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2012 MOEMS-MEMS

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Conference 8248: Micromachining and Microfabrication Process Technology XVII

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8248-18, Poster Session

Electro-hydrodynamic printing using hole-type electrode

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Additive direct writing has many advantages compared with the subtractive conventional MEMS fabrication process. With its reduced manufacturing steps, the processing time is shortened and the overall process costs less. Also, the process is non-toxic and its flexibility in the manufacturing gives the capability to alter printing patterns promptly. Among many direct writing methods, electro-hydrodynamic (EHD) printing is also receiving a huge interest due to its capability of high resolution printing. However, there are still many issues to be resolved for the high volume fabrication process, such as the realization of multi-nozzle drop on demand system, etc.

In this work, high resolution EHD printing was demonstrated using a hole-type electrode with stainless steel nozzle to which the liquid is supplied from a constant pressure reservoir. With varying square voltage pulses between the nozzle and the electrode, three types of jet emission modes are observed; continuous mode, fine jet pulsating mode and droplet pulsating mode. Among these modes, the droplet pulsating mode and the fine jet pulsating mode were optimized to print relatively large patterns and high resolution patterns, respectively. In addition, to demonstrate near field printing for high position accuracy, EHD printing was carried out with a nozzle penetrating the hole-type electrode, so that the distance between nozzle tip and the substrate could be shortened.

8248-19, Poster Session

Laser-based microstructuring of material surfaces using low-cost microlens arrays

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Frictional interactions in microscopically small components are becoming increasingly important for the development of new products in electronics, life sciences, chemistry, sensors and by extension for all modern technology. We present a laser-based technique for micro-patterning surfaces of materials using low-cost microlens arrays. The used microlens were fabricated on soda-lime glass using a laser direct-write technique followed a thermal treatment into an oven. By combining a laser direct-write and the thermal treatment its was able to obtain high quality elements using a low cost infrared laser widely implemented in industry which make this technique attractive in comparison with other more expensive methods.

The main advantage of using microlens arrays is the possibility of fabricating a large number of identical structures simultaneously, leading to a highly efficient process. In order to study the capabilities of the microlens fabricated for microstructuring materials, identical structures and arrays of holes were fabricated over a variety of materials , such us, stainless steel, polymer and ceramic. The minimum diameter of the individual microstructure generated at surface is 3 µm. Different nanosecond lasers operating at Infrared, Green and UV were used. The topography and sizes of the elements obtained were determined using a confocal microscope SENSOFAR 2300 plm. The roughness was determined using a contact profilometer.

8248-20, Poster Session

Thermopower of various phases and states of Si at high pressure

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In the 1980s, silicon was suggested as mechanical material and Si-based devices have been called micro-electro-mechanical systems (MEMS) [1]. The strong “interplay” between the electronic and mechanical properties of Si [2], revealing particularly in “semiconductor-metal” phase transition occurring under micro-hardness measurements[2], is used in MEMS-devices[1]. In all Si-based devices the high local mechanical stresses may arise tending to phase transitions even at negligible loading [2]. The various phases of Si are registered usually by x-ray diffraction and Raman spectroscopy techniques [3]. In the present work the technique of high-pressure thermoelectric (TE) investigation has been developed for the phase transition recording at Si and the values of thermopower (S) for different phases of Si have been obtained.

The band structure calculations of several phases of Si were carried out using linear muffin-tin orbital’s method (LMTO). The technique of Raman scattering, as well as ultra-soft x-ray emission spectroscopy [2], have been used for control of both the initial and metastable states at ambient conditions. The TE method suggested allowed to record six various phases of Si at pressure range 0-25 GPa. The technique was shown also to be sensitive to all the pre-treatments applied to a sample including annealing, doping, and irradiation by high-energy particles. The experimental values of thermoelectric power of various phases of Si are compared with the theoretical estimations basing on the band structure calculations performed.

The TE properties of various phases and states of Si were established which may be potentially used in Si-based nano-thermoelectric devices [4]. The results of the investigation of thermoelectrical properties of Si seems to be relevant also due to recent progress in Si-based thermomechanical data storage systems [5]

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[1] M. Esashi, T. Ono, J. Phys. D: Appl. Phys. 2005, 38, R223-R230.

[2] S. V. Osyannikov, et. al., Solid State Communications 2004, 132, 8, 545-549.

[3] A. Mijica, A. Rubio, A. Munoz, R. J. Needs, Rev. Mod. Phys. 2003, 75, 863-912.

[4] A. I. Hochbaum, et.al., Nature 2008, 451, 163-167.

[5] G. Binnig, et.al., Appl. Phys. Lett. 1999, 74, 1329-1331

8248-01, Session 1

Optically transparent, flexible pressure sensor array micromachined utilizing plasma assisted bonding

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Traditional capacitive pressure sensors are constructed out of rigid materials such as silicon. Recent work to develop ultra-sensitive pressure sensors has explored the utilization of fluids as the sensing material since they are very susceptible to mechanical loads. In a prior work, a microfluidic network constructed out of polydimethlysiloxane (PDMS) is covalently bonded onto an oxide-rich, rigid substrate to housing an electrically conductive, non-evaporative ionic liquid limiting its application its application to planar measurements. There, the sensor utilizes the interfacial capacitance between this liquid and patterned transparent conductive oxide (TCO) and fluidic displacement amplification through careful design of the sensing chamber and sensing channel. This paper describes the development of an array of ultra-sensitive capacitive, pressure sensors which is constructed using both optically transparency and flexible materials. To achieve this goal, the effects of oxygen plasma are studied to bond the microfluidic network constructed out of polydimethlysiloxane (PDMS) and various flexible, plastic substrates showing improved adhesion properties. The dynamic range of the pressure sensor extends the dynamic range of the previous work by utilizing a long, meandered sensing channel achieving sensitivities on the order of 0.23nF/kPa. These pressure sensing elements have potential applications in lab-on-a-chip environments, biosensors, biophotonics and photonic switching.

8248-02, Session 1

Rotary MEMS comb-drive actuator with large deflection for photonic applications

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Rotary comb-drive electrostatic actuators with smooth vertical sidewalls have been designed and fabricated for photonic applications. Silicon on insulator (SOI) wafers with device layer thicknesses of up to 100 micron and oxide layers of 1-2 micron were used. Structures were fabricated through bulk micromachining of handle layer followed by removal of the buried oxide. Deep reactive ion etching (DRIE) of device layer resulted in defining the comb structure and releasing of the moving arm. Thick photoresist and oxide masking layers were used for the high aspect ratio deep etches. Nothching effects or depth variations of device layer were not observed. Etch/ passivation cycles in DRIE were optimized for smooth sidewalls. Traces of etch scallops were confined only in the first few microns of top and bottom edges of the reflecting sidewall. Movable arm length of 2 mm with a rotation of 3 degrees was achieved. The edge deflection was over 100 microns at 100 volts. The fabricated structure provides long reflecting sidewall that is accessible for hybrid integration in three dimensional space. The movable floating arm was found suitable for attachment of thinned external reflectors of mm dimensions. Structures were stable for operations in kilohertz range. Reflection of collimated light from coated sidewall was achieved. The rotary actuators were found suitable for applications in integrated external cavity lasers in mid infrared range. Tuning range over 100 nm is estimated in Littrow or Littman mode of operation for chip level configurations involving the fabricated comb-drive actuators.

8248-03, Session 1

A photovoltaic retinal prosthesis for restoring sight to the blind: fabrication and optoelectronic performance

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We have designed and fabricated a silicon photodiode array for use as a subretinal prosthesis aimed at restoring sight to patients who lost their photoreceptors due to retinal degeneration. The device operates in photovoltaic mode. Each pixel in the two-dimensional array independently converts pulsed infrared light into electrical current in order to stimulate remaining retinal neurons without a wired power connection. To enhance the maximum voltage and charge injection levels, each pixel contains three photodiodes connected in series. An active and return electrode in each pixel ensure localized current flow and are sputter coated with iridium oxide to provide high charge injection. The fabrication process consists of eight mask layers, and includes deep reactive ion etching, oxidation, and a polysilicon trench refill for in-pixel photodiode separation and isolation of adjacent pixels.

Three sizes of pixels (280um, 140um, and 70um) with active electrode diameters of 80um, 40um and 20um have been fabricated. The device layer thickness is 30um to allow subretinal implantation. On all three pixels sizes, the reverse-bias dark current is adequate for our application (10-100pA) and the reverse breakdown voltage is sufficiently high (>20V). The turn-on voltages of one-, two- and three series-connected photodiode structures are approximately 0.6V, 1.2V and 1.8V, respectively. The measured photo-responsivities at 880nm wavelength for large, medium and small pixels per diode are 0.33 A/W, 0.4 A/W and 0.36 A/W, at zero voltage bias. The measured photocurrent scales with exposed area (23uA, 5uA, 0.7uA for large, medium and small pixels at 6 mW/mm2 light intensity).

8248-04, Session 1

Micromachined edge illuminated optically transparent automotive light guide panels

R. A. Ronny, G. K. Knopf, The Univ. of Western Ontario (Canada); E. V. Bordatchev, M. Tauhiduzzaman, S. Nikumb, National Research Council Canada (Canada)

Edge-lit backlighting is used extensively for various small and medium-sized liquid crystal displays (LCDs). The shape, density and spatial distribution pattern of the micro-optical elements imprinted on the surface of the flat light-guide plate (LGP) are often "optimized" to improve the overall brightness and luminance uniformity. A similar concept can be used to develop interior convenience lighting panels and exterior tail lamps for automotive applications. However, costly diffusive sheeting and brightness enhancement films need not be considered for these applications because absolute luminance uniformity and the minimization of Moiré fringe effects are not significant factors in assessing quality of automotive lighting. A new design concept that involves micromachining cylindrical micro-optical elements on planar and curved light guide panels is described in this paper. The micro-optical element radius, density and spatial pattern imprinted on the optically transparent substrate are predetermined based on the size and shape of the light panel. The variable parameter that controls illumination over the active regions of the panel is the depth of the individual cylindrical micro-optical elements. The optical simulation tool "LightTools" is used to explore how changing the micro-optical element depth can alter the local and global luminance. Numerical simulation and microfabrication experiments are performed on several small 16mmx16mmx6mm polymethylmethacrylate (PMMA) test samples in order to verify luminance behavior. The proposed fabrication method involves direct micromilling the micro-optical elements onto optically transparent plastic substrates. A brief discussion on how the micromilling fabrication technique can be used to create curved light panels is also presented.

8248-06, Session 2

Fabrication of micro structures with continuous surface profiles and very large sag heights by laser lithography

J. Dunkel, F. Wippermann, A. Bräuer, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Laser lithography is a well-established method for the fabrication of diffractive optical elements or refractive freeform structures with continuous surface profiles with sag heights up to a few microns that can be produced with excellent surface accuracies. For high performance micro-optical imaging applications, e.g. the wafer level fabrication of compound eye cameras this is not sufficient. Micro-optical elements with continuous surface profiles and sag heights above 50 µm in combination with minimal profile errors are needed in high performance micro-optical imaging applications such as compound eye cameras. In the study the potential of a laser lithographic process for the fabrication of these elements is investigated. The presented lithographic process is based on the commercially available photo resist AZ 4562 and suitable for the fabrication of elements with continuous surface profiles and sag heights up to 60 µm. Fabrication imperfections due to nonlinearities in the photo resist response and the isotropic characteristic of the development process have been compensated by the adaption of the exposure data to minimize profile deviations. Therefore, an empirical process model is proposed which is based on experimentally determined development rates. The fabricated structures consist of a micro lens array with a sag height of 60 µm and a pitch of 400 µm. The achievable accuracy of the method and their limitations are discussed. The fabricated structures can be used as master structures for subsequent replication processes.

8248-07, Session 2

Design of experiment for the optimisation of deep reactive ion etching of silicon inserts for micro-fabrication

K. Wallis, J. R. Alcock, C. Shaw, Cranfield Univ. (United Kingdom)

The following paper describes the optimisation of deep reactive ion etching of pillar structures on a silicon wafer, to be used in the fabrication of nickel inserts for micro-injection moulding. This was achieved by using a design of experiments approach.

Undercuts occur when the pillar base has a smaller cross-section than the apex of the pillar. They therefore affect tolerances of the subsequent nickel mould, its strength and its demouldability from the silicon form.

The optimised output from these experiments was the degree of undercut of micro-scale pillars (10µm x 10µm x 40µm, 5µm x 5µm x 40µm and 2µm x 2µm x 40µm).

Three parameters were investigated for their effects on undercuts.

Effect of platen power: C4F8 gas flow during the passivation stage and switching times. Literature indicates that platen power is important in the control of etch rates. With regard to switching times: the ratio between the etching and passivation stages, literature indicates that the longer the etching stage in comparison to the passivation stage the higher the likelihood of undercuts to the features. Manufacturer's guidelines regarding C4F8 gas flow during the passivation stage note that an increase in the gas flow can produce a more positive etch profile, desirable when reducing the undercutting of features.

8248-08, Session 2

Impact of initial micro-geometry on the final roughness of laser micro-polished surfaces

M. Chow, The Univ. of Western Ontario (Canada); E. V. Bordatchev, National Research Council Canada (Canada); G. K. Knopf, The Univ. of Western Ontario (Canada)

Unlike conventional material removal polishing processes, laser micro-polishing (LµP) uses a Nd:YAG laser to melt a thin layer of material on the mechanically machined part surface. The micromilling operation used to create the initial part will inherently produce scallops, ridges and valleys as the rotating cutting tool traverses the surface. The negative impact of the surface roughness or "waviness" on part performance is greatly amplified as the dimensions of the machined structures are reduced to the micro-scale. In terms of laser micro-polishing, the molten material in the laser-material interaction zone will flow from the elevated maximum (peak) regions of the initial machined surface to the local minimum (valleys) due to surface tension. The flow of molten material is, however, a complex thermo-dynamic process influenced by the micro-geometries that exist on the initial surface. An experimental investigation into the impact of initial micro-geometry on the final polished surface roughness (Ra) is described in this paper. In the study, several samples of micromilled H13 tool steel are polished using a 1064nm, Q-switched Nd:YAG laser with a maximum power output of 18W and a pulse duration between 40nsec to 70nsec. The two dominant parameters affecting the quality of the finished surface were identified as the initial roughness and the lateral size of the micro-geometry feature (e.g. height and width of micromilled scallops). By adjusting process parameters, it was possible to reduce the Ra of a surface with 33µm scallop period from 733nm to 428nm, thereby improving the final surface quality by 41.5%.

8248-09, Session 2

Sidewall roughness reduction techniques for MOEMS following DRIE

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

Micro Opto Electro Mechanical Systems (MOEMS) utilize deep reactive ion etching (DRIE) process for fabrication of components with very high aspect ratios. The surfaces resulting from this process have high degree of roughness and are unsuitable for use as optical surfaces, due to high levels of diffraction from the scalloping and shower-curtain effects of the process. Secondary processes are needed to reduce the sidewall roughness. Traditional processes, such as sidewall oxidation and oxide stripping, and hydrogen anneal, might not be compatible with some devices. In this paper, we present detailed study on the scalloping defects dependence on the DRIE process parameters, shower curtain defect resulting from the mask edge roughness, and comparison of several methods used to reduce the defects. Low-temperature processes such as chemical etching with KOH and HNA, of various concentrations, are compared to high-temperature process of sidewall oxidation and oxide stripping. Effect of surface oxide film as a hard mask is investigated. The results of sidewall roughness are applied to Lamellar grating device, especially the reduction of noise and increase of sensitivity of the device.

8248-10, Session 3

Fabrication of microchannels in fused silica with femtosecond laser irradiation and hybrid chemical etching process

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Femtosecond laser irradiation and chemical etching (FLICE) technology has become a very useful tool in the field of Optofluidics for fabrication and integration of microfluidic channels with optical elements like waveguide circuits. The effectiveness of FLICE owes to its inherent capability of machining in 3D and fast prototyping. After the first step of irradiation of the fused silica substrate with femtosecond laser, microchannels are obtained by chemically etching out the irradiated zone. So far aqueous solutions of the HF acid were used for the chemical etching of the fused silica glass substrates to fabricate microchannels; recently researchers have also employed KOH solutions for the same. Though the etching with KOH produces long microchannels with high aspect ratios, this technique is rather time consuming as the etching rates with KOH are smaller as compared to etching with HF acid. In this current work we address the ways to circumvent this slow etching rate by carefully tailoring the laser writing parameters. We also demonstrate a repetitive usage of HF acid and KOH acqueous solutions one after the other, to expedite the etching procedure. This novel hybrid etching approach adds another nuance to the FLICE technology by combining the fast etching rates of HF acid and the high aspect ratios obtained by KOH etching. By utilizing this hybrid etching approach, we fabricated complex structures in 3D which could not be fabricated using either HF or KOH solutions individually.

8248-11, Session 3

High aspect ratio microfeatures with laser texturing in mixed ablative-melting regime

P. Romero, N. Otero, Asociación de Investigación Metalúrgica del Noroeste (Spain)

Laser texturing has gained wide industrial interest due to its potential to improve the performance of lubricated contact pairs, fluid-dynamic performance or provide special functionalities. Nevertheless, it has very low productivity for textures in which the fill factor of the embossed features is large (microfins or microchannels).

The possibilities of surface texturing of metallic surfaces is explored in mixed ablation-melting regime, by engineering time and energy laser power distribution for creating textures with positive features (elevated topography with respect to the original surface). Combinations of positive and negative topographies can be exploited to generate microriblets, microchannels and reticulated structures, in a fast and efficient way.

A methodology is presented for producing regular patterns of micron sized features on metals. Features well under the beam size can be obtained, exploiting the recoil pressure to induce controlled molten bath displacement. By engineering the molten bath flow direction, high aspect ratio structures can be obtained. 2-5 microns sized walls, 40 microns high, were obtained with nanosecond lasers of 50 microns beam diameter on titanium. Picosecond laser pulses were also studied.

A model for the mechanism of production of these regular patterns is presented, as well as experiments designed for visualization of the material behaviour during the process. The applicability limits of these techniques, their requirements and limitations are studied, in terms of productivity, flexibility and resulting surfaces.

Several examples of microtextures performed on different materials are shown, ranging from tool steel to aeronautic grade titanium, and the potential applications are discussed.

8248-12, Session 3

Molten pool temperature measurement in YAG laser ablation using pyrometer

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The molten pool temperature is a crucial parameter in laser processing, since it dominates dimensional and metallurgical quality of the component. In order to fabricate components with appropriate properties, full understanding of thermal behavior during the laser processing is important. Through monitoring the molten pool temperature and feeding it back to the controller, the laser-based material processing with precisely controlled manner can be achieved.

In regard to this aim, the Nd:YAG laser with pulse duration 0.5ms, energy per pulse 0.09-1.08 J and Gaussian pulse shape was used to irradiate silicon, stainless steel, and AM50A magnesium alloy. Pyrometer and optical fiber were sited on the laser treated sample in two different configurations i) at 45o and 5 mm distance from laser spot and ii) at the cross section of sample at 250 μm distance from laser spot. To measure temperature accurately, appropriate emissivity of each irradiated matter was adjusted in pyrometer.

The results of temperature monitoring in pulsed laser action gives a unique opportunity to analyze thermal behavior of single laser pulse irradiation and to find some general regularities of its evolution such as sharp temperature spikes, heating and cooling rates. This also provides better insight to optimize the laser-based material processes and can be potentially used for on-line feedback controlling of the processes.

8248-13, Session 3

Direct laser writing of 3D micro/nanostructures on opaque surfaces

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Direct laser writing based on ultra-localized polymerization is an efficient way to produce three-dimensional micro/nanostructures for diverse applications in microoptics, photonics, microfluidics and biomedicine. It is attractive for its flexibility to materialize CAD models out of wide spectrum of materials on the desired substrates. Crosslinking within the volume of transparent material can be achieved by tightly focusing ultrashort laser pulses to a photo- or thermo-polymers. Selectively exposing material to laser radiation allows rapid prototyping of fully 3D structures with submicrometer spatial resolution.

We present laser structuring results of various acrylates, epoxies (SU-8) and hybrid organic-inorganic materials (ORMOCERs, SZ2080) on opaque surfaces such as silicon and various metals (Cr, Al, Ti, Fe). Our studies prove that one can precisely directly fabricate two- and three-dimensional structures even on glossy (highly reflective) or rough surfaces (sand-blasted and chemically etched, roughness up to 1 micrometer). Using femtosecond high pulse repetition rate laser, sample translation velocity can be reached over 1 mm/s ensuring submicrometer structuring resolution. Fabrication of dielectric materials on electro conductive substrates opens a way for novel applications based on plasmonic interactions.

Additionally, we show direct laser formation of PDMS elastomer with accuracy and throughput beyond reported previously by other groups. This enables maskless manufacturing of molds for soft-lithography or three-dimensional components for microfluidics.

8248-14, Session 3

Fabrication qualities of micro-gratings encoding depend on laser parameters by two-beam femtosecond lasers interference

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Femtosecond laser interference is a promising tool for micro-fabrication and micromachining of periodical structures on the surface of samples or inside transparent materials, but femtosecond laser pulses are very hard to interfere due to their spectrum widths may reach to several tens of nanometers, and the spectrum width will be stretched by shorting the duration according to the Fourier transform. We realized two 25 fs pulses interference and encoded micro-gratings on Au-Cr thin films using this interference pattern. The interference patterns of two laser pulses with pulse duration in sub-hundred femtosecond time domain were calculated to explore the influence of pulse durations on processing qualities of encoded micro-gratings. The results show that, the shorter pulses are preferable to fabricate micro-gratings with fine resolution on intractable materials, and longer pulses are helpful to improve encoding efficiency and contrast ratio of bright & dark interfered fringes. The differences between encoded micro-gratings on Au-Cr thin film using these interference patterns validated our analysis, which are hardly observed when pulse duration is longer than 100 fs mainly because the size of interfered area is larger than the focal spots. Moreover, the distance between two focal spots also has been chosen to identify our calculations, and the experimental results are agreement with the calculations.

8248-15, Session 4

Bosch-like method for creating high aspect ratio poly(methyl methacrylate)(PMMA) structures

M. Haiducu, A. M. Parameswaran, Simon Fraser Univ. (Canada)

This paper presents a method for etching millimetre-deep trenches in commercial grade poly(methyl methacrylate) PMMA using deep-UV at 254 nm. The method is based on consecutive cycles of irradiation and development of the exposed areas, much like a Bosch process for silicon. The patterning of high molecular weight PMMA using the aforementioned wavelength has been introduced at the Canadian Conference on Electrical and Computer Engineering (CCECE) 2007. The method reported here differs from previous work in that it increases the aspect ratio of the microfabricated devices (trenches deeper than 120 μm were impossible to be made previously) and alleviates the resulting negative sidewall, which is due to the uncollimated nature of the irradiation source. As such, considering the outcomes of this process and the insignificant costs associated with it, this procedure represents a true 'poor man's LIGA.' This paper will show experimental results of exposing PMMA substrates either directly or through the light semi-collimator. The outcome of this process can be used as is (for example for creating microfluidic devices) or as a template (or mould) to microfabricate 3-D structures on the micron-to-millimetre scale.

8248-16, Session 4

Stress engineering for free-standing SU-8 thin film devices

K. W. Oliver, S. J. Lukes, M. J. Moghimi, D. L. Dickensheets, Montana State Univ. (United States)

The epoxy-based negative photoresist SU-8 is becoming widely used as a structural material for MEMS and MOEMS devices. Spin coated and then directly patterned by lithography, SU-8 can be cured by hard-bake to make a durable structured film. One appealing property of the final material is the potential for low intrinsic stress in the cured film, promoting large displacement of elastic structures using low-voltage electrostatic actuation. While very low values of intrinsic stress have been reported for uncured films, our interest is in free-standing SU-8 structures that must endure a release etch and therefore require a hard-bake step. The final film stress may vary dramatically depending on variables of the fabrication process, so that the process must be properly designed to achieve the desired stress in the finished structure.

In this paper we describe a process for creating thin SU-8 2002 films between 1.5 um and 3.0 um thick that are hard-baked and can withstand a release etch in either aqueous or plasma silicon etchants. Resulting films are characterized using both wafer bow and membrane bulge tests to monitor in-plane stress and Young's modulus. We explore the influence on final film stress of several process variables including film thickness, exposure dose, post exposure bake temperature and hard bake temperature. Illustrative process recipes are described for both patterned and un-patterned free-standing low-stress SU-8 membrane devices.

8248-17, Session 4

Modeling of hot imprint process of periodical microstructure in to polycarbonate

R. Gaidys, B. Narijauskaite, A. Palevicius, G. Janusas, Kaunas Univ. of Technology (Lithuania)

A finite element model for hot imprint process of periodical microstructure into polycarbonate has been developed. In the finite element model polycarbonate is assumed to be a nonlinear elasto-plastic material. The model covers the main three steps of hot imprint process: polycarbonate heating, imprinting and demolding. Periodical lamellar microstructure was chosen as die in the hot imprint process, because it is common structure in the practice. The model is solved using the heat transfer and the solid stress-strain application modes with thermal contact problem between die and polycarbonate. This multiphysics polycarbonate hot imprint model includes the heat transport, structural mechanical stresses and deformations. Finite-element simulation of the hot imprint process has been performed using COMSOL Multiphysics. Nonlinear elasto-plastic model was created. It allows evaluation of temperature distributions and stresses in the polycarbonate during hot imprint process. Obtained theoretical results were compared with experimental.

Conference 8249: Advanced Fabrication Technologies for Micro/Nano Optics and Photonics V

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8249-30, Poster Session

Monitoring of the formation of a photosensitive device by electric breakdown of an impurity containing oxide in a MOS capacitor

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Strong photoconductivity of single junctions between two CNTs, deposited by drop casting on a thermally oxidized silicon wafer has been found. During the fabrication process thermally oxidized silicon wafer single junctions were contacted with platinum arms deposited by means of a Dual-Beam Focused Ion Beam.

A very small quantity (not measurable in weight) of multi walled carbon nanotubes (MWCNTs) was mixed with about the same quantity of sodium dodecyl sulfate (SDS). Then highly deionized water was added and the solution sonicated for 20min at RT. A small drop was taken from the supernatant part of the solution in order to avoid cluster residues and deposited on top of the thermally oxidized silicon wafer substrate, heated to a temperature of 50°C.

Scanning electron microscope and FIB imaging revealed an interesting interconnection morphology between the drop casted multi walled carbon nanotubes. In particular we found that in a lot of cases the MWCNT were connected to each other in a geometry similar to a double helicoidal structure. The dark current voltage characteristics was stable over a long time and at low voltage levels a rather stable bistability has been measured.

Time resolved photoconductivity measurements revealed a cut-off frequency under blue light LED excitation at 430nm of about 100kHz. The frequency behavior was mainly limited by the value of the contact pad capacitances and hence a further optimization of the geometry may give the possibility to strongly increase the operation frequency and enable applications in the telecommunication field.

8249-44, Poster Session

Use of ALD thin film Bragg mirror stacks in tuneable visible light MEMS Fabry-Perot interferometers

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Tuneable MEMS Fabry-Perot interferometers are suitable for realizing miniature low-cost spectrometers, which can be used in various applications ranging from gas concentration measurements in the IR to fluorescence/NIR imaging in diagnostics and industrial process monitoring. Atomic layer deposition (ALD) technique allows processing of high quality pin-hole free thin film coatings with good conformality and uniformity, which meet the requirements of the very thin optical film thicknesses (λ/4) in the UV-visible spectral range, while also making it possible to develop low temperature MEMS processing methods utilizing non-traditional materials such as polymers and polyimides as sacrificial layers. This paper discusses the use of ALD thin films as Bragg mirror structure materials in MEMS Fabry-Perot interferometers in the visible spectral range. Utilizing polyimide sacrificial layer in the FPI fabrication process is also discussed as an alternative method to allow higher temperature (T= 300 °C) ALD FPI processing. ALD Al_2O_3 and TiO_2 thin films grown at T= 110 °C and T= 300 °C are optically characterized to determine their performance in the UV - visible range (λ > 200nm), and effects of the ALD temperature on the thin film stacks and the FPI process is discussed. Optically simulated 5-layer Bragg mirror stacks consisting of ALD Al_2O_3 and TiO_2 for wavelengths of 420 nm, 500 nm, 670 nm and 750 nm are presented and corresponding MEMS mirror membrane structures are fabricated at T= 110 °C and tested for their release yield properties. As a result, the applicable wavelength range of the low-temperature ALD FPI technology can be defined.

8249-45, Poster Session

Optical characterization of subwavelength-scale solid immersion lenses

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We report on the fabrication and optical characterization of submicrometer-size solid immersion lenses (SILs) with sizes down to subwavelength range. First, submicron cylindrical structures are fabricated in polymethyl methacrylate (PMMA) using electron-beam lithography. Since PMMA is a thermoplastic, a thermal reflow process transforms a cylinder into a spherical cap. For optical characterization in the visible spectrum, the fabricated nanoscale SILs (nano-SILs) are replicated on a transparent (glass) substrate using soft lithography. The SIL is made of a UV-curable polymer (Norland, NOA65, n=1.52). Three-dimensional (3D) amplitude and phase distributions of the focal spots with/without the nano-SILs are measured using a high-resolution interference microsope (HRIM), which incorporates a 100X/NA1.4 objective and a Mach-Zehnder interferometer. The full width at half maximum (FWHM) and the full spot (Airy disc) sizes are retrived from the transverse amplitude and phase distributions at the focal plane, respectively. Analysis of the 3D intensity data provides not only the transverse spot size but also the longitudinal spot size, and moreover the peak intensity enhancement that is caused by the tighter focus. For 642-nm wavelength, the nano-SIL of 500-nm diameter and 45-nm height is considered to be a subwavelength-size object. For the first time, we experimentally confirm the immersion effect due to such a nano-SIL. The spot size reduction ratio was found to be approximately 1.35, less than the expected value of 1.5 most likely due to the slightly non-ideal shape of the nano-SIL.

8249-46, Poster Session

Performance evaluation of direct laser lithographic system for rotationally symmetric diffractive optical elements

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Representative rotationally symmetric diffractive optical elements, such as Fresnel zone plates (FZPs) and computer-generated holograms (CGHs) are mainly used in the scientific area. FZP can be applied to ultraviolet or X-ray lithography as a diffractive focusing lens, and CGH is used as a null corrector for measuring shape of aspheric optical surfaces. The precision of such diffractive optical elements is closely related to the precision of a fabricating lithographic system. For such a reason, we have developed a cylindrical-type precision direct laser lithographic system whose working area and minimum linewidth are up to 360 mm and 0.5 μm, respectively. To assure the performance of the lithographic system, the performance evaluation was carried out on the moving stages, the writing head module, and the light source, respectively. In this paper, we report the performance evaluation results including the standard uncertainties of each parts and the combined standard uncertainty on the lithographic system.

8249-47, Poster Session

Energy-dependent temperature dynamics in femtosecond laser microprocessing clarified by Raman temperature measurement

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Focused femtosecond laser pulses can be used for fabricating photonic devices inside transparent materials. However, the processing mechanisms are not fully clarified. Previously, we investigated the local and rapid temperature dynamics of fused silica during femtosecond laser microprocessing by time-resolved micro-Raman temperature measurement. We found therein that it is crucial to suppress background signals as well as so-called double-pulse processing. To cope with these issues, we have improved the scanning condition and optimized the energy of Raman pump pulse. In the experiment, a Ti:sapphire laser system generated 80-fs pulses and a frequency-doubled Nd:YAG laser system generated 10-ns pulses. These pulses were electronically synchronized and used for microprocessing and Raman excitation, respectively. They were focused by a microscope objective. The sample was a plate of fused silica. The sample was scanned to prevent multiple irradiations. Raman scattering signal generated at the focal spot were detected by a gated spectrometer. The temperature at the focus was calculated from the ratio of the intensity of Stokes and anti-Stokes Raman scattering of the measured spectrum. The measured temperature near the focal point decreased with different delays depending on the pulse energy. When the pulse energy was 16 μJ, the temperature was found to be~2000 K for 100 ns after irradiation. The measured temperature fitted well with the thermal diffusion model. We concluded that energy dependence of temperature dynamics was successfully investigated by using the present system.

8249-48, Poster Session

Effect of reactive monomer on PS-b-P2VP film with UV irradiation

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Poly(styrene-b-2-vinyl pyridine) (PS-b-P2VP) lamellar film which is hydrophobic block hydrophilic polyelectrolyte block polymer of 52 kg/mol -b- 57 kg/mol and PS-b-P2VP film with reactive monomer (RM257) were prepared for photonic gel films. The lamellar stacks, which is alternating layer of hydrophilic and hydrophobic part of PS-b-P2VP, were obtained by exposing the spin coated film under chloroform vapor. The lamellar films were quaternized with 5wt% of iodomethane diluted by n-hexane. We reported about the influence of reactive monomer on those photonic gel films. Added reactive monomer photonic gel film had higher absorbance than pure photonic gel films. And those films irradiated by UV light. We irradiated UV light different time each films. And band gaps of the lamellar films shifted by the time of UV light irradiation. That Photonic gel films were measured with the UV spectrophotometer. As a result the photonic gel film with reactive monomer had more clear color. The lamellar films were swollen by DI water, Ethyl alcohol (aq) and calcium carbonate solution. Since the domain spacing of dried photonic gel films were not showing any color in visible wavelength. The band gap of the lamellar films were drastically shifted to longer wavelength swollen by calcium carbonate solution (absorbance peak 565nm → 617nm). And the lamellar films were shifted to shorter wave length swollen by ethanol (absorbance peak 565nm → 497nm). So each Photonic gel film showed different color.

8249-49, Poster Session

Spectral tuning of IR-resonant nanoantennas by nanogap engineering

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In the present study, we exploit the geometry dependence to tune the surface plasmon resonance (SPR) of rod-shaped nanoparticles (nanoantennas) with lengths in the micrometer range. These structures are of special interest for sensing applications in the infrared (IR) spectral region, e.g. for surface-enhanced IR spectroscopy (SEIRS). By changing the rod length, the spectral resonance position can be tuned to match specific IR active vibrations of molecules. An enhancement of SEIRS signals can be achieved by exploiting the extraordinary near-field enhancement that occurs if two nanoantennas interact with each other across a very small gap (nm range) between their tip ends. However, the reliable preparation of such nanosized gaps in a parallel process suited for large-scale arrays is a challenging task still hampering the success of SEIRS. To address this problem we applied optically induced metal deposition to narrow gaps between IR-resonant nanorods manufactured by conventional electron beam lithography. Covering the nanorod arrays on the substrate with a solution of tetrachloroaureate (HAuCl4) and illuminating them with visible light leads to the reduction of the gold salt, a site-selective gold deposition, and, hence, to a gradual growth of the gold nanostructures. The resulting decrease of the interantenna gaps is monitored using scanning electron microscopy, while increased plasmonic coupling and an associated red-shift of the plasmon resonance is observed by microscopic IR spectroscopy. Since smaller gap sizes lead to enhanced electric fields between the antenna arms, we propose photochemical metal deposition as a fabrication step for surface-enhanced IR spectroscopy (SEIRS) substrates.

8249-50, Poster Session

Effects of electric fields on the photonic crystal formation from block copolymers

T. Lee, J. Ju, W. S. Ryoo, Hongik Univ. (Korea, Republic of)

Effects of electric fields on the self-assembly of block copolymers have been investigated for thin films of polystyrene-b-poly(2-vinyl pyridine); PS-b-P2VP, 52 kg/mol-b-57 kg/mol and 133 kg/mol-b-132 kg/mol. Block copolymers of polystyrene and poly(2-vinyl pyridine) have been demonstrated to form photonic crystals of 1D lamellar structure with optical band gaps that correspond to UV-to-visible light. The formation of lamellar structure toward minimum free-energy state needs increasing polymer chain mobility, and the self-assembly process is accelerated usually by annealing, that is exposing the thin film to solvent vapor such as chloroform and dichloromethane. In this study, thin films of block copolymers were spin-coated on substrates and placed between electrode arrays of various patterns including pin-points, crossing and parallel lines. As direct or alternating currents were applied to electrode arrays during annealing process, the final structure of thin films was altered from the typical 1D lamellae in the absence of electric fields. The formation of lamellar structure was spatially controlled depending on the shape of electrode arrays, and the photonic band gap also could be modulated by electric field strength. The spatial formation of lamellar structure was examined with simulated distribution of electrical potentials by finite difference method (FDM). P2VP layers in self-assembled film were quaternized with methyl iodide vapor, and the remaining lamellar structure was investigated by field emission scanning electron microscope (FESEM). The result of this work is expected to provide ways of fabricating functional structures for display devices utilizing photonic crystal arrays.

