filter pore size and pore geometry on the extrusion of liposome. Furthermore, the miniaturization of the extrusion process in a microfluidic system is the first step toward a complete lab-on-a-chip preparation of liposome from vesicle self-assembly to optical characterization.

9353-32, Session 8

High power laser beam melting of Ti6Al4V on deformed sheet metal to achieve hybrid structures

Bhrigu Ahuja, Lehrstuhl für Photonische Technologien (Germany); Adam Schaub, Lehrstuhl für Fertigungstechnologie (Germany); Michael Karg, Lehrstuhl für Photonische Technologien (Germany); Marion Merklein, Lehrstuhl für Fertigungstechnologie (Germany); Michael Schmidt, Lehrstuhl für Photonische Technologien (Germany)

Motivated by the desire to combine additive manufacturing flexibility with sheet metal forming efficiency, the concept of hybrid fabrication using the two processes emerged. Laser Beam Melting process with its characteristic layer by layer fabrication methodology has already been proved to be successful in fabricating fully dense 3D structures with micro sized Ti6Al4V powder. The presented research focuses on direct fabrication of Ti6Al4V Additive Structures on a deformed Ti6Al4V sheet metal. In the standard Laser Beam Melting process, fabrication of solid structures is done on a support structure attached to a thick conventionally manufactured base plate. The state of the art also uses a 200°C pre-heating of the base plate in order to reduce the effect of heat induced stresses on the fabricated structures. Within the hybrid fabrication concept 3D structures are directly fabricated on a thin sheet metal and the thermodynamic conditions are significantly different in comparison to the conventional process. The research aims to understand the fundamental aspects of the interaction between the deformed sheet metal and additive structure and determine the corresponding mechanical characteristics. The interaction process during the fabrication exposes the alloy locally to non-optimum thermal cycles and the research therefore aims to understand the various influencing factors involved during the fabrication process. The system technology modifications required to achieve the aimed fabrication are also discussed in the presented research.

9353-33, Session 8

In situ process monitoring of selective laser melting at 200 kHz

Jordan A. Kanko, Christopher M. Galbraith, Queen's Univ. (Canada); Paul J. Webster, Laser Depth Dynamics Inc. (Canada); James M. Fraser, Queen's Univ. (Canada)

Although recent advances in selective laser melting (SLM) have allowed for the production of geometrically unique metallic parts, the complex and geometry-dependent nature of the SLM process still presents significant challenges that have yet to be overcome. Intra-layer variation in local thermal properties due to the surrounding/underlying material (bulk vs. powder) necessitate intensive process development to determine suitable processing parameters. Further advancement of the SLM industry requires in situ monitoring that is capable of providing a more extensive picture of the process dynamics, but at acquisition rates sufficient to ultimately achieve voxel-by-voxel feedback control of the process.

In this work we directly monitor the SLM process using Inline Coherent Imaging (ICI) – an inline low-coherence interferometric imaging technique similar to spectral-domain optical coherence tomography. Here, ICI is used to optically monitor process dynamics at 200 kHz measurement rates with ~10 micron-scale resolution (axial and transverse) and >60 dB dynamic range. Inline coherent imaging of selective laser melting provides unique insight into process dynamics undetectable by temperature-based melt pool measurements. Using ICI, melt pool and surrounding powder bed dynamics are imaged during single track processing. Additionally, post-process ICI measurements are used for in situ single track characterization and process parameter evaluation. Experiments involving ICI measurements of static SLM processing also allow the powder melting and solidification process to be imaged on microsecond timescales. The ability of this technique to monitor melt pool dynamics at 200 kHz offers immense potential for future online feedback control and process parameter optimization.

9353-34, Session 8

Process monitoring in additive manufacturing of metal parts *(Invited Paper)*

Corey M. Dunsky, Aeos Consulting, Inc. (United States)

Within the past two years, powder-bed additive manufacturing (AM) of metal parts has drawn an enormous surge of industrial interest and now appears to be a technology on the threshold of industrial acceptance. Despite this, in anticipation of the coming volume part-production ramps at major aerospace manufacturers, questions remain about process reliability and the repeatability of finished parts' material properties. Variability in the state of the AM machine or the laser-material interaction can perturb the metal's microstructure or macroscopic mechanical properties. Due to the repeated layer-upon-layer melting and rapid solidification of the metal in the Selective Laser Melting AM process, parts experience a complex thermal history involving directional heat transfer. Some of the major alloys for aerospace and medical/dental applications may also experience repeated solid state phase transformations. The directional heat transfer frequently results in anisotropy of grain structures and material density. In-situ, real-time monitoring of the AM process promises to address these concerns, but the monitoring technology is still in its early days. This review addresses the state of the art of this active area of AM research and equipment development, reporting on the perspectives of AM machine suppliers, small-company innovators, and research institutions.

9353-35, Session 9

Image-inspired 3D multiphoton excited fabrication of extracellular matrix structures by modulated raster scanning for cancer biology studies *(Invited Paper)*

Paul J. Campagnola, Visar Ajeti, Kevin W. Eliceiri, Manish Patankar, Univ. of Wisconsin-Madison (United States)

Multiphoton excited photochemistry is a powerful 3D biomimetic, biocompatible fabrication tool for several biological applications. Here we exploit the freeform nature of the process to create models of the extracellular matrix (ECM), where the design blueprint is derived directly from high resolution optical microscopy images (e.g. Second Harmonic Generation). To achieve this goal, we implemented a new form of instrument control, termed modulated raster scanning, where rapid laser shuttering (~10 MHz) is used to directly map the 8 bit greyscale image data to the resulting protein concentration in the fabricated scaffold. 3D constructs are then created by layering single optical sections, where standard file formats of image data (e.g. tiffs and jpegs) are used. Fidelity in terms of area coverage and relative concentration relative to the image data is ~95%. We compare the results to an STL approach, and find the new scheme provides significantly improved fidelity. Moreover, using .stl files requires hatching and results in limited dynamic range. As an example of the biological utility, we used the scaffolds to examine adhesion/migration dynamics in ovarian cancer, which has biological significance as mis-regulation of migration is a hallmark of cancer. The models are seeded with different cancer cell lines and this allows decoupling of the roles of cell characteristics (metastatic potential) and ECM structure and composition (normal vs cancer) on adhesion/migration dynamics which is not possible by other fabrication methods including lithographies or conventional 3D printing. We suggest the method will enable a variety of studies in cancer biology.

9353-36, Session 9

Preliminary investigation of keyhole formation during single track fabrication in laser additive manufacturing of stainless steel *(Invited Paper)*

Ville-Pekka Matilainen, Heidi Piili, Lappeenranta Univ. of Technology (Finland); Antti S. Salminen, Lappeenranta Univ. of Technology (Finland) and Machine Technology Ctr. Turku Ltd. (Finland); Olli Nyrhilä, Electro Optical Systems Finland Oy (Finland)

Laser additive manufacturing (LAM) is a fabrication technology which enables production of complex shaped parts with good mechanical properties comparable to conventionally manufactured parts. Work pieces are manufactured via melting metallic powder layer by layer with laser beam. This strategy involves various different independent and dependent thermal cycles all having an influence on the final properties of work piece.

It was observed that there are only few public studies about phenomena, like keyhole formation, occurring during single track LAM fabrication of metallic materials. Literature review carried during this study showed that most of studies about single track LAM are focused on properties of single tracks.

Quality of LAM parts depends strongly on each single laser-melted track and each single layer. This is why this study concentrates on investigating effects of the processing parameters, such as laser power, on single-track formation and phenomena occurring during this process.

Experimental tests of this study were made with two different machines: with a modified research machine representing EOS EOSINT M-series and with an EOS EOSINT M280. Material used was EOS stainless steel 17-4 PH.

After microscopy analysis, it was concluded that keyhole is formed during laser additive manufacturing of stainless steel. It was noticed that heat input has important effect on possibility to keyhole formation. Threshold intensity value of 10^6 W/cm^2 for keyhole formation was exceeded in all manufactured single tracks. Laser interaction time has effect on the depth of penetration and keyhole formation, since the penetration depth is increasing when laser interaction time increases.

9353-37, Session 9

Resolution enhancement through three color photolithography

Zuleykhan Tomova, John T. Fourkas, Univ. of Maryland, College Park (United States)

Multiphoton absorption polymerization (MAP) uses nonlinear absorption of near-infrared laser light to create complex, three-dimensional structures. Feature sizes fabricated with MAP lie in the sub-100 nm scale and can be further reduced by employing photoinitiators that can be deactivated in a technique known as resolution augmentation through photo-induced deactivation (RAPID). The original RAPID scheme involves two laser beams, one of which excites photoinitiator molecules to a high energy state, while the second beam is used to selectively deactivate molecules, so that they do not participate in the polymerization reaction, thus effectively reducing the size of the fabricated features.

An alternative approach to achieving super resolution through the depletion mechanism employs three visible light wavelengths. In such three color photolighography, one of the laser beams excites molecules to an energy state, which is not directly available for a deactivation beam. However, exposure to a second excitation beam brings molecules to a higher energy state, from which they could be deactivated directly. This way, polymerization depletion could happen at deactivation beam powers comparable to the excitation beam power. To investigate the most efficient depletion scheme, here we present experiments in which excitation and deactivation exposure wavelengths were varied to probe the states involved in the polymerization depletion reaction.

9353-38, Session 9

A study of transverse laser modes using a novel multi-scale simulation architecture for laser-based manufacturing technologies *(Invited Paper)*

Nachiket Patil, 3DSIM, LLC (United States); Deepankar Pal, 3DSIM, LLC (United States) and University of Louisville (United States); Chong Teng, Kai Zeng, Tim Sublette, 3DSIM, LLC (United States); Brent Stucker, Univ. of Louisville (United States) and 3DSIM, LLC (United States)

Laser-based additive manufacturing processes are particularly difficult to simulate due to high thermal gradients near the laser and very fast laser translation speeds. Typical FEA approaches are only capable of simulating a few mm of travel. A novel finite element architecture has been developed to bring together capabilities for dynamic multi-scale moving meshes, asynchronous time stepping, eigen-based computations, novel periodicity implementations, dislocation density crystal plasticity, and other innovations to make possible predictions of thermal history, residual stress accumulation, and microstructural predictions for full-sized components in a very efficient manner. An overview of this new computational architecture and its applications are given, illustrating the benefits of this approach compared to other computational approaches.

9353-39, Session 9

Laser 3D printing with CAD solid models and adaptive slicing direction improve fabrication accuracy

Tien-Tung Chung, Ya-Hsun Hsueh, Wan-Jou Li, Sheng-Yuan Chen, National Taiwan Univ. (Taiwan); Patrice L. Baldeck, Univ. Joseph Fourier (France)

3D printing technologies are mainly based on layer per layer additive manufacturing. This CAD CAM strategy is straightforward to implement, but it has major drawbacks including lack of precision for surfaces with small angles, and laminate weakness. Laser 3D printing based on two-photon induced photochemistry in transparent photoresists allows for real time adaptation of the slicing angle with the characteristics morphology of the product part being fabricated. We have previously reported on adaptive slicing direction for polygonal mesh 3D models based on local curvature angle criteria. Here, we use 3D CAD solid model to have the possibility to control the fabrication sequence and parameters of model parts. Thus, the slicing directions can also be easily optimized for each part. We demonstrate the final quality improvement with the fabrication of springs using a slicing direction perpendicular to its primitive line, and the fabrication of a horse-shape solid model with parts having vertical or horizontal slicing directions.

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9354-1, Session 1

Back-scattering in rain on bidirectional free-space optical links

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The backscattered effects of light propagation in rain play a very crucial role on the bidirectional FSO system. The backscattered laser pulse of one system will interfere with the receiving system of the other. Rain consisting of water droplets is described by realistic drop size distributions(DSD) with parameters related to physical parameters of hydrometeors such as rain intensity and atmospheric visibility. The backscattering phase function of various rain DSD models is discussed and calculated. A physical model of backscattered laser pulse is set up, and the actual back-scattering affect function is prompted, which can be used to evaluate the back-scattering power. We have verified the model by means of numerical Monte Carlo photon propagation simulations. A backscattered impulse response of optical channel in rain is obtained and the explicit model of the back-scattering power which measured at different horizontal position of the light source is provided. Simulations show that there is an optimal distance between transmitting and receiving system at the same end for a certain laser pulse. To verify the feasibility for the models under practical rainfall condition, the avalanche photodiode(APD) is used to measure the interferential pulse caused by back-scattering. The results have good consistency with the theoretical analysis and the numerical simulation.

9354-2, Session 1

Power-spectrum requirements in ultraviolet optical wireless networks

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Short range communications using an optical wireless channel in a non-line-of-sight regime can be attained by exploiting the solar-blind UV-C band. Here, the combined influence of the power loss and the bandwidth of the diffused wireless channel on signals was examined through simulations for different particle and molecular densities of the wireless medium. The transmissions were simulated for two extreme channel cases, though. OOK with NRZ pulses and PPM are the modulation schemes that are used. At the receiving side, estimations with photoelectrons were considered. The detection without threshold and the higher peak power for PPM are assets when compared to OOK. Moreover, it seems that a sparse medium may limit the performance of both PPM and OOK due to the increased optical losses and the slight ISI that is inserted. On the contrary, the estimated amelioration of the channel attributes for dense atmosphere offered a broader channel with lower losses. This was the reason to resort to the simulation of Code Division Multiple Access (CDMA) transmissions. In CDMA, if the coded signals are transmitted with the same mean and peak power, PPM seems to need more power in order to achieve better results than OOK. This confinement of PPM is mitigated in a dense channel. Finally, the linearity of the Power-Current curve of the LEDs at the transmitting side was also investigated, as intensely non-linear LEDs may limit the peak power and the number of the sources may increase, as well.

9354-3, Session 1

Scintillations of a partially coherent beam in a laboratory turbulence: Experiment and comparison to theory

Anatoly Efimov, Los Alamos National Lab. (United States)

Unlike open atmospheric turbulence the laboratory turbulence is stationary and statistically reproducible allowing for robust scintillation data to be obtained. Previous scarce experiments on propagation of spatially partially coherent beams (PCB) in turbulence did not yield data suitable for theoretical fitting. The high potential of PCBs for free-space optical communication requires thorough experimental confirmation and comparison to existing theories, which is the subject of this work. We measure scintillation index and other statistical characteristics of a PCB propagated through up to 20 meters of laboratory turbulence. Several existing theoretical formulations are fitted to the data, revealing certain discrepancies between them. Our method of PCB generation by coupling a broadband source into a multimode fiber is not only simple and straightforward, but also practical for high-data rate modulation, which we demonstrate in a separate experiment. Current data along with the results of our previous experiments in the open atmosphere confirm the superior performance of our PCB as compared to a coherent beam at all propagation ranges and its suitability for high-data rate communication through turbulent atmosphere.

9354-4, Session 1

Optical channel impact over the PSD of UWB over FSO links

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Impulse radio ultra-wideband (IR-UWB) is an attractive technology that enables the implementation of robust short-range wireless networks of high capacity, low complexity with high tolerance against to interference and very low power consumption. Nevertheless, in order to be able to deploy such technology, interference from UWB based devices to established narrowband deployments must be kept to satisfactory levels. Consequently, several regulatory bodies have established emission limits for UWB devices on the form of power spectral density masks (for instance the Federal Communications Commission - FCC). In this context the topic of power spectral density (PSD) shaping is of major interest for the design of compliant UWB systems.

The power restrictions limit the communication range of UWB devices to just a few meters, which produce UWB wireless networks operating in stand-alone mode. Therefore, with the purpose of increasing the coverage area and achieving seamless communications between stand-alone networks, ultra wideband over fiber (UWBoF) technology has been previously proposed. However, the deployment of fiber connecting stand-alone UWB networks is not always feasible. Thus, in this paper we propose and implement a UWB over free space optic (FSO) horizontal link. Initial results presenting the effects of the optical wireless channel over the UWB signal PSD are demonstrated. These results are analyzed and implementation recommendations are provided based on them.

9354-5, Session 1

A microwave radiometric method to obtain the average path profile of atmospheric temperature and humidity structure parameters and its application to optical propagation system assessment

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The values of the key atmospheric propagation parameters C2/T, C2/Q , and CTQ are highly dependent upon the vertical height within the atmosphere thus making it necessary to specify profiles of these values along the atmospheric propagation path. The remote sensing method suggested and described in this work makes use of a rapidly integrating microwave profiling radiometer to capture profiles of temperature and humidity through the atmosphere. The integration times of currently available profiling radiometers are such that they are approaching the temporal intervals over which one can possibly make meaningful assessments of these key atmospheric parameters. Since these parameters are fundamental to all propagation conditions, they can be used to obtain C2/n profiles for any frequency, including those for an optical propagation path. In this case the important performance parameters of the prevailing isoplanatic angle and Greenwood frequency can be obtained. The integration times are such that Kolmogorov turbulence theory and the Taylor frozen-??flow hypothesis must be transcended. Appropriate modifications to these classical approaches are derived from first principles and an expression for the structure functions are obtained. The theory is then applied to an experimental scenario and shows very good results.

9354-6, Session 2

Array receivers in downlink coherent lasercom

Aniceto Belmonte, Univ. Politècnica de Catalunya (Spain); Joseph M. Kahn, Stanford Univ. (United States)

Free-space laser downlinks have the potential to provide high data rates in space-to-earth communications and become a key enabler of future optical information systems in space. However, when a downlink passes through the atmosphere, clear-air turbulence induces serious phase distortion and fading. Here, we show how field conjugation adaptive array may function in downlink optical communications, overcoming the limitations imposed by the atmosphere by adaptively tracking and correcting atmospherically distorted signals.

The goal of this analysis is to provide measures of performance related to practical downlink coherent receivers using adaptive compensation of atmospheric effects. The analysis reveals that for typical downlink conditions, substantial system performance gains can be obtained using only a small number of apertures, supporting use of the proposed array receivers in future space-based optical communication systems.

9354-8, Session 2

Single-polarization, optical low-noise pre-amplified receiver for heavily-coded optical communications links

Jeffrey M. Roth, MIT Lincoln Lab. (United States); Amrita V. Masurkar, MIT Lincoln Lab. (United States) and Columbia Univ. (United States); Vincent Scalesse, Jeffrey R. Minch, Frederick G. Walther, Shelby J. Savage, Todd G. Ulmer, MIT Lincoln Lab. (United States)

We report on a single-polarization, optical low-noise pre-amplifier (SP-OLNA) that enhances the receiver sensitivity of heavily-coded 1.55-?m optical communication links. At channel bit-error ratios of approximately 10%, the erbium-doped SP-OLNA provides an approximately 1.0-dB receiver sensitivity enhancement over a conventional two-polarization pre-amplifier.

The SP-OLNA includes three gain stages, each followed by narrow-band athermal fiber Bragg gratings. This cascaded filter is matched to a return-to-zero, 2.88-Gb/s, variable burst-mode, differential phase shift keying (DPSK) waveform. The SP-OLNA enhancement of approximately 1.0 dB is demonstrated over a range of data rates, from the full 2.88-Gb/s (non-burst) data rate, down to a 1/40th burst rate (72 Mb/s).

