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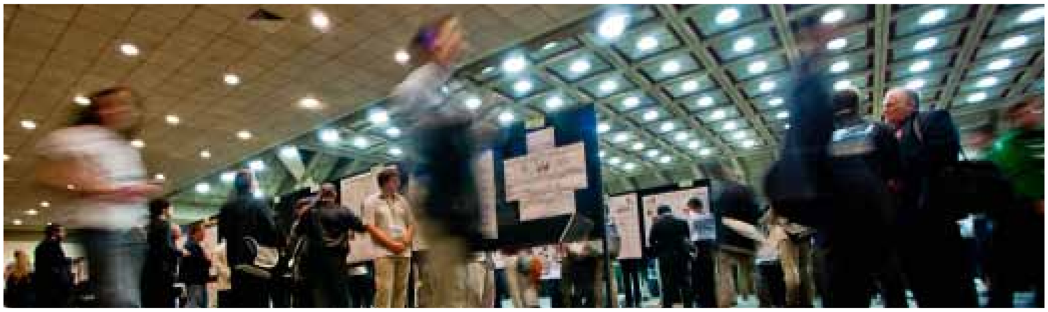

MOEMS-MEMS

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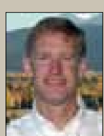

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8612-21, Session PTue

Method of creating microscale rapid prototypes using SLM based holographic lithography

Joseph L. Lawson, Nathan J. Jenness, Scott M. Wilson, Robert L. Clark, Univ. of Rochester (United States)

A method of generating arbitrary structures using holograms created by spatial light modulators is presented. This process allows any arbitrary micro-structure to be created using standard and commercially available CAD software. Enabling the microstructures to be designed using CAD and then realized using dynamic holographic lithography methods enables designers a simple, quick, and robust method of fabricating novel microstructures. The CAD model is first converted to a standard stereolithography file format (STL) available on most CAD software packages. Voxel locations on the interior of the structure are then determined by calculating the subtended solid angles from the surfaces of the STL file. The interior voxel locations can then be saved in a compact sparse array which easily facilitates dynamic hologram generation and the transfer of data between facilities. Based on the capabilities of the holographic lithography set-up, the sparse array of voxel locations is then used to generate holographic patterning routines using either raster scans of one or multiple focal points, exposures of two or three dimensional holograms, or a combination of both techniques. This methodology also enables the location and orientation of the structures to be controlled dynamically simplifying the process of creating multi-scaled structures or complex arrays of arbitrary structures.

8612-22, Session PTue

Super-hydrophobicity of PMMA surface by laser fabrication and thin film coating

Hong-Myeong Jeong, Woon-Young Lee, Jin-Ho Lee, Deok-Cho Yang, Ki-Soo Lim, Chungbuk National Univ. (Korea, Republic of)

Surface wettability depends on both physical surface structure and chemical structure. In this report, we demonstrate super-hydrophobic surfaces of cast polymethyl methacrylate (PMMA) sheet by femtosecond laser fabrication. Two-dimensional micro-array structures with round-shaped pillars in the interval range of 20-100 um were obtained on the PMMA surface by femtosecond laser irradiation and chemical etching. The Yb:KGW femtosecond laser processing system with its wavelength of 1030 nm and 250 fs pulses at a repetition rate of 100 kHz was employed for fabrication. The contact angle of PMMA changed from 64° (hydrophilic plane) to 150° (super-hydrophobic structure) under optimized conditions. To improve super-hydrophobicity, we coated the structured PMMA surface with other polymer materials, such as PDMS and commercial car-wash spray materials to change the surface chemistry. The resultant super-hydrophobic properties are explained by the combination of surface morphology and chemistry. We also measured the hydrophobicity of the coated PMMA without laser fabrication on the surface. The experimental results were compared with those expected values by modified Cassie and Wenzel models considering the coated materials.

8612-23, Session PTue

Fabrication of polymeric microstructures with Au nanoparticles

Cleber R. Mendonca, Vinicius Tribuzi, Daniel Correa, Univ. de São Paulo (Brazil)

Metal nanoparticles have been used to tailor optical properties of microdevices. Au nanoparticles, for instance, are known to enhance local electric field, which can be used to enhance the material´s optical and electrical properties. Most of the methods to dope polymeric matrix with nanoparticles employ the introduction of nanoparticles in the resin, prior to polymerization. The presence of metal nanoparticles, however, interferes with the polymerization processes, limiting such approach when two-photon polymerization (2PP) is used. The 2PP has been used for the fabrication of 3D microstructures aiming at applications from biology to photonics. This method allows fabrication of complex and high resolution microstructures. In this context, this work reports the fabrication of two-photon polymerized microstructures doped with Au nanoparticles. Such doping was carried out by an indirect process, in which the nanoparticles are produced after polymerization. In this approach, the acrylate monomers are mixed with $HAuCl_4$. The 2PP is induced by a Ti: Sapphire laser oscillator delivering 35 fs pulses. After the polymerization, the samples were submitted to a thermal treatment, which induces the production of Au nanoparticles. We have been able to fabricated 3D microstructures doped with Au nanoparticles, whose presence was verified by absorption, electron microscopy and fluorescence measurements. Our results show that gold nanoparticles-doped microstructures exhibit an enhancement of the polymer matrix fluorescence, which is probably due to the Au nanoparticles luminescence. Therefore, the methodology described here seems to be an interesting option for the fabrication of devices for nanoplasmonics and metamaterials.

8612-24, Session PTue

Optimizing mechanical performance of comb drive actuators at low driving voltage

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The main focus of the present study was investigation and simulation of the mechanical performance of lateral comb drive actuators using the Finite Element Analysis (FEA) in ANSYS 12. This step of analysis is very important to design the process of MEMS applications and may help comb drive to express fundamental source of actuation within the chip systems. A two-dimension model was obtained utilizing Reduced Order Modeling (ROM) principles. The special effect of these comb drive design factors on the actuation efficiency was investigated during a parametric study and the outcome of lateral-comb-drive actuators for higher displacements at lower driving voltages was presented. The displacement variation of the lateral Electrostatic comb-drive actuators and electrostatic force by changing the applied voltage, the number of electrodes, thickness and the gap between the fingers were solved and discussed. The simulation results indicated that the large displacement can be achieved by increasing the number of fingers and the voltage and by decreasing the gap between the fingers. The analytical results confirmed the simulation results by ANSYS 12 software and the error of displacement between the simulation results and the analytical results was less than 5%. The present study illustrates that the ROM technique can be accurate and reliable method to simulate lateral electrostatic comb drive actuators.

8612-1, Session 1

Design of microcantilever sensors using SLM based holographic lithography

Joseph L. Lawson, Robert L. Clark, Univ. of Rochester (United States)

A holographic multiphoton fabrication technique is applied to the development of a microcantilever based analyte sensor. Holograms generated using a spatial light modulator initiate the fabrication of sub-micron scaled three-dimensional structures. Chemically functional

microstructures are patterned onto the surface of commercially available piezoelectric microcantilevers using this holographic lithography technique. Controlling the form and location of the added structure enables the resonant frequency of the cantilever to be regulated with a higher accuracy than is currently available using bulk lithography techniques and without the inclusion of additional electronic feedback control components. The form factor is further used to control the sensitivity of the resonant frequency when the micro-cantilever is exposed to a reactive environment based on its chemical functionalization. An analyte sensor is then developed by patterning on an array of multiple piezoelectric microcantilevers which are initially identical within manufacturing tolerances. The resonant frequency, sensitivity, and chemical functionality are tuned such that each cantilever has a unique resonant frequency. Connecting the piezoelectric microcantilevers in parallel enables the response of each sensor element to be measured simultaneously using a single frequency based data acquisition system.

8612-2, Session 1

Graphene-based inkjet printing of flexible bioelectronic circuits and sensors

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Bioelectronics has emerged as one of the frontiers of interdisciplinary science and engineering. The term “bioelectronics” implies interfacing functional biomolecules or living cells with microelectronic circuitry. Advances in inkjet printing technology have further enabled researchers to fabricate conductive microelectrode arrays and sensor circuits on a variety of mechanically flexible substrates such as soft polymers, paper and biocompatible silk. The printing process is accurate, permits high speed microfabrication, and consumes far fewer materials than common lithographic processes. Current research on developing graphene-based inks for printing flexible bioelectronic will be presented. Graphene is a one-atom-thick single layer of carbon that exhibits high electrical conductivity and mechanical strength properties. However, non-conductive graphene-oxide (GO) inks are often used because the solution can be synthesized from inexpensive graphite powders using the well-known Hummer’s method. Once printed on the flexible substrate the electrical conductivity of the micro-circuitry can be restored through thermal reduction. In this research, laser irradiation is used to transform the high resistance printed GO film into conductive oxygen reduced graphene-oxide (rGO). The direct laser writing technique provides highly precise process control, benefiting the localized formation of the conductive and resistive elements to be locally formed on the imprinted GO circuit, which then biofunctionalized using a variety of immobilization techniques to adsorb biomolecules on the electrodes. Light sensitive bacteriorhodopsin proteins are labeled and self-assembled on specific areas of the micro-circuit for this study. The opportunities and challenges in exploiting these emerging technologies for developing biosensors, lab-on-a-chip devices and diagnostic systems will also be discussed.

8612-4, Session 1

Laser direct write system for fabricating seamless roll-to-roll lithography tools

Joseph E. Petrzelka, David E. Hardt, Massachusetts Institute of Technology (United States)

Implementations of roll to roll contact lithography require new approaches towards manufacturing tooling, including stamps for roll to roll nanoimprint lithography (NIL) and soft lithography. Suitable roll based tools must have seamless micro- or nano-scale patterns and must be scalable to roll widths of one meter.

Towards this end, the authors have developed a new centrifugal stamp casting process that can produce uniform cylindrical polymer stamps in a scalable manner. The pattern on the resulting polymer tool is replicated against a corresponding master pattern on the inner diameter of a centrifuge drum. This master pattern is created in photoresist using a UV laser direct write system.

This paper discusses the design and implementation of a laser direct write system targeting the internal diameter of a rotating drum. The design uses flying optics to focus a laser beam along the axis of the centrifuge drum and to redirect the beam towards the drum surface. Using a constant inertia spiral trajectory allows patterning at rates up to 30 square millimeters per second with an 80 mW laser.

Experimental patterning results show uniform coatings of negative photoresist in the centrifuge drum that are effectively patterned with a 405 nm laser diode. Seamless patterns are shown to be replicated in a 50 mm diameter, 60 mm long cylindrical stamp made from polydimethylsiloxane (PDMS). Direct write results show gratings with line widths of single microns in negative photoresist. Using an FPGA, the laser can be accurately timed against centrifuge encoder to create complex patterns.

8612-5, Session 1

Plateau-Rayleigh instability triggered transformation in thin chromium film on glass substrate under nanosecond laser irradiation

Mindaugas Gedvilas, Karolis Ratautas, Bogdan Voisiat, Kestutis Regelskis, Gediminas Raciukaitis, Institute of Physics (Lithuania)

The chromium film on glass is an important material in the photo mask production for lithography, as well as in production of diffraction gratings, and linear optical encoders for metrology. Lasers are frequently applied for patterning the film instead of the wet chemical or plasma etching. When performing micromachining using lasers, bursts of low power irradiation are employed to minimize heating. However, ripples, or laser-induced periodic surface structures, are observed at intensities near the ablation threshold. Transformation of the metal film structure under laser irradiation is to some extent an undesirable effect but at same time it is a promising method for micro and nano-structuring of the functional surfaces. We experimentally and numerically investigated transformations in metal films during their irradiation with the nanosecond laser beam and astigmatic optical system with fluences above the ablation threshold. Non-uniform ridges of the resolidified metal were always formed on edges of the cleaned area. Instabilities during the ablation process forced the molten metal in the ridges to break up into droplets with the periodicity predicted by the Plateau–Rayleigh instability. The droplets on ridges were starting points for formation of ripples of metal film by irradiation with partially overlapping laser pulses. The initial droplets and later the self-organized parallel lines of chromium metal were heat sinks that cooled down the metal in their close proximity. Temperature modulation along the laser irradiation spot was high enough to initiate the Marangoni effect which resulted in movement of the molten metal from hot to colder areas.

8612-6, Session 2

Silicon backside machining using a nanosecond 2-µm Tm:fiber laser

Thomas Ferhat, Martin Richardson, Lawrence Shah, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

This paper discusses the selective ablation of front and backside of silicon samples. Simultaneous machining of the two sides of the sample is also performed.

A Tm doped, pulsed fiber laser source at a center wavelength of 2 µm is used to machine silicon samples of various thicknesses (0.5 mm and 5 mm). At the target, the laser has a 37 µm beam diameter with pulse energies up to 600 µJ with pulse durations of from 10 ns to 100 ns at

a repletion rate of 10 kHz. The laser pulses can reach an irradiance of 5.58 J/cm? easily surpassing the silicon damage threshold of 4.2 J/cm? (1). A motorized 3D stage is used to position the sample insuring the repeatability of the experiment. Utilizing the transparency of silicon at 2 µm, we are able to ablate the backside of the silicon material without causing any damage to the front surface. We describe the effects of laser parameters such as pulse duration and energy density on the ablation, and compare thresholds for front and backside machining. As part of these experiments, we also monitor the ablation process in situ with an InSb camera, which allows us to see into the silicon sample during front and/or backside ablation. These capabilities may lead to new processing techniques for advanced manufacturing in solar cell and microelectronics industries.

(1) Laser-induced damage threshold of silicon in millisecond, nanosecond, and picosecond regimes X. Wang, Z. H. Shen, J. Lu, and X. W. Ni, Journal of applied physics 108, (2010)

8612-7, Session 2

Use of laser transfer processing for producing Al-Bi doped silicon electronic devices

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Laser doping is and attractive process for producing precise heterojunctions by selective diffusion or migration of dopants into a volume of sillicon by local heating or melting of the silicon substrate. As an alternative fabrication path for highly doped heterojunctions on Si devices, a process bed on simultaneous dopant feed and diffusionis proposed, by joining the Laser Induced Transfer (LIFT) proces and the laser induced melting of the substrate.

LIFT is a provn technique to deposit liquid or solid material on a precise location og the trget substrate. Solid Al transfer is being used in hybrid organic-inorganic devices, and laser direct transfer of aluminium with laser has been demonstrated to produce conducting lines on thin film structures. The proposed LIDT (Laser Induced Transfer Doping) technique allows the production of high concentration doped volumes in a single step by using solid dopant source.

Correspondingly to the use of Aluminium as p-dopant, Bismuth is studied in this work as an effective n-dopant compatible with the laser transfer process.

Neither Aluminium nor Bismuth are suitable for the diffusion doping in gas atmosphere usual in industriy. Low termal diffusion capability of both dopants into silicon can be exploited to improve the performance and durability of produced heterojunctions.

As-cut solar silicon wafers wre used to investigate the technical viability of Laser Induced Transfer Doping with pulsd laser source. A 20W diode end pumped Nd:YV4 nanosecond Q-switched, laser source was used for this investigation (up to 200kHz, 10ns pulse at 20kHz), in fundamental and second harmonic. The lase beam is guided to the silicon wafer surface by means of a scanning head with a 255 mm focal lenght field lens, to provide a spot diameter of 40 microns on the focal plane.

The solid dopant source is prepared as a thin film sputtered or evaporated on a glass substrate, transparent to the laser wavelenght. This donor plate is placed directly over the silicon wafer, and laser energy is directed through the glass to the receiver substrate (silicon wafer). Experiments are performed on air, under normal conditions, and wafers are untreated.

Process parameters have been selected in order to achieve the needed energy to transfer the aluminum and bismuth to the substrate while a thin layer of silicon is being melted by the laser irradiation. The solid dopant is incorporated into the molten silicon due to its higher solubility.

Energy levels in the range of 200 to 800 mJ are needed to produce transfer of 50 microns wide tracks when using IR laser, while half of this energy or less is required for producing a simmilar result when using the second harmonic of the laser source.

Scanning speed was set to produce no overlap between spots, resulting in values of 1 to 3 m/s. The gap between the donor and the substrate was kept under 100 microns, without using vacuum or controlled atmosphere.

When transferring and doping in a single step, extra energy is used with respect to the LIFT threshold fluence. SEM observations confirm the presence of molten silicon. The transfer from the glass substrate results in a spray-like deposition which produces an homogeneously disperse micro-droplet distribution of the dopant source on the silicon surface.

Space resolved chemical mapping was used to analyze the surface after laser processing. Analysis of the cross-sections of processed samples reveal a clear increase in the dopant species, within the volume of molten silicon produced by the laser pulse (which heavily depends on the process parameters, and is found to be under 50 microns in all cases).

Dopant concentration improves with repetition of pulses. However, the process is very effective when compared to liquid or gas inmersion laser doping technique. Dopant levels higher than 0.1% in weight were detected for only two repetitions in aluminium with green laser.

8612-8, Session 2

Doping method to glass material using a CO2 laser

Keigo Nakamura, Takayuki Tamaki, Nara National College of Technology (Japan)

In this paper, we present the investigation results on doping to a BK7glass sample (OHARA, S-BSL7) by use of a CO2 laser. CO2 laser system generates CW (continuous wave) laser beam with a wavelength of 10.6 µm. Laser beam was irradiated on a sample substrate (30 mm x 5 mm x 0.7 mm thick). A surface of the glass was applied fluorescent material. The doped regions were created by translating the glass sample perpendicular to the laser axis with a distance of 2 mm and a scan speed of 1 mm/s. After processing, the cross section of sample was analyzed by energy dispersive X-ray analysis (EDX) in scanning electron microscope for revealing the contained element in the glass. The results have demonstrated that carbon was widely distributed in the doped regions although the original glass material did not contain carbon element.

8612-10, Session 3

Deep silicon etch for biology MEMS fabrication: review of process parameters influence versus chip design

Thomas Magis, CEA-LETI (France)

Micro-system for biology is a growing market, especially for micro-fluidic applications (environment and health). Key part for the manufacturing of biology MEMS is the deep silicon etching by plasma to create microstructures. Usual etching process as an alternation of etching and passivation steps is a well-known method for MEMS fabrication, nowadays used in high volume production for devices like sensors and actuators.

MEMS for biology applications are very different in design compared to more common micro-systems like accelerometers for instance. Indeed, their design includes on the same chip structures of very diverse size like narrow pillars, large trenches and wide cavities. This makes biology MEMS fabrication very challenging for DRIE, since each type of feature considered individually would require a specific etch process. Furthermore process parameters suited to match specifications on small size features (vertical profile, low sidewall roughness) induce issues and defects on bigger structures (undercut, micro-masking) and vice versa. Thus the process window is constrained leading to trade-offs in process development.

In this paper process parameters such as source and platen powers, pressure, etching and passivation gas flows and steps duration were investigated to achieve all requirements. As well interactions between

those different factors were characterized at different levels, from individual critical feature up to chip scale and to wafer scale. We will show the plasma process development and tuning to reach all these specifications. We also compared different chambers configurations of our ICP tool (source wafer distance, plasma diffusion) in order to obtain a good combination of hardware and process. With optimized etching we successfully fabricate micro-fluidic devices like micro-pumps.

8612-11, Session 3

Eliminating stiction in NEMS and MEMS release: parameters optimization for an HF vapor process operating at room temperature and ambient pressure

Olivier Pollet, Roselyne Segaud, Carine Marcoux, Francois de Crecy, CEA-LETI-Minatec (France)

This study focused on optimizing a vapor-phase hydrofluoric acid etching process to eliminate stiction occurrence during NEMS release. Indeed, these types of structures are very sensitive to stiction due to their small size. The process is run on a 200mm industrial batch tool operating at ambient pressure and temperature.

A dedicated lithography mask was designed to assess the performance of the HF vapor process from a stiction standpoint. This mask features all typical structures found in NEMS and MEMS devices (beams, combs, ground planes). For each structure type, representative dimensions vary (for instance : for a fixed beam width, length ranges from 1 to 100µm). Therefore, the release efficiency for a given process is the maximum size of a specific structure that is released without observing any stiction.

Several design-of-experiment plans were successively carried out in order to compute different models representing the stiction occurrence for a given structure design as a function of process parameters (HF and IPA flowrates, temperature). The main output parameter in DOEs was the release efficiency on different beam designs, which is characterized on SOI wafers patterned with the mask described above. Though, for industrial considerations, etch rate and etch uniformity were also taken into account. Models accuracies were then tested experimentally and the best fit was found to be a second degree model including only the HF and IPA flowrates as factors, the temperature being held constant at 20°C.

Thanks to this model, optimization was then carried out by targeting the highest release performance achievable. A new set of process parameters was figured out which improved release efficiency by 15% while the etch rate is four times faster than the former process used.

These results have since been confirmed on actual devices.

8612-12, Session 3

Interferometrically defined 3D pyrolyzed-carbon

D. Bruce Burckel, Sandia National Labs. (United States)

Recently, we have demonstrated that we can convert 2D/3D resist structures created using interferometric lithography into amorphous sp2 and sp3 bonded carbon via pyrolysis in a reducing atmosphere 1,2. These structures maintain their basic pattern morphology despite undergoing significant shrinkage. The carbon can be further chemically converted to entirely sp2 bonded carbon via chemical conversion by sputtering conformal nickel and then performing a secondary anneal 3. The ability to create a wide range of 2D and 3D structures with sub-micrometer scale patterning in both sp2 (graphene and other fullerene allotropes) and sp3 (diamond-like carbon) makes possible a wide array of technologically relevant applications. This paper will present detailed fabrication and characterization data of these materials.

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.

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8612-13, Session 3

Fabrication of thin vertical mirrors through plasma etch and KOH:IPA polishing for integration into MEMS electrostatic actuators

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A process was developed for the fabrication of thin vertical mirrors as integrated structures of MEMS electrostatic actuators. The mirrors can be implemented as vertical extension of actuator sidewalls, or can be positioned at any movable part of an actuator. The process involves the fabrication of a mesa structure on the handle layer of a silicon-on-insulator (SOI) wafer through deep reactive ion etching (DRIE). The etch/passivation cycles of the DRIE process were optimized to achieve vertical etch profiles with a depth of up to 180 ?m with an aspect ratio of 10:1. The DRIE process introduced typical etch scallops with peak-to-valley and rms roughnesses on the order of 100 nm and 30 nm, respectively. A mask layer was used to pattern a 1.8 ?m sacrificial oxide layer for the mesa structure. A second mask layer was used to define a large etch cavity for handle layer back-etch. The DRIE etched mesa structure was then etched with diluted potassium hydroxide (KOH) in isopropyl alcohol (IPA). Temperature and etch concentration were optimized for the removal of etch scallops without the formation of {110} etch facets. Mirror quality surfaces with almost no trace of etch scallops were achieved. The developed mesa structures are suitable for integration into actuators that are patterned in the device layer. A third masking layer, aligned through infrared camera, was used to align the thin vertical mirrors with actuator sidewalls. The process provides design flexibility in integrating vertical mirrors of adjustable dimensions to movable elements of MEMS structures.

8612-14, Session 3

High-quality surface micromachining of LiNbO3 by ion implantation-assisted etching

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Lithium Niobate ($LiNbO_3$) is an extensively studied material due to its piezo-electro-optical properties above all. It is a well-established material

for acoustic and optical signal processing and it has recently attracted a renewed interest in the emerging field of acousto-fluidics.

Despite their wide diffusion, commercial devices based on LiNbO3 rarely take advantage of the great potential offered by surface micromachining. A precise control of relief microstructures shape and roughness could be a technologic breakthrough for a new generation of LiNbO3 devices.

A surface microstructuring technique of LiNbO3 substrates, based on an improved implantation-assisted wet etching process, will be presented and discussed.

Relief structures 2.3 microns high with vertical sidewalls and optical quality were fabricated on LiNbO3 by implanting with 5 MeV Cu ions through an SU-8 10 microns thick photoresist masking layer. The LiNbO3 regions amorphized by implantation were then etched away with a HF solution at a rate of 100 nm/s exploiting the high differential etching rate between damaged and undamaged LiNbO3.

The process can be repeated to obtain higher aspect ratios. In this work the results of a two step process will be presented.

The surface quality and vertical sidewalls of the obtained structures make this technology highly promising in integrated optics and acousto/opto-fluidics.

8612-15, Session 3

Characteristics of a tapered hollow micro-tube emitting a Bessel light beam

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We looked at the correlation between an emitted Bessel light beam from a subwavelength annular aperture on metallic film and from a tapered hollow micro-tube, both from a lithography viewpoint. Intensity profiles were investigated by using finite-difference time-domain (FDTD) simulations. Lithography experiments were also undertaken. We discuss the approaches used to couple the incident light into the hollow micro-tube and to the subwavelength annular aperture. The effects caused by a waveguide mode were also studied. We found that the tip size of the tapered hollow micro-tube affects the emitted Bessel light beam properties. In addition, the incident light polarization state was also found to have an influence on the characteristics of the emitted light beam. We confirm that the tube thickness of the tapered hollow micro-tube tip is an important factor in the generation of the Bessel light beam wavelength. Our findings show that lithography can be used with a through silicon via (TSV) process in a far-field region while maintaining a near diffraction-limit spot size and also provide us with full knowledge of the emitted Bessel light beam from the tapered hollow micro-tube.

8612-16, Session 4

Practical implementation of broadband diffractive optical elements

Junoh Choi, Anthony Tanbakuchi, Alvaro A. Cruz-Cabrera, Sandia National Labs. (United States)

Diffractive optical elements (DOE), with their thin profile and unique dispersion properties, have been studied and utilized in a number of optical systems, often yielding smaller and lighter systems. Despite the interest and study on the DOEs, the application of the DOEs has been limited to narrow spectral bands. This is due to the DOEs depths, which are optimized for optical path differences of only a single wavelength, consequently leading to rapid decline in efficiency as the working wavelength shifts away from the design wavelength. Various broadband DOE design methodologies have recently been developed that improve spectral diffraction efficiency and expand the working bandwidth of diffractive elements.

We have designed two such broadband DOEs, one using the multi-layer diffractive design and the second using a harmonic diffractive design. The multi-layer DOE consist of a fused silica element and a calcium fluoride element. The harmonic diffractive was designed to be made with calcium fluoride only. Both of the devices required unconventional zone widths and extremely large depths, pushing the limits of the current fabrication technologies. We have modeled the diffraction efficiency of the two designs and are in the process of fabricating a device for each approach. One design consisting of two materials uses fused silica with grayscale lithography for the patterning, and calcium fluoride using diamond turning. The second design only uses calcium fluoride and was diamond turned.

We will present results from the diffractive efficiency model, fabrication, and the efficiency tests performed at various wavelengths for both manufactured DOEs.

8612-17, Session 4

Simulation of thick film photoresist processes

Stewart A. Robertson, KLA-Tencor Texas (United States); Andy Miller, Patrick Jaenen, IMEC (Belgium)

Lithography simulation has been successfully used in front-end IC manufacturing for more than 2 decades. Many modern processes would not be manufacturable without the use of OPC (Optical Proximity Correction) techniques based on computational lithography.

Although the lithography processing used for MEMS manufacture are certainly less aggressive in terms of critical dimension than that of front-end IC processes, challenges come from other considerations related to the thickness of the resist, such as high aspect ratios and cases where the resist thickness exceeds the depth of focus available from the exposure tool.

In this work, we apply physical lithography modeling to typical MEMS lithography scenarios. Specifically, we develop a resist model for an extremely thick film materials used in one such MEMs application. Although the key elements of image formation and resist processing are similar between the front-end IC and this process, the exact details and the desired critical outputs are distinct.

Front-end IC processes use thin resist layers, typically 100 nm to 2 microns, whilst MEMS applications often require thicker films of 40 – 100 microns. The front-end IC engineer's primary concern is for the critical dimension (CD) of the printed resist feature, whilst the MEMS engineer is often less concerned about the exact size of an imaged structure but very interested in the shape and angles describing its cross-sectional profile.

We present a resist model for a lithography process using a commercially available thick film chemically amplified photoresist using PROLITH (commercial lithography simulation software for front end IC applications – KLA-Tencor Corporation). Model calibration is performed by matching simulation to FEM (focus-exposure Matrix) dimension data, and cross-sectional micro-graphs for various exposure conditions.

We detail how the photoresist model parameters deviate from those observed in front-end imaging materials to capture the effects unique to deep back-end processing. We also detail how simulation metrology algorithms need to be adapted to capture the process characteristics that are important for 3DIC purposes rather than conventional front-end use cases. Finally, examples of how an accurately calibrated lithography model can be used to improve MEMS processing are provided.

8612-18, Session 4

Piezoelectric resonant micromirror with high frequency and large deflection applying mechanical leverage amplification

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Technology ISIT (Germany); Wolfgang Benecke, Fraunhofer-Institut für Siliziumtechnologie (Germany)

Micromirrors are of high interest for automotive and consumer applications, because of their small dimensions and cost efficiency. They enable applications such as head-up-displays, optical switches and laser projection. The driving technologies used for micromirrors are mainly based on thermoelectric, electromagnetic, electrostatic and piezoelectric principles. Compared to the other driving principles piezoelectric materials, especially PZT (lead-zirconate-titanate), deliver higher forces at low driving voltage. Additionally, a piezoelectric micromirror has fewer demands on reducing air damping or being insulated from the thermal or magnetic interferences of the environment. Therefore, along with the development of the processing technology piezoelectric materials offer advantageous performances for driving micromirrors.

This paper presents designs and a fabrication process for single-axis piezoelectric micromirrors with 1 square millimetre apertures. These micromirrors, which feature thin-film PZT actuators and mechanical leverage amplification, are specified for laser projection and meet the requirements on high resonant frequency and large deflection. To identify the optimal micromirror geometries a parametric study by means of FEM simulations and analytic modeling has been performed. According to the results various micromirrors with resonant frequencies up to 56 kHz and ?opt•D products up to 60 deg•mm (extrapolated based on static deflections and an assumed Q-factor of 100) have been designed and fabricated. First characterizations related to the mechanical performance of micromirrors and the material qualities of PZT have been performed. The reliability of the process, the robustness and the operability of the fabricated prototypes have been verified. Furthermore, new designs with larger apertures and deflections are currently being developed.

8612-19, Session 4

Effect of nonlinearity degree on pull in voltage

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Pull in voltage in micro-cantilever beams has an essential role in its control and stability.

Theoretical analysis of the dynamic performance of the micro-cantilever beams is based on linearization of nonlinear ODE. The results predict that the pull in voltage happens when the micro-cantilever beam deflects more that 33.33% of the initial gap between the beam and the substrate. Meanwhile, nonlinear analysis shows that 45% deflection of the beam is necessary to reach pull in voltage. Clearly, nonlinear analyses yield much accurate results, but it requires more effort in the formulation and the solution. Analytical solution of the ODE that is a representation of the phenomenon is under investigation and there is no answer in present time, so there is no exact equation that enables to calculate pull in voltage. From the other side numerical solution of stiff ODE around saddle point can be carried out only with a few very specific methods, like ISOD, and these methods have very weak convergence and high calculation time. The purpose of this investigation is to assist in finding the accuracy of different linearization methods in a way that reduces the computation time and increase stability of calculation without losing accuracy of calculation in comparison with the nonlinear analysis. For this purpose, nonlinear term of ODE expanded by Taylor series and part of those terms are considered. The solutions will be compared with the nonlinear solution. Finally, the effectiveness of each method is presented.

8612-20, Session 4

ThermoEMF of phases and states of Si under high pressure

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Since 1940s Si became the main material for microelectronics mainly due to the crucial experiments under pressure revealing the true electron band structure. In the 1980s, silicon was suggested also as mechanical material and Si-based devices have been called micro-electro-mechanical systems (MEMS) [1]. The strong "interplay" between the electronic and mechanical properties of Si [2], revealing particularly in "semiconductor-metal" phase transition occurring under micro-hardness measurements[2], is used in MEMS-devices[1]. In all Si-based devices the high local mechanical stresses may arise tending to phase transitions even at negligible loading [2]. At present about 13 different phases of Si are known, some of ones being metastable at ambient conditions [3, 4]. In the present work the technique of high-pressure thermoelectric (TE) investigation has been used for the determination of the values of S for different phases and states of Si subjected to high-pressure (mechanical stresses) loading.

The band structure calculations of several phases of Si were carried out using linear muffin-tin orbital's method (LMTO). The technique of Raman scattering, as well as ultra-soft x-ray emission spectroscopy [2], have been used for control of both the initial and metastable states at ambient conditions. The values of S for various phases of Si at pressure range 0-25 GPa have been received. The dependence of S on pressure was shown also to be sensitive to all the pre-treatments applied to a sample including annealing, doping, and irradiation by high-energy particles. The TE properties of various phases and states of Si were established which may be potentially used in Si-based nano-thermoelectric devices [5]. TE power factor of nano-structured Si-systems is known to be enlarged up to 100 times in compare with the bulk material [5]. The experimental values of thermoelectric power of various phases of Si are compared with the theoretical estimations basing on the band structure calculations performed.

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8613-1, Session 1

Precisely controlled plasmonic nanostructures and its application to nanolithography *(Invited Paper)*

Kosei Ueno, Hokkaido Univ. (Japan)

Advanced lithography systems, such as ArF immersion lithography, have achieved a 32 nm node and are already used in the development of electronic device. However, the advanced lithography systems are not suitable for fabricating nanostructures, such as rectangular cuboids, triangular prisms, chains, and nanogaps. These nanostructures are being used for various applications that include plasmonic solar cells and photonic crystal lasers. Here, we report on a novel plasmon-assisted nanolithography system that is used to fabricate nano-patterns with nanometric accuracy. The most attractive merit of this system is to form deep nano-patterns on positive photoresist. The formed nano-patterns are completely reflected in the photomask's design. The key technology is the two-photon-induced reaction of a photoresist promoted by plasmonic near-field light and propagating light in a photoresist film. This propagating light is a radiation mode from a higher order of localized surface plasmon resonances scattered by gold nanostructures. The system does not induce nano-pattern deformation at the time of mask release. This system presents a simple alternative for producing nano-patterns instead of using nanoimprinting.

8613-2, Session 1

3D chiral and nonreciprocal plasmonics *(Invited Paper)*

Harald W. Giessen, Univ. Stuttgart (Germany)

We present a novel approach to create large-area (cm?) 3-dimensional chiral plasmonic structures. Large transmission differences between right- and left-hand circularly polarized light in the percent range have been measured in the near-infrared spectral region. Additionally, by introducing magneto-optical hybrid plasmonic structures and applying a static magnetic field, nonreciprocal Faraday rotation in the near-infrared was measured.

8613-3, Session 1

Fabrication of chiral plasmonic nanostructures and patterns for optomechanical applications

Gediminas Gervinskas, Lorenzo Rosa, Swinburne Univ. of Technology (Australia); Etienne Brasselet, Univ. Bordeaux 1 (France) and CNRS Lab. Onde et Matière d'Aquitaine (France); Saulius Juodkazis, Swinburne Univ. of Technology (Australia) and Melbourne Ctr. for Nanofabrication (Australia)

A unique combination of Ion-beam lithography (IBL; Raith IonLiNE) and electron-beam lithography (EBL; Raith 150-TWO) has been utilized to create chiral plasmonic structures with 15-25 nm wide grooves inscribed onto particles down to a controlled depth. First, EBL was used to define patterns of gold nano-particles on a 2-?m-thick silica membrane or on the surface of a bulk sample. The flexibility, thermal conductivity and optical transmission of the membrane allows to explore integration of such samples into opto-fluidic and optical-MEMS structures. Usual lift-off fabrication of plasmonic nanoparticles on membranes is not possible due to membrane fragility, which is not compatible with ultrasonic bath development during lift-off. Here, we show processing steps for reliable fabrication of nanoparticles on membranes. Uniform patterning with 15-25 nm (at FWHM) grooves and 30 nm diameter hole arrays is demonstrated on 20 x 20 ?m2 areas by utilizing the IBL direct-write technique. The optical performance of the fabricated patterns has been modelled numerically by the 3D-FDTD method, with a total-field scattered-field approach that permits to calculate the wideband cross-section and field enhancement response with a single simulation. Patterned plasmonic nano-particle arrays allow tailoring of light field enhancement in both spectral and spatial domains. Applications in nano-tweezers and chiral sorting are discussed and optical forces and torques are estimated through Lorentz force modelling.

8613-4, Session 1

Nanoscale patterning of colloidal quantum dots for surface plasmon generation

Yeonsang Park, Young-Geun Roh, Un Jeong Kim, Jin-Eun Kim, Sangmo Cheon, Hwansoo Suh, Jaesoong Lee, Dae-Young Chung, Tae-Ho Kim, Kyung-Sang Cho, Chang-Won Lee, Samsung Advanced Institute of Technology (Korea, Republic of)

.The patterning of colloidal quantum dots (QDs) with nanometer resolution is very essential for their application in photonics and plasmonics. Many novel approaches are developed such as the use of polymer composites, molecular lock-and-key methods, inkjet printing, and microcontact printing of quantum dots. However, these methods have limits to apply to conventional CMOS fabrication technologies and difficulties in enhancing positioning resolution and the variation of structural shapes. In this talk, we present an adaptation of a conventional liftoff method for patterning colloidal quantum dots by electron beam lithography (EBL) for patterning. We formed straight lines, rings, and dot patterns of colloidal quantum dots on sapphire and metallic substrates for optoelectronic and plasmonic applications. The patterned structures show highly accurate positioning and well-defined sidewall profiles. We demonstrate a surface plasmon generator elaborated from quantum dots. Finite-difference time-domain (FDTD) method shows that coupling efficiency from the localized plasmonic source to surface wave reaches up to 40%.

8613-5, Session 1

Focused electron-beam induced deposition of plasmonic nanostructures from aqueous solutions

J. Todd Hastings, Neha Nehru, Matthew D. Bresin, Univ. of Kentucky (United States)

Focused electron-beam induced deposition (FEBID) provides a means of locally depositing nanostructures with deterministic geometries and is useful for nanoscale prototyping, repair, modification, and interconnection. We have recently developed a new FEBID technique that uses bulk liquid precursors rather than traditional gas phase reactants. This technique, liquid phase electron-beam induced deposition (LP-EBID), produces deposits with purities significantly greater those obtained from most metal-organic and fluorophosphine gaseous precursors. Here we discuss the patterning and characterization of plasmonic nanostructures, silver and gold dots and wires, deposited from aqueous solutions of silver nitrate ($AgNO_3$) and chloroauric acid ($HAuCl_4$) respectively. Specifically, we present solution concentrations and electron doses required to form the structures, possible chemical reactions involved, composition as determined by energy dispersive x-ray spectroscopy, and VIS-NIR dark-field scattering spectra. We show that the technique provides sufficient geometric control and purity to observe localized-surface plasmon resonances. For example, 5-micron pitch arrays of silver nanodots were deposited on the polyimide membrane of a commercial liquid cell. A 750 micromolar $AgNO_3$ (aq.) precursor solution was used and the dose was 150 pC/dot. The dots were found to be approximately 100-nm in diameter. The primary contaminant was found to be sulfur, presumably from the laboratory environment. Dark-field scattering spectra were collected from a portion of the array (<100 dots). When the structure was immersed in water a scattering peak was observed at 540 nm. This wavelength is consistent with a localized surface-plasmon resonance of a silver nanoparticle on a high index substrate such as polyimide.

8613-6, Session 2

Additive and subtractive three-dimensional nanofabrication using two-photon polymerization and multi-photon ablation *(Invited Paper)*

Yong Feng Lu, Wei Xiong, Yunshen Zhou, Xiang Nan He, Yang Gao, Masoud Mahjouri-Samani, Univ. of Nebraska-Lincoln (United States); Lan Jiang, Beijing Institute of Technology (China); Tommaso Baldacchini, Newport Corp. (United States)

Modern three-dimensional nanofabrication requires both additive and subtractive processes. However, both processes are largely isolated and generally regarded as incompatible with each other. In this study, we developed simultaneous additive and subtractive fabrication processes using two-photon polymerization followed by femtosecond (fs) laser multi-photon ablation. To demonstrate the new capability, submicron polymer fibers containing periodic holes of 500-nm diameter and micro-fluidic channels of 1-µm diameter were successfully fabricated. This method combining both two-photon polymerization and fs laser ablation improves the nanofabrication efficiency and enables the fabrication of complex three-dimensional micro/nano-structures, promising for a wide range of applications in integrated optics, micro-fluidics, and microelectromechanical systems.

8613-7, Session 2

Large-area high-speed 3D laser lithography with high-NA objectives

André Radke, Philipp Simon, Holger Fischer, Christoph Linden, Georg von Freymann, Nanoscribe GmbH (Germany); Michael Thiel, Nanoscribe GmbH (Germany) and Karlsruher Institut für Technologie (Germany)

Three-dimensional (3D) direct laser writing (DLW) based on two-photon polymerization allows for versatile fabrication of micro- and nanostructures for a large variety of applications [1,2]. While DLW has become a standard tool in many scientific laboratories all over the world, the industrial breakthrough has not yet arrived. Here, we demonstrate the combination of our recent technical advances of DLW in order to meet more of the high demands of industrial production.

(i) High-speed fabrication has been enabled by scanning the laser beam instead of using a fixed-focus configuration. Diffraction-limited spot size of oil immersion objectives (NA = 1.4) has been achieved using pivoted mirrors insuring highest spatial resolution. Specially designed imaging optics allows for very small vignetting over the entire scan field. Residues of lateral aberrations are compensated by using synchronous power adjustments. (ii) Recently, we have introduced 3D Dip-in Laser Lithography to overcome the problem of axial aberrations [3]. Using laser-scanning dip-in lithography we demonstrate the patterning of 3D micro-parts with processing times reduced by orders of magnitude. (iii) To achieve large-area patterning, we employ a stage concept to stitch adjacent writing volumes. By this, we have patterned areas in the cm^2 range on a variety of substrates and with highest resolution.

By combining these developments we demonstrate the applicability of our setup for demanding 3D photonic crystals, (mechanical) metamaterials, and micro-optics. Moreover, we evaluate possibilities in the field of photonic-color materials which can potentially be employed for security labels and sensors.

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8613-8, Session 2

Recent progress in SLM based 3D direct laser writing

Erik H. Waller, Georg von Freymann, Technische Univ. Kaiserslautern (Germany)

Direct laser writing is an established technique to fabricate almost arbitrary three-dimensional structures in photosensitive materials. These are locally polymerized [1] within a volume well defined by the iso-intensity surfaces in the focal spot. This voxel (volume pixel) is of ellipsoidal shape. The axial elongation is disadvantageous for generating nanostructures with isotropic feature sizes [2].

