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MOEMS-MEMS

Conferences and Courses
1–6 February 2014

Exhibition
BiOS Expo: 1–2 February
Photonics West: 4–6 February

Location
The Moscone Center
San Francisco, California, USA

MOEMS-MEMS

SPIE Photonics West

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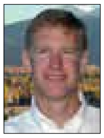

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Conference 8973: Micromachining and Microfabrication Process Technology XIX

Tuesday - Thursday 4 –6 February 2014

Part of Proceedings of SPIE Vol. 8973 Micromachining and Microfabrication Process Technology XIX

8973-23, Session PTue

Design of active temperature compensated composite free-free beam MEMS resonators in a standard process

George Xereas, Vamsy P. Chodavarapu, McGill Univ. (Canada)

Frequency references are needed in every modern electronic device including mobile phones, personal computers, and medical instrumentation. With modern consumer mobile devices imposing stringent requirements of low cost, low complexity, compact system integration and low power consumption, there has been significant interest to develop batch-manufactured MEMS resonators. An important challenge for MEMS resonators is to match the temperature stability of quartz resonators. We present a 20MHz temperature compensated Free-Free beam MEMS resonator that is developed using PolyMUMPS, a commercial multi-user process available from MEMSCAP. We introduce a novel temperature compensation technique that enables high frequency stability over a wide temperature range that is based on three strategies, passive compensation by using a structural gold layer on the resonator, active compensation through using a heater element, and a Free-Free beam design that minimizes the effects of thermal mismatch between the vibrating structure and the substrate. Detailed electro-mechanical simulations were performed to evaluate the frequency response and quality factor (Q). A Q of 10,000 was obtained for the passive compensated design. We introduced an active heater element to achieve a below 1 ppm stability which compares well to many temperature compensated quartz resonators and other MEMS resonators fabricated through complicated and low yield custom processes. Finite Element Modeling (FEM) simulations were used to evaluate the Temperature Coefficient of frequency (TCf) of the resonators between -50? and 125? which yielded +0.638 ppm/? for the active compensated, compared to -1.66 ppm/? for the passively compensated design and -8.48 ppm/? for uncompensated design. Electro-thermo-mechanical simulations showed that the heater element was capable of increasing the temperature of the resonator by approximately 53?. The applied voltage was set at 10V and the power consumption was estimated at 8.42 mW.

8973-24, Session PTue

Design and fabrication of 3-axis accelerometer for harsh environment applications using semi-custom process

Adel Merdasi, Vamsy P. Chodavarapu, George Xereas, McGill Univ. (Canada); Yucai Wang, McGill Univ (Canada)

Silicon Carbide (SiC) has attracted considerable attention in recent years as a potential material for various sensor devices that are required to operate under high stress, high temperature (>250ºC), and resistance to corrosion, erosion, wear, and radiation. In the current work, we use a commercial standard fabrication process, POLYMUMPS, from MEMSCAP to fabricate the structural body of a 3-axis accelerometer. We then perform post-fabrication processing that consists of low temperature deposition and patterning a thin layer of amorphous silicon carbide (SiC). This strategy reduces the device fabrication cost and improves mass-production of the sensor. The proposed multi-axis accelerometer design uses two different devices placed separately on a silicon substrate and each device is sensitive to a specific axis, which reduces the error due to cross-axis sensitivity. The working principle for the two devices is based on suspended proof mass supported by adequate mechanical springs and undergoing a mechanical force due the applied acceleration. The transduction uses differential capacitive measurements for in-plane acceleration (X- or Y- axis) and absolute capacitance measurement along Z-axis.

A transient thermo-mechanical analysis is performed in order to illustrate the maximum generated deflection that can directly alter the measurement. The proposed accelerometer is capable of detecting acceleration with 0.1mg resolution and within a range of ±20g over an operating frequency of 4.5 KHz. SiC possesses a higher Young's modulus and fracture strength than polysilicon which leads to a higher composite strength of the structural layers comprising of the proof mass and the mechanical springs. The coefficient of thermal expansion (CTE) of SiC is close to that of polysilicon, which will allow the composite material to have minimal stress due to temperature gradient.