The SP-OLNA's first stage of amplification is a single-polarization gain block constructed from polarization-maintaining (PM) fiber components, PM erbium gain fiber, and a PM integrated pump coupler and polarizer. This first stage sets the SP-OLNA's noise figure, measured at 3.4 dB. Two subsequent non-PM gain stages allow the SP-OLNA to provide an overall gain of 78 dB to drive a DPSK demodulator receiver. This receiver is comprised of a delay-line interferometer and balanced photo-receiver. The SP-OLNA is packaged into a compact, 5"?7"?1.6" volume, which includes an electronic digital interface to control and monitor pump lasers, optical switches, and power monitors.

9354-9, Session 2

Upwelling radiance at 976 nm measured from space using a CCD camera

Abhijit Biswas, Joseph M. Kovalik, Bogdan V. Oaida, Matthew Abrahamson, Malcolm W. Wright, Jet Propulsion Lab. (United States)

The Optical Payload for Lasercomm Science (OPALS) Flight System on-board the International Space Station uses a charge coupled device (CCD) camera for receiving a beacon laser from Earth. Relative measurements of the background contributed by upwelling radiance under diverse illumination conditions and varying terrain is presented. In some cases clouds in the field-of-view allowed a comparison of terrestrial and cloud-top upwelling radiance. In this paper we will report these measurements and examine the extent of agreement with atmospheric model predictions.

9354-31, Session 2

Achieving operational two-way laser acquisition for OPALS payload on the International Space Station

Matthew Abrahamson, Bogdan V. Oaida, Oleg V. Sindiy, Abhijit Biswas, Jet Propulsion Lab. (United States)

The Optical PAyload for Lasercomm Science (OPALS) began operations on the International Space Station on May 10, 2014 to demonstrate space-to-ground optical communications. The operations phase began with a full system checkout, followed by a series of tests to assess the bi-directional pointing alignment between OPALS and the Optical Communications Telescope Laboratory (OCTL) ground station in Wrightwood, CA. Following the successful tracking system checkout, OPALS transmitted a high-definition video to OCTL on June 5, 2014 at a data rate of 50 Mbps. This paper will discuss operational challenges during the OPALS 90-day prime mission, with focus on bi-directional pointing performance observed under various pass conditions. A key OPALS architecture component is acquiring and tracking a ground beacon illuminated by the OCTL ground station. The acquisition relies on appropriate flight camera exposure time settings based on the lighting conditions of each downlink attempt. In addition, a signal threshold setting is used to differentiate between the beacon signal and background noise during image processing. During OPALS prime mission, this threshold setting was especially difficult to determine during daylight operations when the signal-to-noise ratio was minimal. A higher

threshold setting often caused loss of beacon lock, while lower threshold settings caused temporary lock onto false signals. This paper discusses the benefits and challenges of the strategy implemented during operations. Additionally, the beacon signal received by the flight camera provides important information regarding system performance and alignment. The beacon signal strength indicates atmospheric variability, as well as potential systematic errors in the system performance. Figure 1 depicts the beacon flux strength as a function of gimbal azimuth angle over several downlink passes in June 2014. Positive azimuth angles indicate forward viewing along the travel path as the ISS approaches OCTL, while 0° represents zenith relative to OCTL and negative angles look backward toward OCTL. In this paper, the systematic dips in the observed signal strength will be correlated with flight system image processing and tracking performance. Additionally, the beacon position on the camera CCD provides an indirect alignment measurement of the ExPrESS Logistics Carrier-1 (ELC-1) platform relative to the ISS main truss. The paper will assess alignment performance by correlating beacon position offsets to errors in trajectory prediction, attitude prediction, and platform misalignment. In addition, this paper will summarize unexpected events encountered in OPALS operations. Many of these events were due to flight software limitations. For example, a lack of gimbal acceleration ceiling limits resulted in a loss of pointing knowledge during rapid gimbal slews. The paper will discuss how flight software enhancements during operations improved the OPALS payload performance.

9354-10, Session 3

Free space optical communication link using a silicon photonic optical phased array

William S. Rabinovich, Peter G. Goetz, Doewon Park, Marcel W. Pruessner, Michael J. DePrenger, Rita Mahon, Mike S. Ferraro, James L. Murphy, U.S. Naval Research Lab. (United States)

Components for free space optical communication terminals such as lasers, amplifiers, and receivers have all shrunk in both size and power consumption over the past several decades. However, pointing systems, such as fast steering mirrors and gimbals, have remained large and power-hungry. Optical phased arrays provide a possible solution for non-mechanical beam steering that can be compact and lower in power. Silicon Photonics is a promising technology for phased arrays because it has the potential to scale to many elements and has compatibility with CMOS fabrication. We demonstrate a short-range free space optical communication link that uses a silicon based optical phased array for beam steering. The phased array uses a multimode interference device to split an incoming beam into 12 separate waveguides. Steering is achieved using a single electrode to heat the waveguides and change their index. The electrode is designed so that the amount of heat in each waveguide linearly decreases producing an index gradient that steers the beam in one dimension. The performance of this system and prospects for further improvements are discussed.

9354-11, Session 3

Energy efficient rateless codes for high speed data transfer over free space optical channels

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Terrestrial Free Space Optical(FSO) links transmit information by using the atmosphere (free space) as a medium. In this paper, we have investigated the use of Luby Transform(LT) codes to mitigate the effects of data corruption induced by imperfect channel which usually takes the form of lost or corrupted packets. LT codes, which are a class of Fountain codes, can be used independent of the channel rate and as many code words as required can be generated to recover all the message bits irrespective of the channel performance. We compare the performance of LT codes with that of Bose, Chaudhuri, and Hocquenghem (BCH) and Low Density Parity Check (LDPC) codes over channels perturbed by atmospheric turbulence with Bit Error Rate (BER)and energy per bit consumption as the comparison metrics for signal transmission over the fading FSO channel. FSO channels can be modeled by using different distribution functions based on atmospheric parameters. Atmospheric turbulence can be characterized as weak, moderate or strong depending on the value of Rytov variance associated with turbulence experienced on the channel. We have derived the upper bound for the Binary Phase Shift Keying (BPSK) threshold for LT coded FSO channels with Gamma-Gamma distribution. LT codes, designed for erasure channels, can be used for transmission over error channels when suitable decoding schemes are used. We prove through theoretical computations and simulations that LT codes consume less energy per bit . Achieving error free high data rates with limited energy resources is possible with FSO systems if error correction codes with minimal overheads on the power can be used. Automatic Repeat Request (ARQ) is another method of improving link reliability and is used in erasure channels. However both Error Control Codes (ECC) and ARQ come at the cost of transmitted power. Improved performance can be obtained by using stronger codes with lower power consumption at the transmitter. Performance of ARQ is limited by the number of retransmissions and the corresponding time delay.We validate the feasibility of using energy efficient LT codes over ARQ for FSO links to be used in optical wireless sensor networks within the eye safety limits.

9354-12, Session 4

NASA's Optical Communications Program for 2015 and Beyond *(Invited Paper)*

Donald M Cornwell Jr., NASA Heaquarters, Space Communications and Navigation Program (United States)

NASA's Space Communications and Navigation (SCaN) Program within the Human Exploration and Operations Mission Directorate (HEOMD) at NASA HQ is pursuing a vibrant and wide-ranging optical communications program for future planetary and near-Earth missions following the spectacular success of NASA's Lunar Laser Communication Demonstration (LLCD) from the LADEE spacecraft orbiting the Moon in 2013 and 2014. Current projects include NASA JPL's Deep-space Optical Terminal (DOT) for a potential flight to Mars in 2020, NASA GSFC's Laser Communications Relay Demonstration (LCRD) for launch in 2018, MIT Lincoln Laboratory's LEO Terminal demonstration on the International Space Station (2019) and NASA GRC's integrated Radio and Optical Communications (iROC) development effort.

9354-13, Session 4

Optical payload for lasercom science (OPALS) link demonstration from the International Space Station (ISS) *(Invited Paper)*

Abhijit Biswas, Bogdan V. Oaida, Kenneth S. Andrews, Joseph M. Kovalik, Matthew Abrahamson, Malcolm W. Wright, Jet Propulsion Lab. (United States)

Recently several day and nighttime links under diverse atmospheric and weather conditions were completed using the Optical Payload for Lasercomm Science (OPALS) flight system on-board the International Space Station. In this paper we will compare received optical power and its variance at either end of the link with predictions based on atmospheric propagation models. The link performance in terms of bit-error rate as a function of range and elevation angle over the link durations will also be reported.

9354-15, Session 4

LCT for the European data relay system: In orbit commissioning of the Alphasat and Sentinel 1A LCTs

Frank F. Heine, Tesat-Spacecom GmbH & Co. KG (Germany); Gerd Muehlnikel, TESAT (Germany); Herwig Zech, Daniel Tröndle, Stefan Seel, Matthias Motzigemba, Tesat-Spacecom GmbH & Co. KG (Germany); Rolf Meyer, Sabine Philipp-May, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Edoardo Benzi, ESA / ESTEC (Netherlands)

The European Data Relay System (EDRS) relies on optical communication links between Low Earth Orbit (LEO) and geostationary (GEO) spacecrafts. Data transmission at 1,8 Gbps between the S/Cs will be applied. EDRS is foreseen to go into operation in 2015. As a precursor to the EDRS GEO Laser Communication Terminals (LCT), an LCT is embarked on the Alphasat GEO S/C, which was launched in July 2013. Sentinel 1A is a LEO earth observation satellite as part of ESAs Copernicus program. Sentinel 1A also has an LCT on board. Both the Alphasat and the Sentinel 1A LCT are currently in their in orbit commissioning phase. First LEO to GEO optical communication links are foreseen later in 2014. The presentation will explain the design principle of the LCT applied for EDRS and report on the most recent results of the in-orbit commissioning phase of the LCTs on board of Alphasat and Sentinel 1A.

9354-16, Session 5

TALON: A free space optical communication system for the U.S. Navy and Marine Corps *(Invited Paper)*

William S. Rabinovich, Christopher I. Moore, Linda M. Thomas, Nathan Smith, Harris R. Burris, Michael J. Vilcheck, Reed Smith, Dave Baker, Rita Mahon, James L. Murphy, Naomi Walker, Lindsey Willstatter, U.S. Naval Research Lab. (United States); Andrew B. Kowalik, John P. Janis, Dillen Li, Michael Ahn, Exelis Inc. (United States); James DeBruin, Marty Wand, Gunnar Ristroph, IJK Controls, LLC (United States); Stanley H. Uecke, Selwyn M. Yee, NovaSol (United States); David J. Harrison, LGS (United States); Alex Orgren, LGS Innovations Inc. (United States)

Free space optical (FSO) communication offers data links that have high bandwidth, are difficult to intercept, and are not subject to frequency allocation limitations. For Navy and Marine Corps applications, these characteristics make FSO attractive as an augmentation of existing RF links. The ONR TALON program is an effort to develop reliable, low cost FSO terminals for the Navy and Marine Corps. TALON terminals emphasize modularity, a necessity due to the intended usage characteristics. The optics and pointing and tracking system are enclosed in a head (the "optical antenna"), which can be mounted on a variety of gimbals. Single mode fiber inputs and multimode fiber outputs allow any modem that uses these standards to be hooked into the system. We present results from field-testing conducted over a total period of 18 months. Testing was conducted at three sites. A 16 km link was tested over water at NRL's Chesapeake Bay lasercom testbed. A 4 km link, with both terminals mounted on 100-foot high deployable masts, was conducted at Camp Pendleton, CA. A 50 km link over desert from mountaintop to mountaintop was conducted at China Lake, CA. Measurements of visibility, transmitted optical power and scintillation were taken under a variety of conditions and system settings. Packet error rates were also measured under a variety of conditions and with several different data transmission protocols.

9354-17, Session 5

LEO to ground optical communications from a small satellite platform *(Invited Paper)*

Todd S. Rose, Renny A. Fields, Siegfried W. Janson, Darren W. Rowen, David A. Hinkley, Richard P. Welle, The Aerospace Corp. (United States)

The NASA OCSD effort is a subsystem flight validation mission to test commercial-off-the-shelf components and subsystems that will enable new communications and proximity operations capabilities for CubeSats and other spacecraft. It will demonstrate optical communications using milliradian beam spreads that are compatible with near-term CubeSat pointing capabilities. The baseline mission will use a ~10-W modulated fiber laser with a 0.35o angular beamwidth on a 1.5U CubeSat (AeroCube-OCSD) and a 30-cm- diameter telescope located on Mt. Wilson in southern California to receive optical pulses. We plan on demonstrating 5-Mbps and 50-Mbps optical downlinks. In addition, the spacecraft will also flight test a laser rangefinder system, aerodynamic drag control, a miniature pair of star-trackers, and a steam thruster.

9354-18, Session 5

The meter-class carbon fiber reinforced polymer mirror and segmented mirror telescope at the Naval Postgraduate School

Christopher C. Wilcox, U.S. Naval Research Lab. (United States); Bautista R. Fernandez, John Bagnasco, Naval Postgraduate School (United States); Ty Martinez, U.S. Naval Research Lab. (United States); Robert C. Romeo, Composite Mirror Applications, Inc. (United States); Brij N. Agrawal, Naval Postgraduate School (United States)

The Adaptive Optics Center of Excellence for National Security at the Naval Postgraduate School has implemented a technology testing platform and array of facilities for next-generation space-based telescopes and imaging system development. The Segmented Mirror Telescope (SMT) is a 3 meter, 6 segment telescope with actuators on its mirrors for system optical correction. Currently, investigation is being conducted in the use of light-weight carbon fiber reinforced polymer (CFRP) structures for large monolithic optics. Advantages of this material include lower manufacturing costs, very low weight, and high durability and survivability compared to it's glass counterparts. Design and testing has begun on a 1 meter, optical quality CFRP parabolic mirror for the purpose of injecting collimated laser light through the SMT primary and secondary mirrors as well as the following aft optics that include wavefront sensors and deformable mirrors. This paper will present the design, testing, and usage of this CFRP parabolic mirror and the current path moving forward with this ever-evolving technology.

9354-19, Session 5

Compact optical gimbal as a conformal beam director for large field-of-regard lasercom applications

Jessica E. Kesner, Keith M. Hinrichs, Lawrence E. Narkewich, Timothy Stephens, MIT Lincoln Lab. (United States)

Laser communication offers advantages over traditional RF communication,

including reduced size, weight, and power, higher data rates, and resistance to jamming. However, existing beam directors used for large field-of-regard lasercom terminals have limitations. Traditional gimbals require either domes or large conformal windows to achieve large fields of regard. Risley prism-based beam directors have temperature- and wavelength-dependent pointing necessitating tight temperature control and pointing correction techniques. Other methods, like liquid crystal optical phased array beam directors, have low transmittance and low technology readiness levels (TRLs). This paper presents a detailed design and preliminary performance results of a prototype Compact Optical Gimbal (COG) beam director that provides a 2" beam over a +/- 65o field-of-regard through a small (~12") flat window. The COG differs from the traditional gimbal in that it includes three-axis steering with off-axis elevation and dither control, and a folded refractive afocal telescope incorporated into the body of the gimbal to minimize size. The COG's optical system does not have the pointing challenges characteristic of Risley prisms, and it utilizes high TRL components, including many commercial off-the-shelf parts, to simplify implementation. The compact size and performance support a variety of beam steering applications and platforms.

9354-20, Session 6

Continuous beam divergence control via wedge-pair for laser communication applications

Keith M. Hinrichs, Alan E. DeCew, Lawrence E. Narkewich, MIT Lincoln Lab. (United States); Timothy H Williams, MIT Lincoln Laboratory (United States)

Lasercom terminals commonly scan an area of uncertainty during acquisition with a wide-divergence beacon beam of a specific wavelength. Once the terminal has established cooperative tracking with the remote terminal, a narrow divergence beam of a different wavelength is used for communication. A mechanism that enables continuous beam divergence control can provide significant size, weight and power (SWaP) benefits to the terminal. First, the acquisition and the communication beams can be launched from the same fiber so only a single high-power optical amplifier is required. Second, by providing mid-divergences, it eases the remote terminal's transition from the acquisition stage to the communication stage. This paper describes a mechanism which provides gradual, progressive adjustment of far-field beam divergence, from wide divergence (>300 ?rad FWHM) through collimated condition (38 ?rad FWHM) and that works over a range of wavelengths. The mechanism is comprised of a variable-thickness optical element, formed by a pair of opposing wedges, that is placed between the launch fiber and the collimating lens. Variations in divergence are created by laterally translating one wedge relative to a fixed wedge with no beam blockage. Divergence is continuously adjustable within the thickness range, allowing for a coordinated transition of divergence, wavelength, and beam power. Measurements during testing of this low-loss, low-wavefront error assembly show that boresight error is maintained to a fraction of the communication beam width over divergence, wavelength, optical power, and operating temperature ranges.

9354-21, Session 6

Situational awareness for robot communication using beacon localization

Thomas Shen, Univ. of Maryland, College Park (United States); Robert J. Drost, U.S. Army Research Lab. (United States); John Rzasa, Univ. of Maryland, College Park (United States); Brian M. Sadler, U.S. Army Research Lab. (United States); Christopher C. Davis, Univ. of Maryland, College Park (United States)

Free space optical communication may provide a viable adjunct to RF technology for robot-to-robot communications, especially in "RF-denied" settings in which RF-based communication may be prohibited or impractical. These settings may include military tactical environments, or settings which suffer from RF jamming or interference. Unlike many RF communication systems, point-to-point optical communications between mobile nodes typically require establishing and maintaining alignment, which requires each node to have awareness of the locations of neighboring nodes. We have developed a method to create this situational awareness between nodes using purely optical means. The proposed method utilizes a camera which is focused on a hyperboloidal mirror, thus providing a 360 degree view of the surrounding environment. The camera and mirror are used to detect light emitted from the beacon transmitters from neighboring nodes, with the location of the beacon image in the camera's sensor plane yielding elevation and azimuth information of the beacon. The beacon transmitter itself is modulated, allowing it to be distinguished from the environment. In discussing our experimental realization of this system, we assess its performance, identify and characterize its sources of error, and consider its relevance to robotic communications.

9354-22, Session 7

Evaluation of developing inertial stabilization unit

Masaki Haruna, Kazuhide Kodeki, Seiichi Shimizu, Kazuhiko Fukushima, Osamu Takahara, Toshiyuki Ando, Jiro Suzuki, Eisuke Haraguchi, Mitsubishi Electric Corp. (Japan)

Micro vibrations generated from some internal disturbance sources such as a reaction wheel degrades the pointing stability of an observation satellite. To suppress the pointing error, we have been developing an inertial stabilization unit. A prototype mechanism and control equipment are designed based on concepts that it has non-contact actuators and sensors, and flexural pivots are applied to support a stabilized platform in order to achieve high precise drive. Two kind of inertial sensors are installed on the platform to measure the wideband attitude. Each of these two inertial sensors covers each band signal and these signals are combined as one wideband signal to stabilize the platform in inertial space. In this paper, the developed prototype mechanism and control equipment are described and the basic evaluation results are reported. Less than 0.3urad as a drive precision, and more than 100Hz as a local sensor control bandwidth are verified. The development of the system has not completely finished yet, but the basic performance is certified to meet the design specification. From now on, we continue to develop the unit. These future results can be applied to inter-satellite laser communication system.