Here, a spatial light modulator (SLM) is employed to generate almost arbitrary intensity and phase patterns on the entrance pupil of a high NA objective. We combine in-situ aberration correction and the generation of amplitude filters. The aberration correction is shown to improve the performance of a high-numerical-aperture (NA) objective and is found to be crucial to the filter's functionality. We start our analysis with the investigation of different slit-filters. Despite having different NAs along one axis the axial extend of the generated voxels does not differ considerably, therefore allowing for accurate aspect ratio control. While the higher intensity levels in the close periphery of the focal spot prevent their use in high resolution applications, generated structures display good mechanical stability.

The effect of the proximity intensity was investigated by two shaded-ring-filters (SRFs, [3]) generating similar aspect ratios but with sidelobes of different strength. Woodpile photonic crystals are created and evaluated by their spectral response. The more intense sidelobes do not visibly reduce the quality of woodpiles down to 450 nm rod distance. However, the aberration corrected low proximity SRF outperforms both the aberration corrected objective and the SRF with more intense sidelobes in all our test structures.

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8613-9, Session 2

Dynamic optical methods for direct laser written waveguides

Patrick Salter, Martin Booth, Univ. of Oxford (United Kingdom)

Direct laser writing with ultrafast lasers is widely used to fabricate 3D devices such as photonic crystals, metal nanostructures and embedded waveguides. The fabrication fidelity depends strongly on the focal spot quality, which in many cases is impaired by aberrations, particularly spherical aberration caused by refractive index mismatch. We use liquid crystal spatial light modulators and deformable mirrors as adaptive optical elements to correct aberrations and maintain fabrication performance at a range of depths inside the waveguide chip. More complex aberrations are experienced when focusing near the edge of the chip, as a proportion of the focused light is refracted by the side surface. This results in a focal splitting phenomenon that leads to highly distorted waveguide structure near the side. In practice, writing has been

terminated before the edge and the chip has been cut and polished up to the waveguide. We implement an adaptive optics system that corrects light passing through both the top and side surfaces. This permits writing up to the side face of the waveguide chip, removing the need for cutting and polishing, thus reducing the time required to produce a waveguide circuit. Further increase in fabrication speed can be achieved by parallelisation of the writing process. We describe adaptive methods where multiple controllable foci are used to create single waveguides with tunable cross-sections.

8613-10, Session 3

Tuning of optical properties by atomic layer deposition *(Invited Paper)*

Mato Knez, CIC nanoGUNE Consolider (Spain); Adriana V. Szeghalmi, Friedrich-Schiller-Univ. Jena (Germany)

The anti-reflective property of moth-eye corneal arrays has initiated widespread industrial applications (window panels, displays, camera lenses, etc.) of sub-wavelength nanostructured materials. The function of such nanostructured surfaces is based on the refractive index gradient at the air-facet material interface with a period smaller than the wavelength of light. Additional modifications of the refractive index can lead to so-called Wood's anomalies in the optical properties of structured surfaces. These are sharp changes in the transmittance or reflectance intensity with respect to the wavelength or the angle of incidence.

In this work, we demonstrate that sensitive 2D sub-wavelength nanostructures in polymeric material can be successfully coated with inorganic materials by atomic layer deposition (ALD) to improve their optical functionality. The wave guiding capability and diffraction modes of the nanostructures are thoroughly analyzed. In the near field, the diffracted mode propagating at high angles from the normal are focused, and provide a relatively high intensity narrow bandwidth (ca. 2 nm full width at half maximum FWHM) wave. The ALD coating proved to be essential to produce high quality guided mode resonance filters based on the resonance type Wood's anomaly. The nanostructures coated by a complex nanolaminate film show narrow transmittance/reflectance peaks and high sideband transmittance (ca. 92%) in the UV-VIS. Interestingly, the reflectance peak position can be easily tuned in a broad wavelength range (> 150 nm) through the rotation of the sample around the axis normal to the substrate without any change to the rest of the optical setup. The use of such filters meets the demand for ultra-compact, portable, miniaturized optical equipment. Polarization in the optical transmittance at normal angle of incidence is shown as a function of the rotation of the sample associated to form and polycarbonate birefringence.

Besides, approaches to the design of sensors, based on guided mode resonances, will be shown. Gratings functionalized with inorganic nanolaminates can be tuned highly efficient for sensing gases or liquids even if their refractive indices differ only slightly.

8613-11, Session 3

Nonpolarizing singlelayer inorganic and double layer organic-inorganic one-dimensional guided mode resonance filters

Muhammad Rizwan Saleem, Univ. of Eastern Finland (Finland) and National Univ. of Sciences and Technology (Pakistan); Benfeng Bai, Tsinghua Univ. (China); Seppo K. Honkanen, Jari Turunen, Univ. of Eastern Finland (Finland)

Guided mode resonance filter (GMRF) phenomena occurs when the evanescent orders of a diffraction grating are coupled to the waveguide modes and propagate out at given optical parameters such as wavelength, angle, and state of polarization of incident light. The outcoupling field from a waveguide is, in general, polarization sensitive. Polarization insensitive 1D subwavelength grating structures with high diffraction efficiency at normal and oblique incidence are required, for example, in optical communications where output light may possess any polarization state. This means that an s- or p-polarized input optical field, which generally couples TE- or TM-modes in the waveguide under different resonance conditions, can be tuned at one resonance by selecting suitable grating parameters, regardless of the input polarization state. All of the polarization insensitive devices fabricated to date either employing a method which is not cost-effective or simple enough to some extent.

In this work, we report the design and fabrication of two types of non-polarizing binary-structured one dimensional (1D) GMRF at normal incidence. A single layer binary-profile TiO_2 resonant grating (grating-I) is fabricated by Atomic layer deposition (ALD), electron beam lithography (EBL) and reactive ion etching (RIE), which demonstrates almost perfect non-polarizing filtering effect with 1D grating under normal incidence. A double layer rectangular-profile polycarbonate-TiO_2 1D GMR grating (grating-II) is fabricated by nanoimprint lithography (NIL) and ALD which also shows good non-polarizing property and the potential of cost-effective and mass fabrication of such functional devices.

8613-12, Session 3

III-V access waveguides using atomic layer deposition

Khaled Mnaymneh, Univ. of Michigan (United States); Dan Dalacu, Simon Frederick, Jean Lapointe, Philip J. Poole, Robin L. Williams, National Research Council Canada (Canada)

Being an attractive route for designing novel out-of-plane laser and sensing devices, III-V photonic crystal (PhC) membranes are also a natural choice for scalable quantum information systems. Single quantum dots in PhC nanocavities can achieve high single photon extraction ratios into planar PhC membrane waveguides. However, such membrane waveguides are not practical for planar lightwave circuitry due to the considerable fabrication and dispersion losses incurred when compared to conventional strip waveguides. A low-loss single mode strip waveguide akin to the one commonly used in SOI is highly desired. In this talk, we present an innovative way of fabricating low-loss InP strip waveguides in an InP/InGaAs/InP epi-structure by using an atomic layer deposited (ALD) top insulator layer as the supporting structure. The highly conformal nature of the ALD process makes available advanced fiber-coupling techniques normally available for SOI systems, such as submicron coupling that are critical for increasing the collection efficiency of single photons into and from fiber optic networks.

8613-13, Session 3

Wire grid polarizers fabricated by low angle deposition

Mike P. Watts, Impattern Solutions (United States); Michael J. Little, Steve Stephansen, Agoura Technology (United States)

Polarizers are an essential component of LCD's, and reflective polarizers have found unique application in "polarization recycling" to increase the energy efficiency of LCD's. The traditional polarizers are made from an oriented film impregnated with dichroic molecules. Low contrast recycling polarizers have been developed by 3M Corporation using a 100+ multilayer stack of alternating uniaxial films. Agoura Technology has fabricated thin film, wire grid polarizers using technologies with a well defined path to devices over 1 m on a side.

In order to meet the very low cost requirements of the LCD industry of less than $30 per square meter, we have developed a technique to form the < 65 nm line and space patterns with a single imprint followed by alow angle shadowed aluminum deposition operation.

We have;

1) developed seamless masters 200x200 mm on a side with 130 nm pitch lines and spaces

2) optimal profiles for low angle shadow deposition of wires based on deposition simulation

3) created optimized side wall features

4) replicated patterned films

5) fabricated wire grid polarizers for both polarizers and polarization recycling that we compare to published theoretical and experimental data, to show the highest reported contrast. The spectral results show an improved wavelength dependence as compared to multilayer reflective polarizers.

6) a strategy for fabrication of very large areas

We will describe the fabrication and optical performance results.

8613-14, Session 4

Three-dimensional mechanical metamaterials made by dip-in direct laser writing *(Invited Paper)*

Tiemo K. Bückmann, Robert Schittny, Andreas M. Frölich, Michael Thiel, Aude Martin, Muamer Kadic, Martin Wegener, Karlsruher Institut für Technologie (Germany)

Artificial materials called metamaterials have recently also started to emerge in mechanics and elastodynamics. This field is driven by the quest for more control on material properties and on elastic/acoustic waves, inspired by corresponding progress on optical metamaterials and transformation optics. In three dimensions (3D), the fabrication of the complex structures that have been suggested theoretically poses serious challenges. Direct laser writing (DLW) allows for the making of complex 3D architectures, but it was previously limited regarding overall sample height by the finite working distance of the microscope lens. The concept of dip-in DLW has completely eliminated these restrictions. Here, we exploit these novel possibilities for mechanical metamaterials. For example, 3D pentamode metamaterials, solids that effectively behave like liquids in that their shear modulus is much smaller than their bulk modulus, have been realized. Our theoretical understanding of the corresponding properties, e.g., the phonon band structures and its dependence on structure parameters, is rapidly improving. Furthermore, by combination of dip-in DLW with atomic-layer deposition of ZnO and subsequent reactive-ion etching, ultra-lightweight mechanical metamaterials can be realized as well. Finally, we also explore novel architectures for 3D isotropic auxetic metamaterials.

8613-15, Session 4

Mechanical properties of crosslinked poly(methyl methacrylate) polymer nano coil springs fabricated by two-photon lithography

Satoru Shoji, Shota Ushiba, Kyoko Masui, Satoshi Kawata, Osaka Univ. (Japan)

Micro/nano lithography based on two-photon polymerization (TPP) enables us to fabricate arbitrary three-dimensional polymer micro/nano structures. Since the first proposal of TPP lithography technique, the spatial resolution of TPP lithography has still been improving. Recently, the feature size of achieved minimum structures reached to be about 60 nm, which is 1/13 of the wavelength of the laser light used for TPP excitation. In our research, we aim to explore the physical properties of such thin nano-sized polymers, which could be quite different from the properties of macroscale polymers. In this presentation, we show coil springs made of crosslinked poly(methyl methacrylate) polymer fabricated by means of TPP lithography. The nanocoil springs were consisting of spiral polymer nanowires with their diameters of less than 500 nm freestanding in air. We measured spring constants of the nanocoil springs by means of stress-strain test using an atomic force microscope system. We observed a linear stress-strain relationship following Hooke's law in a large range of up to 300 % stretch ratio. From their spring constant and the diameter of wires, we investigated elasticity of nano-sized polymers. We clearly observed a change in the elasticity depending on the size of polymer wires. Such intrinsic nano size effect in mechanical properties of nanopolymers could play an important role for novel principles of mechanically and/or optically functional nanodevices.

8613-16, Session 4

Talbot optimization of phase mask gratings

Mi-Li Ng, Univ. of Toronto (Canada); Debashis Chanda, Univ. of Central Florida (United States); Peter R. Herman, Univ. of Toronto (Canada)

Diffractive Optical Elements have been widely used for the enhancement of devices in beam shaping, pulse shaping, microscopy and 3D imaging. While the design and underlying theory of surface diffractive structures are generally well understood, volume diffractive elements have not been fully explored nor harnessed for potential benefits of high efficiency and powerful phase and amplitude control. The advent of femtosecond laser writing inside transparent media has enabled the facile embedding of optical devices into novel three-dimensional geometries that offer advanced functionality with compact design. In this work, femtosecond laser writing is pushed to the limits of forming high resolution structures with strong refractive index contrast to develop volume phase gratings with the highest diffractive efficiency. However, the efficiency of such assembled gratings were found to be dramatically diminished by the formation of both positive and negative zones of refractive index contrast together with a rapid Talbot self-imaging inside weakly contrasting phase gratings. A new regime for diffractive optics is therefore proposed that can harness low refractive index contrast gratings even when their period becomes comparable with the incident probe wavelength. With this new insight, the paper defines the concept of coherently stacking of otherwise weakly diffracting phase gratings onto Talbot planes. Vector-based field calculations predict a dramatically enhanced diffraction efficiency from 3% to 95% and we report a 35% efficiency in laser-written grating stacks. This definitive enhancement thereby opens new directions that exploit the powerful diffracting and masking capabilities of such multi-layered gratings for controlling light beams with high efficiency and functionality.

8613-17, Session 4

Reversible microstructuring of lithium niobate by direct laser write technique

Vygantas Mizeikis, Shizuoka Univ. (Japan); Domas Paipulas, Vytautas Purlys, Vilnius Univ. (Lithuania); Ricardas Buividas, Saulius Juodkazis, Swinburne Univ. of Technology (Australia)

We report on fabrication of refractive index modulation structures in lithium niobate crystals by Direct Laser Write (DLW) technique, using non-destructive photorefractive photomodification induced by focused beam of a high repetition rate femtosecond oscillator. In this photoexcitation regime, purely photorefractive photomodification is created almost instantaneously, without any permanent damage to the underlying crystal. The recorded structures are stable within weeks to months after the recording, and can be fully/partially erased/modified using white light/focused laser beam. The ability of DLW technique to record, modify, and erase single features as well as periodic or non-periodic structures is a clear advantage in comparison to holographic recording techniques which can only fabricate periodic patterns and require long exposure. We demonstrate that using a high repetition rate laser as a DLW source leads to pulse-to-pulse local thermal accumulation and defect generation, which allow performance of reversible recording of stable structures in undoped lithium niobate crystals. This would be impossible to achieve with single fs pulses in undoped samples. Utilization of these advantages for reversible optical recording of discrete diffractive optical elements in lithium niobate crystals will be demonstrated.

8613-18, Session 4

Freeform mirror fabrication and metrology using a high performance test CGH and advanced alignment features

Sebastian Scheiding, Stefan Risse, Uwe Detlef Zeitner, Andreas Gebhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The fabrication process of optical surfaces with performance values below the diffraction limit is based on a deterministic correction loop, where surfaces are machined, characterized and figured to minimize the residual shape error.

The interferometric characterization of the surface quality of aspherical optical elements or freeforms by use of computer generated holograms (CGH) is a common method. In such an interferometric setup, the CGH is placed between the exit of the interferometer and the surface under test and adapts the spherical or plane wave coming from the interferometer to the surface shape of the specimen. To achieve a reliable characterization result the alignment of CGH and optical surface is very demanding. If not properly done there is a risk of alignment related wave-front errors being contained in the measurement results.

In the presented work, a proper alignment is achieved by illuminating reference spheres outside the clear aperture of the optical surface with the help of additional holograms next to the test CGH on the same mask blank. The absolute measurement of the quality of freeform mirror shapes including tilt and optical power became possible by the combination of ultra-precision diamond machining and specially designed test-CGH. The results are verified with a tactile ultrahigh accuracy measurement machine. Differences in the metrology process and the compliance are discussed.

Since the reference spheres represent the coordinate system of the mirror and are measured in the same precision as the optical surface, the registration and contour accuracy has to be in the micrometer range. The approach to diamond machine the reference surfaces and the freeform surface in the same machine setup to achieve these demands is shown. The shape correction according to the novel measurement approach is presented and the results for optics fabrication for diffraction limited telescopes are discussed.

8613-19, Session 4

Flexible micro-optics fabrication by direct laser writing toward CMOS compatible 3D optical circuit

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A demand for a computational processing power is continuously increasing. As a result, requirement on data transfer rate is drastically increased. To meet such a requirement, optical-electrical mixed wiring has been of interest. Such system utilizes practically zero-latency of optical channel to mitigate the intrinsic latency of the electric wiring. Inter-board optical interconnection is commonly used for a large scale server system. Inter chip optical interconnection has been implemented by using plastic optical fiber ribbon cables. Intra chip optical interconnection has been actively investigated in the laboratory by using standard CMOS compatible processes. For example a buried waveguide on SOI wafer has been demonstrated. However, so far only a planer optical circuit is feasibly fabricated by such fabrication method.

Toward three-dimensional optical-electrical mixed circuit, a flexible, rapid, and CMOS compatible fabrication method is highly anticipated especially for non-planer optical components. In this work, we focused on a coupling of light from a planer optical circuit to the other layer. A 45 degree mirror is of interest because it is free from optical loss due to undesired diffractions or insufficient coupling specific to the grating based coupling. We fabricated a mirror array by exposing a thick buffer coat layer on a silicon substrate (25x25 mm) by a tightly focused UV laser while varying a dose as a function of location. Inspection by a Linnik interferometer on angle and surface flatness of the mirror facet shows a good surface quality and repeatability over the area fabricated by the method.

8613-20, Session 4

Enhanced performance of organic solar cells by using three-dimensional nanohelix-array electrodes

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Nanostructured three-dimensional electrodes are promising approaches to enhance the performance of organic solar cells, due to their potential advantages such as larger surface-to-volume ratio, higher charge collection efficiency, higher carrier mobility due to the near-single crystallinity of nanostructures, and more light scattering effect than conventional planar electrodes. Although various nanostructured electrodes for organic solar cells such as hydrothermally grown ZnO nanorods[1], epitaxially grown ITO nanowires[2], and e-beam evaporated ITO nanobranches[3] have been reported for enhanced performances, there still be a strong need for new nanostructured electrodes to fully realize the potential advantages with a simple, reproducible, and cost-effective way.

We present organic solar cells with an array of ITO nanohelixes electrodes on ITO/glass substrate fabricated by electron-beam oblique-angle-deposition (OAD) technique. At first, PEDOT:PSS was coated conformally on the 3-dimensional ITO nanohelixes, followed by spin coatings of P3HT and PCBM to form a conformal bilayer heterojunction. Then lithium fluoride and Al was thermally deposited on the active layer. The power conversion efficiency of the device was measured to be highly increased compared to that of the reference devices, which is attributed to the combined effects caused by the unique electrode; (i) enhanced carrier transport through near-single crystalline ITO nanohelixes, (ii) enhanced charge collection efficiency enabled by the P3HT-PCBM bilayer conformally coated on the ITO electrode which increases the effective active layer of the device, and (iii) much higher light scattering by the nanohelix array. The effect of nanostructured reflector metal electrodes on the device performance will be also presented in detail.

Reference

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8613-42, Session PTue

Inkjet printed microlens array on patterned substrate

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Micro lens arrays (MLA) can be utilized in various applications of light sensitive devices such as digital cameras or objective free microscopes, because of their good light collection efficiencies. Therefore there is a need for cost effective fabrication method for high quality MLA.

An inkjet printing based production method for high quality micro lenses is presented here. By pre-patterning the used substrate before inkjet printing, the printing accuracy and the shape of the lenses is improved. In this work, the surface patterning was done with photolithography. Negative photoresist was patterned on the substrate, so that round, shallow (5 µm deep) pools were formed. The liquid lens material was then

inkjet printed into the pools. The edges of the pool prevent the spreading of the ink outside the wanted area increasing the tolerance for printing inaccuracy and resulting to the uniform array of micro lenses. When enough ink was deposited in one pool, the ink forms a convex surface aka a lens. The used lens material is negative photoresist, so after printing it was cured with UV-light and baked on a hot plate to solidify the lens matrix.

The shape of the lenses can be changed by changing the shape of the pool, so also elliptical lenses can be made for example. And changing the amount of ink in a pool changes the height of the lens and thus the focus of the lens can be adjusted making the proposed fabrication method versatile tool for MLA fabrication.

8613-43, Session PTue

Fabrication, replication, and characterization of microlenses for optofluidic applications

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Here we report direct laser writing based fabrication of aspheric microlenses (diameter varying within the range of 10 – 100 micrometers) out of hybrid organic-inorganic photopolymer ORMOSIL (SZ2080, IESL-FORTH). Using the advantages of the flexible manufacturing technique the produced microlenses are embedded inside a fluidic channel. Applying the soft-lithography molding the structures are transferred to the elastomer PDMS and hydrogel PEG-DA materials. Optical and SEM microscopies as well as optical profilometry and AFM are used for their shape characterization. Measurements show that such replica transferring can reproduce the initial structures into other materials on desired substrates with no noticeable losses of quality. Furthermore, it makes femtosecond laser redundant once the original structure is made. The embedded structures are immersed into several liquid media (water, ethanol, methanol, PEG) and the focusing performance corresponding to the change of the optical path length of the microlenses is obtained, being in a good match with the estimated values. Modeling was performed using Oslo 6.5 EDU software. Furthermore, the change of focusing distance is noticed for PEG-DA-258 hydrogel material as it absorbs the surrounding liquid media and by swelling changes its shape. In conclusion, we report a combination of laser fabrication and replication methods as an efficient way to produce optofluidic components, which can be used for light based sensing, trapping or other applications such as MOEMS devices.

8613-44, Session PTue

New fabrication method of glass packages with inclined optical windows for micro mirrors on wafer level

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For most applications it is necessary to cover MEMS devices against environmental impacts which can affect their performance. Recent publications demonstrate that micro mirrors can achieve large optical scan angles exceeding 100 degrees when they are hermetically packaged under vacuum.

For high volume production it is indispensable to develop a packaging on wafer level, because discrete solutions for packaging are too expensive. This paper describes a unique technology to fabricate glass packages with inclined optical windows for micro mirrors on 8 inch wafers. The use of inclined optical windows in contrast to plane optical surfaces in parallel to the micro mirror avoids the occurrence of intense reflections of the incident laser beam in the projected images. The new process is a high temperature glass forming method based on subsequent wafer bonding. A borosilicate wafer is bonded together with two structured silicon wafers. By grinding both sides of the wafer stack, a pattern of isolated silicon structures is defined. This pre-processed glass wafer is bonded on a third structured silicon wafer, wherein the silicon islands are inserted into cavities. By setting a pressure inside the cavities during the final wafer bonding, the silicon glass stack is later extruded during an annealing process at temperatures above the softening point of the glass. Finally the silicon is selectively removed in a wet etching process. This technique allows the fabrication of 8 inch glass wafer with oblique optical surfaces with surface roughness <1 nm and an evenness of < 100 nm.

8613-45, Session PTue

Low-NA focused vortex beam lithography for below 100-nm feature size at 405 nm illumination

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There are varieties of novel methods, which demonstrate the super-resolution. For instance, an optically trapped sub-micron dielectric sphere serves as a near-field focusing lens to directly write patterns of ~100 nm in liquid, and accelerated metallic nanoparticles by optical force form a stamp on the substrate, coined optical force stamping lithography. Two-photon absorption lithography is another good example of super-resolution techniques for 100-nm target. Other breakthrough to achieve sub-100-nm pattern size is using two beams: for initiation and deactivation of polymerization with one color or with two colors and for absorbance modulation. Generally, such two-beam techniques rely on doughnut-shape spots, whose tiny dark center is a key feature to achieve such a small size. Here, we propose a new method to fabricate well-isolated single nano-structures using this doughnut-shape vortex beam but a single beam illumination is applied. Regardless of the NA, focusing of azimuthal polarization always assures the dark center while the radial polarization is often used to create a bright center by a high NA. When such vortex beams at ?=405 nm expose the positive photoresist, nano-cylinder are formed in the center of the circular exposed area. A decomposition of the doughnut beam leads to the two-half-lobes spot and the linear scanning of the decomposed spot produces nano-size line patterns. This is a fast and inexpensive way to fabricate well-isolated nano-solid-immersion-lenses or plasmonic nano-waveguides compared to other nano-fabrication methods, such as, electron beam lithography.

8613-46, Session PTue

Light confinement effect of non-spherical nanoscale solid immersion lenses

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A solid immersion lens (SIL) increases the numerical aperture (NA) by a factor of the refractive index n of the SIL material. Consequently, the immersion focal spot gets smaller by a factor of n. For a macro-scale SIL, this effect is assured for only an aplanatic shape, for example, a hemi-sphere. However, when the characteristic size falls in the range of the wavelength or smaller, aberrations are negligible due to the extremely short optical path length. Recently, wavelength-scale SILs demonstrated robustness to fabrication errors, i.e., non-ideal shapes.

Since it is a challenging task to fabricate the ideally shaped patterns, this robustness is advantageous to overcome fabrication errors and moreover alignment errors. In this study, non-ideally (i.e., non-spherically) shaped nano-SILs are studied to verify the influence of the SIL shape on the spot size reduction and the light confinement. Non-circular pillar patterns are fabricated by electron beam lithography. Subsequent reflow and replication processes produce SILs on a transparent substrate. With complete melting during the reflow process, non-circular pillars are naturally transformed into a spherical shape. However, incomplete melting results in non-spherically shaped SILs. Such non-ideal SILs exhibit a reduction of the spot size comparable to that of the spherical SILs. We demonstrate that for SILs having characteristic sizes in the nanometric range, the influence of shape errors on the spot size reduction is negligible. This assures a large tolerance for the nanofabrication of the SILs.

8613-47, Session PTue

Holographic fabrication of woodpile-type photonic crystal templates using silicon based single reflective optical element

Jeffrey R. Lutkenhaus, David George, Kris Ohlinger, Hualiang Zhang, Univ. of North Texas (United States); Zsolt Poole, Kevin P. Chen, Univ. of Pittsburgh (United States); Yuankun Lin, Univ. of North Texas (United States)

In this work, we present the holographic fabrication of woodpile-type photonic crystal templates in photosensitive polymer using a silicon-on-PDMS based reflective optical element. The reflective optical element is fabricated from four silicon chips placed inside a polydimethylsiloxane (PDMS) mold, which reflects a circularly or elliptically polarized beam into four linearly polarized side beams, arranged four-fold symmetrically about a central beam, with electric fields normal to the incident plane, and also reduces the laser intensity of the side beams. With a single beam and a single reflective optical element, we can generate the desired laser beam intensities and polarization of each beam, thereby creating woodpile-type photonic crystal templates, and improving the contrast of 3D structures.

8613-48, Session PTue

Advanced mask aligner lithography (AMALITH)

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Advanced mask aligner lithography (AMALITH) is a novel lithography technique which is possible due to the MicroOptic Exposure Optics (MOEO) developed and patented by SUSS MicroOptics. The MOEO system is based on micro-lens arrays and improves the optics in a standard mask aligner by adjustable angular illumination spectrum and increasing the uniformity of the illumination. Due to this customized illumination, optical effects such as the Talbot effect can be exploited. The Talbot effect can improve photolithography in two ways: firstly, by enabling high resolution long working distance photolithography. Secondly, the Talbot effect can give rise to sub-micron structures in standard photolithography (i.e., without using a stepper).

In this paper, we demonstrate Talbot lithography for long working distances and sub-micron hole patterns. In doing this we characterize the limits of this lithography for both standard photoresists and highly-transparent chemically-enhanced photoresists.

Long working distance lithography has better yield and lower costs due to less cleaning and wear than contact lithography. Creating a low cost process for submicron pore dimensions satisfies the needs of many applications. As examples, we will show plasmonic colour filters for imaging, and silicon based cell culture membranes with sub-micron pores for toxicology and pharmacology.

8613-49, Session PTue

Single phase mask laser scanning holography for flexibly integrating uniform 3D periodic nanostructures with microfluidics

Liang Yuan, Peter R. Herman, Univ. of Toronto (Canada)

Conventional holographic interference lithography has demonstrated precise fabrication of single-domain 3D photonic crystals (PCs) up to mm scales, with high speed and large area advantages over other techniques such as self-assembly and two-photon direct writing. However, a scaled-up approach for seamless stitching of single-domain structures into large area PCs is not readily available and remains challenging in the direction of wafer-size photonic systems.

Here we employ the recently introduced method of laser scanning holographic interference lithography to substantially extend exposure fabrication area while also improve the structural uniformity. Moreover, we demonstrate the precise stitching of writing many overlapping laser paths with small beam diameters that open a new facile means for retaining benefits of top-down control to tune PCs from uninform to apodized or hetero-structures by controlling the laser dwell time through velocity and power modulation. This scanning lithography method was further extended to form solid walls or open channels and reservoirs into which 3D PCs of varying types could be embedded. Various approaches of beam scanning were examined to scale down the scanning laser diameter and enable a more functional and higher resolution combination of optical and microfluidic components onto a single compact chip. In this way, multi-functional optofluidic microsystems could be formed in a single exposure step through a 2D binary phase mask. The paper presents optimal exposure conditions for generating large area uniform 3D PCs from which strong ?-Z stopbands have been recorded together with examples of tuning the PC stopbands and integrating 3D PCs into microfluidic devices. Such microfluidic integration of 3D PCs opens new possibilities for optical bandgap sensing and chromatography analysis.

8613-50, Session PTue

Precisely shift interference pattern by phase control method based on spatial light modulator

Jie Ma, Yongchun Zhong, Zhe Chen, Jianhui Yu, Jinan Univ. (China)

Holographic Lithography (HL) had been used to fabricate a variety of functional micro-structures for about 15 years. By using this technique one-dimension, two-dimension, three-dimension photonic crystals (PCs) and even some meta-material structures had been fabricated. Recently, using phase control method. We developed a general technique to fabricate PCs structure with periodic defects. But in the application, the defect must be aligned with conventional waveguide to improve the coupling efficiency. In this paper, a phase control method to translate multi-beam interference pattern was demonstrated. Unlike the past work, the interference pattern formed by 8 beams (even more than 8 beams) can be precisely shifted. This technique is based on matrix algorithm. By using the algorithm, we can obtain a variation of phase correspond to the desired translation. In theory, this approach should apply to any kind of multi-beam interference pattern, and with no limited in translation direction and accuracy. In our experiment, Liquid Crystal-Spatial Light Modulator (LC-SLM) was utilized to control the phases of the interference beams. Since the resolution of the phase modulator is about 1/128 of 2π, the shift resolution is about 1/100 of the pattern's period. For a PCs used in visible region, its lattice is about nm. The shift resolution is about 4nm. In addition, the LC-SLM was controlled by a computer, so this system

also has a real-time capability. By taking advantage of this capability, the pattern can move dynamically. That will be very useful in fabricating composite micro-structures based on HL.

8613-52, Session PTue

Silver nanocrystal growth through femtosecond laser direct writing

Kevin Vora, SeungYeon Kang, Michael G. Moebius, Eric Mazur, Harvard Univ. (United States)

Recently, femtosecond lasers have been used to fabricate silver nanostructures in two and three dimensions. The ultrafast laser techniques allow great degree of freedom on the types of silver patterns that can be created. However, the features created by these techniques are composed of silver nanoparticle clusters which affect material properties such as surface roughness and conductivity. We present a technique to grow single-crystal silver nanoparticles using a femtosecond laser. We grow silver crystals ranging in size from several hundred nanometers to micrometers. The crystal growth takes place inside a polymer film doped with silver salts. We induce the photoreduction of silver ions through nonlinear absorption in the thin film. The nonlinear optical interactions between chemical precursors and femtosecond pulses lead to single-crystal nanoparticle growth. The focal volume is scanned by means of a computer-controlled translation stage and the laser exposure is controlled by an acousto-optic modulator.

8613-53, Session PTue

Towards high-rate fabrication of photonic devices utilizing a combination of roll-to-roll compatible imprint lithography and ink jet printing methods

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Traditionally, polymer photonic devices are fabricated using clean-room processes such as photolithography, e-beam lithography, reactive ion etching (RIE) and lift-off methods etc, which leads to long fabrication time, low throughput and high cost. We describe in this paper a novel process for fabricating polymer photonic devices using a combination of imprinting and ink jet printing methods, which provides high throughput on a variety of rigid and flexible substrates with low cost. Particularly, we demonstrate an electro-optic modulator which consists of 0.5 μm thick bottom/top electrode layers for applying modulation voltage, and the bottom (3.5 μm UV-15LV)/core (1.8 μm electro-optic polymer)/top (3.0 μm UFC-170A) polymer layers forming a rib waveguide for light transmission. The imprint lithography transfers the waveguide pattern from a soft mold to UV-15LV bottom cladding layer. The soft mold is replicated from a silicon master mold and rendered hydrophobic to ensure successful de-molding. All other layers are aligned and ink jet printed with pre-defined features. Compared to spin-coating method, the use of print-on-demand method greatly reduces material consumption and process complexity. Every step involved has the potential to be fully compatible with roll-to-roll (R2R) volume production. For example, the soft mold can be wrapped around a cylinder to realized roll-to-roll imprinting. By combining R2R imprint lithography with R2R ink jet printing, fabrication of large volume and large area multilayer polymer photonic devices can be realized.

8613-54, Session PTue

An improved wire grid polarizer for thermal infrared applications

Matthew C. George, Jonathan Bergquist, Hua Li, Bin Wang, Eric W. Gardner, MOXTEK, Inc. (United States)

The ubiquitous wire grid polarizer remains one of the most useful optical components in the field. Widely used in applications such as displays, imaging, sensors, communications, and scientific instrumentation, the wire grid polarizer (WGP) typically consists of an array of metallic lines with sub-wavelength pitch supported by a transparent substrate. Existing WGP products designed for long wavelength thermal IR applications typically suffer from low contrast (≤350) between transmission of s and p polarized states, which is due to their relatively large wire grid pitch (typically ≥370 nm). Moxtek and others have previously demonstrated a dramatic increase in aluminum WGP contrast at visible and ultraviolet wavelengths by reducing the pitch. We postulated that a dramatic reduction in pitch from that found in typical IR WGP products should greatly improve long wavelength IR contrast.

Moxtek has therefore developed a high contrast IR polarizer on Silicon suitable for long wavelength thermal IR applications using our aluminum nanowire, large area patterning capabilities. Between 7 and 15 microns, our 144 nm pitch polarizers transmit better than 70% of the passing polarization state and have a contrast ratio better than 10,000. We are pursuing substrate and antireflection coating refinements to increase and customize this performance based on customer needs. Transmission measurements were made using an FTIR spectrometer with instrument accuracy verified using silicon and germanium standards. Results were compared to RCWA modeling of the WGP performance on antireflection-coated wafers.

8613-55, Session PTue

Asymmetric suspended photonic crystal slab membranes for sensitivity enhancement in optofluidic sensing applications

Ryan Schilling, Costa Nicholaou, Ofer Levi, Univ. of Toronto (Canada)

Photonic crystal slabs (PCS) support in-plane guided mode resonances (GMR) that couple to external radiation. Interaction between the evanescent field and surrounding medium can be exploited for large surface area refractive index biosensing. We present a novel asymmetric suspended platform for substantial enhancement of sensitivity in 2D PCS devices.

The device is fabricated by depositing a 50nm layer of SiNx on a silicon wafer followed by a 5nm Al2O3 etch stop layer and finally a 250nm SiNx layer onto which the PCS is patterned; designed to operate near 1550nm. After PCS fabrication, KOH wet etch is used to etch through the backside of the wafer and suspend the PCS. Microfluidics attached to the top of the PCS allow for fluidic sensing. The air-like substrate pushes the evanescent field of the GMR toward the sensing medium, enhancing sensitivity. Compared to SiO2 substrate designs for TM-like modes, simulated bulk sensitivity (S¬bulk) values show an increase from 190nm/RIU to 540nm/RIU. For TE-like GMRs, simulations show moderate improvements with S¬bulk increasing 13% and Q by 32%.

The proposed air-suspended sensor structure has been fabricated. Initial studies characterized the TE-like GMR. A spectral blue-shift of ~47nm, S¬bulk of 185nm/RIU and Q of 1300 were observed. In current samples, the much higher S¬bulk and Q (540nm/RIU and 30,000 respectively) TM-like GMR was not observed, likely due to the blue-shift – resulting from fabrication imperfections. Ongoing work includes fabrication of modified sensors to observe the TM-like GMR. These devices hold promise for high sensitivity label-free detection applications.

8613-56, Session PTue

Cascaded fiber-optic intrinsic Fabry-Perot interferometers fabricated by femtosecond laser irradiation

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Fiber-optic Fabry-Perot interferometric (FPI) sensors are good candidates for temperature and strain sensing and have attracted considerable interests in the past few decades. There exist many advantages for this type of sensors including small size, good stability, high sensitivity and fast response. Generally, fiber-optic FPIs can be classified into two categories: extrinsic FPI and intrinsic FPI. The intrinsic FPI shows its advantages for multiplexing capability due to the low reflectivity and transmission loss.

In this paper, cascaded fiber-optic intrinsic Fabry-Perot interferometers (IFPIs) were inscribed in a standard single mode fiber using femtosecond (fs) laser irradiation technique. Each element (IFPI) was realized by employing and focusing the fs laser pulses into the fiber core to induce a change in refractive index (RI), where a reflective mirror was formed. The interference pattern of each IFPI including two mirrors provided a high fringe visibility up to 10dB in spectrum. A cascaded structure composed of multiple IFPIs for distributed sensing application was experimentally demonstrated by using a radio frequency interrogation method. The results showed its potential functionality for structural health monitoring.

8613-57, Session PTue

Nanoplasmonic tip array for large area nanolithography

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Lithographic techniques for nanoscale components for biological/medical diagnostics, optoelectronics and the communication and information technology are being developed[1]. Many approaches that hurdle the diffraction limit have been developed, such as e-beam, dip-pen, interference and SAM lithography, etc. However, these methods still have limitations that are time consuming and high-cost method to implement the nanostructure on large area or difficult to implement the arbitrary structures. Recently, sub-diffraction limit structure on large area using beam pen lithography that is advanced near-field scanning optical microscopy (NSOM)-based lithography techniques are demonstrated[2]. However, beam pen lithography still has limitations to implement the nanostructure on large area, because the focused ion bem (FIB) is needed to fabricate the aperture size of 50nm. This work presents the novel substrate with nanoplasmonic tip array for nanolithography on large area. The electrical field through the microtip array with/without Ag nanoislands was numerically analyzed by FDTD method. The tip with Ag nanoislands locally enhances the electrical field in ultraviolet range at the tip-end with a FWHM of 200nm. The nanoplasmonic tip array was fabricated in the wafer level by using conventional photolithography and the SIMD method. The Ag nanoislands were transferred from the silicon master to the PDMS microtip array by the SIMD method. Ag nanoislands were formed on the whole surface of tip array. The nanoplasmonic microtip array substrate can offer the lithography system to fabricate the nanoscale components for biological/medical diagnostics, optoelectronics and IT field.

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8613-59, Session PTue

Fabrication of subwavelength holes using nanoimprint lithography

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Driven by the demand of miniaturized and highly integrated functionalities in the area of photonics and photonic circuits, the metal or plasmon optics has become a promising method for manipulating light at the nanometer scale [1-4].

Especially the application of periodic sub wavelength holes structures within an opaque metal film on a dielectric substrate holds many advantages for the realization of optical filters, since the variation of the hole diameter and the periodicity allows a selective filter response [5,6].

This paper is concerned with the modeling, fabrication and characterization of a sub wavelength hole array for surface plasmon enhanced transmission of light [1]. The theoretical backgrounds as well as the basics of the simulation by Finite-Difference Time-Domain (FDTD) are described for the target structure with a hole diameter of 180 nm and a periodicity of 400 nm.

By using a double-molding technology via nanoimprint lithography the fabrication of this sub wavelength hole array with a peak wavelength of 470 nm and full width at half maximum of 50 nm from a silicon nanopillar master is demonstrated. In order to ensure the dimensional stability of the molded structures, characterization was consequently done by means of a self made non-contact mode atomic force microscope.

8613-21, Session 5

Nanofabrication of surface-enhanced Raman scattering substrates for optical fiber sensors *(Invited Paper)*

Paul R. Stoddart, Swinburne Univ. of Technology (Australia)

Surface-enhanced Raman scattering (SERS) allows the detection of sub-monolayer adsorbates on nanostructured metal surfaces (typically gold or silver). The technique has generated interest for applications in biosensing, high-resolution chemical mapping and surface science. SERS is generated by the localized surface plasmon resonance that occurs when the nano-metal is exposed to laser light. These plasmonic effects rely on features as small as ~1 nm, which poses a challenge for the fabrication of sensitive and reproducible substrates. Consequently a wide range of nanofabrication techniques have been used to make SERS substrates. Further challenges are encountered when transferring wafer-scale techniques to the tips of optical fibers in order to produce devices for in vivo SERS sensing. Here we describe fiber tip substrates based on miniaturization by fiber drawing, physical vapor deposition and nanoimprint lithography. Despite recent progress, the fabrication of sensitive, reproducible and affordable SERS fiber sensors remains an outstanding problem.

8613-22, Session 5

Femtosecond direct laser writing of fluorescence in silver containing glass

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Here we show that we can produce stable highly fluorescent features in the bulk of silver containing glasses using femtosecond direct laser writing. The features exhibit sub-500 nm size while being widely excitable from the UV to the visible-red. The emission spectra show bright white light with an emphasis on the blue part of the spectrum for UV excitation. Fluorescent elements, proven to be silver nanoclusters, are imaged using confocal imaging.

The mechanism leading to these original fluorescence features shows rich physical phenomena (multi-photon ionization, cumulative effects and local heating, heat diffusion, photochemical reactivity and chemical diffusions of species). We show how multiphoton absorption leads to the movement of free electrons and subsequently induces a space charge separation. This modified environment creates a spatially-limited environment where the local electric potential suits to the development and growth of silver nanoclusters. The temperature dependence has been studied, which reveals the importance of the intermediate formation of for the development of silver emitting clusters. The post-irradiation stability of the clusters is shown, depending on the irradiation settings, by reporting the effect of thermal annealing on the clusters nature.

This work displays a phenomenological explanation for all the different stages of formation, as well as a numerical model for the mechanism. Our results point toward the possibility of broadband light generation in optical integrated devices (such as lab-on-chips) and applications in metatronics.

8613-23, Session 5

Holographic fabrication of nano-optical devices using single reflective optical element

David George, Jeffrey R. Lutkenhaus, Hualiang Zhang, Yuankun Lin, Univ. of North Texas (United States)

Here we present holographic fabrications of large area nano-optical devices including nano-antenna and photonic quasi-crystals using a single reflective optical element (ROE) through single beam and single exposure process. These ROEs consist of several silicon wafers arranged with 5 or 6-fold symmetry, supported by two plastic platforms. By changing the polarization of the incident beam, various photonic quasi-crystal including spiral quasi-crystals can be fabricated using the 5-fold symmetrically arranged optical element. Using the single optical element with silicon chips arranged in 6-fold symmetry, large areas of nano gap arrays can be fabricated holographically. These nano-gaps and their shapes can be controlled through the phase delay of one laser beam. These nano gap arrays will be used for nano-antennas after metal depositions.

