Contents

7926: Micromachining and Microfabrication Process Technology XVI ........................................... 2
7927: Advanced Fabrication Technologies for Micro/ Nano Optics and Photonics IV ........................................ 7
7928: Reliability, Packaging, Testing, and Characterization of MEMS/MOEMS and Nanodevices X .................. 18
7929: Microfluidics, BioMEMS, and Medical Microsystems IX .......... 25
7930: MOEMS and Miniaturized Systems X .................................................. 36
7931: MEMS Adaptive Optics V ............................................................... 46
7932: Emerging Digital Micromirror Device Based Systems and Applications III ............................................. 52
Near damage threshold micromachining on the chrome stainless mold steel using the femtosecond laser

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In spite of its advantage over the long pulsed laser, the application of femtosecond laser on the metals especially on the chrome based stainless mold steel had been limited due to the high thermal diffusivity of the material. Most previous femtosecond laser machining on metal focused on the fundamental laser material interactions such as the damage threshold, the ablation rate and the effect of pulse duration.

In this study, the femtosecond laser induced morphological changes on the stainless mold steel were studied, especially at near-damage threshold fluence regime. Two different irradiation modes were employed; the stationary beam and the scanning beam mode. The scanning beam mode was defined as the irradiation of laser beam during the linear translation of the sample. The stationary beam induced damage threshold and the morphology changes were examined using a scanning electron microscopy. The scanning beam induced morphological change was studied using various laser parameters including the pulse energy, scanning speed and the polarization of the incident beam. The correlation between the stationary beam induced damage and the scanning beam induced damage were discussed. We also demonstrated that a femtosecond laser can fabricate micron-size gratings and nano-scale structures on the surface of the chrome stainless mold steel. The potential application of femtosecond laser for the chrome stainless mold steel has been discussed.

Improved out-coupling efficiency of OLED with micro-lens array by screen printing

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Generally, OLED has highly internal quantum efficiency, but the typical out-coupling efficiency is as low as 20% because the most of light is lost due to the mismatch of the refractive index between air and the organic layer. This low coupling efficiency becomes the main limitation of high efficiency. Therefore, many researchers focused on micro-lens array in order to improve out-coupling, but need to complex fabrication procedure such as photo-lithography and micro-molding etc.

In this study, we investigated micro-lens array based on screen printing method to improve out-coupling efficiency for OLED. Proposed micro-lens array has more simple fabrication procedure than reported another method.

OLED device comprises simply five layers (ITO, HIL, HTL, EML, A1), which can be made by all solution process except the electrodes. To form the micro-lens with high degree on fabricated PLED device, we performed hydrophobic treatment on glass substrate by solvent process. The micro-lens array formed with 100 μm by printing method using shadow mask and UV adhesive polymer.

In results, luminescence of device without micro-lens has value of 10,620 cd/m2 and device with micro-lens has value of 13,410 cd/m2. The out-coupling was enhanced about 26% by using micro-lens. Therefore, we suggest the micro-lens array based on screen printing method to improve the out-coupling efficiency of OLED.

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Design and fabrication of a CMOS MEMS logic gate

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This study aims to design and fabricate a MEMS logic gate via commercially available CMOS process. The proposed logic gate design has the advantages of small silicon footprint, and implementing NAND gate, NOR gate functions with the same mechanical structure. Therefore, it is promising if this device can be fabricated in situ with other IC components. Compared to existing CMOS MEMS designs using foundry processes, the proposed design imposes several new challenges: carrying two voltage levels on a non-warping suspended plate, see-saw motions with dimple structures, and metal-to-metal contact between shuttle electrodes and fixed electrodes. In this study, the employed fabrication process is TSMC 2P4M®. The sacrificial layer is designed to be a metal layer; the suspended structure is a composite structure consisting of oxide and metal films; the dimple structures are tungsten plugs. Different combinations of oxide-metal films are investigated to achieve a non-warping suspended plate. The optimized one is the combination of oxide-3, metal-3, and oxide-2 films. Several wet etchants are investigated to remove sacrificial (metal) layer without attacking the oxide films and tungsten plugs. In a prototype design, the device is 250 μm long, 100 μm wide, and 1.5 μm thick. The experimental results show that the suspended plate slightly curls down 0.85 μm. This device can operate at ±10 V and achieve the proposed logic functions. However, tungsten plugs were slightly damaged during the removal of titanium nitride. Currently, the functionality of the device was verified through optical observations instead of electrical readouts.

Develop a novel thermal switch through CMOS MEMS fabrication process

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The present study intends to design and implement a novel CMOS-MEMS thermal switch by using commercially available CMOS process (TSMC, 2P4M). There are three designs should be discussed: the unique contact profile, post-processing and a new thermal actuator design. In order to create the unique contact profile, residual stress effect has been used to make different bending movement. After experiment, the combination of layer Poly1, Metal1 and oxide has biggest residual stress effect to get large bending movement. Because the combination of three layers above let the contact profile bend down, the largest contact area which can get lowest contact miss ability has been set up. In the post-processing, 0.3μm thickness gold will be deposited on the surface of the element. Since gold is non-active than Aluminum, it has more reliability. In the new thermal actuator design, we design a novel folded-flexure with the electrothermal excitation to turn the switch on or off. In the prototype, the area of the device is 500μm × 400μm wide, and the contact side gap is 9μm. From the experimental results, the operation bandwidth of the device is 15kHz. The switch can work stably at 3V, and the temperature is from 20°C to 200°C.
7926-20, Poster Session

**Charge dissipation material for nanolithography**

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Electron beam lithography may be used for producing device structures having dimensions in the nanometer range due to the small wavelength (often less than 1 angstrom) of the electrons used. One problem associated with electron beam lithography is charging of the resist by the electron beam. Static charge build up at the insulating surface of the electron beam resist which can distort the electron beam and lead to pattern registration errors and poor overlay accuracy. Conjugated conducting polymer can be used as charge dissipation material for nanolithography due to its easy process and water solvable. In this paper, history and trends of conjugated conducting polymer such as polyacetylene, polypyrrole, polythiophene, polyaniline, polyphenylene, and poly(phenylene vinylene) (PPV) will be reviewed. Synthesis and application of conductive polymers will be discussed and present in this conference.

7926-21, Poster Session

**Large scale micro-patterning of multiwalled carbon tube: polydimethylsiloxane nanocomposite polymer on flexible 12 inch × 24 inch substrates**

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We present fabrication and micropatterning of electrically conducting multiwalled carbon nanotube (MWCNT) doped nanocomposite polymer on 12 inch × 24 inch poly(methyl methacrylate) substrate. The electrically conducting nanocomposite polymer has been prepared by high frequency ultrasonic agitation of MWCNT in polydimethylsiloxane polymer matrix as previously reported [1,2]. Previously we had reported hybrid fabrication process for combining micromolded nanocomposite with nonconductive polymer against SU-8 polymer micromold. PDMS nanocomposite poured on SU8 micromold, and excess nanocomposite scraped off from the surface of micromold and undoped PDMS poured on the surface of mold. And is finally baked at 800 C for 1 hour and peeled off from the SU8 mold.

The process defined above is expensive and requires use of clean room facilities and is only limited to a maximum of 8 inch substrates in order to fabricate structural mold materials. We present a new cost method to micro mold manufacturing method by laser ablation of cast grade PMMA (Poly Methyl Methacrylate, commercially known as Plexiglass) by using the VersaLASER® laser ablation system which employs a class 3R CO2 laser diode operating at 650nm wavelength. The layout of the heaters was designed using Corel Draw version X4. This software is coupled to the UCP (Universal Control Panel) software which runs the VersaLASER® laser ablation system. This laser ablation system can handle substrates up to 12 inch × 24 inch. The depth and surface roughness of the laser ablation is governed by two parameters namely: the power intensity and the speed of laser ablation. The power intensity and the speed are controlled between ranges of 0 to 100%. In order to achieve a depth of 250 μm the system was operated at 100% speed and power intensity of 30%. The depth of the mold was verified using a micrometer. Depth of 10 micron to 20mm can be achieved easily. The other parameters of micropatterning remain the same.

References:


tunable band-pass filter with AlGaN/GaN DBRs was calculated by using obtained values. The red-shift of the transparent wavelength from room temperature to 500°C is about 9 nm, which is much larger than the width of pass band (0.1 nm).

7926-04, Session 2

Fabrication of large-scale scaffolds for the regenerative medicine by two-photon polymerization

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Biomedical scaffolds serving as cell growth supporting artificial matrices are the key components in current and future technology of regenerative medicine. In order to provide distinctly shaped 3D scaffolds with interconnected micro pores which support cell adhesion, proliferation, and differentiation, a suited 3D fabrication technique is needed.

Two-photon polymerization (2PP) using ultra-short laser pulses has demonstrated its potential as high performance 3D fabrication process, providing structures with a resolution of about 100 nm. However, due to the limited working distances of the focussing optics, and to the prolonged fabrication times, large-scale samples have not been realized yet.

In this work, a modified TPA setup is introduced which allows to produce large structures in the cm range. A resolution down to 1 μm in the xy-plane and 5 μm in the z direction can be achieved by using a diode-pumped Ytterbium laser system emitting 325 fs laser pulses at 515 nm after second harmonic generation, and a focussing optic with a numerical aperture (NA) of 0.60. Scaffolds with interconnected pores in the range of 10 to 500 μm were fabricated using photosensitive inorganic-organic hybrid polymers (ORMOCER®s) with very high reactivity allowing writing speeds up to 50 mm/s. High-resolution μ-Raman spectroscopy is performed in order to investigate the organic cross-linking which is directly related to the mechanical stability. The latter is determined by mechanical characterization methods.

7926-05, Session 2

Laser processing inside transparent materials: dependence on pulse length and wavelength

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This paper discusses the processing of transparent materials using various laser sources emitting short pulses (nanoseconds) and ultrashort pulses (femtoseconds) at different wavelengths. The investigations were carried out with short pulse Nd:YAG lasers (1064 nm, 532 nm, 355 nm) as well as a high repetition rate fs-laser (1030 nm). In our experiments the laser beam was focused onto the sample with both a stationary objective and a laser scanner with an f-theta-objective.

In our study we investigated in detail the dependencies of controlled micro defect generation inside bulk glass (BK glass, fused silica) and polymer (poly(methylmethacrylate), polycarbonate, cyclo-olefin-copolymer) on important process parameters like wavelength, pulse width, and irradiation regime. By applying an irradiation regime with optimal process parameters these local confined material distributions can be arranged in cut surfaces in order to cut 3d parts, consisting of bulk transparent material. Especially for the 3d parts production with an irregular shaped cut surface a CAD-CAM software tool was developed which converts geometry information into a processing program automatically.

7926-06, Session 2

Sub-micron texturing of silicon wafer with fiber laser

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The sub-micro/nano scale laser surface texturing of materials is widely studied for a number of industrial applications. This technique is aimed to alter the surface properties such as surface wettability, and optical properties of the materials.

Laser-induced oxidation is a process of selectively patterning and functionalizing the silicon surface through the oxidizing. Being a low temperature process, the laser-generated oxidation is preferred for the deposition of SiO2, which is free from dopant redistribution and defect generation. The potential industrial applications of this process can be selectivity, environmental friendly, and quickness of the process to locally rapid thermal oxidation (LRT).

In this work, we studied the surface morphology and properties of the crystalline silicon irradiated by a CW fiber laser (λ=1090nm) in ambient and O2 atmosphere respectively. The O2 gas stream with three different pressures (P1=0.25, P2=0.5, P3=0.75 bar) was delivered through a coaxial nozzle to the laser spot. The morphologies reveal that sub-micron bumps are uniformly formed on the silicon surface. Optimum laser power and dwell time were experimentally determined and used to fabricate sub-micron bumps. Surface characterization was performed by a surface profiler and scanning electron microscope (SEM). Furthermore, Energy Dispersive X-ray Spectroscopy (EDS or EDX) and Raman Spectroscopy were conducted to analyze the compositions of the generated sub-micron bumps. Also reflection measurements showed the 20-50 % reduction in the reflectivity depends on the irradiation condition. Thus due to the different size features generated in the different conditions, this technique is capable of switching the surface wettability and reflectivity.

7926-07, Session 2

Reliability of laser micro welding

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Laser micro welding is employed for assembly and attachment of small scale components. As the characteristic length scales become smaller, the process becomes significantly more susceptible to fluctuations and perturbations. This paper investigates the laser micro welding process’ stability and analyzes the relative effect of source function and process parameter fluctuations.

7926-08, Session 3

First results on electrostatic polymer actuators based on UV-replication

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The miniaturization of actuators results in two major consequences: First, the reduction in efficiency depending on the physical principle. Second, the increasing requirements in positioning accuracy during the assembly
and fabrication process in combination with low cost production. Electrostatic polymeric actuators providing out-of-plane motion which can be completely fabricated in parallel fabrication steps and hence be produced on wafer level are compliant to these tolerance and cost constraints.

The electrostatic actuation principle is a surface effect and therefore independent of the volume. In addition, the efficiency of electrostatic actuation increases with a decreasing gap size between the electrodes. The simple morphology of such actuators can be easily produced by UV-replication of polymeric materials. In consequence, the electrostatic actuation principle is predestined for the combination with low cost wafer level fabrication.

This paper reports on the first results of successfully fabricated electrostatic actuators produced on wafer level. Instead of using a standard silicon substrate our approach is based on the lithographic structuring of the non-conducting material ORMOCER. In comparison ORMOCER has a significantly lower elastic modulus (around 2 GPa). Therefore, only a fraction of actuation voltage is necessary for a similar deflection. The material is structured using photolithography and the electrodes are realized with coatings of thin metal layers. Experimental results show a deflection up to 30 μm at 480 V for an 80 μm thick cantilever beam fixed at both ends. Good agreement between measurements and simulations is achieved, proving the applicability of the software and the assumed material parameters.

7926-09, Session 3

Commercial plexiglass mirrors and MEMS: new approach toward low cost polymer micro-systems

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PMMA is a widely used polymers in MEMS and aerospace industry. It has a great potential to be used for μ-TAS devices because of it low cost, biocompatibility, chemical inertness and optical properties. Among other things, PMMA is extensively used in aerospace industry for windows of airplanes.

One of the potential issues is to develop low cost micromachining process PMMA. One of the most commonly used method in order to micropattern PMMA is to use LIGA and sputtering in order to fabricate conductors for signal routing and process control electronics for active μ-TAS devices. For Aerospace industry it extremely important to fabricate micro machined conductors for Electromagnetic shielding.

We present a new technique which uses commercially available Mirrored-Extruded Acrylic (mirrored plexiglass / mirrored PMMA)and can be used for fabricating low cost PMMA based microsystems. The commercially available Acrylic mirrors have a coating of 25 micron thick vacuum metalized Aluminium with an adhesive backing. Acrylic mirror 12 inch x 12 inch sheets (thickness of 5mm, $18/ sheet) were bought from McMastercarr, USA. The Acrylic mirror sheet was cut into 4inch x 4 inch substrate.

The first task is to etch the adhesive backing in order to expose aluminum and we found that IPA was the perfect solvent for this purpose. This step was followed by rinsing the substrate in DI water blow drying using nitrogen. A dehydration bake for performed for 5 minutes at 100 degrees, cooled down to room temperature and spun coated with Shipley 1813 photoresist and baked for 1 minute at 95 degrees. The desired micropatterns were achieved by standard photolithography and wet chemical etching. The smallest feature size achievable is 5 micron. The Aluminum on PMMA can be used as a hard mask for deep UV patterning PMMA for μ-TAS applications, and further processed for signal routing purposes. Large scale machining of these mirrors is possible for EMI shielding purposes for aerospace applications. This is a low cost process which eliminates use of expensive sputtering and is scalable to large substrates of the size of 12 inch x 24 inch substrates and larger for batch processing.

7926-11, Session 3

Fabrication of electrostatic-actuated single-crystalline 4H-SiC bridge structures by photoelectrochemical etching

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Silicon carbide (SiC) is attractive for applications in harsh environment MEMS devices, because of its mechanical and electrical stability at high temperature and chemical inertness. Heteroepitaxially-grown 3C-SiC and polycrystalline SiC have been extensively investigated for such MEMS applications. On the other hand, single-crystalline 4H- and 6H-SiC have been hardly investigated because controllable etching of 4H- and 6H-SiC have been difficult. In this study, we have fabricated single-crystalline 4H-SiC bridge structures by using photoelectrochemical (PEC) etching which has doping-type selectivity. We have also demonstrated electrostatic actuation of the bridge.

P-type 4H-SiC homoepitaxial layers grown on 4H-SiC (0001) 8°-off substrates were prepared. Next, a buried n-type layer with a depth ranging from 100 nm to 800 nm was formed by ion implantations followed by activation annealing. After forming the p-n-p structure, reactive ion etching was carried out to form a line-and-space pattern with a depth of 500 nm (which is also used as a window to access the buried n-type layer). Then, metal contacts were formed and PEC etching was carried out to remove the buried n-type layer selectively.

After PEC etching, both top and bottom p-SiC regions were not etched. In the buried n-type SiC region, however, porous SiC remained just under the p-type top layer. To remove porous SiC, thermal oxidation and successive HF etching were carried out. Electrostatic actuation of the bridge structure was observed under an optical microscope by applying 20V between the bridge and the base plate.

7926-22, Session 3

Poly-HDDA microstructure fabrication using microstereolithography for micro-cantilever based sensor technology

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The rapid development of various scanning probe methods like SFM or AFM involving microcantilever based sensor technology has slowly enabled mechanical motion to regain its place in the field of science and engineering by miniaturization of mechanical systems down to sub-micron dimensions. Such scaling down of dimensions of microstructures exhibit very high sensitivity to mechanical deformations due to various induced loads. The most widely used Optical beam deflection method (OBDM) for measuring such deflections in microcantilever based sensors is limited by diffraction effects due to dimensional constraints of the structures involved [1]. The use of polymer materials like poly HDDA having very low elastic modulus has the potential to achieve high mechanical deformation sensitivity for even moderately scaled down structures [2]. Poly-HDDA based microcantilever sensors are being fabricated in an in house realized Microstereolithographic system [3]. The objective is to fabricate a double micro-cantilever structure of length 700 μm, width 60 μm and thickness 20 μm each with a gap of 40 μm between the two along the thickness dimension. The relative deflection profile of one of the fabricated cantilevers due to induced surface stress by the self-assembly of Alkanethiol on Gold [4] is measured under the p-type top layer. To remove porous SiC, thermal oxidation and successive HF etching were carried out. Electrostatic actuation of the bridge structure was observed under an optical microscope by applying 20V between the bridge and the base plate. Therefore, only a fraction of actuation voltage is necessary for a similar deflection. The material is structured using photolithography and the electrodes are realized with coatings of thin metal layers. Experimental results show a deflection up to 30 μm at 480 V for an 80 μm thick cantilever beam fixed at both ends. Good agreement between measurements and simulations is achieved, proving the applicability of the software and the assumed material parameters.

The simple morphology of such actuators can be easily produced by UV-replication of polymeric materials. In consequence, the electrostatic actuation principle is predestined for the combination with low cost wafer level fabrication.

This paper reports on the first results of successfully fabricated electrostatic actuators produced on wafer level. Instead of using a standard silicon substrate our approach is based on the lithographic structuring of the non-conducting material ORMOCER. In comparison ORMOCER has a significantly lower elastic modulus (around 2 GPa). Therefore, only a fraction of actuation voltage is necessary for a similar deflection. The material is structured using photolithography and the electrodes are realized with coatings of thin metal layers. Experimental results show a deflection up to 30 μm at 480 V for an 80 μm thick cantilever beam fixed at both ends. Good agreement between measurements and simulations is achieved, proving the applicability of the software and the assumed material parameters.
the temperature and higher sensitivity due to small thermal expansion co-efficient ($) variation and very low elastic modulus thus leading to low noise very high resolution detection of mechanical deformation agents.

References


7926-12, Session 4

MEMS product engineering: methodology and tools

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The development of MEMS differs substantially from product engineering methods in industries with fixed manufacturing processes where a sharp interface and separation between design and fabrication facilitates the development of new products. The approach for MEMS is rather characterized by application specific manufacturing processes. Fabrication steps, materials, and technologies are depending on the later product, and vice versa can also affect the design decisions itself. Process step configurations, process parameters and the selection of proper materials are subject to the device properties.

In this paper we are introducing a comprehensive customer-oriented product engineering methodology accompanied by a selection of dedicated tools for the development of MEMS products. MEMS product development tailored towards a distributed, networked operation between customers, designers and semiconductor manufacturing partners are in the focus of this methodology. The complete MEMS design and fabrication process is analyzed with regard to procedures and interfaces since typically different parties (IDMs, fabless design houses, pure play foundry etc.) are contributing to the product development along the value chain. The manufacturing process development is part of this holistic approach and is supported by XPerDesk, a CAD environment for the management and the design of thin-film-based MEMS fabrication processes. This environment has been developed and commercialized by the authors. Within an environment of additional tools provided by partners of a European project (CORONA), XPerDesk forms the foundation of a comprehensive MEMS product engineering software support.

7926-13, Session 4

Automated measurement of centration errors and relative surface distances for the optimized assembly of micro-optics

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Especially for miniaturized optical compound systems the precise geometric alignment of every single element according to the optical design is essential to obtain the desired imaging properties. In this contribution we present a measurement system for the measurement of the complete set of geometric alignment parameters in assembled systems. During the measurement the deviation of each center of curvature with respect to a defined reference axis is measured. These data are further processed in order to provide the shift and tilt of an individual lens or group of lenses with respect to the reference axis. The centration errors of up to 40 surfaces within a system under test can be measured with accuracies in the range of an arc second. In addition, the relative distances of the optical surfaces (center thicknesses of lens elements, air gaps in between) are optically determined in the same measurement system. Subsequently, the acquired results can be applied for the compensation of the detected geometric alignment errors before the assembly is finally bonded (e.g., glued).

The presented applications mainly include measurements of miniaturized lens systems like endoscope optics. However, any type of objective lens from mobile phone camera up to very complex objective lenses can be analyzed with the presented measurement system.

7926-14, Session 4

Impact of using filtration on global and local uniformity of spin on glue materials

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The drive of the microelectronics industry to build vertically has made the use of spin on glues for permanent and temporary bonding an essential part in the processing and handling of thin substrates. The evolution of MEMS device technology into high volume production drives the need for materials that have consistent batch-to-batch performance, resulting in high quality coatings with low defect counts. Today’s MEMS device manufacturers are focused on increasing yields and eliminating waste rendering the need for an accurate dispense system. One of the main concerns for integration of new spin on glue materials is the presence of bubbles within the material that can lead to yield degradation.

Because of their high viscosity; this type of material is usually difficult to dispense and filter at the point of use and achieve high quality, uniform, bubble-free coating. In this paper, we will focus on the use of the Intelligen® HV dispense system and its optimization to improve the temporary bonding material coating uniformity. First the system was utilized without filtration to understand the effect of bubble introduction to the coating. The second phase of the project studied the impact of filtration on the quality of the coating when bubbles were introduced. Coating uniformity data were collected by a Senduro reflectometer and bubble deflection studies were performed using the NandaTech SPARK inspection tool.
Elastic photonic crystals: nano-assembly and functionality on km-scales

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Polymeric opals are a new range of structural-colour nanomaterials which can be mass produced as films on the kilometre scale. While most manmade (and natural) colours exploit dye absorption, there is strong interest in avoiding these carcinogenic and UV-bleached chemicals. Alternative structural colours are produced from periodic wavelength-scale-sized transparent components, and thus are benign, durable, and possess new features. We create polymer opals (or photonic crystals) made of cross-linked polymer spheres dispersed in a soft elastomer. These have high refractive index contrast and allow a layer-by-layer-based assembly using extrusion or compression resulting in fcc-lattice-based nanostuctures of self-assembled spheres. Doping polymer opals with <0.02% by weight of sub-50nm carbon nanoparticles (which uniformly incorporate into the outer polymer matrix) dramatically enhances the resonant Bragg scattering and the resulting structural colour. Simply tuning the size of the spheres changes the colour across the entire visible spectrum, while optimised shearing creates single-domain opal films.

We demonstrate a wide variety of new properties including elastomeric thin films which change colour on stretching, transparent thermochromic films, shape-memory polymer opals possessing colour highlights when deformed, mecha-chromic films, polymer opal fibres that can be woven into iridescent textiles, compression-moulding of polymer opal objects, and opal films embossed to create colour patterns. Such films have a wide variety of uses which are now being explored, including in packaging and security applications as well as for novel photonics. They represent a paradigm for Soft NanoPhotons using smart directed nano-assembly for advanced optical functionality.

On-substrate photonic-crystal nanobeam cavities in electron-beam resist

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On-chip, waveguide-coupled photonic-crystal nanobeam cavities were fabricated directly in electron beam resist on a low-index substrate (periodic mesoporous silica (PMS, n~1.15)). The structure consists of a ridge waveguide perforated by an array of air holes. Periodically spaced holes form a Bragg mirror at each end of the cavity region, which is defined by tapering the size and periodicity of the holes at the center. The tapering, combined with the use of a very low-index substrate (-1.15) minimizes losses in the cavity due to scattering above the light line, and is key in realising high Quality factors in low-index materials. PMS films were fabricated by evaporation-induced self-assembly of a surfactant phase during polymerization of the silica precursor (TMOS). The surfactant template was then removed by annealing at 500°C. The cavities and their coupling waveguides were patterned in the high-resolution electron-beam resist ZEP520, spin-coated on top of the PMS layer, by electron-beam lithography. Cavities modes were simulated using commercial FDTD software, showing Quality factors as high as 100,000 and mode-volumes of a cubic wavelength at 650nm. The devices were experimentally characterized by direct transmission through the coupled waveguide. This approach allows the achievement of photonic-crystal cavities in soft materials (n~1.5) without the need for any etching or releasing steps-the PMS providing sufficient index-contrast to avoid the need for a suspended geometry. We believe that this platform can bring the greater freedom of material properties offered by polymers to many photonics applications.

Photolithographic fabrication of slot waveguides

M. Hochberg, Univ. of Washington (United States)

Silicon nano-slot waveguides have proven to be useful for a variety of applications, including nonlinear optics, biosensing, and electrooptic modulation. One of the significant challenges for many of the applications of these waveguides is the significant cost and complexity associated with electron beam lithography, which has historically been required for fabricating sub-100 nm slot guides. We demonstrate the ability to fabricate very narrow slots in single mode silicon ridge waveguides, with extremely low loss, using conventional stepper-based photolithography. Results include both conventional slot guide and electrically contacted slots, and applications to electrooptic modulation and nonlinear optics will be discussed.
**Advanced fabrication methods for 3D meta-optics**

E. G. Johnson, The Univ. of North Carolina at Charlotte (United States)

Micro-Optics has expanded to include a wide variety of applications for spectral filtering, polarization filtering and beam shaping. Recently, a new class of optical elements have been introduced that can combine the spectral, polarization, and beam conditioning into the same optical element. This engineered optical functionality results in a 3D Meta-Optic structure that relies on sub-wavelength features to essentially engineer the electromagnetic fields within the structure; thereby, resulting in highly dispersive structures that spatially vary across the optical element. However, the challenge is in how one can fabricate structures with this slowly varying structure across large areas without the use of direct writing methods. This talk will summarize recent results in the design, fabrication and applications of 3D Meta-Optics. Results will be presented for devices fabricated using additive lithographic methods comprising binary and analog lithography exposures.

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**A new fabrication method for 3D Si-based photonic crystal structures**

M. A. Taysing-Lara, G. Dang, W. Zhou, U.S. Army Research Lab. (United States)

We have designed and developed a new, simplified 3D Photonic Crystal (PhC) fabrication technique that can fabricate a nanoscale 3D structure from the 2D surface of a Si (or SOI) wafer with a single lithography and self-aligned etching sequence and produces deep trenches with controlled width variation along the vertical direction. This method uses a mask (such as an e-beam resist mask) pattern of repeated lines with periodic narrow and wide linewidths. Using an alternating sequence of Bosch etches and a combined cryogenic and chemical etching process, allows the Bosch etched layers to maintain the width defined by the mask, while the combined cryogenic/chemical etched layer creates a lateral undercut that decreases the width beneath the surface. The undercut is controlled so that it will just etch through the narrow linewidth region, but will not undercut through the wide linewidth region of the mask pattern. This creates a regular pattern of vertical posts. The end result is a 3D lattice structure with a stack of vertical square grids. This method creates a 3D lattice structure without the need of any processing alignment, regrowth, complementary material transfer, etc. Therefore this technique will reduce overall fabrication cost and increase yield. Using this method, one can fabricate a variety of Si/SOI based 3D photonic crystal structures including hollow-core, high contrast grating, waveguide structures. This paper will report on the experimental procedures and results of this fabrication technique, and demonstrate the fabricated 3D structures with SEM pictures. The theoretical design and calculation of photonic crystal structures will be discussed in a future publication.

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**Selective inhibition of polymerization enables sub-diffraction optical lithography**

B. Harke, F. Anjum, F. Brandi, A. Diaspro, Istituto Italiano di Tecnologia (Italy)

Optical writing via multi photon processes has been of major interest in the last years since also the capability of writing in all 3 spatial directions with high resolution opened up a new field of applications. Usually, a photo initiator is excited by the absorbance of multi photons and generates free radicals causing polymerization of the monomer in a strictly defined volume. However, the smallest achievable feature size is still limited to the diffraction limited size of the area of excited photo initiator molecules.

In this work, we present a way to overcome this diffraction barrier. The idea of the RESOLFT (reversible switchable optical transitions) concept has already been verified for fluorescence imaging techniques in which the diffusion limit governs its resolution. To generalize it, 2 states have to be taken into account: one of these is active (A) the other one inactive (B). Sub-diffraction resolution can now be performed by selectively switching between the states A and B. Additionally the beam that causes the switching has to be spatially shaped featuring zero intensity in its center. The area or volume of active molecules can thereby be reduced by adding a second beam that brings the molecules to state B in the outer region of the focal volume. With this method, the size of the active volume only depends on the efficiency of the de-excitation process. First results for sub-diffraction optical lithography will be presented. Also the photo-physical mechanism for this transition as well as the critical parameters for the sub diffraction optical writing will be discussed.
sensor technology has played an important role in the revolution in mobile devices of the last 10 years. Wafer based optics manufacturing leverages the same fabrication equipment used to produce CMOS sensors. The natural integration of these two technologies allows the mass production of very low cost surface mount cameras that can fit into ever-thinner mobile devices. Nano Imprint Lithography equipment has been adapted to make precision asphers that can be stacked using wafer bonding techniques to produce multi-element lens assemblies. This coupled with advances in mastering technology allows arrays of lenses with prescriptions not previously possible. A primary motivation for these methods is that it allows the consolidation of the supply chain. Image sensor manufacturers envision creating optics by simply adding layers to their existing sensor fabrication lines. Results thus far have been promising. The current alternative techniques for creating VCA cameras are discussed as well as the prime cost drivers for lens to sensor integration. Higher resolution cameras face particularly difficult challenges, but can greatly simplify the critical tilt and focus steps needed to assemble cameras that produce quality images. Finally, we discuss the future of wafer level cameras and explore several of the novel concepts made possible by the manufacturing advantages of photolithography.

Fabrication of large area metallic nanoparticle arrays by nanosphere lithography for localized surface plasmon resonance protein biosensors

R. C. Denomme, K. Iyer, P. M. Nieva, Univ. of Waterloo (Canada)

As the field of nanotechnology matures and applications for plasmonic devices increase, the need for inexpensive, scalable production methods is paramount for the quick translation of products from research labs to consumer technology. Nanosphere lithography (NSL) is a potential method for large scale, inexpensive production of plasmonic devices that require ordered nanoparticle arrays. NSL relies on a self-assembled monolayer of hexagonal close packed polystyrene microspheres to be used as a physical mask through which material is deposited. The use of sub-micron spheres allows the production of triangular metallic nanoparticles for use in localized surface plasmon resonance (LSPR) spectroscopy. However, with NSL, nanoparticle arrays usually only exist over a small area and uniformity is poor. Using custom fabrication equipment and a refined technique, we have produced monolayers as large as 5cm2 using 400nm polystyrene beads, which is an improvement over drop coating and spin coating. This is accomplished using a technique known as restrictive meniscus self assembly. A glass spreader is fabricated and a 4% w/v solution of microbeads is spread across a substrate using a motorized stage at a velocity of 58 μm/s. Temperature is controlled to +/-0.1°C using a Peltier element and humidity controlled using a glove box. We focus on adapting the current technology for production of integrated LSPR sensing devices. This is accomplished through the combination of conventional lithographic techniques and NSL to produce multiple large arrays of nanoparticles. These arrays are integrated with a PDMS microfluidic network to produce a multiplexed LSPR protein biosensor.