9354-23, Session 7

Development of a pointing, acquisition, and tracking system for a CubeSat optical communication module

Tam N. T. Nguyen, Ryan W. Kingsbury, Kathleen Riesing, Kerri L. Cahoy, Massachusetts Institute of Technology (United States)

Miniaturized satellites, namely CubeSats, have continued to evolve their capabilities and can now enable valuable scientific missions that produce significant amounts of data. This data must be downlinked during short low-earth orbit ground station passes, a task currently performed using traditional radio systems. Free-space optical communications leverage the high gain from a narrow optical beam and have the potential to improve the data throughput, allowing more valuable data to be downlinked over the mission lifetime. We present the design of a compact free-space optical communication system, capable of providing a typical "3U" (30 x 10 x 10 cm) CubeSat with a comparatively high data-rate downlink communication channel. The optical communication module is designed to fit within a 5 x

10 x 10 cm volume, weigh less than 1 kg, and consume no more than 10 W of power during active communication periods. Our design incorporates a fine-steering mechanism and beacon-tracking system to achieve a 10 Mbps link rate. The design prioritizes pairing its downlink capability with ground stations that can be constructed from commercial-off-the-shelf technology. The system-level requirements are presented along with the design parameters of the critical components, including a transmitter, a beacon tracking camera, and a fast-steering mirror. Finally, we present simulation results of the beacon tracking and fine steering of the downlink beam including expected atmospheric fading levels and on-orbit environmental disturbances to demonstrate the feasibility of this approach.

9354-24, Session 7

Variable acquisition/communication split ratio for lasercom terminals

Todd G. Ulmer, Frederick G. Walther, MIT Lincoln Lab. (United States)

In a lasercom terminal with co-operative acquisition and tracking, it is desirable to be able to devote all of the received power to the acquisition function while the link is being established and then switch most or all of the power to the tracking and communication functions for link operation. This ability can be especially important in a backbone terminal that interoperates with a wide range of edge terminals with different capabilities, as it can eliminate the need to optimize for one edge terminal at the expense of the others. We begin by examining link budgets for hypothetical edge terminals to establish the potential benefit to the system. We then consider three different schemes for implementing a variable acquisition/communication ratio. The first uses a bifurcating mirror to passively separate the acquisition and communications receiver paths in the backbone terminal. The second uses separate wavelengths for the acquisition and communication functions. The third uses polarization with a rotatable wave plate or its equivalent and a polarization beam splitter to vary the split ratio. We find that all three schemes are viable; the bifurcating mirror scheme is completely passive, while the wavelength scheme offers all-electronic implementation, and the polarization scheme can be implemented completely at the receiver end of the link without coordination with the remote transmitter. Any of these schemes could be implemented to relax requirements on edge terminals, allowing lower cost solutions to proliferate.

9354-25, Session 8

AlGaInN laser diode technology for free-space telecom applications

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The AlGaInN material system allows for laser diodes to be fabricated over a very wide range of wavelengths from u.v., ~380nm, to the visible ~530nm, by tuning the indium content of the GaInN quantum well in the laser epitaxy structure. We consider the suitability of AlGaInN laser diode technology for free space laser communication, both airborne links and underwater telecom applications. We measure visible light (free-space and underwater) communications at multi-gigabit transmission rates using a directly modulated 422nm Gallium-nitride (GaN) blue laser diode with single longitudinal mode operation.

9354-26, Session 8

Compact dual channel optical fibre amplifier for space communication applications

Gary Stevens, Liam Henwood-Moroney, Paul Hosking, Efstratios Kehayas, Gooch & Housego Systems Technology Group (United Kingdom); Leontios Stampoulidis, Gooch & Housego (United Kingdom); Andrew Robertson, Gooch & Housego Systems Technology Group (United Kingdom)

We present results from the development of a dual channel Optical Fibre Amplifier (OFA) that consists of two co-propagating low noise EDFAs at 1565 and 1545nm. The two channels have separate outputs but can also be combined via an optical switch to a common output channel for an increased output signal power. The OFA produces up to 35dB gain at low signal input powers and a total of over 350mW optical signal power combined from both EDFA channels with a 5mW signal input. The EDFAs were tested with input signals between 0.1 – 20 mW over the C-band and with pump power varying from 0 – 100% of operating pump power. The OFA module has total mass of 583 g including all electrical and optical components as well as optical and electrical bulkheads and a total module volume of 430 cm3.

Radiation testing has also been carried out on a single booster amplifier test sample, which is optically equivalent to the OFA module. Testing at 10krad has demonstrated a gain drop of ~0.6 dB, which allows the optical amplifier to maintain a >20 dBm output power across the C-band, whilst keeping a constant noise figure, demonstrating the module's suitability for LEO applications. Further gamma irradiation testing was carried out up to 100 krad total ionizing dose (TID), validating the robustness of the optical amplifier against RIA effects and its suitability for LEO and GEO satellite missions.

9354-27, Session 8

Compact optical transmitters for CubeSat free-space optical communications

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In this paper, we present the results of an architectural trade study of optical transmitters suitable for resource-constrained CubeSats. Despite extreme size, weight and power (SWaP) constraints, CubeSats are completing a wide variety of scientific missions. Communications throughput remains a major hurdle for CubeSat developers. We seek to develop a free-space optical (FSO) communications payload that can be used in these applications. Recent advances in CubeSat attitude determination and control systems (ADCS), which provide three-axis stabilization, make FSO communications a possibility. In our application, 0.5 L, 1 kg and 10 W of SWaP have been allocated to the downlink-only free-space optical payload.

Initial radiometric analyses indicated that approximately 1 W optical transmit power was necessary to close the downlink at a target rate of 10 Mbps. Two transmitter architectures were considered: direct modulation of a high-power (1W) pump laser diode (980 nm), and a master oscillator power amplifier (MOPA, 1550 nm). End-to-end link performance estimates, based upon a conservative link budget and commercial detector technology, were key performance metrics. The overall compatibility with the payload's SWaP requirements, particularly the electrical-to-optical conversion efficiency, was another important selection criteria.

Although both configurations are predicted to provide satisfactory link performance, the MOPA-based approach has been selected for future development, providing better scalability to higher modulation rates which will be possible as CubeSat ADCS technology matures.

9354-28, Session 8

Frequency stabilization of laser diodes in an aggressive thermal environment

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Mobile free-space laser communication systems must reconcile the requirements of low size, weight, and power with the ability to both survive and operate in harsh thermal and mechanical environments. In order to minimize the aperture size and amplifier power requirements of such systems, communication links must exhibit performance near theoretical limits. Such performance requires laser transmitters and receiver filters and interferometers to maintain frequency accuracy to within a couple hundred MHz of the design frequency. We demonstrate an approach to achieving high frequency stability over wide temperature ranges by using conventional DFB lasers, tuned with TEC and current settings, referenced to an HCN molecular frequency standard. A HCN cell absorption line is scanned across the TEC set-point to adjust the DFB laser frequency. Once the center of the line is determined, the TEC set-point is offset as required to obtain frequency agility. To obtain large frequency offsets from an HCN absorption line, as well as continuous laser source operation, a second laser is offset from the reference laser and the resulting beat tone is detected in a photo-receiver and set to the desired offset using a digital frequency-locked loop. Using this arrangement we have demonstrated frequency accuracy and stability of better than 8 MHz RMS over an operational temperature range of 0 C to 50 C, with operation within minutes following 8 hour soaks at -40 C and 70 C.

9354-29, Session 8

High energy uplink transmitters based on monolithic microstructured gain fibers

Donald Sipes Jr., Jason D. Tafoya, Optical Engines, Inc. (United States)

We report on our continuing work toward developing a high power Yb doped PM PCF based fiber amplifier for deep space uplink applications. To avoid non-linearites the laser diode seed source was pulsed in a manner to create the widest linewidth possible. Next a variable shape pulse system with a EO modulator was used to place an exponential rise time on the input pulse to achieve near square pulses on the output. Successive mid stage amplifiers are employed to boost the signal before the power amplifier, which consists of a Etched Air Taper Pump combiner and a high power multi-fiber coupled pump. Over 600W is available for pumping the amplifiers and the unit has been packaged into a ruggedized operational system. Updated results from this system and analysis of the system performance under the dynamic conditions of a PPF format will be reported.

9354-30, Session 8

Object recognition through turbulence with a modified plenoptic camera

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Atmospheric turbulence adds accumulated distortion to images obtained by cameras and surveillance systems. And when the turbulence grows stronger or the object is far away from the observer, increasing the recording device resolution helps little to improve the quality of the image. Many sophisticated methods to correct the distorted images have been invented, such as using a known feature on or near the target object to perform a deconvolution process or use adaptive optics. Yet most of the methods depend heavily on the object's location, while optical ray propagation through the turbulence is not directly considered. Alternatively, selecting a lucky image over many frames seems a feasible solution, but at the cost of time. In our work, we propose an innovative approach to improving image quality through turbulence by making use of a modified plenoptic camera. This type of camera adds a micro-lens array to a traditional high-resolution camera to form a semi-camera array that records duplicate copies of the object as well as "add-on" turbulence at slightly different angles. Therefore, by performing several steps of reconstructions, turbulence effect will be suppressed to reveal more details of the object independently (without finding references near the object). Meanwhile, the redundant information obtained by the plenoptic camera raises possibility to perform lucky image algorithmic analysis with fewer frames, which is more efficient. In our work, the details of our modified plenoptic cameras and image processing algorithms will be introduced. The applications of our proposed method to coherently and incoherently illuminated objects are studied separately. The result shows that in the incoherent case, turbulence can be suppressed significantly by the plenoptic camera, while in coherent cases, speckle effects can be suppressed to some extent but overall object recognition is degraded.

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9355-1, Session 1

Micromachining of bio-absorbable stents with ultra-short pulse lasers

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In recent years, implantable medical devices have become increasingly intricate and utilize materials that are more difficult to machine. For example, stents are now being used for peripheral arteries with tiny dimensions. Another trend is to add a controlled surface texture or geometry to stents and prosthetics to improve bio-compatibility, for example to reduce the risk of restenosis. New materials that are bio-absorbable add another dimension to the challenge of fabricating these devices.

The choice of laser for production of stents depends on the type of material and cutting details. Because of the low melting temperature of bio-absorbable polymers (< 200C°) any heat load to the surrounding areas during laser processing should be minimized. Therefore, using ultrafast laser pulses for micromachining of bio-absorbable polymers is highly promising due to the non-thermal nature of laser-material coupling and the possibility of structuring very small micron scale features.

In this paper, we will give an overview of actual applications for ultra-short pulse lasers for industrial micro-processing. In particular, the study on the impact of the processing conditions on the efficiency and quality of laser processing of poly-L-lactic acid (PLLA) polymer, which is commonly used for production of bio-degradable stents, will be presented. Our studies have shown that the pulse duration and wavelength are the key parameter when choosing a proper laser system for laser micro-machining of bio-absorbable polymers.

9355-2, Session 1

Optical and thermal properties in ultrafast laser surface nanostructuring on biodegradable polymer

Shuhei Yada, Mitsuhiro Terakawa, Keio Univ. (Japan)

Surface nanostructures on a scaffold are known to be a key factor in tissue engineering which governs adhesive and anisotropic properties of cells. In this study, we demonstrate the formation of laser induced periodic surface structures (LIPSS) on a poly-L-lactic acid (PLLA) film. PLLA is a typical and widely-used biodegradable polymer, however, LIPSS was difficult to be formed on PLLA due to its thermal and optical properties compared to other polymers. We revealed appropriate conditions for LIPSS formation by carefully investigating the dependences of wavelength, pulse duration, and repetition rate. With incident wavelength of 800 nm, high-spatial frequency LIPSS (HSFL) was formed in a narrow window applying 10000 pulses of femtosecond laser at 1.0 J/cm2 at 1 kHz. With 400 nm, HSFL was formed at fluences higher than 0.2 J/cm2 with more than 3000 pulses at 1 kHz. With 266 nm, shallow LIPSS was formed with femtosecond laser irradiation without ablation craters. LIPSS was easily formed with the repetition rate of 100 Hz compared to that of 1 kHz, although the both repetition rate was low. The result suggests that certain heat effect may be required for LIPSS formation on polymers. Details on the thermal properties and LIPSS formation on biodegradable polymers will be discussed in the presentation.

9355-3, Session 1

High speed deep tissue ablation with nonlinear imaging using an ultrafast fiber laser at 1045 nm

Murat Yildirim, Kaushik G. Subramanian, Adela Ben-Yakar, The Univ. of Texas at Austin (United States)

Background and Objective: Ultrashort pulses can provide a largely non-thermal mechanism of ablation and a unique ability to create targeted damage within bulk tissue. They can also provide nonlinear imaging guidance to give a feedback about the precision of the cuts. The reliable clinical application of this technique requires understanding the limitation of both ablation and imaging depths. Here, we present the study of maximum ablation and imaging depths of an ultrafast fiber laser centered at 1045 nm to create a sub-epithelial planar cuts with nonlinear imaging assistance in porcine vocal folds. Using our new method, we can also extract tissue-specific ablation threshold and extinction lengths of different tissue layers such as epithelium and lamina propria.

Materials and Methods: Two fiber laser systems operating at 776 nm and 1045 nm center wavelengths and 1.5 ps and 1 ps pulse durations, respectively, were tightly focused in the superficial lamina propria of porcine vocal folds. Multi-modal nonlinear imaging modalities such as two-photon, second- and third-harmonic generation microscopies were utilized using the same lasers at low intensities, to characterize the dimension of the cuts.

Results: Measured ablation threshold fluences of porcine vocal folds were 1.9 and 2.2 J/cm2 at 776 nm and 1045 nm, respectively. The extinction lengths for were estimated to be ~ 35 μm at 776 nm, and ~ 55 μm at 1045 nm wavelength. A maximum ablation depth of a 90 μm could be achieved with 1.5 μJ maximum pulse energy available at 776 nm and 170 μm with 4 μJ maximum pulse energy available at 1045 nm. Our analytical calculations showed that maximum ablation depth would be around 160 μm for 776 nm and 230 μm for 1045 nm without any self-focusing effect. We also compared the maximum imaging depths of different excitation wavelengths to optimize the required excitation wavelength for performing nonlinear imaging guided deep tissue ablation with a single fiber laser system.

Conclusions: This study sheds light on required laser parameters for successful high speed deep tissue ablation with nonlinear imaging guidance by turnkey fiber lasers.

9355-4, Session 1

A Kagome fiber based, high energy delivery laser scalpel system for laser microsurgery

Kaushik G. Subramanian, The Univ. of Texas at Austin (United States); Michal E. Pawlowski, Rice Univ. (United States); Tomasz S. Tkaczyk, Rice Univ. (United Arab Emirates); Adela Ben-Yakar, The Univ. of Texas at Austin (United States)

We present the development of a 5 mm, piezo-actuated, ultrafast laser scalpel for microsurgery with a capability to deliver energies in excess of a few microjoules per pulse at a repetition rate of 303 kHz. We achieve this goal using a large air core kagome lattice fiber. To enable the use of this fiber in a small probe we have been additionally developing custom miniaturized optics for diffraction limited performance over the full field of view of 100 ?m. We have recently demonstrated the working of a similar

5 mm probe for high speed vocal fold microsurgery, where up to 450 nJ was delivered by the probe through a single mode hollow core photonic crystal fiber [1]. We established that the maximum energy deliverable was limited by cladding damage at the input face of the fiber, caused by radial coupling misalignments and laser beam pointing instability. We overcome both limitations by utilizing a large, 35 ?m cored inhibited-coupling kagome fiber. To maintain diffraction limited performance over the entire scan range of the piezo-actuated fiber tip, special miniaturized lenses are developed and manufactured in collaboration with the Modern Instrumentation and Bio-Imaging Lab at Rice University. The probe is packaged in hypodermic 304SS stainless steel with a form factor- minimizing in-line configuration. The probe's performance will be tested via metal and tissue ablation studies, characterizing high speed ablation parameters and uniformity of ablation over the scan area. The high energy delivery through the probe system should allow for fast and effective tissue ablation on the surface and for depths of up to 100 ?m.

[1] Ferhanoglu O, Yildirim M, Subramanian K and Ben-Yakar A 2014 A 5-mm piezo-scanning fiber device for high speed ultrafast laser microsurgery Biomed. Opt. Express 5 2023 .

9355-5, Session 1

In situ imaging of reacting single-particle zeolites by non-linear optical microscopy

Paul Wrzesinski, Mikhail Slipchenko, Spectral Energies, LLC (United States); Taslima A. Zaman, Robert M. Rioux, The Pennsylvania State Univ. (United States); James R. Gord, Air Force Research Lab. (United States); Sukesh Roy, Spectral Energies, LLC (United States)

Zeolite catalysis has been exploited by the petrochemical industry since the 1940's for catalytic cracking reactions of long chain hydrocarbons. The selectivity of zeolites strongly depends on a pore size, which is controlled by template structure and by the template decomposition process. Although zeolites are composed of micron-sized crystals, studies of zeolite materials typically focus on bulk measurements to elucidate structure-function information or to optimize catalysts and/or process parameters. To examine these phenomenon on the microscale, non-linear optical microscopy is used to provide real-time imaging of chemical reactions in zeolites at temperatures up to 400°C. The template decomposition mechanism is studied, as elucidation of the mechanism is critical to understanding the relationship between the decomposition chemistry and the nanoscale features of the zeolite (topology, Si/Al ratio, added dopants). Forward stimulated Raman scattering (SRS), forward and epi coherent anti-Stokes Raman scattering (CARS) and epi two-photon fluorescence (TPF) modalities are acquired simultaneously providing video-rate structural and chemical information. A high-temperature cell with gas inlet system is used for the study of reactions under various temperatures and gas environments. Examining the decomposition process with single-particle resolution enables access to ensemble-level and spatially-resolved behavior. Parallel experiments, on bulk zeolite powders are conducted to enable comparison of ensemble and single-particle behavior during template decomposition. Our multi-technique approach has high potential for gaining insight into the link between nanoscale structure and catalytic activity and selectivity of zeolitic materials.