8249-51, Poster Session

Laser-written photonic crystal optofluidics for electrochromatography on a chip

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Open structured photonic crystals (PCs) present a novel medium at the interface of optofluidics for exploiting ordered nano-structures for both chromatography and optical sensing cytometry. An integrated PC sensor offers new functionality in micro-total-analysis-systems such as label-free molecular tagging of analytes and rapid, in-situ, optical detection without chemical alterations. In this paper, we present 2D-PCs integrated within microfluidic channels to harness two benefits for lab-on-a-chip devices: (1) improved analyte separation through the periodically ordered nano-structured medium based on capillary electrochromatography (CEC) and (2) real time optical sensing of the PC stop bands as they shift with the separation of the mobile phase.

Fused silica substrates were exposed with a focused Yb-fiber amplified femtosecond laser (IMRA, FCPA μJewel, λ = 522 nm) for direct laser writing of nanograting and refractive index structures to pattern into open microfluidic channels, buried optical waveguides and porous 2D PCs. Polarization control of the laser rendered selected modification tracks susceptible to hydrofluoric acid etching while leaving optical waveguides intact, thus defining a flexible method to create a three-dimensional integrated optofluidic device. Enhancement of electrophoretic separation of various analytes by the embedded PC column was analyzed by fluorescence excitation recordings and contrasted with the shifting photonic stop bands recorded via laser-written optical waveguides. Optimization of the PC layout and design is explored by scaling towards micron diameter flow-channels and near-IR band stopbands with the objective of both high efficacy CEC and bandgap-based optical sensing together on a compact optofluidic chip.

8249-52, Poster Session

Plasmon enhanced optical photodiodes based on MEH-PPV polymer and fullerene blend on ITO

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We report the fabrication of silver Plasmon enhanced photodiodes with a single active layer sandwich mixture, using ITO with Ag nano particles and poly (2-methoxy-5-(20-ethylhexyloxy)-1,4-phenylenevinylene) (MEH-PPV):fullerene-C60 blend. Silver nano particles were created first by e- beam depositing 20 Å of Ag on ITO followed by RTA annealing under nitrogen at 250 C for 30 min. Devices were fabricated using spin casting the blend over the ITO/Ag nano particles. After baking, Al metal was deposited on top of MEH-PPV fullerene-C60 blend using e- beam evaporation for the metal contacts. We observed enhanced absorbance due to the silver nano particles and increased photo response by the fabricated photo detector. I-V characterization allowed us to determine the barrier height, diode ideality factor, and series resistance. The diode shows a non ideal current-voltage behavior due to high probability of electron and hole recombination in the depletion region or existence of tunneling current or may be due to the presence of interfacial layer or series resistance. The photocurrent and the photoconductive behavior indicate that these devices can be utilized as solar cells.

8249-53, Poster Session

InAs QD light emitting diodes on in-situ nano-patterned substrates using molecular beam epitaxy

D. Fan, J. Wu, Univ. of Arkansas (United States); Z. M. Wang, Univ. of Arkansas (United States) and Univ. of Electronic Science and Technology of China (China); S. Yu, G. J. Salamo, Univ. of Arkansas (United States)

Epitaxy regrowth on patterned substrates using Molecular Beam Epitaxy (MBE) has attracted much interest in last decades. Ex-situ patterning and in-situ ion beam lithography have been used to prepare the patterned substrates. However, the former is limited by the contamination of the regrowth interface that occurs during non-UHV processing steps while the latter requires additional instruments connected with MBE chamber through UHV. In this work, we report an in-situ nano-patterning technique within the MBE chamber which eliminates the needs of taking substrates out. The patterning is achieved by depositing liquid Ga droplets on GaAs substrates followed by crystallization process in As rich environment to drill nanometer size holes. In order to verify the optical quality of the patterned substrates, a light emitting diode (LEDs) structure was grown by incorporating InAs Quantum Dots (QDs) on the nano-patterned template as the active region. Photoluminescence was measured to confirm high optical quality of the QDs. Broad contact edge emitting devices were processed using the as-grown wafer and the devices were characterized electrically. The strong radiation of the LEDs at room temperature suggests good quality of the structures with low defect density and hence confirmed that this in-situ patterning method can be adopted to make optoelectronics devices with high performance.

8249-54, Poster Session

Using a dwell-time increase to compensate for SLM pixelation-limited diffraction efficiency in DMHL

D. R. McAdams, D. G. Cole, Univ. of Pittsburgh (United States)

Dynamic maskless holographic lithography (DMHL) is a new micro-manufacturing technique that uses holograms to create patterns on a substrate instead of a mask. In DMHL, gratings and Fresnel lenses are used to steer light to expose sensitive photopolymers.

Ideally the light can be guided with infinite precision, but pixelation and quantization of the liquid crystal phase array puts limits on positioning range and resolution. The field over which patterning can be performed is affected by the diffraction efficiency of the displayed hologram, the maximum possible spatial frequency, aliasing, and other diffractive orders entering the patterning field. Furthermore, as the spatial frequency of a grating increases, the diffraction efficiency drops. This is especially evident in three dimensional patterning in which a Fresnel lens is used to move the patterning beam deeper into the sample; as the beam moves deeper, it becomes less intense. This paper presents a technique to compensate for these inherent inefficiencies by properly adjusting the dwell time during the lithography process.

The relationship between the spatial frequency of the appropriate grating or Fresnel lens and the dwell time is discussed. Experiments are presented with and without this technique applied, and results show that feature uniformity is improved with dwell-time compensation.

8249-55, Poster Session

Controlling the nanofabrication of metal structures in direct laser writing using various chemistries

S. Kang, K. Vora, S. Shukla, E. Mazur, Harvard Univ. (United States)

Metallic micro- and nano-structures have been long known to play central roles in various areas of research such as catalysis and plasmonics. In the emerging field of metamaterials, metallic structures are once again generating considerable interest, especially in regards to routes towards high-throughput, low-cost, and controllable three dimensional fabrication. We recently demonstrated a direct laser writing technique that can rapidly fabricate 3D metal structures of tunable dimensions embedded in a dielectric ranging from hundreds of nanometers to micrometers. Nonlinear optical interactions between chemical precursors and femtosecond pulses induce metal-ion photo-reduction processes and create metal nanostructures in the focal spot.

Here we show the role chemistry plays in affecting the photoinduced metal growth that ultimately leads to the desired metal structures. By varying the types of solvent, polymer and the concentration ratio between metal ion precursors and a polymer capping agent, we demonstrate our control over the morphology of the resulting metal structures. We also show that certain chemical compositions can optimize the conductivity or flexibility of the resulting structures. From studying the various chemistries we create diverse metal nanostructures for a wider range of applications.

8249-56, Poster Session

Photoresist roughness characterization in additive lithography processes for the fabrication of phase-only optical vortices

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Surface roughness control is desired for the fabrication of phase-only micro-optical elements, since it can be a limiting factor in their performance. In this paper, we will present photoresist surface roughness minimization, for the implementation of a phase-only optical vortex. We used additive lithography, which is based on multiple-exposure techniques, to define the desirable phase profile in the photoresist prior to etching. In a typical additive lithography process the dynamic range for the desired phase profile includes a region of roughness. The process effects of temperature and time, in the post application bake (PAB) and post exposure bake (PEB), were investigated. We found that both variables of the PAB and PEB play a role on photoresist surface roughness reduction. We investigated the effects of different developers, one containing surfactant and one surfactant free, as well. We observed that the surfactant content of the developer affects the surface roughness. The required bias exposure was determined such as to minimize the roughness and maximize the dynamic range of the final phase profile. In order to do this, several exposure thresholds were examined. The vortex phase element fabricated by additive lithography was measured to quantify the surface roughness in all phase steps. Experimental information on the characterization, fabrication and performance of this phase element will be presented.

8249-01, Session 1

Recent advances in RAPID lithography

J. T. Fourkas, M. P. Stocker, Univ. of Maryland, College Park (United States)

Resolution Augmentation through Photo-Induced Deactivation (RAPID) lithography is a nonlinear optical technique that makes possible the creation of two- and three-dimensional patterns with a feature size that is much smaller than the wavelength of light employed. In this technique, a photoinitiator in a negative-tone photoresist is excited with a laser (typically via a two-photon process). The initiator can be deactivated by a second laser before it has time to initiate polymerization. Spatial phase shaping of the deactivation beam allows for control of the region that is deactivated, providing a route to attaining resolution that is far finer than the wavelengths of the excitation or deactivation beams. In this talk we will review recent advances in RAPID lithography. We have identified broad classes of inexpensive, commercially available materials for use as RAPID photoinitiators. Experiments and kinetic modeling reveal the time scale on which deactivation can occur and give insight into the deactivation mechanism. The time scale over which deactivation can occur is orders of magnitude longer than for initiators in which deactivation is driven by stimulated emission, allowing for the use of lower deactivation powers and providing a means of further increasing resolution. We demonstrate a new approach that takes advantage of the long time window for deactivation for improving both axial and transverse resolution with a single phase mask.

8249-02, Session 1

Recent progress on diffraction-unlimited three-dimensional direct-laser-writing optical lithography

M. Wegener, J. Fischer, T. Ergin, Karlsruher Institut für Technologie (Germany)

Three-dimensional (3D) direct-laser-writing (DLW) optical lithography has become a versatile and commercially available tool for fabricating complex 3D nanostructures with lateral linewidths below 100 nm (see, e.g., www.nanoscribe.de). In this context, it is important to distinguish between the linewidth of an individual object and the true resolution in the sense of Abbe, who considered the resolvable spacing of a grating. Abbe's definition is actually relevant to enable fabricating arbitrary and complex 3D structures. After more than a decade of research on 3D DLW, we are not aware of work that has beaten Abbe's limit (of course, corrected for the two-photon advantage) in either the lateral or the axial direction. Recent work regarding enhancing DLW inspired by stimulated-emission-depletion (STED) microscopy has not beaten Abbe's limit either, but has only demonstrated smaller - yet isolated - features leaving the applicable resolution somewhat unclear. By using an especially tailored photoresist based on a ketocoumarin photoinitiator, we have recently beaten both the lateral and the axial Abbe limit in planar gratings and in woodpile photonic crystals ("3D gratings") for what we believe to be the first time. The latter is achieved using a so-called bottle-beam depletion-focus that mainly reduces the axial extend of the polymerized lines. We have systematically studied this axial improvement inside three-dimensional structures. A particularly striking example for the achieved lithographic advance is the realization and characterization of a polarization-independent invisibility cloak, operating down to visible frequencies. Finally, interferometric imaging experiments show that this device not only cloaks the amplitude but also the phase of light.

8249-03, Session 1

Development of a two-color photo-initiation/inhibition lithography system

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In coorporation with the group around Robert McLeod at the University of Colorado at Boulder Heidelberg Instruments developed a Direct Write Laser Lithograpy system based on the STED inspired two color photo-initiation/inhibition lithography suggested by Dr. Mcleod in (Science 324, 913-917, 2009) in order to extend the minimum feature sizes far below the optical diffraction limit.

In the two-color photo-initiation/inhibition lithography, a predefined pattern of photo-inhibitors generated by the absorption at a certain wavelength confine the photo-initiated regions on the resist exposed at a second wavelength. The photo-initiated region can be much smaller than the diffraction limit. For the lithography system developed here, this surrounding pattern is a Gauss-Laguerre "donut-shaped" exposure generated by a spiral phase plate. This customized lithography system is equipped with two parallel laser pathways one at 473nm for the photo-initiation process of the photo resist and the photo-inhibition pathway including the spiral phase plate at 363nm.

The goal of this research project is to verify and solve the questions regarding the time between the inhibition and initiation exposures as depicted in the publication above and to optimize them to build a high-throughput lithography system combined with super resolution.

For the construction and application of the two-color laser lithography system, theoretical descriptions of the beam geometry were derived. The system aims to provide fast exposure up to 1200 um2/s and an minimum structure size below 100nm.

8249-04, Session 1

Polymerization inhibition dynamics for high resolution lithography

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During the last year a new concept for high resolution lithography came up that is related to sub diffraction resolution microscopy. The basic idea is to excite the photo initiator molecules by the absorption of 2 photons within a diffraction limited spot and by a second light beam to inhibit the polymerization in the outer region of that spot. Therefore, the shape of the inhibition beam can be influenced by the use of an appropriate phase mask. Hereby the understanding of the photo-physical mechanism responsible for the inhibition of the polymerization is of great importance in order to optimize the material system for this new lithography technique.

In this work we will present experiments performed in order get a more detailed view of the processes. For this, we were especially focusing on the polymerization inhibition dynamics to extract information about which photo physical states might be involved. These experiments are performed within a standard STED microscope equipped with multicolor options allowing also skipping between one- and two-photon excitation.

8249-05, Session 1

Time-resolved experiments on diffraction-unlimited 3D laser lithography

J. Fischer, T. J. Wolf, A. Unterreiner, M. Wegener, Karlsruher Institut für Technologie (Germany)

Recently, advanced Direct Laser Writing schemes inspired by stimulated-emission-depletion (STED) microscopy have demonstrated reduced feature sizes and have shown potential for improved resolution. These approaches exploit different photo-induced polymerization-suppression effects, not all of which are fully understood. In principle, any of those effects can lead to resolution improvements. STED itself is unique, because it does not inject additional heat into the photo-resist, whereas all other effects based on light absorption do so. However, up to now, no experiment could unambiguously show polymerization suppression caused by STED.

To investigate the depletion pathways of 7-Diethylamino-3-thenoylcoumarin (DETC), the photoinitiator molecule that has so far yielded the best performance in our group, we perform femtosecond pump-probe absorption experiments in ethanol solution. The transients show that within the lifetime of the S1 state stimulated emission dominates over excited-state absorption.

Furthermore, we perform a series of polymerization-suppression experiments with our DETC-based photoresist. Using a pulsed tuneable depletion laser we measure the temporal decay of the intermediate states which can lead to the suppression. First experimental results suggest that there is one depletion channel decaying on a time scale of 1ns and another one with a lifetime considerably longer than the maximum accessible delay time (12.5ns). The spectral sensitivity of the fast decaying process resembles the fluorescence spectrum of the photoinitiator molecule. Hence, we suggest that true STED contributes to the efficient depletion of DETC-based photoresists.

8249-06, Session 2

Nanophotonic laser direct fabrication

M. Gu, Swinburne Univ. of Technology (Australia)

Optical microscopy provides not only an imaging tool for viewing microscopic worlds but also a platform for laser direct fabrication. In this presentation, we will show the application of super-resolution optical microscopy. When two laser beams are introduced into an optical microscope, we have developed superresolution photoinduction-inhibited nanolithography (SPIN), in which case, one laser beam acts for photoinduction and the other for inhibition. A particular example of photoinduction is photopolymerisation. We show that the physical mechanism of this kind of SPIN can be well explained by the kinetic coupling (KIC) model and that the smallest feature size of the polymerised dots we have achieved is approximately 40 nm, which is $\lambda/12$. The integration of SPIN with two-photon excitation potentially provides a 3D platform for nanofabrication.

8249-07, Session 2

Towards visible-wavelength titania-based three-dimensional photonic-band-gap materials via direct laser writing

A. Frölich, J. Fischer, T. Zebrowski, I. Staude, K. Busch, M. Wegener, Karlsruher Institut für Technologie (Germany)

One of the holy grails in the field of photonic crystals has been and continues to be achieving sizable complete three-dimensional photonic band gaps in the visible part of the electromagnetic spectrum. Regarding approaches based on direct-laser-writing (DLW) optical lithography, at least two obstacles had to be removed. First, the resolution of regular DLW has not been sufficient to achieve the necessary feature sizes and lattice constants. For example, to achieve visible band gaps using titania, the rod spacing, a, of a three-dimensional woodpile photonic crystal needs to be around 300 nm. Second, the polymer templates made by DLW need to be converted into a transparent material with sufficiently large refractive index, such as titania. Depending on its phase, its refractive index is around 2.4, which is sufficient to open a complete gap with a gap-to-midgap ratio around 5%.

In this work, we overcome both problems. The first one is solved by employing stimulated-emission-depletion (STED) inspired DLW lithography using a photoresist with 7-Diethylamino-3-thenoylcoumarin as photoinitiator. This resist has recently been introduced by us. Along these lines, rod spacings down to a = 250 nm have become possible. The second problem is solved by modifying our previously introduced silicon-double-inversion procedure. In a first step, we invert the polymer templates made by STED DLW using atomic-layer deposition (ALD) of ZnO. After calcination of the polymer, we apply another inversion step using titania ALD. Finally, the ZnO is selectively etched out, leaving behind a titania replica of the original polymer woodpile.

8249-08, Session 2

Scanning laser holographic lithography: toward flexible ultra-large-size 3D photonic crystal microsystems

L. Yuan, P. R. Herman, Univ. of Toronto (Canada)

A vision for photonics integration entails a large area three-dimensional (3D) photonic crystal (PC) matrix that is embedded with numerous functional photonics components for enabling the diffractionless flow and processing of light. While several methods have demonstrated uniform and highly precise fabrication of such 3D PCs up to several mm2, seamless stitching into larger area has not been scalable and will be challenging towards wafer-size PC microsystems.

Here we extend holographic phase mask lithography for 3D PC structure fabrication from static exposure of small beam size to large area scanning holography in which fabrication area will become unlimited against that of the laser-beam profile. An Argon ion laser beam at 514 nm was collimated to 10 mm diameter to illuminate a binary 2D phase mask of 570 nm period that generates one 0th and four 1st order beams overlapping in near proximity to the phase mask where thick photoresist (~30 m) was positioned (1 mm distance) to capture the 3D periodic interference pattern. Isointensity surfaces and stopbands for the anticipated tetragonal (TTR) PC structure were simulated for various conditions of scan-to-scan overlap that accounted for non-uniform exposure and absence of diffraction orders in the beam's periphery. The optimal exposure configuration for scanning holography provides seamless stitching of the 3D PC over large areas with nearly constant Gamma-Z stopband.

This scanning holography technique should be scalable to ultra-large wafer-size fabrication where spectral tuning, chirping, and apodization of band gap structures could then be introduced by velocity or beam power modulation.

8249-09, Session 2

Synthesis of super-dense phase of aluminum under extreme pressure and temperature conditions created by femtosecond laser pulses in sapphire

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We describe synthesis of a new super-dense phase of aluminum under extreme pressure and temperature conditions created by femtosecond laser pulses. The microexplosions were induced by tightly focused femtosecond laser pulses having a temporal length of ~100 fs and an energy of ~ 100 nJ. Expansion of high-density plasma photogenerated in sub-micrometer-sized regions led to strong transient heating up to 100 000 K and pressure up to 10 TPa which resulted in partial decomposition of sapphire into aluminum and oxygen and formation of regions containing predominantly nanocrystalline bcc-Al phase. This phase is different from ambient fcc-Al phase, and has not been observed experimentally so far. The super-dense bcc-Al phase was permanently preserved in compressed state in the bulk of sapphire by fast quenching, and thus available for characterization by X-ray diffraction (XRD) technique. The experimental XRD patterns allowed unambiguous identification of the new phase from perfect fit of seven experimental XRD peaks with calculated XRD pattern of the bcc-Al phase. This is the first observation of bcc-Al phase which so far has been only predicted theoretically. It demonstrates that laser-induced microexplosions enable simple, safe and cost-efficient access to extreme pressure and temperature ranges using tabletop experimental setup, such as that employed in direct laser writing experiments. This approach allows to avoid tediousness of traditional techniques that use diamond anvil cells, gas guns, explosives, or megajoule-class lasers to achieve extreme pressure and temperature conditions for modification and synthesis of materials.

8249-10, Session 2

Effect of configuration of the microchannels fabricated by femtosecond laser micromachining on topological defects in confined liquid crystals

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Liquid crystals have raised much interest in recent years both for technological applications and for being an interesting playground for testing concepts of soft matter physics. Typically the control and manipulation of the liquid crystal order is achieved with a continuous application of a force field (electric field, light, external gradients), however recently much attention is directed towards systems that exhibit multistability; in these systems a small amount of energy is able to switch the system from a stable state to another stable state which is then maintained over time without any power consumption. Liquid crystals in confined geometries exhibit this multistability potential because of the presence of confinement-induced localized defects in the molecular ordering. To develop a full understanding of the interplay between confinement, defects and multistability, we exploit the fast prototyping capability of femtosecond laser micromachining to realize microfluidic channels with diverse geometries. We studied the ordering of liquid crystals included in various microfluidic channel configurations both in 2D and 3D were fabricated e.g. a) junctions of intersecting channels with 3 to 6 arms, b) structures with 4 channels intersecting a roundabout in the middle and c) networks of channels in 3D. The analysis of the observations has enabled us to formulate a general prediction for the amount of defects induced in liquid crystals by the confinement in porous networks of arbitrary connectivity.

8249-11, Session 3

High precision fabrication of polarization insensitive resonant subwavelength gratings

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Resonant subwavelength gratings have been designed and fabricated as wavelength specific reflectors for application as a rotary position encoder utilizing ebeam based photolithography. The first grating design used a two-dimensional layout to provide polarization insensitivity with separate layers for the grating and waveguide. The resulting devices had excellent pattern fidelity and the resonance peaks and widths closely matched the expected results. Unfortunately, the gratings were particularly angle sensitive and etch depth errors led to shifts in the center wavelength of the resonances. A second design iteration resulted in a double grating period to reduce the angle sensitivity as well as different materials and geometry; the grating and waveguide being the same layer. The inclusion of etch stop layers provided more accurate etch depths; however, the tolerance to changes in the grating duty cycle was much tighter. Results from these devices show the effects of small errors the pattern fidelity. The fabrication process flows for both iterations of devices will be reviewed as well as the performance of the fabricated devices. A discussion of the relative merits of the various design choices provides insight into the importance of fabrication considerations during the design stage.

8249-12, Session 3

Monolithic fabrication and performance control of multilayered, polarization sensitive, guided-mode resonance filters

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Single-step photolithographic fabrication (monolithic) of Guided-Mode Resonance Filters (GMRF) is desirable for the implementation of laser filters and mirrors, as well as for spatial beam shaping. However, due to the layered structure of the GMRF, it is often not possible to fabricate devices with different wavelength resonances within a single substrate, without numerous photolithographic and thin film deposition steps. The method presented here uses a single photolithographic step to establish a wavelength resonance control layer and a second step to form the diffractive layer of the GMRF, without the need to use complex thin film deposition and/or etching steps. The effective index of the control layer determines the desired resonance wavelengths.

The GMRF architecture used includes three functional layers. The lower (imbedded) layer is a resonance control confinement layer, capped with a conventional two-layer GMRF structure, consisting of the waveguiding region and the diffractive region. The imbedded layer includes a sub-wavelength linear grating (SWG) etched in a deposited thin film of silicon oxide, over-coated with a thicker silicon nitride film that forms the waveguide layer of the GMRF. The diffractive region, which acts also as a leaky waveguide, consists of a SWG etched on a second silicon oxide thin film. The planar orientation of the two SWGs is in mutual orthogonal (crossed) directions, each with a different spatial period, in order to avoid coupling of the incident light polarization state to both.

Optical testing of a number of devices confirmed the simulation results.

8249-13, Session 3

Ultra-fast diffractive optical micro-trap arrays for neutral atom quantum computing

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We design, fabricate, and characterize arrays of diffractive optical elements (DOEs) to realize neutral atom micro-traps for quantum computing. We initialize single atoms at each site of an array of optical tweezer traps for a customized arrangement. Each optical trapping volume is tailored to ensure only one or zero trapped atoms. Specifically designed DOEs can:

1) Define an arbitrary optical trap array for initialization,

2) Improve collection efficiency in readout by introducing high-numerical aperture, low-profile optical elements, coupled with optical fibers into the vacuum environment.

3) Dynamically modify trap spacing and configuration for interaction, through relative optical component movement, rotating polarization, scanning wavelength, and varying incident angle of the trapping fields, and

We present design and fabrication of ultra-fast DOEs that establish an optical array of micro-traps through far-field propagation. DOEs, as mode converters, modify the lateral field at the front focal plane of an optical assembly and transform it to the desired field pattern at the back focal plane of the optical assembly. We manipulate the light employing coherent or incoherent addition with judicious placement of phase and amplitude at the lens plane. This is realized through a series of patterning, etching, and depositing material on the lens substrate. The trap diameter when this far-field propagation approach is employed goes as $2.44\lambda F/\#$, where the F/# is the focal length divided by the diameter of the lens aperture. The elements in this presentation are, to our knowledge, the fastest diffractives realized; ranging from F/1 down to F/0.025.

8249-14, Session 3

Fabrication of uniform index material guided-mode resonance filters

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Highly reflective, narrowband spectral mirrors are vital components in creating stable, high power laser systems. Typically, multilayer stacks are used to create a distributed Bragg mirrors, tailored to achieve high reflectivity with a desired spectral width. The requirements on the coatings are complicated by the limited index of available materials, as well as the differential thermal expansions between adjacent layers. Alternative mirror structures have been introduced utilizing Guided Mode Resonance (GMR) and a leaky waveguide layer. Recently, high contrast gratings have been introduced, using an array of encapsulated air holes in a semiconductor substrate. However, silicon based structures are not optimal for high power applications, nor for achieving narrowband resonances. To address these issues, a low-index contrast polarization selective mirror was introduced, based on a buried one dimensional structure using fused silica and silicon oxide.

To eliminate the polarization dependence of the above mentioned structures, a homogenous, narrowband spectral filters with a periodic, hexagonal array of encapsulated air pockets in a fused silica substrate is presented. A leaky waveguide is formed on an etched fused silica grating by depositing silicon oxide via Plasma-Enhanced Chemical Vapor Deposition (PECVD). A resonance wavelength of 1.741µm was found for both TE and TM polarizations, with a 60% reflectivity for either polarization. The resonances demonstrate a full-width at half-maximum (FWHM) of 6 nanometers.

8249-15, Session 3

HSQ resist for replication stamp in polymers

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We investigated the most economic, accurate and large scale production method to fabricate sub-micron featured gratings after replication in to polycarbonate substrate by employing hot embossing technique. We used polymer hydrogen silsesquioxane (HSQ) which is a high resolution, binary, negative electron beam resist on silicon substrate to make a stamp for replication. Usually, HSQ is spin coated on the silicon substrate and then subjected to e-bam patterning followed by wet or dry etching. In order to attain the exact profile height during etching process, a careful and accurate process time must be used. The etching process is not linear with time and substrate depth heights, so in order to get optimize condition, some preliminary experiments needed to be performed before desired depth profile. This etching process utilizes e-beam writing for each trial which is expensive and time consuming. We report first time the replication into polycarbonate substrate by using HSQ resist without any etching process involved. In past, similar stamp fabrication techniques had been used to generate nanoimprinting (NIL) and hot embossing stamps for pattering several sorts of resist, but it never been applied for polycarbonate pattering.

We demonstrated the simple process by first depositing an HSQ resist layer on silicon substrate and measurement of film thickness directly after spin coating. If one could not achieve desired film thickness, HSQ resist layer can be easily removed by dipping the sample in HF solution. Spin coater can be adjusted with near accuracy by controlling spin speed and time. The resist material is subjected to e-beam writing followed by heat treatment for curing to obtain HSQ behavior analogous to solid SiO_2 to use HSQ as hot embossing stamp material.

8249-16, Session 3

Spatially and spectrally varying guided mode resonant filter by modifying the waveguide layer

Z. A. Roth, M. K. Poutous, E. G. Johnson, The Univ. of North Carolina at Charlotte (United States)

In this paper, we will present the concept, fabrication, and experimental results of a novel type of Graded Transmissivity Optic based on a space variant Guided Mode Resonance Filters. This Guided Mode Resonant Filter is comprised of two dielectric layers deposited on a transparent substrate. The top layer is PECVD grown SiOx with a subwavelength grating etched in. The second layer is called the waveguiding layer, and is comprised of PECVD SiN. When light is incident upon the GMRF at the resonant wavelength, the SWG couples light into a waveguide mode. However, due to the SWG on the waveguide, this mode is leaky and re-couples the light back towards the source. The resonance of the GMRF is a function of the optical properties of the materials used; the thickness of the dielectric layers; and the period and fill-fraction of the SWG. The resonance will change across the device by slowly varying the thickness of the waveguiding layer. Previous work has varied the resonance across the structure by varying the fill fraction of the grating. The methods involved in the previous work made that process usable for only a very narrow range of wavelengths, however this new method will be scalable to a larger wavelength range. The waveguiding layer will be sculpted using Additive Lithography and ICP etching. Afterwards, SiO will be deposited onto the surface, and a SWG will be etched into the SiO. Experimental results of the fabrication and the testing of this device will also be presented.

8249-17, Session 4

3D photonic band gap crystals: islands of tranquility in a fluctuating vacuum

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Control of the spontaneous emission and the propagation of light are crucial to a broad range of applications such as single-photon sources for quantum information, efficient lasers and light emitting diodes, solar energy harvesting, and biological emitters. It is well known that the characteristics of spontaneously emitted light depend critically on the environment of the light source. The role of the environment on a source's emission is described by the local density of optical states that counts the number of photon modes available for emission [Spr96]. The density of state can also be interpreted as the density of vacuum fluctuations. Currently, there are many efforts to control the emission of quantum emitters using interfaces, cavities, antennae, or metamaterials. Particularly interesting classes of nanophotonic metamaterials are photonic band gap crystals [Sou01].

We have fabricated inverse woodpile photonic crystals in silicon wafers using new CMOS-compatible methods see [Wol08]. We have studied the polarization-dependent reflectivity of our inverse woodpile crystals. We observe a position-independent stopband overlapping for orthogonal polarizations and many directions [Hui11]. This is the experimental signature of a broad 3D photonic band gap, which is supported by calculations. For good measure, the observed signature of the band gap is no experimental proof yet. A true experimental observation of a band gap entails studies where the density of optical states is probed via the emission rate of quantum dots. Indeed, ongoing studies in our group reveal strongly inhibited vacuum fluctuations in the range of the band gap.

References:

[Bus07] K. Busch, G. von Freymann, S. Linden, S.F. Mingaleev, L. Tkeshelashvili, and M. Wegener, Physics Reports, vol. 444, pp. 101-110, 2007.

[Hui11] S.R. Huisman, R.V. Nair, L.A. Woldering, M.D. Leistikow, A.P. Mosk, and W.L. Vos, Phys. Rev. B 83, 205313 (2011).

[Sou01] C. M. Soukoulis, editor, Photonic crystals and light localization in the 21st century (Kluwer, Dordrecht, 2001).

[Spr96] R. Sprik, B. A. van Tiggelen, and A. Lagendijk, Europhys. Lett. 35, 265 (1996).

[Wol08] L.A. Woldering, R.W. Tjerkstra, H.V. Jansen, I.D. Setija, and W.L. Vos, Nanotechnology 19, 145304 (2008).

8249-18, Session 4

Adaptive amplitude filters for smaller feature sizes in direct laser writing

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Direct-Laser-Writing (DLW) is an established technique for the fabrication of almost arbitrary three-dimensional structures in photoresists. These are locally polymerized via two-photon polymerization [1]. The fundamental building block - the so called voxel (volume pixel) - is a volume defined by the iso-intensity surfaces in the focal spot. This voxel is an ellipsoid, defined by the numerical aperture of the microscope objective and the refractive index of the photoresist. The resulting axial elongation is disadvantageous for isotropic features [2].

To overcome this problem, so called shaded-ring filters (SRF) have been reported [2,3]. However, alignment with respect to the optical axis is crucial and might render SRF impractical for day-to-day use. Recently, stimulated-emission-depletion inspired lithography has been demonstrated to yield aspect ratios of one [4]. Corresponding setups require phase masks and an additional laser source.

Here, we show that spatial light modulators (SLM) can be employed to implement SRF to decrease the aspect ratio, overcoming the alignment issues. Although SRF-parameter-optimization can be done with the SLM, so far SRF have to not been able to generate aspect ratios close to one with acceptable sidelobe levels.

We therefore suggest an adaptive amplitude filter allowing for voxels with an aspect ratio of one, regardless of the scanning direction. This adaptive filter consists of a variable slit with unity transmission imaged onto the entrance pupil of a high numerical aperture objective. We show numerical calculations and experimental data demonstrating the effectiveness of this approach.

[1] Direct laser writing of three-dimensional photonic-crystal templates for telecommunications, Deubel et al., Nature Materials 3, 444 - 447 (2004)

[2] Fabrication of Silicon Inverse Woodpile Photonic Crystals, Hermatschweiler et al., Advanced Functional Materials 17, Issue 14, 2273 - 2277 (2007)

[3] Optimized pupil-plane filters for confocal microscope point-spread function engineering, Neil et al., Optics Letters 25, Issue 4, 245-247 (2000)

[4] The Materials Challenge in Diffraction-Unlimited Direct-Laser-Writing Optical Lithography, Fischer et al., Advanced Materials 22, 3578 - 3582 (2010)

8249-19, Session 4

Calorimetric study of fs-laser polymerizable sol-gel resists

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We report on a combined differential scanning calorimetric (DSC) and Raman scattering study of thermal polymerization of sol-gel organic-inorganic SZ2080 resist. Endothermic peak at 95C signifies drying of the resist and justifies the required pre-bake at around 100 C for 1-2 h for the best performance during femtosecond (fs-)direct laser writing. A strong exothermic peak at 140 C defined polymerization of the resist. Raman scattering taken during DSC revealed spectral changes following the polymerization. Hence, Raman scattering can be used to judge a degree of induced cross linking. By comparison the ratio of the Stokes and anti-Stokes Raman intensities it is possible to reveal the temperature at the irradiation spot during recording providing a tool to monitor polymerization. Such approach will provide a method to determine contributions of thermal and optical pathways of photo-polymerization. We propose a method to write waveguides inside resist via laser-induced densification following the sol-gel transition. Sol-gel resist can be used as an effective anomalous fictive-temperature medium where fast thermal quenching after fs-laser writing forms a higher density waveguiding regions (similarly as in a silica glass; L. Bressel et al., Opt. Mat. Express 2011, in press). A post-writing uniform polymerization by UV exposure is used to fixate the fs-recorded structure. Examples of fs-laser polymerization of micro-optical elements are presented.

8249-20, Session 4

3D inclined structures fabricated by prism assisted inclined UV lithography

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Inclined Ultraviolet (UV) lithography has been widely used for complex three-dimensional (3D) structure fabrications, such as V-grooves, micro filters and inclined mirrors. However, when exposing directly from air, the exposure angle in the resin is limited because of the large index mismatch between the resin and air. Usually, an index matching material, such as water or glycerol, is employed to compensate for the refractive index difference and expand the exposure angle. However, the index matching material may change certain characteristics of resin, such as the water content, which may affect the exposure effectiveness. In this paper, we report our exploration of prism assisted inclined UV lithography to fabricate 3D inclined structures in SU-8. Utilizing this technique, the exposure angle from 0° to 60° can be easily achieved without index matching material. The technique of prism assisted inclined UV lithography will have significant impact on the fabrication of various complex 3D structures.

8249-21, Session 4

Active and adaptive optical methods for rapid fabrication of 3D photonic structures

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Femtosecond direct laser writing permits fabrication of micron-scale three-dimensional structures within bulk substrates. Applications of these techniques include photonic crystals, metamaterials, waveguide structures and microfluidics. All of these applications require focusing of the laser beam, using a microscope objective lens, into the bulk of the fabrication medium. Any refractive index difference between the fabrication and objective immersion media causes refraction at the interface, which in turn leads to aberration of the laser focus. These aberrations distort the focus and cause a significant drop in peak intensity. Consequently, the efficiency and accuracy of fabrication are severely compromised. The aberrations become more severe as one focuses deeper into the material, significantly restricting the thickness of three-dimensional structures that can be fabricated by this method. We have developed adaptive optics methods, based around deformable mirrors and spatial light modulators, to correct these aberrations and provide diffraction-limited fabrication performance at depth in high refractive index substrates, such as diamond and lithium niobate. Aberration correction is further combined with adaptive beam shaping for fabrication of 3D waveguide structures in silica.

Fabrication speed can be considerably increased through parallelization of the direct write approach. We show how holographic multi-spot methods can be combined with spatially dependent aberration correction to produce three-dimensional distributions of more than a hundred features in a single exposure. Furthermore, we present a new hybrid holographic/microlens array method that avoids many of the drawbacks of the purely holographic approach. This permits the fabrication of arbitrary structures using hundreds/thousands of adaptively controlled foci.

8249-22, Session 4

Material processing with 12 femtosecond picojoule laser pulses

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Extremely short near infrared laser pulses offer the possibility of precise sub-100nm processing without collateral side effects. Furthermore, the can be employed to excite a variety of absorbers simultaneously due to their broad 100 nm emission band. We demonstrate two-photon fluorescence imaging of green and red fluorescent proteins in living cells as well as two-photon nanolithography. When increasing the power up to 5-10 mW, direct nanoprocessing in silicon, glass, gold, polymers, and cells was performed at transient TW/cm2 intensities.