Tailored hybrid materials for sub-100 nm two-photon lithography and micro optical applications

S. Steenhuisen, F. Landgraf, R. Houbertz, Fraunhofer-Institut für Silicatforschung (Germany)

Sub-diffraction limit rapid prototyping of hybrid polymers (ORMOCER®s) with visible and infrared laser pulses is presented. In comparison to conventional photopolymers commonly used for two-photon polymerization (2PP), ORMOCER®s exhibit outstanding mechanical, thermal and chemical stability, and they can be considered as multifunctional patternable nanomaterials. In this work, the patterning is carried out with tightly focused femtosecond laser pulses at wavelengths of 515 and 1030 nm, respectively. To get an insight into the cross-linking behavior of these multi-purpose material systems, µ-Raman experiments were conducted on 2PP fabricated structures, and the results are compared to single photon illumination. For a further reduction of feasible feature size, specially tailored ORMOCER®s were synthesized. A voxel size study reveals the impact of the illumination parameters and of different inhibitors, which were added to the resist formulation. It is shown that the voxel size can easily be pushed below 100 nm for an exposure wavelength of 515 nm using these new material systems. Another approach to smaller feature sizes is illumination with 1030 nm laser pulses, where three-photon absorption is expected to be the dominating non-linear process. Again, a voxel size study is presented, and the underlying photochemical processes are discussed. Besides these basic studies on the photochemical response of different hybrid material systems upon laser illumination with different wavelengths, exposure times and average laser powers, we also show three-dimensional functional microstructures. These can for example act as micro optical elements such as diffractive optical elements, phase plates or waveguides.
between chemical precursors and femtosecond pulses, we limit the metal-ion photoreduction process to a focused spot smaller than that of the diffraction-limit. This creates metal nanostructures in a focal volume that is scanned rapidly in three dimensions by means of a computer-controlled translation stage to produce complex patterns. By varying the concentration ratio between metal ion precursors and a polymer capping agent, as well as laser pulse parameters, we demonstrate control over the morphology of the resulting metal structures. We fabricate grid and woodpile patterns over hundreds of micrometers in dimensions. We show that this process is scalable over macroscopic volumes and possesses optical characteristics suitable for surface-enhanced Raman scattering spectroscopy or metamaterial applications.

7927-15, Session 4

Direct laser writing and applications of dielectric microstructures with low refractive index contrast

V. Mizeikis, Shizuoka Univ. (Japan); V. Purlys, Vilnius Univ. (Lithuania); L. Maigyte, K. Staliunas, Univ. Politècnica de Catalunya (Spain); S. Juodkazis, Swinburne Univ. of Technology (Australia)

High versatility of direct laser writing (DLW) technique makes it ideally suited for microfabrication of 3D photonic crystals with complex lattice topologies. However, DLW with high spatial resolution is only possible in materials with relatively low refractive index ($n < 2$), and index contrast of recorded structures is too low for complete photonic band gap. Here we describe functionality, design, and microfabrication by DLW technique of optical structures which do not rely on high index contrast, but nevertheless exhibit interesting optical properties. 1) microstructures recorded in the bulk of iron-doped lithium niobate ($LiNbO_3$:Fe) crystals are meta-stable, can be erased/re-written optically, and promise application in all-optical dynamic interconnects, diffractive elements and optical memories. 2) 3D structures with woodpile architecture recorded in inorganic glasses and organic photoresists are capable of rejecting high spatial frequencies, and are usable as compact, nearly alignment-free spatial filters for optical beams. Fabrication of these structures by DLW technique using Ti:Sapphire femtosecond laser (wavelength 800 nm, pulse length <100 fs, repetition rate 80 MHz), and their characteristics will be described.

7927-16, Session 4

Correcting aberrations in direct laser writing applications

A. Jesacher, Innsbruck Medical Univ. (Austria); B. Cumming, Swinburne Univ. of Technology (Australia); G. D. Marshall, Macquarie Univ. (Australia); M. Gu, Swinburne Univ. of Technology (Australia); T. Wilson, M. J. Booth, Univ. of Oxford (United Kingdom)

Direct Laser Writing (DLW) enables the fabrication of nano-photonic devices such as photonic crystals or embedded waveguide-structures. Recently, dynamic spatial light modulators have been introduced into direct laser writing systems. These elements allow speed-up the fabrication by multiple beam-splitting and the correction of optical aberrations, which are inevitable when there is a mismatch between the refractive indices of the target material and the immersion medium of the objective lens.

We present results from sequentially fabricating three-dimensional Photonic Crystals in lithium niobate and demonstrate the effects of correcting spherical aberration with a spatial light modulator. A significant increase of the artificial bandgap could be observed.

Furthermore, we show how aberrations can be measured in a microfabrication setup and suggest a strategy for parallel multi-spot fabrication, which aims at reducing laser pulse dispersion by choosing a specific design for the beam-splitting diffractive patterns.

7927-17, Session 4

2D nanosphere lithography by using surface plasmon-enhanced optical trapping

S. Chen, Y. Li, National Cheng Kung Univ. (Taiwan)

Nanosphere lithography (NSL) is an inexpensive, simple, and high throughput nanostructure fabrication technique capable of producing a well-ordered two-dimensional (2D) array of nanoparticles. A 2D surface plasmon (SP)-enhanced optical trapping system based on a single high numerical aperture (NA) objective has been developed with a 40-fold electric field enhancement, and then can be utilized to trap strongly single layer dielectric nanospheres spread over a large area with a reduction in feature size to form a hexagonal close-packed structure on a cover slip surface. By chemically modifying the surface, the trapped nanospheres can be adhered on the substrate even if the trapping laser is turned off. High-resolution trapping images of dielectric nanospheres can be simultaneously achieved via the same high NA objective, so the hexagonal pattern is observed in real time and hence a defect-free nanosphere mask can be fabricated easily. After metal deposition, the so-called Fischer pattern is achieved by removing the nanosphere mask. The developed NSL technique via the SP-enhanced optical trapping is successfully applied to trap dielectric nanospheres with a size down to 300 nm on a cover slip surface uniformly.

7927-38, Poster Session

Ultrashort pulse induced nonlinear photo-polymerization and phase separation in liquid crystal and monomer mixtures

K. Hsu, Y. Tseng, National Central Univ. (Taiwan)

Conventional polymer-dispersed liquid crystal films (PDLC) are formed by exposing to uniform ultraviolet light source and liquid crystal droplets around few micrometer diameters is randomly dispersed in the polymer matrix due to phase separation between the monomer and liquid crystal at curing process. To attain advanced applications, electric-field-induced phase separation was demonstrated to provide an alternative PDLC morphology. In this work, we propose and demonstrate the nonlinear photo-polymerization and phase separation in nematic liquid crystal and monomer mixture using femtosecond ultraviolet pulse scanning. PDLC samples containing 30 wt% of nematic liquid crystal E7 and 70 wt% monomer NOA65 (Norland) is filled into two glass substrates with 5 μm cell gap. Frequency-doubled Ti:Sapphire femtosecond pulse of 100-mW with wavelength of 370 nm is scanned to cure the PDLC sample. At high scanning speed, the ultraviolet pulse can induce photo-polymerization and form micrograting-like polymer route in pure monomer thin film. Large-size liquid crystal droplet grating and complicated donut pattern in thin mixture film containing nematic liquid crystal and monomer can further be observed due to ultrashort-pulse-induced nonlinear polymerization and phase separation mechanism.

7927-39, Poster Session

Fabrication of hybrid optical structure by direct machining

T. Saastamoinen, Univ. of Eastern Finland (Finland); J. T. Vayrynen, North Karelia Univ. of Applied Sciences (Finland); J. Mutanen, Univ. of Eastern Finland (Finland); K. Mönkkönen, North Karelia Univ. of Applied Sciences (Finland); M. Kuittinen, Univ. of Eastern Finland (Finland)
A Moore 350FG 5-axis ultra precision machine tool platform with diamond tooling was used to generate V-shaped diffractive pattern on a refractive wave shaped structure. Combining the wave pattern with diffractive structure enhances the performance of the element. The structure was machined on electroless nickel inserts. The design and the simulation of the hybrid structure were performed using raytracing and exact electromagnetic theory. The response of the grating was calculated using Fourier modal method and the data was used in ZEMAX to calculate the amplitude and the phase of the diffracted rays.

A nanometric resolution PRO Engineering part file was generated from a point file generated using MATLAB. Ruling was opted as a machining method since the machining process is more easily controllable than fly-cutting. An electroless nickel insert slab was machined by diamond turning and the whole hybrid structure was cut with a single sharp tool with included angle of 45 degrees. The part was machined with 40 nanometer sidestep.

It is shown that the machining of diffractive/refractive structure can be made by ruling. The path from optical designing to machining of the part was proven. Selection of the tool type and shape plays an important role in the outcome of the part. This method will produce high quality hybrid structures which can be replicated for example by injection molding, hot embossing, or UV-cure methods.

7927-40, Poster Session

Laser processing and monitoring of Ag photodoped patterns in GeS2 amorphous films by dual functional laser scanning micro-processing / micro-scope system utilizing UV / VIS confocal laser scanning microscope

Y. Kanai, Tokai Univ. (Japan) and Genesia Corp. (Japan); Y. Murakami, Tokai Univ. (Japan) and Tsukuba Univ. of Technology (Japan); M. Wakaki, Tokai Univ. (Japan); N. Takeyama, Genesia Corp. (Japan)

Photodoping phenomenon of Ag is one of the light induced phenomena in GeS2 amorphous chalcogenide films. Photonic structures like wave guides and micro-optics may be possible to fabricate utilizing the refractive modulation caused by the doping process of Ag, but the practical fabrication method has not been established yet. The method to monitor the doping also has to be paid attention for precise processing.

In this report, a dual functional laser scanning system, integrating Micro-machining and Micro-scope systems is proposed. Both doping process with arbitrary patterns and monitoring of the doped patterns can be realized in one setup by the system. The developed optical system was optimally designed for applications at two wavelengths of UV (He-Cd laser; 325.0nm) and VIS (He-Ne laser; 632.8nm). An UV laser, effective for photodoping phenomenon, is used to process doping patterns, and a VIS laser, not influential upon the material, is used to monitor the fabricated patterns. In-situ nano scale manipulation and observation processes were possible under same setup in one system. Photonic structures with arbitrary fine doped patterns could be fabricated. As a typical photonic pattern, diffraction gratings of Ag/GeS2 were fabricated and optical performances were evaluated. This system will open the new device fabrication and help to advance the research of nanostructures and photonic crystals.

7927-41, Poster Session

Hydrogen silsesquioxane (HSQ): a perfect negative tone resist for developing nanostructure patterns on a silicon platform

G. Singh, Malaviya National Institute of Technology (India); P. Stenberg, P. Vahima, M. Kuittinen, Univ. of Eastern Finland (Finland); R. P. Yadav, V. Janyani, Malaviya National Institute of Technology (India)

This paper reviews the development of hydrogen silsesquioxane nanostructures (Less then 100nm) on a silicon platform. The effect of HSQ resist in thick (128nm thick resist) and thinner state (30nm thick resist) has been demonstrated and minimum possible structures with these are discussed in details. Most applicable structures like straight lines/spaces, sharp joints/corners and dots were developed to investigate the effects of development time on the lithography properties of HSQ. Soft bake after spinning process had been avoided in view of achieving better contrast and stable resist deposition. We had also reached to a conclusion that increasing the development time could improve resist contrast and pattern resolutions up to certain limits but may vary with type of structures & other conditions.

7927-42, Poster Session

Control of nanoparticle deposition with atomic force based Di-electrophoresis

T. Yeshua, M. Palchan, Y. Lovsky, The Hebrew Univ. of Jerusalem (Israel); H. Taha, Nanonics Imaging Ltd. (Israel); A. Lewis, The Hebrew Univ. of Jerusalem (Israel)

Lithography based on scanning probe microscopic techniques has considerable potential for the accurate and localized deposition of material on the nanometer scale. A subset of this advancing field of research is the controlled deposition of metallic features with high purity and spatial accuracy. Within the context of metal deposition we will review the development of fountain pen nanocoating and its most recent emulsion Atomic Force Controlled Capillary DiElectrophoresis (ACaD). With this development we will demonstrate depositing of single gold nanoparticle with size of 1.3 nm onto surfaces such as semiconductors.

7927-43, Poster Session

Polarization dependent diffraction of gold nanoparticle grating

T. Liu, I. Jiang, W. Hung, National Sun Yat-Sen Univ. (Taiwan)

Diffraction property of gold nanoparticles grating was investigated by varying the polarization of the probe light. The grating was composed of gold nanoparticles and the grating spacing was 8 m. A polarized monochromatic light, ranged from 450 to 750 nm, was used to probe the grating. It was noted that the diffraction efficiency was dependent on the polarization state of the probe light. A 24-mm red-shift of the maximum diffraction efficiency appeared between two orthogonal linear-polarized beams. The polarization dependent diffraction was referred to the geometric variation of gold nanoparticles. The experimental result revealed a possible application of geometry sensor on metallic nanoparticles.

7927-44, Poster Session

In-depth fiber optic two-photon polymerization and its applications in micromanipulation

Y. N. Mishra, N. D. Ingle, S. K. Mohanty, The Univ. of Texas at Arlington (United States)

Two photon polymerization (TPP) has enabled three-dimensional microfabrication with sub-diffraction limited spatial resolution. However, the depth at which TPP could be achieved has been limited due to the high numerical aperture microscope objective, used to focus the ultrafast laser beam. Here, we report on fiber-optic two-photon polymerization (FTP) for in-depth fabrication of microstructures from a...
photopolymerizable resin. A cleaved single mode optical fiber coupled with a tunable femtosecond laser beam could achieve TPP, thus forming an extended waveguide and tapered tip on the fiber itself. The length of the TPP tip was found to depend on the laser power and exposure duration. TPP microfabricated fiber tip was employed to deliver a continuous wave laser microbeam onto polystyrene microspheres in order to transport and manipulate selected particle(s). Such microstructures formed by TPP on the tip of the fiber will also enable micro-surgery of cellular structures. With the use of an axicon tip (fabricated by chemical etching method), in-depth FTP structures were formed on flat as well as curved surfaces. Power required for FTP using a cleaved and an axicon tapered optical fiber was compared taking into consideration the simulated beam profiles. We will present microfabrication using fiber-optic TPP and micromanipulation of microscopic objects using such microfabricated structures.

7927-45, Poster Session

Bimetallic grayscale photomasks written using optical density feedback control and a top-hat shaped laser

G. H. Chapman, J. M. Dykes, R. Qarehbaghi, B. Wong, Simon Fraser Univ. (Canada)

When bimetallic thin films of Bi/In and Sn/In are laser exposed, they oxidize and become variably transparent. By controlling the writing laser power, binary and grayscale photomasks can be produced with the mask’s transparency (optical density, OD), ranging between ~3.0 (unexposed) to <0.22 OD (fully exposed). Targeting the production of grayscale masks with 256 levels, the mask-writing system, combined with photodiode sensors, obtains real-time OD and laser power measurements; using them to adjust the laser’s writing power during the patterning process. For a single-line stepped pattern, laser writing without OD feedback control has up to an average absolute error of 34.5 gray levels, while with OD feedback control and the appropriate parameters, the same pattern is produced with an average absolute error of 10.1 gray levels. The control parameters are shown to influence the characteristics of the resulting mask pattern, particularly the overshoot and rise-time of the pixel transitions. With multi-line mask patterns being raster-scanned written, the overlap of the lines along with the laser’s Gaussian profile creates variations in the mask and measurement problems for the OD feedback control. Modifying the mask writing system with a beam-power stabilizer and a top-hat beam shaper, the amount of line-overlap required to pattern the mask is reduced. In addition, the uniform size and exposure of the focused laser improves the accuracy of the OD measurements and feedback control. Multi-line patterns are written both with and without the feedback control to compare the results of the top-hat and Gaussian shaped laser beams.

7927-46, Poster Session

Efficiency enhancement of silicon solar cells using self-assembly nanospheres

G. Lin, K. A. Lai, H. Chang, C. Lin, P. H. Fu, J. He, National Taiwan Univ. (Taiwan)

Colloidal polystyrene nanospheres with the diameter of 450 nm were used as the antireflection layer for silicon solar cells. According to scanning electron microscopy images, a monolayer of nanospheres is self-assembled on the device surface. This periodic nanostructure results in additional optical absorption of the solar cells. Under the illumination of air mass (AM) 1.5G, fill factor and conversion efficiency of the device are enhanced by 10 % and 13.2 %, respectively. The external quantum efficiency (EQE) is mostly improved at 725-900 nm, with the maximized enhancement of 8.1 % at 820 nm. The enhanced device characteristics are attributed to the significantly reduced surface reflectance on the nanospheres, as compared with the bare surface. The method proposed here opens a pathway for light management on the surface of various optoelectronic devices.

7927-47, Poster Session

Production multilevel DOE with E-beam lithography system for optical security holograms

S. A. Kostyukevich, V. Lashkaryov Institute of Semiconductor Physics (Ukraine); E. V. Braginets, National Taras Shevchenko Univ. of Kyiv (Ukraine); V. Ginryk, Optronics PC (Ukraine); V. Kurashov, Kyiv National Taras Shevchenko Univ. (Ukraine); K. Kostyukevich, V. Lashkaryov Institute of Semiconductor Physics (Ukraine); S. Honcharuk, Kievgolografiya (Ukraine)

The goal of present study is to develop method of producing Diffraction Optical Elements (DOEs) with new properties for applying them in modern digital optical security holograms or other applications where they can be used.

Such DOE could be a on-axis- or off-axis- Fresnel Lenses, focuser element, other phase elements with defined optical parameters.

A secondary objective is to find way of effective use commercial E-beam Lithography System with resolution 200 nm for generating phase multilevel structures on electronic sensitive organic resist layer. One of difficulties, which we faced with, is to using pure lithography system for producing multilevel phase structure. For solving it, we recorded special test to build dependency “exposure energy - phase depth”. Then, using AFM we built appropriate curves for several used recording mediums: organic and inorganic resists. Thus, we able to record 32-64 levels phase structure using commercial lithography E-beam system.

On example of producing security holograms with computer-generated Fresnel lens we are testing possibility of using multilevel phase structure inside of commercial optical security holograms. “The calculations” stage is very typical for such synthesized elements. All calculations are made under scalar theory. For synthesis on-axis Fresnel lens input parameters are focal distance and wavelength, for off-axis lens, respectively, coordinates of focusing point. For calculation more complex DOEs, we need to solve inverse problem of diffraction in general view.

In final part of our paper, we consider several ways to minimize problems appeared during replication recorded high-res structures to holographic foil (choice of optimal exposure level and sampling frequency, basing on measurements of test recordings).

7927-100, Poster Session

Impact of imbalanced power levels of first stage 3-dB coupler on the crosstalk levels of Mach-Zehnder Interferometer arms

G. Singh, S. Gupta, S. Bothra, V. Janyani, R. P. Yadav, Malaviya National Institute of Technology (India)

The 3-dB couplers are essential integrated component of Mach-Zehnder structures and should have uniform power levels at the output ends. In this we reviews a 2x2 symmetric MZI structure and calculated the effect of imbalanced power levels of first stage 3-dB coupler on the crosstalk levels at the end of the interferometric arms. The calculated crosstalk levels at the end of the interferometric arms were (43.75dB and 42.25dB for TM polarized test signals at 1.3 μm and 1.55 μm wavelengths respectively), due to imbalanced power levels of the first stage coupler. We also propose that, the careful selection of Ti-strip thickness could be a useful design criterion for reducing the impact of power imbalance on the crosstalk levels.
7927-19, Session 5

Fabrication of singulated micro-retro-reflectors for textured surfaces

M. K. Poutous, The Univ. of North Carolina at Charlotte (United States); M. Maston, S. Leibholts, VizorNet, Inc. (United States); E. G. Johnson, The Univ. of North Carolina at Charlotte (United States)

The application of micro-retro-reflecting elements on various surfaces is of interest for cases of detection, identification and optical discrimination. The micro-optical elements presented here are designed to retro-reflect coherent or incoherent interrogating light beams, at large distances (>10m), with a high optical signal-to-background ratio. Due to the unpredictable topography of target surfaces, it is desirable for the individual retro-reflectors to be very small (<50μm on a cube side or diameter on a sphere), but not as small as to be biological inhalation hazards. They are also required to be chemically inert with the application surface.

The fabrication of singulated micro-retro-reflectors using conventional photolithography is presented. The elements consist of 4-sided, 3-dimensional corner-cube dielectric skeletons, coated with metallic or dielectric thin films, which are chemically singulated, in order to be applied to textured surfaces of random orientations. The fabrication is accomplished using existing photolithographic technology, on Si-wafer carriers. This allows for the fabrication of large numbers of micro-retro-reflectors, with high yields per wafer carrier, using unmodified equipment. The metallic and/or dielectric conformal coatings are applied using room temperature sputtering techniques. Following the coatings, the individual micro-retro-reflectors are released from the wafer carriers using chemical immersion and ultra-sonic agitation. They are collected and stored in suspension in Methanol, pending their application to surfaces using mechanical means.

The retro-reflectors can be used in visible or near infrared wavelength applications.

7927-20, Session 5

Free-form micromachining of an infrared Alvarez lens

P. J. Smilie, B. Dutterer, J. L. Lineberger, M. A. Davies, T. J. Suleski, The Univ. of North Carolina at Charlotte (United States)

In 1967, Luis Alvarez introduced a novel concept for a focusing lens whereby two transmitting plates with cubic polygonal surfaces with small relative lateral shifts yield a composite lens of variable focal length. Computer simulations have demonstrated the behavior of these devices, but fabricating the refractive cubic surfaces of the types needed with adequate precision and depth modulation has proven to be challenging using standard methods, and, to the authors’ knowledge, such cubic surfaces have not been previously machined in infrared materials. Recent developments in free-form diamond machining capability have enabled the fabrication of such devices. In this paper, we discuss the fabrication of cubic refractive Alvarez plates in germanium using diamond micromilling on a five-axis Moore 350FG Nanosolid Freeform Generator. Machining approaches are discussed, and measurements of surface figure and finish are presented. Initial experimental tests of optical performance are also discussed.

7927-21, Session 5

Wafer level glass optics: precision glass molding as an alternative manufacturing approach

M. Hünten, F. Klocke, O. Dambon, Fraunhofer-Institut für Produktionstechnologie (Germany)

Today, micro optical components are used in a wide range of products such as camera or sensor systems, medical instrumentations or communication devices. It can be estimated that the number of applications containing optics or optical system will further increase within the next years. In conclusion, high volumes of micro optics need to be manufactured.

The computer chip industry impressively demonstrates how to efficiently manufacture millions of small and precise parts. Here, single components are fabricated on large wafers, different wafers are stacked and subsequently diced into hundreds of single parts. Thus, following a wafer based production approach the economics of scale are perfectly used.

In optics manufacturing, the wafer based approach is already established for polymer optics. However, the future requests regarding optical systems such as imaging quality or construction size cannot be met by polymer optics. Here, glass, with higher refraction index and higher transmission, will be the material of choice. But the processes necessary to implement the glass optics manufacturing on wafer level are not yet established.

In this paper the manufacturing approach of wafer scale molded glass optics is described including a detailed view on each process step that needs to be accomplished, especially the mold manufacturing. Thus, it can be demonstrated that precision glass molding must be considered as an alternative and competitive manufacturing approach for the wafer level production of glass optics.

7927-22, Session 5

Manufacturing of cylindrical diffractive lens by ruling

J. T. Vayrynen, North Karelia Univ. of Applied Sciences (Finland); T. Saastamoinen, J. Mutanen, Univ. of Eastern Finland (Finland); K. Mönkkönen, North Karelia Univ. of Applied Sciences (Finland); M. Kuitinen, Univ. of Eastern Finland (Finland)

A Moore 350FG 5-axis ultra precision machine tool platform with diamond tooling was used to generate 10 mm x 10 mm cylindrical diffractive lens on an electroless nickel insert.

A nanometric resolution PRO Engineering part file was generated from a point file containing the optical information of the diffractive structure and a ruling type surface machining tool path was generated on the part file. Ruling was opted as a machining method since the machining process is more easily controllable than fly-cutting. An electroless nickel insert slab was machined by diamond turning and the whole cylindrical diffractive lens was cut with a single sharp diamond tool with included angle of 45 degrees. The part needed to be machined with 40 nanometer sidestep and 1.26 μm microns depth of structure. It took more than 80 hours to finish the lens.

The Moore 350FG machine tool platform used in testing houses also a 100 - 1000 X magnification Keyence VHX-600 confocal microscope camera and a Fisba μ-Phase laser interferometer. Both devices were installed into the machine tool cabinet for online observing of the part machined.

Results indicate that the machining of cylindrical diffractive lens can be made by ruling. The path from optical designing to machining of the part was proven. Selection of the tool type and shape plays an important role in the outcome of the part. This method will produce high quality diffractive lenses for further replication processes.

7927-23, Session 5

Diamond milling or turning for the fabrication of micro lens arrays?: comparing different diamond machining technologies

S. Scheiding, Fraunhofer-Institut für Angewandte Optik und Produktionstechnologie (Germany)

Today, micro optical components are used in a wide range of products such as camera or sensor systems, medical instrumentations or communication devices. It can be estimated that the number of applications containing optics or optical system will further increase within the next years. In conclusion, high volumes of micro optics need to be manufactured.

The computer chip industry impressively demonstrates how to efficiently manufacture millions of small and precise parts. Here, single components are fabricated on large wafers, different wafers are stacked and subsequently diced into hundreds of single parts. Thus, following a wafer based production approach the economics of scale are perfectly used.

In optics manufacturing, the wafer based approach is already established for polymer optics. However, the future requests regarding optical systems such as imaging quality or construction size cannot be met by polymer optics. Here, glass, with higher refraction index and higher transmission, will be the material of choice. But the processes necessary to implement the glass optics manufacturing on wafer level are not yet established.

In this paper the manufacturing approach of wafer scale molded glass optics is described including a detailed view on each process step that needs to be accomplished, especially the mold manufacturing. Thus, it can be demonstrated that precision glass molding must be considered as an alternative and competitive manufacturing approach for the wafer level production of glass optics.
Feinmechanik (Germany)
Micro Lens Arrays (MLA) containing thousands of lenses with aspheric shapes and a precise position are used in sensor devices directly or as master moulds for the low-cost replication. A possible way to manufacture the master array is diamond machining. Depending on the size, the quality requirements and the geometry, servo turning (STS or FTS) or the emerging micro milling with mono crystalline diamond tools are suitable technologies for the manufacturing of the optical components. The paper describes both technologies in detail and shows differences and limitations of each technology. The latest manufacturing results for micro lenses on curved surfaces is described as well. Finally both technologies are compared regarding achievable figure trueness, roughness and economic factors like machining time.

7927-24, Session 5
Fabrication of single mode channel waveguides through microtransfer molding and microfluidics
S. Baig, Univ. of Miami (United States); J. J. Yang, New Span Opto-Technology Inc. (United States); M. R. Wang, Univ. of Miami (United States)

In this paper, we report on various single mode channel waveguide structures fabricated via microtransfer molding and microfluidic techniques. A UV-curable resin is used as the basis material for the waveguide cores. A vacuum assisted microfluidic technique with suitable structure can effective deliver the core resin material through the channels set by a poly-dimethylsiloxane (PDMS) mold. A high intensity UV light source is used to solidify the core resin resulting in the channel waveguide structures. The use of the microfluidic technique eliminated the channel waveguide residue and potential crosstalk associated with the microtransfer molding fabrication. The proposed method utilizing a PDMS mold, containing a negative imprint of the desired waveguide structure, to produce various single and multimode channel waveguide structures will result in an inexpensive and rapid turnover of various types of channel waveguide structures and may be particularly useful for production of these structures on user-desired surface substrates including those of a curved or distorted nature.

7927-25, Session 6
Microfabrication of microsystem-enabled photovoltaic (MEPV) cells
G. N. Nielson, M. Okandan, J. L. Cruz-Campa, P. J. Resnick, Sandia National Labs. (United States); M. W. Wanlass, National Renewable Energy Lab. (United States); P. J. Clews, T. C. Pluym, C. A. Sanchez, V. P. Gupta, Sandia National Labs. (United States)

Microsystem-Enabled Photovoltaic (MEPV) cells allow solar PV systems to take advantage of scaling benefits that occur as solar cells are reduced in size. We have developed MEPV cells that are 2 to 20 microns thick and down to 250 microns across. We have developed and demonstrated crystalline silicon (c-Si) cells with a solar conversion efficiency of 14.9% and gallium arsenide (GaAs) cells with a conversion efficiency of 10%. In pursuing this work, we have identified over twenty scaling benefits that reduce PV system cost, improve performance, or allow new functionality.

To create these cells, we have combined microfabrication techniques from various microsystem technologies. We have focused our development efforts on creating a process flow that uses standard equipment and standard wafer thicknesses, allows all high-temperature processing to be performed prior to release, and allows the remaining post-release wafer to be reprocessed and reused. The c-Si cell junctions are created using a backside point-contact PV cell process. The GaAs cells have an epitaxially grown junction. Despite the horizontal junction, these cells also are backside contacted. The crystalline silicon cells are released using either hydrofluoric acid (HF) with silicon-on-insulator (SOI) wafers or potassium hydroxide (KOH) with (111) oriented wafers. The gallium arsenide cells are released using an aluminum arsenide release layer and a HF release chemistry, similar to epitaxial lift-off (ELO) but without the supporting release handle typically used. We will provide recent developments and details for all steps of the process including junction creation, surface passivation, metallization, and release.

7927-26, Session 6
Atomic layer epitaxy of TiO2/ZnO multilayer optics using ZnO buffer layer for water-window x-ray
M. Murata, H. Kumagai, Y. Tanaka, Y. Sanjo, Osaka City Univ. (Japan); T. Shinagawa, Osaka Municipal Technical Research Institute (Japan)

A novel TiO2/ZnO multilayer deposited by atomic layer epitaxy technique has been fabricated to achieve a high reflective mirror and an attosecond chirped mirror in soft x-rays “water-window” (≈2.332-4.368 nm) wavelengths region. The technique is able to meet the needs for atomic layer control and epitaxial growth using sequential surface reaction and self-limiting nature. In preliminary experimental studies, both rutile TiO2 (200) and wurtzite ZnO (0001) thin films were grown epitaxially on the same sapphire (0001) substrates at 450°C and moreover a high reflectivity of 29.8% at around 2.73 nm and a grazing angle of 2 = 10°. The authors conducted the ALE experiment of TiO2/ZnO multilayer using a ZnO buffer layer. In the result, the multilayer using a buffer layer was able to be grown epitaxially on not only sapphire (0001) but also Si (100). In addition, reflectivity of multilayer remained to be 24.6% even on Si (100) in contrast with that about 27.5% on sapphire (0001). Thus, the ZnO buffer layer has the key material to fabricate the TiO2/ZnO multilayer on various substrates. For using ZnO buffer layer, substrate is deposited amorphous ZnO, so bulk ZnO thin layer is able to be grown on the amorphous ZnO. That’s why the layer enhance TiO2/ZnO multilayer, and the multilayer can be grown on every substrate.

In the presentation, ALE of TiO2/ZnO multilayer mirrors using buffer layer will be shown in detail.

7927-27, Session 6
Fast and economic nanowire fabrication using nano-crack lithography
Y. Peng, Y. Chang, National Cheng Kung Univ. (Taiwan)

Nanowire electronics has been an important technique in the fields of Nanophotonics and Biophotonics. Despite the rapid research achievements for nanowire-based devices, these devices have never been major players in current market due to limitations from current fabricating methods. Electron-beam Lithography (EBL) and Focused-Ion-Beam (FIB) can produce nanowire precisely at the desired location, but the high fabrication cost has limited these methods for prototype fabrications. Self-assembly methods offer economic ways to fabricate nanowire devices, the difficulty to connect the pre-fabricated nanowires and the electrodes results in low-fabrication yields.

In this study, fabrications of nanowires are investigated by Nano-Crack lithography. Nanoscale fractures occur when pre-patterned photoresist subjects to significant thermal stress, such as liquid nitrogen immersion. After the subsequent metal deposition and lift-off procedures, metal nanowires as narrow as 70 nm and 15 micrometers in length can be obtained inside the original photoresist fracture site. The locations of these fracture lines can be pre-determined by using bowtie photoresist patterns that the preferred crack direction are known. Therefore, the connections between the nanowires and electrodes can be achieved by the same fabrication process. This novel Nano-Crack Lithography offers economic solutions to bridge the gaps between the current high-cost
or low-yield fabrication techniques. This fabrication technique was not only cost effectively but also very fast, which should be very attractive for industrial application. Further development of this technique will be beneficial for future biosensing or nanowire optoelectronic applications.

7927-28, Session 6

Fabrication of optical filters using multilayered porous silicon

N. A. Gaber, The American Univ. in Cairo (Egypt); D. Khalil, Ain Shams Univ. (Egypt); A. Shaarawi, The American Univ. in Cairo (Egypt)

In this work we investigate the fabrication of optical filters using multilayered porous silicon 1-D photonic structure. An electrochemical cell was constructed to control the porosity of variable layers in p-type Si wafers. Porous silicon multilayered structures are formed of /4 (or multiples) thin films that construct NIR optical interference filters. By changing the anodizing current density of the cell during layer formation, different porosities can be obtained. As the optical refractive index of the layers depends on the porosity, an optimized filter design can be obtained by the smart control of the anodizing current. This allows obtaining low cost optical filters fabricated by micofabrication techniques. However, this requires precise control of the thickness as well as index / porosity of the formed layers over a wide wavelength range. To determine the morphology, the wavelength dependent refractive index n and absorption coefficient , first, porous silicon free standing mono-layers have been fabricated with different conditions and characterized in the near infrared region (from 1000 to 2500nm). A specific parameter extraction technique is then used to extract the thicknesses and refractive indexes of the formed layers. A wide range of refractive index (from 1.6 to 2.6 up to 3.4) was obtained. Subsequently, multilayer structure have been fabricated and tested. Their spectral response has been measured and shows good agreement with numerical simulations. Inserting etching breaks has also been used to assure the depth homogeneity. The effect of etching/break times on the reproducibility of the filters has also been reported.