8613-24, Session 5

Electrical resistivity of transparent metal nanomesh electrodes

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A metal nanomesh electrode has the potential to realize a low-resistive, a rare-metal-free transparent electrode. Its peak transmittance was greater than the opening ratio owing to the effect of the extraordinary transmission of light. However, the electrical resistivity, which is another important property of a transparent electrode, had not been sufficiently investigated. We fabricated the Ag and Au nanomesh electrodes by nanoimprint or block copolymer lithography and measured its electrical resistivity by the current-voltage characteristics. Comparing with the calculated resistivity of the micromesh electrode, the electrical resistivity of the nanomesh electrode tended to deviate from the calculated values with decrease in the aperture interval and increase in the aperture density. This deviation was considered to be the effects of narrowing the conduction path of electrons and increasing the electron scattering probability by the nano-apertures. Moreover, the electrical resistivity of the metal film having nano-aperture increased regardless of the composing metal materials but highly correlated with the structure of the nano-apertures in the case of the Ag and Au nanomesh electrodes. Although the electrical resistivity of the nanomesh electrode became high by forming the apertures with nano-size compared to the calculated value with micro-size apertures, it was as low as approximately 10-6 – 10-5 ?cm, which was one digit lower than that of the conventional TCOs. Therefore, the transparent metal nanomesh electrode is expected to be used for a low-resistive transparent electrode.

8613-25, Session 5

Femtosecond laser fabrication of gold nanorods aggregate microstructures based on local surface plasmon induced two-photon polymerization

Kyoko Masui, Satoru Shoji, Shota Ushiba, Osaka Univ. (Japan); Xuan-Ming Duan, Technical Institute of Physics and Chemistry (China); Satoshi Kawata, Osaka Univ. (Japan)

We demonstrated a fabrication method of gold nanorods/polymer composite microstructures assisted by two-photon polymerization (TPP). Our method is, rather than to photo-polymerize monomers with gold nanorods dispersed in, to assemble gold nanorods with polymer glue for forming aggregation of nanorods into arbitrary geometries. The principle of this fabrication process is based on a combination of locally initiated TPP at the surface of gold nanorods and optical gradient force towards laser focus spot, by means of femto-second near infrared laser light. Gold nanorods were synthesized with controlling their size and shape so that the local surface plasmon of the nanorods was on resonant to the laser light. The nanorods were then dispersed in methyl methacrylate-based photo-polymerizable resin. When the laser light was tightly focused into the gold nanorod/resin compound, gold nanorods were gathered into the laser spot by optical gradient force. Concurrently occurring excitation of local surface plasmon in gold nanorods led to initiate TPP of the resin only at the surface of nanorods. Local polymerization formed a connection among the neighboring nanorods, resulting in a creation of a micron scale nanorods aggregate. By scanning laser focus spot, solid structures consisting of close-packed gold nanorods wrapped by thin polymer layer were formed. This method would provide potential application for fabricating plasmonic nanostructures and nanodevices.

8613-26, Session 6

Opalux's P-Ink technology: low-power flexible color-tunable surfaces *(Invited Paper)*

Andre C. Arsenault, Hai Wang, Fergal Kerins, Ulrich Kamp, Eric Henderson, Opalux, Inc. (Canada)

Opalux's P-Ink material presents a revolutionary step forward in display technology, offering the ability to reflect bright and vivid colors spanning the rainbow spectrum. By applying low power electrical pulses, the color of this Photonic Crystal-based material can be selected at will with the resulting color states requiring no power to maintain (electrically bi-stable). It can be coated onto both rigid as well as flexible substrates in scale, highlighting its potential to drive the development of bendable form factors for displays.

This presentation will highlight the P-Ink concept and theory, and describe the means Opalux has developed to fabricate such photonic crystal films with nanoscale periodicity on a high area substrates using roll-to-roll (R2R) manufacturing. Following the description of Opalux's success in producing P-Ink active materials using R2R methods, we will continue and describe the construction and integration of robust, flexible P-Ink devices. We will finish off by describing some of Opalux's product development, aimed at tunable color surfaces for the automotive, mobile electronics, and apparel markets.

8613-27, Session 6

Wafer-level electro-optical waveguides with isotropic liquid crystals blends on silicon backplane

Florenta A. Costache, Martin Blasl, Haldor Hartwig, Kirstin Bornhorst, Harald Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Optical waveguides can be induced in layers made from materials of large electro-optical (EO) constants by applying electrical fields across them within regions defined by stripe-shaped electrodes. Special liquid crystal blends in isotropic phase having properties such as large EO Kerr constants, low optical loss and sub-microsecond response time can be used for such waveguide applications.

We show that integrated devices based on field-induced waveguides in liquid crystals blends can be fabricated by means of silicon technology. For this a fiber coupled single-mode 1x2 optical switching device was designed using FEM simulation for operation at 1.55 µm and then fabricated. The wafer-level device assembly comprised two silicon wafers bonded together and enclosing in between a liquid crystal blend layer. In particular, the bottom wafer includes structured aluminum electrodes and V-grooves for positioning of fibers. The top wafer is structured to contain a cavity for the liquid crystal blends where a precise cavity height is defined lithographically to ensure the waveguiding properties of the liquid crystal blend cell.

Using this device sub-microsecond, low loss optical switching as well as variable power splitting could be demonstrated. The propagation loss for a straight waveguide amounts to 2 dB/cm and the insertion loss is around 3 dB. Owing to the special liquid crystal blends used, this device could be operated at room temperature.

We demonstrate that, based on the concept of field-induced waveguides in liquid crystals, with an appropriate electrode design, a variety of waveguide based devices can be fabricated on a silicon backplane.

8613-28, Session 6

Nanostructured antireflective coatings by high throughput optical lithography

Boris Kobrin, Joseph B. Geddes III, Mukti Aryal, Ian McMackin, Rolith, Inc. (United States)

Currently there is great commercial interest in antireflective coatings that can be applied over large areas at low cost. Engineered nanostructured surfaces may meet this need in the solar, flat-panel display, and architecture industries. Bottom-up methods cannot provide the desired accuracy and reproducibility usually required for high efficiency products. Standard top-down instrumentation, such as that used in state-of-the-art CMOS manufacturing, is too expensive and limited in substrate size. We report on a new method of top-down nanofabrication utilizing a tool with rotating cylindrical mask that can dynamically expose photosensitive layers on large substrates. Using this process we have fabricated surfaces with less than 1% specular reflectivity over the entire visible spectrum and a wide range of incidence angles. Our surface engineering process (Fig. 1) starts with coating a substrate material with a thin photosensitive layer, followed by its exposure using our proprietary "rolling mask lithography" (RML) tool in a conveyor or roll-to-roll mode. The photoresist is then developed and the substrate rinsed. Subsequent transfer of the photoresist pattern into the substrate using an etching process creates an advanced surface with desired properties: broad bandwidth anti-reflective response for the light absorbing surfaces of solar cells, the light extraction surfaces of LED devices, or the viewing surface of flat-panel displays.

The cylindrical mask used by RML is fabricated from a quartz material coated with a patterned polymer layer. An ultraviolet light source located inside the cylinder provides uniform exposure of the photoresist through an adjustable slit. Optical phase mask lithography implemented using this system has already demonstrated the capability to print micro- and nanostructures in a wide ranges of feature sizes (100 nm – 100 um), types (positive-pillars or negative-holes from the same mask), and depths (100 nm – 700 nm) over substrates up to 300 mm by 300mm size.

Sub-wavelength nanostructures for advanced anti-reflective properties (also known as "moth-eye" patterns) require a specific geometry of nanostructured elements. For example, optical modeling shows that in order to attain acceptable antireflection performance the nanostructures should be conical in shape, connected at their bases, and possess a high aspect ratio. Fig. 2 presents optical modeling results demonstrating the requirements for the low reflectivity sub-wavelength nanostructured geometry. Fig. 3 shows a nanostructured fused silica glass surface produced using RML lithography and plasma etching.

8613-29, Session 6

Microstructured optics for high performance optical systems

Alexandre Gatto, Carl Zeiss Jena GmbH (Germany)

In modern optics several demands exist for implementing microstructured optical components. For example, diffractive optical elements (DOEs) are of considerable advantage in combination with refractive lenses to form so-called hybrid optical systems. The inverse chromatic dispersion of diffraction in contrast to refraction opens new possibilities for the compensation of chromatic aberrations. Furthermore, the realization of a diffraction grating on a concave optical surface allows the functional integration of imaging and dispersing in one single optical component, which is a key enabler for miniaturization of spectroscopic systems. In the sophisticated illumination systems microstructured beam shaping elements play an essential role. Micro- and nanostructures in the subwavelength range open alternative solutions for antireflective properties and polarization management.

8613-30, Session 7

High-resolution 3D nanofabrication for advanced plasmonic applications *(Invited Paper)*

Isabelle Staude, Manuel Decker, The Australian National Univ. (Australia); Michael J. Ventura, Swinburne Univ. of Technology (Australia); Chennupati Jagadish, Dragomir N. Neshev, The Australian National Univ. (Australia); Min Gu, Swinburne Univ. of Technology (Australia); Yuri S. Kivshar, The Australian National Univ. (Australia)

The unique photonic functionalities offered by 3D metallic nanostructures are manifold, ranging from an isotropic magnetic optical response, over engineering of the complex polarization state of light through chirality, to 3D tapers for light concentration. Various 3D metal nanofabrication approaches have been demonstrated so far, including direct laser writing (DLW) in combination with a metallization procedure [1], membrane projection lithography (MPL) [2], multistep electron-beam lithography (EBL) [3], and electron-beam deposition (EBD) [4]. However, the fabrication of designed high-quality 3D metal nanostructures for near-infrared frequencies still poses a major challenge.

Here we introduce a novel hybrid fabrication approach combining DLW with EBL and a lift-off procedure. This approach makes use of the 3D writing capability of DLW, while preserving the small feature sizes, the capability of selective metallization, and the excellent gold quality of EBL based fabrication schemes. We realize several high-quality key 3D structures, including upright standing split-ring resonators and curved gap nanoantennas. We optically characterize these structures using linear-optical transmittance spectroscopy, revealing their characteristic plasmonic resonances in the NIR spectral range, and demonstrating that our approach offers exciting opportunities for creation of advanced 3D nanoplasmonic structures for photonic applications like isotropoic magnetic metamaterials, broadband circular polarizers, or chiral directional nanoantennas at optical frequencies.

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8613-31, Session 7

Photonic wire bonding: connecting nanophotonic circuits across chip boundaries *(Invited Paper)*

Christian Koos, Juerg Leuthold, Wolfgang Freude, Nicole Lindenmann, Sabastian Koeber, Gerhard Balthasar, Joerg Hoffmann, Tobias Hoose, Philipp Huebner, David Hillerkuss, Rene Schmogrow, Karlsruher Institut für Technologie (Germany)

Reliable and scalable interconnect technologies are of paramount importance for industrial deployment of photonic integrated circuits. Unlike electronics, where highly sophisticated metal wire bonding is the primary method of connecting integrated circuits to the outside world, photonics cannot rely on an interconnect technology of comparable versatility. Monolithic integration is often presented as a method to avoid costly chip-to-chip interfaces in photonic systems, but the associated technological complexity is still prohibitive for many applications. An industrially viable technology for chip-to-chip interconnects could enable novel system concepts that efficiently combine the strengths of different integration platforms, e.g., by complementing large-scale photonic-electronic integration on silicon-on-insulator (SOI) substrates with active optical elements on InP.

In this talk, we introduce photonic wire bonding as a novel technology for single-mode interconnects between nanophotonic circuits that are located on different chips. The technique is based on in-situ fabrication of three-dimensional freeform waveguides between coarsely prepositioned chips. The structures are created by two-photon polymerization of negative-tone resist materials in the focus of a high-NA femtosecond laser beam. The shape of the photonic wire bond waveguides is adjusted to the exact positions of the chips, such that high-precision alignment of optical devices becomes obsolete. This makes the technique particularly attractive for automated industrial fabrication of photonic multi-chip modules. In a first proof-of-principle experiment, we demonstrated broadband chip-to-chip coupling with average insertion losses of only 2.5 dB between 1240 nm and 1580 nm, and 1.6 dB within the infrared telecommunication C-band (1530…1565 nm). The wire bonds can handle multi-Terabit/s data streams comprising tens of wavelength channels, even if phase-sensitive advanced modulation formats are used.

8613-32, Session 7

Fundamental processes of refractive index modifications during femtosecond laser waveguide writing

Dagmar Schaefer, Ingomar Kelbassa, RWTH Aachen (Germany)

By using focused ultrashort pulsed laser radiation refractive index modifications are induced in dielectric materials in order to generate optical components. The understanding of physically fundamental processes induced by laser radiation is the basis for the systematic control and maximization of the refractive index change for the realization of three-dimensional, optical components for integrated optics like in-volume waveguides.

In this work a detailed and independent analysis is carried out for the fundamental thermal and electronic processes which are generated by focused laser radiation in the volume of two different glass materials: fused silica and borosilicate glass D263. The glass materials are structured by temporally modulated laser radiation in the infrared spectral range (lambda=1045nm).

By femtosecond laser pulses with high repetition rates (f=10MHz) thermal processes like heat accumulation effects are induced leading to heat affected zones and thus waveguide cross sections with dimensions of multiple focal volumes.

For the induction of electronic processes laser double pulses with a varied time distance in the range of t=0-2ns are used. The dependency of the temporal sequence of laser pulses on generated defects (excitons, color centers, etc.) and therefore on the refractive index modifications are investigated. The laser induced structural change in the glass matrix is proved with Raman spectroscopy by the increase of three- and four-membered ring structures.

In this work the formation of laser induced refractive index modifications and the corresponding fundamental processes are investigated in order to control and maximize the refractive index change.

8613-33, Session 7

Two photon polymerization lithography for 3D micro fabrication of single wall carbon nanotube/polymer composites

Shota Ushiba, Satoru Shoji, Kyoko Masui, Osaka Univ. (Japan); Junichiro Kono, Rice Univ. (United States); Satoshi Kawata, Osaka Univ. (Japan)

Single wall carbon nanotubes (SWNTs), which consist of a rolled-up single layer graphene with a 1 nm diameter cylindrical shape, exhibit intrinsic optical properties as well as their remarkable mechanical, electrical, and thermal properties. These intrinsic characteristics make it possible to develop some devices, such as photomechanical actuators, and those devices have been already developed in macroscale. However, there remains a huge challenge to develop micro/nano sized devices made of SWNT/polymer composites, so that it is required to establish a way to fabricate micro structural SWNT/polymer composites. In this presentation, we present a novel method for fabricating 3D micro structural SWNT/polymer composites by means of two photon polymerization (TPP) lithography. SWNTs were dispersed in an acrylate monomer by sonication, and subsequently a few amounts of photo-initiator and photo-sensitizer were loaded into the mixture. SWNT-dispersed photo resin was casted on a glass substrate which placed on a 3-dimensional piezoelectric stage. Femtosecond pulsed laser at 780 nm laser, which was focused into the resin, photo-polymerized a nanometric volume of the resin via TPP. Arbitrary 3D micro/nano structures were created such as a 8 micron length bull, a micro lizard, and a 200 nm width nanowire. SWNTs were evenly and entirely distributed in microstructures, confirming by Raman microscopy. This fabrication proceeding may open up the further applications of SWNT/polymer composites such as micro sized photomechanical actuators.

8613-34, Session 7

Nonlinear absorption measurements of commercial and custom made two-photon initiators for direct laser writing application

Paulius Danilevicius, David Gray, Foundation for Research and Technology-Hellas (Greece); Muhammad Rashid Nazir, Daniel T. Gryko, Polish Academy of Sciences (Poland); Maria Farsari, Foundation for Research and Technology-Hellas (Greece)

Molecules exhibiting two-photon absorption (TPA) have attracted the interest of researchers due to their potential applications in two-photon fluorescence microscopy, three-dimensional (3D) optical data storage, two-photon photodynamic therapy, as well as microfabrication by two-photon polymerization (TPP). TPP is a direct laser writing technique, which allows fabrication of 3D polymeric micro-structures reaching sub-100 nm resolution. The TPA cross-section of light sensitive photoinitiator (PI) molecules plays an important role in TPP efficiency. Significant TPP parameters, such as polymerization threshold and rate, dynamic write range depends on the PI's sensitivity. However, conventional PI's used in linear lithography, exhibit low TPA cross-sections. Thus, there is a demand for novel TPA molecules with high cross-section values. By using those, not only can TPP throughput be increased, but also employment of femtosecond systems can be avoided and low-cost micro-lasers can be applied, opening opportunities for commercial applications.

The aim of this work is to screen for efficient PI's by using an open aperture Z-Scan setup. Z-Scan is a particularly sensitive technique to measure materials nonlinear optical properties. Our setup employs an amplified Ti:Sapphire laser (200 fs, 1 kHz). Firstly, reference cross-section values of commercial PI's, such as Irgacure 369, 4,4'-bis(diethylamino) benzophenone were measured. These values were compared to custom synthesized coumarin containing molecules with benzyldihydrazone moieties and phosphine oxide derivatives. They showed significantly higher sensitivity. Moreover, efficiency of radical generation in TPP was investigated. These results are compared to the ones found in literature. Those most efficient PI's were then applied in the TPP fabrication of microstructures.

8613-35, Session 8

Light sensitive holographic waveguides fabricated by vacuum assisted microfluidics

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We report on the fabrication of a light sensitive holographic waveguide via vacuum assisted microfluidic (VAM) soft lithographic technique. UV curable light insensitive and light sensitive waveguides resins have been synthesized for the VAM fabrication. The fabricated light insensitive waveguides function like typical polymer waveguides with desired mode confinements while the light sensitive waveguides formed by an azobenzene based polymer resin can achieve refractive index modulation through green or blue laser illumination. The refractive index modulation is instant and reversible with a response speed of sub seconds. Instant holographic gratings can be recorded in the light sensitive waveguide portions to facilitate a number of waveguide functionalities including light diffraction, phase control, intensity modulation, spectral filtering, and variable optical attenuation. The VAM technique is used for the fabrication of multi-section waveguides using different resins at the same time which is unique as compared to conventional single material waveguide fabrication. The effective use of the soft lithographic VAM technique for realizing various waveguide sections with the light sensitive azobenzene based UV curable resin can result in many functional waveguide devices for photonics applications.

8613-36, Session 8

Optimization of deposition conditions for silica/polystyrene microlens and nanolens arrays for light extraction enhancement in GaN light-emitting diodes

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GaN-based light-emitting diodes (LEDs) have drawn a lot of attention in recent years for solid state lighting and display applications. The light extraction efficiency of conventional LEDs is relatively low due to large refractive index contrast between GaN and air. Recently, the use of low-cost, large-scale, and practical method based on the use of silica / polystyrene microlens arrays were implemented for achieving improved extraction in GaN-based LEDs.

Here, we present a simple method of modifying surface properties of GaN LEDs to improve the light extraction by ~2-3 times via rapid convective deposition (RCD) method. In this work, we extend the use of microlens arrays LEDs from larger microspheres (~1 micron diameter) down to nanospheres (~100nm diameter) for optimizing the extraction efficiency in GaN-based LEDs. The optimization of the deposition conditions for achieving monolayer close-packed 2-D micro-/nano-lens were carried out by varying the deposition speed, blade angle, and suspension concentration. The analysis shows that the light extraction efficiency for LEDs depends strongly on the size of the micro/nanosphere used to form the lens arrays. Thus, the ability for fabricating lens arrays down to nanoscale is of great importance for achieving optimized light extraction efficiency in GaN-based LEDs. The SiO_2 microsphere or nanospheres with various diameters from 500nm down to 100nm (500nm, 400nm, 250nm, and 100nm) were deposited on the GaN LEDs by employing RCD method. The deposition of self-assembled 2-D close-packed lens arrays was obtained, and the comparisons of LEDs devices with lens arrays are carried out.

8613-37, Session 8

Flexible conductive polymer polarizer designed for a chemical tag

Cody M. Washburn, Julia M. Craven-Jones, Steve R. Vigil, Patrick S. Finnegan, Robert R. Boye, Jeffery D. Hunker, David A. Scrymgeour, Shawn M. Dirk, Bradley G. Hance, Sandia National Labs. (United States)

Conductive polymers with high solids loading (> 40wt.%) are very challenging to pattern to single micron feature sizes and require unique techniques or templates to mold the material. The development of a conductive polymer optical tag will be discussed which indicates the presence of hydrofluoric acid (HF) and leverages free standing silicon fins as a template utilizing deep reactive ion etching (DRIE) techniques.

This work is aimed at a future flexible conductive polymer tag to be transferred via adhesive or epoxy for a novel sensor surface. The advantage to this technique over wafer thinning is a high through put of devices without damage to the silicon fins or polymer due to chemical-mechanical interactions or added protective layers. The approach we followed uses a high spatial frequency (1.15 ?m pitch) grating consisting of lines of conductive polymer and lines of silicon which are free standing. A novel running bond pattern aims to minimize the intrinsic stress and allows the conductive polymer to infiltrate without distorting the template. The conductive mechanism has been designed to break down under a chemical binding of fluorine; changing its conductivity upon exposure, and results in a change in the polarization response. The use of a polarization response makes the signal more robust to intensity fluctuations in the background or interrogation system. Additionally, the use of optical interrogation allows for standoff detection in instances where hazardous conditions may be present. Examples of material and device responses will be shown and directions for further investigation discussed.

8613-38, Session 8

Micro-optical grayscale collection lenses for atom and ion trapping

David A. Scrymgeour, Shanalyn A. Kemme, Robert R. Boye, A. Robert Ellis, Tony R. Carter, Jeffery D. Hunker, Sandia National Labs. (United States)

Designing and integrating micro-optical components into atom and ion traps are enabling steps toward miniaturizing trap dimensions in quantum computation applications. The micro-optic must have a high numerical aperture for efficient processing and should not introduce scatter. Due to the extreme collection efficiency requirements in trapped ion and atom-based quantum information processing, even slight losses from integrated micro-optics are detrimental.

We have designed and fabricated aspheric micro-lenses through grayscale transfer into a fused silica substrate in an effort to realize increased grayscale collection efficiency over an equivalent diffractive optical element. The fabricated grayscale lens profile matched the design lens profile well, and the measured and predicted optical performances were in good agreement. The pattern was transferred via coupled plasma reactive-ion etching smoothly to the fused silica with a RMS roughness < 15 nm. The micro-lens had a diameter of 88 um and 14.6 um sag, with an as-designed focal length of 149 um and spot diameter of 2.6 um. Measured efficiency was 80% (86% of theoretical, possibly due to rms roughness); better than the equivalent diffractive lens designed to the same use parameters. The slightly lower grayscale efficiency may arise from minor errors in replicating the lens shape near the lens aperture. Even so, the grayscale approach shows the promise in increasing collection efficiency, at the desired optical focal length, with further refinement.

8613-39, Session 8

A snapshot multispectral imager with integrated, tiled filters, and optical duplication

Bert Geelen, Klaas Tack, Andy Lambrechts, IMEC (Belgium)

Although the potential of spectral imaging has been demonstrated in research environments, its adoption by industry has so far been limited due to the lack of high speed, low cost and compact spectral cameras. We have previously overcome this limitation by monolithically integrating optical interference filters on top of standard CMOS image sensors for high resolution pushbroom hyperspectral cameras. These cameras require a scanning of the scene and therefore introduce operator complexity due to the need for synchronization and alignment of the scanning to the camera. This typically leads to problems with motion blur, reduced SNR in high speed applications and detection latency.

This paper introduces a novel snapshot multispectral imager concept based on optical filters monolithically integrated on top of a standard CMOS image sensor. It overcomes the problems mentioned for scanning applications by snapshot acquisition, where an entire multispectral data cube is sensed at one discrete point in time. This is achieved by applying a novel, tiled filter layout and an optical sub-system which simultaneously duplicates the scene onto each filter tile. Through the use of monolithically integrated optical filters it retains the qualities of compactness, low cost and high acquisition speed, differentiating it from other snapshot spectral cameras. Moreover, thanks to a simple cube assembly process, it enables real-time, low-latency operation. Our prototype camera can acquire multispectral image cubes of 256x256 pixels over 32 bands in the spectral range of 600-1000nm at 340 cubes per second for normal machine vision illumination levels.

8613-40, Session 8

Micro-optical system as integration platform for III-N nanowire based opto-chemical detectors

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Many applications especially in the fields of aerospace require compact and robust sensors for environmental gas monitoring working at elevated temperatures. For this purpose III-N nanowire heterostructures (NWHs) can be applied as opto-chemical transducers as they show a highly sensitive photoluminescence (PL) response to hydrogen (H2) and oxygen (O2) [1]. In combination with other unique properties such as a large surface to volume ratio and a high crystal quality, nitride nanowire structures provide an all-optical approach for the realization of chemical sensors. In our contribution we present the miniaturization of an existing large scale laboratory sensor setup using an efficient micro optical system which serves as platform for integrating the electro-optical components, i.e. the laser diode for excitation and the photo diode for detection, as well as suitable NWHs. For highest detection reliability the micro optical system was designed to completely isolate the electro-optical components from the investigated environment. In our setup the excitation radiation at lambda = 405 nm is efficiently delivered to the NWHs via a tilted, reflective ellipsoid. This mirror surface is designed to image the output facet of the laser diode onto the detection area. Coupling angles are optimized according to ideal imaging conditions and maximum transmission efficiency. The PL signal is detected by a photo diode placed close to the NWHs. Although the excitation radiation and the PL signal are spatially separated at the photo diode, reflected and scattered excitation as well as false light is suppressed by an additional interference filter. For the fabrication of the micro optical system in UV optimized PMMA we used 5-axis ultra-precision micro machining [2]. The design and fabrication approach are proven by profilometric measurements and experimental investigations of the system performance.

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8613-41, Session 8

Hyperspectral Fabry-Pérot filters for HgCdTe infrared detectors

Yong Chang, Christoph H. Grein, Sivananthan Labs., Inc. (United States); Silviu Velicu, EPIR Technologies, Inc. (United States); Neelam Gupta, U.S. Army Research Lab. (United States)

The results of comprehensive modeling of tunable Fabry-Pérot filters that use distributed Bragg reflectors and that can be used together with HgCdTe detectors to form hyperspectral detector modules will be presented in this presentation. The filter tunability is achieved elctrostatically by applying bias voltages across the DBR elements in the filter. In addition to typical filter characteristics such as the cut-off wavelength and maximum transmissivity, the impacts on filter figures of merit of material choice, of the thickness of each constituent material and of each period, of the field of view, of the material surface and interface roughnesses, and of other related material characteristics, of the filter (such as quality factors and finesse) will be discussed in detail. The temperature stability and temperature dependence of the filter characteristics and the sensitivity of thermo-optical fine tuning of the filter to achieve better temperature stability of the detector module also will be presented.

8614-1, Session 1

Probing interfacial contact via MEMS-based microinstrumentation *(Invited Paper)*

Roya Maboudian, Univ. of California, Berkeley (United States)

Recent developments in the micro- and nanoelectromechanical systems (M/NEMS) field have created a growing interest in evaluating the reliability of these miniaturized devices. The critical reliability issues include adhesion, friction, wear and corrosion. In this presentation, the impact of these interactions in the M/NEMS technology will be discussed. I will also present the unique opportunities provided by the MEMS processing techniques to interrogate surfaces at a length scale not easily accessible by other techniques, namely in the mesoscopic length scale. With this view, I will introduce a number of MEMS-based microinstruments that we have developed to study these interactions, and some of the insights we have gained using them about the nature of surface interactions involved in M/NEMS.

8614-2, Session 1

Analysis of metal-metal contacts in RF MEMS switches

Steffen Kurth, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Sven Voigt, Sven Haas, Andreas Bertz, Christian Kaufmann, Technische Univ. Chemnitz (Germany); Thomas Gessner, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Akira Akiba, Koichi Ikeda, Sony Corp. (Japan)

MEMS Switches are deemed to be key components in mobile communication devices. They are used for reconfiguration of filters, of antennas and of front end modules. This contribution reports on the analysis of the characteristics of metal-metal contacts of capacitively actuated Ohmic switches in series SPST configuration for DC up to 75 GHz signal frequency. A novel high aspect ratio MEMS fabrication sequence in combination with wafer level packaging is applied for fabrication of an RF MEMS switch with lateral motion. It allows for a relatively large actuation electrode area in a small package, and for high actuation force in the range of 100 µN resulting in fast on-response time of 10 µs and off-response time of 6 µs at less than 5 Volt actuation voltage. The focus of this contribution is on the contact behavior and its influence on the insertion loss and on the non-linearity of the RF signal chain. It is shown how operation conditions as like actuation voltage, temperature, RF power, and DC bias influence the contact resistance and the power of intermodulation products. It is also shown how the history of the contacts including contact formation and contact degradation affects the performance. Different test methods are introduced and explained. The results are discussed and compared to results from other sources in order to develop an understanding of possible failure modes and to derive possible measures for further improvement of the contact stability and of the reliability of Ohmic switches.

8614-3, Session 1

Reliability of MEM relays for zero leakage logic

Yenhao Chen, Rhesa Nathanael, Jack Yaung, Louis Hutin, Tsu-Jae K. Liu, Univ. of California, Berkeley (United States)

MEM relays are ideal switches in that they have zero off-state leakage and abrupt switching (I-V) characteristics, so that they may be an attractive alternative to CMOS transistors for ultra-low-power digital logic applications. The demonstration of various computational and memory circuit building blocks implemented using only MEM relays as active elements confirmed that they satisfy many of the basic device requirements for VLSI [1]. This paper focuses on the key device requirement of reliability. Specifically, reliability characterization and failure modes will be discussed, for MEM relays designed for digital logic applications.

The logic relay is a 4-terminal device fabricated using conventional planar processing techniques (450 degrees Celsius maximum substrate temperature) in which the movable electrode is suspended at its corners by folded flexures over a fixed electrode. A voltage is applied between these two electrodes to exert electrostatic force (against the spring-restoring force of the flexures) and thereby actuate the movable electrode downward to bring a conductive channel (attached underneath the movable electrode, with an intermediary dielectric layer) into contact with fixed source and drain electrodes which are coplanar with the fixed actuation electrode. Possible reliability failure modes include structural fatigue, contact welding, dielectric charging, and contact oxidation. Endurance testing results will be presented to demonstrate that fatigue is not an issue, and that contact welding is mitigated with reductions in operating voltage. Optimization of the actuation biasing scheme is shown to mitigate the problem of dielectric charging. Contact resistance instability caused by surface oxidation and contamination remains a challenge.

[1] F. Chen, M. Spencer, R. Nathanael, C. Wang, H. Fariborzi, A. Gupta, H. Kam, V. Pott, J. Jeon, T.-J. King Liu, D. Markovi?, V. Stojanovi?, and E. Alon, “Demonstration of integrated micro-electro-mechanical (MEM) switch circuits for VLSI applications,” in IEEE Int’l Solid-State Circuits Conf. Tech. Dig., 2010, pp. 150-151.

8614-5, Session 1

Reliability characteristics of microfabricated Rb mini-lamps for optical pumping in miniature atomic clocks and magnetometers

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With the rising need for microfabricated chip-scale atomic clocks (<10 cm3), to enable high precision timekeeping (<10-12 time uncertainty) in portable applications such as GPS receivers, there has been active interest towards developing miniature (< few cm3), chip-scale alkali vapor lamps which are preferred for optical pumping in double-resonance clocks. We developed a first prototype chip-scale Rb dielectric barrier discharge lamp using microfabrication processes including anodic bonding and the devices’ preliminary results indicated its high potential for such optical pumping applications and wafer-scale batch fabrication. It was observed to be generally robust with no obvious performance decline after being ignited thousands of times, and with no electrode erosion from plasma discharges because of the external Aluminum deposited electrodes. However, as atomic clocks have strict lamp performance requirements including <0.1% sub-second optical power fluctuations, power consumption < tens of mW and a device lifetime of at least several years, it is important to study the long-term reliability of these Rb mini-lamp devices and identify the operating conditions where these devices can be most reliable and stable for a long lifetime. In this paper, we report on the reliability analysis experiments of such microfabricated lamps including a continuous several month run of the lamp where the continuously monitored optical power, electrical power consumption and temperature stability are reported. We also report on the effects of temperature, rf-power and the lamp-drive parasitics on the optical power stability and discuss about steps that could be taken towards further improving the device performance and reliability.

8614-35, Session 1

Reliability studies on MEMS shutters and displays *(Invited Paper)*

Joyce Wu, Lodewyk Steyn, Pixtronix, Inc. (United States)

No Abstract Available

8614-6, Session 2

MEMS gratings for wavemeters and tunable light sources *(Invited Paper)*

Maurizio Tormen, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Thomas Overstolz, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Stephan Dasen, Jacques-Andre Porchet, Real Ischer, Branislav Timotijevic, Ross P. Stanley, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

A MEMS tunable blazed grating is a versatile optical element providing a compact tunable mechanism for optical systems.

The MEMS chip is used to implement a wavemeter, e.g. to measure the central wavelength of Fiber Bragg Grating sensors with high accuracy. The proposed system only comprises the MEMS chip, two collimators and fiber connectors. The system was tested at 1.5 µm: it detected lines as narrow as 0.19 nm, resolved lines 2 nm apart and retrieved the central wavelength with accuracy better than ±200 pm. The expected accuracy for this kind of system is on the order of 1pm.

The same MEMS technology is used to make tunable light sources. The MEMS grating acts as a tunable pass-band filter in combination with a broadband source. Two MEMS chips with different grating periods are cascaded, in order to cancel out undesired grating orders, to improve filter linewidth (~1nm) and extinction ratio (26 dB). The cascaded filter selects an arbitrary wavelength from a 400 to 800 nm source.

The MEMS chip is 5x5 mm2, provides 4% tuning, comprises a position encoder, operates in different spectral regions (Visible to Mid-IR), and is shock resistant up to 3000g. Moreover, using the grating in the Littrow condition significantly reduces the complexity of the optical system.

8614-7, Session 2

Robustness and reliability of MOEMS for miniature spectrometers

Anna Rissanen, Uula Kantojärvi, Mari Laamanen, VTT Technical Research Ctr. of Finland (Finland); Mikael Broas, Jussi Hokka, Toni T. Mattila, Aalto Univ. School of Electrical Engineering (Finland); Jarkko E. Antila, Heikki K. Saari, VTT Technical Research Ctr. of Finland (Finland)

Tuneable MOEMS Fabry-Perot interferometers (FPIs) are key elements in the miniaturization of spectroscopic instrumentation. Robustness and in-use reliability of the MOEMS structure are important factors especially for sensors utilized in challenging environments such as in space- and automotive applications. This paper presents reliability assessment of two types of MOEMS optical filters; a tunable ALD (atomic layer deposition) –based surface micromachined FPI for visible – NIR range, and a tunable FPI for mid- IR applications based on LPCVD (low-pressure chemical vapor deposition) thin-film micromachining. The visible wavelength FPIs have been designed to be used as small-weight miniature imaging spectrometers as part of nanosatellite instrumentation, whereas mid-IR components are aimed at optical measurements in automotive applications. A finite-element model (FEM) was created to assess resonance frequency and step response of surface-micromachined FPIs. High-G shock tests were performed on both MOEMS FPIs. The FPI structures can survive mechanical impacts in the range of 12 000 G – 18 000 G without any detectable changes in the capacitance, while detected failure mechanisms in this range arise from detachment (packaging failure) and not from the MOEMS structures. The effect of DDMS SAM (dichlorodimethylsilane self-assembled monolayer) coating to prevent in-use stiction was evaluated in both humidity- and impact tests. In humidity tests, 20% stiction rate in uncoated devices vs. 0% stiction rate in DDMS-coated LPCVD FPIs under pull-in was observed. These results indicate good shock-impact robustness for both types of surface-micromachined structures, while DDMS SAM can be utilized to improve in-use reliability of MOEMS.

8614-8, Session 2

MEMS and MOEMS resonance characterization by digital holographic microscope (DHM)

Yves Emery, Lyncée Tec SA (Switzerland); Aneta Michalska, Warsaw Univ. of Technology (Poland); Etienne Cuche, Lyncée Tec SA (Switzerland)

Digital Holographic Microscopes (DHMs) have unique features especially relevant for static and dynamical MEMS characterization. They provide both 3D topography with interferometric resolution and intensity image in a single acquisition, without any lateral or vertical scanning. In this presentation, DHM is operated in conjunction with a laser pulsed stroboscopic module providing synchronization of camera, laser pulses, and MEMS excitation signal up to 25 MHz.

Three methods for DHM analysis of resonant frequencies are presented with concrete examples.

The first method uses sine wave excitation with increasing (or decreasing) frequencies. For each frequency, the optical signal is integrated over an entire number of periods of the MEMS. At resonance, constructive and interference build up on the intensity images. It enables fast frequency scan over large ranges. But it provides neither quantitative values of displacement amplitude, nor Bode diagrams.

The second method is to measure the system response to an impulse or chirp excitation signal for instance, and to make a Fourier analysis of this response to determine resonant frequencies.

The third method, more time consuming, gives the more general, precise and complete information. Sine wave excitation with increasing (or decreasing) frequencies is used. For each frequency, laser pulses are used to "freeze" the movement of the MEMS. Using the stroboscopic synchronization, the topography is determined for many positions of the excitation period. As implemented, the change of frequency is continuous: quantitative values in term of displacement amplitude and Bode diagrams can be measured even in presence of non linear resonances

8614-9, Session 2

A smaller footprint MEMS sensor for on-chip temperature measurement

Ali Najafi Sohi, Patricia Nieva, Univ. of Waterloo (Canada)

In bimaterial structures, temperature variation induces a thermal expansion mismatch between the constituent components of the structure which manifests itself in the form of in-plane or out-of-plane deflection. This phenomenon has been extensively used in the design of MEMS temperature sensors, mostly in the form of microcantilevers. Due to initial stresses, the bimaterial structures are initially curled up and consequently exhibit highly varying temperature sensitivity. In this paper, a new design for bimaterial MEMS temperature sensors is presented which is based on a circular silicon membrane on top of which a gold annulus is deposited. The membrane, measuring about 300 micrometer in diameter, is anchored to a substrate on its edge and forms the top electrode of a capacitor. A stationary silicon electrode

beneath the bimaterial membrane forms the second electrode. The new design utilizes geometrical modifications to keep the sensitivity variation below 50% throughout its working temperature range. PolyMUMPs® foundry process has been used to fabricate the device. Our experiments have shown that with an effect area of about 0.1 mm2 the new sensor achieves a sensitivity of 0.75±0.25 fF/°C over the temperature range of 25 to 225 °C, which shows an improvement more than 25% over equivalent microcantilever devices (covering the same area). Moreover, through numerical modeling, it is shown that the new design exhibits a high flexibility in tailoring its sensitivity over the desired temperature range. The new MEMS sensor can thus be used as a simple on-chip temperature measurement device for MEMS characterization.

8614-10, Session 2

Optoelectronic and acoustic properties and their interfacial durability of GnP/PVDF/GnP composite actuators with nano-structural control

Joung-Man Park, Gyeongsang National Univ. (Korea, Republic of) and The Univ. of Utah (United States); Ga-Young Gu, Dong-Jun Kwon, Zuo-Jia Wang, Gyeongsang National Univ. (Korea, Republic of); Lawrence K. DeVries, The Univ. of Utah (United States)

Nano- and hetero-structures of carbon nanotube (CNT), indium tin oxide (ITO), and Graphene nano Platelet (GnP) can control significantly piezoelectric and optoelectronic properties in Microelectromechanical Systems (MEMS) as acoustic actuators. Interfacial durability and electrical properties of CNT, ITO or GnP coated poly(vinylidene fluoride) (PVDF) nanocomposites were investigated for use in acoustic actuator applications. The GnP coated PVDF nanocomposite exhibited better electrical conductivity than either CNT or ITO, due to the unique electrical properties of GnP. GnP nanocomposite coatings also exhibited good acoustical properties. Contact angle, surface energy, work of adhesion, and spreading coefficient measurements were used to explore the interfacial adhesion durability between neat CNT (or plasma treated CNT) and plasma treated PVDF. The acoustic actuation performance of GnP coated PVDF nanocomposites were investigated for different radii of curvature and different coating conditions, using a sound level meter. GnP is considered to be a more appropriate acoustic actuator than either CNT or ITO because of its characteristic electrical properties. A radius of curvature of about 15 degrees was established as being most appropriate. Sound characteristics differed with varying coating thicknesses. The results of this study suggest that it should be possible to manufacture transparent actuators with good sound quality.
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8614-11, Session 2

Developments in packaging and integration for silicon photonics *(Invited Paper)*

Peter A. O'Brien, Tyndall National Institute (Ireland)

This presentation will focus on the challenges faced with packaging Silicon photonic devices. This includes fibre coupling, laser and photodiode integration, thermal aspects and design for high speed operation. Researchers at the Tyndall National Institute have developed novel approaches to fibre coupling to submicron Silicon waveguides, including single and multi-channel waveguides. When combined with the ability to integrate active photonic devices such as lasers and photodiodes, Silicon based photonics now provides a compelling platform to develop advanced communication and sensor systems. The presentation will in particular investigate the implementation of practical technique to fibre couple and integrate active devices on a Silicon photonic platform.

8614-12, Session 3

Temperature compensated silicon resonators for space applications *(Invited Paper)*

Mina Rais-Zadeh, Vikram A. Thakar, Zhengzheng Wu, Adam Peczalski, Univ. Of Michigan (United States)

This paper presents piezoelectric transduction and electrostatic tuning of silicon-based resonators with a center frequency in the low megahertz regime. The temperature coefficient of frequency (TCF) of the resonators is compensated using both passive and active compensation schemes. Specifically, a novel technique utilizing oxide-refilled trenches is implemented to achieve efficient temperature compensation while maintaining compatibility with wet release processes. Using this method, we demonstrate a high-Q resonator having a low TCF of less than 2 ppm/°C and a turnover temperature of around 90 °C, ideally suited for use in ovenized platforms. Using electrostatic tuning, the temperature sensitivity of the resonator is further compensated across a temperature range of +50 to +85 °C, demonstrating frequency instability of less than 300 ppb. The power handling of the resonators was characterized to be -1 dBm of input power. Such devices are ideally suited as timing units in space applications where size, power consumption and temperature stability are the most important parameters. The full paper describes the long-term stability and full characterization of some of the key aspects of the device.

8614-13, Session 3

Wafer level vacuum packaging of scanning micromirrors using glass-frit and anodic bonding methods

Sergiu Langa, Christian Drabe, Christian Kunath, André Dreyhaupt, Harald Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Scanning micro-mirrors are tiny MOEMS devices in the millimetre range oscillating at a certain frequency (e.g. 50 kHz). There are different principles for actuating micro-mirrors. The most prospective, from our point of view, is the electrostatic principle. The main advantages of the electrostatic actuating principle are: small responding times, scalability and CMOS compatibility. Unfortunately micro-mirrors with electrostatic actuation need a relatively high driving voltage of usually more than 100 V for resonant actuation at high frequencies. A way to significantly decrease the driving voltage and thus the power consumption is packaging the micro-mirrors in vacuum.