8249-23, Session 5

Rolling mask nanolithography: the pathway to large area and low cost nanofabrication

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The field of nanotechnology has given birth to a number of nanofabrication and patterning techniques. In parallel, the demand for large area and low cost nanopatterning techniques for optical coatings and photonic devices has increased at a tremendous rate. Important applications include sub-wavelength anti-reflective coatings and self-cleaning coatings for solar panels, displays and architectural glass, light trapping layers and nanostructured absorbers for high efficiency solar cells, light extraction layers for LEDs, wire-grid polarizers for LCD, ultra-sensitive optical detectors, and more. At present, it is clear that currently available nanopatterning technologies are unable to meet the required performance, fabrication-speed, or cost criteria for many applications requiring large area and low cost nanopatterning. Rolith Inc proposes to use a new nanolithography method - “Rolling mask” lithography - that combines the best features of photolithography, soft lithography and roll-to-plate printing technologies. Sub-wavelength resolution is achieved using near-field optical exposure of photosensitive materials. The use of a cylindrically shaped photomask that can be illuminated in a dynamic exposure mode allows high throughput and continuous operation. The use of elastomeric materials for the photomask assures uniformity of contact over large areas and insensitivity to irregularities of the substrate surface. We will report on the first results achieved on a recently built prototype tool and cylindrical mask, which was designed to pattern 300 mm wide substrate areas. We will also present some optical simulation analysis, and discuss our plans for scaling up of this technology to production systems capable of nanopatterning Gen-10 glass substrates.

8249-24, Session 5

Fabrication of 8-channel array single-mode waveguides via vacuum assisted microfluidics

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We report on the production of an array of 8-channel single-mode waveguides via vacuum assisted microfluidic (VAM) soft lithographic technique with the aid of equally spaced and repeated sectional flow tapers. The use of VAM technique allows for the creation of polymer channel waveguides without a residue layer formed in between the core channel waveguide and the under cladding layer. Such residue layer is common to the micro transfer molding fabrication process resulting in the formation of an undesirable planar region that may introduce waveguide mode profile variation and/or channel crosstalk. The VAM technique, however, has limited achievable channel waveguide length when the waveguide cross sectional dimension is small (< 20 × 20 μm) owing to the viscosity of the UV curable core waveguide resin. In our previous work the use of sectional flow tapers were found effective in the production of a long single-mode channel waveguide with small cross sectional dimension. By extending the use of these repeated sectional flow tapers between multiple singe mode channels, and by utilizing a synthesized low viscosity UV-curable epoxy resin as core waveguide medium, an array of long length single mode channel waveguides were fabricated. After construction, each of these independent waveguides were tested and compared to each other. The effective use of VAM, sectional flow tapers, and UV curable core waveguide resins can yield the desired freestanding single-mode channel waveguide arrays at low cost.

8249-25, Session 5

Sub-micrometer pattern generation by diffractive mask-aligner lithography

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The use of mask-aligners for the generation of high resolution structures is limited due to the underlying shadow printing principle. Consequently mask-aligner lithography is barely known as a technology for the fabrication of high dispersive gratings, photonic crystals or similar sub-micrometer structures. However, this limitation is mainly caused by constructive imperfections of the mask aligner and the uninspired use of simple shadow masks.

In our contribution we show a way to overcome these limitations and generate pattern with sub-500nm feature size on a wafer scale using specially designed diffractive photo-masks. The process requires some modifications of the mask aligner. This includes the use of a special illumination optics for tailoring the angular spectrum incident onto the mask by a macroscopic aperture. As the method is based on diffraction of the UV-light at the mask structures adapted exposure models are required for the design of photo-mask and its illumination. Thus, the consideration of the interaction between mask illumination and the diffractively acting mask features is the central point of what we call diffraction control.

We present two different exposure regimes for the generation of periodic sub-micrometer pattern and first examples of non-periodic structures. All of them are realized by diffraction effects with a mask-to-substrate distance of several tenths of micrometers.

The diffraction control technique represents a novel cost-effective method for the generation of high-resolution pattern for different applications.

8249-26, Session 5

Wafer scale fabrication of submicron chessboard gratings using phase masks in proximity lithography

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One and two dimensional grating structures with submicron period have a huge number of applications in optics and photonics. Such structures are conventionally fabricated using interference or e-beam lithography. However, both technologies have significant drawbacks. Interference lithography is limited to rather simple geometries and the sequential writing scheme of e-beam lithography leads to time consuming exposures for single dies.

We present a novel fabrication technique for this class of microstructures which is based on proximity lithography in a mask aligner. Our technology is capable to pattern a complete wafer (4” so far) within less than one minute and offers thereby high lateral resolution and a reliable process. Our advancements compared to conventional mask aligner lithography are twofold: First of all, we are using periodic binary phase masks instead of chromium masks to generate an aerial image of high resolution and exceptional light efficiency at certain distances behind the mask. Second, a special mask aligner illumination set-up is employed which allows to precisely control the incidence angles of the exposure light. This degree of freedom allows both, to shape the aerial image (e. g. transformation of a periodic spot pattern into a chessboard pattern) and to increase its depth of focus considerably. That way, our technology enables the fabrication of high quality gratings with arbitrary geometry in a fast and stable wafer scale process.

8249-27, Session 5

Nano-scale multiple-axis photoelectron source using focused helium ion beam fabricated C-aperture nano-tip

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Electron-beam lithography (EBL) is one of the candidate technologies to push semiconductor manufacturing into the domain of sub-20 nm node processes. EBL is capable of less than 10 nm resolution. However, single beam writing has very low throughput. One solution to this problem is parallel e-beam writing with multiple electron beams. A photoelectron source driven with multiple UV lasers can produce high current density electron-beam sources. In our lab we have previously demonstrated focusing electron beams on wafers with unity demagnification and negligible aberration by applying a uniform magnetic field. Obviously, using this method, the size of the electron source is the same as the UV laser spot size, which is limited to about half wavelength.

In this work, we employ a nanophotonic approach to focus a UV laser with a C-shaped aperture integrated with a nano-antenna at the ridge. We experimentally prove that the C-aperture nano-tip (CAN-Tip) can focus light to the tip with a sub-20 nm optical spot, which is close to the tip dimension. We designed this CAN-Tip photoelectron source using FDTD modeling, and then fabricated the structure itself in an aluminum thin film with a focused helium ion beam; the tip radius is below 10 nm. The CAN-Tip was further planarized with spin-on glass and coated with a 10 nm film of CsBr to act as a photocathode. A preliminary test of the optical spot size at the tip was done with photoresist exposure using a 257 nm UV laser.

8249-28, Session 6

Tuning of random rough surface statistics for optoelectronics

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Optical surface structuration is of primary interest for applications such as photovoltaics or photodetectors. Over last years, periodical patterns allowing antireflective effects have shown efficient properties. Some specific issues such as diffraction of high energy orders being undesired are a direct consequence of the periodical nature of this kind of pattern.

Random rough surfaces allow the antireflective effect without these undesired diffraction effects. By tuning their statistics, random rough surfaces offer new degrees of freedom for antireflection but also for the control of scattering (polarization, directions).

The two main parameters of such surfaces are the height probability density function and the autocorrelation function. The height probability density function carries information about heights of the structures and their distribution. The autocorrelation function is a representation of the lateral distribution of the surface.

Our photofabrication method uses a speckle pattern recorded on a photoresist. By controlling the exposure parameters, such as the number of exposure and the beam intensity distribution, one is able to control the statistics of the speckle, and so of the photofabricated surfaces.

Using interferometric microscope and atomic force microscopy measurement, height mapping of these surfaces are performed. From these mappings, the height probability density and the correlation function are calculated.

The experimental statistics are compared with the predicted theoretical ones showing a good agreement. Results are presented showing a significant modification of the statistics of the photofabricated surfaces.

Finally the scattering properties of the surfaces are investigated using a goniophotometer.

8249-29, Session 6

High precision geometrical characterization and alignment of miniaturized optics

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Miniaturized optical systems like endoscopy or cell phone lenses systems comprise several optical elements like lenses, doublets and plane optics. To receive a good imaging quality the distances and angles between the different optical elements have to be as accurate as possible. In the first step we will describe how the distances and angles between different elements can be monitored and finally we will describe a technique to actively align small optics (diameter approx. 1mm and smaller) with respect to each other. For the measurement electronic autocollimators combined with white-light-interferometers are used. The electronic autocollimator reveals the exact centration errors between optical elements and the low coherence interferometer reveals the distances between surfaces. The accuracy of the centration error measurement is in the range of 0.1µm and the accuracy of the distance measurement is 1µm. Both methods can be applied to assembled multi-element optics. That means geometrical positions of all single surfaces of the final optical system can be analysed without loss of information. Both measurement techniques complement one another.

Once the exact x,y,z - Position of each optical surface and element is known computer controlled actuators will be used to improve the alignment of the optics. For this purpose we use piezo-electric-actuators. This method had been applied to cement e.g. doublets for endoscope optics. In this case the optical axis of one lens has been aligned with respect to the optical axis of a second reference lens. Traditional techniques usually rely on an uncertain mechanical reference.

8249-31, Session 6

Programmed resist sidewall profiles using sub-resolution binary gray-scale masks for Si-photonics applications

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Common IC fabrication processes can achieve only a limited number of etched sidewall profiles: vertical sidewalls through dry anisotropic etching; angled sidewalls dependent on the crystallographic orientation of the substrate through wet anisotropic etching; or undercut profiles through dry/wet isotropic etching. Conversely, there is an ever-increasing interest in a high-volume fabrication technique that can realize gradient height profiles in silicon.

A technique using gray-scale lithography has proven to be a useful batch process to create gradient height structures. This method is a one-level lithography process enabling the development of 3D profiles in a photoresist masking layer, which can then be transferred to the silicon substrate. The gray-scale photomask is manufactured using conventional chrome-on-glass materials and manufacturing methods but utilizes variable density arrays of sub-resolution patterns to create a transmittance gradient. The mask feature dimensional characteristics need to be chosen to meet mask manufacturing requirements. The effective transmittance must be matched to the wafer lithography photoresist response to achieve the desired sidewall profile.

In this paper we present a 45 degree mirror created for optical applications utilizing CMOS high-volume manufacturing processes with a Gray-Scale Lithography technique. The process that is presented here was done by creating a 3D pattern in the photoresist and then by transferring the photoresist profile to the SiSiO2 substrate by specific dry etch processing. We discuss the optimization of the gray-scale pattern to achieve the desired resist profile.

In this work we achieved smooth sidewalls with various sidewall angles. We show that different 3D angles and profiles can be achieved and processed simultaneously.

8249-32, Session 6

Fabrication of diffraction imaging elements for continued terahertz waves

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A simple rapid and cheap method for fabrication of diffraction imaging elements, which can be used to form expected images, is presented. According to common diffraction theory and the desired image, phase distribution of the diffracted Gaussian laser beams in the terahertz frequency range is reconstructed by a special software. The fine surface microrelief patterns of the elements are created by the same software pursuant to the phase distribution and reconstructed in photomask and further etched onto the surface of {100}-oriented silicon wafer by the low cost and rapid wet etching. Being different with the traditional silicon diffractive lenses fabricated by multiple level processes, the elements produced by the method introduced by us can transfer common Gaussian beams into desired images through created fine patterns over the surface of the elements. Two typical types of the generation-image elements, which are used to transform common Gaussian laser beams in terahertz frequency into so-called common focus, and the desired figure of the "umber one", are fabricated. For testing the element, the LASER SIEIR 50 of Coherent Company is used to generate common Gaussian laser beams (the diameter of the beams is ~10mm), and the PYROCAM THERE of Spiricon Company is also used to display the images acquired. Experimental results show that the elements can be used to form images as expected.

8249-33, Session 6

Economic silicon nanowire fabrication using nano-crack lithography

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Silicon 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 the current high-cost fabricating methods. 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 silicon nanowires are demonstrated by Nano-Crack lithography. Cracking of bowtie photoresist pattern was achieved by immersing the sample into liquid nitrogen. Nanoscale fractures revealed after the thermal stressing process. The cracked patterns were used as the lift-off resist for the Cr nanowire fabrication. The resulting Cr nanowires were used as the etch mask of the underneath silicon device layer of a silicon-on-insulator wafer. Silicon anisotropic wet etch produced narrow silicon nanowire with smooth sidewall. >500 nm silicon nanowire that was connected to large electrodes was successfully fabricated. Regular electric characterizations for a typical field-effect transistor were also performed. The fabricated silicon nanowire field-effect transistor exhibited high on/off ratio of 3.26 × 105 and with peak transconductance of 183 nS. The electric characteristics can be further improved by reducing the width of the silicon nanowire. This fabrication technique was not only cost effectively but also very fast, which should be very attractive for industrial application. Further improvements of this technique will lead to more nanowire optoelectronic applications.

8249-57, Session 6

Gallium nitride-based logpile photonic crystals for visible lighting

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Photonic crystals (PC) can fundamentally alter the emission behavior of light sources by suitably modifying the electromagnetic environment around them. Strong modulation of the photonic density of states especially by full 3D bandgap PCs, enables one to completely suppress emission in undesired wavelengths and directions while enhancing desired emission. This property of 3DPC opens up new regimes of photon manipulation and light-matter interaction in particular, creating advanced light sources such as ultralow threshold lasers, single photon sources and energy efficient and high brightness visible lighting. However, creating 3D gap PCs composed entirely from direct band gap semiconductor used in visible lighting, such as crystalline GaN, poses fabrication challenges due to their resistance to etching. An approach based on growth through a three dimensional nanostructured template offers a solution to this problem. Here, we describe the fabrication of a GaN logpile PC with visible photonic bandgap via MOCVD growth of GaN through an 'inverse' SiO_2 logpile PC on GaN seed layer coated sapphire substrate. The SiO_2 template with lattice constants as small as 300nm is fabricated using a multilayer e-beam direct write technique developed at Sandia[1, 2]. Optimization of GaN deposition conditions result in vertical growth of single crystal GaN from the bottom layer and complete filling of the void regions of the SiO_2 template. After SiO_2 template removal, optical reflectance spectroscopy reveals a broad feature centered near 600nm corresponding to the photonic bandgap. We will discuss the potential for this structure for light emission for solid state lighting applications.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

[1] G. Subramania et al., Optics Express 15, 13049 (2007).

[2] G. Subramania, and S. Y. Lin, Applied Physics Letters 85, 5037 (2004).

8249-34, Session 7

Three-dimensional Dip-in Laser Lithography (DiLL)

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In recent years, three-dimensional (3D) laser lithography has become a standard in 3D micro- and nanofabrication [1,2]. Photosensitive material is polymerized via two-photon absorption with tightly focused laser beams. However, photoresists are commonly not perfectly index-matched to the oil immersion system. Aberrations due to this mismatch lead to a dramatic loss of resolution and laser power with increasing writing depth.

To overcome this problem, we introduce a new route in 3D microfabrication: Dip-in laser lithography (DiLL). In the DiLL process the objective lens is directly immersed into a liquid photoresist serving as immersion and photosensitive medium at the same time. Even in case of non-index-matched photoresist material the homogeneity of the writing process is preserved regardless of the writing depth.

Using a dedicated DiLL setup, we proof the concept by fabricating a large variety of 3D structures. Heights in the millimeter range have been achieved with different commercial photoresists and with outstanding structural quality.

The focal intensity distribution depends on the refractive index of the photosensitive material. Theoretical calculations of the intensity distribution are presented for different configurations. Theory is in good agreement with the experiment.

For DiLL, the height of the structure is not limited by the working distance of the objective lens any more, i.e., high-NA objective lenses with short working distances can be used. Accordingly, best resolution is achieved independent on the writing depth or substrate - an important advancement in the field of 3D direct laser writing. Several applications will be discussed.

[1] S. Kawata, H.-B. Sun, T. Tanaka, and K. Takada, Nature 412, 697 (2001)

[2] www.nanoscribe.de

8249-35, Session 7

Hybrid optics for three-dimensional microstructuring of polymers via direct laser writing

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We demonstrate a specially designed diffractive-refractive hybrid optics for focusing ultrashort laser pulses into a polymer for direct laser writing via two-photon polymerization (2PP). 2PP enables the fabrication of arbitrary three-dimensional microstructures with feature sizes smaller than the diffraction limit. In a typical 2PP setup oil immersion microscope objectives are applied for focusing ultrashort laser pulses through an immersion liquid and a coverslip into the polymer located on the backside of the coverslip. Owing to the refractive index mismatch between coverslip and polymer writing depth dependent spherical aberrations occur. Furthermore the microscope objectives consist of complex lens systems that are causing a high internal group velocity dispersion (GVD) leading to temporal broadening of the focused laser pulses if not properly compensated by prechirping the pulses. To overcome these drawbacks we designed and manufactured a diffractive-refractive hybrid optics with a numerical aperture (NA) of 1.33 that allows for diffraction limited focusing over a working distance range of 550 µm with low internal dispersion. The optics comprises an aplanatic solid immersion lens (ASIL) for achieving a high NA and the correction of aberrations with a diffractive optical element (DOE). The immersion liquid consists of the polymer without the photoinitiator, so no light induced polymerization reaction can occur. This homogenous immersion liquid allows for structuring of the polymer with constant focus properties in variable writing depths. To experimentally demonstrate the improvements for volume structuring of the polymer, we compare the achievable spatial resolution of our optics with a commercially available oil immersion objective (100x, NA = 1.4) and present the realized microstructures.

8249-36, Session 7

Electro-optic effect in femtosecond laser written MZIs via microchannel electrodes

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Photonic device fabrication methods have continued to develop for optical telecommunication and sensing applications. Direct femtosecond laser writing provides an alternative to tradition lithographic methods, offering 3D writing capabilities that affords greater prototyping flexibility. Applications based on writing interferometers, lasers and sensors have been widely demonstrated by integrating femtosecond laser written devices with fiber optic and microfluidic systems, while active, integrated photonic circuits such as switches and modulators still present a challenge.

In extending the range of laser-writing applications, a 25-µm wire anode and microchannel cathode was integrated with an MZI written into bulk glass, providing a novel demonstration of the electro-optic (EO) effect. The microchannel electrode was formed beside laser written waveguides by direct laser writing, HF acid etching, and microfluidic metal ion deposition. Both the waveguides and microchannel tracks were written under similar laser exposure conditions (λ = 522 nm, τ = ~220 fs, f = 1 MHz, Ep = 115 nJ, vs = 0.5 mm/s) before dipping into 10% HF acid for 2 hours to open the nanograting-embedded tracks. A silver nitrate solution was vacuum-pulled through the microchannel to silver coat the walls and form a conductive high voltage electrode. Thermal poling was accomplished at 6.34 x 10^5 V/cm field and 300oC heated substrate temperature.

Preliminary work revealed spectral shifts of ~0.1 nm were observed on a 16-nm free spectral range spectrum spanning from 1520-1560 nm when a 4.34 kV voltage was applied across one MZI arm. These results demonstrate the feasibility for EO control and tunability for femtosecond laser written devices.

8249-37, Session 7

Generating high DOF light by using tapered hollow tube in a lithography system

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In this paper, we proposed a tapered hollow tube which can produce a near diffraction-limit spot and focus the incident light in far-field region. From previous researches, the sub-wavelength annular aperture (SAA) made on metallic film generates a Bessel beam in far-field region. Also, the traditional tapered fiber has been widely used in Near-field Scanning Optical Microscope (NSOM) to achieve super-resolution in near-field. Combining these two concepts, tapered hollow tube was shown to have great potential in creating a small sub-micron spot size and long depth of focus (DOF) emitted light beam. By using the commercially available capillary and fiber heat-pulling method, it was found that tube processed per design to be disclosed in this paper can achieve Bessel beam as well. It will be shown that the SAA-like structure was actually implemented by the geometry of the tube tip. From FDTD simulation and experiment, the emitted beam was identified to have more than 10 um DOF and 250-300 nm focal spot excited by using the 408 nm laser source. These results not only can help us pursue lithography applied to create through silicon via (TSV) process in far-field region while maintaining near diffraction-limit spot size. The high throughput and side lobe became a serious problem when continuous incident light was used. To circumvent this problem, the incident light from was changed from continuous to pulse type and a suitable lithography experimental system designed by using three-axis displacement platform was developed. All results will be detailed in this paper.

8249-38, Session 7

Photonic crystal waveguide fabricated by a combination lithography of laser holography and focused ion beam deposition

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Ever since photonic crystals (PCs) were studied, electron beam lithography (EBL) has been the most common technology for device fabrication mainly because of its high resolution and flexibility in pattern generation. However, there also have been parallel efforts to develop more cost-effective method suitable for mass-production. Here in this study, we demonstrate silicon-on-insulator (SOI) based two-dimensional slab PC line-defect waveguide to show the versatility of a combination method of laser holographic lithography (LHL) and focused ion beam (FIB). We employed LHL to generate a triangular-lattice PC backbone pattern over a large area (typically ~1 cm^2) with high throughput, which was followed by FIB-induced platinum (Pt) deposition to define a single line-defect for waveguide formation. From band structure calculations using the plane-wave expansion method, we found that a large bandgap is attainable despite an elliptical (not circular) shape of holes. To examine performance properties of the fabricated waveguide device, 1.5 μm light from a tunable laser source was fed laterally into the line-defect waveguide using a lensed fiber. Infrared camera was employed to monitor the alignment between the fiber and the line-defect waveguide and also to detect light output at the other end of waveguide. When transverse-electric (TE) polarized light was input, guided light was detected clearly at the opposite end of waveguide. We believe that this combination lithography is a fabrication method to replace the present EBL as it provides cost-effectiveness and mass-producibility in addition to the precision and flexibility that the EBL offers.

8249-39, Session 8

Dynamic membrane projection lithography

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Advances in micro/nano fabrication continue to enable the study of light/matter interactions on progressively smaller size scales. Recently, there has been significant progress in the fabrication of nano antenna structures with operational frequencies in the optical/IR range. A critical component in engineering the behavior of micro/nano antennas is the capability to control the size, shape and symmetry of the nano antenna.

In this talk we report our recent progress in creating IR wavelength antennas using a variant of membrane projection lithography (MPL) to create antennas with both closed and split loop structures, allowing both electrical and magnetic excitation. The technique entails directional evaporation through a perforated membrane suspended over a hemispherical cavity. The sample is tilted and rotated in-plane, such that the perforations each trace out a circular antenna on the interior face of the cavity. Split structures can be created by placing one or more shutters subtending a portion of the rotation, blocking deposition while the sample is in the shadow of the shutter, thereby creating engineered symmetry breaking. We will present fabrication details for both a self-aligned approach as well as a more general two-step fabrication approach, along with optical characterization data demonstrating the flexibility of this fabrication approach.

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8249-40, Session 8

Fabrication of large arrays of plasmonic nanostructures via double casting

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Large arrays of periodic plasmonic nanostructures are widely used in various applications, including ultra-sensitive particle sensing, optical nanoantennas, and optical computing. However, creating large-scale arrays via current fabrication processes (e.g., e-beam lithography and nanoimprint lithography) remains time consuming and expensive. To overcome this issue, we present a double casting fabrication methodology, and we demonstrate this technique by creating both 150 nm-nanohole and 150 nm-nanopillar arrays from one silicon master template with nanopillars.

Previously, researchers have demonstrated double casting methods for microscale features; however, employing these techniques at the nanoscale has remained a challenge due to cracking and incomplete transfer of the nanofeatures. Here, we preclude cracking and incomplete transfer problems by using a hard-PDMS/soft-PDMS (h-PDMS/s-PDMS) composite stamp to replicate the features from: (i) the silicon template, and (ii) the resulting PDMS template. This composite stamp minimizes cracking in two ways. First, because the template and casting materials are both PDMS (i.e. with equivalent thermal expansion coefficients), they expand at the same rate as a function of temperature. Second, the flexibility of the s-PDMS (Young's Modulus: ~1.3MPa) backing supports the stamps during the demolding process. The composite stamp facilitates the complete transfer of the nanofeatures due to the low viscosity and rigidity (Young's Modulus: ~9MPa) of h-PDMS. The resulting 150 nm-nanohole array and 150 nm-nanopillar arrays were characterized via SEM. The presented fabrication process dramatically reduces the cost and labor time associated with creating large arrays of nanofeatures, and will allow both researchers and manufacturers to realize a variety of nano-platforms.

8249-41, Session 8

Selective electroless Ag coating of three dimensional SU-8 microstructures for metamaterials applications

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A recent trend in metamaterials research has been to make subwavelength periodic metallic structures in three dimensions (3D). One of the few fabrication techniques that allows one to make any arbitrary 3D structure is direct laser writing (DLW) using the two photon polymerization. The technique utilizes nonlinear optical absorption of a tightly focused pulsed laser beam to selectively crosslink a small volume inside a polymer. By moving the focal point relative to the sample in all three dimensions, arbitrary 3D nanostructures can be fabricated. Due to its high resolution and the high level of control, DLW has been recently applied to many research areas, such as photonics and plasmonics, biomedical microuidics and MEMS devices. One limitation of the DLW technique is that it can only be used to pattern polymers such as SU-8. For metamaterials applications, metallic structures are required. In this work, we overcome this limitation by developing a procedure for selective electroless Ag plating of SU-8 microstructures that utilizes an RF plasma pre-treatment process. Selectivity is important for metamaterials applications because the microstructures need to be electrically isolated, so the substrate cannot be coated. We have optimized the coating process to reduce the surface roughness, increase the selectivity and demonstrate that metamaterials such as split ring resonators and three dimensional chiral structures can be fabricated on various substrates. Optical and physical characterization of the structures has been performed.

8249-42, Session 8

Exposure controlled projection lithography for microlens fabrication

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An Exposure Controlled Projection Lithography (ECPL) process was employed to fabricate microlenses on transparent substrates. This process, which is also referred to as maskless lithography, can be used to create polymer microlenses on flat or curved substrates without involving hard tooling. Incident radiation, patterned by a dynamic mask, passes through a transparent substrate to cure photopolymer resin that grows progressively from the substrate surface.

A basic irradiation model which models the projection optics used in the ECPL system is presented. We also present an in-depth photopolymerization model which explains the photopolymer's response to exposure. Both the irradiation and the photopolymerization models are used to formulate a process planning algorithm to control the ECPL fabrication process. This process planning method is utilized to fabricate microlenses of various specifications on inclined/curved substrates using the ECPL system. The accuracy of the process planning method and repeatability of the ECPL system in fabricating microlenses is discussed.

8249-43, Session 8

Optical micro cavities fabricated using direct proton beam writing

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Optical micro resonators are one of the basic building blocks of photonic circuits. These resonators can be fabricated using various lithographic techniques such as photolithography, direct laser writing, electron beam lithography, reactive ion etching and can be used as optical filters, modulators, sensors, optical delay lines and cavity lasers. In the present work Proton Beam Writing (PBW) is used to fabricate optical micro resonators in SU-8, which is a chemically amplified negative tone photoresist with good optical properties. PBW is a direct write technique that uses high energy protons to fabricate arbitrary structures in many common materials including polymers, semiconductors and inorganic crystals. PBW is well suited to fabricate three-dimensional high aspect ratio micro and nanostructures with smooth vertical sidewalls. This makes it particularly appealing for optical applications, and in particular micro optical resonators.

Optical characterization of the micro disk resonators was performed using evanescently coupled light from an integrated waveguide fabricated very close to the resonator. Micro disk resonators with a quality factor of the order of 104 were achieved. To verify the experimental results we performed various finite difference time domain (FDTD) simulations and compared the results with the experimental measurements. Micro optical laser cavities were also fabricated by doping the SU-8 resist with rhodamine B. The fabricated spiral cavities were optically pumped with 532 nm pulsed laser. The emission from the spiral cavity shows lasing behavior with 9 nm spectral line width and a laser threshold of 125 µJ/mm2.

Conference 8250: Reliability, Packaging, Testing, and Characterization of MEMS/MOEMS and Nanodevices XI

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8250-01, Session 1

Assembly and interconnect formation in MEMS/MOEMS application

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In many applications MEMS and MOEMS have to be integrated with driver, controller, memory and/or RF devices to generate a microsystem. A compact packaging approach does not only provide a miniaturized solution, it also enhances the performance of sensing devices which often have low signal levels. 3D packaging concepts with short interconnects between the sensor and the amplifier or ASIC are therefore favored over planar approaches.

The components are therefore flip chip or die bonded on top of each other. Chip-to-chip or chip-to-wafer assembly is the straight forward way to go. For wafer-to-wafer bonding handlings wafer are reconstituted with the chips to align them to the master wafer.

Other concepts will be shown like embedding the thinned chip into a polymer at wafer level followed by interconnection during thinfilm processing or at board level and further lamination, laser drilling and connection by copper plating.

The interconnection portfolio consists of a wide range of technologies in order to meet device compatibility, technology flow and application oriented requirements like hermeticity, biocompatibility, high temperature environment or optical cleanness.

For the reflow soldering in most cases SnAgCu is used, but for specific applications we favor eutectic AuSn20. Transient liquid phase bonding will transform the solder into intermetallic compounds, which have a higher melting point than the solder and are based on Cu/Sn and Au/Sn. Transient liquid phase soldering is achieved by adding large amounts of metal spheres likeCu or Ag to a solder paste. The solder reacts with the metal spheres to intermetallic compounds. Silver pastes are used for sintering and meanwhile a pressureless pastes are available allowing a wider range of applications for smaller dies.

Finally some applications are shown for the packaging of MEMS and MOEMS devices from different applications like automotive, imaging, medical and optical communication.

8250-02, Session 1

Effects of releasing process parameters and induced in-plane stress on MEMS yield

P. M. Nieva, Univ. of Waterloo (Canada)

The yield of Micro-Electro-Mechanical System (MEMS) devices is defined as the proportion of devices on the wafer found to perform properly. Failure due to stiction is often investigated to improve the yield of MEMS devices at the wafer level. However, process-induced in-plane residual stress can also have a profound impact in MEMS yield as it can present itself at various stages throughout the fabrication process. In this paper, the effect of releasing process parameters in induced in-plane stress is used as a method for characterizing the yield of MEMS devices at the wafer level. The paper reports the main parameters affecting the process-induced in-plane stress on the wafer, along with its effects on the yield of generic structures used in MEMS.

Investigation into the variations of in-plane stress induced by the releasing process and local wafer position is presented. Simple freestanding, bent-beam strain sensors are used to characterize local in-plane stress values. Experiments include several wafer quarters subjected to identical processing parameters but differing releasing conditions. The investigation focuses on both the temperature of the wafer during release as well as the overall duration of the release process. Trends in stress distribution based on local wafer position are studied and observation of stiction correlation with reported local stress measurements are discussed. Yield is evaluated by observational measurements of the stiction of microcantilevers, microbridges and microplates fabricated alongside with the bent beam strain sensors. Conclusions are drawn on viability of determining MEMS yield at the wafer-level based on process-induced residual stress.

8250-03, Session 1

Optoelectronic properties and interfacial coating durability of CNT and ITO on 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 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). Kwon, Dong-Jun is grateful to the second stage of BK21 program for supporting a fellowship.

8250-04, Session 1

Usage induced changes to surface topography and material properties in polysilicon MEMS electrothermal structures

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This paper presents the results of an experimental study of electrothermal poly-Si MEMS structures wherein changes to the surface topography and material properties are observed due to use. The ex-situ AFM characterization reveals changes in the surface topography after cyclic actuation. The extent of topical SiO2 evolution appears to increase with the number of actuation cycles and increasing stress levels on the polysilicon surfaces. The differences in the surface topography and oxide thickness are characterized as a function of fatigue cycling and in-situ annealing of the electrothermal actuators. FEA analyses were performed to evaluate the magnitude and distribution of stresses in the actuators to compare stress effects from oxide development on electrothermomechanical structures. With the observation on topographical changes, the intrinsic material property like resistivity was also affected. A change of 1.4% was seen for a 20% duty cycle, 1.8% for 50% duty cycle and 3.5% for 80% duty cycle. A relationship has been established between the annealing time and amount of oxide formation over the surface. Similar experiments were performed over hermitically sealed devices in order to observe the changes in resistivity under inert conditions. A comparison of change in resistivity for hermetically sealed devices and non-sealed devices infers the role of humidity towards faster degradation of the electrothermal devices. Finally, AFM topographical analysis was done after BOE treatment for the actuated devices to infer the grain size enlargement. The increase in RMS roughness of ~7nm was seen for treated actuated devices in comparison to un-actuated devices.

8250-05, Session 1

High fill-factor polymer refractive microlens array fabricated by stamping replica technique

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In general, polymer microlens arrays (MLAs) suffer from their low fill-factor and undesirable uniformity through the array. We hereby report development of polymer refractive MLAs by utilizing polymer stamping technique. To obtain uniformly arrayed high fill-factor microlenses, we employed isotropically wet-etched single-crystalline quartz as a master stamp with the aim of exploiting precise control ability of etching technique. The etched plano-concave patterns were identically duplicated onto poly(dimethylsiloxane) (PDMS) via two polymer replication steps. The replicated micropatterns exhibited uniform configurations and extremely high fill-factor, and their pitch, height, and radius of curvature were 132, 60, and 105 µm, respectively. A high refractive index UV-curable resin (Norland Optical Adhesive 61) was evenly spin-coated onto the PDMS micropatterns, and then, fully cured by illuminating UV light. The light illuminated through the PDMS-side can be focused on a focal plane at a certain focal distance, depending on microcurvatures and difference in refractive index between PDMS (1.41) and UV-curable resin (1.58). In optical refraction modeling using Light Tools simulation tool, the collimated light was greatly refracted forming beam spot array at the focal length of 890 µm. The experimentally measured focal length of the developed MLAs was approximately 900 µm, showing a great accordance with the calculated one. The spot diameter was measured to be 6.6 µm. Almost negligible deformations were observed in our thermal reliability test. The proposed MLA is highly promising for many opto-electronic devices attributed to its simple fabrication, mechanical flexibility, and great optical properties.

8250-06, Session 2

Axial phase measurements of light interacting with microstructures

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Light that is send on microstructures, for instance, dielectric microspheres [Photonic Nanojet] or micrometer-size metallic discs [the spot of Arago], exhibit peculiar axial phase features when passing the structure, e.g., phase anomaly. We present an experimental method to study such light interactions by means of measureing the three-dimensional (3D) amplitude and phase distributions with a high-resolution interference microscope (HRIM). The instrument combines a high-resolution microscope with a multi-wavelength Mach-Zehnder interferometer and allows measurements in free space and in immersion. Depending on the filling medium of the object space between an observing microscope objective and a sample, the HRIM can be operated in two different measurement modes: "longitudinal-differential" phase mode and "propagation" phase mode. Phase data measured in the differential mode directly give the axial phase deviation with respect to a plane wave. Conventional studies of such samples are often limited to the paraxial approximation and far-field measurements. For the first time, we experimentally demonstrate high-resolution phase studies of light emerging from microstructures of sizes smaller than 10 µm, where propagation is mediated in the Fresnel diffraction regime and non-paraxial field contributions have to be considered. Superluminal phase propagation of a diffractive hotspot (the spot of Arago) and the Gouy phase shift of a scattered hotspot (Photonic Nanojet) will be discussed as examples.

8250-07, Session 2

Non destructive static and dynamic MEMS characterization using supercontinuum scanning white light interferometry

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Scanning White Light Interferometry (SWLI) featuring high vertical precision can measure high steps and multiple stacked surfaces. This makes it popular for MEMS characterization. SWLI performance depends on its light source. To measure layered silicon structures a source with broad bandwidth inside the infrared (IR) region is optimal. On other hand fast light modulation is needed for stroboscopic measurements of oscillating structures. Typical SWLI light sources - LEDs and Halogen (Hg) bulbs - fulfill only one of these requirements.

To overcome this shortcoming we equipped our SWLI setup with a supercontinuum (SC) light source produced by fiberware Gmbh (Ilum 100 USB II). The source can produce short light pulses with high intensity and a wide continuous spectrum both in visible and IR regions. This allows us to see inside silicon, to separate closely spaced layers and to characterize oscillating samples using the same light source. We tested our setup by measuring in plane and out of plane oscillating thermal bridges with visible light, as well as top and bottom surfaces of silicon structures using IR light. The wide SC spectrum creates localized interferograms. This allowed us to measure surfaces with small (4 µm) vertical separation inside a silicon structure. The stroboscopically measured profiles of oscillating thermal bridges were comparable to those measured using a white LED. The results of static measurements were similar to those achieved with an Hg lamp.

8250-08, Session 2

Low coherence interferometry, spectroscopically resolved reflectance, and hyperspectral imaging methods for novel high resolution pressure sensors membrane thickness and MEMS metrology

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In past eight years, we have observed success of fiber optic low coherence probe technology in various areas of manufacturing including packaging, semiconductor, MEMS, photonics, and precision manufacturing industries [1]. The fiber optic probes are commonly used to monitor thickness during wafer thinning for modern nano-scale memories applications and deposition of compound materials for laser and LED applications.