7927-29, Session 7

Microscale, printed LEDs for unusual lighting and display systems

J. A. Rogers, Univ. of Illinois at Urbana-Champaign (United States)

Inorganic light emitting diodes (LEDs) represent important, established technologies for applications in solid state lighting, digital imaging and many others. Eliminating design constraints imposed by the supporting semiconductor wafers can enable alternative modes of use in areas such as biomedicine and robotics. This talk describes systems that consist of arrays of interconnected, ultrathin inorganic LEDs configured in mechanically optimized layouts on unusual substrates, ranging from elastic membranes and bands, to sheets of aluminum foil and paper, to balloons, thin ribbons and fine threads. Light emitting sutures, implantable sheets and balloon catheters that are compatible with complete immersion in biofluids illustrate the suitability of these technologies for use in biomedicine. Waterproof proximity sensor tapes capable of conformal integration on curved surfaces of gloves demonstrate a possibility in robotics. These and related systems may create important, unconventional opportunities for optoelectronic devices.

7927-30, Session 7

CMOS-compatible fabrication, micromachining, and bonding strategies for silicon photonics

J. Heck, Intel Corp. (United States)

The advent of optical technologies by high-volume consumer markets is severely limited by the cost and complexity of manufacturing complete optical transceiver systems. This is in large part because “boutique” semiconductor fabrication processes are required for III-V lasers, modulators, and photodetectors; furthermore, precision bonding and painstaking assembly are needed to integrate such dissimilar devices and materials with high precision. On the other hand, 200mm and 300mm silicon process technology has been bringing ever-increasing computing power to the masses by relentless cost reduction for many years. Intel’s silicon photonics program aims to marry CMOS infrastructure and recent developments in MEMS manufacturing with the burgeoning field of micro photonics to make low cost, high-speed optical links ubiquitous. In this paper, we will provide an overview of several aspects of our silicon photonics technology development in a CMOS fabrication line. First, we will discuss some of the challenges of fabricating hybrid III-V lasers on silicon, including such aspects as hybrid integration of InP-based materials with silicon, etching of InP films, contact formation using CMOS-compatible metals, and current channel definition. Second, we will describe fabrication strategies from the MEMS industry for micromachining silicon to create passive optical devices such as mirrors, waveguides, and facets, as well as alignment features. Finally, we will review several of the bonding technologies that are necessary for hybrid integration of dissimilar semiconductors, as well as precision bonding of different devices to enable complete optical transceivers.

7927-31, Session 7

Single quantum dot (QD) manipulation on nanowire using dielectrophoretic force

J. Kim, J. Park, Korea Univ. (Korea, Republic of); H. J. Shin, Korea Institute of Science and Technology (Korea, Republic of)

We proposed the method of single QD immobilization on nanowire for cavity-free single photon source using DEP force. 25 nm zinc sulfide capped cadmium selenide (CdSe/ZnS) QDs (0.8 nm, emission wavelength: 605 nm) were used and 100 nm width gold nanowires were fabricated with micro scale gold electrode. 100nm width gold nanowires were fabricated on a silicon dioxide (SiO2) using lift-off process after e-beam lithography and e-beam evaporation. First, e-beam resister (ER) was patterned to have 100 nm wide grooves and a 50 nm thick gold layer with a 10 nm thick chrome layer was deposited using e-beam evaporator at low deposition rate of 0.1 nm/sec to acquire smooth surface. Second, photo resister (PR) was patterned to make micro gold electrode and did lift-off process with same condition for nanowire. Third, the gold nanowire was covered with SiO2 layer deposited with PECVD resulting in 1 um thick to prevent leak of current from electrode. Opened end of gold nanowires, the target surface for QD immobilization, were formed using two etching processes for SiO2 and gold, respectively.

Single QD immobilization on the target surfaces was accomplished through DEP force. Positive DEP force is needed to immobilize a 25 nm diameter QD to nanowire. We apply 8 Vpp, 3 MHz sine wave and it occur 108 V/m electric field and electric field gradient around gold nanowire. Single quantum dot attachment on the nanowire is confirmed by optical analysis.
7927-32, Session 7

DFB lasers fabricated by nanoimprint process
W. Liu, Huazhong Univ. of Science and Technology (China)

DFB LDs are key components in DWDM optical network which utilize grating structures to control the wavelength and single mode property. Now DWDM equipment to control not only has been used for backbone networks, but also may be deployed in access networks, like WDM PON. Most basic optical communication devices are pretty cheap now except the DFB LDs which satisfied the DWDM requirement. That is because the LD grating period has to be controlled with very high accuracy and the EBL is currently the most popular solution. Therefore it is highly desirable to develop a low cost DFB LD manufacture process. We propose a high throughput NIL process based on low cost large stamp fabricated by SFIL and soft stamp method. DFB chips at DWDM wavelength were manufactured with both good uniformity and performance. 13 ITU channels from 1540nm to 1560nm of 200GHz space are made on one wafer. Our results show that SFIL has high potential to become another popular technology for DFB LD production, this cost effective and high efficiency manufacture solution may yield a significant impact to the future optical communication industry development.

7927-33, Session 8

Nanofabrication and nano-optics at CNST
J. A. Liddle, V. A. Aksyuk, H. J. Lezec, A. A. Talin, K. Srinivasan, National Institute of Standards and Technology (United States)

Nanofabrication and optics have become inextricably linked over the past few years, with new fabrication techniques enabling advances in nano-optics and advances in optics facilitating novel nanofabrication and manipulation techniques. Plasmonic structures confine light to small volumes very effectively and the intense fields produced can be used to enhance chemical reactions, or to provide methods for measuring their progress. I will discuss the use of simple patterning methods to robustly create large-area plasmonic structures and their properties, as well as the use of precisely formed plasmonic sensing devices that can be used to follow the initial stages of electrochemical processes with high sensitivity. The measurement of the intensity distributions in nano-optical structures is often needed in order to understand, calibrate and optimize their behavior. I will describe the use of a novel sublimation-switch resist, which exhibits a response across the entire visible spectrum, as a tool for the metrology of such structures. Micromechanical systems can be used to measure extremely small forces. I will describe how a combination of advanced deposition techniques, optical lithography, deep reactive ion etching and focused ion-beam machining has been used to create a device to measure the response of a fully volumetric metamaterials. Micrascope structures can also be strongly coupled to optical resonators to form systems that can be used for ultra-precise sensing and actuation. I will describe the use of advanced fabrication techniques to build an optomechanical device with displacement sensitivities on the order of fm/Hz^1/2.

7927-34, Session 8

Fabrication of guided mode resonance filters on conformal surfaces
A. T. Cannistra, M. K. Poutous, E. G. Johnson, T. J. Suleski, The Univ. of North Carolina at Charlotte (United States)

Guided mode resonance (GMR) filters are highly functional micro-optical structures, capable of narrowband spectral filtering. Their relatively simple design includes a subwavelength periodically modulated index layer and a waveguiding layer. This configuration yields efficient and easily tunable devices over a broad range of wavelengths. GMR filters have been extensively used for sensors, polarizers, dichroic laser mirrors, and many other applications when these structures are fabricated on flat surfaces.

In this paper, we demonstrate fabrication of GMR filters on conformal surfaces using non-traditional techniques. Flexible composite molds made of polydimethylsiloxane (PDMS) and high compression modulus or “hard” PDMS (h-PDMS) are used as replication templates in a micro-transfer molding process. SU-8 negative photoresist serves as the moldable polymer with good thermal characteristics compatible with subsequent plasma enhanced chemical vapor deposition (PECVD) of dielectric layers. Fabrication procedures for GMR filters at near-IR wavelengths on concave lens surfaces are discussed, and initial experimental results are presented.

7927-35, Session 8

Novel light-transmitting nano-meshed metal electrode fabricated by self-assembled method
K. Asakawa, E. Tsutsumi, R. Kitagawa, K. Masunaga, T. Nakanishi, A. Fujimoto, Toshiba Corp. (Japan)

A new concept light-transmitting metal electrode is proposed. The structure of this electrode consists of myriad nano-scale holes opening in a metal thin film with slightly disordered periodicity. The continuity of metal parts were short enough to restrict the motion of free electrons and the metallic reflection would be suppressed, as a result, the light would pass through the metal thin film. On the contrary, this structure would not affect the electric current so much and its resistivity remains as low as that of the metal. A nanometer-scale hole array on a metal thin film over centimeters was realized using self-assembled nano-structure as a template. As a result, this nano-meshed electrode exhibited the light transmittance greater than 60% for visible light in spite of the opening area of 27%, and showed more than one digit lower resistivity than that of ITO.

7927-36, Session 8

Design and fabrication of binary multi-phase-level computer generated holograms based on an effective medium approach
W. Freese, Friedrich Schiller Univ. (Germany); E. Kley, Friedrich-Schiller-Univ. Jena (Germany); H. Eckstein, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Diffractive elements like phase-only computer generated holograms (CGHs) are important for many applications modern optics like beam shapers and beam splitters. Due to fabrication constrains, it is necessary to discretize a continuous phase function into a certain number of phase steps with a limited resolution. However, a high resolution is needed to achieve the small feature sizes of the phase pattern which are essential for large deviation angles of diffractive optical elements. Further, as in standard diffractive optics, high efficiencies rely on an increasing number of phase steps. This fact usually complicates the fabrication process due to a more complex topography of the element which requires multiple aligned exposure and etching steps. In this paper we demonstrate an effective medium approach using binary subwavelength structures instead of a conventional surface relief profile to generate a complex CGH phase pattern. Consequently, the fabrication process is simplified to one exposure and one etching step independent from the number of phase levels. This provides new perspectives for designing highly efficient diffractive elements with large deviation angles. The technology to generate binary structures in the nanoscale range is highly developed. The high-speed e-beam writer Vistec SB3500S, as a central part, allows a precise and fast exposure even for largescale applications. For demonstration, a CGH is designed and fabricated as reflective element for 532 nm. A patterned fused silica layer on a reflective substrate acts as a refractive (effective) medium. The experimental data are in good agreement with the theoretical predictions.
Fabrication of novel instrumentation of multispectral imaging technology driven MEMS-based micro-arrayed multichannel optical filter mosaic

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Multispectral imaging is becoming a new powerful tool in a wide range of biological studies by adding spectral, spatial and temporal dimensions to tissue abnormity and the underlying biological processes. A standard spectral imaging setup includes two major components, a band pass selection device (such as liquid crystal tunable filter and diffraction grating) and a scientific-grade monochrome camera. Contemporary multispectral imaging technologies typically use traditional optical filters e.g., filter wheels, a generalized Lyot filter, an electrically tunable filter, multiple-band pass filters or the methods of dispersing light, e.g., optic-acoustic crystals. The instrumented systems are bulky, expensive, require multiple exposures or extensive post-processing to align up multiple images of pure spectral components.

Recently a break-through technology has emerged to instrument multispectral imaging technology into handheld real-time devices using miniaturized filter mosaic containing micro-arrayed multiple channel band-pass optical filters. The filter mosaic can be directly placed near the focal plane immediately in front of the imaging sensor of an off-shelf CCD/CMOS camera, with potentially one such micro-filter covers one pixel of the imaging sensor. This paper reveals the technical details of how such a micro-arrayed multi channel optical filter is fabricated using traditional multi-film vacuum deposition and lithography technologies. The selection of different coating materials, their structures and effects to the adhesive forces between film and substrate, the spatial resolution, width of passing band, and the transmittance of the resulting miniaturized optical filter will be discussed.
Atomic layer deposition/molecular layer deposition for packaging and interconnect of N/MEMS

Y. C. Lee, Univ. of Colorado at Boulder (United States)

Atomic layer deposition (ALD)/molecular layer deposition (MLD) processes are able to fabricate nano-scaled inorganic/organic multilayers. Such multilayers are essential to novel packaging and interconnect technologies for Nano-Electromechanical Systems (NEMS) and Micro-Electromechanical Systems (MEMS). For example, ALD/MLD-based moisture barrier coatings could reduce water vapor transmission rate down to 5X10^{-5} g/m2/day, which is good for hermetic/vacuum sealing of polymer packages and organic LEDs and other photonic and electronic devices. ALD/MLD hydrophilic/hydrophobic/protective coatings are also enabling technologies for nanowire/nanomesh structures critical to flexible thermal ground planes reaching an effective thermal conductivity of 30,000 W/mK and heat flux removal of 200 W/cm2. ALD/MLD coatings over anodes/cathodes can enhance the stability of an embedded Li-ion batteries during a 10X increased charging rate. They can also reduce the battery thickness by 10X through innovation in solid electrolytes and packaging. As a result, future smart phone or microsystems can be flexible with a thickness reaching 1mm. In addition, the ALD/MLD-based inorganic/organic multilayer can be used for the electrical, thermal and mechanical interconnect for GaN nanowire-based nanophotonics. With these nano-scaled multilayers, we are well equipped to develop novel packaging and interconnect technologies for future N/MEMS.

Spherical and non-spherical microlens arrays fabricated utilizing polymer coating on isotropically etched quartz

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Numerous fabrication methods for microlens array (MLA) still suffer from reproducibility, control of lens shapes, and uniformity through the array. We here report development of MLAs via polymer coating on isotropically wet etched quartz substrates for various microlens shapes and optical characteristics. By utilizing etching technique, it is possible to obtain great element uniformity, to repetitively produce regular lens shapes, and to easily alter curvature forms depending on etching conditions. For the fabrication, chromium was deposited on the quartz substrate and then patterned to form open-hole array via photolithography processes. In this procedure, while fixing the other design parameters, we merely varied diameter of the holes (e.g., 2, 4, 6, 8, 10 μm) to obtain various spherical and non-spherical lens appearances at the etching step. After isotropic wet etching of quartz, occurring through the holes in buffered oxide etchant, polymer with a higher refractive index (n = 1.47) than that of the quartz (n = 1.47) was spin-coated on the etched quartz to fill the plano-concave curvatures, resulting in focusing of the collimated light. The fabricated MLAs showed excellent uniformity and different shapes based on hole sizes. For the optical characteristics, the MLAs exhibited various focal lengths and evenly distributed light spots. As the curvatures became flat away from sphere, the focal length was longer gradually. The measured spot size at the focal plane was approximately 1.5 μm. We expect that the simple fabrication, uniform shapes in the array, and good optical properties are promising for many application fields.
structural elements. In order for the moving elements of a MEMS device to move effectively in a well-controlled atmosphere, hermetic sealing of the MEMS device in a cap is necessary. For some MEMS devices, such as resonators and gyroscopes, vacuum packaging is required. Usually, the cap is processed at the wafer level, and thus MEMS packaging is truly a wafer level packaging. In terms of MEMS/MOEMS and nanodevice packaging, there are still many critical issues need to be addressed due to the increasing integration density supported by 3D heterogeneous integration of multi-physic components/layers consisting of photonics, electronics, rf, plasmonics, and wireless. The infrastructure of MEMS/ MOEMS and nanodevices and their packaging is not well established yet. Generic packaging platform technologies are not available. Some of critical issues have been studied intensively in the last years. In this paper we will discuss about processes, reliability, testing and characterization of MEMS/MOEMS and nanodevice packaging.

7928-05, Session 2

Silicon TSV interposers for photonics and VLSI packaging

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Abstract

Miniaturization, higher performance, and higher bandwidth needs of the electronic industry continue to drive technology innovations through increased levels of integration. Through Silicon Via (TSV) technology along with flip chip technology provides significant improvements over the traditional technologies for packaging VLSI circuits. Silicon Interposers built using TSVs and embedded capacitors Si packaging provide solutions to the next generation needs of VLSI Packaging. TSV Si interposers also provide a platform for integrating photonic elements like the laser diodes and optical fibers for next generation high bandwidth VLSI packaging.

The presentation describes (i) the TSV technologies developed, (ii) implementation of Si TSV interposer with embedded capacitors for VLSI packaging, and (iii) development of Si TSV interposer for integration of photonics and VLSI subsystems. Reliability results of interposers with embedded capacitors are also presented.

Vertical stacking of Silicon dies provides a very attractive way of improving functional density of electronics in addition to potentially providing increased electrical performance. Silicon TSV technology along with die stacking on organic substrate is utilized in forming a Silicon Interposer for VLSI packaging. The benefits of high density routing on the Silicon interposer, along with the matching of Silicon CTE provides a reliable packaging technology for next generation VLSI circuits. Very high value capacitors are embedded on the Silicon interposer for low noise decoupling and thus helping to provide a high performance electrical solution. In order to integrate photonics, optical fiber grooves are precision etched, and facets of 45 degree slopes are created to be able to couple light directly from a flip chip mounted laser diode. Interposers built with embedded capacitors are subjected to thermal cycling tests and electrical testing is done at intervals to assess the reliability of the interposers.

7928-07, Session 3

Fiber-based multi-beam laser Doppler vibrometer for measuring transient vibrations

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This paper presents a novel fiber-based multi-beam Laser Doppler vibrometer (LDV). This method uses only one laser source at 1550 nm and one photo-detector instead of multiple detectors according to other reported multi-beam laser Doppler vibrometer. The spatial encoding technique is employed to produce multiple laser beams with different frequency shifts. More exactly, by passing a laser source through two acousto-optic modulators (AOMs) at different regimes, a 4×5 laser beam matrix is generated and then transmitted onto different points of a vibrating target. The backscattered light signals are collected back into a single mode fiber by a fiber collimator and combined with a common reference beam. This mixture of optical signal passes through an Erbium Doped Fiber Amplifier (EDFA) before it is detected by a high-speed fiber-based InGaAs photo-detector. With a digital demodulator, the phase variation on different points can be easily obtained from different frequency bands. The experimental results show it is possible to do a precise vibration measurement on twenty points simultaneously using this method. Recognized as a well known non-contact optical instrument to measure the motions and vibrations of structures and machine components, single-beam LDV has been heavily developed and already become a mature product, driven by vast application demands from many industrial areas. However, it is often required to measure transient events, i.e., to measure vibrations at different points simultaneously. The proposed multi-beam LDV in this paper could provide a new solution to such measurement needs.

7928-08, Session 3

Infrared scanning white light interferometry using a solid state light source

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Scanning White Light Interferometry (SWLI) allows surface characterization of MEMS components. Standard, broadband visible light SWLI instruments measure the 3D profile of the topmost sample surface. With transparent samples SWLI can image structures with multiple stacked layers. However, since silicon is opaque for visible wavelengths, it is impossible to measure profiles of multi-layered silicon structures or to identify delamination of silicon layers with standard SWLI setups. We combined the optical outputs of a number of infrared light emitting diodes (IR-LEDs) to achieve a source with an adjustable (spectral width and mean-wavelength position) broadband spectrum and fast switching time. Broadband IR light allows accurate simultaneous measurement of 3D profiles of internal interfaces between different materials in silicon samples - and MEMS. The fast switching times allow stroboscopic illumination to be used for measuring oscillating samples.

The IR SWLI setup equipped with an IR camera (Xenics XEVA-116), sensitive to 0.9 - 1.3 μm wavelengths from was tested by characterizing 2 - 10 μm thick silicon membranes. Both silicon-air interfaces were successfully defined and the distance between them (membrane thickness obtained with one-sided access) measured for all membranes. The results were compared with other destructive methods. The ability to see through silicon layers advances the state of the art of the field of MEMS characterization by allowing accurate measurement of the internal parts of the devices during operation.

7928-09, Session 3

Vibration and shock testing of a MOEMS tunable grating: new modeling methodology and its experimental validation

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We report on a methodology to predict a lower limit on the acceleration leading to failure of MEMS as a function of vibration frequency, and on the validation of the model by testing a single-crystal silicon MOEMS tunable grating. The method, which we apply to both mechanical vibrations and shocks, is an analytical approach based on experimentally obtained parameters, mainly resonant frequencies and damping
coefficients. This combined analytical-experimental approach avoids the use of FEM, which can be time consuming and does not include fabrication tolerances and material variability.

**The minimum frequency-dependent acceleration** that will lead to surfaces coming into contact, for vibration inputs, is determined for all three axes, based on measured mode shapes, frequencies and damping, thus defining a safe operating region. The computed acceleration value is only a lower limit, as contact between MEMS parts does not necessarily lead to stiction or short -circuits.

The device used to validate this approach is a tunable grating, fabricated from the 10 μm thick single-crystal silicon layer of an SOI wafer. The device consists of a 1x1 mm2 or a 0.5x0.5 mm2 grating, with a 12 μm initial pitch. The pitch can be increased by up to 5 % using comb drives on both sides of the centrally anchored grating. In-plane and out-of-plane vibration (up to 65 g) and shock testing (up to 6000 g) was performed as a function of frequency, maximum acceleration and applied bias to the comb drives, and good agreement was found with the model.

**7928-10, Session 3**

**Reliability of MEMS**

A. Dommann, A. Neels, Ctr. Suisse d’Electronique et de Microtechnique SA (Switzerland)

To achieve the demand on high reliability for MEMS, new methods in testing and qualification of materials and devices are needed. Mechanical properties must be used as design element for MEMS devices. They are of critical importance to reliably predict the performance of micromechanical systems and other micro scale devices. To characterize the small-scale and scale specific mechanical properties of MEMS materials, different micro scale experiments are developed. The aim is to have a strong correlation ship between the experiment on test specimens and the MEMS application.

The understanding of failure requires detailed information about the material structure on the atomic scale. Therefore, HRXRD is a routinely used tool for investigations of the materials composition, strain, orientation and overall quality. In-situ measurements of local deformations and the analysis of the strain field and defects in the critical regions of the loaded structure by HRXRD allow the comparison and correlation with the simulation of deformations by the Finite Element Method (FEM).

**7928-11, Session 3**

**Reliability enhancement of Ohmic RF MEMS switches**

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Switches are deemed to be key components among the RF MEMS, and are used for manifold applications e.g. TX/RX selection, reconfiguration of filters, of phase shifters or of antennas. This contribution deals with capacitively actuatted Ohmic switches in series SPST configuration for DC up to 4 GHz signal frequency (<0.5 dB insertion los, 35 dB isolation) and in shunt switch SPST configuration for a frequency range from RF up to 75 GHz (<1.2 dB insertion los, 20 dB isolation). A novel high aspect ratio MEMS fabrication sequence in combination with wafer level packaging is applied for fabrication of the samples and allows for a relatively large actuation electrode area, and for high actuation force resulting in fast on-response time of 10 μs and off-response time of 6 μs at less than 5 Volt actuation voltage. Large actuation electrode area and a particular design feature for electrode over travel and dynamic contact separation lead to high contact force in the closed state and to high force for contact separation to overcome sticking. The switch contacts, which are consisting of noble metal, are made in one of the latest process steps which prevents contamination of the contact surfaces by fabrication sequence residuals. A life time of 10e9 switch cycles has been achieved.

The proposed paper will cover design for reliability issues and reliability test methods using accelerated life time test. Different test methods have been combined to examine electric and mechanical motion parameters as well as RF performance simultaneously to develop deep understanding of possible failure modes.

**7928-12, Session 3**

**Crack growth and reliability modeling of multi-layer capacitors in microelectronics applications**

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The microelectronics sector is actively replacing SnPb eutectic solders with lead-free solders such as SAC (SnAgCu) in an effort to comply with recent environmental legislation. The alternative materials have raised reliability concerns, including crack formation inside capacitors. Flexible terminations made of silver-filled epoxy are becoming more widely used in place of copper terminations to mitigate the effects of board bending on capacitor cracking. In contrast to the developments in capacitor components, material selections for electrodes, dielectric, printed circuit boards, and board pads have remained relatively stable. Factors affecting the formation of cracks in the ceramic dielectric body of multi layer ceramic capacitors (MLCCs) are explored for several sizes of capacitors. The flexible termination capacitors have shown a tolerance for higher board bending loads with low strain rates, but not for higher strain-rate bending. Lead-free solders have been observed to require a higher temperature for processing during the reflow cycle for connecting the capacitors to the board. The authors examine whether the disparity in performance may be attributed to the change in the material of the termination and the size of the capacitors. Preliminary results indicate a distinct correlation in studies that varied the termination material, shape, and thickness of MLCCs. Under regimes in which boards were subjected to cyclic bending, vibrations, temperature cycling, and high G loading conditions, cracks have tended to appear in the capacitor’s ceramic body on the bottom of the capacitor close to the termination. As capacitors shrink in size, the appearance of cracks has similarly decreased.

**7928-13, Session 4**

**Effects of radiation on MEMS**

H. R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

The sensitivity of microelectromechanical system (MEMS) devices to radiation is reviewed, with an emphasis on radiation levels representative of space missions. As a purely structural material, silicon and most metals show no mechanical degradation after absorbed radiation doses in excess of 50 Mrad, a dose corresponding to several years with no shielding in the radiation belts surrounding the Earth. Yet MEMS devices, even when excluding control/readout electronics, have failed at doses of only 20 krad, though some devices have been shown to operate correctly for doses greater than 10 Mrad. Radiation sensitivity depends strongly on the sensing or actuation principle, device design, and materials, and is linked primarily to the impact on device operation of radiation-induced trapped charge in dielectrics. Ionizing radiation creates electron-hole pairs, which, especially in the presence of an applied voltage, lead to trapped charge in insulators. MEMS devices operating on piezoresistive principles can be highly sensitive to charge accumulation in dielectric layers, especially for designs with dielectrics located between moving parts. In contrast, thermally and electromagnetically actuated MEMS are much more radiation tolerant. MEMS operating on piezoresistive principles start to slowly degrade at low doses, but do not fail catastrophically until doses of several Mrad. An introduction to the space radiation
environment is given, followed by a survey of all published reports of radiation effects on MEMS, as well as a summary of techniques that can improve their radiation tolerance, with an emphasis on techniques that mitigate the effect of trapped charge.

7928-14, Session 4

Reliability of Sn-Pb and Pb-free surface mounted miniaturized passive components for extreme temperature space missions
R. Ramesham, Jet Propulsion Lab. (United States)

Surface mount electronic package test boards have been assembled using tin-lead (Sn-Pb) and lead-free (Pb-free) solders. The soldered surface mount packages include ball grid arrays (BGA), flat packs, various sizes of passive chip components, etc. They have been optically inspected after assembly and subsequently subjected to extreme temperature thermal cycling to assess their reliability for future deep space, long-term, extreme temperature missions. In this study, the employed temperature range (-185°C to +125°C) covers military specifications (-55°C to +100°C), extreme cold Martian (-120°C to +115°C), asteroid Nereus (-180°C to +250°C) and JUNO (-150°C to +120°C) environments. The boards were inspected at room temperature and at various intervals as a function of extreme temperature thermal cycling. Electrical resistance measurements are reported and the tests to date have shown some change in resistance as a function of extreme temperature thermal cycling. However, the change in interconnect resistance becomes more noticeable with increasing number of thermal cycles. Further research work will be carried out to understand the reliability of packages under extreme temperature applications (-185°C to +125°C) via continuously monitoring the daisy chain resistance for BGA, Flat-packs, etc. This paper will describe the experimental reliability results of miniaturized passive components (01005, 0201, 0402, 0603, 0805, and 1206) assembled using surface mounting processes with tin-lead and lead-free solder alloys under extreme temperature environments.

7928-15, Session 4

Displacement damage effects in silicon MEMS at high proton doses
J. F. Gomes, H. R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We report here on a study of the sensitivity of silicon MEMS to proton radiation and mitigation strategies. MEMS systems can degrade due to ionizing radiation (electron-hole pair creation) and non-ionizing radiation (displacement damage), such as electrons, trapped and solar protons, or cosmic rays, typically found in a space environment. Over the past few years there has been several reports on the effects of ionizing radiation in silicon MEMS, with failure generally linked to trapped charge in dielectrics. However there is near complete lack of studies on displacement damage effects in silicon-MEMS: how does silicon change mechanically due to proton irradiation? We report on an investigation on the susceptibility of 50 μm thick SOI-based MEMS resonators to displacement damages due to proton beams, with energies from 1 to 60 MeV, and annealing of this damage. We have developed a methodology for measuring ppm changes on the Young’s modulus and Poisson ratio by means of accurately monitoring the resonant frequency of devices in vacuum using a modified Laser Doppler Vibrometer technique. Motivation for this work is our earlier investigation where we observed for the first time an increase (up to 0.05%) of the Young’s modulus of single-crystal silicon electromagnetically-actuated micromirrors after exposure to low energy protons (1–4 MeV) at high absorbed doses – 100 Mrad(Si). This investigation will contribute to a better understanding of the susceptibility of silicon-based MEMS to displacement damages frequently encountered in a space radiation environment, and allow appropriated design margin and shielding to be implemented.

7928-16, Session 5

MEMS technology to achieve miniaturization, redundancy, and new functionality in space
T. Gronland, NanoSpace AB (Sweden)

Development of MEMS-based (Micro Electro Mechanical System) components and subsystems for space applications has been going on for at least two decades. The main driver for developing MEMS based components for space is miniaturization. Using MEMS can also allow increased redundancy and enable novel spacecraft designs and mission scenarios. However, the commercial breakthrough of MEMS has not occurred within the space business as it has within other branches such as the IT/telecom, the automotive industry, or other areas. Currently there are few flight opportunities allowing extensive use of new technology in space, but one of the exceptions is the PRISMA satellites. PRISMA is an international (Sweden, Germany, France, Denmark, and Norway) technology demonstration program with focus on rendezvous and formation flying. One of the PRISMA satellites has a cold gas propulsion system onboard based on MEMS-technology including a number of miniaturized and novel components. In addition to the added value through reduced mass, volume and power of individual components, increased redundancy and improved performance has also been achieved by using MEMS-based components with the added weight of grams only. MEMS pressure sensors integrated into the mechanical housing of another component is one example and another is an isolation valve which is both redundant and has an integrated particle on a single silicon chip weighing less than one gram. This paper presents a number of miniaturised components, their development status and their maiden spaceflight onboard the Prisma satellite.

7928-17, Session 5

MOEMS for prospective space applications
T. Viard, C. Buisset, Thales Alenia Space (France); F. Zamkotsian, Lab. d’Astrophysique de Marseille (France)

Thales Alenia Space is involved with ESA and CNES from few years now, in the analysis of space applications using MOEMS components. A first concept using a Programmable Micro Diffracting Device (PMDD) has been proposed for an astronomical spectrometer with a quite low field of view. In this application the introduction of a MOEMS component has allowed to reduce the focal plane complexity (one mono detector) and to increase the mission adaptability to the target (programmable mission). An opto mechanical concept has been proposed and first performance assessed. A second concept has been studied by Thales Alenia Space and deals with the use of a MOEMS component to realize a new type of spectrometer. In the proposed solution, a MOEMS was used to realize a shifting spectral window (large spectral width) associated to a slight spectral increment. The signal given by the detector being the convolution between the target spectral density and the spectral window, it is then possible to recover the target spectral signal by a simple deconvolution. A breadboard is currently under realization in partnership with LAM (Laboratoire d’Astrophysique de Marseille). Some result of this test bench will be presented. Some results of analysis will be also given concerning the use of MOEMS for Earth observation associated to a pushbroom detection mode and a large field of view.

7928-18, Session 5

Expanding the spacecraft application base with MEMS gyroes
T. Brady, The Charles Stark Draper Lab., Inc. (United States)
MEMS devices have a promising future in space given their inherent low power, low volume, and low mass qualities. In December of 2006, flight testing of the Inertial Stellar Compass (ISC) onboard the Air Force TacSat-2 spacecraft qualified and demonstrated superb MEMS gyroscope performance in the relevant space environment over a variety of conditions. This development helped reduce the risk and cost associated with selecting MEMS based gyro devices for future space missions further providing spacecraft designers with the full benefits of this new sensor technology. Since the ISC flight, various spaceflight applications in need of low power and low mass rate solutions have been enabled and envisioned for use within the spacecraft application base. This paper describes prior history, proposed applications, and future benefits with the inclusion of MEMS gyro in the spacecraft domain.

7928-01, Session 6
Applications of MEMS in segmented mirror space telescopes
B. Agrawal, Naval Postgraduate School (United States); J. Kubby, Univ. of California, Santa Cruz (United States)

For several future space missions, larger aperture and lightweight deployable mirrors, in the range of 10-20 meters in diameter with high surface accuracy, are required. In order to meet the launch vehicle diameter constraints, the concept of segmented mirrors, such as in James Webb Space Telescope, is used. For these telescopes, alignment of the segments in orbit and achieving the required surface accuracy is a very challenging problem and expensive to develop. In order to achieve lightweight and active surface control, actuated hybrid mirror (AHM) technology is under development that consists of a rib-stiffened silicon carbide substrate, a metallic nanolaminate facesheet to provide optical finish, surface parallel actuators, and a sensing system, typically a wave front sensor, to determine the surface errors. The system consists of hundreds of sensor outputs and hundreds of actuators resulting in a very challenging control problem. These systems also require extensive analysis and testing, resulting in a very high cost for development. The Naval Postgraduate School recently received 3-meter diameter space telescope testbed with six segments that uses and AHM technology. This paper will discuss on how we can use a MEMS deformable mirror to improve the performance of the NPS segmented mirror telescope. The high-stroke, high-order actuated MEMS deformable mirror will correct the residual alignment and surface errors that are not corrected by the actuators on the mirrors. The mirror will use electrostatic actuation to eliminate the need for power to hold its position and will be capable of open-loop, go-to positioning.