8973-25, Session PTue

Facile fabrication of nanogap electrodes for suspended graphene characterization using direct ion beam patterning

Zhengqing John Qi, A. T. Charlie Johnson, Univ. of Pennsylvania (United States)

Graphene is a two-dimensional sheet of carbon atoms with exceptional electronic and mechanical properties, giving it tremendous potential in nanoelectromechanical system (NEMS) devices. Here, we present a method to easily and reproducibly fabricate suspended graphene nanoribbons across nanogap electrodes of various separation lengths, demonstrating a technique with aggressive gap scalability and device geometry control. Fabrication is based on using a focused gallium ion beam to create a slit between joined electrodes prepatterened on a 100 nm thick silicon nitride membrane. The transparency of the nitride membrane provides reduced ion backscattering and added milling resolution. Large-area graphene grown by atmospheric pressure chemical vapor deposition was transferred onto the silicon nitride chip and patterned into a free-standing ribbon geometry via electron beam lithography on organic ebeam resist and O2 plasma etching. We find that commonly used inorganic negative tone resist that requires a buffered oxide etch for resist removal will attack the adhesion layer (Cr_2O_3) between the electrode and nitride membrane, which was exposed immediately after milling. Using this technique, we fabricate a suspended graphene ribbon in the transfer length measurement configuration and extract the contact resistance between freestanding graphene and gold. The resolution of this technique is limited the gallium ion beam, which allows for sub-100 nm gaps. Sub-10 nm gaps are feasible with He ion beams, proving direct applications in probing the high field transport properties of graphene nanoribbons at post-CMOS length scales.

8973-26, Session PTue

Resonator structures on AlN ceramics surface treated by laser radiation

Pawel E. Koziol, Arkadiusz J. Antonczak, Bogusz D. Stepak, Przemyslaw A. Gorski, Wroclaw Univ. of Technology (Poland); Michal Walczakowski, Norbert Palka, Military Univ. of Technology (Poland); Krzysztof M. Abramski, Wroclaw Univ. of Technology (Poland)

Over the last decade, the high concentration of research on the phenomenon of negative refraction index has been observed. The concept of “metamaterial” specifies uniform, artificially produced material displaying the unique electromagnetic properties in the natural environment (negative permittivity and permeability).

The main limitation of metamaterials synthesis is the technology of their production. Structures of this type are obtained mainly through complicated and expensive methods of photo and electro-lithography. Therefore, there is a need to search for new, alternative ways of producing metamaterial structures, through which it will be possible to perform pre-designed structures in a relatively short time.

The proposed method in this work is using direct metallization of the AlN ceramic surface in the laser micromachining process. In the site of the laser beam impact on the surface of non-conductive AlN ceramic, the rupture of nitrogen and aluminum bonds occurs. As a result, nitrogen is released into the atmosphere, and on the dielectric surface conductive aluminum paths are formed. An advantage of using laser micromachining is the rapid prototyping of the designed structures directly on the material surface without having to prepare appropriate mask such as a photolithography process.

In order to optimize the metallization process, there were carried out a series of tests using a solid-state laser Nd:YAG (1.064 ?m) with average power 25W, pulse duration of 9-42 ns and beam size of 35 µm (FWHM). Based on the test pattern there was made a full characterization of the process as a function of process parameters (power, pulse repetition rate and laser scanning speed).

Obtained paths resistance allowed for practical implementation of metamaterial structures designed in the form of a resonant circuits spiral resonators SR and split-ring resonators SSR characterized by a negative permeability ? (MNG).

8973-27, Session PTue

Annular heating of optical fiber by CO2 laser with reflective axicon elements

William Klimowych, AFL (United States)

The need for uniform heating around a fiber's circumference is crucial when fabricating tapers, combiners and end caps, especially for end caps with very large diameters. The axicon optical element provides an evenly distributed CO2 laser beam to heat the circumference of fiber or end-cap with a uniform annular power density distribution to accommodate different diameters of devices.

Figure 1 illustrates two rays, representing the bisection of a generated cone. This cone imposes an evenly distributed band of heat round the fiber using a second element, an internally polished cylindrical surface, which reflects the first cone generated from the axicon element. In Figure 2, the axicon reflector is shown mounted in an acrylic block with the reflected burn pattern surrounding the reflector, exhibited in Figure 3. The pattern surrounding the axicon is perfectly circular. Hot spots are visible and may be attributed to slight axial misalignment and tilt of the axicon. The initial input CO2 laser beam is Gaussian. The circular burn exhibits the same Gaussian characteristics in the ring upon examination and can be further verified using a beam profiler.

Axicons have been incorporated into optical design for many years. Recent applications for heat processing using refractive elements have been applied by Fraunhofer, publication number EP2194404 A1. The method in this paper describes a novel approach, using an axicon reflective element in a unique and simple configuration that can be useful in fabricating many types of optical fiber components, especially for splicing end caps.

8973-28, Session PTue

Complaint MEMS mechanism to extend resolution in Fourier transform spectroscopy

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A complaint mechanical amplifier mechanism has been designed, simulated, and integrated to a Fourier Transform Spectroscopy (FTS) setup to extend its working resolution. The mechanism uses three fixed mechanical sections (localized at a reference frame) and several coupled complaint arms to amplify motion. This is, the mechanism shows an amplification relationship of an input mechanical structure with respect to an output structure. The mechanism is fabricated with Deep Reactive Ion Etching using the Bosch Process. When this mechanism is used to amplify motion of a mirror placed in its output structure, and integrated to a FTS setup, the resolution range of the FTS is extended due to the increase of the optical path interrogation and analysis capability, and hence the resolving power of the FTS system is increased.