Wafer Level Vacuum Packaging (WLVP) is a solution to decrease the complexity during production and simultaneously the energy consumption during the life-time of the chips with electrostatic actuation. WLVP based on wafer bonding methods (WB) is most widely accepted at the moment for MEMS/MOEMS packaging.

In the present work the authors will present the results for WLVP of scanning micro-mirrors developed at Fraunhofer IPMS in Dresden, Germany by using anodic and glass frit bonding methods. A stack of four 150 mm wafers was used to complete the packaging process. After dicing the chips were 6 mm in length, 4 mm wide and 1.6 mm thick.

The tests on chip level show that a vacuum of smaller than 10 mbar was achieved in the package. The vacuum inside the package allowed us to reduce the driving voltage of the scanning micro-mirrors from 70 V to 40 V.

8614-14, Session 3

Influence of ceramic package internal components on the performance of vacuum sealed uncooled bolometric detectors.

Alex Paquet, Sébastien Deshaies, Yan Desroches, Jeffrey Whalin, Patrice Topart, INO (Canada)

INO has developed a hermetic vacuum packaging technology for uncooled bolometric detectors based on ceramic leadless chip carriers (LCC). Cavity pressures less than 1 mTorr are obtained. Processes are performed in a state-of-the art semi-automated vacuum furnace that allows for independent activation of non-evaporable thin film getters. The getter activation temperature is limited by both the anti-reflection coated silicon or germanium window and the MEMS device built on CMOS circuitry. Temperature profiles used to achieve getter activation and vacuum sealing were optimized to meet lifetime and reliability requirements of packaged devices. Internal package components were carefully selected with respect to their outgassing behavior so that a good vacuum performance was obtained.

In this paper, INO's packaging process is described. The influence of various package internal components, in particular CMOS circuit, on vacuum performance is presented. The package cavity pressure was monitored using INO's pressure microsensors and the gas composition was determined by internal vapor analysis. Lifetime was derived from accelerated testing after storage of packaged detectors at various temperatures from room temperature to 120oC. A hermeticity yield over 80% was obtained for batches of twelve devices packaged simultaneously. Packaged FPAs submitted to standard MIL-STD-810 reliability testing (vibration, shock and temperature cycling) exhibited no change in IR response. Results show that vacuum performance strongly depends on CMOS circuit chips. Detectors packaged using a thin film getter show no change in cavity pressure after storage for more than 30 days at 120oC. Moreover, INO's vacuum sealing process is such that even without a thin film getter, a base pressure of less than 10 mTorr is obtained and no pressure change is observed after 5 days at 120oC.

8614-15, Session 3

3D-integration of a vacuum sealed carbon nanotube resonator with its driving CMOS chip

Rokhaya Gueye, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Shih-Wei Lee, ETH Zurich (Switzerland); Terunobu Akiyama, Danick Briand, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Matthias Muoth, Cosmin I. Roman, Christofer Hierold, ETH Zurich (Switzerland); Nico F. de Rooij, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

A complete device composed of a vacuum-encapsulated Single Wall Carbon NanoTube (SWCNT) resonator 3D-integrated with its driving CMOS electronics is presented.

The key element of this System in Package (SiP) is the monolithic integration of the main device with Through Silicon Vias (TSVs) on an SOI wafer. A ferritin-based Chemical Vapor Deposition (CVD) process was chosen for the SWCNT growth. This process is carried out at high-temperature, herein 850 °C. Since a "via first" approach was selected, high-temperature TSVs compatible with the SWCNT growth and release processes were developed. They withstand the CVD process at 850 °C and the release process in wet HF 49 %. Stable ohmic contacts at high temperature were obtained between the platinum TSV metallization and the silicon device layer. The SWCNT resonator and its driving CMOS electronic chip are stacked using stud bumps technologies; a high-speed signal transport, suitable for a RF-NEMS is enabled by the platinum-TSVs. As with many MEMS devices, the properties of the SWCNT resonator are environment-sensitive. An encapsulation process was developed to provide a vacuum operating environment to the SWCNT resonator; a glass cap was processed with an integrated Ti getter inside the cavity in order to enhance and maintain the vacuum level. The glass cap is vacuum bonded to the NEMS chip using a gold-silicon eutectic bonding process.

This SiP concept is suitable for the 3D-integration of delicate RF-MEMS requiring a "via first" approach.

8614-17, Session 3

Solar cell packaged by a microlens array and its long-term optical efficiency enhancement

Minwoo Nam, Kangho Kim, Jaejin Lee, Sang Sik Yang, Kee-Keun Lee, Ajou Univ. (Korea, Republic of)

Solar cells with front metal gridlines commonly suffer from optical losses due to light reflection at the gratings and the optical shading underneath the metallization regions of the photoactive layer. We hereby introduce a technique of mounting a microlens array (MLA) on solar cells to serve as both an incident light manipulator and a passivation layer. For the fabrication of the MLA, quartz was isotropically wet-etched to form negative cylindrical micropatterns, and then UV-curable resin with a high refractive index was filled in the parallel circular grooves. The developed MLA shows uniformly arrayed elements and has an experimental focal length of 800 ?m. The solar cell shows the power conversion efficiencies (PCEs) of 20.52 % for without passivation, 18.92 % for bare glass passivation, and 20.38 % for MLA passivation. Meanwhile, employing an optical spacer between the MLA and the cell highly accelerated the MLA effect. It is primarily attributed to the more efficient conveyance of the refractive light into the bare interfinger regions, avoiding the gridlines. In particular, the highest PCE of 22.33 % was achieved when the optical spacer is equivalent to the focal length of the MLA. This result is 18.5 % higher than that of the bare glass-packaged control cell, and denotes that the photovoltaic effect is maximized in the case that the photoactive layer absorbs the most concentrated solar light. The performance was maintained unchanged for a long time as a result of absolute protection of the cell against oxygen and external physical shocks.

8614-18, Session 4

Impact of radiations on the electromechanical properties of materials and on the piezoresistive and capacitive transduction mechanisms used in microsystems *(Invited Paper)*

Laurent A. Francis, Petros Gkotsis, Valeriya Kilchytska, Xiaohui Tang, Sylvain Druart, Jean-Pierre Raskin, Denis Flandre, Univ. Catholique de Louvain (Belgium)

MEMS could revolutionize avionics and satellite applications provided that the effects of harsh environmental conditions on the reliability of microsystems are well understood. Initial tests with MEMS revealed a vulnerability of some types of devices to radiation induced dielectric charging, a physical mechanism which also affects microelectronics. However, integration of novel materials in microfabrication and the current trend to substitute SiO_2 in ICs with high-k dielectrics pose new questions regarding reliability in radiation environments. In addition, in MEMS possible radiation induced changes in the mechanical properties of the materials could also be important. It is thus necessary to investigate the effects of radiation on the electromechanical properties of materials used in microfabrication and here we report on tests with high energy protons, ? and fast neutrons radiation.

Charging is investigated using MIS capacitors fabricated from ALD deposited Al_2O_3, thermal SiO_2 and LPCVD Si_3N_4 and shifts in midgap voltage after 20 kGy protons equal to respectively 4, 9 and 1 V are obtained. Radiation effects on the properties of sol-gel deposited PZT films are investigated using MIM ferroelectric capacitors. The longitudinal

πL and the transverse πT piezoresistance coefficient of p-type and n-type piezoresistors are measured using a four-point bending test and πT of p-type piezoresistors before and after 20 kGy neutrons was found equal to 0,46±0,05 %/kbar and 0,46±0,04 %/kbar respectively. Prototype SOIMUMPs based MEMS magnetometers developed at UCL are also used as test vehicles to investigate radiation effects on the reliability of magnetically actuated and capacitively coupled MEMS.

8614-19, Session 4

MOMS accelerometers utilizing resonant microcantilevers with interrogated single-mode waveguides and Bragg gratings

Lewis G. Carpenter, Christopher Holmes, James C. Gates, Peter G. R. Smith, Univ. of Southampton (United Kingdom)

Monitoring acceleration and vibration is of interest for a large number of industrial applications, including machine health monitoring, hydrophones and gyroscopes. MEMS is the accepted route for the monitoring of physical signals; however Micro-Opto-Mechanical Systems (MOMS) have a number of advantages, which include the ability to work in extreme environments, over large distances and work with immunity to EMI.

The fully integrated (i.e. not free space) MOMS developed by our group have been demonstrated in a silica-on-silicon planar platform. Devices include micromembranes, microbridges and microcantilevers, ranging in length scales of hundreds of microns to tens of millimetres but with cross sections of tens of microns. Within the developed silica MOMS structures are single mode channel waveguide (1200-1700 nm), with Bragg gratings. These waveguides are low loss (0.04 dB/cm) and are designed to integrate into quasi-distributed sensing network using standard telecommunication components.

Physical actuation induces strain in the microstructures, which are monitored by intrinsically integrated Bragg gratings, strain causing the Bragg central wavelength to shift proportionally. Structural deflection has been monitored both with single Bragg gratings and pairs of spectrally matched gratings forming Fabry–Pérot Bragg grating interferometers. Microcantilevers with Fabry–Pérot interferometers have shown to have wavelength shift force sensitivity of 330 nm/N (tens of nanograms resolution) and is an order of magnitude better than current state-of-the-art integrated Bragg grating based sensors.

Principally our fabrication route includes direct UV writing to create waveguides and Bragg gratings and physical micromachining to define microstructures. We will present new MOMS components for acceleration applications.

8614-20, Session 4

Reliability of reworked CCGA packages for deep space applications

Rajeshuni Ramesham, Jet Propulsion Lab. (United States)

Life testing of advanced electronic packaging and interconnect technologies, mechanical assemblies, and reworked CCGAs and other SMT technologies for flight projects has been addressed to enhance the mission assurance of JPL-NASA projects. The reliability of reworked SMT packages is very important for short- and long-term deep space thermal environmental missions.

The qualification of hardware under extreme temperatures was performed with reference to various project requirements. The flight-like packages, assemblies, test coupons, and subassemblies were selected for the study to survive three times the total number of expected temperature cycles resulting from all environmental and operational exposures occurring over the life of the flight hardware including all relevant manufacturing, ground operations, and mission phases. Qualification/life testing was performed by subjecting flight-like qualification hardware to the environmental temperature extremes and assessing any structural failures, mechanical failures or degradation in electrical performance due to either overstress or thermal cycle fatigue.

The usage of large, high density electronic interconnect packages such as ceramic column grid array (CCGA) have increased in NASA avionics hardware in the last decade and half or so. The boards built with these packages are expensive and often require rework to replace reprogrammed, failed, redesigned, etc., packages. Ideally, a good rework process should have similar temperature-time profile as that used for the original production of solder reflow process. A multiple rework processes will be implemented with COTS CCGA packaging technology to understand the effect of rework on the reliability of CCGA technology. Reliability of the assembled electronic packages reduces as a function of number of reworks. A CCGA rework process will be developed and implemented to design a test board. Reworked CCGA interconnect electronic package printed wiring polyimide boards have been assembled and inspected using non-destructive x-ray imaging techniques. The assembled boards were subjected to extreme temperature thermal atmospheric cycling to assess their reliability for future deep space missions. The resistance of daisy-chained interconnect sections were monitored continuously during thermal cycling. This paper will describe the experimental reliability results of assemblies using reworked CCGA packages under extreme temperature environments.

8614-21, Session 4

Proton irradiation tolerance of single crystal silicon and SU-8 based MEMS devices

Tobias Bandi, Ecole Polytechnique Fédérale de Lausanne (Switzerland) and Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); João Gomes, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Antonia Neels, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We report on the proton irradiation tolerance of single crystal silicon and the epoxy polymer SU-8. While single crystal silicon is a standard structural material in MEMS the SU-8 resin has been developed as a negative photoresist. However, after its discovery it has quickly been recognized as a possible structural material in MEMS devices. Applications which have been investigated range from mass sensing over waveguide-photodiode integration in silicon-based substrates to the fabrication of very high aspect-ratios and complex 3D structures.

In MEMS structures with moving parts the consistency of the elasticity is often a prerequisite for optimum performance over the full life cycle. Therefore we focused our investigations on the Young's modulus of the two materials. MEMS cantilevers were exposed to high energy proton beams to assess radiation-induced changes in the elastic modulus. The irradiation was performed at ion energies in the range between 10MeV and 200MeV, which covers a wide range of the proton energies relevant in space applications. In addition, proton testing allowed combining contributions from displacement damage and ionizing damage. The investigated resonators consisted of SCSi or SU-8 only to minimize side-effects and were driven by capacitive actuation or a piezoelectric element. The resonance characteristics were determined by laser Doppler vibrometry.

The results obtained indicate that the elasticity of single-crystal silicon is highly resistant against displacement damage. Also in the SU-8 only small variations of the Young's modulus were observed, suggesting that this material may perform well in orbit.

8614-22, Session 4

Spaceborne linear arrays of 512x3 microbolometers

Linh Ngo Phong, Canadian Space Agency (Canada); Ovidiu Pancrati, Linda Marchese, François Châteauneuf, INO (Canada)

Linear arrays of microbolometers are a new class of space sensors intended for Earth observation and planetary exploration. The interest in the linear format of the array stems from its small operating power budget. Further, the linear format is suited for remote sensing where relative motion between the spacecraft and target provides an inherent scanning mechanism. Lately, the Canadian Space Agency (CSA) and INO have joined effort in the development and space qualification of 512x3 arrays that offer the capability of simultaneous readout of all pixels. The first generation arrays were integrated in the NIRST (New Infrared Sensor Technology) radiometer as a result of a Collaborative Agreement between the Argentine Space Agency (CONAE) and the CSA. NIRST makes use of two arrays, one in the mid wave and the other in the long wave infrared, to measure land and sea temperatures. In particular, this instrument is intended for the determination of wildfire characteristics. The recent launch of NIRST into low Earth orbit, as part of the international partnership SAC-D Aquarius mission, provided an opportunity to further investigate the on-orbit operation and reliability of the 512x3 arrays and their integrated submicron CMOS readout electronics. This paper provides details on the characteristics of the arrays and the radiometer. A particular emphasis is put on the ground qualification and preliminary on-orbit results.

8615-1, Session 1

Integrated liquid jet waveguide for fluorescence spectroscopy on chip

Gianluca Persichetti, Genni Testa, Romeo Bernini, Istituto per il Rilevamento Elettromagnetico dell'Ambiente (Italy)

An optofluidic jet waveguide for on chip fluorescence analysis is presented. The waveguide consists of an high speed water stream produced by means of a micro-channel coupled with a multimode optical fiber collecting the fluorescence opportunely excited. The liquid jet acts, at the same time, the solution to analyse and an optical waveguide. This configuration allows a strong reduction of the background signal due to the scattering of the excitation light and fluorescence of non analyte substances in the path of the excitation light from the light source towards the detector, e.g. fluorescent impurities in the substrate material of the chip enabling a very low limit of detection (LOD) with respect bulk liquid measurements. The integrated device is fabricated by PMMA micro-machining and permits a self-alignment between the optofluidic and the optical fiber used to deliver the fluorescence to the detector. The performance of the system has been tested on Cy5 water solutions. For a 4.5 mm long water jet waveguide, a detection limit of 1.68 X 10-9 M has been obtained.

8615-2, Session 1

Next generation optofluidic flow cytometers using color-space-time coding

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While flow cytometers have been a standard analysis tool for various biomedical applications, recent innovations in electronics and optics technologies have resulted in performance enhancement as well as reductions in cost and size. Advances in microfluidics, digital signal processing and computation platforms have been one of the key enablers for the advances in flow cytometry. NanoSort has developed a lab-on-chip multi-color flow cytometer that can discriminate multiple fluorescent wavelengths using a single detector employing Color-Space-Time (COST) coding technology. The detection architecture uses COST coding that converts fluorescence signals from cells stained with various fluorophores into differently modulated waveforms in time domain to be registered by a single detector as the cells pass by a spatial slit and color filter array. This provides an integrated solution to multicolor detection thus enabling the construction of lab-on-a-chip flow cytometers that are portable and less expensive than existing commercial systems. In order to achieve rapid prototyping, we have investigated the best platform and software approach that leverages the latest microfluidics and digital signal processing technology. Our latest prototype used a Field Programmable Gate Arrays (FPGA) board, which offers tremendous computing power and parallelism at a low price point with a compact footprint. The lab-on-a-chip multicolor flow cytometer chip can therefore be a powerful, portable, and affordable flow cytometer that can be used in any individual biomedical or clinical labs.

8615-3, Session 1

Lab-in-fiber platform for plasmonic photothermal study

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Photonic crystal fibers (PCFs) or microstructured optical fibers have been widely employed in numerous applications since its devise in 1996 by Knight et al. Its periodic array of air holes enables light propagation via modified total internal reflection or photonic bandgap guidance, while providing microfluidic channels for analytes, allowing for measurable light-analyte interactions, eliciting great interest in its applications for sensing. This trait renders it notably similar to lab-on-a-chip or other microfluidic devices, which unfortunately have the drawback of requiring waveguide incorporation onto polymer chips for optics-based detection. Since lab-on-a-chip devices have also been explored as micro-sized reactors, it seems viable to exploit the advantages of PCFs in similar processes. To highlight the optics cum microfluidic aspects, we propose the study of a photo-induced reaction within a PCF platform (lab-in-fiber). In particular, a recent topic of interest has been the use of metal nanoparticles for enhanced photothermal effects in therapeutic applications. Such metal nanoparticles resonate under excitation light sources, generating localized surface plasmons and subsequently a localized heating effect that has been demonstrated to be effective in the disruption of cellular membranes, ideal for therapeutic applications such as targeting of tumors or bacteria. We therefore aim to achieve the plasmonic photothermal effect within a lab-in-fiber by infiltrating a mixture of gold nanoparticles and commonly used cell phantom (liposomes encapsulating fluorescence dyes), and subsequently observing for membrane disruption (quantified by fluorescence emission) upon a suitable excitation. It is noteworthy that the PCF acts as a mode of delivery for the excitation light as well as a collector of the resultant fluorescence emission.

8615-5, Session 1

Advances in Raman-activated cell sorting using microfluidic chips

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Four technical innovations are reported towards Raman activated cell sorting. First, a microfluidic chip made of quartz is introduced which integrates injection of single cells, trapping by laser fibers and sorting of cells. Second, a chip holder was designed to provide simple, accurate and stable adjustments of chips, microfluidic connections and the trapping laser fibers. Raman spectra could be collected with high signal to noise ratio at 785 nm excitation with 10 seconds exposure time. Third, a new approach of modeling various background contributions is described increasing the sensitivity and specificity of Raman-based cell classification. Fourth, a novel Raman-on-chip setup is introduced which accommodates laser excitation fibers and multi-core single-mode collection fibers. Fiber Bragg gratings were inscribed into the collection fibers to suppress elastic scattered light. The novel Raman setup offers low detection limits for urea and nicotine solutions and enables to collect

Raman spectra of single trapped beads and cells.

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8615-6, Session 2

Results update from Second Sight’s Argus II retinal prosthesis study *(Invited Paper)*

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Methods: Subjects had bare light perception or worse vision due to retinitis pigmentosa. All subjects were implanted with a Second Sight Argus II implant (clinicaltrials.gov NCT00407602). Visual function was evaluated by a grating visual acuity test as well as by assessing the ability to determine the direction of motion of a line and the location of a square on an LCD screen. Orientation and mobility (O&M) tests were also given, which involved following a line and finding a door.

Results: As of December 1, 2011, 30 subjects have been implanted at 10 centers (in the main study). Subjects have been implanted an average of 3.2 ± 0.9 years (range of 1.2 – 4.5), and all have used or are using the System at home. The rate of adverse events, which was moderate to begin with, has been further decreased by approximately 2x in the second half of the subjects (i.e., last 15 subjects). As for implant stability, 28 out of 30 devices are intact and functioning – one device was explanted around 14 months post-implant; a second remains implanted but functions intermittently due to partial loss of the RF link that provides power and data to the array. Results on visual function tests with high-contract stimuli showed a hierarchy of function, progressing from the ability to locate an object, through the ability to detect the direction of motion, and finally to the ability to distinguish the orientation of black and white gratings. To date, the best grating visual acuity measurement was 1.8 logMAR (20/1260). Functional vision O&M tests demonstrate that subjects are significantly better at performing visual tasks with the System ON vs. OFF and that this effect is maintained during long-term follow-up (i.e. >3years).

Conclusions: With over 95 cumulative patient-years of follow-up on 30 subjects, this is the largest study of a visual prosthesis to date. The results confirm previous reports on the ability of the Argus II prosthesis to provide visual function and functional vision over the long-term. The Argus II Retinal Prosthesis System has received CE Mark and is now commercially available in Europe. Higher resolution devices are in development.

8615-7, Session 2

Lissajous scanning endoscopic OCT catheter using asymmetric silicon structures

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This work presents a novel method for scan frequency modulation and three-dimensional image reconstruction for forward viewing endoscopic optical coherence tomography (OCT) catheter based on a resonant fiber scanning. Two-dimensional optical scanning in a Lissajous pattern was realized by a piezoelectric tube with quartered electrodes and asymmetric silicon structures. A series of asymmetric silicon structure, which were defined by deep reactive ion etching (DRIE) process, was attached at a distal end of a fiber cantilever. The silicon structures shift the resonant frequency of a fiber well below an appropriate speed for spectral domain OCT (SD-OCT), typically below 100 Hz, as well as distinguish the resonant frequencies in orthogonal directions to eliminate the cross-talks between each axes. An endoscopic catheter composed of a weighted fiber mounted on a piezoelectric tube was assembled with endoscopic housing of 3 mm in diameter and a gradient-index objective lens of 2 mm in diameter. The endoscopic catheter was then combined with a home built SD-OCT system of 60 kHz A-line scan rate. Three dimensional SD-OCT images of 256 x 256 x 995 voxels were directly reconstructed by mapping the A-line data sets along non-repeating Lissajous scanning trajectories with triangle based interpolation algorithm. The interpolation algorithm effectively reduces distortion effects, which are arose from over-sampled edge region of a Lissajous pattern, by using a non-uniform mesh grid. Besides, the algorithm also can increase temporal resolution by minimizing the number of scanning cycles to cover full image plane.

8615-8, Session 2

Multi hybrid instrumentation with smartphones for innovative in-field and POC diagnostics

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Aim of the paper is the orientation of research and development on a completely new approach to innovative in-field and point of care diagnostics in industry, biology and medicine. Central functional modules are smartphones supplemented by additional hardware apps and software apps. Specific examples are given for numerous practical applications concerning opto-digital instruments.

The methodical classification distinguishes between different levels for combination of hardware apps (hwapps) and software apps (swapps) with smartphones. Selected practical solutions are:

1. smartphones with swapps, for example: color, object and character identifiers for quality control in industrial painting processes

2. smartphones with hwapps, for example: microscopes and telescopes for object identification in bio analytical measurements

3. smartphones with hwapps and swapps, for example: dermoscopes and spectrometers for dermatological investigations in medicine

4. smartphones with multi hybrid hwapps and swapps, for example: Smartphone Lab for analytical applications of different chemical or biological probes.

These methods are fundamental enablers for the transformation of stationary conventional laboratory diagnostics into mobile innovative in-field and point of care diagnostics. The innovative approach opens so far untapped enormous markets due to the convenience, reliability and affordability of smartphone instruments. A highly visible advantage of smartphones is the huge number of their distribution, their worldwide

connectivity via cloud services and the experienced capability of their users for practical operations.

8615-10, Session 3

Tailoring microfluidic systems for organ-like cell culture applications using multiphysics simulations *(Invited Paper)*

Britta Hagmeyer, Heiko Kiessling, Julia Schütte, Martin Stelzle, Naturwissenschaftliches und Medizinisches Institut an der Univ. Tübingen (Germany)

Numerical multiphysics simulations have become a powerful tool to optimize first design elements prior microfabrication, thus avoiding cost- and time-consuming prototype fabrication and testing during the development of a microfluidic chip design. By calculating the physical phenomena occurring inside the microfluidic structures and their concurrence with the specified requirements of the desired application first design iterations can be performed in silico without actual fabrication of prototype devices.

Using the example of microfluidic systems for 3D organ-like cell culture, we describe the benefits of numerical simulations during microchip development.

Microfluidic systems were analyzed and optimized with respect to i) surface and interface effects to ensure bubble-free filling of the microfluidic structures, ii) flow fields, electric fields, dielectrophoretic forces and particle trajectories for dielectrophoretic assembly of cells to form organ-like structures, and iii) temperature distribution, shear stress, nutrition and gas supply in the vicinity of the assembled cells in order to provide for an in vivo like cell micro environment.

Based on these simulation results a microfluidic system was realized and successfully tested for liver-like cell culture applications.

8615-11, Session 3

Human organ-on-a-chip BioMEMS devices for testing new diagnostic and therapeutic strategies

James F. Leary, Pierre-Alexander Vidi, Christy L. Cooper, Ayeeshik Kole, Lisa M. Reece, Sophie A. Lelievre, Purdue Univ. (United States)

MEMS human “organs-on-a-chip” can be used to create model human organ systems for developing new diagnostic and therapeutic strategies. They represent an exciting new strategy for rapid testing of new diagnostic and therapeutic strategies without the need for involving risks to human subjects. We are developing multicomponent, superparamagnetic and fluorescent nanoparticles as X-ray and MRI contrast agents for non-invasive multimodal imaging and for antibody- or peptide-targeted drug delivery to tumor cells inside these artificial organ MEMS devices. Magnetic fields can be used to move the nanoparticles “upstream” to find their target cells in the model human ductal breast cancer organs-on-a-chip. Unbound nanoparticles can then be removed by reversing the magnetic field to give a greatly enhanced image of tumor cells within these artificial organ structures.

Using branched PDMS microchannels and 3D tissue engineering of normal and malignant human breast cancer cells inside those MEMS channels, we can mimic the early stages of human ductal breast cancer to improve the sensitivity and resolution of mammography and MRI of very small tumors and test new strategies for treatments. These nanomedical systems can also be imaged by multicolor confocal microscopy inside these artificial organs to test targeting and therapeutic responses. Currently we are using 2-dimensional MEMS structures, but these studies can be extended to more complex 3D structures using new 3D printing technologies.

8615-12, Session 3

Stationary microfluidics: molecular diagnostic assays by moving magnetic beads through non-moving liquids

Holger Becker, Cornelia Carstens, microfluidic ChipShop GmbH (Germany); Dirk Kuhlmeier, Fraunhofer-Institut für Zelltherapie und Immunologie (Germany); Christian Zilch, Magna Diagnostics GmbH (Germany); Claudia Gärtner, microfluidic ChipShop GmbH (Germany)

Commonly, microfluidic devices are constructed to move fluidics. For molecular diagnostics assays which include steps like PCR, this practically always involves a more or less complicated set of external pumps, valves and liquid controls. In the presented experiment, the fluid after sample introduction remains stationary and the main bioactive sample molecules are moved through a chain of reaction compartments which contain different reagents (buffers, PCR reagents). These reagents are either simple buffers or PCR reagents which have been stored in lyophilized form on chip and are resolubilized by the buffer.

The molecules of interest are attached to paramagnetic polymer beads. The beads are moved from chamber to chamber using an electromagnet on a linear stage. The big advantage of this concept is the lack of any external fluid actuation/control. A single fluid (buffer) as well as the sample is introduced into the cartridge using a Luer-syringe. A linear stage with an electromagnet is the only other mechanically active component of the whole set-up which allows for a very simple instrument which is an important issue for real-world diagnostic applications.

The main challenge of this stationary-fluid concept is to realize the inter-cavity transfer of the sample-laden beads without carry-over of reagents from one cavity to the next, especially in the case of PCR-inhibiting reagents and without significant sample loss. This was realized by the geometrical design of the various reaction compartments. Results on sample carry-over experiments and complete assays will be given.

8615-13, Session 3

Optimized release matrices for use in a BioMEMS device to study metastasis

Ashley N. Clark, James K. Williams, Michael R. Padgen, Jesus Vijay, Univ. at Albany (United States); Patricia J. Keely, Univ. of Wisconsin-Madison (United States); John S. Condeelis, Albert Einstein College of Medicine of Yeshiva Univ. (United States); James Castracane, Univ. at Albany (United States)

Multiple changes within the tumor microenvironment have been correlated with an increase in metastasis, yet the mechanisms are not fully understood. Tumor cells can be stimulated by the release of chemoattractant factors such as epidermal growth factor (EGF) from nearby stromal cells, resulting in increased intravasation and metastasis. Additionally, altered extracellular matrix density can result in changes in gene expression patterns governing increased cellular proliferation and motility. The Nano Intravital Device (NANIVID) has been used to produce gradients of select soluble factors in the tumor microenvironment and to study the role of these changes on cell migration. In previous studies, the NANIVID utilized a synthetic hydrogel to produce a chemoattractant gradient of EGF to attract metastatic breast cancer cells. In this work, additional release matrices, such as silk and alginate, will be explored as an improved soluble factor release medium. A matrigel insert will be introduced into the device outlet to provide an improved substrate for cells to migrate on when entering the NANIVID. Furthermore, different densities of collagen will be created to gauge the cellular motility response when grown within a stiffer matrix. Matrix density will be manipulated through varying the concentration of collagen in the matrix and by introducing crosslinking proteins via the NANIVID. The concentration of the chemoattractant and matrigel comprising the insert will be optimized to produce a suitable gradient for inducing chemotaxis in metastatic breast cancer cells.

8615-14, Session 3

Automation of routine electrochemical sandwich assay for on-chip gene expression analysis of circulating tumorous cells

Ciara K. O'Sullivan, Univ. Rovira i Virgili (Spain)

Cancer remains a prominent health concern afflicting modern societies and if traditional cancer therapy is based on the biology of the primary tumour, it is usually the tumour dissemination to other parts of the body that results in a negative prognosis and death. For this reason, the detection and characterisation of circulating tumour cells in peripheral blood (CTCs) and disseminating tumour cells in bone marrow (DTCs) of cancer patients are believed to be of high therapeutic and prognostic importance.

Financed under the FP7 European framework since 2010, the project MIRACLE (www.miracle-fp7.eu) aims to develop a fully automated and integrated lab-on-a-chip (LoC) microsystem providing the genotype of CTCs and DTCs starting from clinical samples. This requires the integration and automation of all sample pre-processing steps including the enrichment, counting, electrochemical characterization and genotyping of the cells. A number of modular microfluidic chips are being integrated to realise the immunomagnetic purification of large blood samples with high sensitivity, immediately followed by the counting and lysis of the extracted cells. On-chip multiplexed DNA amplification is subsequently carried out on the lysate, the product of which is finally electrochemically detected and analysed on a low-density electrode array to elucidate the genetic profile of the extracted CTCs.

To this end a fully automated microsystem consisting of a disposable 64-electrode array integrated with microfluidics and electrochemical readout, able to perform all assay steps (i.e. incubation, labelling, calibration, electrochemical measurement and regeneration) was constructed. As a proof-of-concept, the system was developed to automatically quantify 6 RNA markers involved in breast cancer resulting from a multiplexed PCR amplification step performed off-chip. Encouraged by the results that will be presented, this system is now being developed into a fully automated "amplification-to-detection" microsystem for the profilling of over 20 genetic markers involved in breast and prostate cancer.

8615-15, Session 4

Inkjet printed structures for smart lab-on-chip systems

Erik Beckert, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Oliver Pabst, Falk Kemper, Zhe Shu, Friedrich-Schiller-Univ. Jena (Germany); Ramona Eberhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Jolke Perelaer, Ulrich Schubert, Friedrich-Schiller-Univ. Jena (Germany); Holger Becker, microfluidic ChipShop GmbH (Germany)

Inkjet printing and subsequent plasma sintering of silver and gold electrodes can be used for a cost efficient integration of conducting structures in lab-on-chip systems. They enable for the driving of active components, for reaction triggering such as Electrophoresis but also for the creation of localized heating zones due to ohmic losses. The manufacturing process and the conducting / loss performance of electrode structures will be presented as well as the homogeneity and accuracy of temperature distribution within certain areas of lab-on-chip systems will be shown. The electrodes can furthermore sandwich-like combined with inkjet printed electroactive polymers (EAP) to create membrane actuators that serve as chip integrated micro pumps and valves. The manufacturing process of the membrane actuators and their pumping performance with respect to driving voltage is discussed. An outlook will develop visions of complete function integration on smart fluidic chips by using even more inkjet printed functional materials.

8615-16, Session 4

Characterizing frangible seals for liquid delivery using blister packs

Tejas Inamdar, Brian W. Anthony, Massachusetts Institute of Technology (United States)

Microfluidic devices may uses blister packs to store and release liquid reagents. Pressure applied to the blister ruptures a seal along its frangible interface resulting in flow into fluidic channels. Predictability and repeatability in the flow pattern exiting the blister via is essential for device operation. This paper investigates frangible seals to broaden the understanding of the nature of the frangible seal before and after the rupture, drawing inferences on rupture mechanics. A Design of Experiments with three factors – time, temperature and pressure involved in sealing parameters is conducted to optimize the process window. This work primarily focuses on seal designs and explores the impact of different frangible seal shapes, profiles and locations on flow patterns using a flow sensor.

8615-17, Session 4

Selecting and designing with the right thermoplastic polymer for your microfluidic chip: a close look into cyclo-olefin polymer

Mark A. Nevitt, Zeon Chemicals L.P. (United States)

As microfluidics are establishing themselves as an accepted technology in the life science arena, more and more academia and biomedical research institutions are now looking to utilize microfluidics for their next generation research and POC devices. While the majority of development work is focused on the reaction chemistries, a key component, and attributing factor to the reliability, efficiency, and optimization of device function, is proper material selection for chip construction. This presentation will provide an overview of the polymeric materials available to fluidic chip designers. Also presented will be a technical, comparative look into the optical, mechanical, fluorescence, and bio-compatibility aspects of cyclo-olefin polymer; a novel, engineered thermoplastic material that has proven to increase sensitivity and consistency of diagnostic detection systems.

In addition to a technical review of the cyclo-olefin polymer's chemical and optical characteristics, attendees will also gain an understanding of the manufacturing and joining techniques suitable for use with cyclo-olefin polymer resin and film for microfluidic chip production. Lastly, an often overlooked, but critical, consideration of fluidic chip production is how the injection molding process can affect fluorescence and other properties of polymer chip components. Actual production process data will be demonstrated to illustrate how attention to the production process can significantly improve a microfluidic device's reliability and performance. Academia research & biomedical OE design engineers involved in microfluidic chip and assay development should attend this presentation.

8615-19, Session 4

Fabrication of micro/nano-fluidic channels by single-beam direct femtosecond laser writing

Fadia Dewanda, KAIST (Korea, Republic of); Md. Shamim Ahsan, KAIST (Korea, Republic of) and Khulna Univ. of Engineering & Technology (Bangladesh); Man Seop Lee, KAIST (Korea, Republic of)

In this paper, we report on the formation of micro/nano-fluidic channels inside fused silica glass using single-beam femtosecond laser. The micro/nano-fluidic channels are fabricated by controlling the irradiation conditions of the femtosecond laser pulses, especially, laser fluence and

scanning speed. We examine the production of this kind of channels both in air and water. In both cases, laser beam is focused inside the glass bar and shown horizontally with very low scanning speeds. In case of water, the glass sample is placed under several millimeters of water, which way is expected to reduce the surface roughness of the channels. The quality of the channels fabricated under different environment is compared as well. We further investigate the influence of various laser parameters on the production of channels. We also evaluate the fluid flowing ability of the fabricated micro/nano-fluidic channels of various diameters, fabricated under different environment and irradiation conditions, by measuring the flow rate of water through the channels.

8615-20, Session 5

System for portable nucleic acid testing in low resource settings *(Invited Paper)*

Hsiang-Wei Lu, Kristina Roskos, Anna Hickerson, Keck Graduate Institute (United States); Thomas Carey, Harvey Mudd College (United States); Tanya Ferguson, Claremont BioSolutions (United States); Deepali Shinde, Keck Graduate Institute (United States); Robert Doebler, Ryan Talbot, Claremont BioSolutions (United States); Angelika Niemz, Keck Graduate Institute (United States)

Rapid cost-effective sample-to-answer diagnosis of infectious diseases in point-of-care settings can greatly improve the accessibility of health care in developing countries. Our goal is to integrate nucleic acid sample preparation, isothermal DNA amplification, and nucleic acid lateral flow (NALF) detection within a compact system to enable timely diagnosis of active pulmonary tuberculosis. The system consists of a disposable cartridge containing a miniaturized bead blender, active and passive valves, flexible pouches, and electrolysis-driven pumps, in conjunction with an instrument that automates blender motor activation, valving, pumping, heating, and timing. The disposable cartridge is manufactured using low-cost and scalable techniques and forms a closed system to prevent workplace contamination by amplicons. Using an early prototype of the amplification and detection unit, we have demonstrated successful execution of an established and clinically validated isothermal loop-mediated amplification (LAMP) reaction targeting Mycobacterium tuberculosis (M.tb) DNA, coupled to NALF detection. Nucleic acid amplification occurs in a two–layer pouch that facilitates fluid handling and appropriate thermal control. We herein present a refined design of the amplification and detection unit, and the characterization of thermal and fluidic control and assay execution within this system. Our next step is to couple this amplification and detection unit to a sample preparation unit, which performs mechanical lysis of mycobacteria and DNA extraction from liquefied and disinfected sputum. The final integrated cartridge and device will enable fully automated sample-in to answer-out diagnosis of active tuberculosis in primary care facilities of low-resource and high-burden countries.

8615-21, Session 5

IFSA: a microfluidic chip-platform for frit-based immunoassay protocols

Nadine Hlawatsch, microfluidic ChipShop GmbH (Germany); M. Bangert, Peter Miethe, Research Ctr. of Medical Technology and Biotechnology (Germany); Holger Becker, Claudia Gärtner, microfluidic ChipShop GmbH (Germany)

Immunoassays represent the gold-standard for clinical laboratory tests for a vast number of biomarkers from hormones to C-reactive protein. For assays carried out in standard microwell plates, assay time and complexity have been identified as factors limiting the performance and usability. By combining miniaturized elements for immunofiltration and microfluidic sample handling, the IFSA platform reduces the protocol complexity and required assay time. The platform consists out of a disposable polymer chip, injection molded out of COP or similar thermoplastic material with the size of a microscopy slide. It contains three lanes to test three different samples independently. Assay reagents are stored in lyophilized form in a reagent well, with just buffer to be added. A second reagent well for liquid reagents is provided as well. Four antibody-coated immunofiltration frits allow the simultaneous measurement of two targets as well as positive and negative control. Colorimetric, or fluorescence detection can be applied. The performance of the chip system was demonstrated for several model analytes. In case of proteins (CRP, Troponin I, MMP8) detection limits in the region of 10 pg/ml were obtained. The detection limits for viruses (Ebola, Marburg) and microorganisms (F.tularensis, Legionella) are in the order of 50 PFU/ml and 100 CFU/ml respectively.

8615-22, Session 5

Integrating sample preparation for magnetic flow cytometry

Oliver Hayden, Michael Helou, Lukas Richter, Siemens AG (Germany); Mathias Reisbeck, Fachhochschule Regensburg (Germany); Evi Bingart, Sandro F. Tedde, Siemens AG (Germany)

Optical flow cytometry is the gold standard for single cell analysis for clinical applications. However, extracting single cell information out of blood requires a time-consuming workflow related to sample preparation and labeling. Here, we discuss an industrially-relevant concept for magnetic flow cytometry with giant magnetoresistance (GMR) devices known form hard disk read-heads, which allows us to detect single cells with high recovery rate in whole blood samples without prior sample preparation, such as hemolysis or removal of excess labels. Key for the integration of the sample preparation is magnetophoresis which in combination with GMR sensors enables us to develop a platform technology for cytometry in whole blood.

8615-23, Session 5

Rapid screening test for gestational diabetes

Bernhard H. Weigl, Roger Peck, PATH (United States)

Gestational diabetes (GDM) is a global epidemic, with many urban areas in SE Asia have found prevalence rates as high as 20%, exceeding the highest prevalence rates in the developed world. It can have serious and life-threatening consequences for mother and baby. GDM can also lead to type 2 diabetes later in life for both mother and child. Current screening practices (the oral glucose tolerance or challenge tests) are cumbersome, require a special visit to the clinic, and make many patients uncomfortable or nauseous. Most antenatal care facilities cannot perform the test for GDM because of their complexity.

An antenatal care visit represents the best opportunity to prevent or treat GDM and to put both mother and child on a health care track that allows prevention, delay, and/or treatment of type 2 diabetes and its consequences.

The test under development is based on the immunological detection of the level of glycated albumin, a protein that develops in response to elevated glucose levels, in finger-stick blood. The test allows opportunistic screening without patient preparation at the first or only antenatal care visit, reducing cost and complexity and avoiding loss to follow-up.

The assay can be read visually, or combined with simple optical readout devices for improved quantitation and connectivity. We will present designs and initial results aimed at overcoming the challenge of visualizing relatively narrow differences between normal and elevated levels of glycated albumin in blood using paper microfluidic approaches. Further, we will show designs and initial results for ratiometric detection and visual readout of the level of glycated albumin as a % of total albumin in blood.

8615-24, Session 5

On-chip trapping of cancer cells using micro-patterned magnetic pathway

CheolGi Kim, Chungnam National Univ. (Korea, Republic of)

We demonstrate on-chip trapping of individual breast cancer cells (SKBR3 cell line) at designated positions on a silicon surface within a microfluidic channel, in which superparamagnetic beads acted as microorganism carriers through micro-pathway patterns.

8615-25, Session 6

Lensfree on-chip microscopy and tomography toward telemedicine applications *(Invited Paper)*

Aydogan Ozcan, Univ. of California, Los Angeles (United States)

In this talk I will introduce new imaging and detection architectures that can compensate in the digital domain for the lack of complexity of optical components by use of novel theories and numerical algorithms to address the immediate needs and requirements of Telemedicine for Global Health Problems. Specifically, I will present an on-chip cytometry and microscopy platform that utilizes cost-effective and compact components to enable digital recognition and 3D microscopic imaging of cells with sub-cellular resolution over a large field of view without the need for any lenses, bulky optical components or coherent sources such as lasers. This incoherent holographic imaging and diagnostic modality has orders of magnitude improved light collection efficiency and is robust to misalignments which eliminates potential imaging artifacts or the need for realignment, making it highly suitable for field use. Applications of this lensfree on-chip microscopy platform to high-throughput imaging and automated counting of whole blood cells, monitoring of HIV+ patients (through CD4 and CD8 T cell counting) and detection of waterborne parasites towards rapid screening of water quality will also be demonstrated. Further, I will discuss lensfree implementations of various other computational imaging modalities on the same platform such as pixel super-resolution imaging, lensfree on-chip tomography, holographic opto-fluidic microscopy/tomography. Finally, I will demonstrate lensfree on-chip imaging of fluorescently labeled cells over an ultra wide field of view of >8 cm2, which could be especially important for rare cell analysis (e.g., detection of circulating tumor cells), as well as for high-throughput screening of DNA/protein micro-arrays.