We present our new system which allows metrology of novel small pressure sensors membranes having dimensions below 50 um without removing them from gelpack plastic enclosure. This novel system provides lateral resolution down to 1 um. We demonstrated the vertical limits for the repeatability membrane thickness metrology to be below 0.1% of the membrane thickness in the combined metrology system. Similar results can be achieved for the silicon on insulator (SOI) structures.

The simple technology based on Michelson interferometer as disclosed in earlier [2], [3] suffers several drawbacks due to sensitivity on strain and length of the probe cable. These shortcomings severely limited application of the technology, and made maintenance and service of the metrology systems difficult. Due to polarization sensitivity applications of this technology on non-stationary robotic arms was difficult.

In this paper we propose a new solution involving novel hardware design, and novel data processing algorithm based on the the analysis of auto-correlation reflection signal from the feature in the proximity of the and of the fiber, eliminating need to additional free space reference mirror.

The solution is applying modified auto-correlation schemes which is not sensitive to stress, and can be used with arbitrary long optical fiber cables. The reduced size of the new sensor is particularly promising for in-site applications where it can be integrated into automated systems involving moving probes.

References:

1.W.J. Walecki, et al “Novel non-contact wafer mapping and stress metrologies for thin and ultrathin chip manufacturing applications” 3 rd International Workshop on Thin Semiconductor Devices - Manufacturing and Applications November 25, 2002, Munich, Germany

2.W.J. Walecki, et al US Patent 7,116,429

3.W.J. Walecki, et al US Patent 7,502,121

8250-09, Session 3

Reliability of high I/O high density CCGA interconnect electronic packages under extreme temperatures

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Ceramic column grid array (CCGA) packages have increasing been in use based on their advantages such as high interconnect density, very good thermal and electrical performances, compatibility with standard surface-mount packaging assembly processes, and so on. CCGA packages are used in space applications such as in logic and microprocessor functions, telecommunications, payload electronics, and flight avionics. As these packages tend to have less solder joint strain relief than leaded packages or more strain relief over lead-less chip carrier packages, the reliability of CCGA packages is very important for short-term and long-term space missions.

We have employed high density CCGA 1152 and 1272 daisy chained packages in this preliminary reliability study. Each package is divided into several daisy-chained sections. The physical dimensions of CCGA1152 package is 35 mm x 35 mm with a 34 x 34 array of columns with a 1 mm pitch. The dimension of the CCGA1272 package is 37.5 mm x 37.5 mm with a 36 x 36 array with a 1 mm pitch. The columns are made up of 80%/20% Sn/Pb material.

CCGA interconnect electronic package printed wiring boards have been assembled and inspected using non-destructive techniques. The assembled CCGA boards will be subjected to extreme temperature thermal cycling to assess their reliability for future deep space missions. The resistance of daisy-chained interconnect sections will be monitored continuously during thermal cycling.

This paper will describe the experimental test results of CCGA packages tested in extreme temperatures. Standard Weibull analysis tools, optical inspection, and x-ray inspection tools will be used to assess the reliability of high density CCGA package for deep space missions.

8250-10, Session 3

Characterization of a flourocarbon SAM coated MEMS tribogauge

A. Vijayasai, T. E. Dallas, G. Sivakumar, C. Anderson, R. Gale, Jr., G. Ramachandran, Texas Tech Univ. (United States)

A MEMS tribogauge was used for on-chip and in-situ characterization of nano-tribological phenomena (stiction, friction, and wear of coated polysilicon surfaces). The device was fabricated using the SUMMiT-V process. Measurements were made on sidewall surfaces on the polysilicon-3 layer. The device consists of two orthogonally positioned comb-drive assemblies that are used for both actuation and sensing. One assembly is used to apply a normal load (Fn) to contacting surface, while the other induces a tangential load (FT). Precise position control is tracked by employing a LabVIEW controlled AD7747 capacitance sense mechanism. The resolution of the characterization apparatus is ±10nm.

Three different types of tribogauge are tested; two of them have a chemisorbed layer of fluorocarbon self-assembled monolayer (FSAM) coatings and one with no FSAM coating. The two types of FSAM coatings are FOTS and FDTS. The tribogauge with no FSAM coating is ‘air plasma’ treated to remove organic contaminants leaving behind -OH bonds on top of the MEMS surface (native oxide, SiO2). Characterization using the tribogauge for each coating type includes: measurement of baseline stiction force, static and dynamic coefficient of friction, induced stiction force calculated after specific load cycles (Finduced). Experiments showed that the induced stiction force increases in proportion to the increase in the number of load cycles, indicating erosion of the FSAM coating and topographical changes to the interacting surfaces. The air plasma treated tribogauge was used to measure the baseline stiction force (Fplasma).

8250-11, Session 3

Characterization of a nanocoating using a MEMS tribogauge

A. Vijayasai, T. E. Dallas, G. Sivakumar, C. Anderson, R. Gale, Jr., G. Ramachandran, Texas Tech Univ. (United States)

A chemisorbed fluorocarbon self-assembled monolayer (FSAM) layer on MEMS surfaces can greatly improve device reliability by reducing the in-use stiction force. In this work, we describe the use of a MEMS tribogauge for FSAM coating and process parameter characterization. Our objective is to obtain an optimized recipe for depositing a conformal FSAM coating on MEMS devices while minimizing precursor chemical usage.

We use a commercially available nanocoating tool for depositing the FSAM coating. The reaction chemistry is started by injecting precursor 1 (a mixture of H2O + alcohol) at 45°C, followed by the timed injection of precursor 2 (tridecafluoro-1,1,2,2-tetrahydrooctyltrichlorosilane, commonly abbreviated as FOTS) at 95°C. Throughout the experiment, the chamber temperature is maintained at 45°C and pressure is controlled by a vacuum pump. Five different coating recipes with different injection times for P2 are evaluated with the tribogauge. Injection times of 2 sec (R1), 5 sec (R2), 7 sec (R3), 10 sec (R4) and 15 sec (R5) were chosen for the experiments.

The MEMS tribogauge measures stiction force between two interacting surfaces. The interacting surfaces are exposed to many load cycles. After a 10,000 load cycle experiment, stiction force increase for R3, R4 and R5 are 1420 nN, 780 nN, 810 nN respectively; whereas for R1 and R2 the device failed at 1600 and 1800 cycles, respectively. We believe in R1 and R2 the tribogauge failed because of in-complete coverage of FSAM on the interacting surfaces. In R3 - R5, we believe there is conformal deposition of FSAM leading to minimal change in stiction force. With ideal usage of precursor chemicals we claim recipe R4 provides the best results for poly-Si MEMS devices.

8250-13, Session 4

Development of a new deformable mirror towards AO commercialization

X. Wu, Microscale, Inc. (United States)

We present an effort of developing a new deformable mirror towards ocular AO commercialization by addressing the technical challenges facing the current ocular AO that include the inability to handle aberrations inherent in clinical populations, significant power dissipation within the array, the size and weight of driver electronics, and the high cost that prohibits mirror integration into commercial ophthalmic instruments such as optical coherence tomography (OCT) systems. This technology holds the promise of enabling an AO commercialization into ophthalmic instruments by improving imaging resolution to up to one order of magnitude, reducing the form factor of the entire programmable adaptive optics (AO) module (with ASIC driver included) to that of a PGA (Pin Grid Array) IC package, and by offering the AO module to ophthalmic OCT manufacturers at an incremental cost of less than 10% of the entire OCT system. The technology is currently being prototyped.

8250-14, Session 4

MEMS deformable mirrors for laser applications

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

An exciting area for wavefront control is in industrial laser micromachining. Lasers are increasingly being employed to micromachine features in a vast array of materials that span application areas such as photo voltaics (PV), high-density interconnect (HDI), and semiconductors. The use of a wavefront correctors in laser machining equipment would enable not only fast focus corrections for tracking parts, but beam shaping as well.

Iris AO has been developing MEMS-based segmented deformable mirrors for high-power laser applications. Coatings of the DMs with >99.75% reflectance dielectric stacks have been demonstrated from UV-NIR. Laser testing of the DMs show the ability to handle 150 W/cm^2 with existing packaging and nearly 10X more for optimized packaging. This paper will describe the fabrication and test results. It will also provide a roadmap for the ongoing development of the dielectric DMs and packaging for them.

8250-15, Session 4

Custom bolometric detector arrays: from MWIR to THz

H. Jerominek, C. Alain, A. Bergeron, INO (Canada)

Uncooled IR bolometric detector arrays are among the most successful MEMS devices ever developed. Several versions of these microdevices are now off-the-shelf products with multiple applications in the areas of defense, security, industrial process control and preventive maintenance, and automobile. Among all the suppliers of these devices, INO is the only one specialized in design and manufacturing of custom bolometric detectors for specific applications and wavelength bands.

This presentation will illustrate INO's unique contribution to development of new detector architectures and the instrumentation based on these devices.

INO's specialty is custom bolometric detector arrays with a pixel count varying from 80x60 to 1280x1024 pixels, a pitch varying from 52 to 12 µm for LWIR, a pitch varying from 35 to 100 µm for THz, and a NETD as low as 25 mK. Several examples of these devices will be presented, including unique detector arrays optimized for THz operation.

Several examples of the instrument platforms will be presented including a miniature radiometer MiRAD built around a 256x1 pixel detector array with an extremely low power consumption, a New IR Sensor Technology (NIRST) instrument based on a 512x3 pixel detector array, a Broad Band Radiometer equipped with an array of 32x1 pixels on a 100 µm pitch, and an IRXCAM camera core using various pixel count bolometric detector arrays operating both in LWIR and THz parts of the spectrum.

8250-20, Session 4

The unsettled world of leak rate physics: 1 atm-large volume considerations do not apply to MEMS packages, a practitioner's perspective

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The world of leak testing, and the applicable physics is unsettled. While globally lower MIL-STD leak rate criteria are under consideration, even for 1 atm-large volume packages, industry is moving rapidly into very small volume MEMS and vacuum packaging for advanced devices. These changes point out serious conceptual disconnects between the reality of properly characterizing a leak and the conceptual tools used to ensure the desired lifetime. The physical understandings and associated tool sets used to test and model the leaks are described. We modeled two actual packages. One package is a large, ≈200 cc internal volume multichip module for aerospace applications and the second is a small ≈0.01cc volume MEMS package for sensor applications. The impacts of various physical models of leak flow into a package are compared to include Fickian Diffusion, The Davy Model, Howl-Mann, and an empirically derived model based on Kr-85 leak testing as called out in the most recent edition of MIL-STD-883. As shown in the comparisons, simple He leak testing and physical models based thereon fall apart in the small volume MEMS packaging space.

8250-21, Session 4

Ultra-compact illumination module for multi-aperture imaging systems

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Current applications in biomedical imaging and machine vision require close-up optical systems with high resolution. The combination of a fast image acquisition with the demand for extended object fields with respect to automation and miniaturization is extremely challenging for the design and fabrication of such systems. Standard commercial optical systems either require bulky setups or depend on scanning techniques in order to meet these requirements. Our group has proposed a multi-aperture approach based on a parallel image transfer to overcome the current constraints. Applying a stack of two-dimensional refractive microlens arrays enables to image an extended field of 36x24 mm2 with a resolution as high as 250 LP/mm. However, so far the system relies on the illumination by external light sources through the object, which limits the application to (semi-) transparent targets.

We demonstrate the optical design, fabrication and testing of an ultra-compact front side illumination module for such a multi-aperture system. A thin integrated glass substrate, which is structured with an array of reflecting microoptical elements, is initially guiding light of attached LED sources. Subsequently, the elements are utilized to efficiently couple out the light into the object space. As a result we maintain the extremely short working distance of 1.3 mm without a degradation of the imaging performance. By tailoring the shape as well as the spatial distribution of the microstructures we optimize the signal-to-noise ratio and assure a high homogeneity over the whole field. The reflecting structures are realized by state of the art microoptical manufacturing techniques on wafer level such as lithography, RIE-etching and metal coating.

8252-08, Session 5

Net flux sensors for the measurement of Mars surface radiation budget

L. Ngo Phong, A. Anas, Canadian Space Agency (Canada); M. Daly, York Univ. (Canada); F. Chateauneuf, INO (Canada)

Unlike orbital measurements, surface measurements of the Martian atmosphere do not require complex inversions of measured radiances. Further, they provide the lower boundary conditions and validation points for orbital retrievals. To date, surface measurements of the radiation budget components have not yet been made and other surface meteorological data remain scarce and suffer from the lack of the time and area coverage. We report on the development of the net flux sensor for the measurement of the downwelling and upwelling solar and longwave radiative fluxes close to the surface of Mars in four bands: 0.3-2.8 um, 14-16 um, 24.3-26.2 um, and 4.5-42 um. This sensor is intended for a wireless network of meteorological sensors (net flux, wind, water vapor concentration, pressure, and temperature) for the in-situ characterization of Martian atmosphere. The low power connectivity of the network relies on the use of the IEEE 802.15.4 standard. Given the need for multiple nodes of the network to ensure time and area coverage, it is required that the sensor nodes be miniaturized. Because of miniaturization, the effects from self-shadowing and re-radiation will require compensation or result in lost data. To mitigate these effects, we devise prototypes that allow subsampling the field-of-view to areas where these effects are not significant. The pyrgeometer of the sensor provides a field-of-view in the range from 140 to 180 degrees. To ensure small spectral variation and high resolution, both the pyranometer and pyrgeometer consist of goldblack coated VOx microbolometers. The details on their microfabrication and packaging will be reported.

8252-09, Session 5

Large MEMS-based programmable reflective slit mask for multi-object spectroscopy fabricated using multiple wafer-level bonding

M. D. Canonica, Ecole Polytechnique Fédérale de Lausanne (Switzerland); F. Zamkotsian, P. Lanzoni, Observatoire Astronomique de Marseille-Provence (France); W. Noell, N. de Rooij, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Multi-object spectroscopy (MOS) gives infrared spectra of faint astronomical objects that provide information on the evolution of the Universe. MOS requires a slit mask for object selection at the focal plane of the telescope. We are developing MEMS-based programmable reflective slit masks composed of 2048 individually addressable micromirrors. Each micromirror measures 100 x 200 µm2 and is electrostatically tilted providing a precise angle of 20°. The main requirements for these arrays are precise and uniform tilt angle over the whole device, uniformity of the mirror electro-mechanical behavior, a low mirror deformation and individual addressing capability of each mirror. This capability of our array is achieved using a line-column algorithm based on an optimized voltage-tilt hysteresis of the electrostatic actuator.

A third generation of micromirror arrays composed of 2048 micromirrors (32 x 64) and modeled for individual addressing were fabricated using fusion and eutectic wafer-level bonding. These micromirrors without coating show a peak-to-valley deformation less than 5 nm, a tilt angle of 20° for an actuation voltage of 120 V. A first experiment of the line-column algorithm was demonstrated under a probe station by actuating individually 1 x 3 micromirrors and 2 x 2 micromirrors. Devices are currently packaged, wire-bonded and integrated to a dedicated electronics to demonstrate the individual actuation of numerous micromirrors.

In order, to avoid spoiling of the optical source by the thermal emission of the instrument, the array has to work in a cryogenic environment (90 K). Therefore, a cryogenic experiment for these devices is currently under preparation and ongoing.

8250-16, Session 5

MEMS technology for miniaturized space systems: needs, status and perspectives

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In the past two decades, Micro-Electro-Mechanical System (MEMS) technology has significantly been advanced. The progress of MEMS offers potentials and opportunities for miniaturized space systems, especially micro-and nano-satellites. By using this technology, also small countries can play a strong role in future space exploration and applications. On the other side, future applications of miniaturized space systems have demanding needs, which call for MEMS components, thus further boosting the development of the MEMS technology.

This paper addresses the needs, status and perspectives of the MEMS technology for miniaturized space systems from the perspective of a spacecraft developer. First, past and expected future missions utilizing miniaturized space systems are discussed , followed by an analysis of mission needs on various aspects, such as performance, reliability, cost and unique functionality of MEMS components. Then, the state-of-the-art MEMS technologies are addressed that have been developed for space applications based upon future mission needs. A special interest is the Research and Development (R&D) for space-based MEMS technology in The Netherlands, which were initiated five years ago and have resulted in considerable achievements. Specific developments for sensors and actuators will be presented. Finally, the perspectives of space-based MEMS technology will be addressed based on the analysis of both future mission needs and technological trend.

8250-17, Session 5

MOEMS devices designed and tested for astronomical instrumentation in space

F. Zamkotsian, Observatoire Astronomique de Marseille-Provence (France); W. Noell, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Next-generation astronomical instrumentation for ground-based and space telescopes could use MOEMS devices. Among them, Multi-Object Spectrographs (MOS) are the major instruments for studying primary galaxies and remote and faint objects. A promising solution for the object selection system is the use of MOEMS devices such as micromirror arrays which allow the remote control of the multi-slit configuration in real time.

We are engaged in a European development of MMA for generating reflective slit masks. Prototypes of MMA with single-crystal silicon micromirrors were successfully designed, fabricated and tested. 100x200μm2 micromirrors can be tilted by electrostatic actuation yielding 20° mechanical tilt-angle. The micromirrors were successfully actuated before, during and after cryogenic cooling at 92K. Line-column addressing for individual mirrors has also been demonstrated. We are currently developing and fabricating arrays of larger size (several thousands micromirrors).

We are also engaged in a technical assessment of using a 2048 x 1080 DMD from Texas Instruments for space applications. For a MOS in space, the device should work in vacuum and at low temperature. Our tests reveal that the DMD remains fully operational at -40°C and in vacuum. A 1038 hours life test in space survey conditions, Total Ionizing Dose radiation, thermal cycling and vibrations/shocks have also been successfully completed. These results do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements.

These developments and tests demonstrate the full ability of this type of components for space instrumentation, especially in multi-object spectroscopy applications.

8250-18, Session 5

Performance prediction and characterization of highly insulated microbolometers for space applications

Z. Xu, Canadian Space Agency (Canada) and INO (Canada); L. Ngo Phong, Canadian Space Agency (Canada); T. Pope, INO (Canada)

There is an increasing demand for high spatial resolutions and large swath widths in Earth observation applications. Previously we developed linear arrays of 512x3 microbolometers that provide a resolution of 350 m from low Earth orbit under the SAC-D Aquarius mission. To improve the resolution and swath width, higher thermal isolation and fill factor of the microbolometer need to be achieved. This paper reports on the investigation of different structures of highly insulated 35 um pitch microbolometers. Each structure consists of two levels of suspended Si3N4 platforms with the upper level containing mainly the bolometer element and the lower level providing room for varying hinge length. In this work the cross section of the hinge was kept to 0.68 um2, and the length of the hinge was in the range from 64 to 105 um. Such structure allows for an increased thermal isolation of the microbolometer without the penalty of decreasing the fill factor. A numerical model was used to predict the figures of merit of the resulting device for each structure. Experimental validation was further carried out on the microfabricated devices, showing a good agreement with the computed results. It was found that the thermal conductance, in the range from 85 to 135 nW/K, varies inversely with the hinge length. The microbolometer structure with the highest level of thermal isolation showed a detectivity of better than 5 × 10e8 cmHz1/2/W and a response time of 8 ms. The selection of the devices for use in specific space applications will be discussed.

8250-19, Poster Session

Enhanced terahertz transmission by surface plasmon resonance

Y. Wen, J. Yang, X. Yu, Peking Univ. (China); Y. Zhao, X. Liu, L. Dong, Beijing Institute of Technology (China)

The surface plasmon resonance (SPR) between metal and dielectric material has a good enhancement on electromagnetic wave transmission. In this paper, a series of two-dimension (2D) metal gratings and spiral structures with different geometrical size were experimentally tested by Terahertz time-domain spectroscopy (THz-TDS). The experiment results show that the 2D metal gratings have almost 70% increasement on terahertz transmission than the pure silicon substrate in the range of 0.2-2.5THz, which indicates a strong coupling in the terahertz range, and the resonance mode shows a blue shift. On the other hand, the influence of different radiation directions was analyzed. It presents that the slightly higher transmission can be achieved when terahertz wave radiate from the front side than the back side. It reveals that surface plasmon resonance can enhance the terahertz transmission efficiently and has potential applications in security imaging, biological analysis and spectroscopy.

Conference 8251: Microfluidics, BioMEMS, and Medical Microsystems X

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8251-01, Session 1

Microfluidic cell culture systems with integrated sensors for drug screening

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Microscale three-dimensional constructs can more closely mimic the natural extracellular environment than traditional two-dimensional cell culture. The tissue culture environment can have a dramatic influence on cell behavior, and this phenomenon has a crucial impact on the responses of cancer cells to therapeutic agents. Our microfluidic platform combines a 3D matrix which can be formed in situ inside the microfluidic platform, encapsulating the cells in well-defined volumes of hydrogels. This 3D system makes it possible to establish growth in multicellular spheroids which mimic solid tumors and will allow us to monitor the response of individual spheroids to drug treatment. With the ability to dynamically control the microenvironment, we can also create physiological drug profiles. In addition, tissue hypoxia in cancerous tumors has been linked with resistance to radiation therapy and many anticancer drugs, as well as increased likelihood of metastasis and decreased likelihood of successful treatment and patient survival. Our work will integrate a thin-film oxygen sensor with a microfluidic oxygen gradient generator to allow us to study effects of hypoxia. This platform will provide a means to assess the impact of treatment standards as well as new treatments designed to achieve more personalized therapy. This platform will also improve cell-based validation in the drug discovery process, decreasing the cost and increasing the speed in screening large numbers of compounds.

8251-02, Session 1

Optofluidic microdevice for algae size measurements and species classification

A. Schaap, Y. Bellouard, Technische Univ. Eindhoven (Netherlands); T. Rohrlack, Norwegian Institute for Water Research (Norway)

The early detection of changes in the level and composition of algae is essential for tracking water quality and environmental changes [1]. Current approaches require the collection of a specimen which is later analyzed in a laboratory: this slow and expensive approach prevents the rapid identification of and response to potential outbreaks [2]. We present a microfluidic chip for classifying and quantifying algae species in water in real-time.

The chip is fabricated by femtosecond laser processing which locally modifies the properties of a monolithic fused silica substrate [3]. A curved waveguide is patterned below the surface, ending perpendicular to a microfluidic channel at the surface; a 1550 nm laser is coupled to the waveguide and illuminates a 4-quad photodetector across the channel while algae travel through the channel. To match this signal to the algae type, a microscope-mounted camera takes a photo of the algae in the channel.

We have previously shown this simple device's ability to distinguish the toxic algae Cyanothece in a five-species mixed sample [3]. Here we present characteristic signals obtained from nine species of algae and demonstrate correlations between the average volume of the individual algae cells of each species with the photodiode signals obtained from that species. The photodiode signals are also used to identify the species of individual algae in a three-species mixture with an 84% success rate and further improvements are anticipated. Preliminary modeling of the light-algae interactions along with other potential applications in particle and biological studies will be discussed.

References

[1] L. Barsanti and P. Gualtieri, Algae: Anatomy, Biochemistry, and Biotechnology, Taylor & Francis, Boca Raton, 2006.

[2] I. Chorus and J. Bartram, Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management, World Health Organization, 1999.

[3] A. Schaap, Y. Bellouard, and T. Rohrlack, Optofluidic lab-on-a-chip for rapid algae population screening, Biomedical Optics Express 2, 658-664, 2011.

8251-03, Session 1

Probing the tumor microenvironment: collection and induction

J. K. Williams, M. R. Padgen, Univ. at Albany (United States); F. Gertler, Massachusetts Institute of Technology (United States); J. Wyckoff, J. Condeelis, Albert Einstein College of Medicine of Yeshiva Univ. (United States); J. Castracane, College of Nanoscale Science & Engineering (United States)

The Nano Intravital Device, or NANIVID, is under development as an optically transparent, implantable tool to study the tumor microenvironment. Two etched glass substrates are sealed using a thin polymer membrane to create a reservoir with a single outlet. This reservoir is loaded with a custom hydrogel blend that contains growth factors or other chemicals to be delivered to the tumor microenvironment. When the device is implanted in the tumor, the hydrogel will swell and release these entrapped molecules, forming a gradient. Validation of the device has been performed in vitro using epidermal growth factor (EGF) and MenaINV, a highly invasive, rat mammary adenocarcinoma cell line. In both 2-D and 3-D environments, cells migrated toward the gradient of EGF released from the device. The chorioallantoic membrane of White Leghorn chicken eggs is being utilized to grow xenograft tumors that will be used for ex vivo cell collection. Currently, device optimization is being performed for use as an in vivo cell collection tool. As a second application, the device is being explored as a delivery vehicle for chemicals that induce controlled changes in the tumor microenvironment. Cobalt chloride (CoCl2), a hypoxia mimetic, has been loaded into the device and in vitro testing was performed. Immunostaining for hypoxia-inducible factor-1α was used to verify the delivery of CoCl2 from the device. In the future, other induction targets will be explored, including the generation of reactive oxygen species and manipulation of extracellular matrix stiffness.

8251-04, Session 1

Mammosphere culture of cancer stem cells in a microfluidic device

K. Saadin, I. M. White, Univ. of Maryland, College Park (United States)

It is known that tumor-initiating cells with stem-like properties will form spherical colonies - termed mammospheres - when cultured in serum-free media on low-attachment substrates. Currently this assay is performed in commercially available 96-well trays with low-attachment surfaces. Here we report a novel microsystem that features on-chip mammosphere culture on low attachment surfaces. We have cultured mammospheres in this microsystem from well-studied human breast cancer cell lines. To enable the long-term culture of these unattached cells, we have integrated diffusion-based delivery columns that provide zero-convection delivery of reagents, such as fresh media, staining agents, or drugs. The multi-layer system consists of parallel cell-culture chambers on top of a low-attachment surface, connected vertically with a microfluidic reagent delivery layer. This design incorporates a reagent reservoir, which is necessary to reduce evaporation from the cell culture micro-chambers. The development of this microsystem will lead to the integration of mammosphere culture with other microfluidic functions, including circulating tumor cell recovery and high throughput drug screening. This will enable the cancer research community to achieve a much greater understanding of these tumor initiating cancer stem cells.

8251-05, Session 1

Fast self-assembly kinetics of alkanethiols on gold nano-particles via microfluidic localized surface plasmon resonance spectroscopy

S. Asiaei, P. M. Nieva, M. Vijayan, Univ. of Waterloo (Canada)

This paper reports on improved kinetics for reducing the formation time of self-assembled monolayer's (SAM) of alkanethiols on gold nanoparticles. In order to load the SAMs on nanoparticles, they are conventionally incubated in 1mM SAM ethanolic solutions for 24-48 hours. Here, we report a considerably faster 8 minute kinetics achieved by modifying the flow rate, concentration and geometry of the microchannel.

SAM growth kinetics are often described by a Langmuir model which ignores fluidic and geometrical effects such as flow rate and height of the self-assembly chamber. Recently, we have succeeded in incorporating these parameters in the study of SAM kinetics on planar gold. The results, accompanied by experimental verification will be presented in IEEE sensors 2011. In this paper the fluidic and geometrical effects on the SAM growth on nanoparticles will be studied. The considered parameters include concentration, flow rate, nanoparticles geometry, and inter nanoparticles distance, which have not yet been comprehensively examined.

A finite element model relates the SAM molecules' mass transport to the available reaction sites on the nanoparticles. The numerical simulation results are verified by an analytical model and localized surface plasmon resonance (LSPR) spectroscopy. SAM quality resulted from the fast protocol is compared to the conventional protocol by real time LSPR monitoring of a standard biotin/streptavidin pair binding to the SAMs formed according to each protocol. The same binding capacity was observed and experimental results agree well with literature. The fast self-assembly achieved has a considerable impact on reducing the preparation time of bio-medical sensors.

8251-06, Session 1

Magnetic particle-based sample-prep and valveing in microfluidic devices

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There is a need to design an integrated microfluidic platform as simple and lean as possible in order to meet the requirements for a miniaturized system. Magnetic particles show a great versatility in performing several of the functions necessary in many microfluidic assays.

We therefore have developed a compact portable system to perform magnetic-bead-based sample preparation steps in a chip such as DNA-extraction or particle-enhanced mixing of reagents.

A central application in a standard biochemical/biological/medical laboratory is represented by PCR. The execution of a cyclic heating profile during PCR is a considerable stress for chip and liquid inside the chip because evaporation and uncontrolled condensation or unintended motion of the PCR solution.

One strategy to overcome this problem consists of the implementation of valves flanking a stationary PCR in appropriate incubation cavities. In addition to the well-known elastomeric membrane valves, wax-valves mechanical turning or rotary valves flanking the PCR chamber, we present in this paper the use of clustered magnetic particles as blocking valves for such reaction chambers.

We report on the capability of assembled magnetic particles to act as rather simple configurated valves during a PCR typical temperature regime. These novel valves efficiently withstand 1.5 bar pressure, prevent loss of aqueous liquid inside the reaction chamber via evaporation or bubble formation, and do not express adverse effects on any biological reaction inside the chip-based PCR cavity. The latter properties have been proven by a set of different PCRs performed in chip-based cavities.

8251-07, Session 1

A microfluidic device for studies of microrod flow dynamics

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We describe a microfluidic device for studying the orientational dynamics of microrods. The device enables us to experimentally investigate the tumbling of microrods immersed in the shear flow in a microfluidic channel with a depth of 400um and a width of 2.5 mm. The orientational dynamics was recorded using a 20X microscopic objective and a CCD camera. The microrods were produced by shearing microdroplets of photocurable epoxy resin. We show different examples of empirically observed tumbling. On the one hand we find that short stretches of the experimentally determined time series are well described by fits to solutions of Jeffery's approximate equation of motion [Jeffery, Proc. R. Soc. London. 102 (1922), 161-179]. On the other hand we find that the empirically observed trajectories drift between different solutions of Jeffery's equation. We discuss possible causes of this orbit drift.

8251-08, Session 2

Miniaturized neural interfaces and implants

T. Stieglitz, Albert-Ludwigs-Univ. Freiburg (Germany)

Neural prostheses are technical systems that interface nerves to treat the symptoms of neurological diseases and to restore at least partially sensory of motor functions of the body. Success stories have been written with the cochlear implant to restore hearing, with spinal cord stimulators to treat chronic pain as well as urge incontinence, and with deep brain stimulators in patients suffering from Parkinson's disease.

Highly complex neural implants for novel medical applications can be miniaturized either by means of precision mechanics technologies using known and established materials for electrodes, cables, and hermetic packages or by applying microsystems technologies.

Examples for both approaches will be introduced and discussed. They include electrodes arrays for recording of electrocorticograms during presurgical epilepsy diagnosis. These devices that have been manufactured using approved materials and a marking laser to achieve high integration density that is necessary for applications in the context of brain machine interfaces, e.g. on the motor cortex.

For further miniaturization, microtechnologies have been used to develop polymer-based flexible and light weighted electrode arrays to interface the peripheral and central nervous system. The material properties of polyimide as substrate and insulation material will be discussed as well as several application examples for nerve interfaces like cuffs, filament like electrodes and large arrays for subdural implantation.

The overview will be concluded with latest results that show possibilities to integrate additional sensor and actuator modalities into neural implants, for example as tools in the neuroscientific research field of optogenetics.

8251-09, Session 2

Integrated multi-sensing optrode for neural stimulation and recording

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Reverse engineering of human brain is one of a grand challenges, but the researchers are presented with relatively few tools at hand, particularly for in vivo studies. Invasive electrical neural probes such as the "Michigan probe" and "Tetrode" have provided tremendous value in recording neuronal action potential. Beyond electrophysiology, recent advances in optics, genetics, and biochemistry have enabled the investigation of brain function at various levels via light-based approaches such as absorption, fluorescence and optogenetics.

To enable the neuroscience and engineering community to better utilize these revolutionized advances, we are currently developing two multisensing optrodes for integrated optical stimulation and electrical recording. Each optrode design has an optical channel for localized light delivery as well as multiple electrodes for electrical recording. He have developed two fabrication methods for precise integration of the optical channel and the electrodes. The first device is based on atom-beam lithography that enables patterning of conductor lines and electrodes on non-planar substrate, in this case a 60 µm optical fiber. An insulating overcoat is then applied with vias opened to expose the electrodes. The second device is based on V-groove guided capillary assembly, where fabricated tetrode or microwire electrodes are inserted and centered inside a capillary filled with transparent polymer. The outer wall of the capillary is then etched to the desired wall thickness and inserted into another capillary filled with transparent polymer. Upon curing, the second capillary is completely removed. The resulting device consists of central electrodes and a surrounding annular light guide.

8251-10, Session 2

Point-of-care, portable microfluidic blood analyzer system

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Recent advances in MEMS technology have provided an opportunity to develop microfluidic devices with enormous potential for portable, point-of-care, low-cost medical diagnostic tools. Hand-held flow cytometers will soon be used in disease diagnosis and monitoring. Despite much interest in miniaturizing commercially available cytometers, they remain costly, bulky, and require expert operation. In this abstract, we report progress on the development of a battery-powered handheld blood analyzer that will quickly and automatically process a drop of whole human blood by real-time, on-chip magnetic separation of white blood cells (WBCs), fluorescence analysis of labeled WBC subsets, and counting a reproducible fraction of the red blood cells (RBCs) by light scattering.

The whole blood (WB) analyzer is composed of a micro-mixer, a special branching/separation system, an optical detection system, and electronic readout circuitry. A droplet of un-processed blood is mixed with the reagents, i.e. magnetic beads and fluorescent stain in the micro-mixer. Valve-less sorting is achieved by magnetic deflection of magnetic microparticle-labeled WBC. LED excitation in combination with an avalanche photodiode (APD) detection system is used for WBC subsets detection using several colors of immune-Qdots , while counting a reproducible fraction of red blood cells (RBC) is performed using a light scatting measurement with a photodiode. Optimized branching/channel width is achieved using Comsol Multi-PhysicsTM simulation. To accommodate full portability, all required power supplies (40v, ±10V, and +3V) are achieved using step-up voltage convertors from one battery. A simple on-board lock-in amplifier is developed to remove to increase the sensitivity/resolution of the readout circuitry.

8251-11, Session 2

A lab-on-a-chip system for the development of complex assays using modular microfluidic components

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For complex biological or diagnostic assays, the development of an integrated microfluidic device can be difficult and error-prone. For this reason, a modular approach, using individual microfluidic functional modules for the different process steps, can be advantageous. However often the interconnection of the modules proves to be tedious and the peripheral instrumentation to drive the various modules is cumbersome and of large size. For this reason, we have developed an integrated instrument platform which has generic functionalities such as valves and pumps, heating zones for continuous-flow PCR, moveable magnets for bead-based assays and an optical detection unit build into the instrument. The instrument holds a titerplate-sized carrier in which up to four microscopy-slide sized microfluidic modules can be clipped in. This allows for developing and optimizing individual assay steps without the need to modify the instrument or generate a completely new microfluidic cartridge.

As a proof-of-concept, the automated sample processing of liquor or blood culture in microfluidic structures for detection of currently occuring Neisseria meningitidis strains was carried out. This assay involves the extraction of bacterial DNA, the fluorescent labeling, amplification using PCR as well as the hybridization of the DNA molecules in three-dimensional capture sites spotted into a microchannel. To define the assay sensitivity, chip modules were tested with bacteria spiked samples of different origins and results were controlled by conventional techniques. For liquor or blood culture, the presence of 200 bacteria was detected within 1 hour.

8251-12, Session 3

Two-component injection molding for micofluidic devices

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In recent years there has been an increasing demand for functional integration in microfluidic devices. This integration often requires the use of different materials in order to generate the demanded performance. Typical examples for such integrated functionalities are on-chip valves or areas used for sealing one component against another, e.g. a microfluidic manifold against a sensor chip. Such functionalities have been described in the literature mainly by using elastomeric materials such as PDMS. However this material suffers from the lack of suitable high-volume manufacturing processes and its high material cost. For production of such hybrid material devices, two-component injection molding can prove to be a suitable microfabrication method. In two-component injection molding, a part is molded in two steps. In the first step, a hard thermoplastic material forms the rigid body of the part. The injection molding tool is then opened without ejecting the part and by applying a second molding cavity to the part, a second component, typically a thermoplastic elastomer, is molded onto the part. Care has to be taken in selecting a suitable material combination in order that the elastomeric component shows good adhesion on the thermoplastic body and that thermal expansion coefficients match. In our paper we will present several examples for such two-component injection molded microfluidic components such as a mechanical turning valve, microfluidic chips with gasketing structures and chips with plug seals to close a fluidic port.