The fabricated device has dimensions of 5700x4630x400 microns in the large, width and thickness respectively, and uses an aspect ratio of ten for the fabrication of the compliant arm structures. Numerical simulations with Ansys software were developed to get the stress limits of arms, and maximum displacement of the output structure, the mechanical gain and the resonance frequency of the device.

Experimental results in both forced and dynamical regimes are presented. In the dynamical range regime, it is found that at resonance frequency of the device exhibits a ten time higher mechanical gain with respect to the forced regime. The device is actuated with a Piezoelectric Actuator.

8973-1, Session 1

Fabrication of microelectromechanical systems (MEMS) cantilevers for photoacoustic (PA) detection of terahertz (THz) radiation

Richard Newberry, Nathan E. Glauvitz, Ronald A. Coutu Jr., Air Force Institute of Technology (United States); Ivan Medvedev, Douglas T. Petkie, Wright State Univ. (United States)

Historically, spectroscopy has been a cumbersome endeavor due to the relatively large sizes (3ft – 100ft in length) of modern spectroscopy systems. Taking advantage of the photoacoustic effect would allow for much smaller absorption chambers since the PA effect is independent of the absorption path length. In order to detect the photoacoustic waves being generated, a photoacoustic microphone would be required.

This paper reports on the fabrication efforts taken in order to create MEMS cantilevers for the purpose of sensing photoacoustic waves generated via THz radiation passing through a gaseous sample. The cantilevers are first modeled through the use of the finite element modeling software, CoventorWare. The cantilevers fabricated with bulk micromachining processes and are on the order of 1mm – 3mm in width, 5mm – 7mm in length, and 5µm – 10µm in thickness on a silicon-on-insulator (SOI) wafer which acts as the physical structure of the cantilever. The devices are released by etching through the wafer's backside and etching through the buried oxide with hydrofluoric acid. The cantilevers are placed in a test chamber and their vibration and deflection are measured via a Michelson type interferometer that reflects a laser off a gold tip evaporated onto the tip of the cantilever. The test chamber is machined from stainless steel and housed in a THz testing environment at Wright State University. We expect to achieve higher sensitivities in our devices than previously reported with deflections approximately 3.8 times higher than previously reported, on the order of 0.2?m.

8973-2, Session 1

Using microelectromechanical systems (MEMS) parallel-plate electrostatic sensors to determine thrust of a Hall Effect Thruster

Rajan Pal, Ronald A. Coutu Jr., David Liu, Air Force Institute of

Technology (United States)

Hall Effect thrusters (HETs) are type of ion thrusters used on-board satellites for attitude control and adjustment. Considerable research is conducted on ground with respect to how well the HET performs under a simulated space environment using large and expensive test equipment. However, weight is at a premium for a deployed satellite system and heavy on-board diagnostic systems are simply not possible. This paper describes the results of using microelectromechanical systems (MEMS) to determine a HET's thrust. Specifically, we discuss the results of using parallel-plate capacitive sensors fabricated using the PolyMUMPs process to determine the thrust. The sensors are 400x400um with two crab-leg flexures in parallel on each side to increase beam stiffness. The laboratory used to conduct the experiments consists of a vacuum chamber that is capable of operating at pressures as low as 10-8 torr and is primarily used to research electric propulsion thrusters. A 9x9 sensor array with an additional 11 test structures were fabricated on a 1x1cm die and placed 14 inches away from the center of the thruster and exposed to the thruster's plume. During exposure of the sensors to the plume, an inductance, capacitance, and resistance (LCR) meter was used to measure the change in capacitance of each sensor. Additionally, a digital voltmeter was also utilized to monitor charge buildup during testing. Finally, the force applied to each sensor was determined from the measured capacitance. The application of these sensors provides a novel method to determine real-time thrust of an ion thruster.

8973-3, Session 1

Isolating the negative stiffness region of a buckled Si/SiO2 membrane

Kyle Ziegler, Robert Lake, Ronald A. Coutu Jr., Air Force Institute of Technology (United States)

Due to the nature of microelectromechanical systems (MEMS) processes and materials, high stiffness is often exhibited in devices, which drives high natural frequencies and low displacement sensitivities. The use of negative stiffness footings reduces the stiffness of devices such as gyroscopes or accelerometers without changing existing geometry. Electrostatic negative stiffness has been demonstrated, but requires external power. The Si/SiO2 membrane presented in this research capitalizes on buckling which results from compressive residual stress. Square 1mm by 1mm etch windows were patterned on the backside of silicon on insulator (SOI) wafer using SU-8. They were subsequently fabricated by deep reactive ion etching the handle portion of the SOI wafer and using the oxide layer as a natural etch stop.