7928-19, Session 6
Improved coupling to integrated spatial heterodyne spectrometers with applications to space
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Multiple Aperture Transform Chip Heterodyne Spectrometers (MATCHeS) have been developed for targeted remote sensing applications in harsh environments. These waveguide-based Fourier Transform Spectrometers (FTS) offer significant improvements in resource efficiency over monolithic glass implementations, but are relatively limited in terms of input coupling efficiency and fill factor of the input facet. Integrated optics spectrometers have significant resource advantages for space applications. Monolithic Spatial Heterodyne Spectrometers are insensitive to vibration and do not require frequent calibration. In addition, Fourier Transform Spectrometers are known to provide significant performance advantages for emission spectroscopy. Ongoing work will improve the MATCHeS input coupling efficiency from free space. This paper discusses the signal to noise improvements expected by incorporation of surface gratings, or back-thinning and stacking of slabs.

We show that the use of surface gratings can increase the throughput over coupling to bare waveguides alone (in a single polarization), and provide close to 100% fill factor, albeit with limited field. Étendue improvements associated with stacked slabs are limited only by the sensing area available, but the fill factor of the input facet is limited to ~10%.

The impact of these improvements is assessed in the context of two space-based applications: 1) Spatial Heterodyne Observations of Water (solar occultation absorption spectroscopy) and 2) LIBS/Raman spectroscopy for mineral identification on a planetary rover, similar to the Mars Science Laboratory ChemCam Instrument.

7928-20, Session 6
Integration of optical waveguides and microfluidics in a miniaturized antibody micro-array system for life detection in the NASA/ESA ExoMars mission
H. Leeuwis, A. Prak, R. G. Heideman, A. Leinse, LioniX BV (Netherlands); G. Borst, Dutch Space B.V. (Netherlands)

A microfluidic fused silica sandwich chip integrates all the relevant components for the analysis/assay procedure (except the pumping which is performed by a syringe), i.e. pretreated sample intake; buffer, hybridization/reaction and reagents dissolution chambers; liquid front sensors; inputs and output ports for the selector valve and a channel structure connecting these components. Moreover, the design is based on three separate pathways in order to allow for three different classes of assays. The whole fluidic design is driven by the requirement that the dead volumes and the total liquid volume is as small as possible. To realize this, a miniaturized and integrated selector valve appeared to have far better properties than a system with numerous integrated and externally, often pneumatically actuated on-off valves, which is applied in many systems found in the literature. Next to this, the connected volume and mass of the whole fluid management system is lower.

An optical array chip incorporates integrated waveguides, which allow for excitation of the fluorescent labels by the evanescent field of the guided light wave. The system had to be designed in such a way that the light of a single chip-coupled fiber is distributed over all the spots (10 x 20) of the array. The LioniX proprietary waveguide technology technology TriPleX is the only mature technology that allows this in the required (VIS) wavelength region. The losses of this silicon-nitride based waveguide system are extreme low, even at the small bends necessary to distribute the light over the matrix spots.

7928-20, Session 6
Ultra-low-power multiplexed electronic driver for high resolution deformable mirror systems
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In principle, electrostatically-actuated deformable mirrors fabricated using micro-electromechanical systems (MEMS) manufacturing offer compelling and intrinsic advantages in size, weight, and power
MEMS-based programmable reflective slit mask for multi-object spectroscopy

M. D. Canonica, Univ. of Neuchâtel (Switzerland); F. Zamkotsian, Observatoire Astronomique de Marseille-Provence (France); W. Noell, Univ. of Neuchâtel (Switzerland); P. Lanzoni, Observatoire Astronomique de Marseille-Provence (France); N. de Rooij, Univ. of Neuchâtel (Switzerland)

Multi-object spectroscopy is a powerful tool for telescopes for the study of the formation of galaxies. This technique requires a programmable slit mask for astronomical object selection. We are developing MEMS-based programmable reflective slit masks for multi-object spectroscopy that consist of micromirror arrays on which each micromirror of size 100 x 200 μm^2 is electrostatically tilted providing a precise angle. The main requirements for these arrays are cryogenic environment capabilities, precise and uniform tilt angle over the whole device, uniformity of the mirror electro-mechanical behaviour and a low mirror deformation. These devices were fabricated by assembling a micromirror chip on top of an electrode chip. A first generation of MEMS-based programmable reflective slit masks composed of 5 x 5 micromirrors was tested in cryogenic conditions at 92 K. Then, first prototypes of large arrays were microfabricated and assembled using a chip level assembly setup, but with short-circuit failure hindering the complete actuation of the array.

To increase the reliability of these devices, a third generation of micromirror arrays composed of 64 x 32 micromirrors is under development. This generation was especially designed for individual actuation of each mirror, applying a line-column algorithm based on the electrostatic hysteresis of the actuator. The fabrication process is now based on multiple wafer level bonding steps and investigation was performed to reduce the short-circuit failure. This third generation of micromirror array will be fully characterized and tested in a cryogenic environment.

Fully integrated imaging spectrometer instrument on a chip: miniaturization effort for space instruments

B. Guldimann, European Space Research and Technology Ctr. (Netherlands)

Starting from the requirements and concept of a state of the art space optical imaging spectrometer aboard MarsExpress, a new, strongly miniaturized imaging spectrometer concept is presented. Typical state-of-the-art optical space spectrometer (for instance MERIS and SCIAMACHY aboard EnviSat and OMEGA on MarsExpress) payloads are based on one or several optical gratings to address the whole spectral range. These spectrometer instruments, typical for remote sensing, without the front optics (telescope, camera objective) have at least the size of a show box. The new proposed concept, essentially based on micro-nano technologies as well as optical MEMS, shrinks such spectrometers down to the size of a few computer chips. A very high integration level of various technologies and functionalities has been conceived while keeping the original top level performance requirements for remote sensing. The result is a concept of a fully integrated 2D mapping spectrometer on a chip placed in the focal plane of the front optics (camera objective, telescope). The working principle allows the new device achieving a very high spectral resolution, as it is often required in remote sensing. This new device concept can therefore not only map a 2D image of a scene, as CMOS camera chips or CCD-chips do, but also deliver continuously a high resolution spectrum for each image pixel. Due to its generic characteristics it has the potential to be used also for airborne and commercial applications on ground. The conceptual design, fabrication aspects and performance limitations are discussed. An alternative conceptual design which is simpler to fabricate, but less compact, is also proposed.

The interference effect of the Rayleigh and shear-horizontal waves for a SAW gyroscope

H. Lee, H. Oh, K. Lee, S. S. Yang, Ajou Univ. (Korea, Republic of)

A 128° YX LiNbO3 is known to have excellent piezoelectric properties because of the relatively-high electromechanical coupling coefficient (K2 = 5.56%). For the characterization of the interference effect of SAWs on a piezoelectric substrate, a 128° YX LiNbO3 wafer is used. The wave velocities on the 128° YX LiNbO3 in the x-direction and y-direction are 3961 and 3656 m/s, respectively.

The device consists of an input and an output IDTs to transmit and receive the Rayleigh wave propagating in x-direction with the oscillation in z-direction and an interference IDT to transmit the intersecting SH wave propagating in y-direction with the oscillation in x-direction. The SH wave interferes the Rayleigh wave at a delay line between the input and the output IDTs and affects the propagation velocity of the Rayleigh wave. We investigate the interference effect of SH wave for various interference IDT structures such as a bidirectional IDT, a split IDT and an SPUDT (single-phase unidirectional transducer). The device is fabricated by simple lithography technology.

The frequency response (S21) of the input and the output IDTs is measured with a network analyzer while the interference IDT is connected to a signal generator to generate SH wave of which the power is increased by 10dBm interval from -60 dBm to 25 dBm at 100 MHz. The frequency response shift is about 8 kHz to the interference power of 25 dBm independent of the interference IDT structures. This result proves the Rayleigh wave’s propagation velocity between the input and the output IDTs is reduced by SH wave interfered perpendicularly.
7928-23, Poster Session

A novel wireless love wave biosensor platform for multi-functional detection

T. Song, K. Lee, Ajou Univ. (Korea, Republic of)

Most of the Love wave biosensors still suffer from inherent problems: portable inconvenience due to their complicated system and large power consumption from additional circuits. Therefore, we introduced a novel Love wave biosensor platform for multi-functional detection. The proposed sensor has many unique advantages over the previously reported Love wave biosensors including battery-free and simultaneous detection ability for two biomolecules in single solution. This wireless Love wave biosensor system utilizing polyimide waveguide layer and DNP receptor layer on 410 YX LiNO3 piezoelectric substrate, is composed of Love wave sensor, antenna, and network analyzer. A coupling of modes (COM) simulation was performed to obtain the optimal design parameters. The device consisting of IDTs and reflectors was fabricated as the elements of the sensor based on the simulation results. Sensitivity tests were performed in different bio-concentration solutions. The devices were placed in bio-solution within the test time. The measured reflection peak at S11 in the time domain showed large signal/noise ratio, sharp peaks, and a few spurious peaks owing to the mass loading effect. The phase shift Δ was detected depending on the different concentration of biomolecules. The binding of anti-DNP induced phase shift of the reflection peaks owing to the mass loading. Excellent linearity, reproducibility, and high sensitivity were observed in the anti-DNP concentration range of 0 – 0.10mg/ml. Thus, we expect that this Love wave biosensor is very promising for multi detection for various types of biomolecules.

7928-25, Poster Session

Investigation into graphene-based MEMS for future deep space telescopes

G. Fercana, Jr., Clemson Univ. (United States) and NASA Goddard Space Flight Ctr. (United States); G. Kletetschka, Catholic Univ. of America (United States) and NASA Goddard Space Flight Ctr. (United States) and Gelogic Institute (Czech Republic); J. Chervenak, NASA Goddard Space Flight Ctr. (United States); V. Mikula, Catholic Univ. of America (United States) and NASA Goddard Space Flight Ctr. (United States); M. Li, NASA Goddard Space Flight Ctr. (United States)

The design of MEMS/MOEMS are often materials-limited with respect to the efficiency and capability of the material. Graphene, a one atom thick honeycomb lattice of carbon, is praised for several of its properties, some of which make it a highly desired material for MEMS applications. Examples of these properties include the material’s optical transparency, magnetic responsivity, high mechanical strength, high energy efficiency, and high electrical conductivity due to its incredible electron mobility. All of the aforementioned properties make graphene the pinnacle of transparent electrode technology and a more appropriate choice than the conventionally used material, indium-tin oxide, which is not nearly as optically transparent as graphene or as strong mechanically. The scope of the research is to provide a proof of concept for future robust MEMS development using a graphene substrate.

By utilizing mechanical exfoliation of highly ordered pyrolytic graphite crystals in conjunction with thermally responsive chemical cross-linking agents, graphene sheets are expected to be isolated with sizes rivaling conventional processes making use of only mechanical exfoliation. The cross-linking agent operates on a mechanism of photoininsertion of dissociated nitrene groups into graphene monolayers, creating a covalent binding between the substrate and graphene. Preliminary results allow isolation of few layer graphene (FLG) sheets (n<3) of approximately 10μm x 44μm. Meticulous modification of aforementioned mechanical exfoliation procedures are expected to produce FLG of approximately 100μm x 100μm with this cross-linking technique, at which point photolithography will be utilized to tailor designs for microshutter technology to be used in future deep space telescopes.

7928-26, Poster Session

Optoelectronic properties and interfacial durability of CNT and ITO on boro-silicate glass and PET substrates with nano- and hetero-structural aspects

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Nano- and hetero-structures of carbon nanotube (CNT) and indium tin oxide (ITO) can control significantly piezoelectric and optoelectronic properties in Microelectromechanical Systems (MEMS) as sensing and actuators under cyclic loading. Optimized preparation conditions were obtained for multi-functional purpose of the specimens by obtaining the best dispersion and turbidity in the solution. Optical transmittance and electrical properties were investigated for CNT and ITO dipping and spraying coating on boro-silicate glass and polyethylene terephthalate (PET) substrates by electrical resistance measurement under cyclic loading and wettability test. Uniform dipping coating was performed using Wilhelmy plate method due to it simple and convenience. Specimen was applied with spraying coating additionally. The change in the electrical and optical properties of coated layer is mainly dependent upon the number of dip-coating, the concentration of CNT and ITO solutions, and the surface treatment condition. Electric properties of coating layers were measured using four-point probe method, and surface resistance was calculated using a dual configuration method. Optical transmittance of CNT and ITO coated PET film was also evaluated using UV spectrum. Surface energy and their hydrophilic and hydrophobic properties of CNT and ITO coated substrates were investigated by wettability test via static and dynamic contact angle measurements. As the elapsing time of cyclic loading passed, the stability of surface resistance and thus comparative interfacial adhesion between coated layer and substrates was evaluated to compare the thermodynamic work of adhesion, Wa. As dip-coating number increased, surface resistance of CNT coating decreased, whereas the transmittance decreased step-by-step due to the thicker CNT and ITO networking layer. Nano- and hetero-structural effects of CNT and ITO solution on the optical and electrical effects have been studied continuously. Acknowledgements: this work was supported by the National Research Foundation Grant funded by the Korean Government (2009-0072538). Wang, Zuo-Jia is grateful to the second stage of BK21 program for supporting a fellowship.
Integrated lab-on-a-chip: a combined sample preparation and PCR system as an ultrafast analytical tool for pathogen detection

H. Becker, N. Hlawatsch, R. Klemm, C. Gärnter, microfluidic ChipShop GmbH (Germany)

The overall aim is the realization of a reliable, ultrafast, and portable system for the identification of pathogens and other B-agents at the point of interest. PCR is the method to be used for the unambiguous identification of e.g. bacteria, and viruses. Miniaturization is the way to include the overall analysis process, from sample preparation to detection, on a microtitreplate-sized consumable device and to allow to carry out the analysis without the need for an equipped biological laboratory.

One of the crucial challenges for many Lab-on-a-chip systems has been the integration of a sample-prep module with functionalities like the liquefaction of samples, filtration, cell lysis, DNA extraction and/or purification. We have developed and validated modules for these functions and will report on the development strategies and results for these modules.

An innovative PCR concept with constant temperature zones allows also for the instrument to become portable, due to much reduced power consumption since no thermocycling is necessary.

An overall concept to implement the biological reactions for the analysis on-chip, the methods of sample preparation on-chip, and the results of the ultrafast PCR with B-agents on-chip, as well as the basic instrument will be presented.

Optical and fluidic design for guaranteed trapping and detection of particles in a silicon microfluidic and photonic crystal system

A. Heiniger, P. M. Fauchet, Univ. of Rochester (United States)

Recent work has shown that optical forces on nanoparticles near photonic devices can be exploited for control of particle trajectories. Demonstrated effects include particle transport in a slot waveguide [1] and dynamic trapping and release of a particle in a photonic crystal (PhC) resonator [2]. Such control could lower the minimum concentration of particles that can be detected in PhC resonator biosensors. These devices can detect the presence of single particles, but only if the particle is located near the resonator [3]. The optical gradient force attracts particles to exactly this high intensity region.

However, optical forces are insignificant just a short distance from the resonator, if the particle is moving too fast, or if the field is too weak. The optical force also can cause the particle to be trapped short of the resonator if it is moving too slowly or if the field is too strong. In these cases, the sensor would fail to detect the particle.

We determine the flow rates and optical powers that ensure that a particle, if present, is captured in the resonator. We consider a slotted-ring PhC resonator and use finite element modeling to determine particle trajectories in the presence of fluidic and optical forces. We find that 10 mW of input power captures a particle traveling between 1 and 100 μm/s.

Nanofluidic Raman spectroscopy: how combining nanofluidics with SERS can provide new insights into protein aggregation

D. Erickson, Cornell Univ. (United States)

The extracellular and/or intracellular formation of protein aggregates is one of the pathological hallmarks shared by many diseases including ageing-related neurodegeneration and systemic amyloidosis. Trace detection and physicochemical characterization of protein aggregates can have a large impact in understanding and diagnosing diseases at early stages. Towards this end, multiple analytical techniques, including size exclusion chromatography, dynamic light scattering, fluorescence spectroscopy, circular dichroism spectroscopy, and nuclear magnetic resonance spectroscopy, have been employed to detect and characterize protein aggregates. While all these techniques are quite functional, it remains extremely challenging to detect and characterize very low levels of protein aggregates. In this talk I will introduce a novel approach for size-selective concentration and label-free detection of protein aggregates with disease implications. The method is based on the formation of micro/nanofluidic junctions on a nano-structured Raman active substrate. Using this technique we show the concentration dependence of protein aggregation over the low concentration ranges, which cannot be investigated with existing analytical tools. As a performance tests of a device, we investigated two types of protein aggregates, Cu/Zn-superoxide dismutase (SOD1) aggregates and amyloid beta (Aβ) fibrils, which are implicated in representative neurodegenerative diseases, Alzheimer’s disease and amyotrophic lateral sclerosis, respectively.

On-chip optofluidic concentrator

J. E. Baker, R. Sriram, Univ. of Rochester Medical Ctr. (United States); P. M. Fauchet, Univ. of Rochester (United States); B. L. Miller, Univ. of Rochester Medical Ctr. (United States)

Photonic crystal (PC) biosensing platforms have the potential to achieve single-pathogen detection using nanoscale optical resonant cavities. Real-time sample analysis requires the PC sensor to be interfaced with a fluidic environment, but current practical fluidic structures typically have dimensions much larger than the PC sensing cavities. To enhance sensing probability, an on-chip optofluidic structure is being developed to concentrate target material within a narrow sensing region of the microfluidic channel. The device relies on fluid drag forces to propel material along the microfluidic channel. Dielectric material is guided transversely within the microfluidic channel by optical gradient forces due to the evanescent field surrounding a ridge waveguide within the channel. Results of computational modeling and preliminary experimental trials are presented.

Merging nanophotonics and nanofluidics for active analyte delivery and biosensing

H. Altug, Boston Univ. (United States)

Label free biosensors are offering a rapid way to detect biomarkers and pathogens, and to determine the kinetics of biomolecular interaction. In particular, nanophotonic biosensors based on resonances are taking
significant attention for detection of low concentrations of analytes with large multiplexing capabilities and signal-to-noise ratios. However, performances of surface biosensors are often controlled by the analyte delivery rate to the sensing surface instead of sensor’s intrinsic detection capabilities. For biosensors integrated with conventional microfluidic channels, analyte transportation to the sensor surface by diffusion severely limiting the performance. At low concentrations, this limitation known as mass transport limitation causes impractically long detection times. Previous approaches based on stirring and mixing strategies resulted in moderate performance improvements. One of the main conceptual constraints so far is that microfluidics and biosensing are always considered as different parts of a sensor platform rather than a fully merged single entity. In this talk, we demonstrate a new biosensing platform merging nanophotonics and nanofluidics. Unlike conventional approaches where the analytes simply stream past over the surface, our platform enables active delivery to the sensing surface. Our detection platform is based on suspended nanohole arrays supporting photonic-plasmonic resonances. The nanoholes also act as nanofluidic channels connecting the fluidic chambers on both sides of the sensors. Using our platform, we show 14-fold increase in mass transport rate constant appearing in the exponential term. Such an improvement means superior analyte delivery to the biosensor surface and dramatically improves sensor response time at low concentrations.

7929-23, Session 1

All-fiber optofluidic biosensor

Y. Guo, H. Li, J. Liu, K. Chinnia Balareddy, X. Fan, Univ. of Michigan (United States)

Optical fiber provides a unique and versatile platform for developing point-of-care optical sensing systems. Here we propose a novel optofluidic biosensor, which fully utilizes optical fibers to achieve highly-sensitive, label-free biomolecular detections with inherent fluidic channels.

This sensor consists of two single mode fibers (SMFs) with reflecting surfaces and a photonic crystal fiber (PCF) vertically sandwiched by them. Firstly, the SMFs act as waveguides for delivering light into and out of an optofluidic device (like PCF); secondly, instead of using the optical properties of the PCF, we take advantage of its inherent multiple fluidic channels and large sensing surface; thirdly, the two reflecting surfaces and the PCF form a Fabry-Perot resonator and its resonance mode is sensitive to the change of the properties in the fluidic channels, which can be used to detect the substances flowing through the fluidic channels or deposit on the channel surface.

In the report, we will explore the operating principle of the all-fiber optofluidic biosensor, theoretically and experimentally investigate its feasibility and sensitivity. The all-optical optofluidic sensor is a promising technology platform for multiplexing, highly-sensitive and accurate biomolecular detection.

7929-24, Session 1

Application of field-modulated birefringence and light scattering to biosensing

L. H. Strong, D. B. Hall, C. Edson, G. Varadi, Radiation Monitoring Devices, Inc. (United States)

Superparamagnetic nanoparticles (NPs) coated with surface ligands are shown to be an effective means to impart magnetic field modulation to optical signals from targeted receptor complexes. The resulting temporally modulated optical signals can be used for a number of important high throughput applications in bio-sensing including: detecting (weaponized) viruses, screening recombinant libraries of proteins, identifying pathogenic conversions of microbes, and monitoring gene amplification. We compare the results of two dynamic methods of measuring target binding to NPs: birefringence and field modulated light scattering (FMLS). These measurements reflect complementary manifestations of NP alignment (orientation) and de-alignment (relaxation) dynamics. Birefringence originates from the specific crystalline properties of a small subset of paramagnetic NPs (for example, maghemite ) when oriented in a magnetic field. Upon quenching the field, it decays at a rate exhibiting the Debye-Stokes-Einstein rotational relaxation constant of the target-NP complex. Birefringence relaxation reflects the particle dynamics of the mixed suspension of NPs, with signal components weighted with respect to both free and complexed NP size distributions. FMLS relaxation signals, on the other hand, originate predominately from the inherent optical anisotropy of the target complexes, show little contribution from non-complexed NPs, and provide a more direct and accurate method for determining target receptor concentrations. Several illustrations of the broad range of applications possible using these dynamic measurements and the kind of information to be derived from each detection modality will be discussed.

7929-25, Session 1

Optofluidic biosensing with colorimetric signatures of deterministic aperiodic metal nanoparticle arrays

S. Y. Lee, S. V. Boriskina, Boston Univ. (United States); F. G. Omenetto, Tufts Univ. (United States); B. M. Reinhard, L. Dal Negro, Boston Univ. (United States)

In this study, we study colorimetric optical sensing of biological substance within microfluidic channels by investigating distinctive changes of light scattering spectra and colorimetric patterns from nanostructured aperiodic surfaces. Aperiodic arrays consisting of metallic nanoparticles on quartz substrates with minimum interparticle separations ranging from 50nm to 200nm were fabricated using electron beam lithography and 20 micron-high microfluidic PDMS channels were imprinted from a SU8-mold. We have recently shown that the colorimetric fingerprints of aperiodic nanostructures feature broadband frequency responses with wide angular intensity distributions and are ideally suited as a novel transduction mechanism for optical biosensing in a microfluidic environment. Our previous work has demonstrated that chromium (Cr) Gaussian prime nanoparticle arrays can detect protein monolayers with attomolar sensitivity by monitoring structural modifications of the scattered fields with simple autocorrelation analysis. In this work, DNA molecules flowing in the microfluidic channel are bonding to the nanostructured gold (Au) surfaces and their scattering spectra are experimentally measured under white light illumination with conventional dark-field spectrosopy. Using DNA molecules as our target, we fabricated and optimized different aperiodic structures, which provide different field localization patterns for enhanced biological sensing in a microfluidic environment. Our results demonstrate for the first time that the characteristic colorimetric patterns observed in a microfluidic environment can be directly utilized as highly sensitive platform for DNA detection and developed as an inexpensive optical biosensor. The integration of this sensitive technique with microfluidic technology may result in the engineering of novel integrated, multiplexed, optofluidic lab-on-a-chip platforms for bio-chemical detection.

7929-26, Session 1

An integrated microfluidic biosensor for the rapid screening of foodborne pathogens by surface plasmon resonance imaging

M. D. Zordan, M. G. Grafton, J. F. Leary, Purdue Univ. (United States)

The rapid detection of foodborne pathogens is of vital importance to keep the food supply rid of contamination. Previously we have demonstrated the design of a hybrid optical device that performs real-time surface plasmon resonance (SPR) and epifluorescence imaging. Additionally we have developed a biosensor array chip that is able to specifically detect the presence of two known pathogens. This biosensor...
detects the presence of the pathogen strains by the selective capture of whole pathogens by peptide ligands functionalized to the spots of the array. We have incorporated this biosensor array into a self contained PDMS microfluidic chip. The enclosure of the biosensor array by a PDMS microfluidic chip allows for a sample to be screened for many strains of pathogens simultaneously in a safe one time use biochip. This disposable optical biochip is inserted into with the hybrid SPR/epifluorescence imaging device to form an integrated system for the detection of foodborne pathogens. Using this integrated system, we can selectively detect the presence of E. coli 0157:H7 or S. enterica in a simultaneously in real-time. Additionally, we have modeled the mechanical properties of the microfluidic biochip in order to manipulate the flow conditions to achieve optimal pathogen capture by the biosensor array. We have developed an integrated system that is able to screen a sample for multiple foodborne pathogens simultaneously in a safe, rapid and label-free manner.

7929-02, Session 2
Integrated single-cell analysis
J. C. Love, Massachusetts Institute of Technology (United States)

The majority of analytical technologies used to assess the identities and functional capacities of cells yield average measures of their phenotypes. These measures obscure unique individuals that contribute significantly to the collective behavior or that may be of particular interest in discovery-based research. This talk will describe the development of a modular collection of techniques that use microfabricated arrays of subnanoliter containers (10^5-10^6) to enable flexible, reconfigurable processes for integrated and dynamic single-cell analysis. Some examples of measurements include phenotypic analysis of surface-expressed proteins, profiles of cytokine secretion, cytolytic activity, and gene expression. Specific applications of these technologies for massively parallel single-cell analyses will be presented in the areas of bioprocess development and immune monitoring of chronic human diseases. The approaches described provide a new basis for advanced clinical monitoring of cellular responses to candidate vaccines and highly quantitative diagnostics to assess the state and evolution of the immune system.

7929-03, Session 2
Complementary approaches to investigating cancer cell dynamics in the tumor microenvironment
M. R. Padgen, W. K. Raja, Univ. at Albany (United States); B. Gligorjevic, Albert Einstein College of Medicine of Yeshiva Univ. (United States); J. Williams, Univ. at Albany (United States); J. S. Condeelis, Albert Einstein College of Medicine of Yeshiva Univ. (United States); J. Castracane, Univ. at Albany (United States)

Metastatic cancer cells respond to chemical and mechanical stimuli in their microenvironment that guide their intravasation into surrounding tissue and eventually into the circulatory/lymph systems. The NANIVID is designed to be an in vivo device used to collect metastatic cancer cells by providing a gradient of epidermal growth factor (EGF) through the controlled release from a customized hydrogel. The model cells, MenaInv rat mammary cancer cells, will migrate towards the device and be collected in the chamber. Transparent electrodes inside the chamber will allow for in vivo imaging and will provide real-time data on the density of cells in the device. The characterization and optimization of the electrodes in vitro will be reported, as will the development of an equivalent circuit model used to describe their behavior. Electrodes integrated into the NANIVID will be used with cell cultures in a 3-D collagen matrix as a proof of concept. The ultimate goal of this work is for the NANIVID to be used for in vivo investigations of a rat model of mammary cancer. Furthermore, since the morphology, mechanical properties, and movement of cells are influenced by their microenvironment, including the presence of chemical gradients, a combined scanning confocal laser microscope and atomic force microscope will be used to study these relationships. The effects of external strain on cell motility and proliferation will also be examined using these tools. This work will further the understanding of the dynamics and mechanics of metastatic cancer cells as they leave the primary tumor and metastasize.

7929-04, Session 2
A completely transparent MEMS for mechanical properties evaluation of a single living cell
R. Fior, S. Maggiolino, Univ. degli Studi di Trieste (Italy); M. Lazzarino, IOM-CNR Lab. TASC (Italy); O. Sbaizero, Univ. degli Studi di Trieste (Italy)

This research involves a new approach for the study of the mechanical properties of single living cells. The main idea is to use micro electro-mechanical systems (MEMS) to investigate the Young modulus and the morphological modification of cells from the engineering point of view. Many different techniques already exist for a local cell analysis but our goal is to be able to test the properties of a single adherent cell in its complexity. We realized a completely transparent device which is versatile and can be coupled with other analysis tools such as atomic force microscopy (AFM) and patch clamp.

Starting from a transparent wafer we developed a system to obtain high transparency suspended structures. All structures are made by using micro fabrication techniques. Our MEMS is composed by 3 main parts: (i) testing, (ii) measurement and (iii) actuation area.

7929-05, Session 2
Inertial microfluidics for continuous separation of cells and particles
A. Chatterjee, I. Papautsky, Univ. of Cincinnati (United States)

We describe the principles of inertial microfluidics to continuously and simultaneously separate multiple cells or particles of different sizes. The design exploits the particle size dependence of the lift forces and Dean forces to equilibrate cell/particle streams at distinct positions in the microchannel cross-section. The focused streams can then be collected in separate outlets. The concept was successfully demonstrated using a mixture of cells and particles in the 7-20 μm diameter range. Cells and particles flowing in a spiral microchannel experience a combination of lift (FL) and Dean drag (FD) forces. The magnitude of these forces depends on the cell/particle size and its position across the microchannel cross-section. For cells/particles with an ap/Dh ≥ 0.07 (where ap is the particle diameter and Dh is the microchannel hydraulic diameter), the lift forces dominate and are responsible for equilibrating particles in multiple positions within the microchannel. The spiral nature of the microchannel exerts a Dean drag force, reducing the number of equilibrium positions to just one near the inner microchannel wall. In this work we take advantage of the ratio of these two forces for focusing particles of varying sizes at different lateral positions across the microchannel width. In summary, cells and microparticles can be completely separated by focusing them into segregated streams and then collecting them in individual outlets. The described approach is ideally suited for rapid blood sample preparation in clinical diagnostics where specific blood cells must be extracted for analysis or pathogen detection.
A pneumatic actuated reversible microfluidic bead trapping device

G. Shao, W. Wang, Louisiana State Univ. (United States); R. M. Ozanich, J. Wang, Y. Lin, Pacific Northwest National Lab. (United States)

Abstract: As a solid phase carrier for chemical reaction, especially biochemical reactions, micro beads offer superior surface-volume ratio, micron range analytes transportation length and large selection of available surface function groups. Microfluidic technology, with its capability to fabricate micro-sized fluid and detection components which are compatible with micro beads in size, has inherent advantages for micro beads manipulation. Previous research effort has been focused on the manipulation of individual beads, however, for certain application, such as in Flow injection analysis (FIA) system or for electrochemical detection, a relatively large amount of beads (thousands) is often needed. In this paper, we report the design and fabrication of a pneumatic actuated reversible microfluidic bead trapping device. The device was fabricated using multilayer soft lithography (MSL) technique. The resulting device consists of a bead chamber and micro filter layer, a pneumatic control layer and a glass substrate. Both bead chamber layer and pneumatic control layer are made of polymethylmethacrylate (PMMA). By pneumatically controlling the deformation of the PDMS membrane underneath the micro filter structure, one can switch the device between “trap” and “release” status. In trap position, micro beads are retained in the beads chamber while fluid reagents are free to pass through; in release position, micro beads can pass through the beads chamber and the device is renewable and ready for the next run. Specially designed micro filter structure ensured the homogenous distribution of the trapped beads. Experimental results have confirmed the feasibility of the designed device and it shows great potential for the various applications in analytical chemistry and bioengineering.

Optical propulsion of mammalian eukaryotic cells on an integrated channel waveguide

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The optical propulsion of mammalian eukaryotic cells along the surface of an integrated channel waveguide is demonstrated. 10µm diameter polymethylmethacrylate (PMMA) spherical particles and similarly sized mammalian eukaryotic cells in aqueous medium are deposited in a reservoir over a caesium ion-exchanged channel waveguide. Light from a fiber laser at 1064nm was coupled into the waveguide, causing the polymer particles or cells to be propelled along the waveguide at a velocity which is dependent upon the laser power. A theoretical model was used to predict the propulsion velocity as a function of the refractive index of the particle. The experimental results obtained for the PMMA particles and the mammalian cells show that for input powers greater than 50mW the propulsion velocity is approximately that obtained by the theoretical model. For input powers of less than ~50mW neither particles nor cells were propelled; this is considered to be a result of surface forces (which are not considered in the theoretical model). The results are discussed in light of the potential application of optical channel waveguides for bioanalytical applications, namely in the identification and sorting of mammalian cells from mixed populations without the need for fluorescence or antibody labels.