8251-13, Session 3

Femtosecond laser written 3D optofluidic microsystems for capillary electrophoresis and cytometry

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The three-dimensional (3D) writing capability of a high repetition rate (1 MHz) femtosecond (fs) laser (IMRA µJewel D-400-VR) with a wavelength of 522 nm was harnessed together with wet-chemical etching for laser-patterning of 3D optofluidic microsystems in fused silica glass (Corning 7980). Selective chemical etching of laser irradiated glass with dilute hydrofluoric acid (5% HF) enabled microfabrication of high aspect-ratio embedded micro-channels and fine-period 3D glass meshes in a 3D inverted woodpile arrangement that permitted high density lab-on-a-chip integration of flow channels, reservoirs, glass chromatography columns, and optical circuit devices. In this paper, we present various 3D optofluidic microsystems formed over an arbitrary length in a two-step process.

Waveguides, reservoirs, micro-channels, and inverted-woodpile structures were first laser patterned and followed by selective wet etching controlled by the polarization orientation of the writing laser. With laser polarization perpendicular to the scanning direction, the volume nanogratings were aligned perpendicular to glass surfaces to facilitate HF etching and thus created designer shaped micro-channels with smooth side-wall surfaces and terminated with open reservoirs. An array of vertical access holes spaced 100 µm apart facilitate etching of continuous and highly uniform buried channels of unrestricted length in the glass to interconnect flow channels and reservoirs. Alternatively, laser polarization parallel to the scan direction provided low-loss optical waveguides with nanograting walls resisting the acid etching. Dual-channel capillary electrophoresis was demonstrated by simultaneous fluorescent detection of separating dyes in a 3D microsystem having over- and under-passing crossed channels. In addition, we demonstrated an on-chip cytometer based on capillary force to drive analytes through an embedded micro-channel into a calibrated reservoir for particle counting. Further, a new type of glass mesh structure is presented where a 3D inverted woodpile micro-channel array with diamond-like symmetry was integrated inside a micro-channel and applied to capillary electrophoretic chromatography. Femtosecond-laser processing thus enables rapid patterning of fully integrated 3D optofluidic systems in bulk fused silica glasses for numerous applications, and more generally opens new 3D design approaches and rapid prototyping methodology for advanced microsystems.

8251-14, Session 3

Automation of a work cell for polymer microdevice production: precise alignment and visual quality inspection

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Within the Microfactory Project, known as muFac, we work to realize a manufacturing assembly line system, and produce high-quality, low-cost polymer-based microfluidic devices with a Takt time of 2 minutes. In this paper we detail our work-cell manipulation strategy and rapid in-line inspection techniques. The manipulation strategy was designed to accommodate interaction among part-feeding, hot embossing, thermal bonding, and inspection machines. The required position repeatability across all processing steps is 10 microns. We designed a vacuum-chuck end-effector for a SCARA robot for coarse positioning. We improved the fine-positioning repeatability through a combination of end-effector compliance and kinematic alignment. The robustness of the alignment was analysed. The tested factors include: variation of the nominal start position, variation of the location of the kinematic mount in the workspace of the manipulator, and variation of the shape of the posts in the kinematic mount (spacing and shape). We achieved a position repeatability of 9.0 µm. A fast in-line inspection technique is used to map variation of embossed features with the variation of feature topology and with the variation of the processing parameters. We designed features whose shape and appearance varies with the processing parameters of embossing. We acquired images of these features produced under a range of processing conditions and determined image properties (based on the contour of a fill shape) related to variation in the processing conditions. We developed an algorithm to automatically analyze these images and to determine the processing parameters.

8251-15, Session 3

Polymer micromolds with near optical quality surface finishes

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Disposable microfluidic systems are used to avoid sample contamination in a variety of medical and environmental monitoring applications. A contactless hot intrusion (HI) process for fabricating reusable polymer micromolds with near "optical quality" surface finishes is described in this paper. A metallic hot intrusion mask with the desired microchannels and related passive components is first machined using a tightly focused beam from a diode-pumped solid-state (DPSS) laser. The polymer mold master is then created by pressing the 2D metallic mask onto a polymethylmethacrylate (PMMA) substrate. Since it is a contactless fabrication process the resultant 3D micro-reliefs have near optical quality surface finishes. Unfortunately, the desired micro-relief dimensions (height and width) are not easily related to the hot intrusion process parameters of pressure, temperature, and time exposure profile. A finite element model is introduced to assist the manufacturing engineer in predicting the behavior of the PMMA substrate material as it deforms under heat and pressure during micromold manufacture. The FEM model assumes that thermo-plastics like PMMA become "rubber like" when heated to a temperature slightly above the glass transition temperature. By controlling the material temperature and maintaining its malleable state, it is possible to use the stress-strain relationship to predict the profile dimensions of the imprinted microfeature. Examples of curved microchannels fabricated using PMMA mold masters are presented to illustrate the proposed methodology and verify the finite element model. In addition, the non-contact formation of the micro-reliefs simplifies the demolding process and helps to preserve the high quality surface finishes.

8251-16, Session 3

Manufacturing for lab-on-chip devices: variation analysis of flow rate delivered using a blister pack

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A 'blister-pack' is an on-chip liquid-reagent reservoir and delivery mechanism necessary for many commercial lab-on-a-chip applications. The blister contents are delivered into fluid channels by the push of an actuated plunger. This paper explores the sensitivity of the flow-rate produced by a blister-actuator pair to the expected manufacturing variations in blister and plunger dimensions and actuator motion. A numerical model of the blister-actuator pair is developed and the tool of Variation Simulation Modeling (VSM) is used to determine the expected and tolerable variation of fluid delivery. The critical dimensions relating flow-rate requirements to manufacturing variation are identified. This work involved performing a variation analysis of blister-packs to det¬ermine the critical sources of variation. A numerical model of the blister-actuator performance was developed and Monte Carlo simulations were conducted. Our product specification includes a flow-rate requirement of +/- 20%. The results show that, given the variation in our manufacturing process, the fluid delivery technique achieves this flow-rate requirement with a predicted out-of-specification rate of less than 0.01%. The plunger radius and starting height along with the blister height and radius were identified as the critical parameters; improved manufacturing control of these critical dimensions would reduce the expected flow-rate variation.

8251-17, Session 4

A simple single-detector system for simultaneous monitoring of O2 and CO2 gas concentration

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In this paper, we present a simple system for fluorescent environmental monitoring of multiple gas concentrations using a simple and robust single detector setup. Two gas-sensitive fluorescent films are illuminated by two separate excitation sources modulated at different frequencies. Cross-polarization is used to shield the excitation light form the detector, allowing fluorescent signals from both films to be simultaneously monitored and quantified using a microprocessor and lock-in detection. Simultaneous detection of O2 and CO2 in a mixture of gases is done as a proof of concept of this frequency discrimination technique. The detection of oxygen is based on the fluorescence quenching of platinum octaethylporphine (PtOEP) lumiphore in presence of O2. The detection of CO2 is based on fluorescence quenching of hydroxypyrene trisulfonic acid trisodium salt (HPTS) in presence of CO2. A single microprocessor is used to drive the excitation source (different color LEDs), and sample and analyze the detector response at the two different frequencies. The device demonstrated minimal crosstalk between the O2 and CO2 signals. The O2 concentration was measured in the useful range between 20% and 0%, and CO2 demonstrated a useful range between 2% and 0%. The whole arrangement is a compact and low-cost simultaneous multi-color fluorescent sensor system suitable for many biological, chemical, and gas-monitoring applications. The polarization filtering is color-independent and can be readily extended to systems with more than two colors; due to the frequency discrimination, it is immune to cross-talk in which one dye excites another.

8251-18, Session 4

Lab-on-a-chip sensor for measuring Zn by stripping voltammetry

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This work reports on the continuing development of a sensor for electrochemical measurement of heavy metal zinc in blood serum. Zinc is an essential trace metal, yet critically ill patients consistently demonstrate abnormally low blood zinc levels and thus supplementation has been proposed as therapeutic strategy. The conventional approach using atomic absorption spectroscopy is sensitive but has a long turnaround time (24-48hrs). Thus, sending blood samples to a centralized lab is not a viable option when patients must be monitored on the timescale of hours. Our electrochemical sensor relies on an environmentally-friendly bismuth electrode for metal determination by anodic stripping voltammetry. The sensor consists of a three electrode system, including a Bi working electrode, a Ag/AgCl reference electrode, and a Au auxiliary electrode. We improved sensor performance by streamlining fabrication and developing integrated interface. We optimized electrodeposition strategies for Bi working electrode with the goal of highly-uniform films and improved sensor performance. The optimized sensor was able to measure Zn in its physiological range 65~95µg/L. Ultimately, the developed point-of-care system will allow rapid (10~20min) metal measurements, and with further development and integrated sample preparation may be converted into a self-check platform for bedside monitoring. The optimization strategies we discuss here for Zn may be extended to other heavy metals.

8251-19, Session 4

Optical sensing for on-chip digital microfluidics

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A digital microfluidic implementation is introduced in this work for localized fluid actuation and optical sensing. The presented lab-on-a-chip device incorporates a digital microfluidic architecture that is inherently reconfigurable, as fluid actuation is brought about by external voltage signals prescribed through user-specified algorithms. At the same time, on-chip sensing is brought about by way of in-situ optical sampling. A form of confocal (resonant) optical refractometry is used as this probe to enhance the sensitivity between the optical probe and fluid of interest.

Contemporary microfluidic actuation challenges related to localization and device scalability are overcome through the introduction of a bi-layered digital microfluidic multiplexer. With such a structure, the onset of motion is set by differential combinations of voltage signals between upper (row) electrodes and lower (column) electrodes. The ultimate layout provides increased scalability for massively parallel microfluidic actuation applications with a minimal number of inputs.

A successful lab-on-a-chip device must incorporate capabilities for both microfluidic actuation (as described above) and sensing. The on-chip sensing technique employed here incorporates a confocal geometry between an electrode and a resonant microlens (fabricated by a new voltage-tuned polymer electro-dispensing technique). Such a geometry heightens the sensitivity between the optical probe and fluid state and allows the device to probe the refractive index of the internal fluid. This optical refractometry technique is merged with the digital microfluidic multiplexer, on a single lab-on-a-chip device, for on-chip sensing and actuation of a variety of fluids.

8251-21, Session 5

Highly accurate measurement of varying drug dosage for real-time analysis of chemo-mechanical response of cardiomyocytes

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A recent advancement in the study of drug development for cardiovascular diseases is based on measuring the mechanical response of a single cardiomyocyte to various drug concentrations. This method requires delivering a specific dose of the drug over a short period of time, while measuring the forces exerted by a cell which is kept inside a microchamber. However, the exact drug dosage is difficult to control for rapid variations in drug concentration, which hinders the accuracy of the measurements. This paper reports a highly sensitive technique for accurate and real-time measurement of minute variations in drug concentration. The fluid electrical conductivity is monitored using an array of electrodes along a micro-channel that eventually leads to the microchamber, where the cardiomyocyte is placed. The microfluidic setup is fabricated through bonding of a moulded PDMS layer to a glass substrate with patterned gold electrodes. The real-time differential measurements let us measure the local drug concentration with accuracies of better than 10pMol/mL. By using the data from all of the array electrodes, the profile of the drug plug as it travels along the microchannel from the injection point to the cell location can be derived with high precision. The multi-domain numerical simulations of the microfluidic setup are in line with the measured experimental data. Our technique can be easily integrated into many existing and new designs thus providing a robust approach for label-free measurement of fluid properties in cell viability studies.

8251-22, Session 5

Optofluidic backplane as a platform for modular system design

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Recently, various optofluidic devices have been proposed, mainly designed as Lab-on-a-Chips. They port highly integrated functionality by combining optics and microfluidics on one chip but are mostly designed for one application only and need external supply and control units to be operated. Here, we present an approach based on standardized backplane modules that serve as a platform for the flexible interconnection and control of microfluidic and optofluidic devices for multiple applications.

Each backplane module is fabricated in polymers (TOPAS 6013S) and consists of three layers (optical, microfluidic, and electronic). By interconnecting multiple modules, each layer builds a network in itself: (1) the optical layer containing waveguides and switches, (2) the microfluidic layer integrating channels and microvalves, and (3) the final layer carrying electronics for control of the active elements in the system.

We developed a linearly actuated mirror assembly, which is used as a light switch. It permits the controlled guiding of light to the optofluidic sensors in the system. We integrated shape memory alloy actuated microvalves into a fluid channel circuit, which allows controlled guiding of fluids.

At each module interface we integrated: (A) magnetic connectors, (B) sealing membranes allowing operation at $24 \cdot 10^5$ Pa, and (C) self-aligning optical connectors with measured coupling losses less than 0.4 dB.

The developed backplane enables the flexible combination of as many optofluidic devices as needed for the dedicated application, thus leading towards the development of custom-made micro total analysis systems. We operated the system with different sensors, micropumps, fluid mixers, and light sources.

8251-24, Session 5

Hybrid membrane-microfluidic components using a novel ceramic MEMS technology

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A novel hybrid nano/microfabrication technology has been employed to produce unique microfluidic components that integrate nanoporous membranes. The components are made by micromachining a self-organized nanostructured ceramic material that is biocompatible and amenable to surface chemistry modification. Microfluidic structures, such as channels and wells, can be made with a precision of <2 microns. Thin-film membranes can be integrated into the bottom of these structures, featuring a wide range of possible thicknesses, from 100 microns to <50 nanometers. These membranes can be made non-porous, to serve as simple sample supports. Alternatively, the membranes can be made porous, with controllable pore sizes from 200 to <5 nanometers, for sophisticated size-based separations. With support from the NIH SBIR program, we have built several unique devices, and used these devices to demonstrate improved bioseparations, cell culturing, and imaging (optical and electron microscopy) compared to standard technologies. Being ceramic, the material is much more robust to demanding environments (e.g. high/low temperatures, organic solvents), compared to polymer-based devices. Additionally, we have applied multiple surface modification techniques, including atomic layer deposition and silanization, to manipulate properties such as electrical conductivity and chemical adsorption. Importantly, surface modification can be applied conformally within the nanostructured ceramic material, without compromising the nanoporous geometry and architecture.

This microfabrication technology is highly scaleable, and thus can yield low-cost, reliable, disposable components and devices. Specific applications that can benefit from this technology includes cell culturing and assays, imaging by cryo-electron tomography, environmental sample processing, as well as many others.

8251-25, Session 5

3D nanoporous optofluidic device for high sensitivity SERS detection

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We report the demonstration of an optofluidic surface enhanced Raman spectroscopy (SERS) device that leverages nanoporous microfluidics to dramatically increase the SERS performance. A number of optofluidic approaches have been used to improve the detection limit of SERS in microfluidic channels, including active concentration of nanoparticles and/or analyte and passive concentration of nanoparticles. Previous reports have used a single nanofabricated fluidic channel to trap metal nanoparticles and adsorbed analytes. In this work, we utilize a significantly simpler fabrication approach by packing silica beads in a microfluidic channel to create a 3D nanofluidic concentration matrix. The device is fabricated using polydimethylsiloxane (PDMS) on glass using typical soft lithography methods. Due to the larger area of the nanoporous fluidic channel, this approach should be less prone to clogging than single nanofluidic inlets, and the loading time is decreased compared to previous reports. Using this microfluidic device, we achieved a detection limit of 4 femtomoles of Rhodamine 6G in 2 minutes. Compared to an open microfluidic channel, the 3D nanoporous concentration matrix increased the SERS signal by a factor of 250 due to the trapping of silver nanoclusters. Fiber optic cables are integrated into the PDMS to deliver excitation light directly to the detection volume and to collect Raman-scattered photons. As a result, the use of a laser diode and alignment-free integrated fiber optics implies the potential for the device to be used in portable and automated applications, such as the on-site detection of pesticides, water contaminants, and explosives.

8251-26, Session 6

Spiral inertial microfluidic devices for continuous blood cell separation

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research. It usually involves expensive instrumentation and skilled personnel (phlebotomist). Herein, we report on inertial microfluidic devices which achieve continuous size-based separation of cell mixtures with high throughput. These devices utilize hydrodynamic forces acting on cells within laminar flow, coupled with rotational Dean drag due to curvilinear microchannel geometry to focus cells in streams. We used Archimedean spirals with a single inlet and three or four outlets, optimized to achieve cell separation within the shorter downstream length (16cm as compared to 40cm in our previous designs). We first tested the devices with 10, 15, and 20 µm polystyrene particles to confirm focusing positions and determine the optimal separation parameters. We then used the spiral devices with 250µm x 100µm channels to separate plasma from blood cells with a >90% efficiency. We also separated RBCs, WBCs and platelets using a four outlet, 6-loop device with channel dimensions 500µm x 100µm, with a separation efficiency of ~70%. These devices offer a path towards performing CBC (complete blood count) on-chip, and reagent-free sample preparation. With simple planar structure and passive mechanism of separation, our approach offers a low-cost separation method that does not rely on biomarkers (immunoselection) and is simple to integrate with existing lab-on-chip systems.

8251-27, Session 6

Multiplexed fluorescence detection for point-of-care

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Fluorescence detection is an important analytical tool in different areas, including biological research and environmental monitoring. The spectrums are usually detected using a spectrophotometer which is cumbersome and expensive. The need of point-of-care (POC) for first responders has led to intense focus on miniaturization of portable detection systems. Such systems usually consist of three key components: light source, wavelength selection, and signal detection. LEDs have been widely accepted as light sources because they are inexpensive and provide various choices in wavelengths. Wavelength selection and signal detection, however, remain active areas of research. Recently, we have introduced a cross-polarization scheme for signal isolation which is inexpensive and wavelength independent. To accommodate the detector to the versatile cross-polarization scheme we employed a CMOS image sensor which composed of an array of photodetectors covered by Bayer filters and is capable for multi-color detections. By combining the CMOS sensor and the cross-polarization scheme, we achieved a portable system for multi-color analyte detection in which a single white emission LED was used as excitation. We demonstrated an application of fluorescent particle detection, ranging from 21µm to 6µm. Microparticles with different fluorescence were excited and detected simultaneously without changing the light sources and filters. We were able to clearly resolve micro-particles, even if aggregated. The raw spatial resolution of ~3µm is sufficient for a wide range of applications. We believe this portable system, processed of high spatial and spectral resolution, is suitable for multiplexed POC detections.

8251-28, Session 6

An active micro-mixer based on low frequency switching transverse electro-osmotic flow using 3D-symmetric planar electrodes

Z. Cai, G. Shao, Louisiana State Univ. (United States); H. Song, CFD Research Corp. (United States); W. Wang, Louisiana State Univ. (United States)

Abstract

Advantages of electro-osmotic micromixer include the ease of control and integration in microfluidic systems. This paper demonstrates a novel approach to enhance the mixing efficiency in microfluidic mixers. In this new design, transverse electro-osmotic flow was generated using three-dimensional (3-D) symmetric planar electrodes to enhance the mixing of two laminar flows in micro channels. Two face-to-face pairs of parallel planar electrodes were placed on the top and bottom of the micro channel respectively. A low frequency, square-wave electric field was applied between the neighboring electrodes, which induces recirculation flows transverse to the direction of the incoming streams. Hence, fluids are stretched and folded by chaotic advection in periodic directions along the channel. Due to the complex 3D spatial flow pattern, the mixing performance is considerably improved. The mixing mechanism was investigated by combining the use of the commercial software CFD-ACE+ and experimental observations under different operational conditions including flow rate, frequency and amplitude of the electric field.

A prototype chip has already been fabricated. The patterned electrodes were coated on glass substrates in a lift-off process and the micro channel was fabricated using a direct UV-lithography using the negative tone resist SU-8.The final device was obtained by aligning and bonding of two parts together. The scope of this research will cover the exploration of the optimal frequency of the electric field to achieve the highest mixing efficiency and the mixing performance in comparison with 2D electrodes.

8251-29, Session 6

Study of multiple streamflows of dissimilar polymeric solutions and its mixing in microfluidic converging/diverging geometries

H. Y. Gan, A*STAR Singapore Institute of Manufacturing Technology (Singapore); Y. C. Lam, Nanyang Technological Univ. (Saint Kitts and Nevis)

The effects of fluid elasticity in multiple streamflows of dissimilar viscoelastic non-Newtonian fluids in microfluidic converging/diverging geometries are investigated. We study the structure and dynamics of viscous-elastic flow instabilities generated by the high deformation rates in the contraction geometry and explore their dependence on the relative magnitudes of elastic stress. Multiple-stream flow instability of polymeric solutions in microchannels was previously investigated, but the dynamical evolution of multiple streamflows instability has not been reported. Here we show that the complex interplay arises between fluid elasticity/viscosity and the elasticity ratio between the mainstream and side streams fluids are key parameters for the viscoelastically induced flow instability. The necessity of elasticity for viscoelastic flow instability and the resultant mixing enhancement were demonstrated experimentally and the induced elastic flow instability depended strongly on the elasticity ratio of the two liquids. Salient and large corner vortices with viscoelastic fluctuation at upstream of the contraction were observed. The chaotic competition of the two fluids at the contraction and across the downstream channel was illustrated. Significant mixing of the two viscoelastic fluids was noticeably observed. The development of viscoelastic instability with an increase in flow rate and Deborah number (De) is identified by the representative flow patterns shown in proposed De operating space diagram. The competing effects of the viscoelasticity of the streams (inertial effects were negligible due to their very small Re) on vortex growth and the structure of flow instabilities were summarized in the space diagram. Our results show that the shape, size and evolution of these flow structures are dependent on the elasticity number, flow kinematics and the elasticity ratio of the fluids.

8251-30, Poster Session

Nonspherical optofluidic lenses

S. Calixto-Carrera, Ctr. de Investigaciones en Óptica, A.C. (Mexico); M. Rosete-Aguilar, Univ. Nacional Autónoma de México (Mexico); M. Calixto-Solano, Instituto Tecnológico y de Estudios Superiores de Monterrey (Mexico)

Usually microfluidic lenses are spherical, plano -concave or plano-convex. These lenses present high spherical aberration. Here we present a method to fabricate small microfluidic lenses with a non-spherical desired profile. To fabricate the lenses a liquid silicone mixture is poured in a small cubic hollow plastic container. Then a glass lens is inserted in the bulk of the silicone mixture. After polymerization the solid silicone, with the glass lens inside, is taken out from the container. Then the glass lens is taken away by cutting with a microtome the solid silicone cube. To seal the hollow cavity a small amount of silicone mixture is placed in the periphery of the silicone halves. With a needle it is possible to replenish the hollow cavity with a desired liquid. Each liquid presents its own refractive index or Abbe number. Liquids inside the cavity can be changed at will, thus the focal distance will change. We present optical and mechanical characterizations of several lenses. Also we present a hybrid optical element composed of a grating and a microfluidic lens and arrays of microfluidic lenses. Applications are also shown.

8251-31, Poster Session

Biochemical liquid analysis using a microfludic chip fabricated by femtosecond laser

Y. Hanada, K. Sugioka, K. Midorikawa, RIKEN (Japan)

Protein carry out many biological, chemical functions, including, but not limited to, catalyzing reactions in living organism, decoding information in cells, regulating biochemical activities, storing and transporting small molecules, providing mechanical support, and serving many other specialized functions. The onset of various diseases usually involves altered protein expression and distribution. Therefore, detection technique for certain proteins at low level is useful for the diagnosis of specific diseases in health care although most of the conventional techniques are only capable of detecting abundant proteins.

In the meanwhile, we have proposed using microchips with three-dimensional (3D) microfluidic structures to detect concentration of liquid samples. In this case, we have developed a technique for fabricating 3D microfluidic structures with smooth internal surfaces inside a photostructurable glass. This method uses femtosecond (fs) laser direct writing followed by annealing and successive wet etching. It permits rapid prototyping of 3D microfluidics with different structures, which is highly desired by biochemical processes. Furthermore, microoptical elements such as optical waveguide can be easily integrated with the microfluidic structure, permitting more functional analysis. In this talk, we attempted fabricating a microfluidic chip integrated with waveguide in the glass for protein concentration assay. By covering the internal walls of microfluidics with low refractive index polymer, high-sensitive protein concentration assay is performed at low level.

8251-33, Poster Session

Design and analysis of a micromachined gyroscope

J. D. Jones, N. Zarei, Simon Fraser Univ. (Canada)

This paper is concerned with the design and analysis of a micromachined gyroscope. We construct a three-dimensional finite-element model of the fluid within a micromachined cavity and define a set of six equations: conservation of mass, of momentum (in each of three directions) , and of energy; and the ideal gas equation. These equations are solved using the `COMSOL' modelling package. It is shown that an imposed pattern of transient heating within the cavity will generate periodic flows of hot gas, driven by expansion forces.

When the cavity and its contents are rotating, these flows will be deflected by the associated Coriolis force, and the deflection of the flow can be measured by the resultant temperature difference between a pair of symmetrically placed sensors. The device thus acts as a gyroscope having no moving parts. The results of simulation are compared with experiment and good agreement is shown. By running the validated simulation with a variety of different input parameters, we are able to calculate the effect of cavity dimensions and choice of working fluid on device performance.

8251-34, Poster Session

Design of a micro-interdigitated electrode for impedance measurement performance in a biochemical assay

L. M. Donoghue, B. W. Anthony, Massachusetts Institute of Technology (United States)

The performance of interdigitated electrodes for impedance measurements is dependent upon the geometric design of the electrode pattern and can be significantly impacted by manufactured variability or defects. For processes which rely on precise electrode performance, such as the biochemical assay in the Daktari CD4 diagnostic system, it is necessary to minimize variation through robust design and quality control. Interdigitated electrode design was investigated to identify design strategies which maximize electrode sensitivity and minimize performance variability in produced parts, while potentially reducing the complexity of quality testing. Several designs were developed to address these goals by increasing the sensing region for a specified electrode area and creating designs which can be more easily manufactured with low variability. Design modifications included alterations to interdigitated finger orientation, finger geometry, and gap width. Test findings indicate that optimal designs contain narrow gap widths with electrode fingers parallel to the longest dimension of the electrode. These benefits may be further enhanced by replacing straight finger edges with geometrical features, such as scalloped edges. The design changes identified can be used to improve interdigitated electrode performance for a variety of applications and reduce performance variability caused by variation in the manufacturing process.

8251-35, Poster Session

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

A. Li, B. L. Gray, J. Lee, P. Li, Simon Fraser Univ. (Canada)

Stimuli-responsive hydrogels such as poly(N-isopropylacrylamide) (PNIPAAm) are excellent biocompatible materials for microfluidic actuators due to their ease of fabrication and localized response to stimulus (pH, ionic strength, or heat) [1]. We have previously presented the design and fabrication of the mechanically flexible diaphragm-based microvalve actuator employing a reservoir of thermally responsive hydrogel PNIPAAm and a conductive nanocomposite polymer (C-NCP) heater element [2]. We now presented the construction, simulation and characterization of a hydrogel-based microvalve and its application for flow control with a different flexible heater design.

This paper shall present the continuing progress of our contribution to this project. The microvalve can be fabricated with traditional semiconductor processes for spin-coating, baking and etching. Swelling and shrinking of the hydrogel forces a diaphragm to deflect into a microchannel resulting in closing 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 typically between 200-400 µm in diameter. New simulations of the hydrogel employing COMSOL® show the pressure distribution and diaphragm deflection , with expected deflections of 100-200µm and pressures of 0.5-2 MPa, which are sufficient to open the microvalve in response to heat with temperature of 32ºC or above allowing fluid flow to pass through the microchannel. We will compare these simulations with experimental results, including: characterization of diaphragm motion in the channel; and fluidic valve characterizations of, e.g., pressure drop, flow rate, and response time, as well as the maximum pressurization limit (burst pressure).

8251-36, Poster Session

Robustness and repeatability of interdigitated electrodes on a substrate tested in an aqueous environment

J. A. Holmes, B. W. Anthony, Massachusetts Institute of Technology (United States)

Interdigitated electrodes are currently being used as sensing components in microfluidic lab-on-a-chip devices. The Daktari Diagnostics system uses these electrodes to measure the change in impedance of a fluid in an assay chamber. In order to improve quality assurance, a new testing method was developed and validated to characterize the sources of potential defects in the electrodes. In the new test, the electrodes are used to measure the impedance when placed in solutions of different known conductivities. The data was used to calculate the slope of a line relating 1/impedance measured to the solution conductivities. The repeatability tests found an average slope of 1.438x10-5 cm/characteristic length with a standard deviation of 8.52x10-8 cm/characteristic length. It was found that the number of defective fingers or bending the electrodes significantly changes the electrode performance.

8251-37, Poster Session

Design of subretinal implants with MEMS

M. Akyurek, Selçuk Univ. (Turkey)

A few million people worldwide suffer from a chronic degeneration of the retina (retinitis pigmentosa or age related macular degeneration), which disables their ability of vision. Several techniques are used, while the retinal approach relies on electrically stimulated neurons in the retina that bypass the damaged photoreceptors and directly create visual excitation. In this research, the subretinal implant has been investigated. The subretinal approaches has been analyzed and microfabrication processes has been described. The subretinal implant is based on a silicon microchip, which contains microphotodiodes. Photodiode cells will be increased as micro/nano scale and multiplexed photodiodes will be inserted on the disc of electrodes. Photodiode cells are designed to convert the light energy from images into electrochemical impulses that stimulate the remaining functional cells of the retina disease related patients.

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8254-01, Session 1

Network based multi-sensor optical 3D acquisition of complex structures

G. J. Frankowski, C. Benderoth, R. Hainich, GFMesstechnik GmbH (Germany)

We present new developments in optical 3d sensors using pico DLP as well as DSP technology. We use enhanced, high-powered pico DLP projection units and compact processing hardware to create likewise compact, light-weight measuring heads, which can perform the acquisition as well as the evaluation of 3D data without external computing power. Moreover, their drastically reduced cost and their networking ability also allows for an economical combination of a multitude of individual sensors into complex configurations. The entire form even of large and complex shapes can hereby be scanned in a very short time. New calibration strategies, integrating all individual sensor coordinate systems into a single, calibrated, global one, lead to an immediate combination of all sensor data into a single, complete point cloud. We show the principle and actual realization of sensors, calibration strategies and procedures, and examples of first realized multi-sensor measuring systems utilizing this new technology.

8252-01, Session 1

Trajectory precision of micromachined scanning mirrors for laser beam scanning pico-projector displays

W. O. Davis, M. Beard, R. Jackson, Microvision, Inc. (United States)

Magnetically-actuated micromachined scanning mirrors have been developed for pico-projectors using laser beam scanning (LBS). In addition to addressing the requirements for low power consumption and small size, the devices provide an extremely precise, repeatable, and stable scanned beam trajectory. The human vision system readily detects imperfections in a LBS display, which become objectionable when scanned beam trajectory errors have amplitudes on the order of only parts per thousand or even parts per ten thousand, depending on the type of error and whether it is static or dynamic. The scanning mirror consists of a gimbal-suspended reflector, where one scan axis operates at a mechanical resonance to generate horizontal lines in the LBS display. The second, orthogonal scan axis corresponds to the vertical dimension in the display. A sawtooth raster scan ideally produces a uniform spacing of the horizontal lines, however one challenge to achieving such trajectory precision is that a sawtooth contains harmonics that will coincide with modes of vibration of the scanning mirror with high quality factors. The resulting nonuniformity of line spacing results in objectionable perceived intensity modulation based on the human contrast sensitivity function. The paper describes the overcoming of such challenges to achieve a high quality LBS projection.

8252-02, Session 1

MEMS-based micro projection system with a 1.5cc optical engine

L. Kilcher, N. Abele, Lemoptix SA (Switzerland)

Lemoptix will present a technical overview of the company's high reliability, high performance and small size magnetic actuated MEMS scanning micro mirror product. While the applications for MEMS mirrors are countless Lemoptix will specifically present the use of its MEMS mirror as core component of its micro projection system.

Based on the combination of its MEMS, ultra small optics and high performance electronics technology, Lemoptix has developed an embeddable micro projector with an optical engine unique in many ways but specifically in its dimensions of only 1.5 cc.

Lemoptix provides its MEMS micro mirrors and micro projectors in consumer and industrial applications ranging from micro projection systems in the automotive industry (HUD) as well as in light scanning devices such as range finders and optical sensing systems.

8252-03, Session 1

Laser projector solution based on two 1D resonant micro scanning mirrors assembled in a low vertical distortion scan head

J. Grahmann, M. Wildenhain, T. Grasshoff, H. Dallmann, C. Gerwig, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); A. Wolter, HiperScan GmbH (Germany); H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

A Scan Head design based on two 1D-scanning mirrors cannot be miniaturized as much as a design with a 2D-scanning mirror. However an advantage of the 1D-scanner approach is the alignment of the two scanners in angles enabling a straight line projection on to the slow axis scanner. This results in almost no vertical distortion. The remaining is determined by manufacturing tolerances of the Scan Head and the alignment tolerances of the micro mirrors inside.

The slow scanning mirror has a frequency of 100Hz accompanied by a die size of 7.4mm x 3.3mm. The resonance frequency of the fast scanner is 29050Hz and die size is smaller since the incident laser spot hits this mirror first. The WVGA resolution with a ratio of 16:9 is given by a mechanical deflection of ±12° : ±6.75°. Die size and Scan Head design influence each other and this Scan Head demonstrator fills a volume of 1.83cm^3 showing the potential to reduce dimensions further.

The developed electronics is divided into a MEMS driving part and a video processing part. The MEMS driver board enables generation of rectangular drive voltages up to 230V and comprises of an amplifier stage for the piezoresistive sensor signals. The video processing board adapts the RGB signal for each picture to the Lissajous figure. The heterogeneous brightness of the picture which is due to varying scanner speeds is corrected by a new approach increasing picture contrast.

8252-04, Session 1

Speckle reduction for laser-illuminated picoprojectors

F. P. Shevlin, Dyoptyka Ltd. (Ireland)

See above.

8252-05, Session 1

Optotune focus tunable lens and laser speckle reduction based on electroactive polymers

M. Aschwanden, Optotune AG (Switzerland)

Optotune develops, manufactures and sells adaptive optical elements. Among others, our patented technology enables the implementation of a compact, inexpensive, high-speed and focus-tunable lens, which simplifies the design of focus and zoom systems across industries. Furthermore, Optotune has developed a laser speckle reducer based on electroactive polymers. This device offers an extremely compact and low cost solution for removing speckles from laser light. The laser speckle reducer is used in laser based pico-projectors, cinema projectors and illumination systems.

8252-06, Session 1

Superluminescent light emitting diodes - the best out of two worlds

C. Vélez, U. Achatz, M. Rossetti, M. Duelk, J. Napierala, Exalos AG (Switzerland)

Since pico-projectors (picoPs) were starting to become the next electronic “must-have” gadget, the experts were discussing which light-source technology seems to be the best for the existing three major projection approaches for the optical scanning module such as digital light processing (DLP), liquid crystal on silica (LCoS) and laser beam steering (LBS). Both so-far used light source technologies have distinct advantages and disadvantages. Though laser-based picoPs are focus-free and deliver a wider color gamut, their major disadvantages are speckle noise, cost and safety issues. In contrast projectors based on cheaper Light Emitting Diodes (LEDs) as light source are criticized for a lack of brightness and for having limited focus. Superluminescent Light Emitting Diodes (SLEDs) are temporally incoherent and spatially coherent light sources merging in one technology the advantages of both Laser Diodes (LDs) and LEDs. With almost no visible speckle noise, focus-free operation and potentially the same color gamut than LDs, SLED could potentially answer the question which light source to use in future projector applications. However, still open application requirements on optical output power and power efficiency need to be answered together with picoP manufacturers.

8252-07, Session 1

Bi-resonant scanning mirror with Piezo-resistive position sensor for WVGA laser projection systems

C. Drabe, D. Kallweit, A. Dreyhaupt, J. Grahmann, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); W. O. Davis, MicroVision, Inc. (United States)

Fraunhofer IPMS developed a new type of small-sized scanning mirror for Laser projection systems in mobile applications. The device consists of a single crystal mirror plate of 1 mm diameter in a gimbal mounting enabling a bi-resonant oscillation of both axes at a resonance frequency of about 100 Hz and 27 kHz respectively. The mechanical scan angle achieved is ± 7° for the slow and ± 12° for the fast axis. The mirror angle position and phase can be read out via two piezo-resistive sensors located at the torsion axes. In order to allow for a minimum device size of the resonantly driven slow axis the sensor of the inner fast axis was connected by a new kind of thin silicon conductors. Those are created by means of an electrochemical etch stop in TMAH etch and kept as thin as possible in order to reduce their contribution to the mechanical stiffness of the mirror-supporting structures. This new system enables to lead six (or even more) independent electrical potentials onto the moving parts of the device, whereas the mechanical properties are mainly determined by only 2 torsion axes. The devices were subsequently characterized and tested. Technology details, simulation and pictures of the device and the new conductor structures as well as measurement results are presented.