Following the fabrication, membrane buckling was verified using a white light interferometric microscope. Devices were then tested using a force sensor actuated by a piezo controller. Together, these tools recorded force data, ranging from 0 to 2000 ?N, at known deflections. An actuation scheme was developed using a meandering resistor deposited on the membrane which heats and consequently reduces the out of plane deflection. Separate testing concerned cantilever beams that were used to overhang and restrict the movement of the membrane. By isolating the negative stiffness region, the force required for further deflection decreased linearly from 2000 to 800 ?N. The results demonstrate the viability of buckled membrane used for stiffness offset applications.

8973-4, Session 1

Thin film fabrication and system integration test run for a microactuator for a tuneable lens

Dominik Hoheisel, Lutz Rissing, Leibniz Univ. Hannover (Germany)

An electromagnetic microactuator, for generation and controlling of a tuneable lens, with an integrated electrostatic element is fabricated by thin film technology. The actuator consists of two parts: the first part with microcoil and flux guide and the second part with a ring shaped back iron on a polyimide membrane. The back iron is additionally useable as electrode for electrostatic measurement of the air gap and for electrostatic actuation. By attracting the back iron an optical liquid is displaced and forms a liquid lens inside the back iron ring covered by the membrane.

For testing the thin film fabrication sequence, up-scaled systems are generated in a test run. To fabricate the flux guide in an easy and quick way, a Ni-Fe foil with a thickness of 50 µm is laminated on the Si-wafer. This foil is also utilized in the following fabrication sequence as seed layer for electroplating. Compared to Ni-Fe structures deposited by electroplating, the foil is featuring better soft magnetic properties. The foil is structured by wet chemical etching and the backside of the wafers is structured by deep reactive ion etching (DRIE). For post fabrication thinning, the polyimide membrane is treated by oxygen plasma etching.

To align the back iron to the microcoil and the flux guide, a flip-chip-bonder is used during system integration test run. To adjust a constant air gap, a water solvable polymer is tested. A two component epoxy and a polyimide based glue are compared for their bonding properties of the actuator parts.

8973-5, Session 1

Fabrication of waveguides containing Ag0 nanoparticles using femtosecond laser micromachining

Juliana M. P. Almeida, Paulo Henrique D. Ferreira, Univ. de São Paulo (Brazil); Danilo Manzani, Mariana F. Napoli, Univ. Estadual de São Paulo (Brazil); Sidney J. Ribeiro, Univ. Estadual Paulista (Brazil); Cleber R. Mendonça, Univ. de São Paulo (Brazil)

Ultrashort laser pulses have allowed controlling the formation of metallic nanoparticles (NPs) in glass via femtosecond laser micromachining. Because glasses containing metallic nanoparticles exhibit ultrafast response times and high third-order nonlinearities, the spatial control of NPs in the micrometric scale is essential to produce all-optical devices. Although waveguides, splitters and amplifiers have been demonstrated using different techniques and materials, 3D-photonic microstructures containing metallic NPs have received little attention despite their importance for integrated optics. In this sense, the purpose of the current study is to produce waveguides containing metallic silver NPs in its core using femtosecond laser micromachining. To achieve this goal, a (70Pb2P2O7-30WO3):1AgCl mol% glass sample was irradiated with a Ti: Sapphire laser, operating at 5 MHz with pulses of 50 fs at 800 nm. The laser pulses were focused beneath the sample surface through a microscope objective, while the sample was moved by a xyz stage at constant speed. Thus, cylindrical waveguides were drawn throughout the sample (4 mm). The formation of Ag0 nanoparticles in the waveguide core was indentified through TEM images and by the plasmon band at 470 nm in the absorption spectrum. An optical system, based on a He-Ne laser and microscope objectives, was used to perform the light coupling. The propagation modes and losses of the light guided have been analyzed as a function of the laser scan-speed. Preliminary results have shown these waveguides are promising for applications in photonic devices.