Development of an integrated microsystem for the multiplexed detection of protein markers in serum using electrochemical immunosensors

C. K. O’Sullivan, Univ. Rovira i Virgili (Spain)

Development of an integrated microsystem for the multiplexed detection of protein markers in serum using electrochemical immunosensors

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Recent advances in the fabrication of microfluidic platforms initiated during the late 90s have facilitated the realisation of micro total analysis systems [1]. The integration of miniaturised fluidic handling and delivery systems with chemical and biochemical sensors provide applied scientists with powerful tools for in-field measurements away from central laboratories [2]. Amongst the various classes of elements able to transduce a chemical or biochemical events into a measurable signal, electrochemical platforms undoubtedly present the most promising advantages. Electrodes of all type, sizes and geometries can easily be integrated within a microfluidic platform and provide excellent sensitivity and versatility in comparison to other transduction techniques based on for example optical or mass sensing [3]. Furthermore, the associated electronics used to drive the electrochemical detection and signal processing can also be easily miniaturised and integrated onto the same platform by carefully designing application specific integrated circuits [4]. We have recently reported a simple and rapid approach for prototype microfluidics and sensor assembly to perform complex protein and genetic electrochemical assays with excellent reproducibility [5]. The microfluidic platform was realized by high precision milling of polycarbonate sheets, which offers flexibility and rapid turn over of the desired designs. Sixteen-electrode sensor arrays were fabricated using photolithographic deposition technologies in order to realize three-electrodes cells comprising of gold counter and working electrodes as well as silver reference electrode. Fluidic chips and electrode arrays were assembled via a laser machined double-sided adhesive gaskets, creating the microchannels necessary for sample and reagent delivery. Surface chemistry methodologies were evaluated in order to achieve the double function of eliminating non-specific binding and optimal spacing of the anchor biocomponents for maximum accessibility to the target proteins. Storage conditions were optimized, demonstrating a long-term stability of the reporter conjugates jointly stored within a single reservoir in the microsystem. The final system has been optimized in terms of incubation times, temperatures and simultaneous, multiplexed detection of the protein markers was achieved in less than 10 minutes with less than ng/mL detection limits. The microsystem has been validated using real patient serum samples and excellent correlation with ELISA results obtained.

References:


Design of a portable point-of-care BioMEMS microfluidic blood analyzer
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Due to a number of recent technological advances, a hand-held flow cytometer can be achieved by use of semiconductor illuminators, optical sensors (all battery powered) and sensitive cell markers such as immunoquantum dot (Qdot) labels. The specific application described is of a handheld blood analyzer that can quickly process a drop of whole, unfraccionated human peripheral blood by real-time, on-chip magnetic separation of white blood cells (WBCs) and red blood cells (RBCs) and further fluorescence analysis of Qdot labeled WBC subsets.

Various microfluidic patterns were fabricated in PDMS and used to optimize flow of single cells and magnetic deflection of magnetically labeled cells. An LED excitation, avalanche photodiode detection system (Sensi Technologies, Ltd., Cork Ireland) was used for immuno-Qdot detection of WBC subsets. A static optical setup was used to determine the sensitivity of the detection system. A capillary uptake and on-chip drive system was used for sample preparation.

In this work we demonstrate: valve-less, on-chip magnetic deflection of immunomagnetically labeled white blood cells, bright Qdot labeling of lymphocytes, and counting of red blood cells. Comparisons of these results with conventional flow cytometric analyses will be reported. Efficiency of the sample preparation system was tested for blood uptake and incubation with labeling particles. Appropriate flow rates were determined for optical detection and confirmed with flowing particles. Several enabling technologies required for a hand-held flow cytometer have been demonstrated. The combining of these technologies in an integrated hand-held instrument is in progress and results on blood cell analysis will be reported.

A sample-in result-out lab-on-a-chip device: from prototype to mass fabrication
R. Klemm, H. Becker, C. Gärtner, microfluidic ChipShop GmbH (Germany)

The development of integrated Lab-on-a-Chip microsystems for automated analysis from sample to result is an extensive process. Currently, this is mostly done by the stepwise integration of prototyped single modules of different applications leading to prototypes of integrated microsystem. The most relevant fact for the benefit of the later production is the intelligent installation of mass fabrication methods.

The microsystem disposables for clinical analysis where fabricated by injection molding processes. With the use of high quality medical compatible materials for this processes huge amounts microsystems can be fabricated in reliable quality. The assembly of all required on-chip controlling element like fluidic valves, membrane integration or interfaces are as well intensive processes for high scale production. These parts are mostly highly complex compound components, consisting out of several parts, which need significant simplification during product development.

For the mass fabrication of on-chip turning valves, a two-component injection molding process was thus developed in order to reduce the number of individual components from ten to three compared to the prototype.

The microsystems were fabricated as ready-to-use systems, requiring a minimum handling from the user. Therefore, the biochemical reagents and components were directly integrated as dried or liquid ingredients within the fabrication processes.

Using these automated assembly methods, effective high volume production of integrated Lab-on-a-Chip microsystems can be achieved.

From bleed-to-read: integrated genotyping and immunological analysis microfluidic platforms for the diagnostic and treatment of coeliac disease
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Coeliac disease (CD) is a wide-spread disorder, in which genetically predisposed individuals develop small intestinal inflammation upon exposure to dietary gluten. Currently, the diagnosis includes the detection of disease-specific antibodies followed by an intestinal biopsy with assessment of the mucosal morphology.

Taking advantage of microfluidic technology, a Lab-on-Chip system is being developed offering the possibility of performing HLA typing to test genetic predisposition to CD and measure the level of immunodeficiency at the point-of-care. These analysis procedures are implemented on two different microfluidic cartridges, both having identical interfacial connections to one automated instrument.

In order to assess the concentration of the targeted analytes in whole blood, the finger prick samples are processed to extract genomic DNA or blood serum containing the antibodies. We present here the different microfluidic modules integrated in one platform, developed for the automated sample preparation and analyte detection.

In summary, this new microfluidic approach will dramatically reduce the costs of materials (cheap polymer for the disposable chips and minute amount of bio-reagents) and minimize the time for analysis in less than 20 minutes. This represents a tremendous improvement for the patient’s welfare as well as for the health care system, in comparison to the state of the art detection of CD.

This work has been carried out with financial support from the European Commission, Project VII PM Nr. 216031 ‘CD-Medics’

Development path and current status of the NANIVID: a new device for cancer cell studies
J. Castracane, W. K. Raja, M. R. Padgen, College of Nanoscale Science & Engineering, Univ. at Albany (United States); B. Gligorijevic, J. S. Condeelis, Albert Einstein College of Medicine of Yeshiva Univ. (United States)

In-vivo cancer cells create a unique microenvironment which helps them to spread to other organs. To understand the tumor microenvironment, special tools and devices are required to monitor the interaction among different cell types as well as the effects of particular chemical gradients. This study presents the design and optimization of a new, versatile chemotaxis device called the NANIVID (NANO IntraVital Imaging Device). The device is fabricated using MEMS techniques and consists of etched Pyrex substrates, a chemotaxant reservoir, fluorescent beads and a microelectrode array for cell quantification. This reservoir contains a customized hydrogel blend loaded with EGF which diffuses out to create a chemotactic gradient. This reservoir sustains a steady release of growth factor into the surrounding environment for many hours establishing a consistent concentration gradient from the device to attract specific cells. The focus of this study is to design and optimize the new device for chemotaxis studies in breast cancer cells in vitro and ultimately, implantable for in vivo work. The current development and testing status of the device will be presented against a backdrop of the College of Nanoscale Science and Engineering (CNSE) of the University at Albany which will include an overview of the infrastructure, personnel
and operational model used by CNSE to integrate basic research with eventual technology deployment.

7929-12, Session 4

A new electrowetting lab-on-a-chip platform based on programmable and virtual wall-less channels

I. Papautsky, J. C. Heikenfeld, Univ. of Cincinnati (United States)

Microscale liquid handling (transport and analysis) has been previously demonstrated via electrowetting on dielectrics. However, electrowetting-based liquid manipulation is limited to control of individual droplets, aptly termed digital microfluidics. There is lack of continuous channel flow control wherein functions such as pressure driven flow control and electrokinetic transport could prove advantageous. Reported herein are electrowetting based virtual channels that are capable of on-demand creation of any desired channel geometry, followed by preserving the channel without external stimulus. The electrowetting channels are based on post arrays conformally coated with a conducting electrode and hydrophobic dielectric which form highly directional liquid channels with virtual side-walls. Furthermore, arrayed voltage controls can be integrated with the posts platform for programmable control, which combines the advantages of digital electrowetting and continuous channel functionality into a single lab-on-chip platform. To fabricate the microposts a newly available negative-acting dry film photore sist (20μm thick) was laminated and patterned on a glass substrate using conventional UV-photolithography. Then, a 150nm of Cu film was sputtered and 1μm Parylene C dielectric was conformally deposited on top. The post array was further coated with ~50nm coat of Cytionx1601V fluoropolymer. The final post designs had ~:1:1 aspect ratio, and were filled with tetradecane oil containing 5wt% Triton X-15 surfactant. The demonstrated operation at ~30-70V is readily compatible with conventional electrowetting LOC drivers. A long term goal is to be compatible with the ~15V operation of a typical active-matrix thin film transistor backplane. With active matrix drive, an electrically programmable platform could offer digital control while at the same time allowing the channels to be preserved.

7929-13, Session 4

Fabrication and testing of hydrogel-based microvalves for lab-on-a-chip application

A. Li, A. Khosla, B. L. Gray, Simon Fraser Univ. (Canada)

Stimuli-responsive hydrogels such as poly(N-isopropylacrylamide) are excellent biocompatible materials for use as actuators in microfluidics due to their ease of fabrication, response to wide range of stimuli (pH, ionic strength, or heat) and fast response time[1, Wang et al]. We have previously demonstrated nanocomposite tungsten microheaters for solidification of thermally responsive hydrogels as a initial step toward the development of highly flexible microvalves[4, Drexbrook et al]. We now employ stimuli-responsive hydrogels (N-isopropylacrylamide) as actuators in microfluidic valves for lab-on-chip applications. Specifically, this paper shall present the design, simulation, fabrication and characterization of a two dimensional (2-D) hydrogel-based microvalve. The microvalve can be fabricated with traditional semiconductor processes for spin-coating, baking and etching. Swelling of the hydrogel forces a diaphragm to deflect and therefore close and opening of the valve. The silicone diaphragm layer is fabricated to separate the hydrogel actuator from the fluidic channel. Our hydrogel actuator diaphragms were micromachined using a Helmholtz coil pair, and is characterized by applying varying currents. The magnetic field, and thus the diaphragm deflection, can be controlled by regulating the current in the Helmholtz pair, and deflection versus field characteristics are discussed. Using varying membrane thicknesses and surface areas, we expect membrane deflections tens to 100 microns in magnetic fields around 30 mT. The actuator has a planar structure and is easily fabricated, allowing it to be readily integrated into uTAS and biomedical designs.

7929-15, Session 4

Cascaded silicon-on-insulator microring resonators for the detection of biomolecules in PDMS microfluidic channels

J. Flueckiger, S. M. Grist, G. Bisra, L. Chrostowski, K. C. Cheung, The Univ. of British Columbia (Canada)

Evanescent field sensors such as surface Plasmon resonance (SPR) or planar waveguide based sensors are amongst the most popular optical detection techniques for sensitive and label free biomolecular detection. Silicon-On-Insulator (SOI) photonic microring resonators have shown promising potential for real time detection of biomolecules because of the sensitivity towards surface binding events. It has been shown that silicon-on-insulator (SOI) waveguides with dimensions smaller than the wavelength of light have a strong evanescent field at the waveguide surface. Hence the interaction with molecules in proximity or surface bound molecules is increased. Previous work shows the use of single ring resonators for sensing applications. Each ring requires an input and output coupler and can be addressed only one at a time. We propose a novel use of cascaded ring resonators (width w = 200 nm and bending Radius R = 30 μm) together with a PDMS microfluidic network fabricated by soft lithography to expose each ring individually with different solutions. The SOI substrate with the planar waveguides and the PDMS with the microchannels are reversibly bonded to each other. The use of cascaded ring resonators offers the possibility to measure transmission spectra of multiple rings in different channels simultaneously. We measured Q-factors of >30’000 in air and >10’000 when exposed to water. Using a water/glycerin solution with known refractive indices we determine the sensitivity to be ~40 nm / RIU.
Computational study of peristaltic micropumps

A. Azarbädegan, I. Eames, E. Moedendarbary, Univ. College London (United Kingdom)

During last two decades there have been several attempts to design robust micropumps, but most of these attempts have been based on experiments and lack of thorough physical understanding of the pumping action and its limitations were present in those studies.

In this study a computational study of peristaltic micropumps is presented. The peristaltic micropumps considered in this study consist of two to five chambers and rectify the flow by means of both peristaltic movement of actuators and diffuser/nozzle elements. A one-dimensional mathematical model, which is consistent with the pump configuration, is derived to provide a framework to interpret the results. This model helps designers to have a reliable tool to design a peristaltic micropump based on required specifications. The numerical results are in good agreement with analytical model. The viability of such pumps to work with cells was examined by calculating the maximum shear stress and strain rate, and shown to agree with the models. We also compared the performance of these peristaltic micropumps with one another.

The developed analytical model and generic computational model can be used to predict the performance of peristaltic micropumps before fabrication and also facilitate the optimization process for this type of micropumps.

Optimum sensor placement in microchannel reactors: design tool applications

G. J. Kowalski, M. Sen, Northeastern Univ. (United States)

The procedure of using a three dimensional computational analysis of a microchannel reacting flow field that includes species diffusion and heat transfer processes to determine design rules for sensor placement is described. The commonly used flow configuration of two parallel running streams of reactants is used. The analysis includes practical thermal boundary conditions. The focus of the investigation is to optimize the positioning of nanohole array sensors, which respond to both concentration and temperature values in the reactor. These sensors use extraordinary optical transmission (EOT) to determine the concentration and temperature values in the medium. Because the position and spacing of the sensors is limited by material constraints, the computational analysis is used to verify the effectiveness and limitations of this approach and to compare it with other types of sensors such thermography and fluorescent measurements. The results provide insight into using measurements at a either fixed spatial location in the flow or that are integrated over a flow dimension to determine parameter values that can be confounded by the thermal and concentration boundary layers. The relationship between the proposed sensor position and the nodes of the numerical solution that limit this design process are discussed. It is shown that the numerical results can be used to place sensors that provide an accurate measurement of the diffusion process and thermodynamics of the reaction.

Phononic fluidics: acoustically activated droplet manipulations

J. Reboud, R. Wilson, Y. Bourquin, Y. Zhang, S. L. Neale, J. M. Cooper, Univ. of Glasgow (United Kingdom)

Microfluidic systems have faced challenges in providing complete diagnostics devices, in particular in handling real samples and the chip interconnection to other instruments. Here we present a simple interface, where surface acoustic waves (SAWs) from a piezoelectric device are coupled into a disposable acoustically responsive microfluidic chip.

By manipulating droplets, SAW technologies have already shown their potential in microfluidics, but it has been limited by the need to rely upon mixed signal generation at multiple interdigitated electrode transducers (IDTs) and the problematic reflecting surfaces, to allow complex fluid operations.

Here, a silicon chip was patterned with phononic structures, arrays of holes (radius 82 mm, pitch 203 mm), engineering the acoustic field by using a full band-gap around the frequency of 12 MHz. It was simply coupled to the 1280 Y-cut X-propagating LiNbO3 wafer, propagating the SAW, via a thin film of water. Contrary to the use of unstructured superstrates, phononic metamaterials allowed precise spatial control of the acoustic energy and hence its interaction with the liquids placed on the surface of the chip, as demonstrated by simulations.

We further show that the acoustic frequency influences the interaction between the SAW and the phononic metamaterial, providing a route to programme complex fluidic manipulation onto the disposable chip, including droplet movement, splitting and nebulisation. In addition, the centrifugation of blood cells from a blood sample as well as a bead-based immunoassay to detect prostate specific antigen are presented as more practical demonstrations of the potential of phononic crystals to realise diagnostic systems.
Microfluidic chips integrated with different functions by femtosecond laser for mechanism study of Phormidium gliding

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We fabricate glass microchips by femtosecond laser (fs) for mechanism study of Phormidium gliding to a seedling root, resulting in acceleration of vegetable growth. Conventional microscopic observation of this phenomenon using a Petri dish takes long time. To shorten the observation time, we fabricated microchips using photosensitive glass by fs laser direct writing followed by thermal treatment and wet etching, in which T-shaped microfluidic channels whose tips were connected to three opening micro reservoirs were embedded. Phormidium and the root were introduced into the two different micro reservoirs respectively with water. The fabricated microchip drastically reduced the observation time. Additionally, the Phormidium always glided to the micro reservoir in which the root was introduced, which suggests some attractants are secreted from the root for the gliding. Then, the microchips integrated with optical waveguides written by fs laser were used to identify the attractant by optical means. Meanwhile, we revealed that the gliding movement proceeds only under a bright condition, which means light illumination is necessary for the gliding movement. To investigate this phenomenon, partial optical filters of visible light with different transmission were formed around the embedded microchannel by the fs laser processing. The filters were realized by the fs laser exposure inside the glass followed by thermal treatment, since the processed regions became lithium metasilicate crystal lattice which has brown color. Then, we determined light intensity necessary for the gliding. More detailed mechanism of Phormidium gliding is discussed using the integrated microchips.

Free-flow electrophoresis with electrode-less injection molded chips

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We present an approach towards low-cost free-flow electrophoresis devices utilising injection moulding as mass replication process. This is achieved by realising a new straight-forward micro free-flow electrophoresis (μFFE) design ensuring both, bubble free electrophoretic separation and effective electrical connection by implementing miniaturised segregation bars which creates a defined open gap of 20 μm in height an 500 μm in width. The thermoplastic μFFE-chips are ready to use, there is no need for a subsequent laboursome implementation of membranes as salt bridges.

Our μFFE design features a 28 mm long and 14 mm wide separation chamber with 50 μm channel depth terminated by two 28 mm long, 500 μm wide and 300 μm deep electrode channels. To ensure bubble free operation, gas bubbles produced by electrolysis are prevented from entering the separation bed by two segregation bars. In contrast to previous membrane free designs, the liquid junction is positioned at the bottom side of the channel structure. Electrical connection is achieved by gold sputtered electrode structure on the sealing polymer slide. Alternatively the use of external electrodes introduced at the in- and outlets of the electrode channels has been realized.

The hydrophobic nature of the thermoplastic polymers could be overcome by a combination of plasma treatment of the COP chips and by dynamic coating with the surface active hydrophilic polymer hydroxypropylmethyl cellulose.

A femtosecond laser inscribed biochip for stem cell therapeutic applications


Human embryonic stem cells (hESc) offer therapeutic potential for many diseases involving chronic or acute cell loss. However, viable therapeutic application of hESc would require the elimination of residual undifferentiated cells that present a cancer risk, prior to transplant. Current separation techniques cannot be used effectively for stem cell therapy because of problems including cell damage, difficulties in scale-up or cost and are not suitable for larger quantities of cells. Microfabricated devices not only create the possibility of separating hESc from their differentiated progeny but also offer a means to quantitatively analyse factors leading to variations in the cytoskeleton which in turn alter cell deformability. We report on the design and fabrication of a pressure controlled microfluidic biochip in fused silica using focussed femtosecond laser pulses operated in a regime below the ablation threshold. The biochip is defined in a single femtosecond laser inscription step, at wavelength 1047 nm and 350 fs pulse width at a repetition rate of 500 KHz. This is followed by selective chemical etching using 5 % HF acid in water. This biochip is able to separate green fluorescent protein tagged hESc from differentiated human dendritic fibroblast cells based on the dissimilarity in elasticity of their cytoskeletal architecture. The device is designed to enable straightforward world - to - chip interfacing with a robust leak-proof assembly. The elasticity of hESc can be utilised to create a standalone, scalable device to segregate stem cells from differentiated cells thus providing a suitable separation platform for larger quantities of cells.

Nanoplasmonics as nanofluidics: transport and sensing in flow-through nanohole arrays

C. Escobedo, A. G. Brolo, R. Gordon, D. Sinton, Univ. of Victoria (Canada)

In this talk I will describe our research on the combined photonic and fluidic characteristics of flow-through nanohole arrays and their application to sensing. Nanostructures exhibit both nanofluidic and nanophotonic phenomena that can be exploited in sensing applications. Particularly in the case of void nanostructures, such as nanoholes, the confinement provided by the hole can increase both the sensing field strength as well as the rate of transport through rapid diffusion. The electromagnetic field from incident light is concentrated within the metallic nanoholes as a consequence of surface plasmons. The resulting enhanced optical transmission is dependent on the near-surface refractive index providing a bio-sensing mechanism. These structures are typically dead-ended (or ‘blind’) holes, and therefore fail to harness potential benefits of nanconfined transport combined with plasmonic sensing. I will describe our flow-through nanohole array sensing format, and the implications for sensing. Flow-through nanohole arrays provide a biomarker sieving capacity that is unique among plasmonic sensors as well as rapid transport of reactants to the sensing surface. Our experiments indicate a order of magnitude improvement in sensor response time for flow-through operation as compared to otherwise similar fluid-over sensing methods. Through transport analysis, these results are generalized in terms of improvement factor as a function of the inherent chemical binding kinetics timescale. Results indicate a 20-fold improvement is expected for small biomolecules with rapid reaction
9729-25, Session 6
Fabrication of an implantable stretchable electro-osmosis pump
A. Jahanshahi, Univ. Gent (Belgium) and IMEC (Belgium); F. Axisa, J. M. Vanfleteren, Univ. Gent (Belgium)

The aim of this paper is to demonstrate the feasibility of an implantable, low voltage driven microfluidic pump to deliver drugs. The micropump has a high degree of bio-compatibility and mechanical deformation capability, thanks to the use of elastic silicone elastomers (PDMS) for integration and embedding of the pump. We are using the new method of transverse DC electro-osmosis, which is demonstrated already in the litterature. The method uses the fabrication of periodic grooves on top of the micro channel and the application of a DC voltage across the channel. These grooves contribute to a non-uniform surface charge inside the channel and, despite the main flow which is across the channel, result in a flow along the channel. Until now these microfluidic pumps were fabricated using rigid substrate materials. In this contribution, for the first time the production and operation of soft elastic versions of such a pump, compatible with body tissue, is demonstrated.

For the interconnects, gold is selectively electrodeposited on Cu-foil and is transferred to PDMS layer. For the fabrication of channels and grooves, PDMS is molded with the soft-lithography technique using a two layer SU-8 master, and then precisely aligned and bonded to the electrical interconnect PDMS layer using air plasma dry-bonding.

The advantages of this pump are much lower operating voltages (<10V) compared to conventional electro-osmosis pumps, moderate flow rates (0.20μL/min) per each micro channel and a non laminar flow which is a great opportunity and motivating feature for mixing different drugs and liquids along with pumping. The flow is observed with introducing dyed polystyrene and fluorescence micro particles in the liquid.

9729-26, Session 6
Automated platform for multiparameter stimulus response studies of metabolic activity at the single-cell level

We have developed a fully automated platform for multiparameter characterization of physiological response of individual and interacting cells. The platform allows for minimally invasive monitoring of single cell metabolism while inducing a variety of physiological insults and stimuli by means of precisely controlled microenvironments. It features the capability to employ a variety of intra and extra cellular fluorescent probes for sensitive metabolite detection. The platform allows for application of other, post-measurement analyses of individual cells such as transcriptomics.

The approach is based on the measurement of extracellular metabolite concentrations in hermetically sealed ~200 μl microchambers each containing a single cell. The major components of the system are a) confocal laser scan head to excite and detect emission photons from sensors with single-photon counting capability, b) microfluidic cassette to contain and incubate individual cells, as well as dynamic application of various external stimuli, and c) integration module consisting of software and hardware for automated cassette manipulation, environmental control, and data collection. The custom-built confocal scan head allows for fluorescence intensity detection with high sensitivity and spatial confinement of the excitation light to the extracellular sensor area. In this way the phototoxic effects in cells can be minimized. The platform is specifically designed to permit incorporation of multiple different optical sensors for simultaneous detection of various metabolites of interest. The modular detector structure allows for several imaging modalities, including intracellular imaging with high spatial resolution and extracellular sensor readout. We present experimental results of system characterization and multiparameter metabolic response analysis of individual and interacting eukaryotic cells.

9729-27, Session 7
PharmaSat: drug dose dependence results in microgravity from a free-flying integrated biofluidic/optical culture-and-analysis satellite
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We designed, built, tested, space-qualified, launched, and collected telemetered data from PharmaSat, a 5-kg free flying satellite that supports microorganism growth in 48 microfluidic wells, doses microbes with multiple concentrations of a chosen drug, and monitors their growth and metabolic activity using a dedicated 3-color optical absorbance system at each well. PharmaSat comprises a structure approximately 10 x 10 x 30 cm, including triple-junction solar cells, bidirectional communications, power generation and energy storage system, and a sealed vessel (internal volume 1.2 L) for the biology experiment that houses the biofluidic, optical, thermal, sensor, and electronic subsystems. Dose dependence of an antifungal drug in the microgravity conditions of low Earth orbit will be reported.

9729-28, Session 7
Process analysis in micro-reactors: challenges and solutions with Raman spectrometry
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With the increasing interest in the exploitation of microreactors, there is a growing demand for process monitoring and control methods suitable for application in this environment. At present off-line analysis methods such as chromatography and mass spectrometry are the dominant tools in the field. Although these methods provide exceptionally rich chemical information they require removal of samples from the system and the analysis is not instantaneous. In many microfluidic applications these limitations overweight the benefits because of the importance of real-time detection and ability to analyse the fluid in different locations non-invasively. Therefore optical detection methods such as fluorescence and Raman spectroscopy are becoming increasingly popular in this field, with most attention being drawn to miniature integrated optical sensors. However, integration of sensors into a microreactor can change the flow conditions and make the system difficult to scale out. It is also impossible to move the integrated sensor along the flow path. These issues make on-chip process analysis a challenging subject that is still at the early stages of development. The purpose of this paper is to discuss opportunities for non-invasive process analysis in microreactors focusing the main attention on Raman spectrometry as a powerful technique, whose potential in this field has not been widely recognised yet.

With a specially developed probe we demonstrate ability to monitor fluid delivery stability and perform fast real-time analysis of a model esterification reaction. The discussed approach brings unique benefits to kinetics studies, efficient process optimisation and process control.
Real time ultrafast optical interferometry of NEMS operating in fluidic environment

O. Svitelskiy, The Univ. of North Carolina at Charlotte (United States); V. Sauer, National Institute for Nanotechnology (Canada); N. Liu, Univ. of Alberta (Canada); K. Cheng, E. Finley, National Institute for Nanotechnology (Canada); M. R. Freeman, National Institute for Nanotechnology (Canada) and Univ. of Alberta (Canada); W. K. Hiebert, National Institute for Nanotechnology (Canada)

Due to their unique resonant qualities, in particular high values of Q-factor and sensitivity of the resonant frequencies to the slightest changes in the environment, NEMS are promising candidates for usage as ultrasensitive sensors of various physical properties: mass (sensitivity could be so high that a mass load of a single proton can be detected), temperature, viscosity, pressure, etc. Most of the applications require understanding the ultimate performance of nanoelectromechanical systems outside of vacuum. Yet interactions of nanoscale structures with fluids are of fundamental interest in the elucidation of fluid dynamics at these small scales. We present a comprehensive study of nanomechanical damping in three gases (helium, nitrogen, and carbon dioxide), and in liquid carbon dioxide. Resonant dynamics in multiple devices of varying size and frequency (10-400 MHz) is measured over 10 decades of pressure (1 mPa-20 MPa) using the real time-domain ultrafast stroboscopic optical interferometry. The wide pressure range allows full exploration of the regions of validity of Newtonian and non-Newtonian flow damping models. Observing free molecular flow behavior extending above 1 atm, we find a fluid relaxation time model to be valid throughout, but not beyond, the non-Newtonian regime, and a Newtonian flow vibrating spheres model to be valid in the viscous limit. Measurements of nanoscale devices in this broad pressure and frequency range were done for the first time. The results of our work will increase understanding necessary for creating practical NEMS sensor devices.

Multi-parameter detection by spatially modulated fluorescence emission in a compact flow cytometer platform

J. Martini, P. Kiesel, M. Beck, M. F. Huck, N. M. Johnson, Palo Alto Research Center, Inc. (United States)

We will present an optical detection technique that delivers high signal-to-noise discrimination without precision optics to enable a flow cytometer that can combine high performance, robustness, compactness and low cost. The enabling technique is termed “spatially modulated emission” and generates a time-dependent signal as a continuously fluorocesing (bio-)particle traverses a optical transmission pattern. Correlating the detected signal with the known pattern achieves high discrimination of the particle signal from background noise. The analyte’s fluidic path, the optical excitation and detection volume need to be aligned for reliable particle detection. Our method uses a large excitation volume along the fluidic channel in order to increase the total flux of fluorescence light that originates from a particle while requiring minimal optical alignment. Despite the large excitation volume, the mask patterning enables a high spatial resolution in the micron range. This allows for detection and characterization of particles with a separation (in flow direction) comparable to the dimension of individual particles. In addition, the concept is intrinsically tolerant of background fluorescence originating from fluorescent components in solution, fluorescing components of the chamber and contaminants on the surface.

We will present the characterization of different particles by multi-wavelength excitation/emission measurements. We encode a two color emission measurement into a time dependent intensity signal on a single large area detector. This is performed by filtering fluorescence emission of different moving particles through a patterned color mask. We will demonstrate that the system is suitable for a multiplexed microbead based flow assays.

Efficient control system for PCR chips

J. D. Kim, Hallym Univ. (Korea, Republic of); J. Kim, Biomedlab Co., Ltd. (Korea, Republic of)

While biochemical analysis systems are miniaturized and integrated onto a chip, most researches still deal only with a part of the whole analysis such as sample preparation, DNA amplification, or detection. This requires a system that can control and monitor the miniaturized analysis chips. The system is responsible not only for the basic analysis steps but also for system management functions such as data handling and user interface. Regardless of the level of the integration, the latter functions are inevitable. They usually reside in a general purpose computer system because most users prefer the graphical interface, and the analysis data tends to be accessed through the internet. As the separate local system for the basic control functions are mandatory, the system for the chip naturally has the host-local system architecture. Well-defined systems such as PC’s are adequate for the host system taking advantages of the powerful development environment. Also the local system has to be connected to the host through the standard link provided to avoid additional costs and the loss of portability.

In this paper, as an example bio-chip, PCB-based PCR chips were designed and fabricated. A local system processor to cover the basic control functions was selected for the chip and PC was employed as the host. The basic functions were analyzed under real-time and flexibility constraints and partitioned into the host or the local system. Examples of the data management and GUI were presented and discussed. PCR performance was provided to verify the proposed design approach.
Initial experiments with flexible conductive electrodes for cancer tissue screening

D. Chung, A. Khosla, B. L. Gray, A. M. Parameswaran, Simon Fraser Univ. (Canada); R. Ramaseshan, K. Kohli, Fraser Valley Cancer Ctr. (Canada)

Breast cancer is the most common cause of death in women aged 45-55, with early detection key to survival. The gold standard for breast cancer screening is mammography, but it is not recommended for screening of women under 40 due to radiation. We are developing a non-invasive, easy to use, inexpensive system for breast cancer screening based on Electrical impedance scanning (EIS). Towards this goal, we describe novel highly flexible electrodes for tissue impedance measurements.

EIS produces an impedance map based upon the spatial electrical characteristics throughout the volume of a scanned object, and can be used to differentiate cancerous from normal tissue. The adoption of EIS has been hindered due to electrode design limitations, which are typically macroscale, few in number, and inflexible, resulting in poor electrical contact with skin and low spatial resolution.

These problems are solved by our new approach: making conductive flexible polymer electrodes using soft lithography. We have developed conductive nanoparticle composite polymers to use as high density EIS electrode arrays. Our fabricated electrodes consist of dispersed silver nanoparticles (20~80nm) in PDMS polymer matrix, that is cured against a molding master.

The electrodes are connected to an impedance analyzer, and employed to make measurements in a breast tissue phantom with anomalies representing bone and lipids. The impedance analyzer and computer measure impedance and generate data including cole-cole plots. We have generated baseline data showing lower impedance for the presence of anomaly, using our flexible electrodes that we compare to that generated using wire electrodes.

Robust detection of peak signals for lateral flow immunoassays

J. D. Kim, Hallym Univ. (Korea, Republic of); J. Kim, Biomedlab Co., Ltd. (Korea, Republic of); K. Nahm, E. Y. Choi, Hallym Univ. (Korea, Republic of)

The lateral flow immunoassay has been popular for rapid diagnose of analytes, by lower cost and no necessity of trained personnel and expensive equipment. The target analytes are quantified with reporters such as colloidal gold, carbon black and fluorescent dye. Control ligand is commonly added to approximate non-specific binding or to check the target existence, therefore two extinguishable peaks in the scanned signal are observed: for the target analyte and the control ligand. The detection of peak regions is mandatory because the ratio of the peak signal's areas relate to the concentration of the target analyte. The signal derivative along the scan line or the background-elimination algorithm should be employed to compensate the non-uniformity and non-stationary of the background signal. However both methods require adjustment of the algorithmic parameters for each immunoassay lot or scan reader.

This paper introduces a template with two pulses that are separated with the distance of the control and the target ligand line in the assay. The template was convolved with the scanned signal to deliver the maximum at the center of the two peaks. The peak regions were identified with the predefined distances from the center.