8252-08, Session 2

Net flux sensors for the measurement of Mars surface radiation budget

L. Ngo Phong, A. Anas, Canadian Space Agency (Canada); M. Daly, York Univ. (Canada); F. Chateauneuf, INO (Canada)

Unlike orbital measurements, surface measurements of the Martian atmosphere do not require complex inversions of measured radiances. Further, they provide the lower boundary conditions and validation points for orbital retrievals. To date, surface measurements of the radiation budget components have not yet been made and other surface meteorological data remain scarce and suffer from the lack of the time and area coverage. We report on the development of the net flux sensor for the measurement of the downwelling and upwelling solar and longwave radiative fluxes close to the surface of Mars in four bands: 0.3-2.8 um, 14-16 um, 24.3-26.2 um, and 4.5-42 um. This sensor is intended for a wireless network of meteorological sensors (net flux, wind, water vapor concentration, pressure, and temperature) for the in-situ characterization of Martian atmosphere. The low power connectivity of the network relies on the use of the IEEE 802.15.4 standard. Given the need for multiple nodes of the network to ensure time and area coverage, it is required that the sensor nodes be miniaturized. Because of miniaturization, the effects from self-shadowing and re-radiation will require compensation or result in lost data. To mitigate these effects, we devise prototypes that allow subsampling the field-of-view to areas where these effects are not significant. The pyrgeometer of the sensor provides a field-of-view in the range from 140 to 180 degrees. To ensure small spectral variation and high resolution, both the pyranometer and pyrgeometer consist of goldblack coated VOx microbolometers. The details on their microfabrication and packaging will be reported.

8252-09, Session 2

Large MEMS-based programmable reflective slit mask for multi-object spectroscopy fabricated using multiple wafer-level bonding

M. D. Canonica, Ecole Polytechnique Fédérale de Lausanne (Switzerland); F. Zamkotsian, P. Lanzoni, Observatoire Astronomique de Marseille-Provence (France); W. Noell, N. de Rooij, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Multi-object spectroscopy (MOS) gives infrared spectra of faint astronomical objects that provide information on the evolution of the Universe. MOS requires a slit mask for object selection at the focal plane of the telescope. We are developing MEMS-based programmable reflective slit masks composed of 2048 individually addressable micromirrors. Each micromirror measures 100 x 200 µm2 and is electrostatically tilted providing a precise angle of 20°. The main requirements for these arrays are precise and uniform tilt angle over the whole device, uniformity of the mirror electro-mechanical behavior, a low mirror deformation and individual addressing capability of each mirror. This capability of our array is achieved using a line-column algorithm based on an optimized voltage-tilt hysteresis of the electrostatic actuator.

A third generation of micromirror arrays composed of 2048 micromirrors (32 x 64) and modeled for individual addressing were fabricated using fusion and eutectic wafer-level bonding. These micromirrors without coating show a peak-to-valley deformation less than 5 nm, a tilt angle of 20° for an actuation voltage of 120 V. A first experiment of the line-column algorithm was demonstrated under a probe station by actuating individually 1 x 3 micromirrors and 2 x 2 micromirrors. Devices are currently packaged, wire-bonded and integrated to a dedicated electronics to demonstrate the individual actuation of numerous micromirrors.

In order, to avoid spoiling of the optical source by the thermal emission of the instrument, the array has to work in a cryogenic environment (90 K). Therefore, a cryogenic experiment for these devices is currently under preparation and ongoing.

8250-16, Session 2

MEMS technology for miniaturized space systems: needs, status and perspectives

E. Gill, J. Guo, Technische Univ. Delft (Netherlands)

In the past two decades, Micro-Electro-Mechanical System (MEMS) technology has significantly been advanced. The progress of MEMS offers potentials and opportunities for miniaturized space systems, especially micro-and nano-satellites. By using this technology, also small countries can play a strong role in future space exploration and applications. On the other side, future applications of miniaturized space systems have demanding needs, which call for MEMS components, thus further boosting the development of the MEMS technology.

This paper addresses the needs, status and perspectives of the MEMS technology for miniaturized space systems from the perspective of a spacecraft developer. First, past and expected future missions utilizing miniaturized space systems are discussed , followed by an analysis of mission needs on various aspects, such as performance, reliability, cost and unique functionality of MEMS components. Then, the state-of-the-art MEMS technologies are addressed that have been developed for space applications based upon future mission needs. A special interest is the Research and Development (R&D) for space-based MEMS technology in The Netherlands, which were initiated five years ago and have resulted in considerable achievements. Specific developments for sensors and actuators will be presented. Finally, the perspectives of space-based MEMS technology will be addressed based on the analysis of both future mission needs and technological trend.

8250-17, Session 2

MOEMS devices designed and tested for astronomical instrumentation in space

F. Zamkotsian, Observatoire Astronomique de Marseille-Provence (France); W. Noell, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Next-generation astronomical instrumentation for ground-based and space telescopes could use MOEMS devices. Among them, Multi-Object Spectrographs (MOS) are the major instruments for studying primary galaxies and remote and faint objects. A promising solution for the object selection system is the use of MOEMS devices such as micromirror arrays which allow the remote control of the multi-slit configuration in real time.

We are engaged in a European development of MMA for generating reflective slit masks. Prototypes of MMA with single-crystal silicon micromirrors were successfully designed, fabricated and tested. 100x200µm2 micromirrors can be tilted by electrostatic actuation yielding 20° mechanical tilt-angle. The micromirrors were successfully actuated before, during and after cryogenic cooling at 92K. Line-column addressing for individual mirrors has also been demonstrated. We are currently developing and fabricating arrays of larger size (several thousands micromirrors).

We are also engaged in a technical assessment of using a 2048 x 1080 DMD from Texas Instruments for space applications. For a MOS in space, the device should work in vacuum and at low temperature. Our tests reveal that the DMD remains fully operational at -40°C and in vacuum. A 1038 hours life test in space survey conditions, Total Ionizing Dose radiation, thermal cycling and vibrations/shocks have also been successfully completed. These results do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements.

These developments and tests demonstrate the full ability of this type of components for space instrumentation, especially in multi-object spectroscopy applications.

8250-18, Session 2

Performance prediction and characterization of highly insulated microbolometers for space applications

Z. Xu, Canadian Space Agency (Canada) and INO (Canada); L. Ngo Phong, Canadian Space Agency (Canada); T. Pope, INO (Canada)

There is an increasing demand for high spatial resolutions and large swath widths in Earth observation applications. Previously we developed linear arrays of 512x3 microbolometers that provide a resolution of 350 m from low Earth orbit under the SAC-D Aquarius mission. To improve the resolution and swath width, higher thermal isolation and fill factor of the microbolometer need to be achieved. This paper reports on the investigation of different structures of highly insulated 35 um pitch microbolometers. Each structure consists of two levels of suspended Si_3N_4 platforms with the upper level containing mainly the bolometer element and the lower level providing room for varying hinge length. In this work the cross section of the hinge was kept to 0.68 um2, and the length of the hinge was in the range from 64 to 105 um. Such structure allows for an increased thermal isolation of the microbolometer without the penalty of decreasing the fill factor. A numerical model was used to predict the figures of merit of the resulting device for each structure. Experimental validation was further carried out on the microfabricated devices, showing a good agreement with the computed results. It was found that the thermal conductance, in the range from 85 to 135 nW/K, varies inversely with the hinge length. The microbolometer structure with the highest level of thermal isolation showed a detectivity of better than 5 × 10e8 cmHz1/2/W and a response time of 8 ms. The selection of the devices for use in specific space applications will be discussed.

8252-10, Session 3

Translatory MEMS actuator and their system integration for miniaturized Fourier transform spectrometers

T. Sandner, T. Grasshoff, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (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. 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. In this paper, we present a translatory MEMS device enabling an extraordinary large stroke of 1 mm. The translatory MOEMS actuator was specially designed to enable a miniaturized MEMS based FTIR spectrometer with improved system performance of 1000 and fast operation of ≥ 500 scans / sec. 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. 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.

Beside the MEMS device this paper focuses on the system integration into a miniaturized FTIR spectrometer. The optical vacuum MEMS packaging is discussed in detail and first experimental results of the FTIR spectrometer are shown. The new translatory MEMS device enables potentially a completely new family of low cost handheld FTIR analyzers e.g. applied by individuals for ad-hock inspection of food or environmental parameters.

8252-11, Session 3

Advances in performance and miniaturization of a FT-IR spectrometer system based on a large stroke MOEMS piston mirror device

A. Kenda, Carinthian Tech Research AG (Austria); T. Sandner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); S. Lüttjohann, Bruker Optik GmbH (Germany)

Standard FT-IR spectrometers are large, usually static, expensive and require operation by qualified personnel. The presented development involves achievements in MEMS technologies and electronics design to address size, speed and power requirements and develop a fully integrated miniaturized FT-IR spectrometer. A suitably matched interaction of multiple new components - source, interferometer, detector and control and data processing - develops unique MEMS based spectrometers capable of reliable operation and finally results in compact, robust and economical analyzers. The presented system now aims at a high performance level to measure in the range between 5000-750 cm^-1 at a spectral resolution better than 10 cm^-1. The Michelson interferometer design and the desired performance put several demands on the MOEMS device. Amongst these, a mirror travel of ± 500 µm and a minimal dynamic deformation of < λ/10 peak-to-peak in combination with a large mirror aperture of 5 mm were the most challenging goals. However, a SNR of 1000:1 is required to qualify a FT-IR system as a sensor for industrial applications e.g. process control. The purpose of the system, presented in this work, is to proof that this is feasible on the basis of MEMS technology and it is demonstrated that most of these specifications could be already met.

8252-12, Session 3

Spectral imaging characterization of MOEM tunable Fabry-Perot filter

N. Gupta, U.S. Army Research Lab. (United States)

A miniature MOEM tunable Fabry-Perot (FP) filter development program to fabricate filters operating over spectral regions from the visible to the longwave infrared has recently succeeded in fabricating filters operating over visible/near infrared wavelength region from 400 to 800 nm. The main objective of this program is to design miniature hyperspectral imagers by placing such a miniature tunable FP filter in front of a commercial focal plane array with a suitable optical train. This novel MOEM filter design is based on using two semitransparent 30-nm thick silver film mirrors-one fixed and one moving with application of an electrostatic force. The silver films were grown on low-cost thin commercial quartz wafers with low total thickness variation. The moving mirror is held in place by three leaf spring arm structures which were fabricated by wet etching of the quartz substrate. The size of the MOEM device is 18x24 mm2. The tunable FP filter has a 6-mm optical aperture. The fixed part has three electrodes to apply voltages and the moving mirror is used as a ground electrode. Au bumps were deposited in both parts in order to control the initial air gap distance and Au-Au bonding was used to bond two parts together. The electrostatic actuation changes the spacing between the two mirrors which changes the transmission wavelength. The spectral imaging performance of MOEM filter was characterized using a tunable source and a CCD camera with suitable optics. This paper describes the MOEM filter, the characterization experiment and present spectral imaging results.

8252-14, Session 3

Modulator for a micro Mach-Zhender spectrometer

A. G. Rojas Hernández, A. Garcia-Juarez, Univ. de Sonora (Mexico)

The modulators employing p-i-n configuration show high modulation depth but, as opposed to the MOS configuration, a relatively slow operation speed, Due to the slow injection of electrons and holes in forward bias operation. On the other hand, MOS configuration can achieve high speed, but the modulation depth is rather small, resulting from the poor overlap between the carriers concentration changing region and the waveguide mode. To overcome this problem the Lipson's team a micrometer scale ring resonator based electro optic modulator, using the resonating nature of the micro-ring, the transmission at the resonance wavelength is highly sensitive to small index change, making the modulator can break the slow speed limitations. The propose is a SOI waveguide modulator with modified MOS dual capacitor structure, by enhancing the overlap between the carriers concentration changing region and the waveguide mode, the modulation depth can be improved greatly.

The structure is formed by a thin film oxide layer that served as the first gate oxide formed on the SOI N-type doped top silicon layer (B1) with thicknes of tB and doping concentration of 1.0x1017 cm-3, the core layer have the same concentration but in P-type polysilicon deposited on the oxide layer with a thickness of thA. The second gate oxide is formed on the core layer with the same thickness as first oxide layer and covered by a N-type polisilicon upper cladding layer (B2). The cross section of the active region of the modulator is divided in 3 part along y axis by 2 gate oxide films, forming the dual capacitor MOS structure.

The wavelength of the modulator is set to be 1.55um.

To obtain high speed performance (exceeding GHz), the inner rib width of the waveguide must be around 1um indicating a bandwidth of exceeding 7GHz.

8252-15, Session 4

Shared shuttles for integrated silicon optoelectronics

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

CMOS-compatible silicon is not an obvious material system for building high-performance optical devices. But, over the last ten years, it has become possible to build fairly complex integrated optical systems at telecommunications wavelengths on electronics-compatible silicon substrates. In fact, over the last few years, the complexity of these systems has been approximately doubling every year, and this trend is projected to continue for at least the next several years.

With a combination of CMOS electronics and photonics in the same chip, we can gain control of both photons and electrons, while preserving the powerful economics of the VLSI revolution. Furthermore, silicon waveguides can be engineered for low optical loss and high cladding overlap, while preserving nano-scale modal areas: As a result, it is possible to add a variety of cladding materials in order to bring new functionality into the silicon system. For instance, highly nonlinear engineered organic claddings can be added to silicon waveguides in order to create ultrafast nonlinear devices. A number of recent results have emerged showing that silicon photonics has significant advantages for highly scaled biosensing applications.

The focus of this talk will be on the OPSIS project, which is a new initiative aimed at creating an open foundry and associated infrastructure for building fully integrated optoelectronic devices and systems in silicon.

8252-16, Session 4

One dimensional light modulator

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The Fraunhofer IPMS develops and manufactures micro mirror based light modulators (MOEMS, micro opto electromechanical system) in a wide variety of types and configurations. A very versatile type among that is the One Dimensional (1dim) Light Modulator. Such a device can be applied in a wide range of applications. Examples are computer to plate (CTP), laser direct imaging (LDI), waferlevel packaging / interconnect, holography, material marking and processing and IP protection.

The new 1dim Fraunhofer IPMS light modulator demonstrator device consists of 1000 pixels which are arranged in a line. The modular concept of this MOEMS allows for extension of the number of pixels up to several 1000. Each pixel can be switched to black, white or even arbitrary gray values with very high speed.

As a novelty each pixel is composed of a number of micro mirrors, aligned in a row. That approach allows for, in principle, very long pixels with uniform surface properties. This concept in turn results in reduction of power density at the light modulator surface and hence enables the way to high power applications.

This paper summarizes device design, working concept, mechanical properties for both static and dynamic operation, and surface properties. Application relevant subjects as stability under intense laser illumination complete the presentation, examples of applications will be discussed.

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8252-17, Session 4

Detection of resonant cantilevers using the evanescent fields of silicon nanophotonic waveguides

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Nano-optomechanical system (NOMS) devices use nanophotonic systems to resonate/detect oscillating mechanical structures. Compared to some traditional measurement methods, nanophotonic methods have a much larger frequency bandwidth and the displacement read-out can be easily extended beyond the diffraction limit. This allows for smaller and higher frequency resonant devices to be created which have greater sensitivity in sensor applications. In most NOMS devices the mechanical resonator is integrated directly into the waveguide. This limits the minimum size of the resonator to be equal to that of the waveguide, which therefore limits the sensitivity. This size restriction has been circumvented with a doubly clamped beam, but this has not yet been shown for a cantilever device. Cantilevers are 3x more sensitive than identical doubly clamped beams due to their smaller effective mass, which is why demonstrating a non-size limited method is important. Here, a silicon nanophotonic Mach-Zehnder interferometer (MZI) is used to detect the resonant frequency of a cantilever external to the waveguide. Sub-5 um long cantilever devices less than 250 nm thick in the oscillating direction were fabricated ~100 nm away from one MZI arm. The evanescent field from the nanophotonic waveguide interacts with the resonator, and the effective index changes as the resonator moves toward and away from the waveguide. This causes a modulating phase shift between the two arms which results in a modulating output power of the device. By measuring this power the resonant frequency of the cantilever can be found. Resonant frequencies of cantilevers up to 43 MHz are measured with mechanical quality factors as high as ~8000.

8252-18, Session 4

Low voltage vertical flaps arrays as optical modulating elements for reflective display and switchable gratings

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A novel technology is presented for arrays of electrostatic low voltage actuated optically modulating flaps. The flaps are suspended by torsion beams and are vertical at their rest state, letting incoming light pass through. By applying low voltages of 30 to 50 V on an opposing electrode the flaps turn by angles of up to 90° to horizontal position. We will show the actuation of 5 by 5 flaps arrays with typical vertical flap dimensions of 50um and width of 250um by line-column addressing. The main application is a reflective display giving higher contrast and reflectivity than nowadays available systems. At the rest state light is absorbed by an underlying layer, giving a black pixel and reflected back when the flaps are in horizontal position, making a pixel white. The devices can also be used in transmissive mode as shutter arrays with a fill factor of up to 50%.

The sturctures are fabricated by filling thin high-aspect ratio trenches having a SiO_2 liner in SOI-wafers with poly-Si, ALD-metal or Parylene. The silicon between flaps and electrode and a backside opening is dry-etched and the devices released in HF-vapour. A poly-silicon (or ALD-metal / Parlyene) flap is obtained with the shape of the initial trench.

Besides flat reflecting flaps, a large variety of geometries are demonstrated, such as grid-, lens- or grating-shaped structures. A switchable blazed grating is shown, which is actuated with the same low voltages as the flat structures.

8252-19, Session 4

Dynamically deformable reflective membrane for laser beam shaping and smoothing

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We show a simple laser beam shaping device made of a deformable continuous reflective membrane fabricated over a scanning stage. The combination of two actuator schemes enables shaping and smoothing of a laser beam with a unique compact device. It is designed to shape an input laser beam into a flat top intensity profile, to support high optical loads and it could potentially be used for speckle reduction. One single electrode is needed to deform the whole membrane. When actuated, the shape of the reflective membrane is determined by the disposition of the underlying supporting structures to create sub-reflecting elements. These structures are posts or bars that can be randomly distributed. However, even if the sub-elements are randomly distributed an interference pattern is generated over the output flat top intensity profile. The scanning stage is used simultaneously to smooth out the interferences. Optical simulations and prototypes showed that a scanning angle of only 0.1° is sufficient to smooth the optical profile. Silicon on insulator (SOI) wafer is employed as a base to fabricate the scanning stage. Comb drives are used to actuate the stage at its first resonant mode at 1 kHz. Two large springs connect the stage to the chip frame to optimize heat transfer for high optical input. The etched structures on the SOI are refilled with parylene and a membrane is deposited and patterned on top of the scanner. Release of the membrane by dry etching of the sacrificial refilling material from the back side enables the fabrication of a continuous 5 by 5 mm deformable membrane. Applications for such device are laser machining and laser display.

8252-20, Session 5

Compact read head with MEMS focus control and spherical aberration correction for multi-layer optical disks

S. J. Lukes, D. L. Dickensheets, Montana State Univ. (United States)

In optical disk units, a means for focus control to read/write multiple layers or to change from the data to the label layer is required. Focus adjustment is typically achieved by the translation of a lens to adjust the focal position in the disk medium. Lens translation is accomplished with a bearing and a motor, limiting response speed and contributing to read head volume. Furthermore, changing the focus depth in the disk introduces spherical aberration because of the varying glass layer thickness and because the objective lens must operate over a range of object depths. The spherical aberration may therefore need to be corrected by a liquid crystal or similar device, especially for the Blue-ray Disk (BD) standard which has a high objective lens NA of 0.85. A single MEMS deformable mirror can replace both the lens translation mechanism and the aberration correction device for optical disk readers, simplifying the read head design and decreasing the focus response time by more than an order of magnitude.

We describe in this paper a very simple optical disk read head comprising a fixed objective lens with a right-angle MEMS varifocus mirror. We examine the requirements for a deformable membrane used for multi-layer focusing, both in terms of overall optical power (and corresponding membrane stroke) and ability to compensate the attendant spherical aberration, for both DVD and BD objectives. We then experimentally verify the use of a SU-8 2002 large stroke elliptical boundary mirror at 45o incidence for multi-layer focusing with concurrent aberration compensation.

8252-21, Session 5

Deformable mirror with controlled damping for fast focus tracking and scanning

M. J. Moghimi, K. N. Chattergoon, Montana State Univ. (United States); C. R. Wilson, Bridger Photonics, Inc. (United States); D. L. Dickensheets, Montana State Univ. (United States)

Deformable membrane mirrors can be used as variable-focus elements in miniaturized imaging systems. There are several applications where high-speed focus control would be useful, including optical storage read heads, confocal laser scanning microscopy and optical coherence microscopy. The electrostatic deformable mirror comprises a membrane suspended above a substrate with an air gap between. Deflection of the membrane displaces the air from the gap, and viscous air flow is the dominant damping mechanism.

In this paper we describe new mirrors that incorporate a perforated backplate, facilitating air flow from the gap beneath the membrane and significantly reducing the air damping. A flexible, metalized membrane and a thick spacer element, both made from photo-patterned SU-8, are attached to a rigid silicon substrate (the backplate) which has holes etched vertically through it for air flow. Holes are arranged in concentric rings, with the location of the rings, the number of rings and the number of holes per ring all influencing the damping and the resultant frequency response for the membrane mirror. We show experimental results from 4 mm diameter mirrors illustrating that the small-signal frequency response of our mirrors can be extended to more than 7 kHz. Furthermore, large displacement step response shows a settling time less than 100 microseconds for the same 4 mm diameter mirrors undergoing a 10 micrometer deflection. We discuss the analytical basis for our design and show the similarity of the MEMS deformable mirror to the MEMS condenser microphone for small signal behavior.

8252-22, Session 5

Miniature non-mechanical zoom camera using deformable MOEMS mirrors

B. M. Kaylor, C. R. Wilson, N. J. Greenfield, P. A. Roos, E. M. Seger, Bridger Photonics, Inc. (United States); M. J. Moghimi, D. L. Dickensheets, Montana State Univ. (United States)

We present a miniature non-mechanical zoom camera using deformable MOEMS mirrors. Bridger Photonics, Inc. in collaboration with Montana State University, has developed electrostatically actuated deformable MEMS mirrors for use in compact focus control and zoom imaging systems. Applications including microscopy, endomicroscopy, robotic surgery and cell-phone cameras. In comparison to conventional systems, our MEMS-based designs require no mechanically moving parts. Both circular and elliptical membranes are now being manufactured at the wafer level and possess excellent optical surface quality (membrane flatness < /4). The mirror diameters range from 1 - 4 mm. For membranes with a 25 µm air gap, the membrane stroke is 10 µm. In terms of the optical design, the mirrors are considered variable power optical elements. A device with 2 mm diameter and 10 µm stroke can vary its optical power over 4 diopters or 4 mm^(-1). Equivalently, this corresponds to a focal length ranging from infinity to 25 mm. We have designed and demonstrated a zoom system using two MEMS elements to achieve an optical zoom of 1.9x with a 15° full field of view. The total optical track length of the system is 36 mm. The design uses commercial, off the shelf components and is approximately 30 mm x 30 mm x 20 mm including the optomechanical housing and image sensor.

8252-23, Session 6

Microelectrofluidic iris for variable aperture

J. Chang, K. Jung, E. Lee, M. Choi, S. Lee, Samsung Advanced Institute of Technology (Korea, Republic of)

This paper presents a variable aperture design based on the microelectrofluidic technology which integrates electrowetting and microfluidics. The proposed microelectrofluidic iris (MEFI) consists of two immiscible fluids and two connected surface channels formed by three transparent plates and two spacers between them. In a basic MEFI, the bottom plate has concentric control electrodes covered by an insulating dielectric, and a reference electrode for grounding the opaque aqueous. The middle plate has edge holes for the 1st fluid, opaque aqueous, and a center hole for the 2nd fluid, air or oil. In the initial state, the confinement aqueous ring makes two fluidic interfaces on the hydrophobic surface channels on which the Laplace pressure is same. When a certain voltage is applied between the control electrode beneath the three-phase contact line (TCL) and the reference electrode on the 1st channel, the contact angle changes on the activated control electrode. At high voltage over the threshold, the induced positive pressure difference makes the TCLs on the 1st channel advancing to the center and the aperture narrowing. If there is no potential difference between the control and reference electrodes, the pressure difference becomes negative. It makes the TCLs on the 1st channel receding and the aperture widening to the initial state. It is expected that the proposed MEFI is able to be widely used because of its fast response, circular aperture, digital operation, high aperture ratio, and possibility to be miniaturized for variable aperture.

8252-24, Session 6

Thin varifocal liquid lenses actuated below 10V for mobile phone cameras

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Camera phones tend to integrate more optical quality enhancement functions (auto-focus, zoom or image stabilization) in conjunction with very demanding constraints in terms of size, power consumption and cost. New types of variable-focus liquid lenses were developed recently, but these devices usually operate at high voltages (typically above 50V) making the driver integration more complex.

In this paper a novel liquid lens technology is discussed. The lens is made of a polymer membrane that encapsulates a liquid in a cavity created on a glass wafer. Annular electrodes situated below the membrane and on the glass wafer form the electrostatic actuator. The electrostatic force reduces the gap between the electrodes and pushes the liquid towards the center of the lens changing the curvature of the membrane. The actuator is situated as close as possible to the optical area allowing very compact devices (less than 5x5mm for an optical diameter of 3mm). In the z-direction, the device is active on a distance 0-30µm such that the thickness is determined by the glass and silicon support wafers that can be easily thinned down below 0.5µm. Finally, the lenses fabrication steps use microelectronics processes and the lenses can be manufactured at a very low cost. The key parameters to enhance the device optical performance and minimize the applied voltage are the membrane and electrode rigidities. By properly adjusting the membrane Young modulus and residual stress and balancing the metal electrode stress, more than 10m-1 optical power variation is demonstrated at 9V applied voltage.

8252-25, Session 6

Novel resistive electrodes structure for liquid crystal modal lens shifting

N. Fraval, F. Berier, Evosens (France); O. Castany, TELECOM Bretagne (France)

Miniaturization of image sensors and increase of their resolution leads to development of new miniaturized optical components which could ensure classical functions in optics, such as auto-focus (AF) and optical image stabilization (OIS).

To realize AF and OIS functions in miniaturized components, several ways was explored like electro-wetting liquid lenses, MEMS components or liquid crystal (LC) lenses. Last development in LC lenses extended to OIS showed possibility of image shifting but some limits appeared. The sectorisation of electrodes used to shift the optical axis generates some aberrations due to the discontinuities of the resulting electric field in the lens.

To overcome these limitations, we propose a new resistive electrodes structure. This structure consists in substrates with thin chromium electrodes joined with a ring shaped resistive electrode (10kOhm) made with PEDOT-PSS and etched by oxygen plasma etching process. A high resistive layer (10MOhm) is then coated in the optical aperture and the cell is closed like in classical LC modal lenses process. Thanks to this electrode structure, we succeeded to linearize the electric potential between electrodes and to reduce aberrations of the resulting wavefronts.

First we simulated the lens by finite elements method to study the impact of the ring shaped resistive electrode and to calibrate the physical parameters of each components (metallic electrodes, ring shaped electrode, high resistive layer, LC...).

Then, we realized lenses with 1 and 2 mm diameter and filled with 20 and 50 µm thick layers of high birefringence LC. Finally, we characterized the lenses in term of focus, deviation angles, aberrations and response time.

8252-26, Session 6

Modeling and simulation of the surface profile forming process for optimum control of the lithographically fabricated microlenses and lens arrays

Z. Miao, W. Wang, Louisiana State Univ. (United States)

Numerical simulation is an indispensable tool during the design process of many scientific and engineering systems to improve performances and reduce the cost and times. In this paper, we report a research work of using a cellular automata model to numerically simulate the surface profile forming process of microlens array that is fabricated using a novel ultraviolet tilted lithography technology.

During the fabrication process, two light beams with desired profiles are projected into the photoresist in perpendicular to each other. With the exposure dosage carefully controlled, the single exposed area has about half of the full dosage with the intersected region obtained the double exposure. The surface profile of the double exposed region formed by the intersected cylindrical light beams is combined with four pieces of cylindrical surfaces. During the development process, the half exposed region is dissolved at much high rate than that of the double exposed region, and the development solution helps to smooth the edges of the double exposed area. The real surface profile therefore will tend to become a spherical surface. The final profile of the microlens is determined mainly by three factors: the geometrical shape of the photoresist, the exposure dosages and the development time. The exposure dosage also determines the etching rate during the development process. The relationship between exposure dosage and etching rate has been measured. In the numerical simulation, these parameters were used in a three-dimensional cellular automata model to numerically simulate the final profile of the microlens.

This study is very important for further improvement of the microlens and precise control of the focal lengths. It may provide a computer-aided design tool for the fabrication of the out-of-plane microlens and lens arrays. During the study, the surface profile and focal length of microlens with different expose dosages and development time were measured. The simulation results were well accordant with the experiment results.

8252-27, Session 7

Optical position feedback for electrostatically driven MOEMS-scanners

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

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

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

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

8252-28, Session 7

Closed-loop control for quasi-static MOEMS mirrors

A. Tortschanoff, D. Holzmann, M. Lenzhofer, Carinthian Tech Research AG (Austria)

In this paper we present a control loop for accurate positioning of micro optical mechanical system (MOEMS) based scanner mirrors. MEMS mirrors achieve more and more interest in miniaturized applications like for example compact projection devices, microscanners, or spectrometers. Quasistatic MOEMS mirrors enable arbitrary scan trajectories. In order to optimize settling times and the accuracy of the mirror motion, closed loop control is desirable because MOEMS elements can show a significant spread in their mechanical properties like resonance frequency and response curve.

In this contribution we present a driver concept for electrostatically driven quasi-static scanner mirrors. Simulation and microcontroller based implementation of the control loop is shown. The measured results are compared to the characteristics of the devices when driven in open loop mode. Settlings times and operating bandwidth can be improved by a factor of 10 compared to open loop operation. Furthermore, inherently, closed-loop operation can provide synchronization of different devices, which can be used, among others, for synchronization of sending and reception branch or for aperture increase in laser scanner devices. Experimental results achieved with different quasi-static mirror devices with resonance frequencies in the range of 100 Hz to 2 kHz demonstrate the capabilities but also show the limitations of our control loop.

8252-29, Session 7

Vertical comb drive microscanners for beam steering, linear scanning and laser projection applications

D. Jung, T. Sandner, D. Kallweit, T. Grasshoff, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

This paper reports a new concept of quasi-static micro scanning mirrors enabling large static deflections and linearized scanning using vertical out-of-plane comb drives. The vertical combs are realized from a planar scanner substrate by a functionalized wafer bonding process. The new device concept is highly flexible by design; different kinds of vertical combs (e.g. staggered and angular) can be realized without changing the process flow. First demonstrator devices are presented: a) quasi-static 1D-scanners with 4mm mirror diameter and 8° mechanical tilt angle for beam steering and b) a quasi-static / resonant 2D-scanner enabling 2D raster scanning with SVGA resolution.

8252-30, Session 7

A high-speed, bimodal, CMOS-MEMS resonant scanner driven by temperature-gradient actuators

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This work reports the design, fabrication and characterization of a novel one-dimensional microscanner. Its novelty is that thermoelastic resonant actuation is implemented using internal moments induced by temperature gradients across two frequency-selective directions; i.e. upon cyclic Joule heating, the first bending resonance of the device is driven by longitudinal temperature gradients; whereas its second bending resonance is driven by transverse temperature gradients.

This design, while preserving high-speed characteristics of temperature-gradient actuators, differs from previous works in two respects. First, temperature-gradient actuation is applied to excite higher vibration modes as a strategy to decrease damping; second, the heat source is embedded in a composite structure, which allows tuning of the thermal diffusivity of the structure with respect to the heat conduction direction.

The device was fabricated using 0.35-μm CMOS technology and released using aspect ratio dependent etch modulation. The composite cantilever structure consists of a double metal-oxide stack, in which the uppermost metal provides high-reflectivity to light; its topology includes a 300μm×300μm plate supported by a parallel array of ten electrothermal actuators. Resonance peaks were measured around 6.4 and 44.7 kHz at atmospheric-pressure conditions with respective minimum quality factors of 3.45 and 16.55, which confirm the lower damping effect at higher modes. However, the modal power sensitivities (2.8 and 1.6 °/W) of the device may compromise its performance for low-power, large-angle applications. Therefore, although vacuum packaging could improve vibration magnitude, bimodal resonant actuation may be more suitable for applications requiring a variation from low- to high-stability conditions with increasing operating speed.

8252-31, Session 7

Self-sustained oscillation of MEMS-based micromirrors

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Synchronization between elements of a MEMS-based micromirror resonator array enables each and every element of the array to vibrate in phase, at a frequency dictated by the synchronization signal overlaid on top of element-specific actuation signals. Synchronized motion between array elements is critical for their use in applications where each element needs to vibrate in unison with its neighbor, thus covering a larger active modulation area, without the expense of reduced vibrational frequency, or increased power consumption and micromirror surface deformation associated with equivalent single-element implementation.

To achieve synchronization, the first step is to enable self-sustained oscillations for each resonator element in the array. Phase and frequency of only a self-sustained oscillator can be changed by a relatively weak synchronization signal without influencing its oscillation amplitude. This phase and frequency shifting technique forms the essence of synchronization between resonator array elements.

Self-sustained oscillation has not been previously reported for the type of resonator under investigation, a torsional micromirror out-of-plane actuated and detected by in-plane combdrives at twice the frequency of its mechanical oscillations.

In this paper, novel findings on self-sustaining resonant mechanical oscillations of these torsional micromirrors in the 4-30 kHz regime are presented. Furthermore, implications of achieving self-sustained oscillation towards application of these MEMS-based micromirror resonator arrays for x-ray modulation are also discussed.

8252-32, Session 8

Micro optical system based 3D imaging for full HD depth image capturing

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A 3D image capturing optical device and its system prototype are presented. For 3D image capturing, the system realized Time-of-Flight (TOF) concept including 850nm IR modulated light source and 20MHz-switching high speed image modulator, so called optical shutter. The optical shutter positioned in front of a standard high resolution CMOS image sensor, modulates incoming image frames with period of several tens of nanoseconds.The modulated image frames are processed to get a depth image with Time-of-Flight (TOF) scheme. The optical shutter exploits multi-layered optical resonance cavity principle combined with variable electro-absorption characteristics. In the optical shutter, electrically controlled absorption is maximized by the micro-scale optical cavity. The optical shutter device is composed of low resistance-capacitance cell structures to get small RC-time constant. Suggested novel optical shutter approach enables capturing of a full HD resolution of depth image, which is very fine among the-state-of-the-art, in most case the depth resolution has been limited upto VGA. The system prototype was realized to capture full HD depth as well as 14Mp color images, simultaneously. The resulting high definition color/depth image and its capturing device can play a leveraging role in 3D business eco-system such as 3D camera, 3D display, gesture recognition, and motion UI. In this paper, MEMS-based optical shutter design/fabrication, opto-electric characterization, and 3D camera system architecture and image test results, are presented. Also the presentation covers a brief of 3D imaging technology trend, expected user experiences as well.

8252-33, Session 8

Fabrication and characterization of wavelength selective microbolometers using a planar self-aligned process for low deformation membranes

J. Y. Park, D. P. Neikirk, The Univ. of Texas at Austin (United States)

We will present fabrication and characterization of wavelength selective germanium dielectric supported microbolometers using a self-alignment technique to help insure a flat microbolometer membrane. The fabricated microbolometers consist of a resistive sheet as an infrared absorber layer above a germanium dielectric/air gap/mirror interference structure. Germanium has been adopted as a structural layer above a polyimide sacrificial layer instead of silicon nitride as structural layer in general microbolometers. By using only germanium as both the interference layer for wavelength selectivity in the dielectric coated Salisbury screen and the structural layer the problems associated with highly absorbing and dispersive silicon nitride layers can be avoided. In addition, to achieve low thermal mass, the membrane of dielectric germanium was fabricated 300nm thickness. The most commonly used microfabrication approach for free-standing, thermally isolated uncooled microbolometers uses as the sacrificial layer a high-temperature stable polyimide with patterning process. We use a self-aligned process without a polyimide patterning process that helps eliminate deformation and stress in the structure membrane. We demonstrated that the fabricated wavelength selective microbolometers have flat, robust membranes using self-alignment process. To characterize the wavelength selective spectral responses of the fabricated microbolometers, FTIR microscope measurements have been made on the different geometric devices. In order to electrical characterization of device, temperature coefficient of resistance (TCR) measurements have performed at different temperature. We demonstrated that the fabricated germanium dielectric supported microbolometers are able to produce excellent tunable narrowband absorption in MWIR/LWIR band, and experimentally show efficient multi-color IR spectral response using wavelength selective pixels.