9355-6, Session 2

Ultrafast laser surgery of transparent ocular tissues *(Invited Paper)*

Daniel V. Palanker, Stanford Univ. (United States)

No Abstract Available

9355-7, Session 2

Ultrashort pulse laser interactions with cortical bone tissue for applications in orthopaedic surgery

Simon A. Ashforth, Miriam C. Simpson, The Univ. of Auckland (New Zealand)

Using a femtosecond pulsed laser system (pulse width = 110 fs, repetition rate = 1 kHz, ? = 800 nm), ablation threshold studies of freshly culled bovine and ovine cortical bone samples were identified using the diameter regression technique. The ablation threshold was found to be 11.21 ± 0.11 J cm-2 in ovine and bovine bone tissue suggesting that laser ablation of bone insensitive to species. The relationship between cortical bone tissue removal and the number of applied pulses was also explored. By altering the laser spot translation rate, we varied the number of pulses at each point along scribed linear cuts. Optical Coherence Tomography (OCT) and PDMS casting indicated that cut depth is linearly dependent upon the number of pulses applied to the tissue. The results show a single pulse depth that increases linearly from 0.54 ?m to 3.47 ?m upon application of peak pulse fluences between 7.81 J cm-2 and 59.79 J cm-2 respectively. Lateral cutting dimensions of 48.7?m can be achieved on the order of 10X finer than commercially available cutting blades. Structural analysis of the ablation features using environmental scanning electron microscopy and optical microscopy was utilised to assess the ablation features and identify signs of damage to surrounding tissues. We observed no structural indications of thermal shockwave cracking, molten debris deposition or charring of the tissue. SEM imaging of ablation surface identify intact hydroxyapatite crystal structure further reinforcing the ablation mechanism is a cold-cutting process.

9355-8, Session 3

Perspectives in nanostructure assisted laser manipulation of mammalian cells *(Invited Paper)*

Dag Heinemann, Laser Zentrum Hannover e.V. (Germany)

No Abstract Available

9355-9, Session 3

Selective optoporation of cells targeted with functionalized gold nanoparticles enhancing ultrafast laser pulse irradiation

Eric Bergeron, Alexandre Torres, Rosalie Martel, Camille Rodriguez, Christos Boutopoulos, Ecole Polytechnique de Montréal (Canada); Jukka Niskanen, Univ. de Montréal (Canada); Jean-Jacques Lebrun, Royal Victoria Hospital (Canada) and McGill Univ. Health Ctr. (Canada); Françoise M. Winnik, Univ. de Montréal (Canada); Michel Meunier, Ecole Polytechnique de Montréal (Canada)

Plasmonics enhanced ultrafast laser has been recently developed to perforate living cells with high efficacy (70%) and high cell viability (80%) [1]. This process is based on the fact that cells barely absorb at the irradiation wavelength of 800 nm and to specific phenomena occurring around the gold nanoparticles (AuNPs) due to the plasmonics near field enhancement, thus perforating the cell membranes [2]. One of the main advantage of this technique is the possibility to functionalize AuNPs to target only specific cells. These targeted cells could be eventually either transiently perforated or destroyed by adjusting the laser parameters. As a

proof-of-principle, we present targeting optoporation of in vitro co-cultured cells. We have developed AuNPs functionalization using 5kDa poly(ethylene glycol) layers and monoclonal antibodies recognizing a specific receptor of the targeted cells. As a case study here, we targeted cancer stem cells (CSCs) that are generally more resistant than other cancerous cells to radiotherapy and chemotherapy. CSCs expressing the CD44 cell surface receptor are responsible for the tumorigenic, invasive and metastatic potential in many cancers. UV-visible spectroscopy, darkfield microscopy and fluorescent labeling confirmed stable CD44-AuNPs functionalization and efficient selective targeting of CSC-like phenotype in a physiological environment containing serum proteins. We have also shown that selective treatment of co-cultured CD44+ MDA-MB-231 and CD44- RGC-5 leads to an highly efficient optoporation of target cells without affecting non-targeted cells. We anticipate that this non-invasive treatment will prevent complications and improve the treatment of cancer patients.

[1] Baumgart et al. (2012) Biomaterials 33:2345; [2] Boulais et al. (2012) Nano Letters 12:4763.

9355-10, Session 3

Mechanical response of single nerve cells estimated by femtosecond laser-induced impulsive force

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Mechanical response of nerve cell is one of important issues for understanding function of nerve system. However, the response has been still unclear because of difficulty to stimulate single cells by controllable mechanical stress. As a controllable mechanical stimulator, our group has focused on shock and stress waves generated by femtosecond laser under a microscope. In this work, we demonstrated the mechanical response of the single nerve cells by loading the waves as an impulsive force.

Neuro2a cells were cultured as an experimental model of the nerve cells. Femtosecond laser pulse (800 nm, 150 fs) was focused at a position 20 ?m from edge of the cell body through a 20x objective lens. This operation allowed for loading the impulsive force on the targeted cell. The cell response was evaluated based on time evolution of intracellular Ca2+ concentration ([Ca2+]), which was monitored as an intensity of fluorescence induced by Ca2+ indicator (Fluo-8).

When the pulse energy was larger than 200 nJ/pulse, increase of intracellular [Ca2+] was observed immediately after the force loading. The increase started in a part nearest to the laser focal point and then it spread in whole of the cell body in a time scale of 10 seconds. After that, the increase propagated along the neurite. When the neurite was in contact with another neuro2a cell, [Ca2+] increase was also induced in another neuro2a cell. We indicated that the impulsive force could be available for mechanical stimulation of the neuronal network at cellular level.

9355-11, Session 3

Femtosecond-pulse plasmonic ionization kills cancer cells

Limor Minai, Adel Zeidan, Daniella Yeheskely-Hayon, Dvir Yelin, Technion-Israel Institute of Technology (Israel)

Short laser pulse irradiation of cells and tissue specifically conjugated by gold nanoparticles can target malignancies with low toxicity and high specificity; however, the complex mechanisms underlying the observed cell damage are still poorly understood and have large sensitivity to the specific experimental parameters.

In this paper, we study the dependence of cell damage on pulse duration, and show that pulses in the femtosecond range could be more effective in damaging nanoparticle-targeted cells compared with picosecond pulses of similar fluence levels. Our experiments included lymphoma B cells that were incubated with anti-CD20 gold nanorods (4.1 aspect ratio) and irradiated by intense single pulses at varying pulse durations and irradiance levels, either at resonance (800 nm) or off-resonance (550 nm) wavelengths. We have found that above certain intensities, cell death was non-linearly dependent on pulse duration, with significantly higher death rates at shorter pulses. Death rates, as well as levels of intracellular reactive oxygen species, were particularly high above approximately 10^12 W/cm^2, suggesting the involvement of multiphoton ionization in the cell damage process. Interestingly, experiments have also shown linear dependence of the cell death on irradiance levels for 50 fs pulses, suggesting the possible involvement of additional linear optical processes such as cascade ionization or thermally driven cavitation bubbles. The paper will present our experimental findings and discuss potential models for the complex physical and biological interactions.

9355-12, Session 4

Effect of nanoparticle size on plasmonic enhanced off-resonance femtosecond laser nanocavitation

Christos Boutopoulos, Ecole Polytechnique de Montréal (Canada) and Univ. of St Andrews (United Kingdom); Ali Hatef, Matthieu Fortin-Deschênes, David Rioux, Rémi Lachaine, Michel Meunier, Ecole Polytechnique de Montréal (Canada)

The interaction of femtosecond (fs) laser pulses with plasmonic nanoparticles (NPs) can lead to controllable nanocavitation in liquid. Our group has recently demonstrated that an off-resonance irradiation ensures the preservation of the optical and structural properties of the NP that is acting as a "nanolens". This technique plays a crucial role in the development of advanced laser nanosurgery applications such as cell optoporation and transfection. In this context, we have studied plasmonic bubble (PB) dynamics, generated in liquid by off-resonance fs laser excitation (? =800 nm, ? = 50 fs) of a variety of Au plasmonic NPs with sizes ranging from 50 nm to 200 nm. PB dynamics were investigated in a single NP approach using a pump-probe shadowgraphic ultrafast imaging technique. Furthermore, in-situ dark field imaging has been employed to investigate the deformation thresholds for the different plasmonic NPs. A clear dependence of both the PB generation and NP fragmentation thresholds on the NP size has been observed. The experimental results have been correlated with simulations of the nanolens effect, involving near field enhancement and generation of a nanoscale plasma around the vicinity of the NPs. We show that the cavitation threshold is controlled by the enhanced power density, which takes into account the near-field amplification. In conclusion, the appropriate selection of the NP size optimizes the nanocavitation efficiency and prevents NP fragmentation for an extended laser processing window. The latter offers a key advantage for the development of optimized cell nanosurgery applications.

9355-13, Session 4

Laser transfection with gold nanoparticles: Current state and new particle structures as a perspective

Stefan Kalies, Lara Gentemann, Georgios C. Antonopoulos, Mirko Rakoski, Dag Heinemann, Markus Schomaker, Tammo Ripken, Laser Zentrum Hannover e.V. (Germany); Heiko Meyer, Laser Zentrum Hannover e.V. (Germany) and Hannover Medical School (Germany)

Laser-based transfection techniques have gained significant interest during the last decade. Either single cell manipulation by focusing on the cell membrane or high-throughput can be realized with laser transfection. The latter is for example provided by gold nanoparticle mediated laser transfection. It is based on the heating of gold nanoparticles through laser irradiation, which permeabilizes the membrane. This technique satisfies most prerequisites of a reliable transfection technique, like efficiency and minimal cell impact. In order to bring it closer to routines usage, we investigated new particle configurations for gold nanoparticle mediated laser transfection. Our setup employs a 532 nm and 850 ps laser system. We immobilized gold particles on cell culture surfaces or modified silica particles with a gold particle surface coverage. Furthermore, first experiments achieving cell perforation with an organic nanoparticle based on polypyrrole were conducted. These three options achieved comparable efficiencies to the incubation of cells with free gold nanoparticles. With regard to the underlying mechanisms of perforation, we performed fluorescence microscopy based imaging of the cell state combined with holographic imaging directly after perforation. First results indicated a power dependent ion (calcium) and volume exchange with the extracellular medium in the first two minutes after perforation. In conclusion, our results can pave the way to a safer and more efficient way of high-throughput laser transfection with gold nanoparticles.

9355-14, Session 4

Plasmonic cell transfection using micropyramid arrays

Nabiha Saklayen, Daryl I. Vulis, Marinus Huber, Harvard Univ. (United States); Lauren E. Milling, Univ. of Illinois at Urbana-Champaign (United States); Sebastien Courvoisier, Univ. de Genève (Switzerland); Valeria Nuzzo, ECE PARIS Ecole d'Ingenieurs (France); Eric Mazur, Harvard Univ. (United States)

We present a new cell transfection method that uses femtosecond laser-excited localized surface plasmons (LSPs) on a nanostructured micropyramid array. Our gold-layered micropyramids have nano-apertures at the apex to form high local electric field enhancements, or "hot spots." These hot spots form microbubbles that temporarily perforate mammalian cell (HeLa S3) membranes and allow dye molecules and plasmid vectors to diffuse through the membrane openings. We introduce an emerald green fluorescent protein (EmGFP) reporter plasmid into the cells to determine the LSP-mediated transfection efficiency of the substrate. We optimize our laser parameters for successful transfection and high cell viability. Our nontoxic, efficient, and scalable technique offers an innovative approach to the advancement of regenerative medicine and the study of LSP-cell interaction.

9355-15, Session 4

Sorting on the basis of deformability of single cells in a femtosecond laser fabricated optofluidic device

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Optical stretching is a powerful technique for the mechanical phenotyping of single suspended cells that exploits cell deformability as an inherent functional marker. Dual-beam optical trapping and stretching of cells is a recognized tool to investigate their viscoelastic properties. The optical stretcher has the ability to deform cells through optical forces without physical contact or bead attachment. In addition, it is the only method that can be combined with microfluidic delivery, allowing for the serial, high-throughput measurement of the optical deformability and the selective sorting of single specific cells. Femtosecond laser micromachining can fabricate in the same chip both the microfluidic channel and the optical waveguides, producing a monolithic device with a very precise alignment between the components and very low sensitivity to external perturbations.

Femtosecond laser irradiation in a fused silica chip followed by chemical etching in hydrofluoric acid has been used to fabricate the microfluidic channels where the cells move by pressure-driven flow. With the same femtosecond laser source two optical waveguides, orthogonal to the microfluidic channel and opposing each other, have been written inside the chip. Here we present an optimized writing process that provides improved wall roughness of the microchannels allowing high-quality imaging. In addition, we will show results on cell sorting on the basis of mechanical properties in the same device: the different deformability exhibited by metastatic and tumorigenic cells has been exploited to obtain a metastasis-cells enriched sample. The enrichment is verified by exploiting, after cells collection, fluorescence microscopy.

9355-16, Session 4

Design, simulation, and fabrication of plasmonic pyramid substrate for cell transfection

Marinus Huber, Harvard Univ. (United States); Daryl I. Vulis, Harvard School of Engineering and Applied Sciences (United States); Nabiha Saklayen, Harvard Univ. (United States); Sébastien Courvoisier, Jean-Pierre Wolf, Univ. de Genève (Switzerland); Eric Mazur, Harvard School of Engineering and Applied Sciences (United States)

Femtosecond laser-excited surface plasmons can be used to achieve optoporation in cells for the purpose of low toxicity genetic transfection. We present the method for a photolithography-based fabrication of a gold pyramid array substrate and its characterization using two-photon fluorescence microscopy . The substrate is designed using FDTD simulations to achieve high field enhancements at the apex of the pyramids for the temporary poration of mammalian cells (HeLa S3). To achieve high throughput cell transfection, we fabricate a simple microfluidic device on the plasmonic substrate. Poration experiments are performed to determine the scalability of a transfection device based on the pyramid array substrate. This design offers the potential for large scale cell transfection through optoporation.

9355-17, Session 5

Nonlinear compression of industrial ultrafast lasers in hypocyloid-core Kagome hollow-core fiber

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The duration of energetic ultrashort pulses is usually limited by the available gain bandwidth of ultrashort amplifiers used to amplify nJ or pJ level seed to hundreds of µJ or even several mJ. In the case of Ytterbium-doped fiber amplifiers, the available bandwidth is of the order of 40 nm, typically limiting the pulse duration of high-energy fiber chirped-pulse amplifiers to durations above 300 fs. In the case of solid-state amplifier based on Yb:YAG crystals, the host matrix order restricts the amplification bandwidth even more leading to pulses in the low picosecond range. Both architecture would greatly benefit from pulse durations well-below what is allowed by their respective gain bandwidth e.g. sub-100 fs for fiber amplifier and sub-300 fs for solid-state Yb:YAG amplifier. In this contribution, we report on the post-compression of two high energy industrial ultrashort fiber and thin-disk amplifiers using an innovative and efficient hollow core fiber structure, namely the hypocycloid-core Kagome fiber. This fiber exhibits remarkably low propagation losses due to the unique inhibited guidance mechanism that minimize that amount of light propagating in the silica cladding surrounding the hollow core. Spectral broadening is realized in a short piece of Kagome fiber filled with air at 1 atmosphere pressure. For both amplifiers, we were able to demonstrate more than 200 µJ of energy per pulse with duration < 100 fs in the case of the fiber amplifier and < 300 fs in the case of the thin disk amplifier. Limitations and further energy scaling will also be discussed

9355-18, Session 5

Simple single-shot complete spatiotemporal characterization of the intensity and phase of a complex ultrashort pulse

Zhe Guang, Michelle Rhodes, Rick Trebino, Georgia Institute of Technology (United States)

We demonstrate a simple device, called Spatially and Temporally Resolved Intensity and Phase Evaluation Device: Full Information from a Single Hologram (STRIPED FISH), for completely characterizing the intensity and phase of an arbitrary ultrashort pulse in space and time (x,y,t) on a single shot. STRIPED FISH generates multiple holograms using a very simple setup of a coarse two-dimensional diffractive optical element (DOE), an interference band-pass filter (IBPF), imaging optics, and a camera. The complete spatiotemporal information of an arbitrary unknown pulse can be retrieved from the holograms by using a spatially filtered and FROG-measured reference pulse. We have made significant improvements on the aberration eliminations, measurable bandwidth, the intensity uniformity of the multiple holograms, and the display method. Specifically, to remove the central-spike artifact and ghost pattern seen in measurements using our previous setup, we convert to a negative DOE with the same diffracted-pattern in transmission. Also, we now implement our imaging system by using two camera lenses and an apodizing neutral density filter (ANDF). The camera lenses, designed for highly divergent light, image the beams with minimal aberrations, allowing a large measurable bandwidth. Further, the ANDF, with a Gaussian optical density, equalizes the intensities of the various diffracted orders from the DOE. To intuitively display the resulting intensity and phase vs. x, y, and t, we now compute spectrograms of the measured pulse at each point in space. Then we calculate overlap integrals of each spectrogram with red, green, and blue response functions and generate movies using the resulting RGB values. To demonstrate our new capability, we perform single-camera-frame measurements of spatiotemporally complex subpicosecond crossed and chirped double pulses from a Ti:Sapphire oscillator. Crosschecks and numerical simulations are also performed to confirm the measured results. As a result, this simple STRIPED FISH device should be able to perform single-shot spatiotemporal measurements for pulses important in many research areas, such as high-intensity pulse amplification and fiber optics.

9355-19, Session 5

Broadband midinfrared frequency comb with tooth scanning

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Frequency combs are a massively parallel source of extremely accurate optical frequencies. Frequency combs generally operate at the visible or near-infrared wavelengths, but fundamental molecular vibrations occur at midinfrared wavelengths. We demonstrate an optically-referenced, broadband midinfrared frequency comb based on a doubly-resonant optical parametric oscillator (OPO). By tuning the wavelength of the reference laser, the comb line frequencies are tuned as well. By scanning the reference wavelength, any frequency can be accessed, not just the frequencies of the base comb. Combined with our comb-resolving Fourier transform spectrometer, we can measure 200 wavenumber wide broadband absorption spectra with 200 kHz relative linewidth.

Our OPO is pumped by an amplified Tm fiber frequency comb, with phase-locked carrier envelope offset frequency, and repetition rate fixed by phase-locking a frequency comb line to a narrow linewidth diode laser at a telecom channel. The frequency comb is referenced to GPS by long-term stabilization of the repetition rate to a selected value using the temperature of the reference laser as the control. The resulting pump comb is about 3W of 100 fs pulses at 418 MHz repetition rate at 1950 nm. Part of the comb is used for supercontinuum generation for frequency stabilization, and the rest pumps an orientation-patterned gallium arsenide (OP-GaAs) crystal in a doubly-resonant optical parametric oscillator cavity, yielding collinear signal and idler beams from about 3 to 5.5 µm.

We verify comb scanning by resolving the 200 MHz wide absorption lines of the entire fundamental CO vibrational manifold at 11 Torr pressure.