Glycated haemoglobin immunoassay strips from Boditechmed Inc. were used to demonstrate the method. Their fluorescent strip readers were employed to obtain the raw signals. The lot and reader variations of the concentration measurands were compared with the existing algorithm using the signal derivative. The results showed that the propose method delivered stable measurands.
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MOEMS and Miniaturized Systems X

7930-01, Session 1

MEMS-based laser scanning microscope for endoscopic use
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This paper presents a miniaturized MEMS based laser microscope for being used in narrow environments, e.g. for endoscopic investigations in medicine, biology, and industry. It consists of an optical head of only 8 mm diameter, containing a small silicon MEMS mirror of 1.9 by 1.9 mm² chip size, and optical components that direct the light onto the object surface as well as receive reflected light for detection and image reconstruction. The MEMS mirror oscillates resonantly in two axes in order to scan the object surface. The laser beam is focused by an objective in front of the MEMS scanner for achieving a microscopic resolution of about 15 μm within an object field of approximately 3 mm feed size. This enables a variety of new endoscopic applications, e.g. in vivo cancer investigation in medicine.

The optical head has been designed for being micro-assembled from necessary components and materials. It is coupled by a combined cable with optical fibers and wires to a distant control unit joining the laser light source, optoelectronic detectors, and all embedded electronics that is needed for control and signal processing. The control unit offers enough space and full flexibility for choosing and combining light sources and wavelength(s), different detectors, optical filters, electronics, etc. The current demonstration setup uses a green laser with 532 nm wavelength, an appropriate detector and an electronic subsystem connected to a PC or notebook, which is used for final image reconstruction, image display and storage.

7930-02, Session 1

An improved focus control mirror using SU-8 wafer bonding process
M. J. Moghimi, J. B. Lutzenger, K. W. Oliver, S. C. Gates, Montana State Univ. (United States); B. Kaylor, Bridger Photonics, Inc. (United States); D. L. Dickensheets, Montana State Univ. (United States)

We are developing MEMS deformable mirrors for focus control in miniature optical systems, including endoscopic microscopes and small form-factor camera lenses. This paper describes a new process to create mirrors made from an aluminum coated layer of the photoset polymer SU-8. Ours is a two-wafer process, with the membrane formed on one wafer and electrostatic drive electrodes and spacer layer formed on another. We use SU-8 also as the adhesive layer for wafer bonding, resulting in a simple, low cost fabrication process. Compared to our previous process we have introduced two major improvements. The first is full wafer bonding, rather than die-bonding after dicing. The second is a dry release of the membrane using reactive ion etching. These improvements result in higher yields and mirrors with excellent initial flatness and lower aberrations such as astigmatism when actuated. The paper presents the process details and the optical properties of the resulting focus control mirrors, which have a large stroke and very low residual aberration. Circular mirrors with 1 mm, 2 mm and 3 mm diameter have been characterized. An air gap of 25 microns allows displacements in excess of 10 microns when actuated open loop, and multiple actuation electrodes permit adjustment of several waves of spherical aberration. We have also studied the influence of bonding temperature on both bond quality and final membrane mechanical properties. Lower bond temperature results in lower residual stress in the membranes and lower required actuation voltage, but a threshold temperature for reliable bonding must be met.

7930-03, Session 1

SU-8 focus control mirrors released by XeF2 dry etch
S. J. Lukes, D. L. Dickensheets, Montana State Univ. (United States)

We previously presented a surface micromachining process for SU-8 2002 deformable membrane mirrors. This paper describes mirrors created using an improved release process leading to more than 50% increase in stroke, larger mirrors and higher yield. Recently we have investigated the use of the photoset polymer SU-8 2002 as a membrane material because it has low intrinsic stress that allows large electrostatic deflection and cured SU-8 can also have very good optical qualities. Our initial process involved wet-etching of a sacrificial phosphosilicate glass layer in BOE and wet-etching the underlying silicon in TMAH for full release of the membranes. The largest devices realized were 1 mm circular and 1 mm x 1.4 mm elliptical mirrors, limited by stiction or significant delamination of the membrane at the die edges. The largest displacement stroke achieved was 6.8 μm. To remedy these issues and improve displacement stroke we have investigated a dry release etch using xenon difluoride. This paper describes mirrors comprising 2.25 mm SU-8-2002 membranes with a 150 nm gold reflective coating, fabricated on single-side-polished silicon wafers. The membrane is dry released in XeF2 through etch vias with 30 μm spacing between vias. We show greater than 50% improvement in stroke and successful release of mirrors as large as 3 mm x 4.24 mm ellipses. We discuss the use of these simple, low-cost mirrors for focus control in microscopy and camera imaging applications.

7930-04, Session 1

In vivo skin microscopy
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We demonstrate a Dual-Axes Confocal (DAC) fluorescence microscopy and obtain in vivo skin images in mouse models and humans. The DAC microscope delivers an excitation wavelength of 785 nm with a maximum laser output of 2.5 mW at the surface mucosa. Confocal images can then be collected at a scan rate of 5 frames/second. The transverse and axial resolutions are 5 μm and 7 μm, respectively. Intravital volumetric in vivo imaging of a mouse footpad after administration of near-infrared dyes by topical formulation revealed individual keratinocytes in the epidermis. A clinical study was performed to test the ability of the in vivo imaging system to monitor the effects of a siRNA-based gene therapeutic (TD101). Indocyanine green (ICG) was topically applied to non-affected as well as vehicle- and TD101-treated skin of a pachyonychia congenita (PC) patient and healthy skin of a normal volunteer. Confocal images of ICG can then be collected at a scan rate of 5 frames/second. The transverse and axial resolutions are 5 μm and 7 μm, respectively. Intravital volumetric in vivo imaging of a mouse footpad after administration of near-infrared dyes by topical formulation revealed individual keratinocytes in the epidermis. A clinical study was performed to test the ability of the in vivo imaging system to monitor the effects of a siRNA-based gene therapeutic (TD101). Indocyanine green (ICG) was topically applied to non-affected as well as vehicle- and TD101-treated skin of a pachyonychia congenita (PC) patient and healthy skin of a control patient as a formulation of cream, and then imaged to assess penetration and differences in skin structure. The data collected in human subjects with the DAC microscope indicate that topical application of cream-based gene therapeutic readily penetrates and delivers ICG to hyperkeratotic PC skin (or calluses of a normal volunteer) and non-affected skin in PC patient and non-callused skin in a normal volunteer are more difficult to access by topical delivery. Taken together, these
restrictions of liquid lenses for endoscopy and our present development
In the presentation an overview will be given of the possibilities and
will not survive heat sterilization in the autoclave. We are working on
laser beam steering for treatment is possible. And on top of that they
motor. Moreover, they could also be used for image stabilization. Even
Electrowetting-based liquid lenses could solve this issue, as they change
a mechanically adjustable focus system is often not feasible.
Endoscopic imaging is reported, which uses the distal-end surface of
a conical tip that served both as reference mirror and focusing lens.
Because this conical-tip configuration requires that the sample is placed
very close to the reference mirror, the configuration is not suitable when
circumferential scanning is required, especially for large lumens such as
the gastrointestinal tract.
A MEMS motor based common-path Fourier-domain OCT for
endoscopic imaging is reported, which uses the distal-end surface of
the fiber interfaced with an index match oil as the self-aligned reference
mirror. The reference beam's intensity can be easily tuned by altering the
index of the match oil to optimize the signal to noise ratio of the system.
A GRIN lens is used to focus the sample beam, and a right angle prism
mirror, which is mounted on the shaft of a MEMS micromotor, is used to
realize a circumferential OCT scan.
An external Michelson interferometer is used to compensate for the
optical path difference and mismatch of dispersion due to index match oil
and GRIN lens. This arrangement allows arbitrary probe fiber length and
provides sufficient space for imaging optics and circumferential scan,
and thus is suitable for OCT imaging of lumens of various sizes. Due
to this common-path design, the OCT signal is immune to bending or
handling of the catheter. This feature makes it suitable for clinical use.
With high speed spectrometer, our system could achieve 20,000 lines/s
scanning speed. A free space Ti:sapphire laser beam is coupled into a
fiber optics and provides a spectrum with 35nm bandwidth centered at
830nm. As a result 7µm axial resolution is achieved.

7930-06, Session 2
Liquid crystal lens with auto-focus and optical image stabilization for wafer level camera
N. Fraval, F. Berier, Eovensens (France)
Miniaturization and reduction of production cost of optical components
in consumer electronics lead to wafer level optics. This miniaturization,
associated with the increase of CMOS sensors resolution, generate new
needs such as auto-focus (AF) and optical image stabilization (OIS) in
order to reduce the blurring caused by hand jitter.
In this paper, we propose a wafer scale technology to perform AF
and OIS. We succeed to create a tunable focal lens by filling with
nematic liquid crystal (LC) an assembly of two glass substrates coated
with annular chromium electrodes and resistive transparent layers of
Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT-PSS).
When a voltage with tunable magnitude and frequency is applied to the
electrodes, the resistive layer creates a non-uniform voltage distribution
from the edge to the center of the aperture which depends on electrical
parameters of PEDOT-PSS and LC. The resultant electric field generate
a gradient orientation of the nematic director which allow to focus light
polarized along the director. It is also possible to shift the optical axis of
the lens, to ensure the OIS function, by dividing the annular electrodes in
several sectors and apply different voltages on each sectors.
We realized a set of lenses with various aperture diameters, thickness
of LC layers and number of sectors in the electrodes. The diameter
classified each lenses in term of focus, deviation angle, aberrations
and response time. The production of these lenses is compatible
with wafer optic process used for mass product of cameras, e.g. in
smartphones or webcams.

7930-07, Session 2
Tunable liquid lens with reduced chromatic and spherical aberration
H. Yu, G. Zhou, F. S. Chau, H. Leung, National Univ. of Singapore
(Singapore)
Tunable liquid lens, inspired from biological vision systems (human
and animal eyes), has attracted much research interest due to its large
tunability on the lens physical optical parameters, such as focal length,
umerical aperture and even lens type, and relatively compact system
configuration. One significant drawback associated with this type of
lenses however is their spherical aberration (mainly primary spherical
aberration) appearing throughout the operation range. At the same
time, considering its configuration and refractive nature, the presence
of chromatic aberration would also be inevitable.
Currently, a novel liquid lens with a simple and compact structural design
is presented, the key idea of which lies in the adoption of a diffractive
surface with an aspherical phase contour. The diffractive surface together
with the refractive one (namely deformable membrane) is combined to
reduce chromatic aberration, whilst the spherical phase contour is used
for compensation for the spherical aberration caused by the near-spherical
contour of the deformed membrane. The lens is fabricated by combining the
fast and powerful shaping capability provided by the single point
diamond turning (SPDT) method with the simple process and massive
production potential associated with the well-known soft lithography
technique. Both simulation and measurement results agree well with each
other and demonstrate improved chromatic and spherical aberration
within the tunable range of the lens. To the best of our knowledge, this
is the first time that improved spherical and chromatic aberration can be
simultaneously realized in a single liquid lens without overly complicating
the lens structure and its operational control. At the same time, the
relatively fast prototyping process and the advantage of simple and low
cost fabrication enhance its potential for many varied applications.
A multi-aperture approach to wafer-level camera lenses
A. Brückner, R. Leitel, P. Dannberg, A. Bräuer, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The application of miniaturized camera systems for portable devices and sensors (e.g., mobile phones) demands not only the shrinking of opto-electronic and electronic but also the mechanical components. The basic requirements to achieve that goal are (1) a short focal length and (2) an optical system with low complexity. However, the ongoing miniaturization of the image sensor size also causes a demand for a higher image resolution and light sensitivity. Wafer-level fabrication techniques for camera lenses and modules turned out to be promising candidates for the high-volume production in the low-cost regime. The existing concepts for wafer-level optics (WLO) apply complex aspherical lens profiles and vertical integration techniques which put limits to the process yield so far.

We propose an alternative approach using a multi-aperture imaging system which captures different portions of the object field of view within separated optical channels. These different partial images are joined together digitally to form a total image of the full field of view. The segmentation of the full field of view partly decouples focal length from the size of the field of view. Therefore, a short total track length is realized for each optical channel. On the other hand, simple optical components such as reflow microlenses with small sags can be applied due to the short focal length and small size of field per channel. These may be fabricated with well-established microoptical fabrication techniques such as UV-lithography, reflow and UV-molding which show sub-μm precision and are cost-efficient due to wafer-level manufacturing. Alignment and assembly may at least partially be done on wafer-level which further reduces production costs.

The optical design and technological realization of such artificial compound eye imaging systems is discussed at the example of an electronic cluster eye. In contrast to former developments, such a system makes more efficient use of the active silicon area and exhibits a higher resolution. Additionally, the use of signal processing is discussed in order to perform a channel-wise correction of partial image distortion. Optical simulations indicate that these types of multi-aperture imaging system may be suitable to achieve megapixel image resolution with a total track length below 2mm.

Ultra-compact imaging system based on multi-aperture architecture
J. Meyer, A. Brückner, R. Leitel, P. Dannberg, A. Bräuer, A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

In the electronic communication industry, it can be observed that there is a trend that systems get smaller and at the same time cheaper. As a matter of course, there are cameras integrated in those systems. Because single-aperture systems have a limit of miniaturization, while simultaneously keeping the same resolution, there is a need of new ideas like the multi-aperture optical systems. In the proposed camera system the image is formed with many different channels each consisting of four microlenses which are arranged one after another in different microlens arrays. A partial image which fits together with the neighbouring one is formed with every single channel, so that a real erect image is generated on the sensor. Therefore a conventional image sensor can be used. The microoptical fabrication process and the assembly are well established and can be carried out on wafer-level. Laser writing is used for the fabrication of the masks. UV-lithography, a reflow process and UV-molding is needed for the fabrication of the apertures and the lenses. The developed system is very small in terms of total lens length and lateral dimensions and has a VGA resolution and a diagonal field of view of 65°. This microoptical vision system is appropriate for being implemented in electronic devices (e.g. as webcams integrated in the display of notebooks).

Design of an ultra-thin objective lens based on superposition compound eye
A. Garza Rivera, F. J. Renero-Carrillo, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

We present the optical design of an ultra-thin non-conventional objective lens (UTOL), based on the concept of superposition compound eye that some insects and arthropods have. One of the features of the UTOL is the capability to achieve zoom by using tunable lens. Lens parameters and fabrication technique options are described. This system intends to achieve a very thin camera objective that will have a good quality and that will be able to be used in other devices that will have very small dimensions.

Microbolometers for thermography and night vision markets
E. Mounier, Yole Développement (France)

Initially developed for the military market by US defense companies, use of uncooled infrared (IR) cameras in commercial applications has been growing over the last ten years. In the infrared spectrum, Long Wave Infrared (LWIR) is the most commonly used wavelength (8-12 microns). Thermography and a variety of vision enhancement applications are the main growth markets for uncooled IR cameras. Camera prices have been significantly reduced in the thermography business, which has allowed expansion of the use of IR cameras to maintenance engineers and building inspectors.

This camera cost reduction will continue through 2015 in the thermography business and will also be a strong factor in the vision market (also called night vision or vision enhancement) with the growth of the security/surveillance and automotive markets.

Driven by the continued cost reductions, the volumes of camera sold will triple by 2015 from more than 200,000 cameras today to more than 700,000 units, meaning + 25 % annual growth rate. Microbolometers are the dominant uncooled IR detector technology with more than 95 % of the market in 2010. More than 75 % of the production is based in USA but this landscape will change in the next five years; many new players (Sensonor, Faun Infrared, Bosch...), focusing only on selling detectors, often in Europe, will enter on the market place with aggressive price strategies.

The following technical trends make detector cost reduction possible: wafer Level Packaging and even Pixel Level Packaging, smaller pixel size, 3D integration.

MEMS-based handheld projection systems and a survey of applications
M. K. Brown, Microvision, Inc. (United States)

MEMS based handheld projection systems entered the consumer markets in 2009 and 2010. These MEMS based projection systems are based either on the DLP(TM) projection systems or laser scanning projection systems using a MEMS based bi-axial scanning mirror. These low cost, compact and handheld devices enable many and diverse possibilities for consumer applications. Already, the community of both consumers and industrialist are demonstrating applications that will be able to be used in other devices that will have very small dimensions.
and software platform capable of supporting these applications. This development requires a thorough understanding of the myriad of applications that are currently being explored and those that remain to be invented. In this paper we will discuss results obtained that explore the use of handheld projectors to produce 3D images using structured light and time of flight methodologies. We will discuss implementations that have been explored to produce 2D and 3D touch applications based on gesture recognition algorithms. And we will discuss applications within the field of augmented reality for the gaming environments. Finally, we will discuss performance requirements that will be needed to support these applications.

7930-13, Session 3
MEMS-scanned laser head-up display
M. O. Freeman, Microvision, Inc. (United States)

Head-up displays (HUD) in automobiles and other vehicles have been shown to significantly reduce accident rates by keeping the driver’s eyes on the road. The requirements for automotive HUDs are quite demanding especially in terms of brightness, dimming range, supplied power, and size. Scanned laser display technology is particularly well-suited to this application since the lasers can be very efficiently relayed to the driver’s eyes. Additionally, the lasers are only turned on where the light is needed in the image. This helps to provide the required brightness while minimizing power and avoiding a background glow that disturbs the see-through experience. Microvision has developed a couple of HUD architectures that are presented herein. One design uses an exit pupil expander and relay optics to produce a high quality virtual image for built-in systems where the image appears to float above the hood of the auto. A second design uses a patented see-through screen technology and pico projector to make automotive HUDs available to anyone with a projector. The presentation will go over the basic designs for the two types of HUD and discuss the component design tradeoffs.

7930-14, Session 3
Vertical, electrostatically 90° turning flaps for reflective MEMS display
F. Jutzi, W. Noell, N. de Rooij, Univ. of Neuchâtel (Switzerland)

Nowadays available reflective displays lack in contrast and angular response. A new MEMS-based reflective concept, working only with ambient light, is being developed having high contrast and reflectivity and working at low-power. The system employs novel vertical flaps, which can be rotated by electrostatic actuation. After fabrication, the poly-silicon flaps are vertical to the substrate surface and on the top suspended by torsion beams. The flaps can be electrostatically turned by 90° to be parallel to the wafer surface and reflect ambient light, thus constituting a white pixel. In the vertical rest state light is absorbed by an underlying absorptive layer, giving a black pixel. Line-column addressing is proposed for actuating flaps in an array. The novel microfabrication process is self-aligning using only three masks. High aspect ratio cavities with a SiO2 liner in a silicon bulk wafer are filled with poly-silicon. After patterning the top poly-silicon layer as torsion beams, the flaps are released by etching the surrounding Si and SiO2. The flaps have a vertical dimension of 30-50μm, sub-μm thickness and a large lateral design variety. Thanks to auto stress-compensation the flaps are not deformed due to intrinsic stresses. Other materials such as metals and Parylene will also be employed for the flaps and beams.

First devices are actuated with 120V, but by using less stiff torsion beams, actuation voltages down to 20V can be achieved. Previously fabricated horizontal flaps with similar geometries, which are surface micromachined of 100nm poly-silicon, were actuated at 20V.

7930-15, Session 4
Out-of-plane translatory mems actuator with extraordinary large stroke for optical path length modulation
T. Sandner, T. Grasshoff, H. Schenk, Fraunhofer Institute for Photonic Microsystems (Germany); A. Kenda, Carinthian Tech Research AG (Austria)

Fourier Transform Infrared (FT-IR) spectroscopy is a widely used method to analyze different materials - organic and inorganic. Current FT-IR spectrometers are large, usually static, and are operated by qualified personnel. By using translational MOEMS devices for optical path length modulation instead of conventional highly shock sensitive mirror drives a new class of miniaturized, robust, high speed and cost efficient FTIR-systems can be addressed. An early approach of a miniaturized MEMS based FTIR spectrometer has been developed in the past by IPMS and the CTR. It was a combination of classical infrared optics with a translatory 5 kHz MEMS mirror using a folded bending spring mechanism. Due to the limited amplitude of ± 100μm a spectral resolution of 30 cm-1 was realized allowing dynamic FTIR measurements in the ms-range. To enhance the stroke IPMS introduced a first translational MEMS device with two pantograph mirror suspensions - originally designed for larger stroke of 500 μm. But due to superimposed parasitic torsional modes only ± 140μm amplitude could be measured.

In this paper, we now present an optimized MEMS device which overcomes the previous limitations enabling an extraordinary large stroke of 1 mm. The novel translatory MOEMS actuator was specially designed to enable a miniaturized MEMS based FTIR spectrometer with improved system performance of 5 cm-1 spectral resolution (±2.5...16μm), SNR > 1000 and fast operation of ≥ 500 scans / sec. Hence, a large mirror aperture of 5 mm, enhanced amplitude of ± 500 μm and a small dynamic deformation of < /4 is required. Due to the significant viscous gas damping in normal ambient the translatory MEMS devices have to operate in vacuum - requiring a long term stable optical vacuum package with broadband IR window. The paper discusses the design, fabrication and experimental characteristics of the novel translatory MEMS actuator including first results of the optical vacuum packaging.

To realize a large stroke of the mirror plate a pantograph like suspension was chosen. The new translatory MEMS actuator consists of four symmetric pantograph suspensions in contrast to two pantographs used for a previous MEMS design, where only ± 140μm amplitude could be achieved due to parasitic tilt modes. One single pantograph consists of six torsional springs - two springs arranged on the same axis - and connected by stiff levers. The torsional springs are used to deflectable elements instead of bending springs which reduces significantly parasitic mirror deformation due to mechanical stress. Due to the optimized mechanical design using 4 pantograph suspensions the new translatory MEMS actuator can provide a precise out-of-plane trans-lation with ± 500 μm amplitude in vacuum of 50 Pa at 90V. This enables a completely new family of low cost handheld FTIR analyzers with a spectral resolution of up to 5cm-1, 500 scans/s and SNR > 1000 e.g. applied by individuals for ad-hock inspection of food or environmental parameters. The work was performed in the context of the FP7 project MEMFIS. We acknowledge financial support by the European Commission.

7930-17, Session 4
Characterization of MEMS FTIR spectrometer
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High resolution MEMS FTIR spectrometers are now of growing interest on both the academic and industrial levels. Such spectrometers are characterized by their small compact size, high speed of response and input/output fiber coupling. They usually need special characterization techniques. In this work we present the characterization of an FTIR MEMS spectrometer based on the use of wide spectral range Si/Air beam splitters fabricated by DRIE in SOI technology. The mirror motion...
achieved using a long travel range comb actuator. The spectrometer characterization includes electrical, electro-optical and optical characterization. The electrical characterization is used to extract the circuit elements of the equivalent circuit model of the actuator in the frequency domain. The developed method eliminates the need for fitting and optimization by direct extraction from the measured data. The electro-optical measurement is then used to assist the model by measuring the actuator in the time domain. The results of the characterizations carried out in the two domains match within 2%. The optical characterization is performed on both static and dynamic levels. In static optical measurement the mirrors are kept unmoving and the interferometer is characterized using a low coherence interferometry technique. Quasi-static optical measurement with very narrow linewidth 1550 nm laser source is then carried out to characterize the mirror displacement. Finally the calibrated spectrometer is used to measure the spectrum of a given optical power by dynamic measurements. With this spectrometer, different wavelengths can be resolved with resolution better than 10 nm.

7930-18, Session 4

Tunable mid-infrared filter based on Fabry-Pérot interferometer with two movable reflectors

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Electrically tunable infrared filters are one of the major components of small-sized infrared analysis systems. Besides of tunable wavelength range and wavelength selectivity, the maximum actuation voltage and the robustness against gravitation and vibration are key specifications. This contribution reports a novel FPI based tunable IR filter with two movable reflectors, which makes benefit from relatively low stiffness of the mirror suspensions, compensation of vibration and gravitation induced forces on the central wavelength, and much lower actuation voltages as a result. The reflectors made of dielectric layer stacks are deposited on two 300 μm thick reflector carriers of single crystalline silicon, which prevents warping and tilting. Both reflector carriers are movable and are actuated by electrostatic forces. A symmetric design and springs mounted in the center of gravity lead to nearly equal deflections of both reflectors as reaction of forces from gravitation. Further damping areas reduce the vibration and shock sensitivity significantly. The infrared filter can be tuned over a wavelength range from 10.2 μm to 8 μm with voltages lower than 30 V. The FWHM bandwidth is lower than 150 nm and the peak transmittance is larger than 70%. Simulation and practical shock tests both showed that the device is able to withstand 1500 g, 0.5 ms shocks according to Mil-Std-883 test condition B. The new infrared filter measures 8.5 mm x 8.5 mm and is suitable for the integration in a TO-8 housing in combination with a broadband infrared detector.

7930-19, Session 4

Fabrication and testing of MEMS-based optical filter combined with HgCdTe detector

D. A. Kozak, Univ. of California, Santa Cruz (United States) and EPIR Technologies, Inc. (United States); S. Velicu, EPIR Technologies, Inc. (United States); J. Kubby, Univ. of California, Santa Cruz (United States)

The Mid-wave infrared (MWIR) spectrum has applications to many fields, from night vision to chemical and biological sensors. Existing broadband detector technology based on HgCdTe allows for high sensitivity and wide range, but lacks the spectral decomposition necessary for many applications. Combining this detector technology with a tunable optical filter has been sought after, but few commercial realizations have been developed. MEMS-based optical filters have been identified as promising for their small size, light-weight, scalability and robustness of operation. In particular, Fabry-Pérot interferometers with dielectric Bragg stacks used as reflective surfaces have been investigated. The integration of a detector and a filter in a device that would be compact, light-weight, inexpensive to produce and scaled for the entire range of applications could provide spectrally resolved detection in the MWIR for multiple instruments. Continuing on our theoretical and simulation work, we present a fabrication method for the optical components of such a filter. The emphasis was placed on wafer-scale fabrication with IC-compatible methods. Single, double and triple Bragg stacks composed of germanium and silicon oxide quarter-wavelength layers were designed for MWIR devices centered around 4 microns and have been fabricated on Silicon-On-Insulator (SOI) wafers, with and without anti-reflective half-wavelength silicon nitride layers. Optical testing in the MWIR and comparison of these measurements to theory and simulations are presented. The effect of film stress induced by deposition of these dielectric layers on the mechanical performance of the device is investigated. An optimal SOI substrate for the mechanical performance is determined. The fabrication flow for the optical MEMS component is also determined. Part of this work investigates device geometry and fabrication methods for scalable integration with HgCdTe detector and IC circuitry.

7930-01, Session 5

Applications of MEMS in segmented mirror space telescopes

B. Agrawal, Naval Postgraduate School (United States); J. Kubby, Univ. of California, Santa Cruz (United States)

For several future space missions, larger aperture and lightweight deployable mirrors, in the range of 10-20 meters in diameter with high surface accuracy, are required. In order to meet the launch vehicle diameter constraints, the concept of segmented mirrors, such as in James Webb Space Telescope, is used. For these telescopes, alignment of the segments in orbit and achieving the required surface accuracy is a very challenging problem and expensive to develop. In order to achieve lightweight and active surface control, actuated hybrid mirror (AHM) technology is under development that consists of a rib-stiffened silicon carbide substrate, a metallic nanolaminate facesheet to provide optical finish, surface parallel actuators, and a sensing system, typically a wave front sensor, to determine the surface errors. The system consists of hundreds of sensor outputs and hundreds of actuators resulting in very challenging control problem. These systems also require extensive analysis and testing, resulting in a very high cost for development. The Naval Postgraduate School recently received 3-meter diameter space telescope testbed with six segments that uses and AHM technology. This paper will discuss on how we can use a MEMS deformable mirror to improve the performance of the NPS segmented mirror telescope. The high-stroke, high-order actuated MEMS deformable mirror will correct the residual alignment and surface errors that are not corrected by the actuators on the mirrors. The mirror will use electrostatic actuation to eliminate the need for power to hold its position and will be capable of open-loop, go-to positioning.

7930-19, Session 5

Improved coupling to integrated spatial heterodyne spectrometers with applications to space

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Multiple Aperture Transform Chip Heterodyne Spectrometers (MATCHeS) have been developed for targeted remote sensing applications in harsh environments. These waveguide-based Fourier Transform Spectrometers (FTS) offer significant improvements in resource efficiency over monolithic glass implementations, but are relatively limited in terms of input coupling efficiency and fill factor of the input facet. Integrated optics spectrometers have significant resource advantages for space applications. Monolithic Spatial Heterodyne Spectrometers are insensitive to vibration and do not require frequent calibration. In addition, Fourier Transform Spectrometers are known to provide significant performance advantages for emission spectroscopy.

Ongoing work will improve the MATCHeS input coupling efficiency from free space. This paper discusses the signal to noise improvements expected by incorporation of surface gratings, or back-thinning and stacking of slabs. We show that the use of surface gratings can increase the throughput over coupling to bare waveguides alone (in a single polarization), and provide close to 100% fill factor, albeit with limited field. Etendue improvements associated with stacked slabs are limited only by the sensing area available, but the fill factor of the input facet is limited to ~10%.

The impact of these improvements is assessed in the context of two space-based applications: 1) Spatial Heterodyne Observations of Water (solar occultation absorption spectroscopy) and 2) LIBS/Raman spectroscopy for mineral identification on a planetary rover, similar to the Mars Science Laboratory ChemCam Instrument.

**Integration of optical waveguides and microfluidics in a miniaturized antibody micro-array system for life detection in the NASA/ESA ExoMars mission**

H. Leeuwis, A. Prak, R. G. Heideman, A. Leinse, LionIX BV (Netherlands); G. Borst, Dutch Space B.V. (Netherlands)

A microfluidic fused silica sandwich chip integrates all the relevant components for the analysis/assay procedure (except the pumping which is performed by a syringe), i.e. pretreated sample intake; buffer, hybridization/reaction and reagents dissolution chambers; liquid front sensors; inputs and output ports for the selector valve and a channel structure connecting these components. Moreover, the design is based on three separate pathways in order to allow for three different classes of assays. The whole fluidic design is driven by the requirement that the dead volumes and the total liquid volume is as small as possible. To realize this, a miniaturized and integrated selector valve appeared to be the most promising solution.

An optical array chip incorporates integrated waveguides, which allow for excitation of the fluorescent labels by the evanescent field of the guided light wave. The system had to be designed in such a way that the light of a single chip-coupled fiber is distributed over all the spots (10 x 20) of the array. The LionIX’ proprietary waveguide technology technology, TriPlex is the only mature technology that allows this in the required (VIS) wavelength region. The losses of this silicon-nitride based waveguide system are extremely low, even at the small bends necessary to distribute the light over the matrix spots.

**Ultra-low-power multiplexed electronic driver for high resolution deformable mirror systems**

M. N. Horenstein, R. Sumner, Boston Univ. (United States); J. Stewart, S. Cornelissen, Boston Micromachines Corp. (United States); P. Miller, Boston Univ. (United States); T. Bifano, Boston Univ. (United States) and Boston Micromachines Corp. (United States)

In principle, electrostatically-actuated deformable mirrors fabricated using micro-electromechanical systems (MEMS) manufacturing offer compelling and intrinsic advantages in size, weight, and power in comparison to all other wavefront controllers. These chip-scale, thin-film silicon devices are made in foundry-scale semiconductor batch processes, allowing economical, high-yield production. They are extraordinarily compact, with active structures weighing less than one gram for DMs capable of more than a thousand optical degrees of freedom. The DM occupies a volume of less than one cubic centimeter, exclusive of packaging and drive electronics. As capacitive, electrostatic devices, MEMS DM actuators theoretically consume negligible power (microwatts per actuator). In practice, however, the electronic circuits needed to drive DMs consume considerable power. In fact, DM drive electronics often represent the primary power demand in MEMS DM adaptive optics (AO) systems. While ground-based applications are rarely limited by the DM driver’s power consumption or compactness, for emerging and important space-based applications these are critical limitations.

In this presentation we will discuss the new driver multiplexing electronics design that trades DM frame rate for reduced power consumption. Simulation and experimental results of the new design used to control a 140 element MEMS DM will be presented.

**MEMS-based programmable reflective slit mask for multi-object spectroscopy**

M. D. Canonica, Univ. of Neuchâtel (Switzerland); F. Zamkotsian, Observatoire Astronomique de Marseille-Provence (France); W. Noell, Univ. of Neuchâtel (Switzerland); P. Lanzoni, Observatoire Astronomique de Marseille-Provence (France); N. de Rooij, Univ. of Neuchâtel (Switzerland)

Multi-object spectroscopy is a powerful tool for telescopes for the study of the formation of galaxies. This technique requires a programmable slit mask for astronomical object selection. We are developing MEMS-based programmable reflective slit masks for multi-object spectroscopy that consist of micromirror arrays on which each micromirror of size 100 x 200 µm2 is electrostatically tilted providing a precise angle. The main requirements for these arrays are cryogenic environment capabilities, precise and uniform tilt angle over the whole device, uniformity of the mirror electro-mechanical behaviour and a low mirror deformation. These devices were fabricated by assembling a micromirror chip on top of an electrode chip. A first generation of MEMS-based programmable reflective slit masks composed of 5 x 5 micromirrors was tested in cryogenic conditions at 92 K. Then, first prototypes of large arrays were microfabricated and assembled using a chip level assembly setup, but with short-circuit failure hindering the complete actuation of the array. To increase the reliability of these devices, a third generation of micromirror arrays composed of 64 x 32 micromirrors is under development. This generation was especially designed for individual actuation of each mirror, applying a line-column algorithm based on the electrostatic hysteresis of the actuator. The fabrication process is now based on multiple wafer level bonding steps and investigation was performed to reduce the short-circuit failure. This third generation of micromirror array will be fully characterized and tested in a cryogenic environment.
42

7930-21, Session 5

CANEUS
M. Primpikar, CANEUS International (Canada)

No abstract available

7930-36, Session 5

Fully integrated imaging spectrometer instrument on a chip: miniaturization effort for space instruments

B. Guldimann, European Space Research and Technology Ctr. (Netherlands)

Starting from the requirements and concept of a state of the art space optical imaging spectrometer aboard MarsExpress, a new, strongly miniaturized imaging spectrometer concept is presented. Typical state-of-the-art optical space spectrometer (for instance MERIS and SCIAMACHY aboard EnviSat and OMEGA on MarsExpress) payloads are based on one or several optical gratings to address the whole spectral range. These spectrometer instruments, typical for remote sensing, without the front optics (telescope, camera objective) have at least the size of a show box. The new proposed concept, essentially based on micro-nano technologies as well as optical MEMS, shrinks such spectrometers down to the size of a few computer chips. A very high integration level of various technologies and functionalities has been conceived while keeping the original top level performance requirements for remote sensing. The result is a concept of a fully integrated 2D mapping spectrometer on a chip placed in the focal plane of the front optics (camera objective, telescope). The working principle allows the new chip-device achieving a very high spectral resolution, as it is often required in remote sensing. This new device concept can therefore not only map a 2D image of a scene, as CMOS camera chips or CCD-chips do, but also deliver continuously a high resolution spectrum for each image pixel. Due to its generic characteristics it has the potential to be used also for airborne and commercial applications on ground. The conceptual design, fabrication aspects and performance limitations are discussed. An alternative conceptual design which is simpler to fabricate, but less compact, is also proposed.