8252-34, Session 8

Microscopy using water droplets

F. A. Chowdhury, K. J. Chau, UBC Okanagan (Canada)

Water droplets are an attractive medium to realize visible-frequency optical elements. The smoothness of a droplet surface mitigates losses due to light scattering, the shape of a water droplet is reconfigurable by either applying pressure or a potential, water is nearly transparent over the visible frequency range, and water is highly abundant. Here, we demonstrate the use of a water droplet as the magnifying component in a reflection-mode microscope. A water droplet is created at the end of syringe and then coated with oil to mitigate evaporation. By applying pressure to the water droplet using a metal tip, the shape of the droplet is tuned to yield excellent focusing properties. A reflection-based microscope system is created where the droplet acts as both the condenser and objective lenses. We demonstrate the collection of images of samples having micron-scale features at various magnifications using the droplet-based microscope. The magnification of the imaging system is tuned by varying the volume of the water droplet. The results demonstrate a novel application of water droplets and the potential for variable zoom microscopy using reconfigurable fluidic elements.

8252-35, Session 8

Microbolometers, a market perspective

E. Mounier, Yole Développement (France)

Microbolometers are currently the dominant IR detector technology. The microbolometer market will grow from $253M in 2010 to $570M in 2016 (CAGR: 14.5%). The volumes will boom to 1.18 M units in 2016 with a +29 % CAGR. Amorphous silicon and VOx are fighting for this market but VOx is still the most widespread thanks to its longer history and more numerous producers. Microbolometers are produced in small, medium and large formats. Medium format (320 x 240 pixels) is the most widespread today thanks to its good resolution/cost ratio and will stay the dominant one thanks to large volume in automotive and surveillance/CCTV.

Microbolometer manufacturers are fewer than ten, so this market is very concentrated. The market will change significantly in the next five years with the arrival of new players that are coming from the MEMS business (Sensonor, Bosch, Faun Infrared, Mikrosistemler, Teledyne Dalsa, Silex, Magnity, Melexis) with strong production capabilities that will help lower the microbolometer cost. It is expected that the cost will be reduced up to 70 % between 2011 and 2016. This huge cost reduction will open the door to new applications unknown up to now.

Micobolometers will be further improved by the following technologies, some of which are coming from the MEMS industry: New sensitive material, Wafer Level Packaging, Wafer Level Optics, 3D integration. WLP is confirmed as a significant trend with high detector weight/volume reduction (-25%) and potential packaging cost reduction: FLIR start to use WLP in 2011 on its new Quark core with WLP in 2011, and soon other players will follow (Raytheon, Sensonor, NEC...).

Conference 8253: MEMS Adaptive Optics VI

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8253-23, Poster Session

Aberration correction for improving the performance of a DMHL system

D. R. McAdams, D. G. Cole, Univ. of Pittsburgh (United States)

Dynamic maskless holographic lithography (DMHL) is a new micro-manufacturing technique that has no moving parts. The laser light that is used for patterning is directed in all three dimensions with a hologram displayed on a liquid crystal spatial light modulator. Optical aberrations, like spherical aberration due to refractive index mismatch between the photoresist and the immersion oil of the high-NA objective or astigmatism due to the deformations in the surface of the SLM, can degrade the performance of the system. Degraded performance includes a decrease in potential patterning volume and an increase in patterning time. This paper presents a way to correct for these aberrations using Zernike polynomials, and the optimal coefficients are found by maximizing a sharpness metric. The effect of aberration correction on the DMHL process is quantified, including resolution and repeatability. For example, aberrations become worse with increasing depth into the sample, and the quality of the beam will be evaluated at different objective-coverslip distances. DMHL manufactured features made with this aberration correction show a marked improvement over features made without correction. It is even possible to correct for misaligned optics with this method.

8253-24, Poster Session

Biomimetic accommodating lens with implementation in MEMS

A. Hogan, B. Baker, The Univ. of Utah (United States); C. Fisher, Utah Nanofab (United States); S. Naylor, The Univ. of Utah (United States); D. Fettig, Aptina Imaging Corp. (United States); I. R. Harvey, The Univ. of Utah (United States)

We describe an accommodating lens patterned after the crystalline lens of the eye: a molded PDMS plano-convex shape stretched at the periphery by many cilia-like fibers to modify the optical path. We present initial characterization of the prototype macroscale device constructed through traditional machining techniques, and also demonstrate a MEMS implementation of the lens actuator constructed using the Sandia SUMMiT-V (TM) surface micromachining process.

Testing of the macro-scale lens indicated a 22% change in focal length through the range of radial stretching, with degradation of the spherical lens shape but no hysteresis after low-cycle testing.

8253-01, Session 1

MEMS adaptive optics in the Gemini Planet Imager

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

The Gemini Planet Imager is an advanced adaptive optics (AO) system designed to directly image giant planets orbiting nearby stars. It incorporates a 4096-actuator MEMS constructed by Boston Micromachines and will be the first MEMS-based AO instrument to use such a high-order DM, as well as the first facility-class MEMS AO instrument on a large telescope. Although the MEMS mirror allows GPI to be compact and powerful it also presents several challenges, from defective actuators to sharp influence functions. We will discuss the implementation of the MEMS AO system, lessons learned, and requirements for MEMS AO for future instruments.

8253-02, Session 1

Space-based planet detection concept using two MEMS DM's and a shaped pupil

N. J. Kasdin, T. Groff, A. Carlotti, Princeton Univ. (United States)

NASA and the astronomy community hope to soon launch a new space-based telescope to detect and characterize extrasolar planets. Detecting extrasolar planets with angular separations and contrast levels similar to Earth requires not only a large space-based observatory but also advanced starlight suppression techniques. One promising approach is coronagraphy via shaped pupils. Shaped pupil coronagraphs are binary pupil functions that modify the point spread function of a telescope to produce regions of high contrast. Unfortunately, the contrast performance of coronagraphs is highly sensitive to optical errors, thus necessitating wavefront control to retrieve the necessary contrast levels. Using two MEMS deformable mirrors in series with the coronagraph allows us to control both the phase and amplitude aberrations over a finite wavelength range. Given an estimate of the wavefront we have developed an optimal controller that minimizes actuator strokes on the deformable mirrors subject to a constraint that it achieve a targeted contrast level in a defined region of the image. To provide an estimate for the controller that is accurate enough to converge to a solution that will achieve the required ten orders of magnitude, the electric field must be estimated using the science camera to avoid any non-common path errors. The estimate is found by either using a batch process or Kalman filter technique which uses multiple image pairs with conjugated deformable mirror settings to estimate the field prior to evaluating the control shape. This talk will outline the algorithms used and present our laboratory results.

8253-03, Session 1

MEMS practice, from the lab to the telescope

K. M. Morzinski, D. T. Gavel, D. Dillon, A. P. Norton, M. Reinig, Univ. of California, Santa Cruz (United States); S. Cornelissen, Boston Micromachines Corp. (United States)

Large MEMS-based astronomical AO systems such as the Gemini Planet Imager are coming on-line. As MEMS users, we discuss our decade of practice with the micromirrors, from inspecting and characterizing devices to evaluating their performance in the lab. Finally, we demonstrate visible-light, open-loop, on-sky MEMS AO with "Villages" at Lick Observatory. Our work shows the maturity of MEMS technology for astronomy.

8253-04, Session 2

Push-pull deformable mirror: characterization and close loop operations

T. Occhipinti, A. Acciari, Adaptica S.r.l. (Italy); S. Bonora, Univ. degli Studi di Padova (Italy) and Adaptica S.r.l. (Italy); I. Capraro, Adaptica S.r.l. (Italy); F. Frassetto, Consiglio Nazionale delle Ricerche (Italy); C. Trestino, G. Meneghini, V. Scalzotto, Adaptica S.r.l. (Italy)

In this paper a "push-pull" deformable mirror is described. This device is compared to a "pull-only" deformable mirror. The first has the advantage that the mirror membrane can either be attracted from the back or from the front giving several advantages such as: doubled dynamic, better accuracy in mode reproduction, and bidirectional deformation that allows closed loop operations without biasing the deformable mirror. For this reason the electrodes are placed on both side of the membrane. The top-side electrodes are conductive and transparent (realized in Indium Tin Oxide, ITO) whereas the back electrodes are printed on an electronic printed circuit board. The ITO structure is realized with an antireflection coating; it is designed in such a way that the 11 mm in diameter active area of the mirror covers the central actuator, avoiding unwanted diffraction effects due to the actuator pattern. The key idea when developing this push-pull deformable mirror was to have good compromise between performances and practical applicability into scientific and industrial equipments, making it a good tool for series production. For this reason, an analysis of the constraints/practical limitations is described using simulations and laboratory tests. Finally, the paper describes the benefits of inserting a this device in practical applications such as ophthalmology and microscopy.

8253-05, Session 2

Advances in MEMS deformable mirror development for astronomical adaptive optics

S. Cornelissen, Boston Micromachines Corp. (United States); T. G. Bifano, Boston Univ. (United States)

We report on advances made in the development of high actuator count MEMS deformable mirror and associated drive electronics for high contrast imaging astronomical imaging. MEMS Deformable mirrors with 2000-4000 actuators are under development with fabrication process enhancements to improve to actuator yield and further enhance reliability as required for space-based operation. This paper will provide an overview of the challenges associated with the manufacture of high actuator count, large aperture MEMS DMs and enhanced manufacturing and design solutions to improve overall actuator yield and optical surface quality. In addition, we will present progress in DM technology for space-based telescopes for which actuator reliability enhancements and ultra-low power, high precision, drive electronics are under development

8253-06, Session 2

Development of high-order segmented MEMS deformable mirrors

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

The areas of biological microscopy, ophthalmic research, and atmospheric turbulence correction require high-order DMs to obtain diffraction-limited images. Iris AO has been developing high-order MEMS DMs to address these requirements. This paper will discuss progress in the development of 500-actuator class segmented MEMS DMs and experimental results from them. It will describe recent developments in the fabrication of high-reflectance dielectric-coated DMs for high-power laser applications as well.

8253-07, Session 3

Large stroke actuators and mirror devices for ocular adaptive optics

X. Wu, H. Ou, L. Yao, Microscale, Inc. (United States); H. Li, C. Pang, Sichuan Normal Univ. (China)

After laboratory studies have demonstrated that the DM-based adaptive optics ophthalmic instruments are promising for future clinical applications, the next step would be to further enhance the functionality of ocular adaptive optics for research and commercialize it for clinical applications. The first essential requirement is the stroke which should cover most wavefront errors of the eyes in clinical population, for which, we presented here design, modeling, and experiemental performance of PMN-PT unimorph actuators suitable for generating large stroke up to 50um per 1-mm pixel in order to cover wavefront correction for older adults and patients with diseased eyes. Clinical acceptance will also requires DMs to be low cost, have a small form factor, running low power, have satisfactory speed, and be an easy add-on for system integration, thus we furthur presented an effort of developing a high voltage amplifier (HVA) based application specific integrated circuits (ASIC) for driving the mirror actuators with significantly reduced power and system form factors.

8253-08, Session 3

Characterization of a miniaturized unimorph deformable mirror for high power CW-solid state lasers

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

We have developed a new type of unimorph deformable mirror which is suitable for real-time intra-cavity phase control of high power cw-lasers. The approach is innovative in its combination of super-polished and pre-coated substrates, the miniaturization of the unimorph principle, and the integration of a monolithic tip-/tilt functionality.

Despite the small optical aperture, which is only 10 mm in diameter, the mirror is able to produce a stroke of several microns for low-order Zernike modes, paired with a residual static aberration of less than 0.04 µm rms.

In this paper, the characteristics of the mirror such as the influence functions, the dynamic behavior, and experiments for testing the power handling capability are reported. The mirror was subjected to 600 W of laser power and an intensity of up to 1.5 MW/cm2 at a wavelength of 1030 nm. Due to the high reflectivity of over 99.998%, the mirror was neither significantly thermally deforming nor damaged at this laser load.

8253-09, Session 3

Novel hierarchically-dimensioned deformable mirrors with integrated ASIC driver electronics

X. Wu, H. Ou, L. Yao, Microscale, Inc. (United States)

We report on an effort of building a new form of deformable mirror (DM) driven by an array of giant piezo microactuators and being integrated with an ASIC driver electronics. The actuator layer is obtained by bonding a thin Si wafer with a thin PMN-PT crystal substrate, and is in attachment with a bulk-micromachined mirror hierarchy comprising of a supporting Si layer as the spacer, a Si post layer as the motion sampler, and atop of which a Si micromembrane layer as the deformable mirror. The ASIC employs a charge controlled approach to actuate the large capacitance (~nF) in associating with the high-energy-density actuators, capable of charging/discharging an array from quasi-static to 20 kHz framing rate, and with ultra-low-power dissipation that approximates the theoretical minimum of a driver electronics. The DM to ASIC integration is currently accomplished at chip level. An integrated DM prototype has 32x32 actuator elements at 600um pitch, weighing ~50 grams, as compact as ~1 cubic inch, and uses 25 wires to access the 1024 actuators. Fundamental characterizations of a few PMN-PT actuators, DMs, and on the ASIC drivers will also be presented in this paper.

8253-10, Session 4

Finite element modeling for a thin-shelled composite mirror for use with a MEMS active optical system

C. C. Wilcox, U.S. Naval Research Lab. (United States); M. S. Baker, D. V. Wick, Sandia National Labs. (United States); R. Romeo, R. Martin, Composite Mirror Applications, Inc. (United States); B. Clark, N. L. Breivik, B. Boyce, Sandia National Labs. (United States)

Thin-shelled composite mirrors have been recently proposed as both deformable mirrors for aberration correction and as variable radius of curvature mirrors for phase diversity, auto focus, and adaptive optical zoom. The requirements of actuation of a composite mirror far surpass those for MEMS deformable mirrors.

This paper will discuss the development of a finite element model for a 0.2 meter carbon fiber reinforced polymer mirror for use as a variable radius of curvature mirror in conjunction with a MEMS deformable mirror for aberration correction.

8253-11, Session 4

Monolithic fabrication and packaging of gold MEMS deformable mirrors

B. R. Fernandez, J. Kubby, Univ. of California, Santa Cruz (United States)

Monolithic fabrication of continuous facesheet high-aspect ratio gold Micro Electro Mechanical Systems (MEMS) deformable mirrors onto a thermally matched ceramic-glass substrate (WMS-15) has been performed. The monolithic process allows for thick layer deposition (tens of microns) of sacrificial and structural materials thus allowing high-stroke actuation to be achieved. The fabrication process does not require wafer bonding to achieve high aspect ratio 3-dimensional structures.

Critical point drying has been utilized to prevent stiction from occurring during release of a continuous facesheet mirror attached to 16×16 and 10×10 arrays of X-beam actuators. This paper will discuss device characterization, pull-in vs. voltage displacement tests, as well as initial results for the high-aspect ratio gold MEMS 16x16 continuous facesheet mirror that has been wire-bonded and packaged in a ball-grid array housing.

8253-12, Session 4

Thermo-mechanical properties of a deformable mirror with screen printed actuator

C. Bruchmann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany); M. Appelfelder, E. Beckert, R. Eberhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); A. Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

This paper reports on the thermo-mechanical modeling and characterization of a screen printed deformable mirror. The unimorph mirror offers a ceramic LTCC substrate with screen printed PZT layers on its back side and a machined copper layer on its front side. We present the thermo-mechanical model of the deformable mirror based on Ansys multiphysics. The FEM simulations evaluate the static and dynamic properties of the membrane for piezoelectric activation and different thermal loading. The thermal considerations define the optimum copper thickness to optimize the thermal induced deformations of the mirror membrane under homogeneous temperature increase. In a second set of simulations is the laser load incorporated into the model.

The developed mirror design is practically demonstrated and characterized. The homogeneous loading of the optimized design results in a membrane deformation with a rate of -0.2 µm/K, while a laser loading causes a change with a rate of 1.3 µm/W. The proposed mirror design is also suitable to pre-compensate laser generated mirror deformations by homogeneous thermal loading (heating). We experimentally show that a 40 K pre-heating of the mirror assembly could compensate an absorbed laser power of 6 W. The application of a mirror coating with a reflectivity of 99 % (1 % absorption) would therefore lead to a laser load of 600 W that is compensated by a temperature increase of 40 K.

8253-13, Session 5

Coherence-gated phase-shifting wavefront measurements

T. van Werkhoven, H. C. Gerritsen, Utrecht Univ. (Netherlands); J. Antonello, Technische Univ. Delft (Netherlands); R. Fraanje, Technische Univ. Delft (Netherlands) and TNO Science and Industry (Netherlands); M. Verhaegen, Technische Univ. Delft (Netherlands); C. Keller, Utrecht Univ. (Netherlands)

Two-photon excitation microscopy (TPEM) illuminates a sample with a strongly converging, near-infrared laser beam, where fluorescent light is created when two NIR photons are simultaneously absorbed, and a single photon is emitted at shorter. The fluorescent light is then collected, and by scanning beam, an image is created.

The inhomogeneities in index of refraction of the sample aberrate the laser beam. This significantly decreases the intensity at the focus and thus reduces the fluorescent light while increasing the size of the fluorescing volume. This degrades the image quality and limits the depth penetration.

This can be solved by using adaptive optics, but it is not trivial to measure the wavefront of only the light scattered back from the laser focus. Common wavefront sensing approaches are therefore difficult to use. Instead, simple intensity-optimization schemes have been used, which are less favourable.

This problem can be mitigated by using coherence gating where a reference beam and the back-reflected NIR light from the sample interfere. Since we are using a 100fs-pulsed laser, the interference occurs only over a 30-micron length. This can thus be used to select a narrow depth range of interest, and filter out any unwanted scattered light, as has been shown by Tuohy (2010).

We take this approach one step further and directly measure the wavefront from the interference pattern. Using either spatial or temporal modulation of the phase, we reconstruct can the wavefront in an interferometric fashion. This method provides full wavefront information while being insensitive to light reflected and/or scattered from volumes and surfaces outside of the range of interest.

8253-14, Session 5

Assessing correction accuracy in image-based adaptive optics

D. Débarre, A. Facomprez, E. Beaurepaire, Ecole Polytechnique (France)

Aberration correction has been shown in recent years to significantly improve the quality of nonlinear images when focussing inside thick biological samples. In image-based adaptive optics, a metric (such as brightness or sharpness) is calculated from images acquired with a series of aberration applied, and the initial amount of aberration is then estimated using a simple maximization algorithm. This approach has proven successful in two-photon fluorescence microscopy and third-harmonic generation microscopy[1-3].

Here we investigate experimentally the precision of the achieved correction as a function of the algorithm parameters, such as the number of measurements per corrected aberration mode, the amount of aberration corrected, the number of photons per image, etc. A theoretical model provides understanding of the role of these parameters. In particular, we show that the optimal parameters for precise correction depend on the initial amount of aberration that needs be corrected for and on the time and illumination that can be used for correction.

We subsequently propose optimized algorithms for various practical situations and present examples of use in various biological samples such as embryonic tissues, brain slices and ex-vivo skin samples.

[1] Débarre et al, Opt. Lett. 34 (2009).
[2] Olivier et al, Opt. Lett. 34 (2009).
[3] Débarre et al, in preparation.

8253-15, Session 5

Adaptive optics for biological microscopy using phase retrieval and phase diversity

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

The lack of natural guide stars in biological samples has led to the development of methods for optimizing the wavefront in an adaptive optics fluorescence microscope without the use of a wavefront sensor. These methods involve taking multiple images while changing the wavefront. The images are evaluated to determine the optimum mirror shape. Either the wavefront is varied to search for the optimum image or the wavefront is varied to infer the wavefront. A difficulty with these methods is that they require many images to optimize the wavefront if a high degree of correction is desired which wastes time and photons. Here we discuss the measurement and correction of the wavefront in fluorescence microscopy using phase retrieval and phase diversity. These methods have the advantage that they can measure the wavefront to a high resolution with only a few images. We demonstrate the application of these techniques to wide-field fluorescence imaging of C. elegans.

8253-16, Session 5

Critical considerations of pupil alignment to achieve open-loop control of MEMS deformable mirror in nonlinear laser scanning fluorescence microscopy

W. Sun, Wellman Ctr. for Photomedicine (United States) and Boston Univ. (United States) and Massachusetts General Hospital (United States); Y. Lu, T. G. Bifano, Boston Univ. (United States); C. P. Lin, Wellman Ctr. for Photomedicine (United States) and Harvard Medical School (United States) and Massachusetts General Hospital (United States)

Nonlinear fluorescent microscopic imaging, with its unique advantages over conventional confocal fluorescent microscopy, has been widely adapted to reveal biological processes at cellular level. However, like all the other optical imaging techniques, nonlinear microscopy suffers from focal degradation due to the optical aberrations in the system, from both optical alignment of the microscope and the inhomogeneity of specimen refractive index.

We integrated a microelectromechanical system (MEMS) deformable mirror (DM) into our non-linear laser scanning fluorescence microscope. With the development of an accurate open-loop control mechanism which predicts the control voltages and generates a prescribed surface shape on the MEMS deformable mirror, known aberrations in the system can be compensated in this computationally simple and inherently fast way.

Open-loop compensation of known aberrations represented in Zernike modes requires precise alignment of the optical pupil. We show that by the careful alignment procedure with the aid of a Shack-Hartmann wavefront sensor and a CMOS camera, one can evaluate the alignment quality by manually imposing one Zernike mode on the DM and measuring with the Shack-Hartmann wavefront sensor at the conjugated pupil plane. We also characterize of the open-loop performance to correct for known aberrations introduced to the nonlinear laser scanning fluorescence microscope during imaging of specimens.

8253-17, Session 5

Adaptive optics for high-resolution microscopy and three-dimensional photonic fabrication

M. Booth, Univ. of Oxford (United Kingdom)

We present here results from adaptive laser-based microscopes and fabrication systems with applications in different areas. In the microscopes, adaptive optics are used to compensate specimen-induced aberrations, leading to improved signal levels and resolution. In particular, we have implemented aberration correction using deformable mirrors and spatial light modulators in two-photon fluorescence and harmonic generation microscopes. We investigate optimum modes for control of the adaptive system, taking into account the properties of the adaptive element and the imaging modality. We develop methods for adaptive optics for aberration measurement and correction when aberrations vary across the field of view.

Laser direct writing is used for fabrication of micron-scale three-dimensional structures within bulk substrates, with applications in e.g. photonic crystals, metamaterials, waveguide structures and microfluidics. Refractive index differences between the fabrication substrate and objective immersion medium introduce aberrations that compromise the efficiency and accuracy of fabrication. The aberrations become more severe as one focuses deeper into the material, significantly restricting the thickness of the fabricated 3D structures. We have demonstrated adaptive aberration correction for direct laser writing in a range of substrates, including wave-guiding structures in fused silica, photonic crystals in lithium niobate, and graphite structures within diamond. This correction enabled the fabrication of extended 3D high fidelity structures over a range of depths. One limitation of the 3D direct write method is long fabrication time, which can be improved by parallelization. We describe adaptive holographic and hybrid holographic/microlens-array methods employing hundreds of individually controllable foci permitting significant reductions in fabrication time.

8253-18, Session 6

Adaptive optics for biological light microscopy

C. D. Saunter, C. J. T. Bourgenot, J. M. Girkin, G. D. Love, J. M. Taylor, Durham Univ. (United Kingdom)

The addition of adaptive wavefront correction to biological microscopy has demonstrated many tangible benefits, for example increasing the signal levels in non-linear microscopy and improving both the lateral and axial resolution in confocal microscopy. However, biological microscopy is a very diverse and challenging field compared to many other application areas of adaptive optics. Many processes being examined under the microscope are highly dynamic, and common imaging modalities such as florescence have detrimental effects on the samples and fluorophores. Both of these introduce requirements for fast, light efficient adaptive correction whilst working with a wide variety of sample types. Our talk will begin by examining the success and challenges of adaptive optics as applied to biological microscopy. We then give an overview of the adaptive optics platform we have developed at Durham for biological microscopy. This platform employs both closed loop adaptive optics and 'sensor-less' optimization-based techniques. We will present the aims and results of various experiments designed to address the challenges faced by adaptive optics for biological light microscopy, such as our implementation of closed loop adaptive optics using a 'sample-safe' laser guide star and exploitation of brightfield imaging.

8253-19, Session 6

Improving spatial resolution in photoacoustic imaging with adaptive optics

H. F. Zhang, Northwestern Univ. (United States); S. Jiao, The Univ. of Southern California (United States)

We want to develop system to achieve cellular resolution photoacoustic imaging as well as multimodal imaging of the retina. To this end, we have to solve several potential problems. First of all, we need to improve the speed of the existing photoacoustic microscopy, which needs several minutes to acquire an image. Second, we need to design a different image acquisition mechanism so that no mechanical scanning is required in order to prevent potential damages to the cornea. Finally, we have to improve the spatial resolution in retinal imaging, which is fundamentally limited by the optical quality of the eye, to image individual cells. We have solved the first two issues by developing system that uses the same optical scanning method as optical coherence tomography and keeping a small footprint ultrasonic transducer stationary. In order to further improve the spatial resolution in photoacoustic retinal imaging, we plan to employ adaptive optics to maximize the effective numerical aperture in retinal imaging. The feasibility has been demonstrated in ex vivo ocular tissue samples. The spatial resolution in our current photoacoustic retinal imaging is around 20 µm in rodent eyes and we expect a 4-5 fold improvement with adaptive optics in the future.

8253-20, Session 6

MEMS spatial light modulators for controlled optical transmission through nearly opaque materials

T. G. Bifano, Y. Lu, C. Stockbridge, A. Berliner, Boston Univ. (United States); R. G. Paxman, Paxman Consulting (United States); S. Tripathi, K. C. Toussaint, Jr., Univ. of Illinois at Urbana Champaign (United States)

We describe MEMS-based control of optical phase to achieve sharp focus of a laser beam after transmission through highly scattering media.

In recent years, a number of research groups have reported on controlled propagation through scattering media using liquid-crystal spatial light modulators (LC-SLMs) to pre-compensate the wavefront.

A limitation is that the time required for optimization scales with SLM frame refresh rate. To date, that optimization time is measured in minutes or hours. The work presented here describes experiments using a fast, high-order MEMS SLM for control, with a goal of reducing optimization times by up to three orders of magnitude.

A collimated, spatially filtered laser beam was reflected from the MEMS SLM and trough a scattering medium comprised of a film of white paint on a glass slide. A microscope objective on the far side of the scattering medium reimaged a portion of the resulting speckle pattern on a camera.

The optimization objective was to maximize the intensity on a pixel at the center of the camera. A stochastic parallel gradient descent algorithm was used for optimization.

At the conclusion of a typical 5000-iteration, 40-second optimization, the peak intensity of the central pixel was ~140 times larger than the spatially averaged mean intensity of the initial image. The optimization time was regulated primarily by the camera refresh rate. This improvement is comparable with the best results achieved to date by any research group, at a substantially higher optimization convergence rate than has been reported previously.

8253-21, Session 6

Adaptive optics confocal microscopy using fluorescent protein guide-stars for brain tissue imaging

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

Optical aberrations due to the inhomogeneous refractive index of tissue degrade the resolution and brightness of images in deep tissue imaging. We introduce a direct wavefront sensing method using cellular structures labeled with fluorescent proteins in tissues as guide-stars. As a non-invasive and high-speed method, it generalizes the direct wavefront sensing method for AO microscopy. An adaptive optics confocal microscope using this method is demonstrated for imaging of mouse brain tissue. The adaptive optics system includes a deformable mirror (DM, 140 actuators, Boston Micromachines Multi-DM) and a Shack-Hartmann wavefront sensor (SHWS). A laser guide star was generated by focusing a solid state laser on the fluorescent proteins in the cell body or dendrites of the neurons. The relationship between the wavefront measurement errors and photons per sub-aperture of SHWS is investigated experimentally. In the current set-up, the measurement error is 0.03 λ with 2047 photons per subaperture. The size of the guide-star is limited by the illumination PSF. In our current system, the size of the PSF at a depth of 70 μm in the mouse brain tissue is 1.4 μm, which is smaller than the diffraction limit of the wavefront sensor, 5.4 μm.

Confocal images with and without AO correction are collected. The results show increased image contrast and 3x improvement in the signal intensity for fixed mouse tissues at depths of 70 μm. The image of the dendrite and spines are much clearer after correction with improved contrast. The Strehl ratio is improved from 0.29 to 0.96, a significant 3.3x improvement.

8253-22, Session 6

Adaptive optics applied to super resolution localization microscopy: the practical results

J. Ballesta, Imagine Optic Inc. (United States); J. Andilla, X. Levecq, Imagine Optic SA (France)

Adaptive Optics has over the last 5 years became an obvious technique to improve imaging capabilities of microscopy techniques such as wide field multi-photon and confocal. Recently the use of a deformable mirror has been demonstrated to even more improve localization performance of super resolution microscopy techniques including Palm, Storm and their 3D derivatives.

Imagine optic is an industrial pioneer in the development of AO solutions applied to microscopy, in this paper we'll present details about very recently obtained obtained in Palm and Storm 3D.

Conference 8254: Emerging Digital Micromirror Device Based Systems and Applications IV

Monday-Wednesday 23-25 January 2012

Part of Proceedings of SPIE Vol. 8254 Emerging Digital Micromirror Device Based Systems and Applications IV

8225-55, Session 1

Multivariate optical computing using a digital micromirror device for Raman and fluorescence spectroscopy

Z. J. Smith, S. Strombom, S. Wachsmann-Hogiu, UC Davis Medical Ctr. (United States)

A multivariate optical computer has been constructed that utilizes an imaging spectrograph with a digital micromirror device placed in the image plane to act as a programmable optical filter, with the length of the DMD chip corresponding to wavelength and the height to position within the spectrometer slit. Pixels of the DMD that are turned on direct light to a point detector, while off pixels send light to a beam dump. By rapidly varying binary patterns, 8-bit greyscale patterns can be displayed on the chip at 60 Hz. The measurement at the point detector represents the projection of the source spectrum onto the axis defined by the pattern displayed on the DMD. Assuming the sample spectrum can be represented as a linear model of component spectra (principal components, pure reference spectra, vertex components, etc.), such measurements can provide quantification of absolute concentrations of these components with a signal-to-noise advantage over standard detection utilizing a spectrograph and CCD array. Experiments have been performed on ternary mixtures using fluorescence and Raman spectroscopy showing accurate quantification of absolute concentrations. Simulations have been performed using Raman spectra of cancerous and noncancerous T-cells, showing that computing the first two principal component scores (which are diagnostic for disease) directly using the optical computer provides greater robustness to noise compared to computing them from detected spectra. This could have important implications for the feasibility of Raman-activated cell sorting. These and continuing results will be presented.

8225-56, Session 1

Realization of an endoscope equipped with microprojection system for optogenetics

R. Pashaie, Univ. of Wisconsin-Milwaukee (United States)

Abstract- Optogenetics is the science where recent progresses in the field of photonics are combined with the techniques in molecular genetics to develop a methodology for modulation of neural activities. Despite enormous enthusiasm in using optogenetics for brain studies, little has been done on the engineering side such as technology development for light delivery or realization of reliable systems for optical monitoring of the induced activities.

In this project, we have implemented a Digital Micromirror Device based microprojection system capable of delivering illumination patterns through a high-resolution imaging fiber bundle that guides the pattern to the region of interest on the surface or within the brain tissue. The system is also equipped with an imaging path for detection of calcium signals and monitoring the induced patterns of cellular activities.

A very interesting application of the system is extracting topographic computational maps of cortex or cellular receptive fields in-vivo. It is known that such maps are the engine of information processing in the cortex. Better understanding of the structure of such maps will help to unravel the mysteries of brain higher level computations. Another application of this system is related to the high-resolution stimulation patterns that cannot be produced with electrode arrays. Production of high-resolution patterns is important in the study of specific modes of brain activities.

We report the details of our optical design, preliminary results produced by testing the system on tissue phantoms, and we discuss our strategy to extract new data from the brain tissue.

8225-57, Session 1

Design and development of a wide-field structured illumination fluorescence imaging system for breast tumor margin assessment

H. L. Fu, N. Ramanujam, J. Q. Brown, Duke Univ. (United States)

Cancer is associated with specific morphological changes at the cellular level, such as increased nuclear size and crowding due to rapidly proliferating cells. In situ imaging of these hallmarks may be useful for microscopic detection of residual cancer in breast tumor margins. We have previously presented a contact-based high resolution micro-endoscope system for imaging microanatomy in situ in combination with topically-applied fluorescent nuclear stains. However, breast tumor margins are often large (~4.5x4.5cm) and difficult to cover with the small single-shot field of view (FOV = 0.3 mm2) afforded by micro-endoscopy.

We have developed a custom wide-field fluorescence microscope system with a single-shot FOV of 2.1x1.6 mm (3.36 mm2). The ability to resolve cell nuclei in thick tissues in situ is achieved by rejecting out of focus fluorescence via structured illumination microscopy (SIM). The system is designed to image a 20 cm2 tissue sample at sub-cellular resolution within 10 minutes. Using a supercontinuum fiber laser and bandpass filters, the system can excite a variety of fluorescent contrast agents, and the LCTF allows collection of spectral emission images.

The system was tested on solid phantoms consisting of 10 µm fluorescent spheres (to simulate cell nuclei) embedded in a PDMS matrix and TiO2 spheres to yield a reduced scattering coefficient of 10 cm-1 (at 630 nm). The 10 µm spheres were clearly resolved with a 13 dB SNR increase from the non-sectioned to sectioned images. We are currently evaluating the tool for detection of microscopic residual disease in a transgenic murine cancer model.

8225-58, Session 1

Investigation of in situ fluorescence optical detection based on a programmable spatial light modulator

J. Choi, K. Kim, D. Kim, Yonsei Univ. (Korea, Republic of)

Microfluidic 3D cell culture systems have received tremendous attention because they provide an in vitro microenvironment in which cellular dynamics can mimic those obtained in in vivo conditions. In this study, we investigated enhancement of imaging resolution for in situ fluorescence optical detection of 3D cell cultures using a digital micro-mirror device (DMD) as a programmable binary-intensity spatial light modulator. The fluorescence optical detection system was designed for various architectures of 3D microfluidic cell-based assays to be measured in situ in a conventional incubator. Through the combination of DMD-based multiple-pinhole scanning and fast axial scanning by a motorized stage, the optical detection system was developed to provide 3D fluorescence imaging. The performance was initially tested by the measurement of an USAF target and fluorescent microbeads (diameter: 10 μm; emission λ = 515 nm) that are similar in size to stained mammalian cells. Furthermore, we studied cellular dynamics of 3D cultured cells embedded in an alginate-based extracellular matrix and stained by Celltracker Green, which is a fluorescence indicator representing cell viability. Preliminary results indicate objective-dependent enhancement of imaging resolution by at least 2.5 times. Further improvements in 3D fluorescence images are under way based on multiple approaches including programmable structured illumination and optimized image reconstruction algorithm. The in situ fluorescence optical detection system that employs a programmable spatial light modulator is expected to offer a simple and useful analytical tool for measuring cellular dynamics in diverse 3D cell assays while maintaining dynamic culture environments.

8254-01, Session 2

Network based multi-sensor optical 3D acquisition of complex structures

G. J. Frankowski, C. Benderoth, R. Hainich, GFMesstechnik GmbH (Germany)

We present new developments in optical 3d sensors using pico DLP as well as DSP technology. We use enhanced, high-powered pico DLP projection units and compact processing hardware to create likewise compact, light-weight measuring heads, which can perform the acquisition as well as the evaluation of 3D data without external computing power. Moreover, their drastically reduced cost and their networking ability also allows for an economical combination of a multitude of individual sensors into complex configurations. The entire form even of large and complex shapes can hereby be scanned in a very short time. New calibration strategies, integrating all individual sensor coordinate systems into a single, calibrated, global one, lead to an immediate combination of all sensor data into a single, complete point cloud. We show the principle and actual realization of sensors, calibration strategies and procedures, and examples of first realized multi-sensor measuring systems utilizing this new technology.

8252-01, Session 2

Trajectory precision of micromachined scanning mirrors for laser beam scanning pico-projector displays

W. O. Davis, M. Beard, R. Jackson, Microvision, Inc. (United States)

Magnetically-actuated micromachined scanning mirrors have been developed for pico-projectors using laser beam scanning (LBS). In addition to addressing the requirements for low power consumption and small size, the devices provide an extremely precise, repeatable, and stable scanned beam trajectory. The human vision system readily detects imperfections in a LBS display, which become objectionable when scanned beam trajectory errors have amplitudes on the order of only parts per thousand or even parts per ten thousand, depending on the type of error and whether it is static or dynamic. The scanning mirror consists of a gimbal-suspended reflector, where one scan axis operates at a mechanical resonance to generate horizontal lines in the LBS display. The second, orthogonal scan axis corresponds to the vertical dimension in the display. A sawtooth raster scan ideally produces a uniform spacing of the horizontal lines, however one challenge to achieving such trajectory precision is that a sawtooth contains harmonics that will coincide with modes of vibration of the scanning mirror with high quality factors. The resulting nonuniformity of line spacing results in objectionable perceived intensity modulation based on the human contrast sensitivity function. The paper describes the overcoming of such challenges to achieve a high quality LBS projection.