9355-20, Session 5

High-throughput on-chip analysis of single ion tracks created by laser-driven plasma accelerators

Wei Luo, Faizan Shabbir, Chaokun Gong, Cagatay Gulec, Jeremy Pigeon, Jessica Shaw, Alon Greenbaum, Ting-wei Su, Ahmet F. Coskun, Sergei Y. Tochitsky, Chandrashekhar J. Joshi, Aydogan Ozcan, Univ. of California, Los Angeles (United States)

Because of its single-ion detection sensitivity, CR39 detectors are considered as one of the gold standards for ion-tracking applications including the characterization of beams from laser-driven plasma accelerators. However, the analysis of CR39 detectors is laborious mainly because of the limited space-bandwidth product of conventional optical microscopy. For example, the sample has to be etched for ~4 hours to enlarge the ion pits for visualization, and a microscope has to mechanically scan across the exposed area (e.g., 10-16 cm^2). This time-consuming process hinders broader applications of these highly sensitive detectors when many samples need to be characterized. Here, we report a high throughput CR39 analysis platform based on lensfree holographic on-chip microscopy. With unit-magnification, this lensfree on-chip microscope can achieve an ultra-large FOV of ~18 cm^2 using a state-of-the-art CCD imager chip. Through pixel super-resolution techniques, this on-chip microscope mitigates undersampling caused by the sensor's limited pixel-pitch (~6.8 ?m) and boosts the resolution to ~2 ?m across ~18 cm^2. This improvement allows a significant decrease in sample etching time down to ~1 hour, and the total imaging time is reduced to 10-60 seconds as opposed to ~20-30

minutes using a lens-based scanning optical microscope that has a similar resolution. A highly parallelized algorithm has also been implemented on GPU clusters, which allows characterization of >6,000 ion-tracks on each detector within ~90 seconds. This rapid analysis of large area CR39 detectors enables us to monitor the development of individual ion-tracks during the etching process that is impractical using conventional imaging methods.

9355-21, Session 5

Pulse splitter to produce ultrafast bursts

Antoine Courjaud, Vincent Clet, Areti Mourka, Amplitude Systèmes (France); Aghasi Lorsabyan, Candle Synchrtron Research Institute Foundation (Armenia); Eric P. Mottay, Amplitude Systèmes (France)

Ultrafast lasers naturally produce pulse trains with equal temporal spacing. However, increasing number of applications require a more sophisticated distribution of energy in time, taking into account saturation effects in the interaction physics. This is the case for filamentation-assisted micromachining, but also for accelerator-based instruments, such as Free Electron Lasers. In this last case, the repetition rate is usually fixed by the LINAC power supplies, therefore multipulse generation, also called burst mode, allows to increase the photon flux,.

We report on a passive module able to produce up to 16 pulses of equal energy, with 20ns pulse separation, and an overall transmission efficiency >70%. This efficient system is coupled to a standard diode-pumped photocathode laser based on s-Pulse HP? and its FHG module, producing up to 500µJ @258nm, with 500fs pulse duration, 350fs rms jitter when locked to a RF reference, and a repetition rate of 1 to 100Hz.

This passive module, called Pulse Splitter, is based on partial reflectors and polarizers for separation and recombination, relay imaging systems as compact delay lines. The overall size of the module is 600x600mm. The adjustment of the temporal spacing between each pulse is done with a femtosecond precision, by using translation stages on each delay line, and controlling the delay by cross-correlation technique. Influence of the critical parameters impacting the pulse energy distribution within the burst will be also detailed. The replicas are subsequently converted into UV in a dedicated frequency conversion module.

9355-22, Session 6

Low-noise supercontinuum: Development, characterization, and programmable biomedical imaging

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Nonlinear biomedical imaging has not widely benefited from the broad spectral coverage of fiber supercontinuum generation mainly due to the poor coherence, or rather equivalently, the high optical noise of the supercontinuum itself. Since 2010, we and others have avoided the input-shot-noise-amplified relative intensity noise using unconventional supercontinuum generation in all-normal dispersion (ANDi) circular or photonic crystal fibers. Unfortunately, this supercontinuum generation suffers decoherence at high output powers or long fiber lengths, significantly limiting the power and bandwidth for potential biophotonics application. To understand the mechanism of this decoherence, we compare the supercontinuum generation from a conventional zero-dispersion-wavelength photonic crystal fiber, a regular (weakly birefringent) ANDi photonic crystal fiber, and the polarization-maintaining counterpart of the later. The decoherence is attributed to an unreported optical noise associated with polarization modulation instability, which has been masked by the total intensity measurement in the past, but can be easily detected by filtering the supercontinuum with a linear polarizer. By suppressing the polarization modulation instability in the polarization-maintaining ANDi photonic crystal fiber, we generate a low-noise high-average-power (480 mW) broadband (780-1320 nm) coherent supercontinuum. The spectrum of the supercontinuum, which would otherwise be uncertainly modified by random fiber birefringence, can be theoretically predicted by the generalized nonlinear Schrödinger equation. Because of the broadband coherent spectral coverage, two- (or three-) photon fluorescence microscopy, second- (or third-) harmonic generation microscopy, and coherent Raman microscopy can be integrated by a programmable pulse shaper to image various endogenous molecules in unlabeled animal and human tissues.

9355-23, Session 6

Yb:CaF2 femtosecond laser in versatile burst mode: A powerful tool to optimize laser interaction

Antoine Courjaud, Amplitude Systèmes (France); Jean-Gabriel Brisset, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Eric P. Mottay, Amplitude Systèmes (France)

Ultrafast lasers naturally produce pulse trains with equal temporal spacing. However, increasing number of applications require a more sophisticated distribution of energy in time, taking into account saturation effects in the interaction physics, such as plasma generation. The positive impact of distributing the pulse energy in two or more pulses separated by 10 ns has already been demonstrated.

We report on the development of a femtosecond laser, delivering bursts with a total energy as high as 5mJ with 450fs pulse duration @1032nm. The burst shape is designed to be highly flexible, in terms of pulse to pulse temporal separation, as well as interpulse energy distribution. The number of pulses in the burst is limited to 4 pulses, in a temporal window limited to 10ns in this configuration.

This versatile energy and temporal distribution is allowed by a passive pulse splitter placed between the stretcher and the regenerative amplifier, limiting the impact of the losses of this component in the overall laser architecture.

Therefore, the laser can provide up to 5mJ in a single pulse, or 1.2mJ distributed into 4 pulses on 10ns scale, or any other shape in between.

This versatile ultrafast laser source in burst mode was used to parametrically study the impact of burst shape on filamentation, and therefore optimize the laser to filament coupling efficiency, by measuring the electrical conductivity variation in the air.

9355-24, Session 6

Compressive ultrahigh-speed continuous imaging using spectrally-structured ultrafast laser pulses

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Ultrahigh-speed continuous imaging is a powerful technology for high-throughput screening of cells, drug discovery, rare cell detection for cancer diagnostics, and numerous other applications throughout the life sciences. Recently, cutting-edge imaging architectures employing ultrafast laser pulses and fiber- optic-based information processing yielded a performance leap in ultrahigh-speed imaging. Still, such approaches remain fundamentally limited in speed by the measurement rate of electronic ADCs. Specifically, in these architectures the pixel acquisition rate is equal to the electronic sampling rate. However, most images are highly compressible and can be represented by far less information than their full capacity as evidenced by data compression technology (e.g. jpeg, mpeg). Moreover, recent advances in compressive sensing indicate that such signals can be acquired with far fewer measurements than conventionally deemed necessary. Thus cutting-edge ultrahigh-speed imaging systems are inefficient, collecting far more data than is required to characterize the signals of interest, which limits their operating speed. Here, using chirp processing and pseudorandom modulation, we demonstrate compressive ultrahigh-speed imaging using spectrally-encoded ultrafast laser pulses. We generate greater than 300 features per laser pulse updated at the full 90-MHz laser repetition rate such that each pulse serves as a unique pseudorandom structured illumination pattern. Using compressive sensing reconstruction, we demonstrate continuous imaging of microscale objects moving at 35.8 m/s through a 2–3-mm wide 1-D field of view with only 1-10% of the samples required for traditional Nyquist sampling. This corresponds to line rates of several MHz and greater than 1 Gigapixel/s using only a 90 Msample/s electronic ADC.

9355-25, Session 6

Compact fixed wavelength femtosecond oscillators for multi-photon applications

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In recent years technical development of Yb fs-oscillators has been resulting in air-cooled, compact laser systems with high output powers of 1.5 W at a wavelength of 1045 nm with a pulse duration of < 250 fs. The footprint of such lasers can be as small as about 200 mm by 200 mm including an optional second harmonic generation (SHG) for 522 nm output. The pulses are sech?-shaped and near transform limit with a spectral width of 6.5 nm. The group velocity dispersion of optical materials such as BK7 glass at a wavelength of 1045 nm is about a factor of four lower than at 800 nm (d?n/dl? = 0.012 µm-? at 1045nm compared with 0.049 µm-? at 800nm). Thus pulse broadening due to dispersion in optical materials (e.g. beam path in a microscope) is less pronounced as with common Ti:Sapphire fs-lasers so that multi-photon effects can be generated at the sample without dispersion compensation or pre-chirping the ultrafast pulses.

The 1040nm laser proved to be very efficient in exciting two-photon fluorescence from YFP and red fluorescent proteins (RFP) and dyes. Also SHG signals from muscle tissue and collagen could be created very efficiently.

Other applications are multi-photon polymerization and nanoprocessing.

With this work we demonstrate that air-cooled, small-footprint fixed-wavelength lasers can present an adequate replacement in multi-photon applications, where longer excitation wavelengths and pulse durations are adequate.

9355-26, Session 7

Efficient generation of continuum spectrum above 2 micron using microstructured fiber

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We propose a Ti:Sapphire pumped microstructure fiber geometry able, by nonlinear interplay with visible/Uv spectral components, to generate continuum components up to 2.5 micron, with a spanning of over 2 micron.

The efficiency is due to the generation of visible/UV components propagating in the firts order mode. Those components provide nonlinear interplay to effectively generate power in the MIR.

In particular a large and flat peak is generated between 2 micron and 2.5 micron.

The paper will discuss the source but at this stage we are unable to predict report of an application by the time of the conference.

9355-27, Session 7

Low-phase-jitter CEP few-cycle laser system locked by high bandwidth direct modulation of a 'Finesse CEP' pump laser

Thomas Binhammer, Stefan Rausch, Jan Ahrens, VENTEON Laser Technologies GmbH (Germany); Albrecht Bartels, Laser Quantum GmbH (Germany); Alan Cox, Laser Quantum UK (United Kingdom)

In this work, a comparison of the CEP locking performance of acousto-optic feedback generation and direct current control with the 'Finesse CEP' pump laser is presented. It is found, that the CE phase noise of the Ti:Sapphire laser benefits from the much higher modulation bandwidth of the direct current locking scheme. Whereas the sideband noise is almost identical below 1 kHz, a significant noise suppression can be achieved for higher frequencies, resulting in a CE phase noise (integrated over an interval of 1 kHz to 1MHz) which more than 10 mrad lower compared to the locking performance using an AOM-based feedback. The high modulation bandwidth of the 'Finesse CEP' is possible, as a phase shift (from modulation signal to optical power output) of less than 90 degrees is achieved for frequencies up to 750kHz, allowing for an increased bandwidth CEP feedback loop capable of achieving a reduced phase jitter by comparison to AOM use. In addition, this simple replacement of a pump source and AOM combination with a Finesse CEP system shows a significant improvement for a simplified optical setup and avoids additional optics in the pump beam.

Further improvement can be expected by an adaption of the feedback electronics to fully exploit the high modulation bandwidth. With this new locking scheme, ultralow CE phase noise can be reached which allows a jitter of below 30 as. This excellent noise performance will be especially helpful for all CEP sensitive experiments e.g. generation of attosecond pulses.

9355-29, Session 7

Femtosecond pulse laser notch shaping via fiber Bragg grating for the excitation source on the coherent anti-stokes Raman spectroscopy

Seung Ryeol Oh, Won Sik Kwon, Jin Hwan Kim, Soohyun Kim, Kyung-Soo Kim, KAIST (Korea, Republic of)

Single pulse coherently controlled nonlinear Raman spectroscopy is the simplest method among the coherent anti-Stokes Raman spectroscopy systems. In recent research, it has been proven that notch shaped femtosecond pulse laser can be used to collect the coherent anti-Stokes Raman signals. In this study, we applied a fiber Bragg grating to the notch filtering component on the femtosecond pulse lasers. The experiment was performed incorporating a Ti:sapphire femtosecond pulse laser source with a 100 mm length of 780HP fibers which is inscribed 50 mm of Bragg grating. The fiber Bragg grating has a 785 nm Bragg wavelength with 0.9 nm bandwidth. We proved that if the pulse laser has group delay dispersion of 3000 ?fs?^2 or more, it is sufficient to propagate in the fiber Bragg grating without any wave-breaking occurrence. After passing through the fiber Bragg grating, the pulse laser is reflected on the chirped mirror for 40 times to make the transform-limited pulse. Finally, the pulse time duration was 37 fs, average power was 50mW, and showed an adequate notch shape. Furthermore, the simulation of 3rd order polarization signal is performed using MATLAB tools and the simulation result shows that spectral characteristic and time duration of the pulse is sufficient to use as an excitation source for single pulse coherent anti-Stokes Raman spectroscopy. In conclusion, the proposed method is more simple and cost-effective than the methods of previous research which use grating pairs and resonant photonic crystal slab.

9355-30, Session 8

Plasma dynamics during fs-laser fabrication of waveguides inside zinc phosphate glass

Javier Hernandez Rueda, Vladimir A. Semenov, Neil W. Troy, Univ. of California, Davis (United States); Charmayne E. Smith, Richard K. Brow, Missouri Univ. of Science and Technology (United States); Denise M. Krol, Univ. of California, Davis (United States)

We have investigated the dynamics of the electron plasma generated under conditions of femtosecond (fs) laser waveguide fabrication inside zinc phosphate glasses. To this end we have employed fs time-resolved pump and probe microscopy, which allows monitoring the transient optical properties of the laser-affected volume with spatial, temporal and fluence resolution.

In order to optimize the optical quality of the inscribed waveguides inside glasses, we have tuned laser pulse duration and fluence as parameters of paramount importance, while inspecting the laser processing dynamics. At early temporal delays after the pump pulse arrival (from 100 fs up to few ps), time-resolved microscopy data provide information about the evolution of the electron plasma through relative changes in the probe transmitted light. It allows for discrimination of optimal processing conditions along with the visualization of unwanted propagation effects. The transmission values from the pump-probe experiments along with the Drude model give an estimate of the carrier density of the plasma, which may be related with the laser induced change in the refractive index. Furthermore, unwanted non-linear propagation effects, such as beam filamentation or self-focusing, can be monitored as dark lines along the laser path inside the glass. Therefore, by tailoring the laser processing conditions (pulse duration and fluence), it is possible to enhance the energy coupling through the optimization of the plasma density and the minimization of nonlinear propagation effects.

9355-32, Session 8

Increasing performance of mobile devices: fs laser assisted high quality photonic devices in display glass screens

Jerome Lapointe, Mathieu Gagné, Raman Kashyap, Ecole Polytechnique de Montréal (Canada)

The miniaturization of electronic devices is increasingly in demand to increase the performance, capacity and number of applications of multimedia devices such as smart phones. The glass screen of such devices has great potential for photonic devices implementation. We present here the first three dimensional transparent waveguides, recently demonstrated [1], of sufficient quality to be integrated in such screens. Dense glass, used in many smart phones and other mobile devices, is shown to generate the lowest linear loss waveguides (<0.03 dB/cm loss through multimode waveguide and <0.06 dB/cm loss through single-mode waveguide), to our knowledge, fabricated using focused femtosecond laser. To prove that these results can be reproduced on tablets and other larger multimedia devices such as smart TVs, the longest high quality straight and curved waveguides (up to 1m) are also reported. The fabrication method is simple, relatively low cost and the fastest reported to date. An authentication security system, we believe for the first time, which could be used for financial transactions, is reported. New photonic sensor devices, capable of measuring characteristics of material touching the screen, will be presented. This work is a very first step towards future transparent smart phones.

[1] J. Lapointe, M. Gagné, M.-J. Li, and R. Kashyap, "Making smart phones smarter with photonics," Optics Express, vol. 22, pp. 15473-15483, 2014.

9355-33, Session 8

Highly functional fiber cladding photonics: Real-time monitoring to control femtosecond laser writing of optical taps and filters

Jason R. Grenier, Univ. of Toronto (Canada); Luis André Fernandes, OZ Optics Ltd. (Canada); Peter R. Herman, Univ. of Toronto (Canada)

Optical fibers form the backbone of our modern communication systems and are also broadly applied as sensors that underpin the many advances in distributed sensing and medical diagnostics. Laser technology has offered a significant opportunity for adding functionality to this fiber backbone by structuring optical and other components inside or around the core waveguide. In particular, femtosecond lasers enable precise processing in a small focal volume in which higher performance fiber core and cladding devices are now emerging. However, the major technical challenge has been on controlling beam delivery alignment to efficiently interconnect the laser-formed structures precisely with the fiber core waveguide.

In this work, second harmonic (522 nm), high repetition rate (500 kHz) femtosecond laser pulses were focused through a high numerical aperture lens with oil immersion to address the challenge of laser processing inside cylindrically shaped single mode optical fibers. With ~1 μm accuracy, refractive index modifications of precise shape, position, and birefringence can build and interconnect to photonic cladding circuits operating in the telecommunication band (1200 nm to 1700 nm). S-bend and cross-couplers offer broadband coupling (>350 nm) and less alignment sensitivity. However, as the laser modification moves into the evanescent and core regions, alignment errors become dramatically amplified. To address this challenge, our group has developed real-time monitoring for in-situ device tuning. In this way, optical tapping between the core and laser-formed cladding waveguide can be controlled from 0 to nearly 100% efficiency. Further, laser-induced birefringence can be tuned to fabricate strongly isolating (>25 dB) in-fiber polarization-selective taps, and in-line fiber polarizers with >20 dB extinction ratio (in ~3 nm band). The overall compactness and high integration of such functional fiber devices opens opportunities for structural and industrial distributed sensing, applications in wide-area sensor networks, as well as for powerful new biomedical and optofluidic devices.

9355-34, Session 8

Catheter shape sensing with 3D fiber-cladding photonics based on femtosecond laser direct-written Bragg grating waveguides

Kenneth K. C. Lee, Kyle H. Y. Cheng, Univ. of Toronto (Canada); Victor X. D. Yang, Ryerson Univ. (Canada); Peter R. Herman, Univ. of Toronto (Canada)

Fiber Bragg grating (FBG) strain sensor offers important advantages over conventional metallic strain gauges, including electromagnetic interference immunity, high sensitivity and multiplexing capabilities. In recent years, there has been an increasing interests in distributed shape sensing based on FBGs for a wide range of application directions such as aerospace, energy and medical industries to monitor the shape of an airplane wing, wind turbine blade or surgical tools. While distributed shape sensing has been reported by deploying multiple FBGs in either multiple optical fibers or multicore optical fibers, simultaneous interrogation of the multiple waveguides remains a major packaging challenge in these approaches. Alternatively, femtosecond laser writing of 3D optical circuits directly in a standard optical fiber offers a unique solution to make freestanding fiber sensor devices that can be monitored from a single core waveguide.