7930-22, Session 6

Shaping light with MOEMS

W. Noell, Univ. of Neuchâtel (Switzerland)

Modulating light for telecom applications and signal processing is greatly mastered by optoelectronics. Shaping light, however, is still a great challenge for many applications, in particular for high optical powers and sensitive systems.

MOEMS provides means to shape or modify the main properties of a light source, namely intensity profile, wavelength spectrum, speckle formation, wavefront, pulse shapes and direction. The main optical elements in MOEMS are mirror arrays, deformable membranes and tunable gratings and beam steering mirrors. A general trend in MEMS and MOEMS is to bridge the large gap between classical microfabricated devices, which measure only a few square millimeters, and precision machined microoptics, which measure a couple of square centimeters. Industry and research show a great demand for devices that have micrometer-sized features but are vast in size in comparison to classical micro-systems.

Typical devices are large tunable gratings, pulse shapers for fs-laser systems, large steering mirrors, large deformable membranes for tunable beam shapers and speckle reduction. In particular for large optical powers, the classical suspension of MOEMS devices are a risk factor and new avenues have to be pursued. The suspension and packaging of these elements are more and more playing other roles than simple mechanical supports, when being faced with high thermal loads from high-power optical beams.

The presentation is intended to give an overview on how MOEMS can meet these very challenging new requirements and what new road blocks have to be overcome and pushed aside, when cm large MOEMS devices are fabricated and operated.

7930-23, Session 6

Large diameter dual-axis MEMS-based mirror for laser beam steering

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The main goals of this work is the development of a large dual-axis MEMS mirror, about 3mm in diameter, capable of steering a laser beam within an angular cone of 60°. The targeted application involves the control of a laser beam with a particular interest for the resulting far field beam direction and profile.

Finite element simulations using ANSYS modeling program were conducted to optimize the mirror design and determine the main characteristics of the mirror. The voltage amplitude required to tilt the mirror by 16° around each of the two axes was evaluated to be in the range of 700 V.

The construction of this device is based on high precision structural dies assembly which relies on innovative developments in the fields of selective electroplating, deep reactive ion etching (DRIE), flip-chip bonding and micropackaging. The fabrication process involved the microassembly of 4 mirror parts, i.e. address electrodes, thick pedestal, gimbals structure and mirror plate. Single crystal silicon was used as material for the fabrication of the thick pedestal and mirror plate which provided the required large mirror-electrode gap and a high quality mirror with high flatness and low roughness. Soldering based on SnAu was considered for the microassembly of the thick pedestal to the address electrodes while thermocompression bonding was considered to achieve the assembly of gimbals and mirror. The gimbals were supported by a polyimide sacrificial film to avoid damaging the hinges during assembly. Packaging of the device was based on a modified off-the-shelf package compatible with high voltage operation.

7930-24, Session 6

MEMS scanning laser projection based on high-Q vacuum packaged 2D-resonators


Small size, low power consumption and the capability to produce sharp images without need of an objective make MEMS scanning laser based pico-projectors the adequate solution for embedded cell-phone projection displays. Leaving the conventional raster scanning scheme and changing to vacuum encapsulated resonant 2D-MEMS scanning mirrors that scan the laser beam in a Lissajous pattern offers the advantage of providing high image resolution while power consumption can be kept at a very low level of only a few milliwatts. To meet the very low cost expectations for such sophisticated MEMS scanning devices Fraunhofer ISIT established a fabrication process that includes vacuum encapsulation on 8-inch wafer level. Quality factors as high as 90.000 require dedicated closed loop control electronics to enable stable image projection even at rapidly changing laser intensities. A capacitive feedback signal is the basis for controlling the 2D MEMS oscillation and for synchronisation of RGB lasers. This paper reports on design and fabrication of two-axis wafer level vacuum packaged scanning
micromirrors. It presents two different approaches of overcoming the well-known reflex problem of packaged MEMS scanning mirrors and furthermore this paper reports on problems and solutions of a laser projection concept based on such high-Q scanning mirrors.

7930-25, Session 6

Optical position feedback and phase control of resonant 1D and 2D MOEMS-scanners

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We have developed compact devices to drive resonant MOEMS micro-mirrors with closed loop control, which ensure stable resonant operation of 1D and 2D micro-mirrors with well controlled amplitude under varying environmental conditions.

The scanner mirrors, developed at the Fraunhofer IPMS, are driven electrostatically with a pulsed driving voltage close to the double of their eigenfrequency. Position encoding of the mirror movement is crucial in many applications and can be obtained using trigger signals generated from a laser beam reflected from the backside of the mirror. This approach was successfully implemented for 1D scanner mirrors in the past.

Extending the approach to 2D mirrors adds significant complexity. In our device the backside of the mirror is hit by two crossed orthogonal laser beams, whose reflections pass a cylindrical mirror (in order to suppress the orthogonal dimension) before being sent onto the photo-diodes for the timing signals. This reduces the problem to the control of two independent 1D-oscillations and allows accurate position sensing and closed loop control.

In our device, which has a size of only ~2 cm^3, the mirror is driven close to its resonance frequency, thus ensuring stable operation with large amplitude. Phase stability better than 1/10.000 can be obtained, sufficient even for demanding display applications. The amplitude can be kept constant via the driving voltage.

Closed-loop control of MOEMS mirrors within small modules will significantly improve the performance and applicability of these devices and will be highly relevant e.g. for the development of compact MEMS based projection devices.

7930-26, Session 6

Integration of near-field probes and photonic crystal nanocavities for precise and low-loss resonance control

X. Chew, G. Zhou, F. S. Chau, National Univ. of Singapore (Singapore)

Research interest for silicon nanophotonics is a topic of heavy interest currently due to the requirements for high density communications of integrated devices with small footprints in the semiconductor industry. Silicon photonic crystals (PhC) are nanoscale subwavelength periodic structures that possess the capability to induce strong interaction between light and matter. PhC nanocavities utilizes the photonic bandgap effect to trap certain frequencies of light within a small confined region for a diverse range of applications such as enhancement and suppression of spontaneous emission, efficient and compact lasers, add/drop multiplexers, optical filters and sensing etc. In this paper, we introduce a mechanically perturbation near-field probe with a peculiar design shape to achieve low-loss and precise control of PhC nanocavities. One-dimensional (1D) PhC are chosen for our study due to ease of integrating with low-loss SOI waveguide technology and easy integration with nanomechanical structures. Sub-micron microelectromechanical systems (MEMs) technology is introduced as an ideal integration platform with such near-field probe designs due to its capabilities to accurately control fine displacements without the need of bulky equipment such as atomic force microscopy (AFM), scanning near field microscope (SNOM) or even highly sensitive piezo-controlled micromanipulator stages. We propose that such near-field probe designs are capable of achieving low resonance spectral tuning of up to few nm with high reconfigurability, highly accurate actuation displacements and low power consumption and portability. The innovative design of dielectric near-field probes are of our interest as without careful design mechanical perturbative methods will induce certain losses to the nanocavity causing a drop in transmission or even broadening in the resonance of high-Q PhC. In this paper, we propose a systematic approach utilizing numerical methods namely the (FDTD) to study and characterize the electromagnetic interaction between PhC nanocavities and nanomechanically displaced near-field probes. Various innovative and peculiar design of a nano-probe are presented and shown to exhibit low-loss and accurate resonance control on 1D PhC nanocavities.

7930-27, Session 7

MEMS eye for fast and high-precision 3D tracking and position measurement

V. Milanovic, Mirricle Technologies, Inc. (United States)

This project proposes to dramatically advance 3D position input and motion sensing systems with a MEMS-mirror based optical 3D tracking and position measurements system. This may enable real time interaction with computers and robotics in ways that are more intuitive, precise and natural compared to existing technologies. Having controllers that can follow our hands or fingers and interpret our intentions would make human-machine interaction a more enjoyable, ergonomic, and precise experience. We believe that input devices based on 3D tracking can be developed into intuitive and natural ways for people to interact with augmented and virtual reality environments.

Using fast beam-steering MEMS mirrors, lasers, and optical sensors, this tracking system can quickly and precisely determine location, direction, and rate of movement. Object being tracked is either a light source (e.g. a near-IR LED,) or a retro-reflector labeled passive object. Each “MEMS eye” unit can track and determine X and Y angles of the object with high speed and precision. When two or more such units are utilized, relative position can be fully determined because distance information also becomes available. This final, X,Y, and Z position information down to sub-millimeter precision in relatively large volumes can be obtained at update rates below 0.1ms.

7930-28, Session 7

Integrated piezoresistive position detection for electrostatic driven micro scanning mirrors

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For closed loop operation of micro scanning mirrors a position detection is necessary to detect the zero position crossing. Moreover the amplitude measurement and the real mirror movement during oscillation are of great interest to improve the optical resolution of projecting and imaging applications. For a monolithic solution a piezoresistive position sensor was developed at IPMS. The maximum stress respectively strain changing the resistivity of the sensor is located near the surface of the SOI device layer. The mechanical stress field is symmetric over the entire device layer thickness. Hence an asymmetry of the current field density is necessary to detect the zero position crossing. Moreover the amplitude measurement and the real mirror movement during oscillation are of great interest to improve the optical resolution of projecting and imaging applications.
The sensor sensitivity is correlated to the resonance frequency of the mirror. High frequencies (kHz-range) require stiff springs. Hence high mechanical stress is coupled into the sensor geometry causing a high sensitivity. For low frequencies down to 100Hz it is of essential importance to have a high coupling efficiency and to obtain a uniformly distributed stress field in the sensor structure. A novel sensor design shows a normalized sensitivity increase (independent of the nominal resistance) of factor 5. The sensitivity increase with dependence on the nominal resistance is even improved by a factor of 5.

7930-29, Session 7
Large electrostatically and electromagnetically actuated mirror system
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MEMS-based optical-beam steering scanners are used in various systems. Dimensions of these mirrors vary from 10 μm to a few millimeters. The current project aims at developing a compact scanning mirror system of relatively large size (1 cm diameter) that is microfabricated with silicon. The advantages of silicon microfabrication over conventional fabrication methods like Electric discharge machining and Laser cutting are the increased fabrication precision and several superior material properties of crystalline silicon over bulk materials.

The system is intended for precise beam positioning applications and tracking and consists of two mirrors that work synchronously. Having two mirrors allows one mirror to have large static mechanical scan angles (resonance frequency ~ 150 Hz) and the other to have fast fine pointing capabilities with smaller scan angles (resonance frequency ~ 1 kHz). This configuration separates the contradicting issues of large angular range and fast addressing from each other and is used in many adaptive-optics systems for telescopes and imaging systems.

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The mirror with large scan angle is magnetically actuated using a “moving magnet - stationary coil” arrangement with planar double layer coils that are microfabricated on a ceramic substrate.

The second mirror is electrostatically actuated with vertical combs that are etched into the device layer of an SOI wafer and traverse the buried oxide into the handle layer, thus creating two sets of completely self-aligned combs with one set of combs in the device layer and the other in the handle layer.

7930-30, Session 7
Design and fabrication of an integrated free-space micro-optical interconnection device
Z. Miao, W. Wang, Louisiana State Univ. (United States)
Compared with waveguide-based optical chip-to-chip connection, free-space optical interconnection (FSOI) approach has the advantages of larger interconnection density, lower power consumption, and better crosstalk performance. The biggest challenge for FSOI approach has been the precision alignment of the optical components. In this paper, we propose a novel polymer-based FSOI. The technology is based on direct UV-lithography fabrication of mold masters using the negative tone resist SU-8, and fast component replication using UV curable polymer such as NOA73. The optical components of a FSOI such as microlens array, mirrors, prism, and beam splitter can all be fabricated in out-of-plane fashion, and the alignment can be accomplished during mask design stage. This will allow production of integrated optical systems similar to conventional optical benches in micro-scale and eliminates the need for tedious high-precision assembly.

We have designed and fabricated an all-passive FSOI system with all basic optical components integrated on it. A prototype chip has been fabricated using UV curable polymer (NOA73) molded from the SU-8 master mold. This approach takes the advantage of the superior optical properties of NOA73 polymer (close to glass) and a fast replication method which will reduce the chip cost. Simulation of an optimal optical and mechanical setup is one of our current interests. The ongoing work is focused on attaching vertical-cavity surface-emitting lasers and detectors to the optical chip to test the performance of the fabricated FOSI and validate our concept.

7930-31, Session 8
Microassembly of 3D MOEMS: rotating inclined mirrors and optical delay lines
M. A. Bashra, Univ. of Waterloo (Canada)
This work describes the development of micro-opto-electro-mechanical systems (MOEMS). In particular, the development and use of 3D Rotating Inclined Mirrors (3DRIM) to create various micro-optical devices including free-space optical delay lines and micro-optical cross-connect switches. To construct these advanced devices, a robotic-based serial microassembly technique has been used to assemble together a number of microparts that were fabricated by surface micromachining. The microassembly system used to construct these devices is the PMKIL (Passive Microgripper with Key and Inter-Lock) system. The 3DRIM consists of a micromirror assembled on a top of rotating platform. The micromirror can be elevated and inclined at any pre-designed angle. The rotating platform provides full rotations using electrostatic micromotors, or continuous small angle rotation using rotary comb-drive actuators based on the requirements for the specific optical applications. Several prototypes of the 3DRIMs were assembled and tested. We also provide an overview of our robotic-based method, which includes: (a) the overall grasping, manipulation and joining strategy, (b) the use of passive (non-powered) microgrippers, and (c) the use of various micromechanical joints to create the 3D devices. The present advantages and challenges with this system are discussed, along with avenues for future development.

7930-32, Session 8
Development of on-CMOS chip MOEMS micro-systems
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Si Avalanche LEDs have been developed that emit up to 10nW / μm 2 in the 450–650nm regime. (Snyman et al, Japanese Journal Applied Physics, 2007; Snyman et al., Proc SPIE, 2008, 2009, 2010; Snyman et al., IEEE Journal of Quantum Electronics, June 2010). Correspondingly, small micro-machined structures with pW/ μm 2 sensitivity (for the same wavelengths ) can be realized also in CMOS integrated circuitry. Lately Si Av based LEDs have been developed that emit at 750nm which offer greater compatibility with Si2N3 and SixOyN waveguides.

We have subsequently used advanced optical simulation software (RSoft BeamPROP and RSoft FULLWAVE) in order to investigate the realization possibilities of CMOS chip-based MOEMS micro-systems. The analyses show that 0.2 to 2 microns Si2N3 and Si creates no image degradation or loss of single mode operation and losses of less than 1dB.cm-1, and are good candidates for providing interaction between optical excitation and mechanical or evanescent field coupled systems. Micro-bending, multi-plane coupling as well as far field lateral and focusing manipulation of the fibre emitted radiation is possible. Lateral and crevice based cantilever structures can be fabricated with CMOS post processing procedures. Sections of the developed waveguides can be open ended with RP etching such that coupling of environmental parameters occurs with the evanescent field of the waveguides. A crevice based CMOS based cantilever structure was designed such that the emitted rays interact with the cantilever at an angle. A linear array of detectors is used to analyze the displacement behavior of the cantilever. The emission levels of the
Si CMOS Av LEDs is 10+3 higher than the detectivity of silicon p-i-n detectors offering good dynamic range in detection and analyses. First iteration realizations are underway.


7930-34, Session 8

In situ surface topography measurement of MOEMS structures under laser exposure

A. Mai, M. Krellmann, S. Sinning, S. Wolschke, U. A. Dauderstädt, M. Wagner, Fraunhofer Institute for Photonic Microsystems (Germany); D. Schmeißer, Brandenburgische Technische Univ. Cottbus (Germany); H. Schenk, Fraunhofer Institute for Photonic Microsystems (Germany)

Spatial light modulators (SLM) developed at the Fraunhofer Institute for Photonic Microsystems (Fraunhofer IPMS) are based on arrays of tiltable micro mirrors on a semiconductor chip. Development and optimization of such complex MOEMS (Micro Opto Electro Mechanical Systems) requires detailed knowledge of the device behaviour under application specific operating conditions. In this context, the need for a high resolution surface topography measurement under laser exposure (in situ) was identified at Fraunhofer IPMS, complementing ex situ characterizations where light exposure and micro mirror topography measurements are carried out sequentially. Now, such in situ measurement capability has been developed and implemented and is presented in this paper. The new setup is based on white-light interferometer technology using the phase-shift principle. A series of interferograms, phase-shifted to each other by a specified value, is recorded and a topography map is generated thereof, which describes the shape of the micro mirrors surface. Measurements on calibration samples with a 50nm step revealed a standard deviation of about 0.1nm. For measurement setup verification SLM were illuminated at 248nm (pulsed laser) with some mJ/cm² to determine the repeatability of exposure effects under constant experimental conditions. In general, the setup is neither limited to a specific illumination wavelength nor to micro mirrors as structures under test. Influences of different illumination parameters such as energy density, laser repetition rate etc. on the mirror topography can be studied in detail. Results obtained so far reveal valuable feedback for further technological optimization of mirror array devices.

7930-35, Session 8

Steering micromirrors for high optical loads and with scalable actuation schemes

W. Noell, C. Ataman, S. Lani, N. de Rooij, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

High optical power densities are used in optical beam steering, laser positioning and optical beam shaping. In order to increase their versatility while reducing their dimensions, these systems require micromirrors that can withstand and dissipate high optical loads safely and without compromising their optical and mechanical performance. We will present micromirror devices based on a suspension design, which was thermomechanically optimized to withstand a continuous heat flux of more than 1 kW/m². The compactly integrated MEMS actuator allows a two degree-of-freedom large optical-steering range of about ±10° in non-resonance. Depending on the design, optically flat mirrors were fabricated with sizes in the mm range. The mechanical suspension is designed for an optimum compromise between thermal conductivity and compliance (tilt-range). Two different actuation concepts were pursued, firstly a highly integrated electrostatic actuator with vertical electrodes embedded in the substrate underneath the micromirror, and secondly an electromagnetic actuator based on a moving-magnet and planar micro-coils, integrated as well underneath the micromirror. The optically flatness of the micromirror is guaranteed by a minimized mechanical link between the micromirror and its suspension and by utilizing a relatively thick mirror substrate. The mirrors are eutectically bonded to the suspension. Both actuator designs were microfabricated and tested. The thermal-mechanical characterization proved the thermal dissipation capabilities of the design. The highly integrated design allows scalability and is suitable for beam shaping and multiple-beam steering applications alike.
Applications of MEMS in segmented mirror space telescopes

B. Agrawal, Naval Postgraduate School (United States); J. Kubby, Univ. of California, Santa Cruz (United States)

For several future space missions, larger aperture and lightweight deployable mirrors, in the range of 10-20 meters in diameter with high surface accuracy, are required. In order to meet the launch vehicle diameter constraints, the concept of segmented mirrors, such as in James Webb Space Telescope, is used. For these telescopes, alignment of the segments in orbit and achieving the required surface accuracy is a very challenging problem and expensive to develop. In order to achieve lightweight and active surface control, actuated hybrid mirror (AHM) technology is under development that consists of a rib-stiffened silicon carbide substrate, a metallic nanolaminate facesheet to provide optical finish, surface parallel actuators, and a sensing system, typically a wave front sensor, to determine the surface errors. The system consists of hundreds of sensor outputs and hundreds of actuators resulting in very challenging control problem. These systems also require extensive analysis and testing, resulting in a very high cost for development. The Naval Postgraduate School recently received 3-meter diameter space telescope testbed with six segments that uses and AHM technology. This paper will discuss on how we can use a MEMS deformable mirror to improve the performance of the NPS segmented mirror telescope. The high-stroke, high-order actuated MEMS deformable mirror will correct the residual alignment and surface errors that are not corrected by the actuators on the mirrors. The mirror will use electrostatic actuation to eliminate the need for power to hold its position and will be capable of open-loop, go-to positioning.

Improved coupling to integrated spatial heterodyne spectrometers with applications to space

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Multiple Aperture Transform Chip Heterodyne Spectrometers (MATCHeS) have been developed for targeted remote sensing applications in harsh environments. These waveguide-based Fourier Transform Spectrometers (FTS) offer significant improvements in resource efficiency over monolithic glass implementations, but are relatively limited in terms of input coupling efficiency and fill factor of the input facet. Integrated optics spectrometers have significant resource advantages for space applications. Monolithic Spatial Heterodyne Spectrometers are insensitive to vibration and do not require frequent calibration. In addition, Fourier Transform Spectrometers are known to provide significant performance advantages for emission spectroscopy.

Ongoing work will improve the MATCHeS input coupling efficiency from free space. This paper discusses the signal to noise improvements expected by incorporation of surface gratings, or back-thinning and stacking of slabs.

We show that the use of surface gratings can increase the throughput over coupling to bare waveguides alone (in a single polarization), and provide close to 100% fill factor, albeit with limited field. Étendue improvements associated with stacked slabs are limited only by the sensing area available, but the fill factor of the input facet is limited to ~10%.

The impact of these improvements is assessed in the context of two space-based applications: 1) Spatial Heterodyne Observations of Water (solar occultation absorption spectroscopy) and 2) LIBS/Raman spectroscopy for mineral identification on a planetary rover, similar to the Mars Science Laboratory ChemCam Instrument.

Integration of optical waveguides and microfluidics in a miniaturized antibody micro-array system for life detection in the NASA/ESA ExoMars mission

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A microfluidic fused silica sandwich chip integrates all the relevant components for the analysis/assay procedure (except the pumping which is performed by a syringe), i.e. pretreated sample intake; buffer, hybridization/reaction and reagents dissolution chambers; liquid front sensors; inputs and output ports for the selector valve and a channel structure connecting these components. Moreover, the design is based on three separate pathways in order to allow for three different classes of assays. The whole fluidic design is driven by the requirement that the dead volumes and the total liquid volume is as small as possible. To realize this, a miniaturized and integrated selector valve appeared to have far better properties than a system with numerous integrated and externally, often pneumatically actuated on-off valves, which is applied in many systems found in the literature. Next to this, the connected volume and mass of the whole fluid management system is lower.

An optical array chip incorporates integrated waveguides, which allow for excitation of the fluorescent labels by the evanescent field of the guided light wave. The system had to be designed in such a way that the light of a single chip-coupled fiber is distributed over all the spots (10 x 20) of the array. The LioniX® proprietary waveguide technology technology TriPlEx is the only mature technology that allows this in the required VIS wavelength region. The losses of this silicon-nitride based waveguide system are extreme low, even at the small bends necessary to distribute the light over the matrix spots.
7931-21, Session 1

**MEMS-based programmable reflective slit mask for multi-object spectroscopy**

M. D. Canonica, Univ. of Neuchâtel (Switzerland); F. Zamkotsian, Observatoire Astronomique de Marseille-Provence (France); W. Noell, Univ. of Neuchâtel (Switzerland); P. Lanzoni, Observatoire Astronomique de Marseille-Provence (France); N. de Rooij, Univ. of Neuchâtel (Switzerland)

Multi-object spectroscopy is a powerful tool for telescopes for the study of the formation of galaxies. This technique requires a programmable slit mask for astronomical object selection. We are developing MEMS-based programmable reflective slit masks for multi-object spectroscopy that consist of micromirror arrays on which each micromirror of size 100 x 200 μm² is electrostatically tilted providing a precise angle. The main requirements for these arrays are cryogenic environment capabilities, precise and uniform tilt angle over the whole device, uniformity of the mirror electro-mechanical behaviour and a low mirror deformation. These devices were fabricated by assembling a micromirror chip on top of an electrode chip. A first generation of MEMS-based programmable reflective slit masks composed of 5 x 5 micromirrors was tested in cryogenic conditions at 92 K. Then, first prototypes of large arrays were microfabricated and assembled using a chip level assembly setup, but with short-circuit failure hindering the complete actuation of the array. To increase the reliability of these devices, a third generation of micromirror arrays composed of 64 x 32 micromirrors is under development. This generation was especially designed for individual actuation of each mirror, applying a line-column algorithm based on the electrostatic hysteresis of the actuator. The fabrication process is now based on multiple wafer level bonding steps and investigation was performed to reduce the short-circuit failure. This third generation of micromirror array will be fully characterized and tested in a cryogenic environment.

7931-02, Session 2

**Development of an enhanced adaptive optics system for the Lick Observatory Shane 3-meter telescope**

D. T. Gavel, Univ. of California Observatories (United States)

We present our plans for a second-generation laser guide star adaptive optics system for the 3-meter Shane Telescope at Lick Observatory. The Shane hosted the first groundbreaking experiments in sodium laser guidestar adaptive optics, with observations starting in 1986, and provides for regular astronomical science observing to this day. The replacement new generation system will incorporate many of the recent advancements in AO technology and lessons learned from laboratory and on-sky experiments in order to provide higher Strehl, higher sensitivity, and greater wavelength coverage for astronomers. The proposed system uses a 32x32 actuator MEMS deformable mirror, along with higher sensitivity wavefront sensor, and a new fiber laser developed at Lawrence Livermore National Laboratory. Our experiences from the Villages project, reported at earlier Photonics West meetings, provide much of the basis for the new system design.

7931-03, Session 2

**The use of a high-order MEMS deformable mirror in the Gemini Planet Imager**

L. A. Poyneer, B. A. Macintosh, Lawrence Livermore National Lab. (United States)

No abstract available.

7931-04, Session 2

**MEMS adaptive optics for horizontal turbulence correction**

S. R. Restaino, J. R. Andrews, T. Martinez, Air Force Research Lab. (United States); D. M. Payne, Narrascape, Inc. (United States); F. Santiago, C. C. Wilcox, Air Force Research Lab. (United States)

The Naval Research Laboratory is investigating the use of various miniaturized imaging spectrometer concept is presented. Typical state-of-the-art optical space spectrometer (for instance MERIS and SCIAMACHY aboard EnviSat and OMEGA on MarsExpress) payloads are based on one or several optical gratings to address the whole spectral range. These spectrometer instruments, typical for remote sensing, without the front optics (telescope, camera objective) have at least the size of a show box. The new proposed concept, essentially based on micro-nano technologies as well as optical MEMS, shrinks such spectrometers down to the size of a few computer chips. A very high integration level of various technologies and functionalities has been conceived while keeping the original top level performance requirements for remote sensing. The result is a concept of a fully integrated 2D mapping spectrometer on a chip placed in the focal plane of the front optics (camera objective, telescope). The working principle allows the new chip-device achieving a very high spectral resolution, as it is often required in remote sensing. This new device concept can therefore not only map a 2D image of a scene, as CMOS camera chips or CCD-chips do, but also deliver continuously a high resolution spectrum for each image pixel. Due to its generic characteristics it has the potential to be used also for airborne and commercial applications on ground. The conceptual design, fabrication aspects and performance limitations are discussed. An alternative conceptual design which is simpler to fabricate, but less compact, is also proposed.
Adaptive Optics (AO) techniques to mitigate the effects of atmospheric turbulence in imaging systems that are collecting imagery in marine and coastal environments. These cases present a different atmospheric turbulence regime. We have initiated a program to develop a realistic laboratory set-up for generating aberrations consistent with these regimes. In addition we are also evaluating the use of cascaded AO systems in order to mitigate both phase and amplitude fluctuations. In this paper we will describe the preliminary results of our test bed and some of the field test data that we use to corroborate the experimental set-up. The integration of MEMs in these testbeds will be highlighted and discussed.

7931-05, Session 2

Wide field of view retinal imaging one-micrometer adaptive optics scanning laser ophthalmoscope

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Wide field of view (FOV) and high resolution adaptive optics scanning laser ophthalmoscope (AOSLO) using one-micrometer probing beam was developed for quantitative analysis of retinal microstructures, namely photoreceptors, nerve fibers and micro-capillaries. Residual aberrations were measured by a Shack-Hartmann wavefront sensor (HASO32, Imagine Eyes) using a 840-nm beacon light source (Superlum) and corrected by a magnetic deformable mirror (Mirao52d, Imagine Eyes). The AO operated at 14.5 Hz closed loop. To obtain a wide FOV retinal image, several continuous regions on the retina were scanned with AOSLO. A patch of retina, which has a 1.49 degree by 1.86 degree FOV, was scanned by a 15 kHz resonant scanner and a 28.8 Hz galvanometric scanner. For wide FOV scanning, the offset of each scanner was changed to position the probing beam at neighboring regions. During post-processing, using an algorithm based on information entropy, unsuccessfully acquired AOSLO images were rejected. After the rejection, images were aligned to generate a wide FOV montage using a phase correlation based image registration algorithm. The right eye of a healthy subject was examined. A wide FOV retinal image with a dimension of 3 degree by 4.5 degree was obtained in 1.39 s. In conclusion, our AOSLO provides wide FOV and high resolution retinal imaging. This is useful for quantitative analysis of retinal microstructures.

7931-06, Session 3

Novel unimorph deformable mirror with monolithic tip-tilt functionality for solid state lasers

S. Verpoort, U. Wittrock, Fachhochschule Münster (Germany)

We present a new type of unimorph deformable mirror with monolithic tip-tilt functionality. The tip-tilt actuation is based on a spiral arm design. The mirror is dedicated to be used in high power lasers. The mirror is manufactured from a superpolished glass substrate with very low surface scattering and excellent coating. At the conference, we will present the achievable surface deformations and the power handling capability of this mirror.

7931-07, Session 3

MEMS DM development at Iris AO, Inc.

M. A. Helmbrecht, M. He, C. Kempf, M. Besse, Iris AO, Inc. (United States)

Iris AO is actively developing MEMS DMs and adaptive optics controllers for these DMs. This paper will discuss ongoing research at Iris AO that advances the state-of-the-art for these devices and systems. Areas to be described are: 1) efforts in scaling the technology to larger actuator counts; 2) development and testing DMs with dielectric coatings; 3) testing of snap-in prevention devices; 4) increases in DM response speed and update rates; 5) improved packaging, and 6) a DSP-based, standalone AO controller geared for industrial and life-sciences applications.

7931-08, Session 3

Recent developments and future challenges for MEMS adaptive optics

F. Rooms, ALPAO (France)

The MEMS deformable mirror (DM) performances have been dramatically increased during the last years. Although adaptive optics has the potential to address many optical problems faced by engineers and scientists, it has not yet reached all domains of applications that it might reach. In this article, I will focus on three points:
1. Summarize the latest MEMS DM developments
2. Present the trade-off between the different parameters of the adaptive optics
3. Highlight some key points needed to successfully address future applications of adaptive optics.

7931-09, Session 4

High-stroke monolithic gold MEMS deformable mirror for adaptive optics

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Adaptive optics for the next generation of extremely large telescopes (30-50 meter diameter primary mirrors) requires high-stroke (10 microns), high-order (100x100) deformable mirrors at lower-cost than current technology. Lowering the cost while improving the performance of deformable mirrors is possible using Micro-Electro-Mechanical Systems (MEMS) technology. In this paper the fabrication and testing of an array of high-stroke gold MEMS X-beam actuators attached to a continuous gold facesheet will be described. Both the actuator and the facesheet were fabricated monolithically in gold plated onto a thermally matched ceramic-glass substrate (WMS-15) using a high-aspect ratio fabrication process. The results of the monolithic fabrication process will be compared with a fabrication process that required bonding of two wafers to create a deformable mirror consisting of a continuous membrane attached to an array of actuators.

7931-10, Session 4

Tunable refractive beam steering using aluminum nitride thermal actuators

S. Leopold, D. Paetz, Technische Univ. Ilmenau (Germany); F. Knöbber, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); T. Polster, Technische Univ. Ilmenau (Germany); O. Ambacher, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany); S. Sinzinger, M. Hoffmann, Technische Univ. Ilmenau (Germany)
Tunable refractive beam steering elements potentially improve the resolution and efficiency of compound eye cameras [1]. Additionally, a tunable prism increases the field of view of e.g. of fibre-optic endoscopes [2].

So far, only a few approaches for the implementation of tunable micromirrors using electrowetting on dielectrics have been discussed. In this case a liquid surface is modified by applying a voltage. Often, a passive plate is introduced, in order to achieve a flat meniscus and appropriate image quality [2, 3, 4].