8615-26, Session 6

Rapid white blood cell detection for peritonitis diagnosis

Tsung-Feng Wu, Zhe Mei, Yu-Jui Chiu, Univ. of California, San Diego (United States); Sung Hwan Cho, Nanosort, Inc. (United States); Yu-Hwa Lo, Univ. of California, San Diego (United States)

Nearly 26 million Americans suffer from chronic kidney disease (CKD) and over 400,000 of these patients are diagnosed as the end-stage renal disease (ESRD). The ESRD patients require hemodialysis (HD) or peritoneal dialysis (PD) to maintain their health due to the lost kidney functions. Peritonitis is a common complication for patients undergoing PD. Without timely diagnosis, peritonitis may cause sepsis and become life threatening. Clinically the diagnosis for peritonitis includes severe abdominal pain and cloudy dialysis effluent with a white blood cell (WBC) count of over 100/mL. For early diagnosis of peritonitis for PD patients, a point-of-care lab-on-a-chip (LoC) system is demonstrated to detect WBCs in the dialysis effluent. The LoC system consists of two microfluidic devices: a spiral microfluidic channel as a pre-concentrator and a microfluidic device to produce encoded forward scattering signals for cell classification. The spiral device utilizes hydrodynamic forces, Dean force and inertial force, to concentrate cells in the dialysis effluent. Then the concentrated fluid flows through the optical-coding device where the optical forward scattering, cell speed and position produce fingerprints for WBCs such as neutrophils. In a preliminary study, we spiked WBCs extracted from lysed whole blood into 10mL of urine of a healthy donor and detected ~3.04 WBCs/μL from our device, comparable with the result from a commercial flow cytometer (~3.33/μL). The results are encouraging for a point-of-care system to monitor peritonitis for kidney disease patients receiving PD.

8615-27, Session 6

A microfluidic platform utilizing enzymatic assays for lab-free pathogen detection

Richard Klemm, Nadine Hlawatsch, Sandra Julich, Holger Becker, Claudia Gärtner, microfluidic ChipShop GmbH (Germany)

The ability to integrate complete assays on a microfluidic chip helps to greatly simplify instrument requirements and allows the use of lab-on-a-chip technology in the field. A core application for such field-portable systems is the detection of pathogens in a CBRN scenario such as permanent monitoring of airborne pathogens, e.g. in metro stations or hospitals etc. As one assay methodology for the pathogen identification, enzymatic assays were chosen. In order evaluate different detection strategies, the realized on-chip enzyme assay module has been designed as a general platform chip. In all application cases, the assays are based on immobilized probes located in microfluidic channels. Therefore a microfluidic chip was realized containing a set of three individually addressable channels, not only for detection of the sample itself also to have a set of references for a quantitative analysis. It furthermore includes two turning valves and a waste container for clear and sealed storage of potential pathogenic liquids to avoid contamination of the environment. All liquids remain in the chip and can be disposed of in proper way subsequently to the analysis. The chip design includes four inlet ports consisting of one sample port (Luer interface) and three mini Luer interfaces for fluidic support of e.g. washing buffer, substrate and enzyme solution. The sample can be applied via a special, sealable sampling vessel with integrated female Luer interface. Thereby also pre-anaytical contamination of the environment can be provided. Other reagents that are required for analysis will be stored off chip.

8615-28, Session 6

Organic photovoltaic cells based on photoactive bacteriorhodopsin proteins

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The most common energy harvesting technology in use today is the photovoltaic cell. Advances in materials engineering have enabled these devices to be fabricated from solid-state semi-conductors, photosensitive organic dyes, and photoactive proteins. One type of organic photovoltaic cell is based on the light-harvesting protein bacteriorhodopsin (bR) which is naturally found in the plasma membrane of the salt marsh archaebacteria Halobacterium salinarium. When exposed to sunlight, each bR molecule acts as a simple proton pump which transports hydrogen ions from the cytoplasmic to the extracellular side through a transmembrane ion channel that connects both sides of the membrane. The design and fabrication of photosensitive dry and wet bR thin films are described in this paper. The self-assembled monolayer of oriented purple membrane patches from the bR protein is created on a bio-functionalized gold (Au) surface using a biotin molecular recognition technique. The biotin enables the extracellular side of the bR purple membranes to be accurately labeled. An optically transparent Indium Tin Oxide (ITO) electrode is then placed on top of the finished assembly to complete the circuit of the cell for testing and performance verification. The dry bR monolayer generated a photo-electric response of 9.73 mV/cm2, while the wet bR produced 41.7 mV/cm2 and 33.3 μA/cm2. Small energy harvesting photoelectrochemical cells based on these photoactive proteins are fabricated and can be used to convert

natural or artificial light into voltages and currents for powering various microelectromechanical systems (MEMS) and microfluidic devices.

8615-29, Session 6

Instrument-free exothermic heating with phase change temperature control for paper microfluidic devices

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There is a great need to simplify nucleic acid-based assay systems so that they can be used in low resource settings in global health. Many infectious diseases, as well as some cancers that affect global health are most accurately diagnosed through nucleic acid amplification and detection.

Reliable electric power, as well as a lack of a sustained supply and maintenance chain for complex diagnostic instruments is a common infrastructure shortfall. Disposable-based assays requiring no instrument, such as immunochromatographic strip tests have been very successful in low resource settings, with hundreds of millions of such rapid diagnostic assays (RDTs) sold and used annually in developing countries; however, such assays generally work on the immunoassay principle and cannot be used to directly detect nucleic acids from pathogens or cancer cells. Instrument-free, low-cost chemical heating allows the design of disposable nucleic acid amplification assays that provide similar user characteristics as RDTs, but with much better sensitivity and specificity.

We present current status and results of work towards developing disposable, low cost, temperature-controlled heaters designed to support isothermal nucleic acid amplification assays that are integrated with paper microfluidic circuits. Heat is generated through exothermic chemical reactions, and the temperature is controlled by engineered phase change materials. By selecting appropriate exothermic and phase change materials, temperatures can be controlled over a wide range suitable for various isothermal amplification methods, and stabilized for over and hour, and at an accuracy of +/- 1 degree C.

The heaters are being integrated with a paper microfluidic system that serves as a platform for a variety of nucleic acid amplification assays for global health applications.

8615-30, Session 7

Laser guidance in a microfluidic biochip

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Laser-guidance technique has been demonstrated to be able to distinguish sub-cell types with very high sensitivity by simply measuring the guidance speed. Consequently, it has high potential to be applied in the field of cell sorting, which plays an important role in life science and clinical applications. Compared with conventional cell sorting methods, laser guidance based sorting technique is noninvasive and easy to control. It relies on the intrinsic optical properties of cells (e.g., refractive index, shape, and size). In this study, we develop a microfluidic chip to achieve cell sorting with the assistance of laser guidance. Polydimethylsiloxane (PDMS) is used to make the chip with soft lithography. It can be irreversibly sealed to a coverslip by a corona treater (ELECTRO-TECHNIC PRODUCTS, Inc., BD-20AC), creating a leakless microchannel. A single mode optical fiber is mounted into the PDMS chip to transmit the guiding beam (CW, 800 nm) into the chip. The cells, flowing in the microfluidic channel while being laser guided, are captured by a high-speed camera (Photon Focus MV1-D1312I). CUDA compatible GPU-Tesla 1060 and Quadro FX 1800 are utilized to assess the sizes and moving speeds of the cells and in real time with a imaging rate of approximately 130 to 170 frames per second. The experimental results demonstrate that different cells with the same feature (e.g., size, shap, etc.) can be effectively distinguished from each other by the difference of recorded speeds (the flow rate minus the guiding speed). This technique is expected to provide a new approach to high-throughput cell sorting with a high resolution.

8615-31, Session 7

Continuous cell lysis in microfluidics through acoustic and optoelectronic tweezers

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Micro total analysis systems offer the potential to speed up and simplify diagnostic procedures. The miniaturization of chemical and biological assays, where small sample volumes are used, is an important step towards point of care testing. In recent decades several strategies for sensing and analysing samples for specific biomarkers have been developed. However, improvements are needed for on chip sample preparation steps to ensure sensitive and selective detection. For instance, cell lysis, for cell content analysis or to enrich a particular cell type, has to be performed under appropriate conditions to allow subsequent sampling steps.

This work presents a novel, non-contact and electrolysis-free on chip strategy for lysing cells. In a continuous flow mode cells are concentrated and precisely positioned in a microchannel by applying an acoustophoretic force. A photoconductor embedded in the channel induces an electric field upon illumination and triggers the rupture of cells in the acoustic pressure node. Lysis efficiencies of 100% are obtained, with blood cells (106 cells/ml) traveling along a 40µm light pattern (at 50kHz and 20Vpk-pk) with cell lysis times of 0.2s. Furthermore, lysis is investigated using FEM simulations which indicate that the electric fields, generated under these conditions, induce transmembrane potentials high enough to promote rupture of the lipid bilayer (e.g. 1 V for red blood cells). We present a flexible tool for single or massive parallel lysis of cells with the potential to realize selective lysis of certain cell species based on their electrical or acoustic properties.

8615-32, Session 7

The same single cell bioanalyzer (SASCA) tracks the same single blood cancer cell over a long duration: simultaneous optical observation and fluorescent measurement

Avid Khamenehfar, Lukas-Karim Mehri, Paul C. Li, Simon Fraser Univ. (Canada)

We have constructed the microfluidics-based same single-cell bioanalyzer (SASCA) for tracking and measuring the same single particle such as a cancer cell. The glass chip designed for this experiment is composed of four channels, four reservoirs and one chamber containing the cell retention structure. The right and left reservoirs serve as the inlet and waste reservoirs, respectively; whereas, the top reservoirs are used for drug delivery. This instrument allows real-time monitoring of chemotherapy drug efflux from cancer cells with multidrug resistance (MDR) in response to the application of various MDR-inhibitors. This permits an accurate assessment for a particular patient to determine which MDR modulators will be the most effective. This instrument is compact and is suitable for measuring only a few cells in a rare cell population. It also provides simultaneous optical observation and fluorescent measurement. The use of a laser allows one to use a small spot size to measure the cell fluorescence related to drug retention. The SASCA was used in order to measure drug accumulation on the same AML cell in 2 steps. First, the accumulation of an anti-cancer drug in the single cell was measured in the absence of MDR inhibitors. Then, in the same cell, the drug accumulation is measured in the presence of a

P-glycoprotein (Pgp) or Multidrug resistance protein (MRP1) inhibitors. These measurements can be done on multiple single cells to increase throughput. We believe the SASCA will be helpful to determine the effectiveness of MDR cancer treatment of patients prior to chemotherapy.

8615-33, Session 7

Optimization of microfluidic trap-based microsphere arrays

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Microarray assay based devices are promising platforms for building lab-on-a-chip systems. However, the potential of these devices has yet to be fully realized due to the lack of systematic optimization for their design and implementation. In this work, we consider a trap-based microsphere array device by employing microfluidic techniques and a hydrodynamic trapping mechanism. We design a novel geometric structure of the trap array in the device, and develop a comprehensive and robust framework to optimize the values of the geometric parameters to maximize the microsphere arrays' packing density. We also simultaneously optimize multiple criteria, such as efficiently immobilizing a single microsphere in each trap, effectively eliminating fluidic errors such as channel clogging and multiple microspheres in a single trap, minimizing errors in subsequent imaging experiments, and easily recovering targets. We perform microsphere-trapping experiments using the optimized device and a device with un-optimized geometric parameters. These experiments demonstrate easy control of the transportation and manipulation of the microspheres in the optimized device. They also show that the optimized device greatly outperforms the un-optimized one by increasing the packing density by a factor of two, improving the microsphere trapping efficiency from 58% to 99%, and reducing errors from 48% to a negligible level (less than 1%). The optimization framework lays the foundation for the future goal of developing a modular, reliable, efficient, and inexpensive lab-on-a-chip system.

8615-34, Session 7

Multivariate analysis of apoptotic markers versus cell cycle phase in living human cancer cells by microfluidic cytometry

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Measurement of apoptotic markers in tumors can be directly correlated with the cell cycle phase using flow cytometry (FCM). The conventional DNA content analysis requires cell permeabilization to stain nuclei with fluorescent probes such as propidium iodide or use of a costly UV-exitation line for Hoechst 33342 probe. The access to FCM is also still limited to centralized core facilities due to its inherent high costs and complex operation.

This work describes development and proof-of-concept validation of a portable and user-friendly microfluidic flow cytometer (?FCM) that can perform multivariate real time analysis on live cells using sampling volumes as small as 10 microlitres. The ?FCM system employs disposable microfluidic cartridges fabricated using injection moulding in poly(methylmethacrylate) transparent thermoplastic. Furthermore, the dedicated and miniaturized electronic hardware interface enables up to six parameter detection using a combination of spatially separated solid-state 473 (10 mW) and 640 nm (20 mW) lasers and x-y stage for rapid laser alignment adjustment.

We provide new evidence that a simple 2D flow focusing on a chip is sufficient to measure cellular DNA content in live tumour cells using a far-red DNA probe DRAQ5. The feasibility of using the ?FCM system for a dose-response profiling of investigational anti-cancer agents on human hematopoietic cancer cells is also demonstrated. The data show that ?FCM can provide a viable novel alternative to conventional FCM for multiparameter detection of caspase activation and dissipation of mitochondrial inner membrane potential (??m) in relation to DNA content (cell cycle phase) in live tumor cells.

8615-35, Session 8

Programming paper networks for point of care diagnostics *(Invited Paper)*

Barry R. Lutz, Shivani Dharmaraja, Univ. of Washington (United States)

Diagnostic tests using body fluid samples are typically carried out in a well-equipped laboratory by an expensive instrument or a trained human. At the other end of the spectrum are simple paper strip tests, like pregnancy tests, that are easy-to-use and give fast results, but they are only capable of one-step chemical reactions, which limits access to many high performance testing methods. We are developing paper-based tests that can be "programmed" to carry out high performance multi-step protocols without an instrument at a cost and ease-of-use comparable to a pregnancy test. Here, we describe how we use electrical circuit analogies to program networks for multi-step reactions. The model is used to understand the effects of fluid sources and network design, and it is used to develop a strip-based design for multi-step fluid delivery.

8615-36, Session 8

Personal exposure assessment to particulate metals using a paper-based analytical device

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The development of a paper-based analytical device (PAD) for assessing personal exposure to particulate metals will be presented. Human exposure to metal aerosols, such as those that occur in the mining, construction, and manufacturing industries, has a significant impact on the health of our workforce, costing an estimated $10B in the U.S and causing approximately 425,000 premature deaths world-wide each year. Occupational exposure to particulate metals affects millions of individuals in manufacturing, construction (welding, cutting, blasting), and transportation (combustion, utility maintenance, and repair services) industries. Despite these effects, individual workers are rarely assessed for their exposure to particulate metals, due mainly to the exorbitant cost and effort associated with personal exposure measurement. Current exposure assessment methods for particulate metals call for an 8-hour filter sample, after which time, the filter sample is transported to a laboratory and analyzed by inductively-coupled plasma (ICP). The time from sample collection to reporting is typically weeks and costs several hundred dollars per sample. To exacerbate the issue, method detection limits suffer because of sample dilution during digestion. The lack of sensitivity hampers task-based exposure assessment, for which sampling times may be tens of minutes. To address these problems, and as a first step towards using microfluidics for personal exposure assessment, we have developed PADs for measurement of Pb, Cd, Cr, Fe, Ni, and Cu in aerosolized particulate matter.

8615-37, Session 8

Low-cost microsystems integrating sample treatment and electrochemical detection for the diagnosis of celiac disease through a combination of automated HLA typing and autoantibody measurement

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Disposable polymeric microsystems integrating sample processing and detection, with the only required end-user intervention being addition of a fingerprick blood sample, are reported. The microsystems have been developed for the diagnosis of coeliac disease based on the newly defined diagnostic criteria of a combination of HLA typing and the detection of total IgA, anti-tissue transglutaminase (IgA) and anti-deamidated gliadin peptide (IgG) autoantibodies. One microsystem integrates cell lysis, DNA extraction, amplification and direct detection of the PCR product and is used for medium resolution HLA typing to provide information on a patient's genetic predisposition to coeliac disease. Upon a positive output, another microsystem integrates generation of serum, metering, dilution, mixing and multiplexed quantitative detection of the relevant autoantibodies. This second microsystem is used for patient monitoring. Despite the fact that both microsystems have different functionalities, they have equivalent interfaces with a specifically developed reader instrument, facilitating that both microsystems can be used within the same instrument. The dedicated instrument exploits a CCD-camera for fluidic flow and represents a highly flexible fluidic control, moving towards the realisation of standardisation for microsystems. Arrays of 36 electrodes were cost-effectively fabricated via screen-printing and the surface chemistry with the coating antigen/DNA probe optimised to be stable for at least 18 months, whilst allowing for minimum non-specific binding and maximum signal. The assay from "bleed-to-read" takes less than 25 minutes for both microsystems and have a target sales costs of 12€ and 25€ for the serology and HLA-typing, respectively. Following completion of the assays, the results are encrypted and uploaded to the patient's electronic record on the health information server. The performance of the microsystems have been clinically validated using real patient samples at the point of care, and furthermore, sensors and dedicated instrument have also been applied to the diagnosis of other autoimmune diseases.

8615-38, Session 8

Piezoresistive pens for dip-pen nanolithography

Albert K. Henning, Joseph S. Fragala, Roger Shile, Pamela Simao, NanoInk, Inc. (United States)

DPN (dip-pen nanolithography) has found wide-ranging applications, from electronics to materials science to biology, at size scales from at small as 10 nm for dry ink printing, and several um for wet ink printing. Typically, DPN requires one pen for writing, and another for reading position, and reading what has been written. Also typically, optical lever means have been employed to determine vertical position for the reader pen. In this work, we present a novel approach to an integrated DPN pen. Piezoresistive silicon stress sensors are integrated into a silicon nitride cantilever. Connecting two such sensors on the cantilever, and two reference sensors off the cantilever, into a Wheatstone bridge, provides electrical readout of vertical pen displacement. For some of the pens, thermal actuators are also integrated, allow active pen control plus electrical vertical pen position readout. We will demonstrate the fabrication method for building these sensors, and sensor-actuators.

8615-39, Session 9

Rapid biochemical functionalization of technical surfaces by means of a photobleaching based maskless projection lithography process *(Invited Paper)*

Ansgar Waldbaur, Björn Waterkotte, Juerg Leuthold, Karlsruher Institut für Technologie (Germany); Katja Schmitz, Technische Univ. Darmstadt (Germany); Bastian E. Rapp, Karlsruher Institut für Technologie (Germany)

MEMS/MOEMS based systems are increasingly applied in the biological and biomedical context, e.g. in form of biosensors or substrates for monitoring biological responses (such as cell migration). For such applications, technical surfaces have to be provided with suitable biochemical functionalization. Typical functionalization procedures include wet-chemical techniques based on self-assembled monolayers of thiols on gold or silanes on glass. These processes create binary patterns and are often of limited use if spatially constrained non-binary patterns (such as surface bound biochemical gradients) have to be provided. In order to create gradients or patterns, methods such as direct spotting or dip pen nanolithography can be used. Here, gradients can be emulated by varying the spot density or the concentration of the solutions employed. However, these methods are serial in nature and are thus of limited use if large surface areas have to be patterned.

We present a technique to generate gradients of biochemical function by a lithography-based process allowing fast large-scale patterning. The process is based on photobleaching leading to light-induced coupling of a fluorescently tagged biomolecule to a technical surface by concerted bleaching of the fluorophore. We custom designed a maskless projection lithography system based on a digital mirror device that allows the rapid creation of 8-bit grayscale protein patterns on any technical surface from digital data (e.g. bitmap files). We demonstrate how this process can be used to obtain patterns of several cm? lateral size at micrometer resolution within minutes.

8615-40, Session 9

Development of a new selective biosensor for the early detection and diagnosis of nosocomial infectious pathogens

Ioanis Katakis, Bruno Teixeira-Dias, Univ. Rovira i Virgili (Spain); Pablo Lozano, Katia Uliaque, iMicroQ (Spain); Angel Gonzalez, Univ. Rovira i Virgili (Spain)

Hospital-acquired nosocomial infections represent one of the most difficult diagnosis and treatment challenges in infectious diseases. Many studies suggest that the timely administration of appropriate pathogen-specific therapy can constitute a lifesaving condition, avoiding by this way the application of wide spectra antibiotics in infected patients, which could promote resistance conditions for certain pathogens. Actually, for the detection and identification of these infectious agents, the public health system is organized in methodologies based in pathogen cultures, and in molecular methodologies. Unfortunately this methodologies are time and money dispending (normally its required 1-3 day for the pathogen identification, and till 7 days for characterize the resistance).

The objective of this study is to develop a new, fast, low-cost, reliable and high selective biosensor based in screen-printed carbon electrode for the identification of 6 different nosocomial pathogens from patient's samples, which could assure the absence of infectious pathogens in only 8 hours and the detection of 100 colonies forming units per milliliter (CFU/ml) in less than 30 min, improving a better and faster diagnostic. Till the obtaining and validation of the main objective (high selective biosensor), it's necessary to apply a complete microbiological study (pathogen capture, culture mediums for selective growth), immunological study (characterization of immune complexes), and electrochemical study (amperometric detection and identification of the pathogens, based in microbiological and immunological results).

8615-41, Session 9

Development of a micro in-situ oil detection device

Yuxuan Zhou, Wanjun Wang, Louisiana State Univ. (United States)

This paper will report a work in developing a new technology for improved detection associated with oil spills. The project's goal is to develop a highly sensitive and handheld instrument that can be used for in-situ detection of spilled oil. The device will have higher sensitivity, lower cost, easier to operate and maintain, and smaller size compared with the commercially available ones. The applications of the instrument are not limited to oil detection and may also be used to measure any organic samples that can be measured in fluoresce detection principle.

The system has a built-in sample extraction/pre-concentration function to eliminate external sample preparation kit. The oil detection is based on fluorescent detection principle. In its heart is a disposable, micro-sized detection cartridge with a built-in oil pre-concentration unit. It will also contain a micro-sized optic detection unit consisting of microlenses, micro-chamber for detection, and holders for optical fibers. The optic detection unit is integrated on the same substrate as the sample pre-concentration to form an integrated micro-fluidic-optic detection cartridge. All the components on the cartridge will be passive with no power requirement. This micro-cartridge can be replaced easily and disposable. All the active components such as UV light source, photodetector, power supplies, etc., are outside the cartridge and thus, do not require replacement for each test. The micro-cartridge can be easily interfaced to these active elements. The micro-cartridge was inexpensively fabricated through mass production using micro-replication method. It can be disposable and eliminates the problem of cleaning and contamination as in a permanently assembled fluidic device. A small dimension bench top model was built and tested to demonstrate feasibility. Promising preliminary results have been obtained.

8615-43, Session 10

Electrochemically actuated passive stop-go microvalves for flow control in microfluidic systems *(Invited Paper)*

Ioanis Katakis, Alemayehu Washe, Diego Bejarano Nosas, Univ. Rovira i Virgili (Spain); Pablo Lozano, iMicroQ (Spain); Bruno Teixeira-Dias, Univ. Rovira i Virgili (Spain)

The ability to precisely control timing of flow at a specific location in microchannels is key to microfluidics in many lab-on-a-chip applications, particularly in applications where mixing or incubation is entailed by sluggish kinetics of biological reactions.1 Flow control is provided using a combination of pumps and valves. A wide range of active and passive methods for generating flow of liquids within networks of channels, or to position liquids within arrays have been proposed.2 Active methods generally rely on electrokinetic phenomena driven by high voltages (several kilovolts), pneumatic pumping, electrochemical reaction and actuators that are complicated to fabricate and too expensive to be disposable. Alternatively, capillary flow has been used as a passive pumping mechanism with the driving force simply originating from the combination of microchannel surface energy and geometry.1 The challenges of using capillary driven (CD) flow whilst having attractive features including simplicity to fabricate and integrate, low cost, portability, low dead volume and zero power consumption, is ascribed to its being typically laminar (poor mixing) due to the low Reynolds number of the microchannel. On the other hand, the dependence of capillary flow on surface energy provides attractive opportunity for on-chip manipulation of the motion of liquid because surface energy can be modulated by electrical,3 photochemical,4 thermal,5 electrochemical,6 or by direct hydrophobic-hydrophilic7 patterning of the surface. All of these techniques require structuring of the surface to provide it desirable electrical, photochemical or thermal properties. Current methods of surface structuring such as lithography or micromachining involve expensive and time consuming fabrication steps and actuation techniques that limit miniaturizability and applicability of the devices thereof for real time flow control in microfluidic devices. While electrical control of surface energy (electrowetting) has advantages, including miniaturizability, simplicity and absence of moving parts, its effective implementation requires surfaces with unique sensitivity for electrical stimuli to allow low voltage electrowetting mechanism. Herein we report an on-off microfluidic control through the combination of patterned surface energy and low voltage electrochemically actuated passive stop-go microvalves. Two closely spaced highly porous superhydrophobic graphitic carbon electrode, Figure 1-E2, and the other wettable electrode (carbon or silver, Figure 1-E1) when incorporated into a microchannel constitute the electrochemically actuated passive stop-go microvalve. The superhydrophobic conductive surface was fabricated by amplification of the roughness of a naturally hydrophobic (water contact angle, CA= 1100) screen printed carbon surface by a two step original method involving simple dipping of the electrode surface in a judiciously selected organic solvent (N, N-dimethylformamide) for just minutes for selective etching followed by drying to produce a porous superhydrophobic surface (CA ?1500, Figure 2). The relatively hydrophilic entry part and E1 surface of the built plastic based microchannel (depth x width x length = 100 µm x 300µm x 5 cm) containing the microvalves allowed autonomous CD flow of aqueous electrolytic liquid until it reached E2, the passive stop valve (PSV), where it stopped until stimulated to resume by application of a potential. Application of a potential (?1V) across the two electrodes causes a fast response (2.5 sec) of the liquid crossing the PSV to the CD flow zone ahead; which is consistent with the voltage dependent large contact angle changes recorded in the in-situ electrowetting experiments, Figure 3. The ultra sensitivity of the valve to the applied extremely low voltage is proposed to be ascribed to the high capacity of large surface area porous electrode which facilitates the interfacial energy modulation and the energetically driven wettability transition from a metastable less wetted Cassie-Baxter to a complete wetting via Wenzel regime, Figure 4. The porosity and capacitive behavior of the electrode surface was characterized using scanning probe microscopy, electrochemical impedance spectroscopy and nitrogen adsorption-desorption experiments. This approach, in addition to the aforementioned advantages of electrowetting, uses extremely low voltage and is applicable directly to miniaturized microfluidic systems such as in point-of-care applications.

8615-45, Session 10

An all-at-once factorial method to optimize dip-pen deposition of liquid protein inks

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Protein arrays for disease assay, and pharmaceutical development, are a recent advancement taking off from genomic array successes.

Dip-pen methodologies enable droplet array printing with small volumes, needed for proteins. Array evaluation demands small coefficients of variation (CV%). Droplet diameters down to 0.5 um can be printed. A wide range of protein inks may be printed. Each has unique fluid characteristics (surface tension, contact angle, and evaporation rate). Even with external condition control, liquid transfer from pen to surface can vary dramatically. Easy optimization of pen designs therefore becomes desirable, in order to make best ink use.

Here, an all-at-once factorial method is presented which optimizes protein ink deposition pens. Pen features associated with capillary ink transport are varied according to statistical design-of-experiment principles, and evaluated using a special 1D pen array. Variable parameter pens are bracketed by control pens. Each pen array element embodies one component of the SDOE matrix. All parameters are evaluated simultaneously with a single droplet writing pass. Results can also be evaluated simultaneously, leading to rapid choice of pen parameters which deliver the greatest number of printed features having the smallest coefficient of variation.

8615-47, Session 10

Integrated Fabry-Pérot sensors and separation columns for micro-gas chromatography

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The increasing need for on-site volatile organic compound detection has led to intense development of micro-gas chromatography (?GC) components. Traditionally, ?GC systems feature stand-alone sensors and columns that are then connected together. While this is easy to fabricate; it results in an increased footprint, and dead volumes and hence a reduction in separation efficiency. Here, we have developed a monolithic subsystem that incorporates Fabry-Pérot (FP) sensors and a separation column on a single silicon chip. The device was fabricated using deep reactive ion etching of silicon to create fluidic channels and polymers were deposited on the same silicon chip to act as a stationary phase or a sensor. The deposited polymer behaves as an FP interferometer whose characteristic interference pattern is affected by the adsorption of an analyte. The device was connected to the injection port of a standard GC, and a 785 nm laser was used to interrogate the sensor. A CMOS imager was used to record the intensity change in reflected light as the sensing signal. With this system, we show that the sensors have detection limits of about 30 picograms with sub second response times. Multiple FP sensors formed by different sorptive polymers are exhibited to respond to a mixture of analytes separated by the integrated separation channel, allowing for the construction of response patterns, which, along with retention time, can be used as a basis of analyte identification.

8615-9, Session PTue

Transdermal extraction and measurement of interstitial fluid based on a microfluidic system

Haixia Yu, Dachao Li, Yongjie Ji, Kexin Xu, Tianjin Univ. (China)

Diabetes is a global epidemic forcing millions of people to regularly measure their blood glucose levels. The transdermal interstitial fluid (ISF) extraction technique through the use of ultrasonic pretreatment and vacuum to enhance skin permeability offers promise of non-invasive, continuous, and real-time glucose monitoring, but unfortunately only a minute volume of ISF is extracted and scatters on the skin surface, making it unsuitable to be collected and measured with macroscale systems. Furthermore, skin permeability varies with time, requiring precise ISF volume measurement in order to calculate the blood glucose concentration accurately. In this paper, an integrated microfluidic system for the automatic extraction, collection and volumetric measurement of transdermally extracted ISF is developed. This device consists of a venturi tube generating vacuum for ISF extraction and fluid manipulation, pneumatic valves for fluid management, and a novel volume sensor for normal saline input volume control and ISF volume measurement. The system is fabricated from five polydimethylsiloxane (PDMS) layers using standard SU-8 micromolding techniques. After molding, the five PDMS layers are aligned and bonded together using oxygen plasma. Under the management of pneumatic valves and using the 95kPa vacuum force generated from the venturi tube, this system has been shown to successfully manipulate fluid transport in the system and extract “ISF analogue” through ultrasound pretreated full-thickness pig skin. A novel integrated volume sensor has been demonstrated which is capable of consistently measuring the volume of extracted ISF. The absolute error of the volume measurement is less than 0.05?L. And the volume measurement results correlate well (R2=0.9993) with those calculated with the measured glucose concentration.

8615-42, Session PTue

A portable instrument based on micro-fluidic chip and micro glucose sensor for glucose continuous monitoring by interstitial fluid transdermal extraction

Yongjie Ji, Dachao Li, Wenshuai Liang, Tianjin Univ. (China)

The continuous glucose monitoring technology based on transdermally extracted interstitial fluid (ISF) is a hot research topic recently. Limited by the low skin permeability, only a minimal volume of ISF can be transdermally extracted, and the scattering distributions of the extracted ISF make the collection and transport very difficult. Based on a micro-fluidic chip for ISF transdermal extraction and a micro sensor for glucose concentration measurement, a minimally invasive blood glucose monitoring micro instrument was developed in this paper, which aimed at realizing the transdermal extraction, collection, transport, volumetric detection and glucose concentration measurement of the minimal volume of ISF. In this work, various parts of the device and their interface circuit were designed; the hardware and software of the micro instrument were built; the simulating experiment of transdermal ISF extraction, collection and volume detection with full-thickness pig skin was performed using this integrated system; and the functionality of this device was verified. In the experiment, driven by 95 kPa negative pressure which was generated by the internal venturi of this instrument, the system continuously and automatically realized the functions of defined volume normal saline injection, normal saline (with different glucose concentrations) extraction through low frequency ultrasound pretreated pig skin, lossless collection of the sample solution. Finally the total functionality of this device was verified for future clinical applications.

8615-48, Session PTue

Optofluidic spectrometer and scanner

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Optofluidic devices are being used in different fields of science and technology. Among optofluidic elements are lenses, apertures, refractometers, pressure meters, and more. Here we present two new optofluidic devices: a spectrometer and a scanner. The former is made of an optofluidic lens and a standard blazed grating. The lens carries a fluid with some unknown substance. After the lens a blazed grating diffracts the light focused by the lens. At the focal length a CCD can be used to collect the spectrum and send it to a computer for analysis. There are several methods which can be used to scan a light beam. Most of them comprise the use of electronic devices and moving optical parts like mirrors. Here we suggest the use of two hollow prisms to perform the X – Y movement. Hollow prisms are embedded in silicone. The beam movement can be done by changing the liquid contained in the hollow prisms. Each liquid will present a different refractive index. One prism will perform the beam movement in one direction and the other in the perpendicular one. Thus a X –Y scan can be achieved.

8615-49, Session PTue

Dynamic analysis of angiogenesis in transgenic zebrafish embryos using a 3D multilayer chip-based technology

Jin Akagi, Feng Zhu, Chris Hall, The Univ. of Auckland (New Zealand); Khashayar Khoshmanesh, Kourosh Kalantar-Zadeh, Arnan Mitchell, RMIT Univ. (Australia); Kathryn Crosier, Philip

Crosier, Donald Wlodkowic, The Univ. of Auckland (New Zealand)

Transgenic zebrafish (Danio rerio) models of human diseases have recently emerged as innovative experimental systems in drug discovery and molecular pathology. Despite some progress in robotic liquid handling, the dispensing, treatment and analysis of zebrafish embryos is still largely labour-intensive and not easy suceptible to laboatory automation. None of the currently available technologies allow for automated immobilization and treatment of large numbers of spatially encoded transgenic embryos during real-time developmental analysis.

This work describes the proof-of-concept design and validation of a 3D multilayer microfluidic chip-based system fabricated directly in the poly(methyl methacrylate) transparent thermoplastic using infrared laser micromachining. In contrast to any previously described technologies, our 3D microfluidc device creates a dynamic embryo array. It can automatically: (i) transport embryos, (ii) immobilize individual embryos using negative pressure for a high-resolution fluorescsent imaging, (iii) continuously deliver medium and drugs under perfusion during time-resoved microscopic examination, and also (iv) retrieve specimens post-analysis for further processing. The microfluidic system was designed as a monolithic and fully integrated device with no moving parts.

Our results show that the innovative device has 100% embryo trapping efficiency while supporting normal embryo development for up to 72 hours in a confined microfluidic environment. We also present data that this microfluidc system can be readily applied to kinetic analysis of a panel of investigational anti-angiogenic agents in transgenic zebrafish Tg(fli1a:EGFP) line. The optical transparency and embryo immobilization allow for convenient visualization of developing vasculature patterns in response to drug treatment without the need for specimen re-positioning.

8615-50, Session PTue

Huge volume fluorescence sensors for parallel measurement in multichannel microfluidic devices

Georg Meineke, David Flitsch, Achim Lenenbach, Reinhard Noll, Fraunhofer-Institut für Lasertechnik (Germany)

In the present work we investigate different approaches for fluorescence sensors which enable multistep sorting devices with several sorting stages in a row. The sensors presented are highly parallelizable, can be adjusted to different channel geometries, and, thanks to MEMS micromirror arrays, several sensors can be integrated in one microfluidic system. The study concentrates on fluorescence sensors for microfluidics with no hydrodynamic focusing for reducing the problem of growing flow rate with each sorting stage. As a consequence the detection volume has to cover the entire cross-section of the channel. The sensors are realized by a diode laser beam focused by miniaturized optics. The fluorescence light is collected collinear to the laser beam and measured by a SPAD. The detection volumes are scanned with immobilized fluorescence labeled beads and the applicability of the sensors in different channel geometries is qualified by measuring labeled beads and dyed mortified bacteria in suspension. Channel widths of up to 400 µm are addressed by an elliptic detection beam with a maximum aspect ratio of 70:1. Using integration times from 0.1 ms to 1 ms signal-to-noise ratios ranging from 660 to 2420 are reached.

8615-51, Session PTue

Blister pack bonding process and its relationship with reagents flow pattern

Aabed S. Saber, Brian W. Anthony, Massachusetts Institute of Technology (United States)

In lab-on-a-chip products “blister packs” are a means of storing and delivering the liquid reagent. This work focused on optimizing the bonding process of the blister pack to the backbone (the product component that blister pack sits on). Also, the relationship between the bond strength and the reagent flow pattern is studied. Experiments were designed where independent variables were the heat sealing parameters (pressure, temperature and dwell time) and accelerated aging and the dependent variables were bond strength and the reagent flow pattern. Experiments showed that optimal heat sealing parameters are: a pressure of 4.5 psi, a temperature of 210o C and dwell time of 2.0 seconds, which yielded bond strength of 10.5 Newton/mm. Results showed that bond strength drop for accelerated-aged samples was not significant. In addition, undesired flow patterns tended to go away with higher bond strength between the blister pack and the backbone.

8615-52, Session PTue

Microfluidic microsphere-trap arrays for simultaneous detection of multiple targets

Xiaoxiao Xu, Washington Univ. in St. Louis (United States); Zhenyu Li, The George Washington Univ. (United States); Arye Nehorai, Washington Univ. in St. Louis (United States)

Microsphere arrays are useful to detect, identify, and quantify biological targets such as mRNAs, proteins, antibodies, and cells. We design a microfluidic array of traps for diverse-size microspheres. This array enables simultaneous, efficient, and accurate screening of multiple targets on a single platform. Different target types are captured on the surfaces of the microspheres with different sizes. We optimize the geometric parameters of the microfluidic hydrodynamic traps to immobilize the microspheres of different sizes at different regions. Thus, the targets are detected according to the microspheres’ positions (position-encoding). This simplifies the screening and avoids errors in target identification. We test the design through fluid-dynamic simulations and microsphere-trapping experiments on the fabricated device, for microspheres of two sizes. The results demonstrate that our device achieves the position-encoding of the microspheres with negligible fluidic errors. The proposed device is promising for simultaneous detection of multiple targets as an inexpensive and fast disease diagnostic tool.

8615-53, Session PTue

Electrochemical (bio)sensors for detection of biochemically relevant liver parameters

Ciara K. O’Sullivan, Alex Fragoso, Carmen Bermudo, Nick Daskalakis, Univ. Rovira i Virgili (Spain)

The liver supports almost every organ in the body and is a complex organ with numerous vital functions in synthesis, detoxification and regulation; its failure therefore constitutes a life-threatening condition and it can either occur without preceding liver disease. Liver failure (LF) can be effectively treated by liver transplantation with good long-term outcomes, but this course of action is very limited by the number of donor organs. As consequence, in many cases are required alternative support technologies which, although there are no curative treatments, could provide safe and support to improve the quality of life of patients as well as enhance the quality of medical treatment and management, reduce the incidence and duration of hospitalization and consequently reduce the health economic burden of chronic liver disease.

The present work is part of a European project where the effort is focus on the development of physiological, wireless, wearable and unobtrusive sensors to monitor biochemical (e.g. electrolytes, small molecules, clotting) and/or physiological parameters (e.g. heart rate, skin body temperature, blood pressure) associated to LF

In particular we focus on the development and integration of a sensor for detection of albumin and coagulation using impedance measurements, as well as enzymatic sensors for detection of bilirubin, creatinine and bile acids, all of them important biochemical parameters of the liver. We also describe the development of first prototype detection arrays and their characterisation.

This work has been carried out with financial support from the

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Commission of the European Communities, ICT-enabled, cellular artificial liver system incorporating personalized patient management and support (d-LIVER), Grant Agreement no. 287596. It does not necessarily reflect its views and in no way anticipates the Commission's future policy in this area.

8615-54, Session PTue

Enhanced electrochemical detection of nucleic acids via nanostructuring using lyotropic liquid crystalline phases

Ciara K. O'Sullivan, Thomas Esterle, Samuel Dulay, Pablo Lozano, Univ. Rovira i Virgili (Spain)

The terroristic attacks with non conventional weapons as the B-agents attacks in the US of October 2001, or the avian flu of recent years in Asia and Europe, or finally the present swine flu demonstrate not only the limited capacities of the different national analytical labs, but also highlights the handling of such major threats and the proper response to them being massively hindered by the lack of rapid, safe and portable detection and identification methods to securely determine an infection or contamination of people, animals, food or sensitive infrastructure.

Most of the presently available commercial detection methods for biological pathogens are based on three fundamental methods and have different drawbacks. Microbiological and immunological procedures are usually quite cost-efficient, but can only be carried out within a suitably equipped laboratory infrastructure. Furthermore, they are time-consuming and not very sensitive. Analytical instruments based on nucleic acid detection are very specific with respect to the different biological pathogens and also very sensitive, but usually they cannot be used in a mobile environment, are time-consuming and complex, and can only be handled by trained staff. Analysis times are still in the 1 – 2 hours range, which is unacceptable in critical situations like those involving victims of B-agents.

Financed under the FP7 European framework since 2011, the project MULTISENSECHIP (http://www.multisense-chip.com/) aims at the identification and detection of biological pathogens via a portable integrated system delivering a rapid response at a molecular and immunological level. This system includes the detection reactions, PCR and immunoassays, and the extraction of the target molecules for the sample preparation performed on lab-on-a-chip devices. The detection techniques for the sensor technology are based on electrochemical methods, electrochemiluminescence or fluorescence. The automation of the steps from the transfer to the uptake of the sample avoids manual handling though compelled in a laboratory. The concept of the sample-in-result-out offers not only a rapid detection of multiple biological pathogens but also in the field with a minimum of human operations.

Our study details the electrochemical detection of single stranded DNA of Francisella Tularensis. The immobilisation of biomolecules on the electrode surface plays an important role in the overall performance of biosensors, and specifically for DNA it is critical to control the orientation, spacing and density of a DNA probe. To date, self-assembled monolayers of DNA probes has been widely reported for probe immobilisation due mainly to its simplicity. However, the adsorption of the thiolated DNA on a gold substrate can produce a high surface packing density of the DNA probes affecting the overall efficiency of the biosensor. Several strategies have been reported to obtain a controlled surface probe density, including co-immobilisation and backfilling. A novel route for obtained a nanostructured surface for a controlled immobilisation of the DNA probes was explored using lyotropic liquid crystalline phases as templates. Different lyotropic phases (Figure 1) were evaluated and the phase of most interest was the hexagonal phase, which features surfactant molecules forming micellar rods organised into an hexagonal lattice. DNA probes are attached on the electrode surface with a regular space between them over a long-range lattice. The electrochemical response of the electrode modified with DNA probes using a template was enhanced by seven orders of magnitude (Figure 2). The results can be explained by the space between the DNA probes whereby the path of the electrons to electrode surface is facilitated.