We demonstrate temperature-compensated 3D fiber shape sensing with axially and radially distributed Bragg grating waveguides that were formed inside a single coreless optical fiber. The integrated optical circuit was precisely formed in a single exposure step with a femtosecond laser and oil immersion lens focusing while being tuned with a real-time characterization system. A laser-written 1?3 directional coupler enabled efficient coupling and balancing of light between the optical circuit components and a SMF core waveguide through simultaneous interrogation of nine Bragg gratings as they formed and coupled to a single waveguide port at 1-kHz sampling rate. The 3D fiber circuit permitted real-time shape and temperature profile sensing along the fiber length. The sensor was inserted into a commercial steerable catheter and was tested in vitro using a flow phantom, followed by an animal trial to determine the catheters 3D orientation in vivo with the objective to minimize X-ray dosage in minimally invasive surgical procedures.

9355-35, Session 8

Ultrafast laser filamentation for scribing transparent optical glasses

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With an appropriate balance between Kerr effect based self-focusing and laser electron plasma induced defocusing, laser filaments, especially with high intensity ultrashort laser pulses, can be formed in transparent materials including solids, liquids and gases. In contrast to conventional laser focus volume with the scale defined by Rayleigh length, ultrafast laser filaments can extend the laser interaction far outside the conventional laser focal volume to narrow tracks of multiple Rayleigh length. Such a unique temporal-spatial laser energy distribution, together with the strong nonlinear multiphoton absorption of high intensity ultrashort pulse laser light, has triggered numerous applications, for example, supercontinuum generation, Terahertz emission, remote sensing, lightning protection, as well as laser material processing such as laser micro-welding and ultrafast laser direct writing of optical waveguides and diffractive optical elements in transparent glasses.

We have further applied ultrafast laser filamentation to the scribing of optical glasses that is highly promising for the flat panel display and smart-phone industry. Ultrafast laser filaments have been formed in bulk silica glasses with 200-fs to 10-ps pulse duration and appropriate pulse energy and focusing geometry. Compared with conventional diamond or other laser scribing approaches, filament scribing has shown advantages including fast processing speed, low kerf width, small heat affected zone, and minimal surface damage or crack generation. The formation of the stress-inducing tracks is examined in-situ by time-resolved side-view microscopic imaging with a time-gated intensified CCD camera of 2-ns resolution. Real-time characterization of the laser self-focusing, plasma defocusing, and relaxation mechanisms are reported over a wide range of laser exposure conditions, varying with wavelength, pulse duration, pulse energy, focus geometry and burst trains at high and low repetition rates. An optimization of the laser scribing process follows from the time dynamic studies.

9355-36, Session 8

Femtosecond laser waveguide writing inside zinc phosphate glasses: Role of composition on permanent photo-induced changes

Vladimir A. Semenov, Denise M. Krol, Javier Hernandez Rueda, Neil W. Troy, Univ. of California, Davis (United States); Jeffrey D. Smith, Richard K. Brow, Missouri Univ. of Science and Technology (United States)

We have recently found that fs-laser writing in binary zinc polyphosphate glasses yields good quality waveguides for compositions with [O]/[P] ratios close to 3.25 [1,2]. For practical applications multicomponent glasses offer more robust stability as well as better corrosion resistance. In order to determine if an [O]/[P] ratio of 3.25 is also required in such glasses we have investigated femtosecond laser waveguide fabrication in a series of zinc aluminium and zinc magnesium phosphate glasses with [O]/[P] ratios varying between 3.00 and 3.50.

For each glass composition lines were written using a wide range of fs-laser processing conditions by varying fluence, writing speed and pulse duration, in order to determine if good-quality waveguides could be obtained. Samples that yielded good waveguides were further investigated. Changes in refractive index, induced in the glass by the fs-laser, as well as the optical losses in the waveguides were measured. Fluorescence and Raman spectroscopy were utilised to characterize the various atomic-scale structural changes in the glass.

Our investigations into the structural changes caused by fs-laser modification will also be correlated with the results on processing dynamics, which are being carried out in our group using fs-laser pump-probe experiments. Finally we will discuss the results in terms of different laser-electron and electron-lattice energy coupling mechanisms.

References:

1. Luke B. Fletcher et al. “Direct femtosecond laser waveguide writing inside zinc phosphate glass”, OptExp 19, 7929 (2011).

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9355-37, Session 9

Optimization of laser process conditions for cutting of thin metal and polymer sheets with femtosecond laser

Klaus Stolberg, Susanna Friedel, Nikolas von Freyhold, Markus Röhner, JENOPTIK Laser GmbH (Germany)

Thin sheets and foils of metals and polymers are widely used in electronics, medical devices and other industries. The use of ultrashortpulse lasers opens the opportunity of processing these materials with minimized thermal impact. The quality of the cut is influenced on a manifold of different parameters like laser repetition rate, laser pulse energy and laser pulse duration, optical, thermal material characteristics and geometrical sample parameters, but also on process parameters like focusing conditions, process speed.

In the previous paper laser parameters as well as process parameters are optimized under the aspects of productivity (cutting speed) and cutting quality. For this an industrial 10W femtosecond laser (JenLas femto10, 1030nm, 400-800fs, 50µJ, 500kHz) was used.

Stainless steel thin sheets in the range of 10...100 µm were used as a reference and an optimum pulse overlap was found for maximum ablation rate of 1 mm?/min. In contradiction to stainless steel, polymers are significantly more sensitive to thermal load, because of lower melting point and lower heat conduction. Polycarbonate (PC) was used as a reference polymer material in the same thickness range. It usually does not show linear absorption at NIR and visible wavelength. This gives chances for volume absorption in NIR. Indeed we reached 20 mm?/min ablation rate. For SHG femtosecond wavelength we observed strong multiphoton effects with strong surface absorption. As a result the use of SHG option does not enhance cutting speed or cutting quality.

9355-38, Session 9

Conditions for random and periodic hole formations during surface ablation of silicon with ultrashort pulsed lasers

Matthias Domke, Fachhochschule Vorarlberg (Austria)

The ablation of silicon with ultrafast lasers enables precise control of the ablation depth. However, individual or periodic holes with a depth of several µm can be usually observed on the ablated surface. The goal of this study is to investigate the conditions for these hole formations.

For this purpose, Si wafers with a thickness of 525 µm were ablated using a 400 fs-laser at a wavelength of 520 nm. An area of 500x500 µm? was scanned several times with unidirectional parallel lines at different speeds. The distance between pulses and lines was kept constant. Since laser and scanner are not synchronized, the pulses hit the sample on different positions in each line after each overscan.

At low fluences of about 1.2 J/cm?, periodic surface structures orientate perpendicular to the polarization and increase the surface roughness. At a fluence of 5.8 J/cm?, both the formation of liquid droplets and the scribed furrows create high peaks and deep valleys on the surface. With increasing number of overscans, holes appear spontaneously in the deeper valleys and finally form a periodic pattern. In both cases, the polarization has no influence on the surface roughness.

However, at a fluences of around 2.4 J/cm?, the formation of periodic surface structures can be suppressed if the polarization is oriented parallel to the scan direction. In addition, the formation of smaller droplets decreases the depth of the valleys. Under these conditions, the hole formation can be suppressed to minimize the surface roughness.

9355-39, Session 9

Erasure and formation of femtosecond laser-induced nanostructures

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Within recent years ultrashort pulse laser processing of glasses has gained particular interest, in particular the fabrication of sub-wavelength structures which build the basis of strong form birefringence. These so-called nanogratings with feature sizes smaller than the wavelength of light self-assemble during irradiation while their orientation is always perpendicular to the laser polarization. Remarkably, when the laser polarization orientation is changed during inscription the initial nanograting is erased and new nanometric sheets corresponding to the new polarization state are formed. However, up to now no comprehensive and microscopic picture of this complex physical process exists. Thus we performed optical retardance measurements as well as microscopic techniques, such as small-angle X-ray scattering (SAXS) and scanning electron microscopy (SEM) to address this issue.

Our results reveal that only few laser pulses already lead to erasure of nanometric pores which is mapped by the total (X-ray) scattering volume as well as by the strong reduction of the initial form birefringence. Simultaneously, new nanostructures form which arrange in individual grating planes with ongoing irradiation. However, since the rewrite process is no ideal mechanism some of the old sheets remain, which perturb the quality of the new nanograting. When rewriting multiple times the glass becomes even more porous due to repetitive annealing and quenching. This promotes the formation of new inhomogeneities and in turn leads to an increase in optical retardance.

9355-40, Session 9

Adaptive optics for the laser fabrication of 3D graphitic microwires in diamond

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Graphitic wires embedded beneath the surface of single crystal CVD diamond are fabricated using a femtosecond pulsed laser and tight focusing. When the laser is focused into the diamond, the electric field is sufficiently strong at the focus for non-linear absorption leading to breakdown of the diamond lattice and the formation of a graphitic phase. The ultrashort nature of the pulse minimises thermal effects such that the structural modification is highly localised. By tracing the diamond through the laser focus, continuous graphitic wires may be machined within the diamond bulk. The microwires, with lateral dimensions as low as 400nm, can be fabricated to follow any three dimensional path within the diamond. Essential to the accurate fabrication of the wires is compensation of the optical aberrations induced when focussing inside the diamond. To this end, adaptive optic elements are used during the machining to remove the depth-dependent aberration and create high resolution uniform features deep into the diamond. Microwires with a range of cross-sections, lengths and depths are demonstrated. The resistivity of the microwires is analysed as a function of frequency and the d.c. value (? = 0.02 ?cm) is found to be an order of magnitude lower than those previously reported in the literature for similar laser machining of diamond.

9355-41, Session 9

Transient imaging with gated avalanche photodiodes

Mauro Buttafava, Alberto Tosi, Politecnico di Milano (Italy); Kevin W. Eliceiri, Andreas Velten, Univ. of Wisconsin-Madison (United States)

No Abstract Available

9355-42, Session 10

Spatial and temporal temperature distribution of ultrashort pulse induced heat accumulation in glass

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We report on the temporal and spatial temperature dynamics in borosilicate glass after the irradiation with ultrashort laser pulses at high repetition rates. To this end, we developed a pump-probe micro Raman setup to determine the temperature dependent ratio between Stokes and Anti Stokes scattering. Here, ultrashort laser pulses are used to excite the sample. Subsequently a nanosecond pulse is applied to measure the Stokes and Anti Stokes scattering of the heated material. This technique allows the spatial and temporal mapping of the local temperature.

We detected strong emissions of the focal area after laser excitation due to blackbody radiation of the heated material and fluorescence of the laser induced defects. This background signal hinders the direct acquisition of the local temperature within the focal area. However, the measured data can be fitted, taking the heat accumulation of successive laser pulses into account. The fitted results were in good agreement with the appropriate microscope images of the modified areas.

Our results indicate a critical influence of the pulse energy on the induced temperature.

In borosilicate glass, the maximal temperature directly after the excitation (pulse energy of 1.1 ?J, repetition rate of 1 MHz, pulse duration of 600 fs, 2000 pulses per laser spot) is more than 5000 K. This central temperature drops within 500 ns to about 2500 K, which is still above the softening point.

The results obtained by the in-situ Raman technique are the first comprehensive experimental results concerning the temporal and spatial temperature distribution induced by heat accumulation of ultrashort laser pulses.

9355-43, Session 10

Adaptable acylindrical optofluidic lenses fabricated by femtosecond laser micromachining

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Optofluidic tunable lenses are a powerful tool for many lab-on-a-chip applications, ranging from sensing to detection and imaging, enabling a high degree of integration and compactness of these devices. In this work, we present the realization of such a compact microfluidic lens with reconfigurable optical properties.

The technique used to realize the device we present is femtosecond laser micromachining followed by chemical etching, which allows the straightforward fabrication of 3D microfluidic devices with arbitrary shape. Thanks to the versatility of this technology, it has been possible to easily fabricate in fused silica glasses different lenses based on cylindrical microchannels filled with liquids of proper refractive index. The optical properties of these devices have been tested and are shown to be in a good agreement with the theoretical model implemented for their design. Furthermore, in order to reduce the effects of spherical aberrations in the focal region, we have also optimized the design of these microlenses in order to implement different acylindrical microfluidic lenses, whose validation is also reported.

In this work the lens adaptability is achieved by varying the liquid inside the microchannel, so as to easily tune the properties of the focused beam. In particular, we show the possibility to adapt the focus position and also to switch between a converging and a diverging lens, thus implementing an on-chip optofluidic shutter.

9355-44, Session PTue

Time-resolved fluorescence polarization spectroscopy of visible and near infrared dyes in picosecond dynamics

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Molecules undergo vibrational and rotational motion in the relaxation of the excited electronic states. Near-infrared (NIR) dyes which absorb and emit light within the range from 700 to 900 nm have several benefits in biological studies. However, because of the less than ideal anisotropy behaviour of NIR dyes stemming from the fluorophores elon-gated structures and short fluorescence lifetime in picosecond range, no significant ef-forts have been made to recognize the theory of these dyes in time-resolved polarization dynamics. In this presentation, the depolarization of the fluorescence due to emission from rotational deactivation in solution will be measured with the excitation of a linearly polarized femtosecond laser pulse, and detected using a streak camera. The theory, expe-riment and application of the ultrafast fluorescence polarization dynamics and anisotropy are illustrated with examples of the most important medical dyes in NIR range, namely Indocyanine Green (ICG). A set of first-order linear differential equations was devel-oped to model fluorescence polarization dynamics of NIR dye in picoseconds range. Using this model, the important parameters of ultrafast polarization spectroscopy were identified: risetime, initial time, fluorescence lifetime, fluorophore's rotation time. It is the first time to present the fundamental theory of NIR dye in picosencond dynamic range and verify it by the ultrafast spectra obtained by streak camera.

9355-45, Session PTue

All-optical characterization of fs-laser induce refractive index changes in bulk and at the surface of zinc phosphate glasses

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We have studied the permanent refractive index change in zinc phosphate glasses upon irradiation with ultrashort laser pulses. Both surface and bulk laser processing have been performed in order to investigate the intrinsic role of the surface defects as well as the incubation effects in bulk. Our main goal has been to elucidate the relation between materials changes associated with waveguide formation in the bulk and changes in the pre-ablation regime at the surface and how the laser processing conditions can affect each regime.

In order to investigate the structural modifications induced in bulk, under conditions of waveguide fabrication, we have carried out Raman spectroscopy. The changes of the peak position and the integrated area below the Raman bands reveal subtle modifications of the phosphate glass network structure. In particular, recent studies have shown that the peak position of the 1209 cm-1 band is very sensitive to small variations in the P-O network bond length and can be used to monitor these alterations. In addition, the modification of the refractive index linked to the inscribed waveguides was characterized studying the far field output profiles.

For surface irradiations, we have performed optical microscopy using monochromatic light sources. The images show the appearance of Newton rings; this interferometric effect is due to the resultant multilayer system (unmodified glass, thin laser-modified layer, air) and the monochromatic nature of the light source. By taking into account the theory of Abeles for multilayer systems it is possible to calculate the surface reflectivity modulation, linking the complex refractive index components with the amplitude modulation of the experimental reflectivity data.

9355-46, Session PTue

High speed fabrication of amorphization-induced periodic surface structures in crystalline silicon upon irradiation with a high repetition rate fs-laser

Javier Hernandez Rueda, Jan Siegel, Consejo Superior de Investigaciones Científicas (Spain); Ruth Lahoz, German F. de la Fuente, Univ. de Zaragoza (Spain) and Instituto de Ciencia de Materiales de Aragon (Spain); Francisco Javier Solís Céspedes, Consejo Superior de Investigaciones Científicas (Spain)

The fabrication of a new type of laser-induced periodic surface structures (LIPSS) in crystalline silicon upon high repetition rate ultrashort laser pulse irradiation has been investigated. To this end we have made use of a galvo-scan mirror system combined with an F-theta lens in order to generate large LIPSS areas (few cm2) in few minutes.

So far LIPSS in silicon have been mostly investigated for processing energies above the ablation threshold. In this work, we have found that it is possible to produce LIPSS-like structures without material removal. We attribute the appearance of this type of LIPSS to local amorphization of the crystalline silicon wafer. Similar results have been obtained in a phase change material, although only on a micrometer scale without beam scanning [1]. We have characterized the structures by using optical microscopy with a monochromatic light source. An analysis of the reflectivity modulation enabled a verification and characterization of the two-layer system produced (amorphized surface layer and unmodified crystalline silicon underneath), supporting the phase change hypothesis. It is worth noting that this type of LIPSS is produced only within a narrow window of processing conditions due to the sensitivity of the phase transformation to local fluence.

We have investigated the controllability of the spatial period for the inscribed LIPSS by adjusting different processing parameters, such as repetition rate, scan speed, wavelength and energy per pulse. These dependencies are discussed and compared with theoretical models for conventional LIPSS presented by Sipe [2] and Öktem [3] as well as previous experimental results found by Bönse [4]. Furthermore, we demonstrate that LIPSS induced by amorphization can be written over the large macroscopic areas, which can be easily observed with the naked eye as a uniform diffraction grating with few cm2 surface.

1.- Y. Katsumata et al., Appl. Phys. Lett. 105, 031907 (2014).

2.- J. E. Sipe et al., Phys. Rev. B 27, 1141 (1983).

3.- B. Öktem et al., Nat. Photonics 7, 897 (2013).

4.- J. Bönse et al., Appl. Surf. Sci. 257, 5420, (2011).

9355-47, Session PTue

Ultrafast electron dynamics of N2 under femtosecond and XUV attosecond laser pulse train irradiation

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This study investigates the photoexcitation and ionization of a nitrogen molecule under ultrafast (femtosecond/attosecond) laser pulse irradiation. The real-time and real-space time-dependent density functional (TDDFT) is applied to describe the electron dynamics during the linear and nonlinear electron-photon interactions. The calculations describe well the behavior of the ionization process, and the results of ionization rates show good correspondence with the experimental results. In addition, the effects of near-infrared femtosecond laser pulse trains and the selected extreme ultraviolet attosecond laser pulse trains on electron dynamics are discussed. It is demonstrated that: (1) the real-time and real-space electron dynamics including energy absorption, electron excitation, electron density, and electron density oscillation can be controlled by the pulse train technology; (2) at the same total laser intensity, the emitted electrons and excitation energy obviously decrease with the increase in the pulse number; (3) more electrons can be emitted with the presence of the XUV attosecond laser pulse train; (4) the electron density oscillation can be controlled by selecting laser frequency; and (5) the electron dynamics, including electron ionization, density, and distributions, can be changed by the pulse delay between the femtosecond laser pulse and attosecond laser pulse train.

9355-48, Session PTue

Plasmonic substrates for cell transfection

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We investigate two different types of plasmonic structures (nanocavities and nanopyramids) for laser-based cell transfection. In both cases, a femtosecond laser is used to excite localized surface plasmons, which leads to a high near-field enhancement and an enhanced laser absorption. This creates microbubbles that perforate mammalian cells on the substrate and allow genetic vectors to enter the cell through the transient holes in the membrane. We performed numerical calculations to optimize the parameters for our substrate and to increase our understanding of the cell poration process.