8973-6, Session 2

Calibrating bimetallic grayscale photomasks to photoresist response for precise micro-optics fabrication

Glenn H. Chapman, Reza Qarehbaghi, Santiago Roche, Simon Fraser Univ. (Canada)

Microfabricating high resolution micro-optics structures requires shape control to <1/8th wavelength (~60nm) in both vertical and horizontal surface precision. Grayscale bimetallic photomasks are bi-layer thermal resists consisting of two thin layers of Bi-on-Indium or Tin-on-Indium. A focused laser spot creates a thermal metal oxide with a controllably transparency set by the beam power of optical density from ~3OD (unexposed) to <0.22OD (fully exposed). A direct-write raster-scan photomask laser system with a CW Argon-ion laser at 514nm for the bimetallic writing and 457nm line for measuring the OD change used a feedback-controlled Gaussian beam to achieve 256-level grayscale masks. Setting the graylevels required to achieve uniform vertical steps in the photoresist requires adjustment in transparency based on the exact response curves of a given resist/development process. An initial model is developed using the classic resist threshold dose exposure D0 and dose to clear Dc creating a power law relation between the required exposure dose for each thickness step and the mask transparency. However real resists behave differently than the simple model near the threshold requiring careful calibrating of mask graylevel transparencies with the photoresist response curve for a given resist/development process. Test structures ranging from steps to ramps and complex patterns were examined via both SEM and profilometry from the resulting bimetallic grayscale masks. Secondary corrections modify the needed bimetallic OD due to the exposure source spectrum differences from the 457nm measurement. This enhances the patterning of micro-optic and 3D MEMS structures.

8973-8, Session 2

Numerical analysis of laser-assisted micro-hole drilling process

Maziar Ramezani, Thomas Neitzert, Timotius Pasang, Auckland Univ. of Technology (New Zealand)

Laser micro-machining, such as micro-hole drilling, is a direct, flexible and noncontact process without tool wear. Although the process has been extensively studied experimentally, only few numerical analyses are available in literature. This paper uses ANSYS software to simulate the micro-hole drilling with CO2 laser beam. Several materials are investigated and the effect of different parameters such as laser diameter, laser power, and thermal properties of materials on the process is investigated. The distribution of the temperature field after laser irradiation and the depth and width of the hole during the process is also studied. The element birth and death technique of ANSYS software is used to deactivate selected elements during the micro-hole drilling process. The technique uses a melting threshold and removes part of the material and forms micro-holes if the temperature of the material is beyond the melting value. A theoretical model is further developed to calculate the steady-state surface temperature in terms of thermal properties of substrates and laser beam power and dimension. In the theoretical model, it is assumed that the CO2 laser energy is fully absorbed by the material and the energy loss is negligible in the phase change. The results show that ANSYS software is capable of capturing the time history of depth and width of the hole and the numerical analysis can be used as a guide to laser drilling experiments.

8973-9, Session 3

Deep silicon etching: current capabilities and future directions *(Invited Paper)*

Russell J Westerman, Linnell Martinez, David Pays-Volard, Ken Mackenzie, Thierry Lazerand, Plasma-Therm LLC (United States)

Deep Reactive Ion Etching (DRIE) has revolutionized a wide variety of MEMs applications since its inception nearly two decades ago. The DRIE technology has been largely responsible for allowing lab scale technology demonstrations to enable manufacturable and profitable. consumer products. As applications which utilize DRIE technologies continue to expand and evolve, they continue to spawn a range of new requirements and open up exciting opportunities for advancement of DRIE. This paper will examine a number of current and emerging DRIE applications including nanotechnology, and DRIE related packaging technologies such as. Through-Silicon-Via (TSV) and plasma dicing. The paper will discuss a number of technical challenges and solutions associated with these applications; including: feature profile control at high aspect ratios, the use of metal masks, causes and elimination of feature tilt/skew, processing options for fragile device structures, and problems associated with through substrate etching. The paper will close with a short discussion around the challenges of implementing DRIE in production environments as well as looking at potentially disruptive enhancements / substitutions for DRIE.

8973-10, Session 3

Chemical mechanical polishing of boron-doped polycrystalline silicon

Hamidreza Pirayesh, Kenneth C. Cadien, Univ. of Alberta (Canada)

Chemical mechanical polishing (CMP) is a technique which helps to print a smaller depth of focus and smoother surface smoothness (<10Å roughness) in micro fabrication industry. In this project, boron doped polysilicon is used as a fill material for Through Silicon Vias (TSV) creating a 3D package. In this process after the via is filled by CVD, the overburden which remains on the surface of the wafer needs to be polished by CMP.

It is believed that the presence of boron as dopant suppresses the polysilicon polish rate. Understanding the mechanism of polish rate retardation assists the development of slurry and method with higher polish rate. We believe that the electrical effects play the major role in this phenomenon and by reducing this effect we are able to increase the polish rate. Increasing the polish rate and consequently decreasing the polish time and slurry usage reduces the production cost significantly.

Studying the effect of polish conditions (temperature, friction, pressure and etc.) and the slurry on removal rate requires characterization techniques and tools such as TEM (transmission electron microscopy) to determine the abrasive size, SEM (scanning electron microscopy) and XRD (X-ray diffraction) to determine the wafer thickness and other properties, AFM (atomic force microscopy) to determine the surface roughness, Zeta potential analyzer to determine the stability of particles in the aqueous solution and also XPS (X-ray photoelectron spectroscopy), FTIR (Fourier transform infrared spectroscopy), 4-point probe, SIMS (secondary ion mass spectrometry) and SFA (surface force apparatus).