8615-55, Session PTue

Ultrasensitive electrochemiluminescent detection of biological pathogens at molecular and immunological level

Ciara K. O'Sullivan, Mabel Torrens, Thomas Esterle, Mayreli Ortiz, Univ. Rovira i Virgili (Spain); Rainer Gransee, Institut für Mikrotechnik Mainz GmbH (Germany); Diego Bejarano, Univ. Rovira i Virgili (Spain); Julian Höth, Achim Breitruck, Institut für Mikrotechnik Mainz GmbH (Germany)

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Here we present novel platforms for the point-of-care detection of biological pathogens at molecular (Francisella Tularensis) and immunological levels (lipopolysaccharide antigen) using electrochemiluminescence (ECL) detection. ECL is a process whereby species generated at electrodes undergo high-energy electron-transfer reactions to form excited states that emit light. ECL is an electrochemical detection method enabling to measure low concentrations of samples down to the picomolar level. In this work, the ECL setup includes the detection reactions, PCR and immunoassays, and the extraction of the target molecules for the sample preparation performed on lab-on-a-chip devices (Figure 1).

The general strategy involves the linking of ruthenium derivative labelled DNA capture probe to the grafting diazonium salt modified with a carboxylic group via streptavidin – biotin interactions. This probe can hybridise the DNA target in a 'sandwich'-type format. A secondary DNA probe labelled with a quencher is used to suppress the ECL signal (Figure 2a, "switch-off" approach). The second approach is also based on a sandwich assay with a secondary probe labelled with a ruthenium complex to give the ECL signal (Figure 2b, "switch-on").

When DNA probes are immobilized on the surface, the ECL response is lost after the first excitation and cannot be retrieved, probably due to the stripping off the DNA probes or a much lower signal after the first excitation. As high potentials should be applied to excite the active center, the presence of a robust biorecognition surface is compulsory. A diazonium layer was successfully immobilised to provide a strong bond between the DNA probes and the electrode surface. However, solutions need to be put forward in order to amplify the ECL signal to reach a higher sensitivity. Different approaches have been suggested: either developing nanostructures on the electrode surface or modifying the ruthenium complex, to enhance the ECL signal through a resonance energy transfer mechanism, as well as emitting light more efficiently at a lower applied potential of excitation.

8615-56, Session PTue

Multi-responsive water microdroplet adhesions on a superhydrophobic surface

Daisuke Ishii, Nagoya Institute of Technology (Japan)

In nature, many functional superhydrophobic surfaces have been observed such as lotus leaves, rose petals and morpho butterflies. We focused the functions of rose petals composed of nano-micro structured surfaces, showing not only strong water repellency but also size-selective adhesion of water microdroplet. Our group has reported that superhydrophobic surfaces composed of polymer pillar arrays are obtained by peeling off the top layer of honeycomb-patterned porous films (honeycomb films) prepared by self-organization process. Furthermore, high adhesive superhydrophobic surfaces composed of metal-dome/polymer-pillar hybrid structures are obtained by metal deposition into several pores of the honeycomb film before peeling process. In this report, we fabricated a superhydrophobic structured surface showing multi-responsive water microdroplet adhesions prepared from the polystyrene honeycomb film. Multi-responsive polymer domains composed of polyallylamine skeleton severally modified with glycidyl isopropyl ether were introduced into the polystyrene superhydrophobic surface. Adhesions of water microdroplets on the surface were controlled by changes of surface temperatures; pinning at low temperature and rolling at high one (>30?), and pH of water droplets; pinning at low pH and rolling high one (>8.3). Responsivity of water droplet adhesions on the surface was accurately regulated by components of the responsive molecules and surface microstructures such as amounts and sizes of the responsive domains. Such surfaces will be expected for novel application of microfluidics devices in order to manipulate water droplet under various environments by facile external stimuli.

8616-101,

Towards Future Systems with Nano-Optics Contributions

Bozena Kaminska, Simon Fraser Univ. (Canada)

The long anticipated deployment of nano-optics and nanotechnologies that enable ubiquitous computing has now encountered several practical impediments that delay adoption for demanding business processes. However, the global market in nano-enabled products is expected to grow to over $80B within the next 3 years.

In response, the research community is creating enabling solutions to overcome such challenging issues as reliability and cost-effective fabrication. New approaches for sensing, continuous uptime powering, and post silicon manufacturing will maximize overall performance and allow unprecedented business applications.

This presentation reviews present limitations of nano-optics and then considers the new generation of devices and their manufacturing that will be able to turn the envisioned promises into reality. It will highlight several recent innovations: high sensitivity/selectivity sensing nano-optical devices; sustainable power from photo polymer energy harvesting and storage; permanent color-mark signatures embedded in trustworthy documents for visible authentication; and master nano-hole templates for high-volume manufacture.

The shared roots of these enabling technologies are nano-optics: surface plasmonic 3D devices, nano-particle polymers, and fabrication of nano-scale holes and pillars to create custom iridescent signatures. Related nano-technologies can be applied to biomedical sensors, authentication keys, and self-powering solutions for individualized use across multiple industries. Related business case examples will be reviewed.

8616-102,

MOEMS Pressure Sensors for Geothermal Well Monitoring

Aaron J. Knobloch, GE Global Research (United States)

The technology for enhanced geothermal systems (EGS), in which fractures connecting deep underground wells are deliberately formed through high pressure stimulation for energy generation, is projected to enormously expand the available reserves of geothermal energy in the U.S. EGS could provide up to 100,000 MWe within the U.S. by the next 50 years. Nevertheless, there are still many challenges to understand and develop this resource for low cost energy production. In particular, there are a variety of parameters that one would like to measure within the geothermal well, both during stimulation and for long term monitoring, including temperature, acoustic strain, flow, pH, and pressure. Pressure measurements, in particular, are important for determining the state of the fluid, i.e., liquid or steam, the fluid flow, and the effectiveness of the well stimulation. However, it has been especially difficult to accurately measure pressure at temperatures above ~200 C.

MEMS technology has been employed for many years for extremely accurate pressure measurements through electronic readout means. By substituting optical readout of a sensor at the end of a fiber optical cable, it is possible to employ these highly accurate sensors within the harsh environment of geothermal wells. A two year, DOE-funded project has developed MEMS-based sensors specifically for this purpose. A multidisciplinary team of researchers from GE, QOREX LLC, AFL Telecommunications and Sandia National Labs developed the MEMS optical sensor and readback electronics, fabricated a fiber optic cable for downhole testing, and has scheduled a field test of the sensor in a geothermal well.

The sensor has been tested in the laboratory for temperature and pressure response and accuracy, reliability and survivability at temperatures up to 400 C and for hydrogen darkening of the fiber at high temperature and pressure. Resonant frequencies of the sensors vary between ~15 kHz and 90 kHz depending on sensor design, and laboratory measurements yielded sensitivities of frequency variation with external pressure of 0.9-2.2 Hz/psi. The sensors were calibrated up to 260 C with 0.1% accuracy, with operation to even higher temperatures possible. An opto-electronic feedback loop was designed and implemented. To mitigate the effects of hydrogen diffusion into the fiber with subsequent large absorption losses and reduction of mechanical strength, a comprehensive survey and evaluation of the specialty fiber was performed prior to fabrication of the cable. http://www1.eere.energy.gov/geothermal/enhanced_systems.html

8616-1, Session 1

Optical probe design with extended depth-of-focus for optical coherence microscopy and optical coherence tomography

Seungwan Lee, Minseog Choi, Eunsung Lee, Kyu-Dong Jung, Jong-hyeon Chang, Woonbae Kim, Samsung Advanced Institute of Technology (Korea, Republic of)

In this paper, design of an optical probe system for optical coherence tomography (OCT) and optical coherence microscopy (OCM) is presented. In order to control the back focal length from 4 mm to 26 mm the probe is designed using two varifocal lenses, one tunable iris and several glass/plastic lenses. The driving mechanism of the tunable iris and varifocal lenses is digital microelectrofluidics. The narrow depth of focus (DOF) in microscope is extended by using a phase modulation filter such as cubic filter. The filter is designed in the way that only the annu-lar portion has filtering function so that it only has an effect on the DOF for OCM mode not for OCT mode. The selection of the mode is carried out by a tunable iris. Design result shows that the probe dimension is less than 4 mm in diameter and less than 60 mm in length. The transverse and the depth scanning range of the light beam is 2 mm by 2 mm for OCT mode and 230 ?m by 2 mm for OCM mode.

8616-2, Session 1

Multi-wafer bonding technology for a 3D micro-optical lens scanner

Christophe Gorecki, Sylwester Bargiel, Nicolas Passilly, Maciej Baranski, FEMTO-ST (France); Maik Wiemer, Chenping Jia, Jörg Frömel, Fraunhofer-Institut für Elektronische Nanosysteme (Germany)

Three dimensional scanning of focused light is a basic function for many photonic applications because one can focus light on arbitrary points located in 3D space. A miniaturized 3D scanning module with low power and low cost can enable very challenging and exciting optical MEMS applications such as high throughput 3D imaging with array of MEMS microscopes with special emphasis to optical coherence tomography (OCT), on-chip confocal microscopy or endomicroscopy.

This work describes the construction and technology of an optical, millimeter-size 3-D microscanner, which is a key-component for a number of scanning imaging microsystems, such as optical coherence tomography (OCT) probes for micro endoscopy or on-chip confocal microscopes. The construction of the device relies on vertical integration of silicon, glass and ceramic building blocks, which are mechanically and electrically connected on the wafer level only by anodic bonding. The silicon was used for fabrication of electrostatic X-Y and Z microstages. The glass substrates were used to fabricate microlenses - two scanning microlenses were integrated onto movable platform of X-Y and Z microstages to provide well controlled deflection of laser beam, whereas one microlens was monolithically integrated within glass bottom lid for focusing purposes. In addition, glass substrates encapsulated the whole device while ensuring the optical transparency through the stack. Required distance between silicon components was achieved by use of a spacer, made of bondable low temperature co-fired ceramic (LTCC).

In order to drive electrostatic microactuators, sandwiched between glass

and ceramic components, the technology of through wafer vias (TWV) was applied to create electrical connections through a stack of two SOI wafers, one glass wafer and one ceramic wafer. Vias on different levels were connected by use of pressed-type pads during sequential multi-level anodic bonding.

In this work we present bonding/connection technologies that are of general importance for developing of various silicon-based devices based on vertically integration scheme. This approach offers space-effective integration of complex MOEMS devices and the effective integration of various heterogeneous technologies.

8616-3, Session 1

Electrostatic MEMS resonating micro polygonal scanner for circumferential endoscopic bio-imaging

Xiaojing Mu, Guangya Zhou, National Univ. of Singapore (Singapore); Hongbin Yu, Julius Ming-Lin Tsai, A*STAR Institute of Microelectronics (Singapore); Wee Keong Neo, A. Senthil Kumar, Fook Siong Chau, National Univ. of Singapore (Singapore)

An electrostatic actuation based resonating microelectromechanical systems (MEMS) polygonal micro-scanner is developed for endoscopic probes used in clinical investigations. In this paper, the proposed endoscopic optical coherence tomography (EOCT) probe utilizes multiple parallel incident light beams to drastically reduce the required mechanical rotation angle to achieve 360-degree circumferential scanning. In our configuration, this compact MEMS micro-scanner is placed at the distal side of the endoscopic probe and orientated perpendicularly to the incident light beams. A micro-pyramidal polygon reflector with eight highly reflective facets is mounted on top of MEMS micro-actuators to redirect the focused light. An eight-pieces-in-one fiber-pigtailed GRIN lens bundle is utilized to direct the focusing incident light beams to the slanted facets of the micro-reflector. Once the micro-reflector is driven to rotate, a circumferential light scan will be realized. A circumferential tissue image may be reconstructed by recording the data from the eight fiber optic "channels" sequentially or simultaneously. Micro-assembly technology is utilized to construct this device, which consists of a micro-actuator with four sets of electrostatic comb-drives and a pyramidal polygonal micro-reflector. The pyramidal polygonal micro-reflector is developed using the high precision diamond turning and soft lithography molding technologies. An optical scan angle of near-360 degrees is achieved at a resonant frequency of 180 Hz when driven by electrostatic comb-drive resonators with 80 Vpp ac voltage. This MEMS device provides an alternative for endoscopic optical coherence tomography (EOCT) applications owing to its advantages of circumferential imaging capability, fast scanning speed and low operational power consumption.

8616-4, Session 1

A water-immersible 2-axis scanning mirror microsystem for ultrasound and photoacoustic microscopic imaging applications

Chih-Hsien Huang, Texas A&M Univ. (United States)

Fast scanning is highly desired for both ultrasound and photoacoustic microscopic imaging, whereas the liquid environment required for acoustic propagation limits the usage of traditional MEMS scanning mirrors. Here, a new water-immersible scanning mirror microsystem has been designed, fabricated and tested. To achieve reliable underwater scanning, flexible polymer torsion hinges fabricated by laser micromachining were used to support the reflective silicon mirror plate. Two efficient electromagnetic microactuators consisting of compact RF choke inductors and high-strength neodymium magnet disc were constructed to drive the silicon mirror plate around a fast axis and a slow axis. The performance of this water-immersible scanning mirror microsystem in both air and water were tested using the laser tracing method. For the fast axis, the resonance frequency reached 224 Hz in air and 164 Hz in water, respectively. The scanning angles in both air and water under ±16 V DC driving were ±12?. The scanning angles in air and water under ±10 V AC driving (at the resonance frequencies) were ±13.6? and ±10?. For the slow axis, the resonance frequency reached 55 Hz in air and 38 Hz in water, respectively. The scanning angles in both air and water under ±10 V DC driving were ±6.5?. The scanning angles in air and water under ±10 V AC driving (at the resonance frequencies) were ±8.5? and ±6?. The feasibility of using such a water-immersible scanning mirror microsystem for scanning ultrasound microscopic imaging has been demonstrated with a 25-MHz ultrasound pulse/echo system and a target consisting of three optical fibers.

8616-5, Session 2

Quasistatic microscanner with linearized raster scanning for an adaptive 3D-laser camera *(Invited Paper)*

Thilo Sandner, Thomas Grasshoff, Markus Schwarzenberg, Harald Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Andreas Tortschanoff, Carinthian Tech Research AG (Austria)

We present advanced MEMS scanning mirror developed for the novel concept of an adaptive 3D TOF laser camera with foveation properties to allow e.g. future autonomous robots to better interact with their surroundings. The sensor concept of foveation - that is acquiring distance images with coarse spatial resolution, rapidly detecting regions of interest (ROI), and then concentrating further image acquisition on these ROIs with adaptive scanning – requires a challenging 2D scanning device with quasi-static actuation, large effective aperture ≥ 5mm and > 60° FOV. The best technical compromise of the fast adaptive scanning unit were found in a synchronized driving of multiple raster scanning MEMS mirrors to meet opposite requirements of fast scanning (> 1000Hz), large scan range and large effective mirror aperture. Therefore we developed a quasi-static resonant MEMS raster scanning mirror, were vertical comb drives enables a quasi-static deflections of ±10° and with driving control a linearized scanning bellow its eigen frequency of 125Hz. Resonant horizontal scanning at 1600Hz guaranties a large optical scan range of up to 80° even for a 2.6x3.6mm large single mirror. To provide the full 5mm effective reception aperture of the TOF camera five hybrid assembled MEMS scanning mirrors are precisely synchronized operated in respect to the sending mirror of the TOF laser scanner. For real time feedback control piezo-resistive position sensors are integrated on chip for both scanning axis. Beside the experimental results of the MEMS scanning device itself we present the system integration and driving control of the synchronized MEMS scanner array essential for the final 3D sensor. The novel 3D TOF camera provides a distance measuring rate of 1MVoxel/s and an uncertainty of TOF distance measurement of 3mm at 7.5m measuring range enabling e.g. 3D images with 1Mpixel per second or 100Kpixel frames per second, respectively, over a 40°x60° (potentially 60°x80°) large FOV.

8616-6, Session 2

Close-loop controlled stainless steel scanner based hyperspectral confocal laser scanning imaging with scanning status monitoring

Youmin Wang, Nicolas Triesault, Daghan Y. Gokdel, Sheldon F. Bish, Bin Yang, Kazunori Hoshino, Xiaojing Zhang, The Univ. of Texas at Austin (United States)

Due to the requirements of high speed and large field of view (FOV) for laser scanning imaging, analog micromirrors are often actuated at their natural response frequencies for maximum scanning angles. While the MEMS analog micromirrors are designed with aims of smaller

form factor and compatibility with standard semiconductor fabrication techniques, additional active components are rarely added up onto them, including the real-time scanning status monitoring. Therefore analog micromirror enabled laser scanning imaging system usually lacks the capability of precise positioning comparing with traditional mechanically driven scanning devices such as galvanometers, though having its own advantage of easier fabrication and packaging. Adding a closed-loop monitoring to the analog scanning micromirror based scanning imaging system would be a method to deal with these deficiencies. In our new developed magnetically actuated stainless steel scanner enabled hyperspectral fluorescence imaging system, we used a position sensitive device array to detect the real-time scanning information such as frequency, amplitude and phase shift for both scanning axis. By placing a 10:90 dichroic mirror on the imaging optical path, small amount of excitation light was reflected onto the feedback signal detection arm and collected by the position sensitive device. Those real-time acquired signals were used for accurate measurement and precise intensity mapping in image re-construction after necessary filtering and conditioning. These benefits enables us with capabilities of well aligned fluorescence images with less distortion. The imaging quality of our closed-loop controlled scanning status monitoring with position sensitive device was greatly improved, with comparisons of presivous open-loop controlled imaging systems and control images from commercial microscopes.

8616-7, Session 2

Optical scanners based on thermo-optical tuning of an integrated-optical waveguide mode

Eric Markweg, Martin Hoffmann, Technische Univ. Ilmenau (Germany)

For many applications the deflection of beams is a main challenge, and often a small deflection e.g. for alignment issues is already enough. For beam deflection in an integrated optical device a deflection system without moving mechanical parts can be used that is based on the thermo optical effect.

Axial to a silicon oxynitride waveguide a GRIN lens is glued. The monomode waveguides are design for operating at 632.8 nm. Near the cut of the waveguide, thin film heaters are located that allow for changing the temperature profile and thus the index profile in the waveguide system. The guided mode follows the temperature gradient and finally the resulting new effective index distribution. That harms into a displaced position of the guided mode. Because of the short distance between the heated area and the cut of the waveguide the displaced mode finally doesn't reach the position of a not heated index distribution. The thus achieved non-axial incident of the beam into the lens leads to a deflection of the free-beam. With optimized position of the heaters a deflection in two dimensions is possible.

We present first measurement of the deflection behavior of the system. We show thermal simulation for the optimization of the heater position. Results of the thermal simulation are used in a BPM simulation to determinate the change of the mode position during heating.

8616-8, Session 2

Thin-film PZT actuated vertical translational microscanner stage

Choong-ho C. Rhee, Zhen Qiu, Jongsoo Choi, Thomas D. Wang, Kenn R. Oldham, Katsuo Kurabayashi, Univ. of Michigan (United States)

Multi-beam thin-film PZT vertical actuators are proposed to increase translational z-axis motion of the central mirror stage on which a 2D planar micro-scanner is assembled, for use in dual-axes confocal microscopy. The fabrication process permits thin-film PZT actuator integration with multi-layer silicon structures having higher-aspect ratio than previous related processes, using vertical silicon dioxide barrier trenches to provide robust encapsulation of the silicon during xenon difluoride release. Two types of prototype multi-beam thin-film PZT-actuated micro-mirror stages achieve large translational vertical motions of 40-150?m for two-fold and 140–500?m for four-fold actuators at 10-15Vdc. Under low driving voltage and at resonance with 2Vac and 3Vdc offset, the vertical scanning displacement is measured to be 80?m at 150Hz for a two-fold actuator and 93?m at 80Hz for a four-fold actuator, respectively. Under higher offset driving voltage and at resonance with 2Vac and 8Vdc, the displacement of the four-fold actuator achieves 430?m at 90Hz. However, non-zero initial tilting angle of the central stage is observed due to intrinsic residual stresses of the metal stacks in the actuator structure. As all vertical actuators are driven by a single input for the current prototype micro-mirror stages, future device development of differentiated actuation mechanisms continues.

8616-9, Session 2

Resonant biaxial 7-mm MEMS mirror for omnidirectional scanning

Ulrich Hofmann, Joachim Janes, Frank Senger, Vanessa Stenchly, Hans-Joachim Quenzer, Bernd Wagner, Wolfgang Benecke, Fraunhofer-Institut für Siliziumtechnologie (Germany)

An electrostatically driven two-axis MEMS mirror for omnidirectional laser beam scanning in a time-of-flight LIDAR sensor is presented. The resonant biaxial MEMS mirror has a mirror diameter of 7mm and features a tripod suspension to enable circular scanning at large oscillation amplitude. Vacuum encapsulation on wafer level is applied requiring the fabrication of dedicated glass wafers with 1.6 mm deep cavities. This paper presents the optical concept for an automotive LIDAR sensor, as well as design fabrication and first results of the large aperture MEMS mirror.

8616-11, Session 3

Position sensing and tracking with quasistatic MEMS mirrors *(Invited Paper)*

Stefan Richter, Carl Zeiss AG (Germany)

We report on a position sensing system for quasistatic MEMS mirrors using a point source LED imaged onto the backside of the mirror.

The position signal is detected by a 4-quadrant-diode and can be used for digital closed-loop control. The resulting resolution is about 13 bit at a sampling frequency of 500 kHz.

The whole detection system is integrated in a package carrying the MEMS mirror, the optical beam path as well as the amplifier circuit of the 4-quadrant-diode.

Furthermore a laser steering system for searching and tracking of moving objects, marked by retroreflectors, will be presented.

During an initial search, the system identifies objects by their initial position within the detection range of about 5m distance and a detection angle of about 20 degrees. The system follows the detected object on random trajectories by minimizing the zero-position error of the back reflected beam on a 4-quadrant-diode. Angular velocities of more than 100 degrees per second have been measured.

8616-12, Session 3

Aluminum nitride supported 1D micromirror with static rotation angle >11°

Stefan Weinberger, Martin Hoffmann, Technische Univ. Ilmenau (Germany)

Although a lot of micromechanical mirror devices are already available, there is still a lack of devices for measurement applications with large reflective surface and static deflection >10° in analog mode. In our approach aluminum nitride (AlN) deposited by reactive sputtering is used as torsional spring material. In contrast to crystalline and amorphous materials such as silicon or silica, the nanocrystallinity of AlN inhibits the propagation of cracks. Material tests show high mechanical strength and linear elastic behavior. A fatigue of material couldn't be observed till now. Those material attributes enable the fabrication of thin and compliant springs. Aside from the geometric parameters, spring stiffness can be tuned by the mechanical film stress during deposition. To reach highly dynamic mirror deflection, electrostatic actuation is used. Planar plate electrodes enable high static rotation angles with the drawback of a nonlinear voltage vs. angle correlation. Measurement results show an analog mechanical deflection range of ±11.7 ° at 199 V. Using pull-in, a digital tilt angle of about ±23.6 ° can be reached. These results match well with simulations. The mirror plain is stiffened by bulk-silicon. The samples have a mirror surface of up to 1.5 x 1.2 mm? suspended by 20 till 40 µm wide, 200 till 350 µm long and 0.4 µm thin stacked AlN (300 nm) /Al (100 nm) torsional springs.

8616-13, Session 3

Wide steering angle microscanner based on curved surface

Yasser M. Sabry, Univ. Paris-Est Marne-la-Vallée (France) and Si-Ware Systems (Egypt); Diaa Khalil, Ain-Shams Univ. (Egypt) and Si-Ware Systems (Egypt); Bassam Saadany, Si-Ware Systems (Egypt); Tarik Bourounia, Univ. Paris-Est Marne-la-Vallée (France)

Intensive industrial and academic research is oriented towards the design and fabrication of optical beam steering systems based on MEMS technology. In most of these systems, the scanning is achieved by rotating a flat micromirror around a central axis in which the main challenge is achieving a wide mirror rotation angle. In this work, a novel method of optical beam scanning based on reflection from a curved surface is presented. The scanning occurs when the optical axis of the curved surface is displaced with respect to the optical axis of the incident beam. To overcome the possible deformation of the spot with the scanning angle, the curved surface is designed with a specific aspherical profile. Moreover, the scanning exhibits a more linearized scanning angle-displacement relation than the conventional spherical profile. The presented scanner is fabricated using DRIE technology on an SOI wafer. The curved surface (reflector) is metalized and attached to a comb-drive actuator fabricated in the same lithography step. A single-mode fiber, behaving as a Gaussian beam source, is positioned on the substrate facing the mirror. The reflected optical beam angle and spot-size in the far field is recorded versus the relative shift between the fiber and the curved mirror. The spot size is plotted versus the scanning angle and a scanning spot size uniformity of about 10% is obtained for optical deflection angles up to 100 degrees. As the optical beam is propagating parallel to the wafer substrate, this scanner structure can be integrated with other optical systems fabricated on the wafer. This opens the door for a completely integrated laser scanner with filters and actuators self-aligned on the same chip that allows low cost and mass production of this important product.

8616-14, Session 3

SOI based electromagnetic MEMS scanners and applications in laser systems

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MEMS scanners are of interest for their potential as low-cost, low operating power devices for use in various photonic systems. Electrostatic comb driven scanners have the advantages of very low power consumption while producing high scanning angles (but at only one or two resonant frequencies) while electrothermal microactuated scanners allow the micromirror to be held at an arbitrary angle, but with smaller scan angles and scan rates that are limited to a few 10s Hz. The devices reported here use the electromagnetic force between a static external magnetic field and a current flowing through the device that allows the mirror to be held at a specific angle, and to be moved at higher scan rates than electrothermal actuated devices. The use of an external magnetic field, generated by compact rare-earth magnets, allows a simple and cost-effective commercial fabrication process to be employed (the multi-user SOI process provided by MEMSCAP) and avoids the requirement to deposit magnetic materials on the MEMS structure.

Modelling and experimental results will be presented for electromagnetic scanners with two different suspension geometries. When positioned within a field of 150 mT the devices can achieve a mirror tilt angle of 30 for a power consumption of 75 mW in a quasi dc mode and respond linearly up to 500 Hz. Greater tilt angles (600) can be achieved when the devices are operated at mechanical resonance. The application of these electromagnetic scanning micromirrors as intra-cavity temporal control devices for solid-state laser systems will also be presented.

8616-15, Session 4

Arrayed beam steering device for advanced 3D displays *(Invited Paper)*

Jungmok Bae, Yoon-Sun Choi, Kyuhwan Choi, Yunhee Kim, Kwon Yongjoo, Hoon Song, Eoksu Kim, Sangyoon Lee, Samsung Advanced Institute of Technology (Korea, Republic of); Seon Hyeong Choi, Junghoon Lee, Seoul National Univ. (Korea, Republic of)

An arrayed beam steering device is an essential element in slim form factor based multi-view 3D display since current manufacturing limits the resolution of image panels. An array device consisting of microscale liquid prisms is presented, where the prism surface between two immiscible liquids is electrically controlled to steer light beams, by the principle of electrowetting. Each prism has in-dependently controllable electrodes, separated vertically, on each of four sides of a pixel containing the liquids. A device prototype, 50 by 50 array with 200um x?200um pixels, was fabricated and demonstrated of its full optical performances, for the first time to our know-ledge. The maximum steering angle of each prism was measured to be 22.5 degree in average, with a tracking resolution of less than 0.04 degree. A distortion from the ideal planar shape is mainly caused by the electrode gap where the electric field is in sharp transitions. The transmitted beam quality was verified in the design phase with various simulations including electric field distributions, liquid surfaces, and optical ray tracing analysis. The process based on electroplating was developed for it high aspect ratio sidewall patterns with lowest critical dimensions and uniformity. Various driving schemes were also tested to maintain the distortion to minimum, currently 2.3 degree in 90% full width. The resulting high steering beam quality and its microscale prism array can open up the possibility for future multiview 3D displays based on eye tracking scheme, 2D/3D switching modes, and other 3D imaging schemes. In this paper, design and fabrication of eletrowetting based prism array, opto-fluidic simulations, optical characterizations, as well as system architectures to achieve low fatigue and natural 3D display will be presented.

8616-16, Session 4

2D electrostatic micromirror array with high field factor for high-power application

Sébastien Lani, Dara Bayat, Yves Petremand, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

A dual-axis "20 X 20" micromirror array with novel spring and actuator design is presented. The application aims at high thermal loads, spectroscopy or beam shaping. Each mirror in the array is suspended by three intertwined spiral springs and is actuated electrostatically with vertical electrodes, formed using a through-silicon-via process. Mirrors have only 40µm gap while each mirror is 600 X 600µm2 with a chip frame of only 500µm. Therefore mirror-Chips can form larger arrays by modular assembly using magnetic clamping and achieve (>88%) fill factor. A 3-wafers based process is used for the microfabrication which includes bonding of the mirror and actuation platform wafers, ASIC integration using chip to wafer assembly on the backside of actuation wafer, and bonding of a interconnect wafer over the ASIC where the ferromagnetic material for magnetic clamping is then bonded. The ASIC provides all the needed electrical connections to the actuator backside. Electrical connections inside the backside membrane connect the ASIC to the outside electronics. Mirrors can attain a mechanical DC rotation angle of ±4 degrees around any arbitrary axis with 170V excitation. Currently the maximum temperature rise of simultaneously heated mirrors with an absorbed thermal load of 6.1 kW/m2 at 100 Pa pressure is 1055 °C without any damage on the mirrors.

8616-17, Session 4

Fabrication of vertical moving micro-optical switch for display applications

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In this paper, we present a new concept and fabrication of micro optical switch of which application is transmissive display devices. The micro optical switch consists of two parallel plate electrodes and is driven by electrostatic force. The first electrode is patterned on the glass substrate and the second electrode is disposed spaced apart from the first electrode. Each electrode has holes and the holes in each electrode do not overlap with one another. Light passes through the holes in the second electrode via the holes in the first electrode. All dimensions and fabrication process of the micro optical switch were designed to be compatible with Liquid Crystal Display (LCD) fabrication process. The size of the fabricated micro optical switch was 254 ?m ? 254 ?m. The micro optical switch was fabricated by surface micromachining. Aluminum was used as electrodes and patterned by plasma etching process. Photoresist was used as a sacrificial layer, which defined the gap between the two electrodes. Plasma ahsing was used to remove the sacrificial layer. Finally, anti-stiction layer was coated by Molecular Vapor Deposition (MVD) process. When voltage applied, the second electrode moved down and contacted with the first electrode. When voltage applying stopped, the second electrode returned to its original postion. Required voltage to pull in the second electrode was below than 15 V. The sum of transition time, from on to off state and from off to on state, was below than 100 us and operating frequency was more the 10 kHz

8616-18, Session 4

Development of a fully programmable MEMS diffraction grating

Frédéric Zamkotsian, Lab. d'Astrophysique de Marseille (France); Branislav Timotijevic, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Robert Lockhart, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Ross P. Stanley, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Patrick Lanzoni, Lab. d'Astrophysique de Marseille (France); Markus Luetzelschwab, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Michael Canonica, Massachusetts Institute of Technology (United States); Wilfried Noell, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Maurizio Tormen, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

Programmable MEMS diffraction gratings are used for spectroscopic applications because of their potential in tailoring visible and infrared spectra. A fully programmable MEMS diffraction grating (FPMDG), where every micro-mirror can move independently in a range 0 - lambda/2, where lambda is the wavelength of light, leads to a better control of the intensity for each wavelength in the synthetized spectrum – the intensity can take any value from 0 (micro-mirror lambda/4-condition) to the maximum (no micro-mirror displacement).

The FPMDG chip contains 64 micro-mirrors which are actuated electrostatically. Rigid Si micro-mirrors are connected to side electrodes via linkage arms, permitting the micro-mirror to follow a pure vertical displacement, reducing the micro-mirror bending throughout actuation. Microfabrication is based on a 4 mask photolithography process, using SOI and Pyrex wafers.

Each micro-mirror of the FPMDG chip can move by 1.25µm at voltages below 100 V. Two families of micro-mirrors, 50µm or 80µm wide, show negligible cross-talk during actuation. The micro-mirror bowing is as small as 0.14 µm over 700 µm and remains unchanged throughout actuation. Extinction ratios of up to 100 have been achieved by actuating only 3 adjacent micro-mirrors. The measurements have shown high stability and good reproducibility over time.

Finally, FPMDGs are used to demonstrate shaping of the input spectrum: the intensity in a particular wavelength region is controlled through independent actuation of a set of adjacent micro-mirrors. The result is attenuation or cancellation of the corresponding wavelengths.

8616-19, Session 5

Design and Characterization of a hybrid-integrated MEMS scanning grating spectrometer *(Invited Paper)*

Heinrich Grüger, Jens Knobbe, Tino Pügner, Harald Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

Spectrometers based on scanning grating monochromators are well established tools in the fields of medical care, food chain management, industrial measurement technology or other tasks in research and development. New applications arose in the last few years with decreasing system effort. There is a growing demand especially for sophisticated miniaturized spectroscopic measurement systems working in the near infrared (NIR) spectral range. The next generation of MEMS (micro electro mechanical systems) based devices will exhibit very small dimensions and mass, enhanced portability, low power consumption and high robustness. Classical spectrometers and even modern compact designs do not satisfy these challenging requirements. A MEMS based spectroscopic system with a volume of only 15 x 10 x 14 mm? and a few milliwatts of power consumption that has the potential to fulfill the demands of the upcoming applications has been designed.

The new approach is based on two development directions. First, a resonantly driven MEMS scanning grating invented by Fraunhofer IPMS has been applied. The MEMS approach has been used to reduce size, weight, cost and power consumption. In the latest generation of the MEMS scanning grating device two optical slits and a piezoresistive position detection sensor have been integrated in addition to the already existing miniaturized scanning grating plate. However, the task of miniaturizing a MEMS based optical system cannot be solved by simply putting more functionality into the MEMS chip only. Thus, further research has been performed to take advantage of the hybrid integration of optical components by highly sophisticated manufacturing technologies and packaging. This leads to a planar mounting approach where the different substrates can simply be stacked on top of each other within the alignment tolerances available by state of the art automated micro assembly production platforms. Furthermore, the combination of MEMS technology and a planar mounting of different optical substrates, manufactured in large quantities, facilitate the mass production of spectroscopic systems with a significant reduction of cost per unit. The optical system has been designed for the near infrared (NIR) range between 950 nm and 1900 nm with a spectral resolution of 10 nm. The miniaturized scanning grating spectrometer system has been realized. After processing the MEMS device and the optical components by means of MEMS technology and ultra-precision micromachining, first samples of the sophisticated spectroscopic measurement device have been mounted from the single components by an automated sub-micron die bonder. First measurements have been performed to characterize the system and improve the properties with the next iteration of development.

The miniaturized MEMS based scanning grating spectrometer realized can serve a wide variety of applications for handheld devices and autonomous systems from medical services to food quality analysis or materials identification.

8616-20, Session 5

SWIFTS: a groundbreaking integrated technology for high-performance spectroscopy and optical sensors *(Invited Paper)*

Christophe Bonneville, Resolution Spectra Systems (France); Etienne P. Le Coarer, Institut de Planétologie et d'Astrophysique de Grenoble (France); Pierre Benech, IMEP-LAHC (France); Thierry Gonthiez, Fabrice Thomas, Bruno Martin, Renaud Puget, Eric Morino, Resolution Spectra Systems (France); Jumana Boussey, LTM-CNRS/CEA-Leti (France); Sébastien Labau, CEA-LETI (France)

SWIFTS – Stationary-Wave Integrated Fourier Transform Spectrometer – is a new highly integrated high-resolution spectroscopy technology which is a major advance in spectroscopy. This presentation is the first public overview of the SWIFTS state-of-the-art development.

SWIFTS combines groundbreaking nanotechnology research, integrated optics, microelectronics and embedded software, resulting in high resolution spectrometer technology bundled into a simple component that is over 100 times more powerful in terms of spectral resolution than existing mini-spectrometers and more than 2,000 times smaller than high-end spectrometers offering a similar level of performance.

Systems based on this technology can typically achieve spectral resolution of few pm / 0.2 cm-1 / 3 GHz with a good SNR over a bandwidth from several nm to a few hundred of nm on a few mm? chip, opening a way to product development based on the most demanding applications today performed in research laboratories.

The principle of this patented technology will be explained as well as the technology choices which have been made by Resolution Spectra Systems and the different involved research teams. We will present the most challenging bricks of the technology: nanoimprint patterns deposition, hybrid chips assembly, light collection, calibration and data processing.

We will demonstrate how, in order to fit applications, SWIFTS principle can be implemented into numerous configurations: multi-bands, multiplexing, spectro-imaging, integrated bio-sensors…

Many results have been obtained with research setups or new products in the Visible and Near-Infrared, among which: analysis of tunable, multi-modes or high-stability lasers, laser spectroscopy, high depth Optical Coherent Tomography.

8616-21, Session 5

Fabrication and evaluation of a 500-W cladding-light stripper

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Fiber lasers have reached kW levels of output power. To be able to reach this level it is necessary to use reliable high-power components that sustain these power levels. Double-clad fibers (DCFs) are often used in high-power fiber lasers. Cladding-light strippers (CLSs) are used to remove unwanted light from the inner cladding of the DCF. This unwanted light consists of residual pump light or signal light that leaked into the cladding, thus requiring that the CLS remove both high-NA (>0.4) and low-NA (<0.1) light. Often high-index polymers are used to remove the unwanted light from DCFs. Because the CLS has to be able to withstand several 100W and most polymers are not capable of exceeding temperatures of 200°C, we investigated a CLS without polymers based on an etching process. We present results from a CLS that was tested up to 500W of stripped power. We determined the angle dependence of the stripping efficiency by launching both high- and low-NA light and numerically evaluating the observed far-field pattern on a CCD camera. Furthermore, we measured the dependence of the stripping efficiency on the length of the etched area and the etching time. With optimized parameters an attenuation of more than 20dB when launching high-NA light and 9dB with low-NA light was achieved. The CLS did not show any degradation in terms of attenuation or thermal behaviour in a six-hour stability test.

8616-22, Session 5

Spatial beam splitting for fully integrated MEMS interferometer

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In this paper a novel approach for optical beam splitting for MEMS based Fourier transform spectrometer is proposed. This approach is mainly based on spatial truncation of the input Gaussian beam into two symmetric Semi-Gaussian beams using V shape mirror and hence eliminating the use of a beam splitter and allowing the integration of optical spectrometers. It can be used over wide spectral range including infrared and visible region. Unlike the traditional Michelson interferometers which return half of the optical power to the source, the reflected power is negligible. This enables the use of multiple reflecting mirrors increasing the optical path difference by a factor of four. The analytical model describing the beams propagation and interference is derived using Fourier optics techniques and verified using Finite Difference time domain method. Mechanical model providing the mirror displacement to produce the optical pass difference is conducted and verified using finite element method. Mechanical displacement of 160?m is achieved which is multiplied by a factor of four, resulting is a resolution of 9nm at wavelength 1.55?m. Finally, the effect of different design parameters on the interference pattern, interferogram and resolution are demonstrated.

8616-23, Session 5

In-plane diffraction loss free optical cavity using coated optical fiber and silicon micromachined spherical mirror

Yasser M. Sabry, Univ. Paris-Est Marne-la-Vallée (France) and Si-Ware Systems (Egypt); Tarik Bourounia, Univ. Paris-Est Marne-la-Vallée (France); Bassam Saadany, Si-Ware Systems (Egypt); Diaa Khalil, Ain-Shams Univ. (Egypt) and Si-Ware Systems (Egypt)

Light trapping in optical cavities has many applications in optical telecommunications, biomedical optics, atomic studies, and chemical analysis. Efficient optical coupling in these cavities is an important engineering problem that affects greatly the cavity performance. One interesting way to form an optical cavity, while simultaneously connected to the rest of the optical systems, is to use an optical fiber surface as one of the cavity mirrors while the second mirror is fabricated by MEMS technology. In this way, cavity tuning with a MEMS actuator is a simple achievable task with low cost in mass production. The main problem in this solution is the high diffraction loss associated with the small spot size at the output of the standard single-mode fiber (SMF). Diffraction loss in the cavity is usually overcome by using an expensive lensed fiber or by inserting a coated lens in the cavity leading to a long cavity with small free spectral range (FSR). In this work, we report a Fabry-Perot cavity formed by a multilayer-coated cleaved-surface SMF inserted into a grove while facing a spherical micromirror; both are fabricated by silicon micromachining. The light is trapped inside the cavity while propagating in-plane of the wafer substrate. The light is injected in and collected from a Corning SMF-28 optical fiber with a coated surface reflectivity of about 98% at 1330 nm (O-band). The silicon mirror surface is aluminum metalized with a reflectivity of about 92%. The measured cavity has a line width of 0.45 nm around 1330 nm with a FSR of 26 nm. The obtained results indicate an almost diffraction-loss free optical cavity with a quality factor close to 3000, limited by the optical surfaces reflectivity that can be improved in future by an optimized mirror fabrication process and better matching of the fiber multilayer coating.

8616-24, Session 5

A tunable split-ladder photonic cavity through MEMS driven nano-deformation

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1D photonic crystal cavity has attracted much attention because of its merits, such as small dimension, ease of fabrication and better integration with optical waveguides. Recently, an advanced ladder-shaped quasi-1D photonic crystal cavity has been invented, whose Q value can experimentally be as high as 7.2?105. In this paper, we modify the design and demonstrate a novel split-ladder cavity, which can be tuned across a large spectral range by its intrinsic micro-electromechanical systems (MEMS) deformation. Two MEMS actuators are located in two sides of the cavity, which can control the cavity's central gap. When cavity' gap is narrowed or widened, the wavelength of resonance will shift to right or left correspondingly. Band structure of split-ladder lattice is analyzed by 3D RSoft BandSOLVE. The modulation method of "defect" region in split-ladder cavity is described, and resonance mode is calculated by 3D FDTD (RSoft FullWAVE). The device is fabricated by electron beam lithography and inductively coupled plasma reactive ion etching. The experimental results show that d?/dg is around 1, in which ? is resonance wavelength and g is the gap distance in the center of cavity. We test d?/dg experimentally with the second order resonance mode, which has a Q value of a few thousands. In a tuning spectral range of 20 nm, there is no obvious drop of Q. The response time of the MEMS actuator is very short, because these two actuators for nanopositioning have very strong rigidity. As far as we know, this is the first demonstration of quasi-1D cavity's tuning through its intrinsic MEMS driven mechanical deformation.