Poration and transfection experiments indicate that both structures could be used as a high throughput transfection device. Our innovative approach offers a technique for cell transfection that is non-toxic, efficient, and easily scalable. We expect this to open up new opportunities in the field of gene therapy.

9355-49, Session PTue

Ultrashort pulsed laser tools for testing of semiconductor device hardness to local radiation effects caused by cosmic heavy ions

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The installations for laser testing of microelectronic elements (first of all - integrated circuits) of devices for space applications for hardness to local radiation effects from heavy charged particles are presented. The possibility of a focused pulsed laser radiation application to the study of local radiation effects, caused by single heavy charged particles, is explained. The fundamentals of an approach to the construction of test sets, based on the picosecond and femtosecond lasers and systems for focusing their radiation, are considered. The main technical requirements for the basic modules of laser testing tools (laser wavelength and pulse duration, repetition rate, spatial beam parameters and minimal spot size, speed of object movement and so on) are substantiated. All worked out sets have a full-featured software for the operational management of all modules of the laser test facility, including the positioning of the object, to provide feedback from the measurement results of the object response on the laser excitation. The parameters of developed laser hardware and software systems and their foreign analogues are compared. Further directions for improvement of laser testing tools are briefly outlined. The discussion is also presented of described hardware technical and operational characteristics, allowing to use it for a variety of scientific research studies, based on selective object excitation (with submicron spatial resolution) by ultrashort laser pulses and recording responses to this effect with the exact timing of the moment of excitation, for example, ultrafast microelectronic devices characterization.

Conference 9356: High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications IV

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9356-1, Session 1

Hollow core fiber delivery of sub-ps pulses from a TruMicro 5000 Femto edition thin disk amplifier

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We report the fiber-based transmission of sub-ps single-mode pulses with an average power of 50 W at a wavelength of 1030 nm generated by a TruMicro 5000 Femto Edition thin disk amplifier. The used hollow-core fiber exhibits an air-filled Kagome-type photonic pattern as well as a hypocycloid core wall, which are tailored to offer very low dispersion and nonlinearity at 1030 nm while minimizing the mode overlap with the glass components to obtain a sufficiently high damage threshold. With propagation losses of only 20 dB/km and an optimized mode matching and coupling by means of a telescope and a 5-axes table we achieve an overall transmission efficiency of more than 80% with a resulting M^2 of 1.15. Our laser source offers the selection of repetition rates from 200 to 800 kHz which translates to pulse energies between 60 and 250 uJ. The pulse duration of 900 fs is maintained at the fiber exit, whereas we observe a spectral broadening of 20 nm due to self phase modulation in the air core, which could be used to further compress the pulses temporally. Using a fiber-based beam transport as presented allows to decouple the laser head and the processing head mechanically, which poses a great enhancement in terms of flexibility and application possibilities in the field of material processing with our ultra-short pulsed laser tools.

9356-2, Session 1

Industrial beam delivery system for ultra-short pulsed laser

Max C. Funck, Björn Wedel, Ilya Kayander, Jörg Niemeyer, PT Photonic Tools (Germany)

Beam delivery systems are an integral part of industrial laser equipment. Separating laser source and application fiber optic beam delivery is employed wherever great flexibility is required and today, fiber optic beam delivery of several kW average power is available for continuous wave operation using step index fibers with core diameters of several 100 μm. However, during short-pulse or even ultra-short pulse laser operation step index fibers fail due to high power density levels and nonlinear effects such as self-focusing and induced scattering. Hollow core photonic crystal fibers (HC-PCF) are an alternative to traditional fibers featuring light propagation mostly inside a hollow core, enabling high power handling and drastically reduced nonlinear effects. These fibers have become available during the past decade and are used in research but also for fiber laser systems and exhibit a growing popularity. We report on using HC-PCF fibers and their integration into an industrial beam delivery package comparable to today's fiber optic standards and will discuss power handling, beam quality and efficiency as well as future prospects of this technology.

9356-3, Session 1

Wavefront-sensor-induced beam size error: physical mechanism, sensitivity-analysis and correction method

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When using a commonly-used quadri-wave lateral shearing interferometer wavefront sensor (QWLSI WFS) for beam size measurements on a high power CO2 laser, we observed artifacts in the measured irradiance distribution. The grating in the QWLSI WFS not only generates the diffracted first orders that are required for introducing the shear, but also diffracts significantly into higher orders. Consequently, in the few mm's of free space propagation between the QWLSI WFS grating and its imaging device, the beam size may increase significantly (particularly for infrared wavelengths). This error is currently not accounted for in the subsequent processing of measurement data.

To gain insight in this undesirable behavior, we have physically modeled the QWLSI WFS using both complex wave propagation and analytic propagation of the D4sigma beam diameter (and its associated M2) throughout the system. The models show excellent agreement to experimental data, and indicate that in typical situations the sensor-induced beam size error can easily be 40% or more.

Although the QWLSI WFS may not originally be intended for beam size measurements, in most industrial applications cost- and volume limitations will often lead to multiple use of sensor data. To aid in the adequate implementation of a QWLSI WFS for determining beam size, we have determined the dependence of the sensor-induced beam size error on various system parameters (e.g. grating-to-imager distance, incoming beam size, grating geometry, wavelength). Using the presented models and guidelines, the sensor-induced beam size error may be minimized and corrected for.

9356-4, Session 1

Wavelength- and magnification adaptive beam expansion with one set of components

Ulrike Fuchs, Sven Wickenhagen, asphericon GmbH (Germany)

In complex laser systems, such as those for material processing, and in basically all laboratory applications passive optical components are indispensable. Matching beam diameters is a common task, where Galileo type telescopes are preferred for beam expansion. Nevertheless researches and customers have found various limitations when using these systems. Some of them are the complicated adjustment, very small diameter for the incoming beam (1/e?), fixed and non-modifiable magnifications. Above that, diffractionlimitation is only assured within the optical design and not for the real world set-up of the beam expanding system. Additionally, one would like to have a system that can be adapted to the wavelength used without varying the magnification.

Therefore, we will shortly discuss limitations of currently used beam expanding systems to some extent. We will then present a monolithical solution, which is based on the usage of only one aspherical component. We will present experimental data on the performance of cascades with up to five monolithical elements and show that this set-up still yields a

diffraction limited wavefront. Additionally, we will present a new add-on element, which allows for wavelength tuning and adaption of divergence of the incoming beam without changing the beam diameter. This additional component allows for the usage of the monolithical beam expanders over the complete wavelength range from 500nm up to 1600nm, which makes them very flexible to use. We will present experimental results on the diffraction limited performance for some typical combinations out of the 230 possible set-ups.

9356-32, Session 1

Effect of large deflection angle on the laser intensity profile produced by AOD scanners in high precision manufacturing

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Laser beam scanners have found wide applications in a variety of laser-assisted advanced microprocessing technologies, such as printing, patterning and doping. Traditional galvo-scanners affect the accuracy of beam positioning and repeatability in high precision manufacturing due to mechanical motion of the mirrors and backlash errors. An Acousto-optic Deflector (AOD), which is made of a transparent photoelastic medium bonded to a piezoelectric transducer, is a promising device to overcome these limitations. AODs are commonly used in laser direct writing systems to provide flexible and high-speed beam scanning with high precision and accuracy.

We have developed an analytic model based on Bessel functions, which will be referred to as Bessel model, to calculate the strain tensor, stress tensor and stress-induced birefringence, and the change in the refraction index of the crystal. This refraction index variation produces the volume phase grating and provides a mechanism for diffraction, and consequently, deflection of the laser beam as it propagates through the AOD crystal. Various laser parameters, such as the diffraction efficiency and the laser intensity of the diffraction pattern at different deflection angles are studied in this paper.

9356-6, Session 2

Optical differentiation wavefront sensor based on binary pixelated transmission filters

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High-resolution wavefront sensors are of great interest for laser engineering and astronomy. The optical differentiation wavefront sensor allows for high signal-to-noise ratio broadband characterization of the spatial phase of optical waves. When a filter with a field transmission that is linear with respect to a spatial coordinate is located in the far field of the optical wave, the spatially resolved wavefront slope along that coordinate can be recovered from the near field of the filtered wave. The complete spatially resolved wavefront is recovered from a set of two orthogonal wavefront-slopes maps. We study the characteristics of such wavefront sensor when the far-field linear-transmission filter is implemented with a pixelated binary filter. These filters allow for quasi-arbitrary gray-scale continuous transmission patterns using arrays of small (e.g., 10-micron) transparent or opaque pixels that can simply be fabricated by conventional lithography techniques. The pixelated filters are shown to lead to similar wavefront reconstruction than continuous filters, with the advantage of simpler fabrication and ability to generate a large variety of filter transmission profiles. Various wavefronts are theoretically reconstructed using a least-square algorithm applied to two wavefront slopes obtained after far-field filtering with pixelated binary filters. The trade-off between pixel size, filter size, beam parameters, and wavefront reconstruction accuracy is studied. Experimental reconstruction of the wavefront of a HeNe laser with Cr-on-glass pixelated binary transmission filters is demonstrated.

9356-7, Session 2

Generation of doughnut spot for high-power laser technologies using refractive beam shaping

Alexander V. Laskin, Vadim V. Laskin, AdlOptica Optical Systems GmbH (Germany); Aleksei Ostrun, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Doughnut and inverse-Gauss intensity distributions of laser spot are required in laser technologies like welding, cladding where high power fiber coupled diode or solid-state lasers as well as fiber lasers are used. In comparison to Gaussian and flat-top distributions the doughnut and inverse-Gauss profiles provide more uniform temperature distribution on a work piece – this improves the technology, increase stability of processes and efficiency of using the laser energy, reduce the heat affected zone (HAZ). This type of beam shaping has become frequently asked by users of multimode lasers, especially multimode fiber coupled diode lasers. Refractive field mapping beam shapers are applied as one of solutions for the task to manipulate intensity distribution of multimode lasers. The operational principle of these devices presumes almost lossless transformation of laser beam irradiance from Gaussian to flat-top, doughnut or inverse-Gauss through controlled wavefront manipulation inside a beam shaper using lenses with smooth optical surfaces.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying with high-power multimode lasers. Examples of real implementations and experimental results will be presented as well.

9356-29, Session PTue

Bioceramic coating of hydroxyapatite fabricated on Ti-6Al-4V with Nd-YAG laser

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Hydroxyapatite (HAP) is the most research calcium phosphate material in the field of biomaterials for bone re-engineering applications. HAP is a brittle and heat sensitive synthetic material with similar properties to that of a natural bone. It cannot however, be used as a stand-alone material for bone support, but only as a coating material on base metals where it can only serve as a biointegration material from which human tissues can grow in and around the implanted metal. HAP coatings can be fabricate on base metal like Ti-6Al-4V and stainless steel using thermal spraying, cold spraying or laser assisted direct metal deposition techniques. The most popular method is plasma spraying since it is characterised with high deposition rates and efficiency even though the produced HAP coatings are less desirable for bone regeneration application. Plainly, the plasma produce HAP coatings turn to crack, weakly bonded and have reduced crystallinity due to heat which generally decomposes it during deposition. Recently, lasers have been used to cure such coating to improve their crystallinity. Yet,

the operating process parameters for direct laser melting have not being reported. This work will report these processing parameters by carefully examining the optical images of the HAP coatings produced with Nd-YAG laser on Ti-6Al-4V, and reporting on the bioactivity of the coatings.

9356-30, Session PTue

Laser transmission welding of absorber-free thermoplastics using dynamic beam superposition

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Laser transmission welding of thermoplastics has successfully been used in several industrial applications for many years. The development of new laser sources providing new wavelengths extends the process limits to material combinations which were considered as non-weldable some time ago. One of those combinations is two transparent joining partners with none of them containing infrared (IR) absorbers. Using a proper wavelength the intrinsic absorption of thermoplastics can be exploited to deposit energy into the material without IR absorbers. To achieve a targeted energy input optics with a high numerical aperture are used. Thereby, the intensity is meant to exceed the melting threshold of the material only in the joining area. Practice shows, however, that the heat affected zone (HAZ) within the material extends over a large area along the beam axis regardless of the optics used. Without clamping or convective cooling thermally induced expansion of the material can cause blowholes or deformation of the irradiated surface. In this paper a new irradiation approach is presented in which the laser beam is performing a precession movement. The movement is achieved by irradiating the inside area of a ring mirror built into the optical path. In contrast to the TWIST® welding the beam does not execute any lateral movement in the focal plane which leads to a locally limited energy input in the joining area. In the critical area, the sample surface, the thermal stress can be kept low as the energy is distributed over a large area by the circular motion of the beam.

9356-31, Session PTue

2500W monolithic CW near diffraction-limited fiber laser for industry applications

Wei Shi, Tianjin Univ. (China) and Tianjin Institute of Modern Laser & Optics Technology (China); Qiang Fang, Yuguo Qin, Xiangjie Meng, HFB Photonics Co., Ltd. (China)

We have implemented a monolithic, multi-kilowatts, CW ytterbium-doped fiber laser source at ~ 1080 nm in MOPA configuration. The laser source can produce ~ 2.5 kW CW laser power with near diffraction-limited beam quality (M2<1.3). The optical to optical efficiency with respect to the launched pump power for the whole laser system is > 77.9%. The all fiber construction of the whole laser system enables compact size, maintenance-free, robust operation and thus allows various practical applications in laser cutting, laser drilling etc. The metal cutting applications were demonstrated with the investigated high beam quality and high power fiber laser.

9356-8, Session 3

Advantages and challenges of dissimilar materials in automotive lightweight construction *(Invited Paper)*

Jan-Philipp Weberpals, Philipp A. Schmidt, Daniel Böhm, Steffen Müller, AUDI AG (Germany)

The core of future automotive lightweight designs is the joining technology of various material mixes. The type of joining will be essential, particularly in electrified propulsion systems, especially as an improved electrical energy transmission leads to a higher total efficiency of the vehicle. The most evident parts to start the optimization process are the traction battery, the electrical performance modules and the engines. Consequently aluminium plays a very central role for lightweight construction applications. However, the physical-technical requirements of components often require the combination with other materials. Thus the joining of mixed material connections is an essential key technology for many of the current developments, for example in the areas e-mobility, solar energy and lightweight construction.

Due to these advantages mixed material joints are already established in the automotive industry and laser remote welding is now a focus technology for mixed material connections. The challenge of the laser welding process with mixed materials is within the different areas of the melting phase diagram depending on the mixing ratio and the cooling down rate. According to that areas with unwanted, brittle, intermetallic phases arise in the fusion zone. Therefore, laser welding of mixed material connections can currently only be used with additional filler in the automotive industry.

Hence the aim of the BMBF-sponsored project „ReMiLas“ and particularly of the AUDI AG is to enlarge the application on the CW (continuous wave) laser remote welding of automotive lightweight mixed material connections particularly of aluminium-copper. Thereby the postulated electrical resistance, the mechanical resistivity and the corrosion resistance of the fusion zone should be implanted on demonstrator parts. In order to reach this aim, the BMBF project ReMiLas also includes providing an efficient laser system in addition to the examination of the suitable process operation.

9356-9, Session 3

Laser hybrid joining of plastic and metal components for lightweight components

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Plastic-metal hybrids are replacing all-steel structures in the automotive, aerospace and other industries at an accelerated rate. The trend towards lightweight construction increasingly demands the usage of polymer components in drive trains, car bodies, gaskets and other applications. In particular, carbon-fiber-reinforced polymers (CFRP) are sought after, due to their favorable strength-to-weight ratio. However, laser-joining of polymers to metals presents significantly greater challenges compared with standard welding processes.

We present recent advances in laser-hybrid joining processes. Firstly, several metal pre-structuring methods, including selective laser melting (SLM) are characterized and their ability to provide undercut structures in the metal assessed. Secondly, process parameter ranges for hybrid joining of a number of metals (steel, aluminum, etc) and polymers (ABS, PA, PC, PP) are given. Both transmission and direct laser joining processes are presented. Optical heads and clamping devices specifically tailored to the hybrid joining process are introduced. Extensive lap-shear test results are shown that demonstrate that joint strengths exceeding the base material strength (cohesive failure) can be reached with metal-polymer joining. Weathering test series prove that such joints are able to withstand environmental influences typical in targeted fields of application. The obtained results pave the way toward implementing metal-polymer joints in manufacturing processes.

9356-10, Session 3

Microstructure and mechanical performance of carbon steel and stainless steel dissimilar laser welding

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This investigation has demonstrated the feasibility of producing a laser welded joint between low carbon steel and austenitic stainless steel that is mostly homogeneous and of austenitic microstructure. It is shown that the homogeneity of the fusion zone is associated with the weld pool convection, which is influenced by the laser beam specific point energy. A fusion zone with austenitic microstructure can be achieved by shifting the laser beam away from the centre to influence the weld pool dilution. In a 0.9mm thick dissimilar laser welded joint, a predominantly homogeneous microstructure was produced with specific point energy of greater than 17J. A predominantly austenitic microstructure was produced with a beam offset of 0.2-0.4mm towards the stainless steel, while a beam offset towards low carbon steel resulted in of a martensitic microstructure formation. CFD analysis has been applied to verify these findings and to further understand the fundamental phenomena of melt pool dynamics. The CFD analysis confirms the experimental findings and provides additional information such as cooling profiles and alloying composition that potentially could be used to predict phase transformation in more complex alloys.

9356-11, Session 3

Application of laser beam welding for joining ultra-high strength and supra-ductile steels

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In terms of lightweight design and assembly ultra-high strength steels and laser beam welding are going hand in hand. Two ultra-high strength steels applicable to hot stamping and one supra-ductile high-manganese steel are investigated with view to their weldability by laser radiation. All materials are excellent candidates for modern light-weight construction and functional integration. As example for ultra-high strength steels the stainless martensitic grade 1.4034 and the bainitic steel UNS K53835 are highlighted. The processing routes for strengthening are quenching and portioning (QP) and quenching and tempering (QT), respectively. For the supra-ductile steels stand two high austenitic steels with 18 and 28 % manganese.

Because of the high carbon content from 0.3 to 0.6 weight percent the weldability of the materials is rated as limited. This requires an approach from the metallurgical base on. In order to adjust the weld microstructure of weld and heat-affected zone the Q+P and the QT steels require some weld heat treatment whereas the HSD steel seems to be weldable without. Due to their applications the ultra-high strength steels are welded in as-rolled and strengthened condition. Also the reaction of the weld on hot stamping is reflected in the case of the martensitic grades. The supra-ductile steels are welded in two states of deformation, solution annealed and strengthened by 50%.

Besides the metallographic inspection of the weld zones the mechanical properties are evaluated by Vickers hardness testing. In case of the Martensitic grade also first results on fatigue testing and crash assessment are displayed.