8973-11, Session 3

A novel process for the fabrication of microstructures half the listed minimum feature size of a direct-write laser lithography system

Robert Lake, Ronald A. Coutu Jr., Air Force Institute of Technology (United States)

A method for fabricating structures half the size of the listed minimum feature size of a direct-write laser lithography system was demonstrated by taking advantage of the offset spacing allowed between write paths of the machine. This unique process allows MEMS structures to be fabricated with minimum features smaller than equipment specifications.

The Heidleberg mPG 101 desktop micro lithography system has a listed minimum feature size of one micrometer. Additionally, the minimum offset these features may be spaced from each other is 40 nanometers. By taking advantage of this small offset, features can be created by utilizing

the space between write paths, and with the use of a positive photoresist such as the S1800 series photoresist, feature sizes of 500 nanometers were fabricated with this machine.

A sacrificial layer of silicon dioxide (SiO2) was thermally grown on the top of a (100) silicon wafer. Anchor holes were then etched into this layer. A subsequent structural layer of silicon approximately 120 nanometers thick was sputtered on top of this sacrificial layer of SiO2. Once this layer was deposited, a layer of S1818 photoresist was applied and patterned with the Heidelberg mPG 101. A recipe for both power settings and development times was found that ensured the minimum features survive the lithography process. An array of fixed-fixed beams was aligned to the previously etched anchors. Once this layer of photoresist was patterned and developed, the beams were profiled using reactive ion etching (RIE.) Finally, these beams were released by etching away the remaining sacrificial SiO2 by using an HF vapor etching system. This method is much less turbulent than submersion in liquid HF and CO2 drying and ensures the survival of the released structures.

This process resulted in 500 nanometer wide beams which half the size of the minimum feature size specified for our equipment. This ability allows for the design and fabrication of structures, such as sensors, with an increased degree of sensitivity over those previously designed with the same equipment.

8973-12, Session 3

Off-normal patterned etching through suspended membranes

D. Bruce Burckel, M. David Henry, Robert L. Jarecki, Paul J. Resnick, Sandia National Labs. (United States)

Recently we have demonstrated membrane projection lithography (MPL) as a fabrication approach capable of creating 3D cubic unit cells with sub-micron metallic inclusions for use in metamaterial and plasmonic applications using polymer material systems[1-3]. We have begun transitioning this approach to all-inorganic material systems compatible with CMOS processing, and intend to generalize the fabrication approach from deposition to other vacuum processes such as ion implantation and dry etching (RIE, ICP, IBE). The high vacuum conditions present in typical metal evaporation deposition systems render high fidelity deposition of the membrane pattern upon the interior surfaces of the unit cell. In RIE systems, several factors combine to complicate this picture. This paper will present our findings including process conditions and exploration of custom fixtures to accomplish off-normal etching through patterned membranes, emphasizing the processing trade space and resulting structures.

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

1. D. B. Burckel, J.R. Wendt, I. Brener and M.B. Sinclair, Optical Materials Express 1, pp. 962-969 (2011).

2. D.B. Burckel, J.R. Wendt, G.A. Ten Eyck, J.C. Ginn, A.R. Ellis, I. Brener, and M.B. Sinclair, Advanced Materials, 22, 5053-5057, (2010).

3. D.B. Burckel, J.R. Wendt, G.A. Ten Eyck, A.R. Ellis, I. Brener, and M.B. Sinclair, Advanced Materials, 22, 3171-3175, (2010).

8973-13, Session 3

Periodic nano structures fabricated by Talbot extreme ultraviolet lithography

Mario C. Marconi, Wei Li, Dinesh Patel, Lukasz Urbanski, Carmen S. Menoni, Colorado State Univ. (United States); Aaron G. Stein, Brookhaven National Lab. (United States)

A defect-free Extreme Ultraviolet (EUV) lithography technique based on the utilization of the Talbot effect is presented. This approach combined with coherent illumination from a EUV laser constitutes a compact lithography tool for nanopatterning. The lithographic technique is based on the self-imaging produced when a periodic transmission mask is illuminated with a coherent light, known as the Talbot effect. [1]. The periodic mask is composed of unit cells with arbitrary design arranged in a 2D periodic matrix. Under coherent illumination, the periodic mask produces images which are 1? replicas at certain distances determined by the Talbot planes. These images are produced by the collective contribution of the diffraction of the thousands of cells in the mask. Thus any defect in some of the unitary cells is averaged over a very large numbers of tiles consequently rendering a virtually defect-free image.[2, 3] This is a unique characteristic of this photolithographic approach.