8616-45, Session PTue

Closed-loop control driver for quasistatic MOEMS mirrors

Andreas Tortschanoff, Dominik Holzmann, Martin Lenzhofer, Carinthian Tech Research AG (Austria); Thilo Sandner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Andreas Kenda, Carinthian Tech Research AG (Austria)

Electrostatically driven MOEMS scanner mirrors have important applications in various fields of optics, telecommunication and spectroscopy. Position feedback, providing accurate information about mirror deflection angles is an important issue for most applications.

For MOEMS devices, which do not have an intrinsic on-chip feedback, this can be provided with optical methods, most simply by using the reflection from the backside of a MOEMS scanner. Previously, we have presented a compact device based on the accurate measurement of timing signals using fast differential photodiodes, which can be used with resonant scanner mirrors performing sinusoidal motion with large amplitude. While this approach provides excellent accuracy (phase accuracy better than 1/10000) for high frequency scanners, it cannot be directly extended to arbitrary trajectories or static deflection angles.

Most recently, we realized a new position sensing device applicable to arbitrary trajectories, which is based on the measurement of the position of the reflected laser beam with a quadrant diode. In this work, we present the position sensing device and compare both approaches in much detail showing first experimental results from the implemented device, but also theoretical considerations and optical simulations in order to analyse dependencies on resonance frequency and mirror dimensions. Errors resulting from the projection of the laser beam reflected by a 2D gimbal mounted mirror on a flat detection plane are also discussed.

Accurate position feedback will enable closed-loop control of the MOEMS devices and, thus, will significantly improve their performance and applicability.

8616-46, Session PTue

Uncooled microbolometers for selective infrared spectral responses

Jong Yeon Park, Dean P. Neikirk, The Univ. of Texas at Austin (United States)

Development of wavelength selective detection in the infrared spectral region would have highly desirable for a variety of applications such as thermography, chemical processing and environmental monitoring, spectroradiometry, medical diagnosis, Fourier transform infrared spectroscopy, night vision, mine detection, military defense, astronomy and so on. Commercial Fabry-perot resonant cavity based uncooled microbolometers (Air gap: 2 to 2.5?m) have limited design parameters for narrow band spectral response. Here, we will present fabrication and characterization of uncooled microbolometer for wavelength selectivity in infrared spectral regions. The fabricated wavelength selective uncooled microbolometers consist of a resistive sheet (Rs = 377?/?, using Chromium, Titanium, Tantalum nitride) as an infrared absorber layer above a germanium dielectric (625nm)/air gap /mirror interference structure. By using only germanium as both the interference layer for wavelength selectivity in the dielectric coated Salisbury screen and the structural layer the problems associated with highly absorbing and dispersive silicon nitride layers can be avoided. To characterize the fabricated wavelength selective uncooled microbolometers, optical spectral measurements have been made on the different devices such as infrared absorber materials and device geometry. To electrical characterization of uncooled microbolometer, resistance (R)-power

(P) and temperature coefficient of resistance (TCR) measurements have performed at different temperature (temperature range: 300K to 323K). We demonstrated that the fabricated wavelength selective microbolometers are able to produce excellent tunable narrowband absorption in mid-wavelength infrared (3 to 5?m) and long-wavelength infrared (8 to 12?m) region.

8616-25, Session 6

Compact holographic printer using RGB waveguide holographic optical elements *(Invited Paper)*

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We propose compact holographic printer using RGB waveguide holographic optical elements (HOE) while reducing overall device size and quantity of elements with integrated functionality of each optical element. The exploding mobile IT devices will make 3D image available everywhere and expedite the usage of compact 3D printers. However, to record and reconstruct 3D, huge number of optical components is required which makes a device bulky and image quality degraded due to the error-prone tuning. Holography provides glasses-free 3D experience that users can view a natural 3D. Thus, it is critical to make holography device that can be as compact and integrated as possible. There are two main advantages for our solutions. First, this solution utilizes integrated optical elements to provide small size of a device, where each of them is a united, flat, and rigid element to eliminate tuning and make mass production possible. Second, color hologram prints are recorded through the novel multi-stacked RGB waveguide HOE. Compared to the conventional optics-based structure, RGB Waveguide HOE-based one reduces the overall size by 10 times, the number of components by 2 times, and improves the optical efficiency by 3 times. We implemented the compact holographic printer and actually recorded color holograms using RGB Waveguide HOE. The waveguide HOE-based prints show comparable holographic quality to the conventional optics-based ones in terms of gray level, area uniformity, viewing angle, and angular resolution. Proposed research can be useful for both general consumers and professionals like 3D photography and medical 3D image printing applications.

8616-26, Session 6

Design and simulation techniques for shaping light using diffractive diffusers and grating cells arrays

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Methods for reshaping the spatial distribution of light are essential in lighting and any other applications in which a predefined light pattern is to be generated. We discuss and compare concepts for shaping light by diffractive diffusers, arrays of diffusers and grating cells arrays.

Using those micro-structured elements for shaping light introduces additional freedom for the design of compact optical systems. In the case of a diffuser, the light spot is deflected by locally linear phases resulting in overlapping spots forming the light pattern in the target plane. For non-paraxial sources, for examples LEDs, the concept is to be generalized. Then, using an array of diffuser cells is of advantage in order to compensate the large divergence angle of the incident light. Another alternative for shaping light uses a grating cells array, where in each cell a grating is placed. Each cell of the array deflects the light into a predefined direction and results in a light spot in the target plane. The light spots of all array cells together form the desired light pattern.

All design approaches require the accurate handling of microstructures in the design and simulation process. The inclusion of diffraction and interference effects is mandatory. We show how this is achieved by applying field tracing techniques and discuss their advantages compared to ray tracing.

For several design tasks we present solutions discussing pros and cons of the presented design techniques. The results are obtained using the optical simulation and design software LightTrans VirtualLab (www.lighttrans.com).

8616-27, Session 6

Innovative approach to high stroke electrostatic actuators

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The electrostatic actuation is still a preferred principle in modern microelectromechanical systems (MEMS). Based on the Coulomb attraction between two different point charges, the electrostatic actuation is a surface effect and thus volume-independent. In addition, the efficiency of electrostatic actuation increases with a decreasing gap size between the electrodes. The relatively simple morphology of an electrostatic actuator allows low-cost wafer-level fabrication, making it a versatile and convenient principle for MEMS actuators.

Although the electrostatic principle seems only to be applicable for actuators in micrometer scale, this paper presents the successful upscaling of an electrostatic actuator to the millimeter scale, still utilizing the major advantages of the said principle and providing a high stroke with low actuation voltage.

For such an actuator, we replace the common silicon with the non-conducting OrmoComp, a UV-curable hybrid polymer, suitable for wafer-level fabrication. With a significantly lower elastic modulus (around 2 GPa), only a fraction of actuation voltage is necessary for a similar deflection. The electrodes are realized with additional coatings of thin metal layers. To achieve a high stroke, while maintaining a relatively low voltage, the actuator design is based on an improved zipper actuator. With our developed fabrication process, we are able to create a highly displaced out-of-plane actuator, while almost eliminating the initial gap between the electrodes.

Experimental results of a wafer-level fabricated zipper actuator show an out-of-plane motion up to 450 µm at an actuation voltage of 450 V.

8616-28, Session 6

Tunable MEMS diffraction gratings with improved displacement profile of the fixed-fixed beams

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MEMS diffraction gratings whose period can be tuned during operation find applications in micro-spectrometers and in display devices. These structures are designed using fixed-fixed beams of 10µm width and spacing of 2µm between them and are actuated in out-of-plane motion. It is found that non-planar bending of fixed-fixed beams reduce the amount of light diffracted into first order by about 4% compared to ideal planar beam displacement. A new fixed-fixed beam design with modified spring constant and actuation mechanism is proposed to improve the planarity of the beam during actuation. The profiles of the two structures (proposed design and normal beam) when displaced by ?/4(relative displacement between two beams required for diffraction), have been extracted using Intellisuite simulations and this data is fitted with a ninth order polynomial to model the beam displacement. The grating transfer

function is modeled with displacement profiles acquired and it is found that new design improves the light in first order by about 4% when simulated in MATLAB for 633nm wavelength. The grating structures are fabricated using a 4 mask process and are released using a wet release process developed in the lab. The electroplating parameters are optimized to have smooth gold metal beams. The surface profiler images and the electrical characterization of the devices conformed that the devices are released and pull-in voltages are found to be 20V. The grating structures are tested optically to verify the simulated results using an optical setup built in the lab and results are found to closely match with the simulations.

8616-30, Session 6

Optimization of biogas production using MEMS based near infrared inline-sensor

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With regard to climate protection and increasing oil prices, renewable energies are becoming extremely important. A particularly environmentally and resource-saving way of heat and power production are anaerobic digestion in biogas plants. These plants can be operated decentralized and weather-independent and allow peak load operation. To maximize the energy production the plants should be operated at a high load factor of more than 90 percent. However, the current plant utilization in many areas is significantly less, which is economically and environmentally inefficient. Main reason for that is the biochemical process, which responds to fluctuations in boundary conditions, e.g. temperature and substrate composition. At present only a few easily accessible parameters such as fill level, flow rates and temperature determined on-line. Monitoring of the substrate composition occurs only sporadically with the help of laboratory methods.

A direct acquisition of substrate composition combined with a smart control and regulation concept enables a significantly improvement of the plant efficiency. This requires a compact, reliable and cost efficient sensor solution. For that reason a MEMS sensor system based on NIR spectroscopy has been developed. Requirements are a high accuracy, which represents the condition for exact chemometric evaluation of the sample, as well as optimized MEMS design and packaging in order to work in rough environmental conditions. Another important point is sample connection, which needs an exact adopted optical-mechanical system. In this paper, the development and application of MEMS-based analyzer for biogas plants is explored. Above mentioned problems and challenges will be discussed. In addition advanced performance issues and reliability test results of the device will be reviewed.

8616-31, Session 7

Integrated photonic and plasmonic MEMS and NEMS with high optomechanical coupling *(Invited Paper)*

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Photonic and plasmonic nanostructures can confine light with extremely small mode volumes and narrow optical resonances. Combined with micro- and nano-electromechanical systems, tight coupling between mechanical motion and optical modes is achieved for improved transducer performance and novel functionality. By evanescently coupling a small silicon microdisk optical cavity with a moving structure we sense on-chip displacement with fm/Hz^1/2 sensitivity and GHz bandwidth. In one example, such self-contained, optical fiber pigtailed and highly stable sensor was integrated to measure motion of a picogram-scale nanomechanical probe for applications in high sensitivity, high speed atomic force microscopy. The design variations covered four decades of mechanical stiffness (0.01 N/m to 290 N/m) and frequencies from 250 kHz to 110 MHz. Regenerative mechanical oscillations, useful for frequency-modulation sensing, could be induced under continuous wave excitation. In another device, a similar sensor measured the position of a MEMS electrostatic actuator. The sensor output was used in an electronic feedback loop to suppress the random thermal motion of the actuator by 1000x, while performing a Langevin force measurement with bandwidth exceeding the sensor mechanical frequency by 2.5x. The third example explores NEMS for optical phase modulation in a subwavelength plasmonic slot waveguide with high optomechanical coupling.

8616-32, Session 7

InGaAsP optical device integration on SOI platform by Ar/O2 plasma assisted bonding

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A III-V/Si hybrid optical devices such as a laser, detector that were fabricated by the Ar/O2 plasma assisted direct bonding of an InP-based III-V active layer on highly doped silicon micro rib on SOI are presented. Direct current injection from silicon micro rib to InGaAsP MQWs to generate FP lasing was successfully demonstrated at a threshold current of 70 mA at 5 °C, and we have fabricated a Si/InGaAsP PIN diode. The semiconductive and optical properties of the hetero-junction between Si rib and InGaAsP MQWs or an InGaAsP active layer under direct current injection were measured and discussed.

8616-33, Session 7

A new method of fabricating nano-gratings using the high flexibility Of PDMS

Min Cui, Binzhen Zhang, North Univ. of China (China); Wanjun Wang, Louisiana State Univ. (United States)

In this article, we introduce a method to fabricate nano grating with much lower-cost and no accurate instrument needed. The technology is based on utilizing the high flexibility of PDMS and the nano molding process. The main procedures are as follows: (1) Fabricate the microscale grating structure on a substrate using the UV lithography of a positive photoresist; (2) Using PDMS casting method with the patterned positive photoresist to fabricate the PDMS grating structure; (3) Stretch the PDMS membrane along the gating lines and then fix it, and therefore the period of the grating in the PDMS membrane was reduced because of the elasticity; (4) Transfer the grating pattern on the PDMS membrane to PMMA, the material that is applicable for nanoimprint; (5) By repeating the steps of (2)~(4) several times, the period of the grating was reduced in each step until the desired nanoscale grating was achieved; (6) At last, mold the nano grating using NOA73, which is an optically clear, liquid adhesive that quickly cures when exposed to long wavelength ultraviolet light. Using this method, the nano gratings can be fabricated in very low-cost and no expensive or high precision equipment is needed. Because of the excellent replication property of PDMS molds, large number of gratings can be made with a single master mold. Our preliminary results have proved the feasibility of this technology. Figures 1, 2, and 3 shows the images of the gratings made using lithography (Fig. 1), and PDMS master mold (Fig. 2), and the molded NOA73 grating (Fig. 3).

8616-34, Session 7

Development of a focusing micromirror device with an in-plane stress relief structure in SOI technology

Wolfgang Kronast, Ulrich Mescheder, Bernhard Müller, Rolf Huster, Hochschule Furtwangen Univ. (Germany)

A dynamically focusing micromachined silicon mirror with 6 mm diameter and actuated electrostatically was realized. A stress relief design of the membrane`s suspension of this device which eliminates the residual stress to achieve an optical flat (bow< ?/10) micro-mirror is presented.

Silicon membranes fabricated in SOI technology mostly suffer from buckling by residual compressive stress caused by mismatch in the coefficients of thermal expansion between silicon and the buried silicon oxide layer [1,2].This leads to severe distortion of the optical quality of micromirror devices [3]. In case of an intrinsic tensile stress the membrane´s stiffness increases causing a decrease in deformation at a given voltage. Different methods are reported for stress compensation or stress relief in membranes [4].

We developed and fabricated a new stress relief structure, which reduces the stress induced deformation of membranes and leads to substantially flat micromirrors of high optical quality. This is achieved by a special tangential beam suspension which allows an in-plane expansion or contraction of the membrane proportional to its inherent compressive or tensile stress. Optimized beam structures and the voltage dependence of the mirror's deflection were determined by 3D FEM simulations. Simulations show a decrease in bow to values <17nm in comparison with 300nm for a conventional suspended membrane. The stress is reduced to <5% of original pre-stress.

A deflection of 14.5µm within an aperture of 5mm diameter is achieved by a voltage U0=200V resulting in a minimal focal length of 107mm.

The device will be characterized by interferometric optical measurements.

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8616-35, Session 8

Development of adaptive liquid microlenses and microlens arrays

Shaun R. Berry, Todd Thorsen, Jason B. Stewart, Ingrid Guha, MIT Lincoln Lab. (United States)

We report on the development of sub-millimeter size, adaptive liquid microlenses and microlens arrays using two immiscible liquids to form individual lenses. Microlenses and microlens arrays having aperture diameters as small as 50 microns were fabricated on a planar quartz substrate having patterned hydrophobic/hydrophilic regions. Liquid lenses were formed by a self-assembled oil dosing process that created well-defined lenses having a high fill factor. Variable focus was achieved by controlling the lens curvature through electrowetting. Greater than 70° of contact angle change was achieved with less than 20 volts, which results in a large optical power dynamic range.

8616-37, Session 8

Tunable microlenses based on aluminum nitride membranes

Steffen Leopold, Daniel Pätz, Technische Univ. Ilmenau (Germany); Fabian Knöbber, Oliver Ambacher, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); Stefan Sinzinger, Martin Hoffmann, Technische Univ. Ilmenau (Germany)

Tunable micro-lenses gain more and more importance in applications such as mobile camera systems and mobile optical measurement systems. One approach are membrane lenses [1], which are made of PDMS, filled with a liquid and tuned by variation of pressure. Unfortunately, PDMS membrane lenses with high tuning ranges show creep during loading [2].

We introduce sputtered aluminium nitride (AlN) thin films for tunable micro-optics [3]. During lens fabrication, AlN is deposited on a silicon substrate. Silicon is structured by using DRIE, which allows fabrication of circular, rectangular and irregular membrane shapes. The deposition of AlN is conformal on pre-structured substrates and it can be structured with plasma etching. Hence complex three-dimensional elements can be manufactured, like pre-shaped membranes, which carry diffractive elements.

In this contribution, we present the characterization of circular AlN membranes, which are 500 nm thick and 3 mm in diameter. For pressures of 0..20 kPa, spherical membrane deflections of up to 50 µm are observed. The measured tuning range in refractive power is 0..25 dpt (nLiquid=1.51). The results show no creep. Additionally, an optimized membrane shape is investigated for cylindrical lenses. While maintaining the cylindrical deflection, the "dogbone" membrane allows shorter lenses than rectangular membranes. This increases the element density in an array by the factor of 1.33. For this design, deflection profiles are measured and compared to simulation results.

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8616-38, Session 8

Liquid lens based on electrowetting: actual developments on larger aperture and multiple electrodes design for image stabilization or beam steering

Bruno Berge, Jérôme Broutin, Hilario Gaton, Géraldine Malet, Eric Simon, Florent Thieblemont, Varioptic-A BU of Parrot SA (France)

We will detail measurements of the Zernike modes evolution after a voltage step and present a mean of characterizing the lens response dynamics, through a wave front error including the defocus error.
We will show how this method allows an objective monitoring of the actual response time of a liquid lens in an imaging application where the liquid lens is used to vary the focus. We will show how this can be used practically to accelerate the response of the lens through proper filtering of the control voltage and how it enables faster AF algorithms (golden search, dichotomy etc…). We will also show comparative results between the internal fluid model and the experimental tilt response of a 4- electrode lens, capable of generating focus, tiltX, tiltY and one astigmatism. We will also discuss the main physical challenges to produce large aperture liquid lenses. We will present the latest designs of such lenses both in imaging and non-imaging applications.

8616-39, Session 8

The fabrication of out of plane aspherical microlens arrays

Yong Zhang, North Univ. of China (China); Wanjun Wang, Louisiana State Univ. (United States)

MOEMS (Micro-Opto-Elecro-Mechanical Systems) has brought new inspirations to the traditional optics design and manufacturing, due to their advantages such as small size, low cost, good performance, easy to integrate and mass production etc. From the microfabrication technology perspective, the microlens is among the most difficult components to make, and it is also the most important component of all free space micro-optic components. In recent years, the aspherical lens with controllable curvature has become one of the most popular research subjects since it is helpful in eliminating aberration. In this paper, we report a new method of fabricating and replicating aspherical microlens array with primary optic axis in parallel with the substrate surface. The technology was based on UV lithography of SU-8 thick resist. A novel water bath oblique lithography technique was adopted. Diameter of the prototype microlenses fabricated is about 280 ?m. By changing the pattern of mask and other process parameters, aspherical microlenses with different sizes and surface curvatures can be obtained. After quick replication through PDMS casting, followed by molding using UV light-sensitive material NOA 73, the microlenses with much better optical performances than cross-linked SU-8 resist were obtained. Fig. 1 (1) shows an SEM image of the aspherical microlens array, Fig. 1(2) shows the photo image of letter “F” for the microlens array made of SU8, and Fig. 1(3) shows the photo image of letter “F” for the microlens array made of NOA73. The microlens made using this technique has its main optical axis in parallel with the substrate, this makes it much easier to be integrated with other components into on-chip optical platforms such as optical switch and the imaging systems. This kind of micro-lens arrays will also be incorporated to microfluidic systems such as micro flow cytometry for fluorescence detections.

8616-40, Session 9

MOEMS-based time-of-flight camera for 3D video capturing *(Invited Paper)*

Jang-Woo You, Yong-Hwa Park, Yong-Chul Cho, Chang-Young Park, Heesun Yoon, Sang-Hun Lee, Jong-Oh Kwon, Seungwan Lee, Samsung Advanced Institute of Technology (Korea, Republic of)

We suggest a Time-of-Flight (TOF) video camera capturing real-time depth images (a.k.a depth map), which are generated from the fast-modulated IR images utilizing a novel MOEMS modulator having switching speed of 20MHz. In general, 3 or 4 independent IR (e.g.850nm) images are required to generate a single frame of depth image. Captured video image of a moving object frequently shows motion dragg between sequentially captured IR images, which results in so called ‘motion blur’ problem even when the frame rate of depth image is fast (e.g. 30 to 60Hz). We propose a novel ‘single shot’ TOF 3D camera architecture generating a single depth image out of synchronized captured IR images. The imaging system constitutes of 2x2 imaging lens array, MOEMS optical shutters (modulator) placed on each lens aperture and a standard CMOS image sensor. The IR light reflected from object is modulated by optical shutters on the apertures of 2x2 lens array and then transmitted images are captured on the image sensor resulting in 2x2 sub-IR images. As a result, the depth image is generated with those simultaneously captured 4 independent sub-IR images, hence the motion blur problem is canceled. The resulting performance is very useful in the applications of 3D camera to a human-machine interation device such as user interface of TV, monitor, or hand held devices and motion capturing of human body. In addition, we show that the presented 3D camera can be modified to capture color together with depth image simultaneously on ‘single shot’ frame rate.

8616-41, Session 9

Simultaneous multispectral imaging using lenslet arrays

Michele Hinnrichs, Pacific Advanced Technology, Inc. (United States)

There is a need for small compact multi-spectral imaging systems that simultaneously images in many spectral bands across the infrared spectral region from short to long-wave infrared. This is a challenge for conventional optics and usually requires large, costly and sensitive optical systems. However, with the advances in materials and photolithographic technology, MOEMS can meet these goals.

Pacific Advanced Technology would like to present the work that we are doing under a US Army supported SBIR program using MOEMS based diffractive optical lenslet array to perform simultaneous multi-spectral imaging with relatively high spatial resolution. This program has developed a design for a diffractive optical (DO) lenslet array that images 1024 x 1024 pixels in 16 colors every frame of the camera. Each color image has a spatial resolution of 256 x 256 pixels. The purpose of this work is to simultaneously image multiple colors of a field and reduce the temporal changes between colors that is apparent in sequential multispectral imaging.

This paper will describe the design of a 4 x 4 MOEMS diffractive optical (DO) lenslet array integrated with the Focal Plane Array. Each lenslet images a 256 x 256 pixel section of a 1024 x 1024 MWIR/SWIR FPA. The spectral images are collected simultaneously allowing high resolution spectral-spatial-temporal information each frame of the camera. This allows implementation of spectral-temporal-spatial algorithms in real-time with high sensitivity for the detection of weak signals in a high background environment with low sensitivity to camera motion. Using MOEMS actuation the DO lenslet array is translated to complete the full hyperspectral data cube in just a few frames of the camera, i.e. less than 1 second. Applications in biology and medicine can use this new approach for simultaneous spectral imaging.

8616-42, Session 9

Batch fabrication of micro-optical sensing and imaging devices

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As demonstrated in microelectronics, the batch fabrication based on the processing of wafers leads to a significant reduction in prize as well as in size. This concept was adapted to the fabrication of imaging optics extensively used in mobile phone cameras relying on small pixels and low resolutions such as VGA. We report on batch fabricated customer specific opto-electronical modules used in machine sensing and automotive applications relying on large pixel sizes and innovative non-conventional sensor characteristics. We specially focus on the lens mold mastering for the subsequent UV-replication since comparatively large sag heights of 250µm were required. Two technological approaches were applied, first, based on reflow of photoresist and, second, using diamond turning for the generation of a single lens mold and a subsequent step&repeat-process for array mastering on 8” wafers. Aspects of the optical design and simulation, the batch fabrication based on 8” wafers and characterization results are provided by the example of an f/1.1 opto-electronic sensor and an objective for a global shutter imager using 550x550 pixels with 3.6µm pitch.

8616-43, Session 9

Diffraction and photometric limits in today's miniature digital camera systems

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The mass application of digital camera systems for portable devices and sensors (e.g. in mobile phones) lead to a progressive shrinking of the overall camera size which is driven by pushing the smallest structuring limits in CMOS semiconductor technology. While mobile phones and laptop displays become ever slimmer, the requirements for the total track length of the integrated miniature camera modules decrease.

We demonstrate that state-of-the-art miniature camera systems such as wafer-level cameras are fundamentally limited by physical boundaries of photometry and diffraction when using smallest pixels and their scaling is not simply a switching to the next step of pixel size.

By applying a general image acquisition model which takes into account lens, image sensor and scene characteristics it can be shown that current smallest camera systems are surprisingly close to the photometric limit of photon shot noise for indoor scenarios. Whereas miniature camera systems may provide images with sufficient quality if there are plenty of photons available such as in outdoor scenarios, their resolution is basically limited by diffraction in this case. The different limitations are discussed in the context of an ideal system, a system which resembles the radiometric curves of the human eye and a camera system using state-of-the-art technology. Our conclusions suggest a fundamental end of the scaling of conventional digital camera setups. The results demonstrate that there are good reasons for the evolution of alternative imaging principles such as multi aperture optical systems when it comes to smallest and especially thinnest camera modules.

8616-44, Session 9

Optical MEMS in space instruments for Earth observation and astronomy

Frédéric Zamkotsian, Lab. d'Astrophysique de Marseille (France); Arnaud Liotard, Thales Alenia Space (France); Patrick Lanzoni, Lab. d'Astrophysique de Marseille (France); Thierry Viard, Thales Alenia Space (France)

Optical MEMS could be major candidates for designing future generation of space instruments. In addition to their compactness, scalability, and specific task customization, they could generate new functions not available with current technologies. We have listed new functions associated with several types of MEMS. Instrumental applications are derived and promising concepts are chosen using object selection and spectral tailoring techniques.

In Earth Observation instruments, observation of scenes including bright sources leads to an important degradation of the recorded signal. We propose a new concept to remove dynamically the bright sources and obtain a field of view (FOV) with an optically enhanced SNR. Our concept consists in replacing the plain slit in classical designs by an active row of MOEMS. Experimental demonstration of this concept has been conducted on a dedicated bench: a scene with a contiguous bright area has been focused on a micromirror array and imaged on a CCD detector. After the programmable slit, the straylight issued from the bright zone is polluting the scene; the micromirrors located on the bright area are switched off, removing almost completely the straylight in the instrument.

In Astronomy and Earth Observation, a programmable wide-field spectrograph is an innovative reconfigurable instrument where both the FOV and the spectrum could be tailored thanks to a 2D micromirror array: the FOV is linear and each point spectrum could be modified dynamically along the second direction. A demonstrator has been designed and its realization is under way for testing the unique performances of this instrument.

8617-18, Session PTue

Characterization of a MEMs deformable mirror by far field intensity evaluation

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Unlike typical WFS approaches, the point spread function (PSF) is a more meaningful measure since it is sensitive to scatter, does not act as a low pass filter and is not dependent on the WFS calibration. For these reasons, we decided to examine the far field PSF to characterize the performance of a deformable mirror (DM). Specifically, a 489 actuator, 163 segment piston/tip/tilt micromechanical systems (MEMS) based DM was evaluated for adaptive optics (AO) retinal imaging. The DM, which has an inscribed aperture of 7.7 mm, is designed with up to 8 µm stroke capability. Each DM segment has a center to center spacing of 600 µm with 6 µm gaps. Initial evaluations of the DM with a model eye included determining the ability of the DM to generate individual Zernike polynomials, in addition to evaluating the far-field PSF to measure wavefront correction performance. For individual Zernike polynomial terms, the DM was found to be capable of correcting the aberration magnitudes expected from previously published human population studies (Porter et al., JOSA A 2001 and Thibos et al., JOSA A, 2002). Finally, the DM was used in an AO fundus camera to successfully acquire images of cone photoreceptors in 3 normal subjects. Retinal images with and without AO were acquired over a 1 degree field of view through a 6 mm exit pupil. Ongoing work will incorporate the DM into an AO scanning laser ophthalmoscope where the form at the PSF at the confocal pinhole is crucial for optimal imaging.

8617-1, Session 1

A 19-element segmented MEMS deformable mirror based on electrostatic repulsive-force actuator *(Invited Paper)*

Weimin Wang, Institute of Optics and Electronics (China) and Univ. of Electronic Science and Technology of China (China); Fenggang Tao, Qiang Wang, Chuankai Qiu, Institute of Optics and Electronics (China); Zexiang Chen, Univ. of Electronic Science and Technology of China (China); Jun Yao, Institute of Optics and Electronics (China)

As a critical parameter, the stroke of MEMS deformable mirrors (DMs) determines their feasible applications. Parallel plate electrostatic actuators was used in conventional MEMS DMs for adaptive optics, but it limited stroke due to the “pull-in” effect and the gap between two plates [1-3]. Therefore great efforts have been given to improve the stroke [4-8]. One effective way is the employment of electrostatic repulsive-force microactuators, which can achieve larger stroke than parallel plate electrostatic actuators by a same fabrication process [9,10]. The working principle of electrostatic repulsive-force actuators is shown in Fig.1.

A 19 element segmented MEMS deformable mirror based on electrostatic repulsive-force actuator is proposed and fabricated using a commercial surface micromachining process PolyMUMPs [11]. Fig.2 is the 3D schematic diagrams and a partial micrograph of the DM array. The impacts of different sizes of actuator on DM’s characterizations such as stroke, work bandwidth and fill factors are analyzed and experimentally tested. A maximum stroke of 2.6?m is obtained, which is larger than the 2?m sacrificial layer thickness of PolyMUMPs. Dynamic characterization of DMs is mainly restricted by two factors, the structural flexibility and the air damping[12]. An analytical express and numeric simulation have been performed on the bandwidth regarding the air squeeze-film damping of release holes, Fig.3 shows the simulation results of air damping and the test results of DM bandwidth. These analytic insights could provide guidelines for future MEMS DMs optimum design. One DM prototype with a 600?m pitch is also fabricated successfully, and the preliminary aberration correction of the whole DM array is analyzed. Fig.4 is the experiment configuration and correction result. Compared to conventional MEMS DMs, this design demonstrates the advantage of large stroke over a standard surface micromachining fabrication process with a thin deposited layer, and it would expand the application of MEMS DMs in adaptive optics.

8617-3, Session 1

A continuous single-crystal-silicon membrane deformable mirror using bimorph spring

Tong Wu, Takashi Sasaki, Masayuki Akiyama, Kazuhiro Hane, Tohoku Univ. (Japan)

We propose, design and fabricate here a electrostatically actuated continuous single-crystal-silicon membrane deformable mirror (DM) for astronomical observation. The electrostaically actuated DM has been limited by the initial gap between the mirror and electrode. In this study, a 2?m-thick membrane is transferred to a flexible bimorph array by combining bulk micromachining and Au-Si eutectic bonding technology. Other than the poly-silicon mirror membrane used in the surface micromachined DM, a single-crystal-silicon of a SOI wafer is used as the mirror membrane as it provides excellent mechanical and optical properties for a specular surface. The HfO2 stress layer of the bimorph spring introduces a large out-of-plane deflection and thus generates a large initial gap. Au-Si eutectic bonding guarantees the desired bonding strength and electric interconnect. Two types of DM (with and without the side suspension) are fabricated by combining bulk micromachining, Au-Si eutectic bonding technology and the subsequent all-dry release process. A 0.86mmx0.86mm mirror membrane with a underlying 2x2 electrode array is supported by a 3x3 bimorph spring array. The initial gap of the fabricated mirror is ~20?m. The stroke of the two types of DMs are 3.7?m at 120V (with suspension) and 7.6?m at 110V (with suspension), respectively. The fill factor of the fabricated mirror is ~99.9%. A mirror with a 8?8 electrode array is under fabrication.

8617-4, Session 1

Performance analysis of two high actuator count MEMS deformable mirrors *(Invited Paper)*

Peter J. Ryan, Steven Cornelissen, Paul A. Bierden, Boston Micromachines Corp. (United States)

Two new MEMS deformable mirrors, one having a continuous facesheet with an active aperture of 20mm and 2040 actuators and a similarly sized segmented tip tilt piston DM containing 1021 elements and 3063 actuators, have been designed and fabricated. The surface figure, electro mechanical performance, and actuator yield of these devices, with statistical information on each individual actuator will be reported in this paper. The statistical distributions of these measurements directly illustrate the surface variance of Boston Micromachines deformable mirrors. Measurements of the surface figure were also performed with the elements at different actuation states. Deviations of the surface figure under actuation versus its rest state, the electromechanical distribution, and a dynamic analysis of individual elements are also presented here.

8617-5, Session 1

Development of variable-focal lens with liquid-membrane-liquid structure and 30-mm optical aperture

Lihui Wang, Hiromasa Oku, Masatoshi Ishikawa, The Univ. of Tokyo (Japan)

A variety structure of variable-focal lenses has been proposed, and in which liquid-liquid structure based on electrowetting and pressure-actuation theory was widely used and shown with high optical performance. In liquid-liquid lens, an immiscible liquid-pair with high transparent with the same density and different refractive indices is considered as an ideal candidate. Even through, certain additives can be added to match the liquid-pair on certain temperature; density difference appears again when temperature changed. Hence, researchers set lens aperture much smaller than capillary length, which is defined by interface tension depended on the used liquids, so that effect of gravity is negligible. Because of the physical limitation that interface tension cannot reach at a large number, it becomes a bottleneck to enlarge lens aperture.

With the purpose of designing a variable-focal lens with large optical aperture, it is assumed that elastic force takes place of interface tension, since elastic force is much stronger. In this paper, a liquid lens prototype is developed with a liquid-membrane-liquid structure. In this prototype, an elastic membrane is inserted and separates a device chamber into two sections; meanwhile the membrane also works as a refractive surface with a 30mm optical aperture. Liquid volume in each chamber is controlled via a medical syringe separately. Mechanics analysis of membrane's deformation and finite element simulation was employed to demonstrate the elastic force maintains the deformation into a parabolic shape, and optical performance with a refractive power range of 7.7Diopters, and 7.13line-pair/mm resolution was measured in experiments.

8617-6, Session 1

Electrostatic-pneumatic membrane mirror with positive or negative variable optical power

Mohammad J. Moghimi, David L. Dickensheets, Montana State Univ. (United States)

Deformable mirrors can be used in microscopy for optical focus scanning and in-situ focus range is linearly dependant to membrane deflection. In this work a novel actuation scheme for MEMS deformable mirrors is introduced to increase the membrane deflection and focus range as well. Membrane deflection is limited by the snap-down effect in electrostatic actuation. Also the electrostatic force is attractive regardless of polarity of the applied voltage so the concave surface curvature only is achieved. In this method electrostatic actuation is combined with pneumatic actuation to achieve either convex surface curvature or concave surface curvature to increase the membrane deflection. The fabricated device consists of two membranes made of the photoset epoxy SU-8. The cavities beneath the membranes are connected through etched channels in silicon. Cryogenic silicon etching is used to create those high aspect ratio air channels in silicon. One membrane serves as the deformable mirror and the other one as the pneumatic actuator. The actuator membrane creates a built-in valve for pressure stabilization. When the actuator is deflected by electrostatic actuation the air inside the cavity is compressed and the pressure is increased. The elevated pressure pushes the membrane mirror to create a convex mirror. This talk will discuss the fabrication and performance of the membrane, and illustrate for the first time pneumatic actuation combined with electrostatic actuation to control asphericity of the deflected membrane.

8617-7, Session 2

Wavefront control in space with MEMS deformable mirrors *(Invited Paper)*

Kerri L. Cahoy, Anne D. Marinan, Benjamin Novak, Caitlin Kerr, Matthew Webber, Kezi Cheng, Massachusetts Institute of Technology (United States)

To directly image an Earth-like planet, space telescopes equipped with coronagraphs need wavefront control systems and deformable mirrors (DMs) due to the challenging high contrast requirement of 10^10 to image an Earth-like planet around a Sun-like star at visible wavelengths. DMs are needed to correct for imperfections, thermal distortions, and diffraction in the telescope and optics that would otherwise corrupt the wavefront and ruin the contrast.

Microelectromechanical systems (MEMS) DMs meet the size, weight, and power limitations for space operation and have enough actuators to control high spatial frequency distortions. Operated in tandem with a coronagraph, MEMS DMs can create a large and dark enough "hole" around a target star to detect an Earth-like exoplanet. One candidate MEMS DM uses electrostatic parallel-plate actuators that are coupled to a continuous facesheet mirror through mechanical attachment posts.

However, wavefront control with these DMs has not yet been demonstrated in space. The Deformable Mirror demonstration mission (DeMi) tests the ability of a MEMS DM to perform wavefront control on orbit using a generic DM wavefront control test system designed for a university-class CubeSat nanosatellite platform.

The DeMi system consists of a deformable mirror, mirror driver, a simple static wavefront sensor such as a pyramid sensor or Michelson interferometer, a detector, and supporting subsystems. The goal is to demonstrate operational DM flight software, a calibration plan, and couple DM control and detector feedback into the attitude determination and control system. Additional applications include surveillance imaging and space-based optical communications.

8617-8, Session 2

KAPAO: a MEMS-based natural guide star adaptive optics system

Scott A. Severson, Sonoma State Univ. (United States); Philip I. Choi, Daniel S. Contreras, Pomona College (United States); Blaine N. Gilbreth, Sonoma State Univ. (United States); Erik Littleton, Harvey Mudd College (United States); Lorcan P. McGonigle, William A. Morrison, Alexander R. Rudy, Jonathan R. Wong, Pomona College (United States); Andrew Xue, Erik R. Spjut, Harvey Mudd College (United States); Christoph Baranec, Reed L. Riddle, California Institute of Technology (United States)

We describe KAPAO, our project to develop and deploy a low-cost, remote-access, natural guide star adaptive optics (AO) system for the Pomona College Table Mountain Observatory (TMO) 1-meter telescope. We use a commercially available 140-actuator BMC MEMS deformable mirror and a version of the Robo-AO control software developed by Caltech and IUCAA. We have structured our development around the rapid building and testing of a prototype system, KAPAO-Alpha, while simultaneously designing our more capable final system, KAPAO-Prime. The main differences between these systems are the prototype's reliance on off-the-shelf optics and a single visible-light science camera and the final design's improved throughput and capabilites due to the use of custom optics and dual-band, visible and near-infrared imaging. In this paper, we present the instrument design and on-sky closed-loop testing of KAPAO-Alpha as well as our plans for KAPAO-Prime. The primarily undergraduate-education nature of our partner institutions, both public (Sonoma State University) and private (Pomona and Harvey Mudd Colleges), has enabled us to engage physics, astronomy, and engineering students in all phases of this project. This material is based upon work supported by the National Science Foundation under Grant No. 0960343.

8617-9, Session 2

Performance assessment of competing architectures for real-time woofer/tweeter controllers: simulation and experimental results

Andrew P. Norton, Don Gavel, Renate Kupke, Srikar Srinath, Marc Reinig, Daren Dillon, Univ. of California, Santa Cruz (United States)

We compare the performance of competing woofer/tweeter controller architectures for closed-loop AO control. The performance of a proposed distributed modal command architecture is compared with other means of splitting control between the woofer and tweeter mirrors. The performance metrics include Strehl and the efficiency in offloading control authority to the woofer so as to minimize saturation of tweeter actuators. We use on-sky closed-loop deformable mirror telemetry data from currently running AO systems, which may or may not have a Kolmogorov statistic particularly in the low order modes intended for the woofer. The on-sky data is used to anchor simulations of an upgraded system for the Shane Telescope (Lick Observatory) laser guidestar adaptive optics system. This new system will employ a MEMS high-order tweeter, with limited stroke, and a low-order woofer with large stroke capacity.

8617-10, Session 3

Deep tissue imaging by iterative multiphoton compensation technique (IMPACT) and ultrasound guided digital phase conjugation *(Invited Paper)*

Reto P. Fiolka, Ke Si, Meng Cui, Howard Hughes Medical Institute (United States)

Fluorescence microscopy is an indispensable tool in biological research as it allows minimally invasive 3D imaging of living samples combined with highly specific labeling. Unfortunately, optical imaging is so far limited to a few scattering path lengths due to the exponential decay of ballistic light inside biological tissue.

Iterative multiphoton compensation technique (IMPACT) exploits the nonlinearity of the two photon fluorescence process to iteratively compensate the wavefront distortions encountered in biological tissues and thereby restores diffraction limited resolution. Besides the increased clarity of the images, IMPACT also enables tremendous gains in signal, since not only aberrations but also the scattering process is partially compensated. As a result, the focus intensity does no longer decay exponentially with imaging depth.

We demonstrate imaging through highly scattering media like thinned mouse skull or fixed brain tissue. To highlight the possibilities in biological imaging we acquired images of GFP labeled Tcells inside Lymph nodes at 800 micron depth.

For even deeper imaging beyond the ballistic regime we present recent progress on ultrasound guided digital optical phase conjugation (DOPC). Here, an ultrasound focus serves as a source for frequency shifted light that is recorded and then phase conjugated. By raster scanning the ultrasound focus and performing DOPC, 3D images can be formed at depths above two transport mean free paths where light is completely diffused.

To demonstrate the potential of this new technique, we show fluorescence imaging through thick tissue phantoms (>20 scattering mean free paths) and through a fixed brain slice of 1.2mm thickness.

8617-11, Session 3

Image transmission through an opaque material *(Invited Paper)*

Sylvain Gigan, Sébastien Popoff, Geoffroy Lerosey, Mathias Fink, A. Claude Boccara, Institut Langevin (France)

Scattering of coherent light in heterogeneous biological media and tissues, leads to strong scattering and interferences phenomena which destroy both the spatial amplitude and phase information of any laser illumination. At the spatial level, it gives rise to the well-known “speckle” interference patterns. At the temporal (or spectral) level, a short pulse entering a scattering medium will be stretched due to the multiplicity of path lengths in the propagating medium. Consequently this greatly limits the imaging of an object through a scattering medium.

Multiple scattering is a highly complex but nonetheless deterministic process: it is therefore reversible, in the absence of absorption. Speckle can be coherently controlled. By « shaping » or « adapting » the incident wavefront, it is in principle possible to control the propagation and to overcome the scattering process.

Thanks to a phase-only spatial light modulator and an interferometric measurement scheme on a camera, we recently showed that it was possible to measure the so-called transmission matrix of a thick opaque multiple scattering medium. I will detail our recent results on spatial focusing, temporal focusing, imaging and phase conjugation through such a multiple scattering media, and show the interest of spatial light modulators for coherent light manipulation in complex media.