9356-12, Session 4

Photonic processes and tools to produce light weight structures and components enabling energy and resource savings *(Invited Paper)*

Uwe Stute, 4JET Technologies GmbH (Germany)

In the transformation of bulk light weight materials such as CFRP or specialized metals into parts, photonic processes reveal specific advantages such as small heat affected zones in cutting of CFRP, welding former “uncombinabel” material combinations, preparing surface for glueing, creating 3D-parts. The research initiative fosters these new processes together with the development of the required photonic tools. The presentation will give an overview about the targets of the involved projects.

9356-13, Session 4

Laser based metal and plastics joining for lightweight design

Max Kahmann, Trumpf Laser- und Systemtechnik GmbH (Germany) and TRUMPF Inc (United States); Ulf Quentin, Marc Kirchhoff, TRUMPF Laser- und Systemtechnik GmbH (Germany); David L. Havrilla, TRUMPF Inc. (United States); Rüdiger Brockmann, Klaus Löffler, TRUMPF Laser- und Systemtechnik GmbH (Germany)

Lightweight design is becoming more and more important in the automotive industry, particularly since the CO2 emission of new cars has to be reduced to 95 g/km by 2020. Besides using new manufacturing methods, and employing high-strength steels and non-ferrous metals (Al, Mg) to enable lightweight construction, plastics and fiber reinforced plastics (CFRP, GFRP) currently gain relevance. Furthermore, different materials are joined into single components to exploit the full potential of weight reductions. Hybrid metal/plastic constructions are used to combine high stiffness and strength of metals with the enhanced design flexibility and low weight of thermoplastics. The paper at hand demonstrates a laser approach to joining such dissimilar materials in industrial applications.

9356-14, Session 4

Enabling lightweight designs by a new laser based approach for joining aluminum to steel

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As sustainability is an essential requirement, lightweight design has become increasingly important, especially for mobility. Reduced weight ensures more efficient vehicles and enables better environmental impact. New materials and material combinations are one major trend to achieve the required weight savings. Aluminum has several advantages compared to other material options, such as CFRP. As aluminum is a metal material, production technologies for high volume cutting and joining applications are already developed. In addition bending and deep-drawing can be applied, which makes this material relevant for automotive applications. Finally, aluminum is much more affordable compared to other light weight material options.

However, the thermal joining of aluminum to steel material is difficult.

The main reasons are: different thermal expansion coefficients, corrosion (electrical potential between steel and aluminum), and metallography (brittle inter-metallic phases are build).

Previous studies showed that joining of aluminum to steel is manageable by using a laser beam to limit the growth of inter-metallic phases to below 10µm. Therefore joints with a reasonable tensile strength could be made. A new laser based approach to join aluminum to steel is applying the laser metal deposition process. Two of the main advantages are gap bridgeability and the possibility to influence the metallography by using an appropriate powder.

First trials were very promising. This paper will show the latest results of the new application approach as well as limitations and gives some ideas for automotive lightweight design. The advantages compared to conventional processes are explained and possible joint geometries will be discussed.

9356-15, Session 4

Laser transmission welding of long glass fiber reinforced thermoplastics

Kira van der Straeten, Fraunhofer-Institut für Lasertechnik (Germany); Christoph Engelmann, Alexander Olowinsky, Arnold Gillner, Fraunhofer Institute for Laser Technology (Germany)

Over the past years, fiber-reinforced polymers are gaining more importance in lightweight construction. Especially in the automotive industry, in which the weight-reduction leads to new innovative lightweight constructions, not only bodywork parts, but also structural components from the chassis and safety relevant parts from the passenger compartment are being made from fiber reinforced composites. Since classical laser transmission welding techniques have been studied and established in industry for many years joint-strengths within the range of the base material can be achieved. Due to its flexibility, minimal energy input and the potential for automation laser transmission welding is suitable for serial production. Until now these processes were only used for unfilled and short glass fiber-reinforced thermoplastics using laser absorbing and laser transparent matrices. This knowledge is now transferred for joining long glass fiber reinforced PA6 with high fiber contents without any additives.

As the polymer matrix and glass fibers increase the scattering of the laserbeam inside the material, their optical properties changing with material thickness and fiber content influence the welding process and require high power lasers. In this paper the influence of these material properties (fiber content, material thickness) are researched and welding parameters like joining speed, laserpower and welding pressure are presented and discussed in detail. The process is also investigated to its limitations. Additionally the gap bridging ability of the process is shown in relation to material properties and joining speed.

9356-16, Session 4

Direct diode lasers and their advantages for materials processing and other applications

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Direct diode lasers may not be able to compete with other technologies as fiber or CO2-lasers in terms of power or beam quality. But diode lasers offer a range of features that are not possible to implement in a classical laser. We present an overview of those features that will make the direct diode laser a very valuable addition in the near future, especially for the materials processing market.

Not only the brightness of diode lasers is constantly improving, BPP of less than 5mm*mrad have been reported with multi-kW output power. Especially single emitter-based diode lasers further offer the advantage of very fast current modulation due to their low drive current and therefor low drive voltage.

State of the art diode drivers are already demonstrated with pulse durations of <10µs and repetition rates can be adjusted continuously from several kHz up to cw mode while addressing power levels from 0-100%. By combining trigger signals with analog modulations nearly any kind of pulse form can be realized.

Diode lasers also offer a wide, adaptable range of wavelengths, and wavelength stabilization. We report a line width of less than 0.1nm while the wavelength stability is in the range of MHz which is comparable to solid state lasers.

In terms of applications, especially our (broad) wavelength combining technology for power scaling opens the window to new processes of cutting or welding and process control. Details of the system and the possibility of backside hole drilling in non-transparent materials will be discussed.

9356-17, Session 5

Fatigue life enhancement of high reliability metallic components by laser shock processing *(Invited Paper)*

José Luis Ocaña, Juan A. Porro, Marcos Díaz, Leonardo Ruiz de Lara, Carlos Correa, David Peral, Univ. Politécnica de Madrid (Spain)

Laser Shock Processing (LSP) is a leading emerging technology for metallic materials mechanical properties improvement. Fatigue life and overall surface properties of critical components can be decisively improved by the action of high intensity pulsed laser in a confined laser plasma expansion regime

In the present paper, experimental results on the residual stress profiles and associated surface properties modification successfully reached in typical materials (especially stainless steels and Al and Ti alloys) under different LSP irradiation conditions are presented. In particular, the effect of thermal treatments on the residual stress profiles and fatigue life obtained by means of LSP treatment is analysed.

It is interesting to note that, because of the rather permanent character of the material dislocations induced by the LSP (thermo-mechanical) treatment, the thermal stability of the compressive stress field induced by LSP is reasonably maintained up to 500 ºC, providing a good mechanical performance after thermal treatments at this temperature.

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9356-18, Session 5

Laser chemical vapor doping of platinum in MP35N micro lead wires of pacemaker implants for MRI compatible bio-medical applications

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Laser assisted chemical vapor doping by solid state diffusion of platinum atoms into microwire leads of pacemaker implants is accomplished at high vapor pressure and temperature in a custom made thermonuclear

reactor chamber. The platinumacetylacetonate, Pt(acac)2 metal organic compound (MOC) solute is dissolved in 50 mL Acetyleacetone solvent to form the Pt precursor (PtPc) vapors by induction heating in a 250 mL capacity nuclear vacuum reactor. The PtPc vapor is mixed with inert Ar gas to get a total partial pressure of 5 atmospheres at RT. Then PtPc vapor is transported to laser vacuum chamber along with Ar inert gas at total vapor pressure of 7 atmosphere after heating up to 160 0C. The laser doping of Pt atoms in the 100 micron diameter MP35N wire is accomplished by solid state, localized heating at 900-1100 0C using 1mm x 0.1 mm line beam shape of 1064 nm Nd:YAG laser of 5-8 W power. A radio frequency (RF) transmitter is connected to a pair of Helmholtz magnetic coils (solenoids), a prototype developed to mimic and measure the induction heating effect of the pacemaker implants of patients undergoing the procedure for MRI treatment. The laser doping of Pt in MP35N is confirmed by XRD, SEM and EDAX spectroscopic studies. The laser doping of platinum was investigated for the electromagnetic induction resistance of MP35N wire by the RF transmitter at radio frequency of 55 – 85 MHz. A significant reduction in voltage induced by the radio frequency of the magnetic field is confirmed in laser doped Pt of MP35N micro lead wires. The laser doping of platinum in MP35N wires seems to be very promising in reducing the magnetic induction heating effect of micro wire leads of pacemaker implants caused by RF magnetic field during MRI treatment.

9356-19, Session 5

High power laser sources in industrial applications: A comparative perspective

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Lasers, ever since their invention in the sixties have been finding an ever increasing range of use in medical, industrial, scientific and military applications. Here, we focus on the relative merits, de-merits of three different classes of High Powered lasers (CO2, YAG and Fiber), all of which have found widespread use in industrial applications such as drilling, cutting and welding. We report on novel techniques, using these lasers, which are now beginning to be widely used to achieve state-of-the-art performance in specific applications (e.g. in drilling and welding). Market trends driven by purchase price, maintenance and operation costs, long term reliability and performance, are also discussed. In particular laser performance, within the context of integrated system performance is discussed; the resulting point of view that emerges clearly indicates that there is no one single solution to the myriad of different applications that these laser sources are brought to bear on, and that in fact, each and every problem has a corresponding ‘best-laser-source’ solution. Segmenting the market on the basis of major industrial applications, we are nevertheless still able to identify key laser sources, with specific characteristics (wavelength, power, beam quality, pulse energy etc.), that are expected to dominate the industrial laser market.

9356-20, Session 5

Development of a low cost, 3-DOF desktop laser cutter using 3D printer hardware

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In recent years, 3D printing has made significant leaps in terms of cost reduction, simplification of user interface and technology implementation. As a result, technology that had only been within the reach of design firms, engineering firms and universities can now be seen on the table tops of homes and smaller companies, at fractional costs. Besides 3D printing itself, the mechanical and electrical components most 3D printers are assembled of (linear stages, drive electronics, control electronics) allow for easy and low-cost development of other technologies that use multiple prismatic degrees-of-freedom (DOFs). One such example of this is laser cutting. Most commercially available laser cutters that are used for cutting materials like wood, plastic and metal use bulk-optic mirrors and lasing cavities; this increases size, cost and robustness of the system. High powered fiber lasers are able to overcome these limitations and allow for a potentially compact final design. In this study we present the development of a laser cutting system that involves the integration of a re-commissioned MakerBot® Replicator 2X chassis (with intact linear stages and electronics, print head removed) with a high-powered fiber laser (1064nm wavelength, 1kW peak-power) to create a compact, easy to use desktop laser cutter that the .stl file format. Special attention is paid to tear-down, modification and integration of the objective lens in place of the print head. Example cuts in wood and metal will be presented, as well as design of an exhaust system. Special focus is given to depth analysis of three dimensional structures cut into various materials. Optimization of spot size and feed-rate (“print speed”) will also be discussed.

9356-21, Session 6

Latest progress in laser process monitoring and control

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Laser Welding, laser cutting, laser drilling and many other laser based materials processing methods have been widely established in industrial use today. Since the beginning of these applications it has always been of great interest whether the processing results are of good quality, i.e. if the parts manufactured are within give boundaries of quality features.

However, only during the recent years the development of process monitoring and control system has reached a status where real process features and parameters can be measured directly. The former approach of detecting process emissions and thus deriving information about the manufactured quality is now replaced by the measurement of real process features. This can be achieved by the use of cameras, spectroscopic detectors, temperature signals or even combinations of individual signal sources.

This contribution describes the current state of art and research, new recent achievements and gives an outlook to future application of process monitoring and control systems and their expected reliability.

9356-22, Session 6

Real-time analysis of laser beams by simultaneous imaging on a single camera chip

Stefan Piehler, Meiko Boley, Marwan Abdou Ahmed, Thomas Graf, Univ. Stuttgart (Germany)

The fundamental parameters of a laser beam, such as the exact position and size of the focus or the beam quality factor M? yield vital information both for laser developers and end-users. However, each of these parameters can significantly fluctuate on a short time scale due to thermally induced effects in the processing optics or in the laser source itself, leading to process instabilities and non-reproducible results. In order to monitor the transient behavior of these effects online, we have developed a camera-based measurement system, which enables full laser beam characterization in real-time. A novel monolithic beam splitter has been designed which generates a 2D array of images on a single camera chip without aberrations, each of which corresponds to an intensity cross section of the beam along the propagation axis separated by a well-defined spacing. Thus, using the full area of the camera chip, a large number of measurement planes is achieved, leading to a measurement range sufficient for a full beam characterization conforming to ISO 11146 for a broad range of beam parameters of the incoming beam. The exact beam diameters in each plane are derived by calculation of the 2nd order intensity moments of the individual intensity slices. The processing time needed to carry out both the background

filtering and the image processing operations for the full analysis of a single camera image is in the range of a few milliseconds. Hence, the measurement frequency of our system is mainly limited by the frame-rate of the camera.

9356-23, Session 6

Process observation in selective laser melting (SLM)

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Selective Laser Melting (SLM) is moving towards industry. This process builds products from a combination of powder material and laser radiation which create layer by layer a solidified geometry. On this track, from layer to layer , a variety of parameters influence the outcome of the process. Such parameters start at the amount of energy emitted by the laser source and span towards properties of the powder. At ILT, we created a manufacturing system which allows us to simultaneously observe of the thermal emission of the process and the geometric properties of the melt pool. Based on this temporally aligned data, it is possible to show correlations between signals in the thermal emission that is captured from the melt pool and changes in the geometry of the interaction zone at the work piece. We show the benefit of combining the two sources of information and the conclusions which can be drawn.

9356-24, Session 6

Wide spectral band beam analysis

Oren Aharon, Duma Optronics Ltd. (Israel)

The reality in laser beam profiling is that measurements are performed over a wide spectrum of wavelengths and power ranges. Many applications use multiple laser wavelengths with very different power levels, a fact which dictates a need for a better measuring tool.

Rapid progress in the fiber laser area has increased the demand for lasers in the wavelength range of 900 - 1030 nm, while the telecommunication market has increased the demand for wavelength range of 1300nm - 1600 nm, on the other hand the silicone chip manufacturing and mass production requirements tend to lower the laser wavelength towards the 190nm region. In many cases there is a need to combine several lasers together in order to perform a specific task. A typical application is to combine one visible laser for pointing, with a different laser for material processing with a very different wavelength and power level. The visible laser enables accurate pointing before the second laser is operated.

The Beam profile of the intensity distribution is an important parameter that indicates how a laser beam will behave in an application.

Currently a lab where many different lasers are used will find itself using various laser beam profilers from several vendors with different specifications and accuracies.

It is the propose of this article to present a technological breakthrough in the area of detectors, electronics and optics allowing intricate measurements of lasers with different wavelength and with power levels that vary many orders of magnitude by a single beam profiler.

9356-25, Session 7

A new pulsed Q-switched CO2-laser as a tool for surface pre-treatment of CFRP for adhesive bonding

Fabian Fischer, Stefan Kreling, Malte Cohrs, Klaus Dilger, Technische Univ. Braunschweig (Germany)

The use of composite materials (CFRP) is growing significantly in all areas of lightweight construction. A key step is joining like adhesive bonding, which enables the designing engineer to capitalise the advantages of this material. However, the bonding performance is well reduced because of contaminations. An adequate pre-treatment of the surface is unalterable. One method for the pre-treatment of CFRP is the application of laser radiation. Because of the good absorption inside the resin matrix a CO2-laser (wavelength=10600 nm) was chosen. But laser radiation with this wavelength can be considered as thermal emitter, thus the matrix material could be damaged by the deposited heat. To reduce this deposited heat a new pulsed Q-switched CO2-Laser - prototype from Coherent Inc., US – was used with the aim of combining the good absorption behaviour and a pulsed laser system. To evaluate the quality of the laser pre-treatment optical and SEM analyses of the surfaces have been performed. Furthermore specimens have been pre-treated, bonded with a one component epoxy film adhesive, tested and compared with other pre-treatment methods.

9356-26, Session 7

Active optical system for advanced 3D surface structuring by laser remelting

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Structured surfaces have a vast distribution in everyday life and appear virtually everywhere in nearly every field of application. Particularly polymer components as product or part of a modern product such as car dashboards strongly influence both the visual appearance and haptic. Common production technologies for mass market manufacturing involve injection molding techniques that multiply the surface of a structured metallic tool several thousand times. The processing of the injection mold itself suffers from time consuming and expensive process steps that usually include milling, turning, photochemical etching, laser ablation or other technologies. These conventional techniques exhibit some crucial deficiencies such as geometrical limitations with mechanical based methods or the utilization of harmful chemicals and low efficiencies with photochemical etching and laser ablation respectively. All conventional processes have in common that they result in expensive, time consuming manufacturing what interferes with flexible and mass-market oriented manufacturing.

Structuring by laser remelting is an innovative approach for structuring of metallic surfaces with increased flexibility and speed. The superposition of up to three laser beams from different radiation sources facilitates the generation of high dynamic intensity distributions in the working zone. The control of the phase transformation of a local generated melt pool volume allows for periodic and aperiodic structuring without any waste but redistribution of molten material. A sophisticated active optical design takes into account the necessary degrees of freedom and features adaptive beam shaping performance for the processing of 3D surfaces.

9356-27, Session 7

Very high speed large area surface processing using nanosecond pulsed lasers

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Many types of material surfaces are commonly modified by laser processes. For industrial applications it is often desirable to scale these processes to large surface areas and high process speeds. Typically this requires an increase in average laser power by using either a single higher power beam or several multiplexed beams. For pulsed laser processes, as average power increases the pulse parameters must also be retained within an acceptable range. Nanosecond pulses are optimum for many processes because they can be produced with sufficient pulse energy to achieve high irradiance and high fluence over large areas, enabling single pulse ablation and other thin layer processes. Nanosecond pulses also allow efficient frequency conversion to give easy selection of properties such as differential absorption and absorption depth. We present the latest results on surface modification using solid-state nanosecond infrared, green and UV lasers with average power >1.6 kW and area processing speeds >150 cm2/s. Laser and process parameters such as pulse duration, wavelength and scanning strategy are described for a range of applications from surface cleaning and paint stripping through to surface patterning and annealing.

9356-28, Session 7

Study of fundamental laser material interaction parameters in powder melting

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Powder-bed-based layered manufacturing is a fusion process of creating three-dimensional parts by scanning a preplaced powder by a laser beam. The processing parameters are often applied based on engineering approach. Therefore, the melting characteristics may switch between the two major laser welding processes, keyhole and conduction. In the current state it is unclear if the powder-bed layer manufacturing is carried out mainly in keyhole or conduction regime. This makes the quality assurance and process control more difficult. Additionally, the characterisation of layer profile in terms of system parameters (laser power and travel speed) is complex and dependent on laser system. To make the process more robust, it is necessary to understand the process regime and identify parameters that control the fusion characteristics and profile of deposited tracks, independently of the laser system. This study proposes using fundamental laser material interaction parameters from conduction laser welding for characterising properties of deposited layers. Initial studies in solid material indicate that the interaction time and specific point energy have the major effect on the weld bead profile and effect of power density is secondary. A simple equation relating melt area to depth of penetration was also found at optimum melting efficiency.