8252-02, Session 2

MEMS-based micro projection system with a 1.5cc optical engine

L. Kilcher, N. Abele, Lemoptix SA (Switzerland)

Lemoptix will present a technical overview of the company's high reliability, high performance and small size magnetic actuated MEMS scanning micro mirror product. While the applications for MEMS mirrors are countless Lemoptix will specifically present the use of its MEMS mirror as core component of its micro projection system.

Based on the combination of its MEMS, ultra small optics and high performance electronics technology, Lemoptix has developed an embeddable micro projector with an optical engine unique in many ways but specifically in its dimensions of only 1.5 cc.

Lemoptix provides its MEMS micro mirrors and micro projectors in consumer and industrial applications ranging from micro projection systems in the automotive industry (HUD) as well as in light scanning devices such as range finders and optical sensing systems.

8252-03, Session 2

Laser projector solution based on two 1D resonant micro scanning mirrors assembled in a low vertical distortion scan head

J. Grahmann, M. Wildenhain, T. Grasshoff, H. Dallmann, C. Gerwig, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); A. Wolter, HiperScan GmbH (Germany); H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

A Scan Head design based on two 1D-scanning mirrors cannot be miniaturized as much as a design with a 2D-scanning mirror. However an advantage of the 1D-scanner approach is the alignment of the two scanners in angles enabling a straight line projection on to the slow axis scanner. This results in almost no vertical distortion. The remaining is determined by manufacturing tolerances of the Scan Head and the alignment tolerances of the micro mirrors inside.

The slow scanning mirror has a frequency of 100Hz accompanied by a die size of 7.4mm x 3.3mm. The resonance frequency of the fast scanner is 29050Hz and die size is smaller since the incident laser spot hits this mirror first. The WVGA resolution with a ratio of 16:9 is given by a mechanical deflection of ±12° : ±6.75°. Die size and Scan Head design influence each other and this Scan Head demonstrator fills a volume of 1.83cm^3 showing the potential to reduce dimensions further.

The developed electronics is divided into a MEMS driving part and a video processing part. The MEMS driver board enables generation of rectangular drive voltages up to 230V and comprises of an amplifier stage for the piezoresistive sensor signals. The video processing board adapts the RGB signal for each picture to the Lissajous figure. The heterogeneous brightness of the picture which is due to varying scanner speeds is corrected by a new approach increasing picture contrast.

8252-04, Session 2

Speckle reduction for laser-illuminated picoprojectors

F. P. Shevlin, Dyoptyka Ltd. (Ireland)

An overview is given of the advantages of using Lasers as illumination sources in picoprojectors. The problem of speckle, which can seriously degrade image quality, is presented. Various solution approaches are discussed with respect picoprojector application constraints including size, power consumption, and optical efficiency. Illumination optical system and projection optical system design are presented to better understand the application constraints. The solution using Dyoptyka's deformable mirror, manufactured using MEMS fabrication techniques, is presented in detail.

8254-05, Session 2

Optotune focus tunable lens and laser speckle reduction based on electroactive polymers

M. Aschwanden, Optotune AG (Switzerland)

Optotune develops, manufactures and sells adaptive optical elements. Among others, our patented technology enables the implementation of a compact, inexpensive, high-speed and focus-tunable lens, which simplifies the design of focus and zoom systems across industries. Furthermore, Optotune has developed a laser speckle reducer based on electroactive polymers. This device offers an extremely compact and low cost solution for removing speckles from laser light. The laser speckle reducer is used in laser based pico-projectors, cinema projectors and illumination systems.

8252-06, Session 2

Superluminescent light emitting diodes - the best out of two worlds

C. Vélez, U. Achatz, M. Rossetti, M. Duelk, J. Napierala, Exalos AG (Switzerland)

Since pico-projectors (picoPs) were starting to become the next electronic “must-have” gadget, the experts were discussing which light-source technology seems to be the best for the existing three major projection approaches for the optical scanning module such as digital light processing (DLP), liquid crystal on silica (LCoS) and laser beam steering (LBS). Both so-far used light source technologies have distinct advantages and disadvantages. Though laser-based picoPs are focus-free and deliver a wider color gamut, their major disadvantages are speckle noise, cost and safety issues. In contrast projectors based on cheaper Light Emitting Diodes (LEDs) as light source are criticized for a lack of brightness and for having limited focus. Superluminescent Light Emitting Diodes (SLEDs) are temporally incoherent and spatially coherent light sources merging in one technology the advantages of both Laser Diodes (LDs) and LEDs. With almost no visible speckle noise, focus-free operation and potentially the same color gamut than LDs, SLED could potentially answer the question which light source to use in future projector applications. However, still open application requirements on optical output power and power efficiency need to be answered together with picoP manufacturers.

8252-07, Session 2

Bi-resonant scanning mirror with Piezo-resistive position sensor for WVGA laser projection systems

C. Drabe, D. Kallweit, A. Dreyhaupt, J. Grahmann, H. Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); W. O. Davis, MicroVision, Inc. (United States)

Fraunhofer IPMS developed a new type of small-sized scanning mirror for Laser projection systems in mobile applications. The device consists of a single crystal mirror plate of 1 mm diameter in a gimbal mounting enabling a bi-resonant oscillation of both axes at a resonance frequency of about 100 Hz and 27 kHz respectively. The mechanical scan angle achieved is ± 7° for the slow and ± 12° for the fast axis. The mirror angle position and phase can be read out via two piezo-resistive sensors located at the torsion axes. In order to allow for a minimum device size of the resonantly driven slow axis the sensor of the inner fast axis was connected by a new kind of thin silicon conductors. Those are created by means of an electrochemical etch stop in TMAH etch and kept as thin as possible in order to reduce their contribution to the mechanical stiffness of the mirror-supporting structures. This new system enables to lead six (or even more) independent electrical potentials onto the moving parts of the device, whereas the mechanical properties are mainly determined by only 2 torsion axes. The devices were subsequently characterized and tested. Technology details, simulation and pictures of the device and the new conductor structures as well as measurement results are presented.

8254-02, Session 3

Hyperspectral imaging in the operating room: what a surgeon wants

S. L. Best, Univ. of Wisconsin School of Medicine and Public Health (United States)

Visualization is the key to surgery, but limiting one's "vision" to visible light images received by the human eye ignores a lot of available data. Imaging technology such as hyperspectral and infrared imaging can greatly expand the amount and type of information available to the surgeon. We propose several areas in which this type of technology can be useful in medicine, paying particular attention to the way in which this technology might be best integrated into current operating room setups.

8254-03, Session 3

Evaluation of a novel laparoscopic camera for characterization of renal ischemia in a porcine model using DLP® hyperspectral imaging

E. O. Olweny, S. L. Best, N. Jackson, E. F. Wehner, S. K. Park, Y. K. Tan, A. Thapa, J. A. Cadeddu, K. J. Zuzak, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States)

Introduction:

Digital light processing hyperspectral imaging (DLP® HSI) has previously been used to characterize renal ischemia during open partial nephrectomy in pigs and humans. By incorporating a light guide, 0-degree laparoscope, customized digital CCD camera (DVC, Austin, TX), and a DLP-based Agile Light source (OL490; Gooch & Housegro, Orlando, FL), we adapted DLP® HSI for use during laparoscopic surgery.

Methods:

Laparoscopic DLP® HSI was performed in 5 adult female pigs (Group 1). 3 pigs that were previously imaged using the open system (Group 2) were selected for comparison. In Group 1, spectra were recorded at several intervals before, during and after clamping the renal hilum for 90 minutes. In Group 2, similar measurements were obtained, but the renal ischemic period was 60 minutes. Spectra obtained over common imaging intervals for each group were analyzed. The relative percentage of oxygenated hemoglobin (relative %HbO2) at each time interval was determined using previously described methodology, and compared for the groups using the Student's t-test.

Results:

For Lap vs. Open respectively, relative %HbO2 was 74.2 vs. 72.8% pre-clamp, dropping by an average of 22% vs.19% during the initial 10 minute interval post hilar occlusion, and rapidly rising to baseline after clamp removal. There were no statistically significant differences between the groups in the relative %HbO2 measured for any of the imaged intervals.

Conclusion:

The laparoscopic DLP® hyperspectral imaging system performs similarly to the open system and has excellent spectral imaging capabilities. Preliminary clinical application during minimally invasive partial nephrectomy is currently underway.

8254-04, Session 3

Instrument validation and applications of a clinic-friendly spatial frequency domain imaging (SFDI) device

D. J. Cuccia, Modulated Imaging, Inc. (United States)

Quantitative characterization of tissue structure and function is one of the most challenging problems in Medical Imaging. We are advancing the Modulated Imaging (MI) technique, toward its application as a clinical research device to provide objective parameters for in-vivo tissue status determination. MI is a spatial frequency domain imaging (SFDI) method, which employs spatially-patterned illumination to non-invasively obtain subsurface images of biological tissues. This non-contact approach enables rapid quantitative determination of the absorption and scattering optical properties of tissues over a wide field-of-view. When combined with multi-spectral imaging, the optical properties at several wavelengths can be used to quantitatively determine the in-vivo concentrations of chromophores that are relevant to tissue health, namely, oxy- and deoxy-hemoglobin.

We present the design, fabrication, testing, can clinical deployment of a robust, user friendly MI instrument appropriate for deployment at clinical sites. This instrument is compatible with a plurality of light sources, provides a wide field of view (~180x135mm), and is sufficiently compact and robust for human subject measurements. It possesses sufficient spatio-temporal resolution to study both fast (<1s) and localized (<1mm) events at depths of several millimeters in thick tissues. The device performance was characterized in a laboratory setting in terms of linearity, dynamic range, reproducibility, and drift. A turnkey software interface was developed facilitating clinical deployment for real-world testing and evaluation. Ultimately, we envision that this platform will enable quantitative insight into disease progression and therapeutic response in areas such as wound healing, dermatology, skin cancer and reconstructive surgery.

8254-05, Session 3

Advances in optical tomography using spatial frequency domain imaging

S. D. Konecky, T. B. Rice, A. Lin, A. Mazhar, R. B. Saager, Beckman Laser Institute and Medical Clinic (United States); D. J. Cuccia, Modulated Imaging, Inc. (United States); A. J. Durkin, B. Choi, B. J. Tromberg, Beckman Laser Institute and Medical Clinic (United States)

Diffuse optical spectroscopy and imaging are rapidly growing fields with applications including human breast, human brain, and small animal imaging. Typically, a collimated beam or optical fiber is used to inject light into biological tissue, and the amount of light remitted from the tissue is measured at several locations. While this approach is useful for determining the average properties of large volumes of tissue, it is not ideal for imaging. Recently, we have begun projecting spatially extended patterns of light on tissue and detecting the remitted light with a CCD array, eliminating the need to use large arrays of optical fibers or raster scan a collimated beam. The spatially varying optical properties of the tissue are determined by measuring the attenuation (or fluorescence) of sinusoidal patterns of light projected onto the sample at varying spatial frequencies and phases. Using this technique, called Spatial Frequency Domain Imaging (SFDI), we image the absorption, scattering, and fluorescence properties of biological tissues. SFDI is wide-field, non-contact, inexpensive, and it eliminates the need for detectors with a wide dynamic range. By combining diffuse optical methods with CCD imaging, SFDI allows one to acquire high resolution images with quantitative spectroscopic information. In this presentation, I will review the underlying physics of SFDI, and then show our recent advances extending SFDI to reconstruct three-dimensional images, determine the orientation of microscopic structures, and image rates of blood flow.

8254-06, Session 4

Digital micromirror device based confocal 4D-microscopy

W. Neu, M. Schellenberg, Fachhochschule Oldenburg/Ostfriesland/Wilhelmshaven (Germany)

Any approach to understand the dynamics of living cells and cell clusters requires time resolved sufficiently fast 3D sampling at high spatial resolution. Confocal microscopy using a digital micromirror device (DMD) realizes both the illumination and the confocal sectioning through a single DMD-array. Making use of the fast modulating frequency DMDs offer, the inherent multifocal sample illumination and simultaneously utilization of each micromirror as a virtual pinhole allows to reduce volume sampling times to a seconds time scale. An electronically intensified CCD-camera synchronized to the DMD takes the images of each single optical slice. Due to the high DMD-frequency (8000 frames/s), each complete measurement plane is recorded within a single frame of the electron multiplying CCD-camera. The z-scan is realized by a piezo-driven microscope objective.

Through purpose designed scan patterns for a particular object, regions of the specimen can be protected from an excess of excitation light intensity, e.g to alleviate fluorophore bleaching. Furthermore, adaptive illumination scenarios are possible such as the tracking of objects within a cell. Through flexible illumination and a system easily adaptable to a standard microscope, conventional microscopy techniques can be implemented, such as Dark Field Microscopy and Phase Contrast Microscopy. In this way non-fluorescent structures within the sample can be imaged and the data can be combined with the fluorescent confocal acquisition.

Objects can be imaged with a diffraction limited spatial resolution of approx. 300 nm laterally and approx. 1000 nm axially @ 405 nm. High temporal resolution of 1 s to 4 s for 50 layers at ca. 1 µm optical slicing distance enables one to visualize and analyse in vivo and in realtime e.g. physiological processes within living cells in a 3D-film.

8254-07, Session 4

A pico projector source for confocal fluorescence and ophthalmic imaging

M. Muller, Aeon Imaging, LLC (United States)

Small, flexible, and low cost, pico digital light projectors (DLPs) incorporate high power LEDs with a digital micromirror array. DLPs can be driven directly from a PC video card to create a versatile and programmable display. In this paper, the pico projector is used in a novel confocal imaging system as both an illumination and scanning element.

Confocal imaging systems traditionally scan light across a target, then descan and spatially filter the light return before detection. An alternative design avoids descanning and instead synchronizes the illumination of the target to the rolling shutter read-out of a CMOS sensor placed in a conjugate plane (US Patents 7,331,669 and 7,831,106). By detecting light sequentially across the 2D sensor array, the rolling shutter creates a linear confocal aperture that is electronically adjustable in width and position. When the illumination and scanning element are replaced with a pico projector, continuous scanning can be approximated by rapidly projecting a series of lines onto the target.

The use of a DLP as an integrated source and scanning element not only reduces the cost and size of traditional confocal imaging devices, but readily allows frame-to-frame software control over the target illumination pattern, timing, and wavelength. With a barrier filter inserted into the detection pathway, the system can switch from standard confocal imaging using the red or green channels (631 or 516nm) to fluorescent imaging using the blue channel (476nm) via software in real-time. With additional optical components, retinal plane images have been acquired using a 2.5mm pupil.

8254-08, Session 4

Medical devices in dermatology using DLP™ technology from Texas Instruments

F. Lüllau, Lüllau Engineering GmbH (Germany)

The market of medical devices is growing continuously worldwide. With the DLP™ technology from Texas Instruments Lüllau Engineering GmbH in Germany has realized different applications in the medical discipline of dermatology.

Especially a new digital phototherapy device named skintrek® PT5 is revolutionizing the treatment of skin diseases like Psoriasis, Vitiligo and other Eczema. The reason is that this device treats fully automated skin lesions with high contour precision and exactly with the right dose of UVA or UVB rays without damaging surrounding healthy skin. Healthy skin will not be irradiated with UV-light and therefore compared with the traditional phototherapy the risk of skin cancer is minimized and other side effects are avoided.

The functions of the new phototherapy device can only be realized through the use of DLP™ technology which is not only be used for the selective irradiation process. In combination with other optical systems DLP™ technology undertakes also other functionalities like 3D-topology calculation und patient movement compensation.

But digital phototherapy is not the sole DLP™ application for dermatology devices. E.g. the supportive diagnostic of skin cancer or inflammatory skin diseases can also be realized. Special optical systems in combination with DLP™ technology and sophisticated software algorithms are the base for such medical devices.

8254-09, Session 4

Implementation of an LED based clinical Spatial Frequency Domain Imaging (SFDI) system

A. Mazhar, S. A. Sharif, Beckman Laser Institute and Medical Clinic (United States); S. Saggesse, D. J. Cuccia, Modulated Imaging, Inc. (United States); B. Choi, A. J. Durkin, Beckman Laser Institute and Medical Clinic (United States)

Spatial Frequency Domain Imaging (SFDI) is a non-contact imaging method that uses multiple frequency spatial illumination to generate two dimensional maps of tissue optical properties (absorption and reduced scattering). We present phantom validation and pilot clinical data of a deployed LED-based system. The system employs four wavelengths (658 nm, 730 nm, 850 nm, 970nm) of light-emitting diodes (LED) to quantitatively assess tissue health by measurement of common tissue constituents (oxy-hemoglobin, deoxy-hemoglobin, and water). The system is compact (10cm x 10cm x 10cm) and light-weight (~ 12 lbs). The projection optics are optimized for the near infrared and typical exposure times (~20 ms) reduce typical acquisition time to seconds making the system twenty times faster than the SFDI system that we have described previously while minimizing the effect of motion artifacts in the clinic. The system is designed for large field of view applications (13.5 cm x 10.5 cm) and integrates a tissue surface profile measurement to correct for errors caused by height variations seen in large fields of view when imaging tissue. An important component of this system as designed is that a co-registered color camera has been integrated to record a simultaneous clinical impression of the sample for every pass of SFDI data. Finally, we have deployed the instrument in the clinic for pilot studies assessing burn severity and efficacy of port wine stain treatment. Maps of oxy-hemoglobin, deoxy-hemoglobin, water content, reduced scattering, and surface topography will be presented for each of these applications areas.

8254-10, Session 5

Realtime 3D holographic display

L. Loreti, Opto-electronics s.r.l. (Italy)

The real time 3D video display of holographic images based on the principle of sequential scanning of holograms with HPO (horizontal parallax only) generated by a high speed computer and sent at high frame rate to the DMD, and visualized by an anamorphic optical group. The device displays binary amplitude and phase modulated images opportunely synchronized and scanned by a galvanometric mirror or polygonal mirror driven by the control electronic circuitry. The elementary holograms are generated by a resident hardware which, through interpolation, generates single elementary holograms starting from images and depth map. The display operates with incoherent light (integral images) or with coherent light (holographic display) by changing the optical visualization group.

8254-11, Session 5

Suppression of the zero-order diffraction beam from computer-generated holograms using a DLP® spatial light modulator

S. Wu, J. Liang, M. F. Becker, The Univ. of Texas at Austin (United States)

We analyze and test an interferometric method to suppress the unwanted zero-order diffraction (ZOD) beam from computer-generated holograms produced by DLP® spatial light modulators (SLMs). In our experiment, two coherent beams from a Mach-Zehnder interferometer with π phase shift are incident on the SLM, generating the reconstructed image by using both ON and OFF pixels The ZOD beam is suppressed by destructive interference. This new technique suppresses the ZOD for binary-amplitude holograms in both near- and far-field reconstructed images. Other advantages include enhanced image contrast, efficient use of light from all pixels, and no need to recalculate the hologram.

8254-13, Session 6

DLP based light engines for additive manufacturing of ceramic parts

J. Stampfl, S. Gruber, R. Felzmann, G. Mitteramskogler, R. Liska, Technische Univ. Wien (Austria)

In the framework of the European research project PHOCAM (http://www.phocam.eu) the involved partners are developing systems and materials for lithography-based additive manufacturing technologies (AMT) which are used for shaping advanced ceramic materials. In this approach a ceramic-filled photosensitive resin is selectively exposed layer by layer. By stacking up the individual layers with a typical layer thickness between 25 and 50micrometer, a three-dimensional part is built up. After structuring, a solid part consisting of a ceramic filled polymer is obtained. The polymer is afterwards burnt off and in a last step the part is sintered to obtain a fully dense ceramic part.

The developed systems are based on selective exposure with DLP projection (Digital Light Processing). A key element of the developed systems is a light engine which uses digital mirror devices (DMD) in combination light emitting diodes (460nm) as light source. In the current setup DMDs with 1920x1080 pixels are used. The use of LEDs in combination with a customized optical projection system ensures a spatial and temporal homogeneity of the intensity at the build platform which is significantly better than with traditionally used light engines. The system has a resolution of 40micrometer and a build size of 79x43x100mm. It could be shown that this system can fabricate dense ceramic parts with excellent strength. In the case of alumina densities up to 99.6% of the theoretical density were achieved, yielding a biaxial strength of 510MPa. Besides technical ceramics like alumina it is also possible to structure bioceramics, e.g. tricalcium phosphate.

8254-15, Session 7

Face recognition via a projective compressive sensing system

B. M. Kaylor, C. J. Keith, P. A. Roos, R. R. Reibel, Bridger Photonics, Inc. (United States)

We present an optical compressive sensing system for face recognition. Compressive sensing presents a joint optical and computational framework where relevant scene features are measured directly with a minimal amount of measurements. This framework eliminates data preprocessing and feature extraction steps, increases system efficiency and eliminates redundancy and complexity. The system uses a digital micromirror device to project measurement vectors onto the scene and a single photodetector to collect the backscattered illumination. Digital micromirror technology enables high-resolution patterns to be projected onto the scene at high frame rate. The measurement vectors were determined using the Fisherfaces method, which is closely related to Fisher's linear discriminant. The training set consisted of 22 images representing two classes gathered in a non-compressive manner at a resolution of 84 x 64 using the same experimental setup. The face images were selected from the Yale face database. Measurements were made at a frame rate of 500 Hz and used an optical power of 8 mW. Experimentally, the face recognition accuracy was 95.5% using only 32 measurements per image. This matches the simulation results. The total number of image pixels was 5,736 resulting in a compression factor of 168 over a conventional imaging system.

8254-16, Session 7

Hi-speed 3D measurement system using DMD-based projector for industrial applications

Y. Mori, K. Saito, K. Homma, Y. Ohnishi, D. Mitsumoto, M. Suwa, OMRON Corp. (Japan)

Higher accuracy and reliability are indispensable especially in the field of industrial 3D measurement applications. 3D measurement based on the phase shifting technique applies for variable application of imaging system. We use a DMD projector for projection of fringe patterns for phase shifting method. DMD projector has a lot of advantage compared with other device such as LCD. We focus on the specifications of speed, linearity, and brightness of DMD. We show, in this paper, our DMD-based 3D measurement system satisfies requirements which come from industrial applications, and also show two representative applications and feasibility of our phase shifting system to these applications.

One is a parts recognition system for robot bin-picking in factory line. The parts recognition system can recognize the shape of parts of industrial product and these results are used to control robot arm for picking up a recognized target. This recognision system utilizes 3D information obtained by the phase shifting technique. Instead of using LCD projector, we adopted the DMD projector with high synchronization of camera and projector. In the result, we get an accurate result.with appropriate high speed.

The other is 3D measurement system for AOI (Automatic Optical Inspection). Our system can measure 3D profile of mounted parts on printed board with enough speed for practical use, as we made a combination of high speed camera and our-own developed DMD projector. Not only static parts, 3D measurement of moving parts would come into sight of our system.

8254-17, Session 7

Volumetric 3D display using a DLP projection engine

J. Geng, Xigen, LLC (United States)

In this paper, we describe a volumetric 3D display system based on high speed DLP projection engine. Existing two-dimensional (2D) flat screen displays often lead to ambiguity and confusion in high-dimensional data/graphics presentation due to lack of true depth cues. Even with the help of many powerful 3D rendering software, three-dimensional (3D) objects displayed on a 2D flat screen may still not be able to provide spatial relationship or depth information correctly and effectively. Essentially, 2D displays have to rely on human's capability of piecing together a 3D representation of images. Despite the impressive mental capability of human visual system, its visual perception is not reliable if certain depth cues are missing.

In contrast, volumetric 3D display techniques to be discussed in this article are capable of displaying 3D volumetric images in true 3D space. Each "voxel" on a 3D image (analogous to a pixel in 2D image) locates physically at the spatial position where it is supposed to be, and emits light from that position toward omni-directions to form a real 3D image in 3D space. Such a volumetric 3D display provides both physiological depth cues and psychological depth cues to human visual system to truthfully perceive 3D objects. It yields a realistic representation of 3D objects and simplifies our understanding to the complexity of 3D objects and spatial relationship among them.

8254-27, Session 7

A high resolution body scanning system based on structured light

M. W. Bellis, Seikowave (United States); D. L. Lau, Univ. of Kentucky (United States)

In this talk, we are presenting a high resolution body scanning system that implements structured light for making 3D measurements. The system is constructed with twelve individual 3D scanners arranged to make a complete measurement of any object inside a volume that is two meters by two meters by one meter. A global calibration is performed to ensure proper integrated of the output from each individual scanner. In total, the integrated point cloud has approximately twelve million points. The accuracy of the system is 0.5mm. The structured light scanners employ a novel dual-frequency pattern. This pattern eliminates the potential for phase unwrapping errors and reduces the measurement time. A DLP projector is used to project the dual frequency pattern and provide the light output needed to cover the measurement volume.

8254-18, Session 8

Considerations for DMDs operating in the infrared

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The evolution of the DMD has enabled the development of a broad range of technologies from sensors to various types of devices to projectors and displays. The low cost and excellent reliability has made the DMD an ideal choice for most applications requiring a spatial light modulator. The aluminum micromirrors can be used over a broad spectral range with an appropriate window; DMD-based systems have therefore been realized across the ultraviolet through and including the longwave infrared. Of particular interest for scene projector, compressive imaging, and spectrometer applications is the use of the DMD in the infrared where diffraction, instrument temperature, and optical resolution impose performance limits. Diffraction and instrument temperature, among other factors, impact the highest achievable contrast, and constraints on the lowest practical illumination and projection f/# limit the ability to resolve a single micromirror at longer wavelengths. In this paper, we present analytical models addressing these issues as well as demonstrated solutions in a DMD-based midwave infrared (MWIR) scene projector as well as a MWIR compressive imaging camera.

8254-19, Session 8

Full color, high contrast front projection on black emissive display

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Front digital projection (FDP) displays have the features of portable, economical and scalable for large size displays. Unfortunately, existing FDP technologies suffer on the poor image contrasts in well-lighted environments, due to the "black-level" issues of the conventional white diffusive screens. More powerful projectors can be applied to enhance contrasts by increasing the brightness, at the expenses of significantly increased costs, weights, power consumption, and eye fatigues to viewers at bright projection screens.

In this joint paper, we demonstrate an innovative full color, high contrast front projective display system on a black emissive screen (BES). It comprises of a novel transparent fluorescent screen on pitch-black substrates, and a digital image projector with optic output that excite the fluorescent screen. The fluorescent screens comprise of at least 3 layers of RGB emissive materials, which are made in fully transparent forms to present the black back-plate. The "excitation" projector is based on DLPTM (digital light processor) projector platform, where a UHP lamp is coupled to a set of optic filters to generate a set of "latent" images to excite the RGB emissions from the screen.

This display combines the best of both worlds of front projection and emissive display technologies. Like projection displays, it is scalable and economic at large displays, the screen has no pixel structure and can be manufactured roll to roll. Like emissive displays (e.g. plasma or field emission displays with phosphor screen), the quality of the emissive images on black back-plate is superior, with large viewing angles and superior contrasts in any environments. The new projection display can favorably compete with existing flat panel displays and other projection displays.

8254-20, Session 9

Multimode fiber-based high-power laser distribution using DLP technology

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Addressing high laser power to several points of space at any given time is of major interest for various military and civil applications. Optical fibers are of great benefit to deliver laser power remotely, with high flexibility and reliability. We developed a compact and efficient system based on a 0.7XGA Digital Micromirror Device (DMD) optimized in the IR. It consists of a multimode high-brightness 1x7 fiber splitter and a 60-Watt 975-nm laser diode (fiber-coupled in a 105-µm NA=0.12 fiber). The 1x7 coupler is made of a homemade bundle of optical fibers fused together on one side and discrete output fibers on the other side. This design enables to distribute independently or simultaneously several Watts of laser power from a single laser source to each or several optical fibers in the bundle consisting of 3, 7, 19 or even 37 fibers. The coupling efficiency and extinction ratio were measured and optimized considering the DMD as an adaptive 2D blazed grating. Coupling efficiency higher than 40% was demonstrated (measured from laser to output fibers) with extinction ratios between 20 and 45dB which is sufficient for key applications. Limiting factors, such as fiber cross-talk, higher diffraction orders, optical aberrations, and damage threshold were studied and quantified. The distance between the DMD and the fiber bundle is 350 mm and can be further reduced for higher compactness. A DMD software was developed to optimize coupling efficiency and extinction ratios automatically by using a feedback loop between multiple fiber output power measurements and DMD mirrors configuration.

8254-21, Session 9

Band-limited laser image projection using a DMD-based beam shaper

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A digital micromirror device (DMD)-based beam shaper is implemented for the projection of band-limited images with precisely controlled intensity. A telescope images the binary DMD pattern with an adjustable pinhole low-pass filter that controls the system bandwidth and converts the image back to grayscale. The quality of output images is analyzed by intensity conformity with respect to the target image and by the input-output energy conversion efficiency.

Previously, we have shown how to form high-precision flattop beams using various coherent and incoherent light sources at both visible and infrared wavelengths. Optimized operation wavelengths were determined by calculating system energy efficiency for different DMD diffraction orders. In addition, system spatial frequency response was characterized in terms of intensity RMS error by generating high-precision sinusoidal flattop beams with different spatial periods.

In this paper, we implement the DMD-based beam shaper to project band-limited images with arbitrary spatial frequency content. The design error of the binary DMD pattern is predicted by spatial frequency decomposition (Fourier analysis) of the target function and the blue-noise induced in the image binarization process. Numerical simulation is conducted to search for the optimized system bandwidth by considering the tradeoff between image precision and spatial resolution.

In addition, we demonstrate high-precision image projection for different spatial bandwidths using various test patterns. Image quality should be improved by iterative pattern refinement based on the point spread function (PSF) for the given system bandwidth. We plan to apply this technique to generate programmable optical lattice shapes in ultracold atom experiments.

8254-22, Session 9

Application of DMD: laser speckle control for rough surface photofabrication

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Digital Micromirror Devices are mainly known for display in video projectors. Increasingly they are used in industrial or research applications. DMD is a versatile tool for lithography allowing photoresist exposure with easy-changing masking step in direct-patterning. Any application where light shaping is necessary can be considered by using DMD.

We show photofabrication of random rough surfaces using an indirect modified beam exposure. A laser beam is enlarged and scattered by a diffusing element. The scattering from this diffusing surface allows the creation of a speckle pattern with a random light distribution. The intensity is then recorded on a photoresist coated silicon substrate. The patterned photoresist is next developed and an etching step enables the transfer on the silicon. It can be shown that the statistical properties of the speckle pattern can be controlled. The intensity distribution is modified by the number of exposures and the correlation function is linked to the spatial distribution of the laser beam. Some examples of such photofabrication can be found using a Gaussian unmodified beam leading to Gaussian correlation photofabricated surfaces [1].

In order to design random rough surfaces having a non Gaussian correlation we need to modify the laser beam shape. This modification is achieved using a DMD.

The experimental processes from photoresist deposition to modified exposure and etching are discussed in this paper. The statistical property modification is demonstrated and theoretical correlations are compared with experimental ones.

Finally, the scattering properties of such photofabricated surfaces are measured showing significant modifications of the scattering diagram.

[1] Gray, P, F ;. “Method of forming optical diffusers of simple known statistical properties”.Optica Acta, 25(8) :765 775, 1978.

8254-23, Session 10

Study of a near infrared digital micromirror device-based snapshot spectral imaging system

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Conventional Digital-Micromirror-Device based Snapshot-Spectral-Imaging (DMD-SSI) systems use a DMD and a double-Amici prism to generate Compressive Sensing (CS) measurements in visible wavelengths. The spatial/spectral information of the original scene is then reconstructed from CS measurements by solving a minimization problem. In this work, we investigate a DMD-SSI system in the near infrared (NIR) spectral range. Specifically, our system operates over the wavelength range of 0.9-1.4 μm, which required us to study the dispersion performance of different glass materials, using a self-defined NIR Abbe-number as a quantitative measure. Based on this approach, a pair of high-dispersion and low-dispersion glasses was selected for building a double-Amici prism for generating NIR CS measurements. In the Zemax environment, we built a light propagation model that included the DMD-SSI system with the NIR double-Amici prism. Using this model we assessed the aberration performance of the NIR DMD-SSI system over the operational band. Optical aberrations as well as the physical characteristics of the DMD (such as pixel-pitch, reflection efficiency, etc.) were considered in a numerical model of the DMD-SSI system, which generates CS measurements accounting for these factors. We evaluated the quality of spatial/spectral data-cubes reconstructed from those non-ideal CS measurements and discuss possible methods for improving the quality of those reconstructed data-cubes.

8254-24, Session 10

Flat spectral response all-digital broadband variable fiber-optic attenuator

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Variable fiber-optic attenuators (VFOAs) are critical components for many applications, including fiber optic communication systems, fiber optic sensors, test and measurement instrumentation and signal processing. Previously, 100% repeatable all-digital VFOAs based on the Texas Instruments (TI) digital micromirror device (DMD) have been proposed in both the narrowband and broadband versions. The DMD is inherently a two dimensional (2-D) blaze grating that causes wavelength-dependent angular spreading of reflected broadband light limiting its use as a broadband VFOA.

In this paper, we propose a novel design that utilizes a double-reflection architecture to counter angular spreading while at the same time eliminates the need to use any narrowband components such as wave plates thus delivering a truly flat spectral response VFOA. The key feature of this design is that the DMD, instead of being oriented in the Littrow retro-reflective configuration for the center wavelength, is oriented at a different angle to the input beam such that the blaze condition is still satisfied albeit for a different diffraction order n. The only wavelength dependent loss (WDL) in this design is due to the fact that the blaze condition is satisfied only for a center wavelength λc at which the diffraction efficiency is maximum while at other wavelengths, the blaze condition is not perfectly satisfied resulting in a loss in diffraction efficiency. Simulation results show a WDL of only 0.01 dB over the C-band compared to the previously reported experimental value of ±0.37 dB thus resulting in a truly flat spectral response VFOA.

8254-25, Session 10

Demonstrator of a multi-object spectrograph based on the 2048x1080 DMD

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Multi-Object Spectrographs (MOS) are the major instruments for studying primary galaxies and remote and faint objects. Current object selection systems are limited and/or difficult to implement in next generation MOS for space and ground-based telescopes. A promising solution is the use of MOEMS devices such as micromirror arrays which allow the remote control of the multi-slit configuration in real time.

We are developing a Digital Micromirror Device (DMD) - based spectrograph demonstrator. We want to access the largest FOV with the highest contrast. The selected component is a DMD chip from Texas Instruments in 2048 x 1080 mirrors format, with a pitch of 13.68μm. Such component has been also studied by our team for application in EUCLID-NIS. Our optical design is an all-reflective spectrograph design with F/4 on the DMD component, including two arms, one spectroscopic channel and one imaging channel, thanks to the two stable positions of DMD micromirrors.

This demonstrator permits the study of key parameters such as throughput, contrast and ability to remove unwanted sources in the FOV (background, spoiler sources), PSF effect, spectrum stability on the detector. This study will be conducted in the visible with possible extension in the IR. The breadboard has been designed and is under realization before integration on an optical bench simulating an astronomical FOV.

The demonstrator is of prime importance for characterizing the actual performance of this new family of instruments, as well as investigating the operational procedures on astronomical objects.

8254-26, Session 10

Hyperspectral image projector applications

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For the past several years NIST has been developing, along with several collaborators, a Hyperspectral Image Projector (HIP). This scene projector produces high-resolution programmable spectra and projects them into dynamic two-dimensional images. The current DMD-based HIP prototype has a spatial resolution of 1024 x 768 pixels and a spectral range of 450 nm to 2400 nm, with spectral resolution from 2 nm in the visible to 5 nm in the short-wave infrared. It disperses light from a supercontinuum fiber source across two DMDs to produce the programmable spectra, which then globally-illuminate a third DMD to form the spatial images. The HIP can simulate top-of-the atmosphere spectral radiance over a 10 mm x 14 mm, f/3 image, and this can be collimated to stimulate remote sensing instruments. Also, the spectral radiance of the projected scenes can be measured with a NIST-calibrated spectroradiometer, such that the spectral radiance projected into each pixel can be accurately known. The HIP was originally developed for applications in multi-spectral and hyperspectral imager testing, calibration, and performance validation, and examples of this application will be reviewed. Conceivable applications for the HIP in optical medical imaging and photovoltaic device characterization will also be discussed.