We show that with this approach it is possible to fabricate nano-scale structures in different materials transferring the periodic pattern without errors. Talbot lithography offers an alternative flexible method for fabrication with sub-micron resolution, allowing generating defined structures even from a heavily damaged master masks. Fabrication of plasmonic structures with ~100nm dimensions using this approach will be discussed. Prospects to extend the technique to the fabrication of features below 50nm will be also presented.

This work was supported by the National Science Foundation, award ECCS 0901806, the NSF ERC for Extreme Ultraviolet Science and Technology, award EEC 0310717. This research was carried out in part at the Center for Functional Nanomaterials, Brookhaven National Laboratory, which is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.

1. Talbot, W.H.F., Facts relating to optical science. Philos. Mag, 1836. 9: p. 403.

2. Urbanski, L., Li,W.,Rocca,J.J.,Menoni,C.S.,Marconi,M.C.,Isoyan, A.,Stein,A., Defect Tolerant Extreme Ultraviolet Lithography Technique. Journal of Vacuum Science & Technology B, 2012. 30, 06F502-1, (2012)

3. Urbanski, L., Isoyan, A.,Stein,A.,Rocca,J.J.,Menoni,C.S.,Marconi,M.C., Defect Tolerant Extreme Ultraviolet Nanoscale Printing. Optics Letters, 2012. 37: p. 3633-3635.

8973-14, Session 3

Fabrication of 3D surface structures using grayscale lithography

Christopher Stilson, Rajan Pal, Ronald A. Coutu Jr., Air Force Institute of Technology (United States)

The ability to design and develop 3D microstructures is of great importance for microelectromechanical systems (MEMS) fabrication and performance. Previous techniques used to create 3D devices included tedious steps in direct writing and aligning patterns onto a substrate followed by multiple photolithography steps using expensive, customized equipment. Additionally, these techniques restricted batch processing and placed limits on achievable shapes. Gray-scale technology enables fabrication of a variety of shapes using a single photolithography step in conjunction with deep reactive ion etching (DRIE). Micromachining 3D silicon structures for MEMS can be accomplished using gray-scale lithography along with dry anisotropic etching. In this study, we investigated: using MATLAB for mask designs; feasibility of using 1 μm Heidelberg mask maker to direct write patterns onto photoresist; using DRIE processing to etch patterns into a silicon substrate; and the ability to tailor etch selectivity for precise fabrication. To determine etch rates and desired etch selectivity, parameters such as silicon loading, chamber temperature, and electrode power were studied. This process successfully demonstrates the ability of using grayscale lithography and DRIE for specific applications. These results are used to produce a known engineered non-planer surfaces for testing micro-contacts. Surface structures are between 5 and 20 μm wide with varying depths and slopes based on mask design and etch rate selectivity. The engineered surfaces will provide more insight into contact geometries and failure modes of fixed-fixed micro-contacts.

8973-15, Session 3

Residual stress control during the growth and release process in gold suspended microstructures

Akshdeep Sharma, Amit Kumar, Deepak Bansal, Kamaljit Rangra, Dinesh Kumar, Central Electronics Engineering Research Institute (India)

In this paper it will be demonstrated that the conditions of the final release process in oxygen plasma and critical point dryer (CPD) strongly influence the shape of suspended gold microstructures. Both single clamped and double clamped cantilever test devices have been examined. The structures have typically a thickness of 2μm, and are produced by patterned gold electrodeposition above a sacrificial photoresist layer which is then removed by oxygen plasma ashing and mild piranha wet etching followed by CPD release. In general, deformations are strongly reduced lowering the temperature, but the release time increases abruptly. A simple model is presented to explain the experimental observations, and from it can be deduced that yield and inelastic relaxation are critical phenomena responsible for most of the deviations from the ideal planar shape of MEMS structures. To overcome these unwanted effects, the parameters to be optimized are mainly the initial stress value, the release temperature; mild piranha wet chemistry and the vertical structural homogeneity of the gold layer.

8973-16, Session 4

Phase Change Materials (PCM) fabricated in vertical structures for reconfigurable and tunable circuits

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Germanium Telluride (GeTe) is typically known as a non-volatile (latching state) phase change material (PCM) used in memory applications. GeTe also exhibits a volatile (reversible state) region when heated and cooled between 80-195 °C. At temperatures higher than this (200-230 °C) the material crystallizes and “latches” until a temperature close to its melting point (725 °C) is reached and cooled rapidly. Germanium Antimony Telluride (GeSbTe) or better known as GST has similar characteristics as GeTe. GST crystallizes between 130-150 °C and its melting point is 600 °C. This research demonstrates the feasibility of fabricating reconfigurable devices and ultimately circuits made out of these two PCMs. Previous work focuses on exploiting GeTe and GST as non-volatile materials in memory applications, and also on characterizing them for their electrical and mechanical properties. The approach in this research focuses on making tunable devices (variable resistors) and ultimately circuits using vertical structures (stacked layers) out of GeTe and GST. For example; a PMC acting as a variable resistor can be paired with a capacitor to make a signal filter for radio frequency and microwave applications. Vertical structures present two main benefits: less susceptibility to ambient contamination and protection from physical damage. The vertical structures are fabricated on a Si wafer with a sputtered Si3N4 top dielectric layer for electrical isolation. Results show this reversible state, paired with a capacitor of 0.9 pF, controls the cut-off frequency of the filter to be from 504 Hz to 310 kHz.