We present novel adaptive tilting plate actuators, which can be easily fabricated in miniaturized and arrayed systems. Optical beam steering is possible if the cavity between these tilting plates and a second flat surface is filled with a transparent liquid or gel. The plate is mounted between step-structured thermal actuators [5, 6]. Both, the plate and the actuators are made of sputtered aluminum nitride, since it offers mechanical stability, suitable optical properties and high thermal conductivity. Hence high tuning speed, compared to SO2 and polymers, is possible. Since the actuators are not in contact to the liquid, high temperatures and thus large static tilting angles up to 10° can be achieved.

Sputtering evolves a stress gradient in aluminum nitride, we present a manufacturing technology including stress compensation. Numerical and analytical optimizations of the geometry for two types of actuator are discussed. The results are verified in a parametric study. Furthermore, the flatness of the tilting plate is measured. Finally, optical experiments, considering steering angle and image quality are presented.

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7931-11, Session 5
A multi-conjugate adaptive optics testbed using two MEMS deformable mirrors
J. R. Andrews, T. Martinez, U.S. Naval Research Lab. (United States); S. W. Teare, New Mexico Institute of Mining and Technology (United States); S. R. Restaino, C. C. Wilcox, F. Santiago, U.S. Naval Research Lab. (United States); D. M. Payne, Narrascape, Inc. (United States)

Adaptive optics (AO) systems are well demonstrated in the literature with both laboratory and real-world systems being developed. Some of these systems have employed MEMS deformable mirrors as their active corrective element. More recent work in AO for astronomical applications has focused on providing correction in more than one conjugate plane. Additionally, horizontal path AO systems are exploring correction in multiple conjugate planes. This provides challenges for a laboratory system as the aberrations need to be generated and corrected in more than one plane in the optical system. Our work with compact AO systems employing MEMS technology in addition to liquid crystal spatial light modulator (SLM) driven aberration generators has been scaled up to a two conjugate plane testbed. Using two SLM based aberration generators and two separate wavefront sensors, the system can apply correction with two MEMS deformable mirrors. The challenges in such a system are to properly match non-identical components and weight the correction algorithm for correcting in two planes. This paper demonstrates preliminary results and analysis with this system with wavefront data and residual error measurements.

7931-12, Session 5
Polymorphic optical zoom with MEMS DMs
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The availability of compact, affordable deformable mirrors (DMs) makes it possible to explore alternatives to conventional optical configurations for zoom, focus and aberration compensation. In particular, it is possible to create a system capable of high-speed optical zoom without translation of components. In this paper we describe experiments conducted with two DMs at fixed locations in an optical microscope imaging system with 2.5X zoom capability. Zoom is achieved by simultaneously adjusting focal lengths of the two DMs, which are inserted between an infinity-corrected microscope objective and a tube lens. In addition to zoom, the test system is capable of automated fine focus control and adaptive aberration compensation. Image quality is measured using contrast modulation measurement, and performance of the system is quantified.

7931-14, Session 6
Implementation of adaptive optics in beam scanning and widefield optical microscopy
J. M. Girkin, Durham Univ. (United Kingdom)

It has now been widely demonstrated that adaptive optics can play a significant role in improving the image quality obtained in optical microscopes, in particular imaging deeply into biological samples. Although there are differences in the challenge of overcoming aberrations in optical microscopy and astronomy, for example effects are generally less dynamic in microscopy; there is a commonality in having to determine the shape to be placed on the adaptive optic element. The common method in astronomy, of using a high power laser guide star, is not an option in a microscope as sample damage is a significant complication! However, the use of image based metrics has proved to be a rapid way of determining the best mirror shape to use, in particularly in widefield camera based imaging systems. Different metrics, however, are suitable for different forms of image and selecting the most appropriate method can have a significant effect on the performance of the AO system.

This presentation will review the in-depth imaging challenge and then present results on different approaches to determining the mirror shape and real-time closed loop control of AO in microscopy. Results will be given for both widefield and beam scanned systems and in particular to the speed of mirror control and how unwanted effects can be minimised through the correct choice of algorithm.

7931-15, Session 6
Coherence gated wavefront sensing in highly scattering tissue
J. R. H. Binding, Ecole Supérieure de Physique et de Chimie Industrielles (France) and Neuroscience Section, IBEns, Paris (France) and Max-Planck-Institut für medizinische Forschung (Germany); M. Roth, S. Gigan, Ecole Supérieure de Physique et de Chimie Industrielles (France); M. Rückel, Max-Planck-Institut für medizinische Forschung (Germany) and BASF SE,
Coherence gated wavefront sensing (CGWS) has been shown to allow wavefront measurement in moderately scattering samples such as zebrafish larva (1). Compared to image-based wavefront determination schemes such as modal wavefront sensing (2) or pupil segmentation (3), CGWS has the advantage of using only backscattered light for wavefront measurement. All aberration modes are determined simultaneously - their number does not influence the amount of data that needs to be taken, apart from spatial sampling and signal-to-noise considerations. Coherence gated wavefront sensing is therefore ideal for systems where bleaching of fluorescence is a problem and/or where a large number of aberration modes need to be determined, barring lengthy optimization schemes.

In highly scattering samples such as cortical slices of the rat brain, coherence gated wavefront sensing has not been successful so far due to multiple scattering. Speckle size decreased too rapidly with penetration depth to allow determination of the backscattered wavefront. Here we present a coherence gated wavefront sensing setup using a Linnik interferometer for dispersion correction and a 20nm spectral bandwidth light source to minimize the coherence length and maximize speckle size. Together with a carefully adjusted aperture conjugated to the objective focus which blocks some of the multiply scattered light without spatially filtering the wavefront, we are able to present the first direct wavefront measurements in the rat cortex.

REFERENCES

7931-16, Session 6
Aberration correction in harmonic generation microscopy
A. Jesacher, Innsbruck Medical Univ. (Austria); A. Thayil, T. Watanabe, T. Wilson, S. Srinivas, M. J. Booth, Univ. of Oxford (United Kingdom)

In harmonic generation microscopy, the sample is scanned with a focused short-pulsed laser beam and the second and/or third harmonic signal which is generated by the specimen is collected. Although the wavelength of the scanning beam can be in the near infrared, which implies a large penetration depth and low scattering, aberrations introduced by imperfect optics and specimen inhomogeneity can have a large effect on image brightness, contrast and resolution. This is due to the distortion of the focal spot and the nonlinear dependence of the generated signal on the intensity. These effects are especially problematic in live cell imaging, where specimens can be highly vulnerable to laser exposure and a loss of signal cannot be compensated by increasing the laser intensity. In such cases, aberration correction can be a valuable tool for bio-imaging.

We show how aberrations in a harmonic generation microscope can be measured and corrected using modal wavefront sensing and a deformable mirror, which is integrated into the optical path of the microscope. We present results obtained from short- and long-term imaging of live mouse embryos.
imaging through 100 micrometer of tissue. The results also show that
the isoplanatic half-width is approximately 19 micrometer resulting in a
corrected field of view 38 micrometer in diameter around the guide-star.

7931-20, Session 6

Adaptive optics in wide-field microscopy

P. A. Kner, The Univ. of Georgia (United States)

Live imaging in cell biology requires three-dimensional data acquisition
with the best resolution and signal-to-noise ratio (SNR) possible. A recent
comprehensive study of several fluorescent microscope technologies
shows that wide-field microscopy is the most sensitive technique for
low-scattering samples. Here we discuss the use of adaptive optics in
wide-field microscopy to improve resolution and SNR by correcting for
the optical aberrations caused by the refractive index mismatch between
the sample and immersion medium (depth aberration) and by the
variations in index in the sample itself (sample-induced aberrations). We
have built a microscope that uses open-loop adaptive optics to correct
the depth aberration. Imaging fluorescent beads in water and glycerol we
demonstrate a corrected point spread function and a 2-fold improvement
in signal intensity. With the same microscope, we have used phase
retrieval to determine aberrations, allowing closed loop correction without
a wavefront sensor. Starting from a severely aberrated system, we
achieve a greater than 10-fold increase in peak intensity.

7931-21, Session 6

Adaptive optics confocal fluorescence microscopy with direct wavefront sensing for
brain tissue imaging

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States); D. C. Chen, Lawrence Livermore National Lab. (United
States); O. A. Azucena, M. Fu, Y. Zuo, J. Kubby, Univ. of
California, Santa Cruz (United States)

Recently, there has been a growing interest in deep tissue imaging for
the study of neurons. For imaging of the long dendrite and tiny dendritic
spines, high-resolution fluorescence imaging deep within brain tissue
is required. Unfortunately, because of the inhomogeneous refractive
index of the tissue, the aberrations in both the excitation and emission
light degrades the resolution and brightness of the final image. Although
different Adaptive Optics (AO) systems have been realized to correct
these aberrations, most of these systems have used optimization
algorithms to estimate the correction parameter. The time required for
image optimization could be a limiting factor for live imaging and could
lead to photo-bleaching and photodynamic damage of the sample.

In this paper, we describe a confocal fluorescence microscope with
adaptive optics which can correct aberrations based on direct wavefront
measurements using a point source reference beacon and a Shack-
Hartmann Wavefront Sensor (SHWS). In order to measure the wavefront
directly, fluorescent microspheres with a diameter of 1μm were injected
into the mouse brain tissue. These microspheres were used as reference
beacons for the adaptive AO system, similar to the artificial guide stars
used in astronomical AO systems. The microsphere is excited by a
HeNe laser (633nm). The emission from the microsphere goes through a
filter, which blocks the emission from the tissue, and is finally collected
by a SHWS comprised of a lenslet array focused on a cooled CCD
camera. The control signal for the deformable mirror is calculated based
on the estimated wavefront error from the SHWS. In the experiment,
mouse brain tissues with different thicknesses are placed on top of the
microsphere reference beacon to test the proposed AO system. The
neurons were marked by the transgenic expression of yellow fluorescent
protein (YFP). The RMS wavefront error measured by the SHWS before
correction at 100μm beneath the surface is 0.089μm. After correction, the
near diffraction limited image is achieved. The signal intensity increased
by 63% and the Strehl ratio by 70% after correction.
7932-01, Session 1

Assessment of renal oxygenation during partial nephrectomy using DLP® hyperspectral imaging

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Introduction

Digital Light Processing (DLP®) hyperspectral imaging (HSI) is a non-invasive method used to construct a highly sensitive, real-time tissue oxygenation map. This near video-rate technology can be used to monitor perfusion/oxygenation of the kidney during surgery. Here, we assessed baseline renal oxygenation parameters during open partial nephrectomy (PN) for kidney tumors.

Methods

HSI was used in 19 patients [mean age 55, (29-77)] undergoing PN for renal tumors. Kidneys were actively illuminated with visible light (520 to 645nm) consisting of a novel predetermined spectral illumination method. Reflectance images are captured by a focal plane array and digitally processed visualizing the percentage of oxyhemoglobin (%HbO2) at each image pixel.

Results

HSI was used in 19 patients undergoing PN for renal tumors. Kidneys were actively illuminated with visible light (520 to 645nm) consisting of a novel predetermined spectral illumination method. Reflectance images are captured by a focal plane array and digitally processed visualizing the percentage of oxyhemoglobin (%HbO2) at each image pixel.

Conclusion

HSI serves as a non-invasive method to assess renal HbO2 saturation intraoperatively. Nadir %HbO2 levels are reached within 11 minutes of initiation of ischemia. This knowledge may allow for future surgical interventions that maintain some degree of renal perfusion/oxygenation using real time assessment of %HbO2 levels. The high speed of image acquisition achieved by combining DLP with HSI is particularly useful in this type of surgery, where minimizing the duration of ischemia is critical to protecting kidney function.

7932-03, Session 1

NIR DLP® hyperspectral imaging system for medical applications

E. F. Wehner, A. Thapa, The Univ. of Texas at Arlington (United States); E. Livingston, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States); K. J. Zuzak, The Univ. of Texas at Arlington (United States) and Digital Light Innovations (United States)

DLP® hyperspectral reflectance imaging in the visible range has been previously shown to quantify hemoglobin oxygenation in subsurface tissues, 1 mm to 2 mm deep. Extending the spectral range into the near infrared reflects biochemical information from deeper subsurface tissues. Unlike any other illumination method, the digital micro-mirror device, DMD, chip is programmable, allowing the user to actively illuminate with precisely predetermined spectra of illumination with a minimum bandpass of approximately 10 nm. It is possible to construct active spectral-based illumination that extends from the visible light range into the NIR (525 nm to 1050 nm) and was configured and tested in several medical applications. The mid-range system can be used to quantify tissue edema in real time, map blood perfusion up to 1 cm deep, enhancing a surgeon’s ability to monitor tissue and prevent tissue necrosis during reconstructive surgery, and after indocyanine green (ICG) fluorophore lymphatic injection, help surgeons locate the large lymphatics of the upper and lower extremities, reducing post-operative complications.

Visible DLP® hyperspectral reflectance imaging in medical applications is limited by the fact that visible light penetrates only about 1 mm of soft tissue. The longer, near infrared wavelengths can penetrate deeper, facilitating biochemical visualization from deeper vessels and tissues. DMD chips allow for programming the light output to contain precisely shaped, simple to complex spectral illumination with spectrally resolved bandwidths as small as 7 nm. Fluorescence can be maximized by programming the DMD chip to illuminate with light precisely configured to contain excitation spectra. We have developed a “mid-range” system that extends from the visible light range into the NIR (525 nm to 1050 nm) and was configured and tested in several medical applications. The mid-range system can be used to quantify tissue edema in real time, map blood perfusion up to 1 cm deep, enhancing a surgeon’s ability to monitor tissue and prevent tissue necrosis during reconstructive surgery, and after indocyanine green (ICG) fluorophore lymphatic injection, help surgeons locate the large lymphatics of the upper and lower extremities, reducing post-operative complications.

7932-02, Session 1

Visible to NIR DLP® hyperspectral imaging system for surgical utility using inherent chromophores and fluorescent probes

M. Mangum, The Univ. of Texas at Arlington (United States); M. Saint-Cyr, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States); E. F. Wehner, University of Texas at Arlington (United States); A. Thapa, The Univ. of Texas at Arlington (United States); E. Livingston, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States); K. J. Zuzak, The Univ. of Texas at Arlington (United States) and Digital Light Innovations (United States)

Visible to NIR DLP® hyperspectral imaging is a non-invasive method used to construct a highly sensitive, real-time tissue oxygenation map. This near video-rate technology can be used to monitor perfusion/oxygenation of the kidney during surgery. Here, we assessed baseline renal oxygenation parameters during open partial nephrectomy (PN) for kidney tumors.

Methods

Visible DLP® hyperspectral reflectance imaging in medical applications is limited by the fact that visible light penetrates only about 1 mm of soft tissue. The longer, near infrared wavelengths can penetrate deeper, facilitating biochemical visualization from deeper vessels and tissues. DMD chips allow for programming the light output to contain precisely shaped, simple to complex spectral illumination with spectrally resolved bandwidths as small as 7 nm. Fluorescence can be maximized by programming the DMD chip to illuminate with light precisely configured to contain excitation spectra. We have developed a “mid-range” system that extends from the visible light range into the NIR (525 nm to 1050 nm) and was configured and tested in several medical applications. The mid-range system can be used to quantify tissue edema in real time, map blood perfusion up to 1 cm deep, enhancing a surgeon’s ability to monitor tissue and prevent tissue necrosis during reconstructive surgery, and after indocyanine green (ICG) fluorophore lymphatic injection, help surgeons locate the large lymphatics of the upper and lower extremities, reducing post-operative complications.

7932-04, Session 1

An examination of spectral diversity of medical scenes for hyperspectral projection

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There are numerous medical conditions which may benefit from hyperspectral imaging. The imagers used for these conditions will need to have the performance validated to ensure consistency, gain acceptance and clear regulatory hurdles. NIST has been developing a DLP based Hyperspectral Image Projector (HIP) for providing scenes with full spectral content in order to evaluate multispectral and hyperspectral imagers. In order for the scene to be projected, a dimensionality reduction is performed in order to project spectral endmembers efficiently. The number of spectral endmembers needed to best represent a scene is an important part in the recombinimg of the image. This paper studies the spectral diversity within and between different medical scenes collected by a DLP based hyperspectral imager. Knowledge gained from this study will help guide the methods used for Hyperspectral Image Projection of medical scenes in the future.

7932-05, Session 1
Hyperspectral retinal imaging with a spectrally tunable light source
R. P. Francis, Raytheon ELCAN Optical Technologies (United States); K. J. Zuzak, The Univ. of Texas at Arlington (United States) and Digital Light Innovations (United States); R. Ufret-Vincenty, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States)

Hyperspectral retinal imaging can measure oxygenation and identify areas of ischemia in human patients, but the devices used by current researchers are inflexible in spatial and spectral resolution. We have developed a flexible research prototype consisting of a DLP®-based spectrally tunable light source coupled to an ocular fundus camera to quickly explore the effects of spatial resolution, spectral resolution, and spectral range on hyperspectral imaging of the retina. The goal of this prototype is to (1) identify spectral and spatial regions of interest for early diagnosis of diseases such as glaucoma, age-related macular degeneration (AMD), and diabetic retinopathy (DR); and (2) define required specifications for commercial products. In this paper, we describe the challenges and advantages of using a spectrally tunable light source for hyperspectral retinal imaging, present clinical results of initial imaging sessions, and describe how this research can be leveraged into specifying a commercial product.

7932-06, Session 2
Maskless lithography for high speed digital printing of printed circuit boards
E. J. Hansotte, W. D. Meisburger, Maskless Lithography (United States)

The printed circuit board (PCB) industry has long used a lithography process based on a polymer mask in contact with a large, resist-coated substrate. There is a limit to this technique, however, as large area PCB substrates undergo distortion during fabrication that makes high resolution or tight registration between layers difficult. In the last several years the industry has increasingly turned to digital lithography techniques which, in addition to eliminating the contact mask, can compensate for layer distortions. Currently, the most widespread digital lithography technique for PCB is laser direct imaging (LDI), whereby a laser is raster scanned over the entire substrate to expose it. This method is slow, however, and at current state of the art can not provide the high throughput to which the industry is accustomed with traditional contact mask lithography. A digital micro-mirror device (DMD), however, offers a much higher speed alternative by addressing several areas of the substrate in parallel. Multiple aerial images of separate DMDs are projected across the plane of the substrate while it is rapidly scanned beneath them. The frame rate of the DMD device is synchronized with the scanning speed in such a way that a single point on the substrate, as it passes under the projected image, receives a separate dose from each of the projected DMD pixels in a column along the scan direction. In addition to achieving high speed, this scheme also allows for the implementation of a technique called gray level imaging (GLI), whereby the positioning accuracy of features is a very small fraction of the pixel size itself. Since the DMD mirrors have only two states (ON/OFF), gray level is achieved by activating greater or fewer numbers of mirrors in a column as a point on the substrate passes under their projected pixel images. In this embodiment, the multiple projected images are staggered by the width of one DMD image. Their number and size are chosen so that the entire PCB substrate can be exposed conveniently with two interlaced, forward and back scans. Other embodiments may use projection optics of different magnifications in order to achieve smaller pixel sizes and higher resolution. Also in this embodiment, each projection “channel” uses a short arc mercury arc lamp for it’s light source, which is integrated through a rectangular integrating rod and projected onto the DMD in a “light engine” that is similar to those used in commercial DLP® projectors. The method has the further flexibility of being able to use other broad band light sources such as Xe arc lamps, or even recent high power LEDs, which can be synchronized with the DMD frames for additional functionality.

7932-07, Session 2
High-precision beam shaper for coherent and incoherent light using DLP® spatial light modulator
J. Liang, R. N. Kohn, Jr., M. F. Becker, D. J. Heinzen, The Univ. of Texas at Austin (United States)

Beam-shaping techniques are essential for creating controlled profiles for real-world lasers and optical sources. Our interest in atomic physics is to form optical standing-wave lattices for quantum emulators using Bose-Einstein Condensates. We designed a precision laser beam shaper using a Texas Instrument digital micromirror device (DMD) with a telescope system containing a pinhole low-pass filter. The performance of a beam shaper can be determined by the intensity and wave-front uniformity compared to the target function and by energy conversion efficiency. We demonstrated flat-top and other beam profiles with 1-1.5% root-mean-square (RMS) error for a raw camera image and nearly flat phase. A noise analysis of the system revealed that lower error is possible and that most of the variance came from coherent speckle noise in the camera. An experiment using a 1064 nm laser produced around 7% beam power conversion efficiency. A mismatch between the blaze angle and diffraction order angle contributed to this significant energy loss. These observations motivate the implementation of an incoherent light source in order to approach the ultimate performance of the shaper. Simulations were conducted to determine the optimized wavelengths for different types of DMDs. For the .7XGA DMD, the 6th diffraction order matches 750-800 nm. We propose to use a 750 nm super-luminescent light emitting diode (SLED) as the light source. With a matched input wavelength, this SLED should significantly enhance the diffraction efficiency. Moreover, it should greatly reduce the speckle noise induced by a coherent source and improve intensity uniformity in a measurement camera.

7932-08, Session 2
Novel emissive projection display on transparent and black screens
T. Sun, SuperImaging Inc. (United States)

An innovative emissive projection display system was recently invented in Superimaging. It comprises of a fully transparent fluorescent screen, with a UV image projector. The screen can be applied to glass windows or windshield, without affecting visible light transmission. The UV projector can be based on either a DLP (digital light processor) or a laser scanner display engine. For DLP based projector, a discharge lamp coupled to a
In this paper, we provide an overview of recent advances in 3D surface and to understand the complexity of real world objects.

This display combines the best of both world from conventional projection and emissive display technologies. Like projection display, the screen has no pixel structure and can be manufactured roll to roll; the display is scalable. Like emissive display (e.g. plasma or CRT), the quality of the image is superior, with very large viewing angles. It also offers some unique features, for example, in addition to a fully transparent display on windows or windshields, it can be applied to a black substrate, for the first front projection display on true “black” screen, with superior image contrast at low projection power. This fundamentally new display platform can enable multiple major commercial applications that can’t be addressed by any of the existing display technologies.

7932-09, Session 2
Successful evaluation for space applications of the 2048x1080 DMD
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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 are engaged in an ESA study for a technical assessment of using a DMD from Texas Instruments for space applications (for example in ESA EUCLID mission). The DMD features 2048 x 1080 mirrors on a 13.68μm pitch, where each mirror can be independently switched between an ON (+12°) position and an OFF (-12°) position. For MOS applications in space, the device should work in vacuum, at low temperature, and each MOS exposure would last for typically 1500s with micromirrors held in a static state (either ON or OFF). A specific thermal/vacuum test chamber has been developed for test conditions down to -40°C at 10-5 mbar vacuum. Imaging capability for resolving each micromirror has also been developed for determining degradation in any single mirror. Our tests reveal that the DMD remains fully operational at -40°C and in vacuum. A 1038 hours life test in space conditions, Total Ionizing Dose radiation, thermal cycling and vibrations/shocks have also been successfully completed. These results do not reveal any concerns regarding the ability of the DMD to meet environmental space requirements.

We have also developed a bench for MOS demonstration using MOEMS devices. DMD chip has been successfully tested revealing good contrast values as well as good functionality for applying any mask pattern, demonstrating its full ability for space instrumentation, especially in multi-object spectroscopy applications.

7932-10, Session 3
Overview of 3D surface measurement technologies and applications: opportunities for DLP®-based structured illumination
J. Geng, IEEE Intelligent Transportation Systems Society (United States)

Physical world around us is three-dimensional (3D), yet traditional cameras and imaging sensors are only able to acquire two-dimensional (2D) images that lack the third dimension (depth) information. This fundamental restriction greatly limits human being’s ability to perceive and to understand the complexity of real world objects.

In this paper, we provide an overview of recent advances in 3D surface measurement technologies. Performance index is discussed and various 3D surface imaging schemes are categorized, illustrated, and compared. Numerous applications of 3D technologies are discussed with several examples.

We focus particularly on these non-contact 3D surface measurement techniques that require structured illumination. The high speed and high resolution pattern projection capability offered by the DLP technology, together with the recent advent of imaging sensor technologies, may enable new generation systems for 3D surface measurement applications that provide much better functionality and performance than existing ones, in terms of speed, accuracy, resolution, modularization, and ease of use.

7932-11, Session 3
Non-contact, 3D fingerprint scanner using structured light illumination
M. Troy, Flashscan3D LLC (United States); L. Hassebrook, Univ. of Kentucky (United States); V. Yalla, R. Daley, Flashscan3D LLC (United States)

As crime prevention and national security remain a top priority, requirements for the use of fingerprints for identification continue to grow. However, as the size of fingerprint databases continues to expand, new technologies that can improve accuracy and ultimately matching rates will become more critical to maintain the effectiveness of the systems. FlashScan3D has developed a non-contact, fingerprint scanner based on the principles of Structured Light Illumination (SLI) that capture 3-dimensional data of fingerprints and quickly, accurately and independently of an operator. For fingerprint scanning, it is especially advantageous because it is an inherently non-contact technique and scalable, being able to scan a field of view as small as a single finger or as large as the complete hand. Unlike the current generation of 2-D scanners that acquire a 2-D representation of a 3-D object, our system makes quantitative 3-D surface measurements that reveal actual ridge shape and depth. The result is an extremely high quality image that when converted to 2-D yields better image quality, minutiae detection and matching results. FlashScan3D will present findings from various research projects performed for the US Army and the Department of Homeland Security.

7932-12, Session 3
DLP®/DSP-based optical 3D-sensors for the mass market in industrial metrology and life sciences
G. J. Frankowski, GFMesstechnik GmbH (Germany)

For a long time GFM has developed and constructed DLP-based optical 3D measuring devices based on structured light illumination. Over the years the measuring devices have been used in industrial metrology and life sciences for different 3D measuring tasks.

In the lecture will be presented and discussed the possibilities of integration the DLP Pico technology and the DSP technology from Texas Instruments for optical 3D sensors for a mass market. In comparison to the point and/or line scan working laser triangulation sensors, frequently used at the moment for the mass market, the new 3D sensors provide a full-field measurement of up to million points less than a second.

Further in the lecture will be presented and discussed different fields of application and advantages of the new generation of 3D sensors for:
- OEM application in industrial measuring and inspection;
- 3D metrology in industry, life sciences and biometrics;
- Industrial image processing.
3D metrology system using an active triangulation with high dynamic range
D. Härter, C. Müller, H. Reinecke, Albert-Ludwigs-Univ. Freiburg (Germany)

We build up a new type of 3D metrology system for measuring the three-dimensional shape of micro-structures and for reverse engineering. The measurement principle is active triangulation with a high dynamic range. The optical imaging is done by a stereomicroscope. This features fields of view from some square-centimeters down to square-millimeters at a constant triangulation angle and furthermore a very rigid construction. Due to working with different magnifications and examining surfaces with particular properties, the size and the spacing of projected measurement labels has to be adaptable.

Using a digital mirror device (DMD) the generation of user definable patterns is very quick and flexible. Furthermore the DMD features high brightness and contrasts values. This is important to distinguish projected measurement labels.

The DMD is illuminated by a collimated high power LED. The generated patterns are coupled to one port of the stereomicroscope. The positions of projected measurement labels are localized by a camera through a second port. The measurement system localizes the positions of measurement labels and assigns them to three-dimensional coordinates. During a measurement as many measurement labels as possible should be visible in the camera image. Therefore the acquisition of measurement data from bright and dark surface areas requires a high dynamic range.

To identify the measurement labels a temporal coding is used. This enables the adaption of the brightness for each measurement label in the projection pattern. As a result the dynamic of the measurement system is expanded by the dynamic of the projection device.

3D triangulation system based on out-of-axis aperture configuration for micro-scaled objects shape measurement
E. Dupont, F. Lamarque, C. Prelle, Univ. de Technologie Compiègne (France); T. Redarce, Institut National des Sciences Appliquées de Lyon (France)

In three-dimensional (3-D) measurement systems based on triangulation, a stereoscopic angle between two distinct viewpoints encodes the depth information. This angle generally generates some distortion known as keystone distortion. In this paper an original 3-D optical configuration in addition with a digital light processing system (DLP) is presented which prevents keystone distortion, resulting in less calibration and post-processing work. The DLP is used to project incoherent white light fringes pattern at high frame rate (30 Hz) on a specimen and a CCD camera dynamically captures this projected pattern. Using a phase shifting algorithm, the reconstruction of the 3-D shape of the specimen is finally computed.

This optical configuration is based on an « out of axis » aperture method combined with an afocal design for both projection and acquisition. With the combination of these two properties, the stereoscopic effect is obtained without any active distortion and a unique objective lens instead of two in a classical 3-D measurement system is used. As a result of this unique objective lens, the global volume of the measurement device can be easily minimized.

This system was designed with the optical software Zemax-EE to limit geometric and chromatic aberrations and to control the diffraction effect. Under this software, we obtain a depth resolution value around 20 μm for a scanned area of 4mm x 3mm. Experiments showed that high surface profile accuracy can be obtained on a variety of surfaces, allowing reverse engineering on micro-scaled objects or precise 3-D measurements of macro-scaled objects.

A novel programmable array microscope (PAM) with digital micro-mirror device (DD)
P. A. A. De Beule, Max-Planck-Institut für biophysikalische Chemie (Germany) and International Iberian Nanotechnology Lab. (Portugal); A. H. B. de Vries, J. D. Arndt-Jovin, T. M. Jovin, Max-Planck-Institut für biophysikalische Chemie (Germany)

We report progress on the construction of an optical sectioning microscope based on programmable array microscope (PAM) implemented with a digital micro-mirror device (DMD) spatial light modulator (SLM) utilized for both illumination and detection. The introduction of binary intensity modulation at the focal plane of a microscope objective in a computer controlled pixilated mode allows for the recovery of a confocal sectioned image. Illumination patterns can be changed very quickly, in contrast to static Nipkow disk or aperture correlation implementations, thereby creating an optical system that can be optimized to the optical setup in a convenient manner, e.g. for patterned photobleaching, photobleaching reduction, or spatial superresolution.

We present a Gen-3 dual path PAM setup2 incorporating the 25 KHz binary frame rate TI 1080p DMD and a newly developed optical system that offers diffusion limited imaging with compensation of tilt angle distortion. We compare the optical performance of the new system with that of a Gen-2 dual path PAM implemented with an LCoS SLM5.


Two-photon time-resolved confocal microscopy using a digital micromirror device
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In conventional confocal microscopy the excitation light is focused onto the sample. A Pinhole (diameter some 10 μm) is positioned in front of a detector in the conjugate focus of the fluorescent light emitted by the sample. This pinhole transmits only light back that is emitted from the focus of the excitation light. Therefore the signal-to-noise-ratio is reduced by blocking light from other than the focussed layer. To obtain a 3D-image of an object the focus-position is usually moved by scanning mirrors to rasterize the object. For confocal microscopy with micromirrors, a pinhole or a scan-device is not required. The excitation as well as the confocal filtering is realized by the DMD-array, with which all kinds of different measurement patterns can be generated. Due to multifocal setting and the high DMD-frequency (8000/s), a complete measurement layer can be imaged within a single frame of a CCD-camera.

When focused a short (100 fs) laser pulse can produce the non-linear two-photon-effect. The high energy-density yields to a high probability that two photons are absorbed simultaneously by one fluorescent molecule. Because two photons of 780 nm do have the same energy as one photon of 390 nm fluorescence is created only in the focus. This reduces bleaching of the fluorophore in the biological sample and yields to a longer observation period. The red excitation light also enhances the penetration depth compared to blue light. With this technique 4D visualization of dynamic processes in living cells is possible.
Development of a DMD-based compressive sampling hyperspectral imaging system (CS-HSI)

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We report the development of a Digital-Micromirror-Device (DMD)-based Compressive Sampling Hyperspectral Imaging (CS-HSI) system. A DMD is employed to modulate the intensity of optical images captured by an imaging lens. A relay-lens and a double-amici prism are used to form spectrally dispersed images on a CCD sensor array. Based on the dispersed images, numeric estimations of the 3-dimensional (3-D) spatial-spectral information of the optical image can be reconstructed by solving an optimization problem. The CS-HSI system acquires the 3-D spatial-spectral information in a snapshot. Therefore, the information-acquisition speed of the system only depends on the exposure settings and the shutter speed of the imaging lens. Conventional CS-HSI systems use a lithographically coated photomask to implement the CS measurement pattern, which does not provide the flexibility of changing the pattern during the system operation. The DMD-based hardware architecture offers that flexibility. It also enables us to implement a multi-shot information-acquisition scheme with the CS-HSI system, and in that case, multiple CS measurement patterns are used to modulate the intensity of the optical image. The multi-shot scheme provides the reconstruction algorithm with more information and thus it can potentially enhance the image-reconstruction speed and improve the reconstruction quality. In this work, we discuss the basic idea of the DMD-based CS-HSI system. We also introduce the fabrication and characterization process of a prototype system.

Spectral transmittance reflectance measurements utilizing a DLP®-based spectral source

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Spectral transmission and reflectance are critical parameters for the evaluation of pigments, textiles and coatings on a number of product surfaces including active displays. In this paper, we evaluate the usage of a DLP®-based spectral source as a tool in such observations noting its advantages in synthesizing not only individual band-passes but full continua present in nature. We discuss how such capabilities are advantages for determining product effectiveness in conditions of real world usage as well as its limitations and future objectives.