8617-12, Session 3

Focusing through dynamic scattering media *(Invited Paper)*

Thomas G. Bifano, Boston Univ. (United States)

Historically, it was believed that the randomization of light by scattering obviated its use in imaging. Recently, it has been shown that by proper wavefront shaping with a DM, imaging can occur through static scattering (nearly opaque) media. We demonstrate steady-state control of coherent light propagating through dynamic scattering media. The phase of an incident beam is controlled both spatially and temporally using a 1020-segment MEMS spatial light modulator. We achieve focal intensity enhancement of up to 400 for dynamic media with speckle decorrelation time constants ranging from less than one seconds to more than ten seconds. The result is consistent with expectations: time reversibility of monochromatic light implies that wavefront shaping will allow focusing of light, even through scattering media. Ultimately, the technique demonstrated here could be extended to allow imaging through highly dynamic scattering media, for sample in human tissue, battlefield obscurants, murky water, etc.

8617-13, Session 3

Interferometric focusing of guide-stars for direct wavefront sensing *(Invited Paper)*

Xiaodong Tao, Univ. of California, Santa Cruz (United States); Ziah Dean, Univ. of California, Santa Cruz (United States) and Univ. of Michigan (United States); Oscar A. Azucena Jr., Joel Kubby, Univ. of California, Santa Cruz (United States)

Optical microscopy has become an important tool for biological research and continues to open new avenues in it capabilities. However the penetration depth for optical imaging is still limited. As light passes through biological tissue it can be absorbed, refracted and scattered, limiting the resolution and depth of optical imaging in biological tissues. To overcome these challenges, adaptive optics using direct wavefront sensing has been applied for live deep tissue imaging. The wavefront measurement depends on the emission light from the guide-star. However the scattering effect will limit the amount of photons delivered to the guide star. The scattering light will also increase the background noise from neighboring guide-stars. Both of these effects decrease the signal to noise ratio for wavefront measurements.

In this paper, we propose to use interferometric focusing, rather than conventional geometric focusing, of excitation light onto a guide-star embedded deeply in tissue to increase its fluorescence intensity, and thus overcome signal loss caused by scattering. Interferometric focusing uses the coherent properties of light to cause constructive interference at the focus. With fluorescence from the illuminated laser guide-star, we have made wavefront measurements. These measurements will subsequently be used in our AO confocal microscope to overcome refractive image aberrations using adaptive geometric optics. With the interferometric focusing of light, we increase the intensity of the laser guide-star through scattering tissue by more than three times and potentially double the thickness of tissue that can be corrected using AO microscopy.

8617-14, Session 3

Mapping optical aberrations in thick tissues with 3D resolution *(Invited Paper)*

Delphine Débarre, Ctr. National de la Recherche Scientifique (France); Jun Zeng, Pierre Mahou, Marie-Claire Schanne-Klein, Emmanuel Beaurepaire, Ecole Polytechnique (France)

In recent years, aberration correction for microscopy has been shown to significantly improve the quality of nonlinear images when focussing inside thick biological samples. In image-based adaptive optics (AO), a metric (such as brightness or sharpness) is calculated from images acquired with a series of aberration applied, and the initial amount of aberration is then estimated using a simple maximization algorithm. This approach has proven successful in two-photon fluorescence microscopy and third-harmonic generation microscopy[1-2].

Here we demonstrate a simple method for mapping optical aberrations with 3D resolution within thick samples. Similarly to usual image-based AO, the method relies on the local measurement of the variation in image quality with externally applied aberrations. We discuss the accuracy of the method as a function of the signal strength and of the aberration amplitude and we derive the achievable resolution for the resulting aberration maps.

We then report on measured 3D aberration maps in human skin biopsies and mouse brain slices. From these data, we analyse the consequences of tissue structure and refractive index distribution on aberrations and imaging depth in normal and cleared tissue samples.

Finally, such aberration maps allow the estimation of the typical aplanetism region size over which aberrations can be uniformly corrected. This method and data thus pave the way towards efficient correction strategies for tissue imaging applications [3].

[1] Débarre et al, Opt. Lett. 34 (2009).

[2] Olivier et al, Opt. Lett. 34 (2009).

[3] Zeng et al, Biomed. Opt. Expr. 3 (2012).

8617-15, Session 3

New adaptive optics methods for superresolution microscopy *(Invited Paper)*

Martin Booth, Brian Patton, Daniel Burke, Univ. of Oxford (United Kingdom); Travis J. Gould, Joerg Bewersdorf, Yale Univ. (United States)

A range of superresolution microscopes have been developed that are able to resolve features well below the diffraction limit. These microscopes - including scanning methods (STED, RESOLFT, etc.) and stochastic wide field methods (PALM, STORM, GSDIM, etc.) - all suffer from the effects of aberrations that compromise resolution, signal and consequently image quality. Adaptive optics (AO) has already been demonstrated in a range of diffraction-limited resolution microscope modalities to compensate for system and specimen-induced aberrations. However, the use of adaptive optics in superresolution microscopes presents new challenges, as the resolution and efficiency of these microscopes can be particularly sensitive to aberrations. We introduce combined adaptive systems using spatial light modulators and deformable mirrors to perform automated alignment and adaptive aberration correction. A new sensorless AO scheme is presented that permits the adaptive compensation of aberrations in the 3D stimulated emission depletion (STED) microscope through optimization of a new image quality metric incorporating both image brightness and sharpness information. This system is used to perform three-dimensionally resolved superresolution imaging through thick (~10 to 50 micrometre) specimens. Significant improvements in resolution and image intensity are achieved. We further investigate the effects of aberrations on the localization precision in stochastic widefield superresolution methods. We present experimental and computational methods for adaptive aberration correction using image information. These developments will be an essential step to the application of superresolution methods in a wider range of biologically relevant specimens.

8617-16, Session 3

Pupil-segmentation-based adaptive optics for in vivo brain imaging *(Invited Paper)*

Na Ji, Howard Hughes Medical Institute (United States)

To image deep inside a mouse brain in vivo, optical aberrations have to be compensated in order to achieve high resolution. Here we present our recent results on characterizing the optical aberrations measured in mouse brains in vivo up to 450 micron depth. We utilized adaptive optical methods based on pupil segmentation to correct these sample-induced aberrations and achieved diffraction-limited resolution using two-photon fluorescence microscopy. Most recent technical advances of adaptive optical microscopy will also be discussed.

8617-17, Session 3

High-speed phase-control for light focusing through dynamic turbid media *(Invited Paper)*

Donald B. Conkey, Antonio M. Caravaca-Aguirre, Eyal Niv, Rafael Piestun, Univ. of Colorado at Boulder (United States)

The optical imaging depth in biological materials is limited by the scattering of light in tissue. New methods which control light propagation through scattering media have been introduced with the potential to overcome the scattering of light in biological materials. These techniques shape the incident wavefront to pre-compensate for the scattering effects of light propagation in the material and beyond. However, living biological materials have speckle decorrelation times on the millisecond timescale. This fast rate of change makes liquid crystal spatial light modulation (LC-SLM) devices too slow for this task. To achieve the required wavefront control with high modulation speeds we present binary-amplitude off-axis computer-generated holography implemented on a deformable mirror device (DMD). Binary amplitude off-axis holography is a method for the generation of arbitrary wavefronts, and in particular uniform-amplitude phase-modulated images. As a result, we are able to simultaneously encode phase modulated wavefronts at the high frame rate of binary amplitude DMDs. This wavefront encoding technique allows for focusing through temporally dynamic turbid materials at a rate which approaches the decorrelation time of living biological tissue. We demonstrate this technique by high speed wavefront optimization focusing through a dynamic, strongly scattering sample with short speckle decorrelation times. With this approach we demonstrate an order of magnitude improvement in measurement speed over the previous fastest wavefront determination method and three orders of magnitude improvement over LC-SLM methods.

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Part of Proceedings of SPIE Vol. 8618 Emerging Digital Micromirror Device Based Systems and Applications V

8618-1, Session 1

Medical applications of real-time 3D camera in image-guided radiotherapy *(Invited Paper)*

Shidong Li, Temple Univ. Hospital (United States); Tuotuo Li, Jason Geng, Xigen, LLC (United States)

Real-time stereovision of patients can be used, together with pretreatment tomography of internal structures, for image-guided radiotherapy (IGRT) of cancer. Due to the lack of robust four-dimensional (4D) sensors and effective synchronization of the real-time stereovision with tomography, almost all existing IGRT systems use 3D or 2D techniques. We have recently exploded 4D solutions to address dynamic changes of human anatomy in clinical situations. First, a unique fast 3D camera (i.e., 4D video imaging) is made by combining multiple imaging sensors within a single compact device to provide dynamic surface imaging. Second, an automatic surface-motion identifier is developed that can recognize respiration patterns according to the moving surface areas. Third, a novel correlation of the surface motion with internal target displacement is proposed that allows us to determine the target displacement and volumetric changes during radiation beam-on time. We captured some 4D video and CT images on motion phantoms and human subjects. Using these 4D data, we are able to demonstrate that the 4D approach can significantly improve the accuracy and precision in IGRT. We have conducted several clinical investigations using 3D video systems in which we have validated the effects of lighting conditions, angle of image acquisition, and skin tone on video images. We have effectively double the precision in stereotactic radiotherapy of brain tumors, intensity-modulated radiotherapy of head & neck cancer and breast cancer. We have recently initiated a clinical trial for 4D-video IGRT. The 4D-video guidance can be used for real-time image-guided biopsy of small lung nodules.

8618-2, Session 1

Performance assessment of 3D surface imaging technique for medical imaging applications

Tuotuo Li, Jason Geng, Xigen, LLC (United States); Shidong Li, Temple Univ. Hospital (United States)

Recent development in Optical 3D surface imaging technique provides a better way to digitalize the 3D surface and its motion in real-time. 3D surface imaging technique has great potential for many medical imaging applications, such as motion monitoring of radiotherapy, pre/post evaluation of plastic surgery and dermatology, to name a few. Various commercial 3D surface imaging systems with different dimension, speed and accuracy have appeared on the market. For clinical applications, the accuracy, reproducibility and robustness across the widely heterogeneous skin color, tone, texture, shape properties, and ambient lighting is very crucial. Till now, a systematic approach for evaluating the performance of different 3D surface imaging systems still yet exist. In this paper, we present a systematic performance assessment approach to 3D surface imaging system assessment for medical applications. We use this assessment system to exam a new real-time surface imaging system we developed for image-guided radiotherapy (IGRT). The assessments include accuracy, field of view, coverage, repeatability, speed and sensitivity to environment, texture and color.

8618-3, Session 1

Automatic respiration tracking for radiotherapy using optical 3D camera

Tuotuo Li, Xigen, LLC (United States); Shidong Li, Temple Univ. Hospital (United States); Zheng Geng, Xigen, LLC (United States)

Respiration tracking is an important topic for accurate 4DCT acquisition and IGRT for lung cancer. With the advance of 3D imaging technology, O3D based systems provide accurate digitized 3D surface in real-time, with no patient contact nor radiation. The accurate 3D surface images provide crucial information for accurate patient reposition and respiration management in radiotherapy. However, due to the difference of body shape and physical condition across different patients and the extremely high dimensionality of the 3D surface data, analyzing the surface motion to extract respiration patterns is no easy task. Commercial O3D IGRT systems currently relays on manual selection of points or makers on the 3D surface for surface motion tracking while ignoring the information from unselected area. Manual selected maker and area can be inconsistent cross different session, and selected area itself can be inconsistent to each other making it difficult to analyze and interpret the respiration patterns. In order to resolve those issues, we propose a new approach to respiration analysis based on linear dimensionality reduction which does not require human intervene. Optical 3D image sequence is decomposed with PCA (principle component analysis) into a limited number of independent (orthogonal) motion patterns (a low dimension eigen space span by eigen-vectors). New images can be accurately represented as weighted summation of those eigen vectors, which can be easily discriminated with a trained classifier. Experimental result shows that our approach is more accurate and robust, even in the presence of incomplete data.

8618-4, Session 1

Spectral light source distribution variations to enhance discrimination of the common bile duct from surrounds in reflectance hyperspectral images

Maritoni Litorja, Mira Fein, National Institute of Standards and Technology (United States); Eleanor F. Wehner, The Univ. of Texas at Arlington (United States); Edward Livingston, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States); Karel J. Zuzak, Digital Light Innovations (United States)

The classification of anatomical features using hyperspectral imaging has been a common goal in biomedical imaging, and has been successfully employed in surgical settings. Identification and location of the common bile duct is critical in cholecystectomies and related procedures. In this study, surgical images where the common bile duct is visible to the surgeon during open surgeries were acquired. The distribution of the light source used during acquisition is effectively nullified through normalization, leaving only the intrinsic reflectance property of the object, i.e., the tissues during a clinical procedure. These normalized images are convolved with simulated light sources to enhance contrast between the common bile duct and surrounding tissue through luminance and chromatic differences. One of the goals of this study is to determine optimal spectral light distribution within the constraints of human visual preferences, i.e., close to the Planckian locus, to promote the use of spectrally tailored light source for feature discrimination in surgery. Optimal spectral source distribution for computational image analysis, where there are no constraints due to visual preferences are also explored. Results from both analyses will be discussed.

8618-5, Session 2

Utility of active DLP hyperspectral illumination in characterizing DIEP flap perfusion: characterization of perforators and clinical validity

(Invited Paper)

Michel Saint-Cyr, Mayo Clinic (United States); Chrisovalantis Lakhiani, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States); Angela Cheng M.D., Emory Univ. (United States); Sumeet Teotia, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States); Karel J. Zuzak, Digital Light Innovations (United States)

Background: The Digital Light Hyperspectral Imager (DLHsI™) consists of a digitally controlled light source, a digital micromirror device consisting of approximately 1 million, 16 µm square mirrors. The system actively illuminates the skin's microvasculature with precisely known continuous convolutions of color, spanning the visible spectrum (380-780 nm). Hemoglobin reflects the light differently based on its level of oxygenation which, when detected by a digital Charge-Coupled Device (CCD) camera and is processed using a chemometric algorithm, visualizes the chemical content (i.e. %HbO2) for large fields of view, for example, the abdomen or breast. The DLHsI™ system is placed remotely, in this case, approximately two feet from the patient making it a non-invasive measure and virtually unobtrusive to the patient and surgical team. Such a system for dynamic visualization of tissue oxygenation may aid in intraoperative perforator selection and decrease patient morbidity by identifying poorly perfused flap areas.

Purpose: To determine the utility of the DLHsI™ system in evaluating DIEP flap perfusion and perforator selection.

Methods: Eighteen patients were imaged before, during, and after DIEP flap harvest. Perforators were marked and compared with DLHsI™ images in order to assess perfusion territory. Clinical outcomes were retrospectively compared with imaging data to correlate DLHsI™ findings with postoperative course.

Results: Flaps raised on a single medial or lateral perforator were individually analyzed to assess perfusion within discrete perforasomes. Zone I had the highest perfusion (%HbO2 = 67%), compared to Zone 2 (66%), Zone III (64.2%), and Zone IV (62.8%), as expected. These results were statistically significant using one-way ANOVA analysis (p=0.01). Two patients (11.1%) developed fat necrosis postoperatively and areas of observed fat necrosis correlated to levels of decreased perfusion found at the time of surgery using DLHsI™ imaging.

Conclusions: Hyperspectral imaging is a novel noninvasive diagnostic tool to quantify tissue oxygenation and generate anatomically relevant maps of microcirculatory changes seen during flap harvest. Unlike CTA, this system allows for dynamic visualization of tissue perfusion intraoperatively. This is of value in perforator selection, obviating the need for multiple perforator harvest, and precluding harvest of poorly perfused areas. This study confirms the reliability DLHsI™ for assessing DIEP flap perfusion, and suggests it may be of value of free perforator flap tissue transfer.

8618-6, Session 2

Hyperspectral image segmentation of the common bile duct in pancreatoduodenectomies

Maritoni Litorja, Daniel V. Samarov, National Institute of Standards and Technology (United States); Eleanor F. Wehner, The Univ. of Texas at Arlington (United States); Edward Livingston, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States)

Over the course of the last several years hyperspectral imaging (HSI) has seen increased usage in biomedicine. Within the medical field in particular HSI has been recognized as having the potential to make an immediate impact by reducing the risks and complications associated with laparotomies (surgical procedures involving large incisions into the abdominal wall) and related procedures. There are several ongoing studies focused on such applications. In the work we present here we focus on pancreatoduodenectomies (commonly referred to as Whipple procedures), a surgical procedure done to remove cancerous tumors involving the pancreas and gallbladder. As a result of the complexity of the local anatomy, identifying where the common bile duct (CBD) is can be difficult, resulting in comparatively high incidents of injury to the CBD and associated complications. It is here that HSI has the potential to help reduce the risk of such events from happening. Because the CBD exhibits a unique spectral signature, we are able to utilize HSI segmentation algorithms to help in identifying where the CBD. In the work presented here we discuss approaches to this segmentation problem and present the results.

8618-7, Session 2

Fluorescence image detection and reconstruction by subtractive light illumination using a digital micromirror device

Jong-Ryul Choi, Donghyun Kim, Yonsei Univ. (Korea, Republic of)

In this presentation, we investigate fluorescence optical detection and image reconstruction based on modulated light illumination using a digital micromirror device (DMD). Fluorescence detection is one of the most common methods to study various cellular dynamics labeled with fluorescent indicators. Although employed in many cell-based assays, wide-field fluorescence microscopy provides poor axial sectioning capability that is insufficient to measure thick cell-based assays, e.g., those with 3D cell complex cultured in a thick extracellular matrix. Confocal fluorescence microscopy, on the other hand, provides highly improved axial sectioning capability compared to wide-field fluorescence imaging. However, confocal microscopy is subject to temporal overhead associated with scanning to acquire fluorescence images.

For the image acquisition at highly improved axial sectioning capability and reduced processing load, we have a developed fluorescence optical detection system based on subtractive light illumination using a DMD. Compared to moving grid masks, a DMD provides fast scanning speed and highly improved flexibility in modulating aperture patterns. In this proof-of concept study, we have observed fluorescence microbeads (? = 10 ?m) for image evaluation which were two-dimensionally deposited on a slide glass and three-dimensionally distributed in a 1-mm thick alginate gel matrix. While DMD-based structured light illumination is not entirely new for super-resolution microscopy, we report here the subtractive reconstruction of improved images by separating in-focus and out-of-focus fluorescence components so that the system can produce 3D fluorescence image stacks with 30% additionally improved axial sectioning capability compared to conventional structured illumination microscopy.

8618-8, Session 2

Attenuation corrected fluorescence extraction using spatial frequency domain imaging

Bin Yang, Manu Sharma, Youmin Wang, James W. Tunnell, The Univ. of Texas at Austin (United States)

Molecular fluorescence imaging has played a significant role in the visualization of tumors and gene expression, and has been demonstrated clinically for image-guided surgery of solid tumors. However, due to strong tissue absorption and scattering, the imaged fluorescent intensity can be distorted. Here, we present a novel technique to image tissue fluorescence free from the distortions of tissue scattering and absorption,

called attenuation corrected fluorescence (ACF) imaging. ACF combines techniques developed for single point (e.g. sensing) extraction of corrected fluorescence and applies it to a whole image using spatial frequency domain imaging (SFDI). We performed in-vitro tissue simulating phantom and ex-vivo tissue studies using a custom built SFDI system. Fluorescein was used for its biological relevance. Three frames of 2D sinusoidal pattern generated by a digital mirror device (DMD) with phase shifts at spatial frequency 0.2/mm were projected to the sample under the illumination of 365nm and 530nm to retrieve the fluorescence and optical properties. Then, a model based on photon migration theory was utilized to perform the correction. In the phantom study, before the ACF correction, the intensity of fluorescence dropped more than 80% at the highest level of the absorption. After ACF correction, this attenuation was reduced to around 10% .The ex-vivo tissue study yielded a similar result. After correction, the fluorescence from the area with and without extra absorption was comparable. The ACF is appropriate for fluorescence applications where attenuation correction is necessary and this approach has the potential for image guided surgery.

8618-9, Session 3

Additive manufacturing of photopolymers using the Texas Instruments DLP lightcrafter

Markus Hatzenbichler, Jürgen Stampfl, Technische Univ. Wien (Austria); Matthias Geppert, Rolf Seemann, FOTEC Forschungs- und Technologietransfer GmbH (Austria)

The use of the Texas Instruments DLP® LightCrafterTM as a compact module in lithography-based additive manufacturing technologies (AMT) is discussed in this paper. For this purpose the light engine is placed underneath a transparent vat which is coated with a PTFE-film and filled with photosensitive resin. By loading an appropriate bitmap into the light engine, the resin can be exposed selectively to obtain a photopolymerized layer. The RGB LED light source exposes with 20 lumen and a DLP 0.3 WVGA chipset is used for light deflection. To integrate the device into the building process a configurable I/O trigger is required, the loaded bitmap should be exposed only in a certain period (exposure time). By stacking up the individual layers with a typical layer thickness between 25 and 50µm, a three-dimensional part is built up. The current setup of the used digital LEDs in combination with a customized optical projection system ensures a spatial and temporal homogeneity of the intensity at the build platform, which is significantly better than with traditionally used engines. It could be shown that this system can fabricate three-dimensional parts with a resolution < 40µm in x-y plane and 15µm in z-axis. Additionally mechanical properties (e.g. bending strength) were measured and the, due to the orientation on the building platform, possible anisotropic effects were assessed. Ceramic-filled polymers were also used and the necessary post-processing steps like the removal of the polymer phase after structuring and the final sintering step to obtain fully dense ceramic parts are discussed.

8618-10, Session 4

Preliminary proton testing digital micromirror devices (DMDs) for space flight

Kenneth D. Fourspring, Zoran Ninkov, Bryan Fodness, Rochester Institute of Technology (United States); Massimo Robberto, Space Telescope Science Institute (United States); Sally R. Heap, NASA Goddard Space Flight Ctr. (United States); Alex G. Kim, Lawrence Berkeley National Lab. (United States)

Astronomers are interested in using DMDs as slit masks in multi-object spectrometers on future space astronomy missions. A favored orbit is at the second Lagrangian point (L2). A requirement for mission planning is to determine how long such MEMs devices would remain operational given the L2 radiation environment, which is primarily composted of solar protons and cosmic rays. To this end we have initiated a program of DMD proton testing. Three DMDs were irradiated with high-energy protons (35-50MeV) at the LBNL 88” Cyclotron at energies sufficient to penetrate the optical window and interact electrically with the device. Modeling was completed using the publically available software package Stopping and Range or Ions in Matter (SRIM). At each irradiation step, an optical test procedure was used to validate the operability of each individual mirror on the DMD array. Each of the DMDs was irradiated to a number of dosage levels and from this lifetime was estimated. Additionally, possible failure mechanisms and unique recoverable single event effects (SEEs) will be discussed. The preliminary results point to DMDs being well suited to use on long-duration L2 space missions.

8618-11, Session 4

Full-frame programmable spectral filters based on micromirror arrays

Steven P. Love, David L. Graff, Los Alamos National Lab. (United States)

Rapidly programmable micro-mirror arrays, such as the DLP digital micro-mirror device (DMD), have opened an exciting new arena in spectral imaging: rapidly reprogrammable, high spectral resolution, multi-band spectral filters that perform spectral processing directly in the optical hardware. Such a device is created by placing a DMD at the spectral plane of an imaging spectrometer, and using it as a spectral selector that passes some wavelengths down the optical train to the final image and rejects others. While simple in concept, realizing a truly practical DMD-based spectral filter has proved challenging. Versions described to date have been limited by the intertwining of image position and spectral propagation direction common to most imaging spectrometers, reducing these instruments to line-by-line scanning imagers rather than true spectral cameras that collect entire two-dimensional images at once. Here we report several optical innovations that overcome this limitation and allow us to construct full-frame programmable filters that spectrally manipulate every pixel, simultaneously and without spectral shifts, across a full 2D image. So far, our prototype, which can be programmed either as a matched-filter imager for specific target materials or as a fully hyperspectral multiplexing Hadamard transform imager, has demonstrated over 100 programmable spectral bands while maintaining good spatial image quality. We will discuss how diffraction-mediated trades between spatial and spectral resolution determine achievable performance. Finally, we will discuss methods for dealing with the DLP’s 2D diffractive effects, and suggest a simple modification to the DLP that would eliminate their impact for this application.

8618-12, Session 4

Infrared adaptive spectral imagers for direct detection of spectral signatures and hyperspectral imagery

Neil Goldstein, Marsha Fox, Steven M. Adler-Golden, Brian Gregor, Spectral Sciences, Inc. (United States)

A MEMS-based hyperspectral imager forms the basis of a compact and robust thermal infrared adaptive spectral imager for visualization, detection, and quantization of chemical species through their characteristic long-wave infrared spectral signatures. The sensor uses a set of concave gratings, a DMD, and a single detector to create spectrally selective scene imagery. Programmable spectral and spatial detection filters superimpose analog spectral detection filter on the image. The sensor may be used as a hyperspectral imager, but more often is used to implement hyperspectral detection filters in hardware to rapidly generate contrast imagery. Programmable spatial light modulators make it possible to switch operating modes and adjust spectral, temporal and spatial resolution. Operating parameters can be optimized in real time, in order to capture changing background and target evolution.

The optical system, consisting of two machined toroidal surfaces, a single-element detector and a digital micromirror device (DMD), covers

the long-wave spectral region of 7-13 microns. Contrast images are obtained by applying an analog transmission function to the DMD using grey scales. Any linear detection algorithm can be implemented in hardware, including traditional methods such as matched filters, orthogonal subspace projection, and principal component analysis.

Results will be presented for field tests and cross-calibration validation experiments, including hyperspectral measurements and the generation of one- and two- dimensional chemical-specific detection images. Methods are described to make generalized matched filters that optimize signal/noise for in-hardware detection.

8618-13, Session 4

A DMD-based multi-object spectrograph on Galileo telescope

Frédéric Zamkotsian, Lab. d'Astrophysique de Marseille (France); Paolo Spanò, INAF - Osservatorio Astronomico di Brera (Italy); Patrick Lanzoni, William Bon, Lab. d'Astrophysique de Marseille (France); Marco Riva, INAF - Osservatorio Astronomico di Brera (Italy); Luciano Nicastro, INAF - IASF Bologna (Italy); Emilio Molinari, Telescopio Nazionale Galileo (Spain); Paolo Di Marcantonio, INAF - Osservatorio Astronomico di Trieste (Italy); Filippo M. Zerbi, INAF - Osservatorio Astronomico di Brera (Italy); Luca Valenziano, INAF - IASF Bologna (Italy)

Next-generation infrared astronomical instrumentation for ground-based and space telescopes could be based on MOEMS programmable slit masks for multi-object spectroscopy (MOS). This astronomical technique is used extensively to investigate the formation and evolution of galaxies. We propose to develop a 2048x1080 DMD-based MOS instrument to be mounted on the Galileo telescope and called BATMAN. A two-arm instrument has been designed for providing in parallel imaging and spectroscopic capabilities. The two arms with F/4 on the DMD are mounted on a common bench, and an upper bench supports the detectors thanks to two independent hexapods. Very good optical quality on the DMD and the detectors will be reached.

ROBIN, a BATMAN demonstrator, has been designed, realized and integrated. It permits to determine the instrument integration procedure, including optics and mechanics integration, alignment procedure and optical quality. First images and spectra have been obtained and measured. Variable spatial bin and variable spectral resolution have been obtained, and any combination of the above modes over the whole FOV is foreseen. MOS as well as IFU-like (scanning slit) modes, with any slit mask configurations are reconfigurable in real time. Finally, observation strategies will be studied and demonstrated for the scientific optimization strategy over the whole FOV.

BATMAN on the sky is of prime importance for characterizing the actual performance of this new family of MOS instruments, as well as investigating the operational procedures on astronomical objects. This instrument will be placed on the Telescopio Nazionale Galileo during next year, in 2013.

8618-14, Session 4

Real-time matched-filter imaging for chemical detection, using a DMD-based programmable filter

Steven P. Love, David L. Graff, Los Alamos National Lab. (United States)

Hyperspectral imaging sensors have proven to be powerful tools for highly selective and sensitive chemical detection applications, but have some significant operational drawbacks, including the large size of the resulting data cubes and a detection time-lag due to the computationally demanding matched-filter analysis. For applications where only a single chemical is of interest, a simple optical filter set, with bands matched to the chemical signature, can trade a hyperspectral sensor's high resolution and continuous spectral coverage for real-time 2D chemical imaging with nearly no post-processing requirements. While a substantial theoretical basis exists for defining optimal spectral band configurations, existing band-pass interference filter technology is severely limited in its ability to reproduce the required spectral complexity. We have recently developed a high-speed, high-resolution, programmable spectral filter based on the DLP digital micro-mirror device (DMD) that can choose or reject dozens or hundreds of spectral bands and present them simultaneously to the camera's sensor to form a complete 2D image. With this new technology, even very complicated matched filters can be implemented directly into the optical train of the sensor, producing an image highlighting the target chemical within a spectrally cluttered scene in real time. Examples of matched-filter images recorded with our visible-spectrum prototype will be presented, and extensions to other spectral regions will be discussed. Finally, we will discuss strategies for implementing more sophisticated clutter-suppressing matched filters on the DMD-based system, including schemes that approximate the subtlety of post-processing algorithms by utilizing the DMD's duty-cycle-based gray-scale capability.

8618-15, Session 5

3D shape measurement of translucent objects using digital fringe projection *(Invited Paper)*

Rongguang Liang, College of Optical Sciences, The Univ. of Arizona (United States)

3D Shape measurement of translucent object is challenge because light scattering inside the object will impact the measurement accuracy. This presentation will discuss the challenges and potential solutions for measuring 3D shape of translucent object.

8618-16, Session 5

Binary pattern codification strategies in an active stereoscopic system based on flexible image guides

Erwan Dupont, YingFan Hou, Frederic Lamarque, Univ. de Technologie Compiègne (France); Tanneguy Redarce, Institut National des Sciences Appliquées de Lyon (France)

A good variety of three dimensional (3D) measurement systems that can extract shape information's with sub millimetric accuracy is available in the industry. However, they generally are of macroscopic size and measuring on confined areas is not feasible. To miniaturize such systems, the step proposed is the integration of flexible image guides combined with compact optical probes.

This miniaturization process is tested on an active stereoscopic measurement system. In the projection channel of the system, a digital micro-mirror device (DMD) generates structured binary patterns from an incoherent white light source and injects them into a first image guide. Then, a compact optical system projects the pattern on the measurement area. The same configuration principle is applied to the acquisition channel and allows the capture of the measurement area through a second image guide and finally to a digital camera.

In this miniaturized system, image guides have lower resolution than in standard imaging devices. Indeed they are equivalent of 70k pixels devices to compare to the almost 800k pixels of the DMD and camera. That implies lower 3D axial and lateral resolutions and consequently the shape reconstruction method must be carefully chosen. In this paper, we tested several reconstruction strategies such as tuning the projected patterns frequency and also phase shift versus gray code based methods. Finally, we obtained a lateral resolution of 25 micrometers, an axial resolution of 10 micrometers over a field of view of 20 square millimeters for a depth of field of 1 millimeter.

8618-17, Session 5

Multi-wavelength compressive computational ghost imaging

Stephen S. Welsh, Matthew P. Edgar, Miles J. Padgett, Univ. of Glasgow (United Kingdom)

Ghost Imaging has been an area of active research for around two decades and works on a classical approach by projecting a random but known ''pattern" onto an object and measuring the reflected signal for that pattern, giving that pattern a weighting factor, or measure of how representative that a given pattern was of the object. After a series of patterns have been measured for a given object, an algorithm can work to reconstruct the object from these weighting factors either iteratively or by matrix inversion when the system is well-conditioned . Recent advances in the field have allowed for much faster image acquisition times from hours to minutes and higher quality image reconstruction which gives the possibility of using this approach to produce a practical imaging device. Moreover, the goal of this work is creating a device with the ability to simultaneously reconstruct in multiple individual wavelength's by both introducing additional detectors and appropriate interference filters. This would lead to a selective hyper spectral imaging device that could reconstruct multiple wavelengths at a sub Nyquist-Shannon sampling level by exploiting sparisity and processing the resultant ill-conditioned data set, which is known as compressed sensing. The resultant practical applications could be a cheap and low power camera or since the wavelength reconstructed is selective it is proposed that one could select appropriate bands to monitor absorption lines in gas mediums.

8618-33, Session 5

Single-image method to depict 3D profiles

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Extracting 3D profile with captured 2D images is a growing area of interest, two of the popular methods include Fourier transform profilometry (FTP) and phase shifting profilometry (PSP). In FTP, a periodic grating is projected on to the surface of a diffusely reflective object. When this grating image is observed under an angle with the projection direction, the grating lines deform due to the object surface shape. Image processing of the captured deformed grating lines reveals the 3D profile of the object of interest. Despite its capability to extract object profiles with single image, FTP fails in reliably extracting 3D profiles of objects with (n is a nonzero integer) phase jumps. Methods involving multiple images like the famous PSP also suffer with the problems of phase unwrapping for objects with phase jumps. This problem stems from the fact that the grating is periodic, lacking a signature for each period.

Proposed method uses a modified Ronchi grating, where the amplitude of the square wave is made unique for every cycle. The grating amplitude is decreased from one end to the other end. This ensures a unique signature to every cycle, which can be used for reliable phase unwrapping even in the presence of $2n\pi$ phase jumps. The modified grating image is split into two images: A gray coded pattern equivalent and a Ronchi equivalent. With these two derived images, one can depict the 3D profile of objects [1]. Current article deals with the theory and experiments of the proposed method.

8618-18, Session 6

Super resolved and field of view enhanced DLP based remote imaging configurations
(Invited Paper)

Zeev Zalevsky, Alex Zlotnik, Bar-Ilan Univ. (Israel)

In this paper we discuss unique super resolving configurations that are integrating two DLPs modules in the aperture and/or in the intermediate image plane. The usage of the DLPs can allow obtaining improved geometrical resolution and to realize optical zooming operation without changing the focal length of the imaging lens. It addition the method can also allow overcoming various common imaging aberrations such as defocusing and blurring that is obtained due to relative movement occurring during the integration time. Further to that, the proposed configuration will be used to increase/enhance the field of view of a given imaging system without physically applying any mechanical scanning operation. The idea behind all the above mentioned applications is to use the DLPs to properly encode the space and the spatial frequency domains such that the object's information can be separated from the above mentioned aberrations, distortions, limitations and noises that are being incorporated by any real imaging system. Besides the unique hardware configurations that the paper will focus on, the paper will also discuss the considerations behind the encoding/decoding codes that are chosen for the processing process such that compressed sensing concepts can be realized.

8618-19, Session 6

DMD-based scanning of steep wavefronts for optical testing of freeform optics

Stephan Stuerwald, Fraunhofer-Institut für Produktionstechnologie (Germany); Robert Schmitt, Fraunhofer-Institut für Produktionstechnologie (Germany) and RWTH Aachen Univ. (Germany)

Optical, full field testing of aspheres and especially freeform optics still remains a challenging task. Till now, various measurement setups for wavefront characterisation have been presented for functional testing. These are primarily based on microlens arrays in front of a photosensitive semiconductor in combination with an analysis logic. Compared to other sensor types for optical testing the Shack-Hartmann sensor (SHS) features a high flexibility with regard to wavefront deformations. For SHS the measurement range is limited due to the measurement principle that all measurement points are detected simultaneously by an imaging device and the signals must be separable - thus the dynamic range is defined by the number of micro-lenses and the resolution of the imaging sensor. Here, we present an approach for wavefront measurements which increases the dynamic range and the lateral resolution simultaneously.

The concept is based on a selection and thereby encoding of single sub-apertures of the wavefront under test and to measure the wavefronts slope consecutively in a scanning procedure. In contrast to the LCD based approaches, here the selection of the sub-apertures and thus the scanning procedure is performed by a digital micro-mirror array (DMD). The use of a DMD allows high lateral resolution as well as a very fast scanning ability. The measurement concept and performance of this method will be demonstrated for different freeformed specimens like progressive eye glasses. Furthermore, approaches for calibration of the measurement system will be characterised comprehensively and the optical design of the detector will be discussed in detail.

8618-20, Session 6

Encoding complex values using two DLP® spatial light modulators

Sih-Ying Wu, Michael F. Becker, The Univ. of Texas at Austin (United States)

We present a method to encode continuous complex values (from the complex unit circle) into quantized complex values for wavefront modulation using two digital micromirror devices (DMDs). The capability to encode complex values offers advantages to eliminate the twin (conjugate) image or suppress the zero order diffraction (ZOD) as well to improve reconstruction fidelity for far-field and Fresnel holograms. The proposed method utilizes the coherent summation of beams from two DMDs. Path phase difference is used to control the type of complex encoding that result from the 4 possible modulation states. The optical architecture utilizes a Michelson interferometer with a DMD in Littrow configuration replacing the mirror in each arm. Continuous phase information is first transformed into binary form and encoded on each DMD. The beams are summed as ([0 or 1]) + [0 or 1]exp(i*phi) for each pixel, where phi is the phase difference between the two beams. For example, the system can encode complex values such as 1,i and (1 + i), or 1 and -1. Different encoding schemes result in different degrees of twin image or ZOD suppression. No twin image is generated if phi = pi /2, and the four states are assigned to quadrants of the complex unit circle. When phi = pi the encoding has three states [-1, 0, 1], and the ZOD can be completely suppressed. We examined the performance of this system using numerical simulation to explore different encoding methods and experimental measurements of the reconstructed hologram quality.

8618-21, Session 6

DMD as a diffractive reconfigurable optical switch for telecommunication

Pierre-Alexandre J. Blanche, Daniel N. Carothers, Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

Digital micro-mirror device (DMD) by their high switching speed, stability, and repeatability are a promising devices for fast, reconfigurable telecommunication switches. However, their binary mirror orientation is an issue for conventional redirection of a large number of incoming ports to a similarly large number of output fibers like with analog MEMS.

We are presenting here the use the DMD as a diffraction based optical switch, where Fourier diffraction patterns are used to steer the incoming beams to any output configuration. Fourier diffraction patterns are computer generated holograms that structures the incoming light into any shape in the output plane. This way, the light from any fiber can be redirected to any positions in the output plane. The incoming light can also be split to any positions in the output plane. This technique has the potential to make an “any to any” reconfigurable switch with high port count, solving some the problems of the present technology.

During the presentation, we will demonstrate the possibility of such a switch, characterize the DMD for the 1.5 micron telecommunication wavelength, address the issues such a technology currently facing, and suggest modifications to the DMD to make it more efficient.

8618-22, Session 7

Highly scalable DLP based head tracking system

Stephen A. Kupiec, Vladimir B. Markov, Advanced Systems & Technologies, Inc. (United States); Arthur R. Hastings Jr., U.S. Army Night Vision & Electronic Sensors Directorate (United States)

We report on the development of a highly scalable head tracking system capable of tracking many users. Throughout the operating area, a series of high-speed near-infrared LED-based Digital Light Processor (DLP) picoprojectors provide overlapping illumination of the volume.

Each projector is driven with a sequence of binary images which encode the position of each pixel within the projected image as well as an identifier sequence for the projector. Overlapping projectors use differing temporal carrier frequencies to allow sensor discrimination and background rejection. Pixel positions from multiple projectors received by each sensor are triangulated to obtain position and orientation.

In many regards this may be considered a time-reversed version of conventional optical tracking systems, in which projectors broadcasting to photosensors replace cameras sensing fiducials.

This eliminates the processing bottleneck associated with analysis of the camera imagery, particularly when the number of users increases. In comparison our system operates in a manner conceptually similar to the Global Position System in that angularly encoded beacons (projectors) broadcast to independent IR receivers. This confers many of the same advantages in that each receiver is independent allowing for any number of users to interact without interference or added computational load. Additionally multiple overlapping projector footprints can be used scale the system volume indefinitely.

8618-23, Session 7

An interactive multiview 3D display system

Zhaoxing Zhang, Zheng Geng, Institute of Automation (China)

The progresses in 3D display systems and user interaction technologies will help more effective 3D visualization of 3D information. They yield a realistic representation of 3D objects and simplifies our understanding to the complexity of 3D objects and spatial relationship among them. In this paper, we describe an autostereoscopic multiview 3D display system with capability of real-time user interaction. Design principle of this autostereoscopic multiview 3D display system is presented, together with the details of its hardware/software architecture. A prototype is built and tested based upon multi-projectors and horizontal optical anisotropic display structure. We apply the Open Source Computer Vision (OpenCV) library to achieve the image perspective transformation from the projectors to the display screen. And we use the Open Graphics Library (OpenGL) to complete the rendering process. In addition, the OpenNI frameworks are involved to enable the user interaction through human hand gestures. Experimental results illustrate the effectiveness of this novel 3D display and user interaction system as a 10 Mega-pixel autostereoscopic multiview 3D scene is realized with the real-time human hand gestures user interaction.

8618-24, Session 7

Single DMD time-multiplexed 64-views autostereoscopic 3D display

Luigi Loreti, Opto-Electronics s.r.l. (Italy)

Based on previous prototype of the Real time 3D holographic display developed last year , we realized a a fully working prototype of a multiview (64 views), wide angle (90°) 3D full color display.

The display is based on a RGB laser light source illuminating a DMD (Discovery 4100 0,55") at 25.000 fps, a scanning system (galvo, polygonal or MEMS) on the Fourier plane, a custom parabolic mirror system and a holographic vertical diffuser.

A VHDL firmware to render in real-time (16 ms) 64 views (16 bit 4:2:2) of a CAD model (obj, dxf or 3Ds) and depth-map encoded video images was developed into the resident Virtex5 FPGA of the Discovery 4100 SDK, thus eliminating the needs of image transfer and high speed links.

8618-25, Session 7

High-dynamic range DMD-based scene projection

Julia Rentz Dupuis, David J. Mansur, Robert Vaillancourt, Ryan Benedict-Gill, Scott P. Newbry, OPTRA, Inc. (United States)

Infrared (IR) DMD-based scene projectors have enjoyed considerable success in IR threat detector testing and training applications, however, their utility for testing future generations of these instruments is limited by the maximum achievable contrast as well as the inherent tradeoff between frame rate and bit-depth. In this paper we describe a novel solution to both issues where we employ a second DMD to impose a structured illumination on the projector DMD. The "source conditioning" DMD is operated in binary mode where the input image is displayed as a half-tone image for the full frame duration of the projector DMD, which is operating with traditional pulse-width-modulated grayscale. The relay optics between the two DMDs impose a low pass filter on the binary image and produce the structured illumination. The resulting product between the structured illumination and the projected image has two important characteristics: the maximum achievable contrast is high since the source conditioning DMD can effectively extinguish the illumination, and the effective bit-depth is infinite, regardless of the frame rate, because the source conditioning DMD is not pulse-width-modulating. The overall result represents a breakthrough with regard to the traditional contrast and bit-depth/frame rate limits of current DMD-based scene projectors.