8973-17, Session 4

Microfabrication of passive electronic components with printed graphene-oxide deposition

Dogan Sinar, George K. Knopf, The Univ. of Western Ontario (Canada); Suwas Nikumb, National Research Council Canada (Canada)

Advances in conductive inks have enabled electrodes and microcircuits to be printed on flexible polymers, paper, and textiles. Research has shown that graphene, and its derivative formulations, can be used to create low-cost electrically conductive inks. Graphene is a one atom thick two-dimensional layer composed of carbon atoms arranged in a hexagonal lattice forming a material with very high fracture strength, high Young’s Modulus, and low electrical resistance. Since the material only absorbs 2.3% of visible light, it is also a good candidate for creating optically transparent electrodes. Non-conductive graphene-oxide (GO) inks can also be synthesized from inexpensive graphite powders. Once deposited on the flexible substrate the electrical conductivity of the printed GO microcircuit traces can be restored through thermal reduction. In this paper, a 775nm femtosecond pulsed laser is used to transform the printed GO film into electrically conductive oxygen reduced graphene-oxide (rGO) passive electronic components using laser assisted thermal reduction process. The heat affected zone produced during the process was minimal and the degree of conductivity exhibited by the microstructures was directly related to the laser power density and exposure time. Several simple passive resistors and capacitors were fabricated and analyzed in terms of performance. Although rGO films have higher resistance values compare to pristine graphene, the ability to inkjet print capacitive elements and precisely control the local resistive properties provides a new method to fabricate sensors and microcircuits on a variety of substrate surfaces.

8973-18, Session 4

Optimal microelectromechanical systems (MEMS) device for achieving high pyroelectric response of AlN

Bemnnet Kebede, Ronald A. Coutu Jr., LaVern A. Starman, Air Force Institute of Technology (United States)

This paper discusses research being conducted on aluminum nitride (AlN) as a pyroelectric material for use in millimeter wave detectors to increase the capability of airborne surveillance. AlN is being investigated because of its high pyroelectric coefficient, thermal stability, and high Curie temperature. In order to determine suitability of the pyroelectric properties of AlN for use as a detector, testing of several structures was conducted. These structures were fabricated using microelectromechanical systems (MEMS) fabrication processes; the devices were also designed to allow for voltage and current measurements. The deposited AlN films used were 150nm – 300nm in thickness. Thin-films were used to rapidly increase the temperature response after the thermal stimulus was applied to the pyroelectric material. This is important because the pyroelectric effect is directly proportional to the rate of temperature change. Two designs were used, a face-electrode bridge with variations in geometry, size, thickness, and number of material layers and a cantilever beam. The bridge design provides thermal isolation which minimizes heat loss to the substrate, thereby improving operation frequency of the pyroelectric device. A thermal stimulus was applied to the pyroelectric material and the response was measured across the nickel chromium electrodes. A thermal imaging camera was used to monitor the changes in temperature. Throughout the testing process, the annealing temperatures, type of layers, and thicknesses were also varied. These changes resulted in optimal design configuration for achieving a high pyroelectric response. The results showed that the highest pyroelectric response was achieved with a thickness of 200nm.

8973-19, Session 4

Fabrication technology to increase surface area of ionomer membrane material and its application towards high surface area electric double-layer capacitors

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In this article, we present a way to increase surface area of the ionomer membrane known as AquivionTM. A low cost heat-press is used to hot-emboss square impressions onto the AquivionTM membrane. The use of hot-embossing technique makes this process compatible with existing commercial process and a high throughput manufacturing can be easily achieved. As a proof of concept, stamps are fabricated on Silicon and glass substrates using conventional microfabrication technologies. The Silicon and glass based stamps are fabricated using wet and dry etching processes.

To reliably imprint the features onto the AquivionTM membrane, different process parameters are evaluated using a low cost heat-press. To characterize the hot-embossing process, temperature, pressure and time of the embossing process is experimented. The temperature of the heat-press platen was varied from 60 ºC up to 80 ºC, the pressure of the heat-press was varied from 20 psi up to 500 psi and finally the embossing time was also experimented from 5 to 10 min.

Square impressions onto the AquivionTM membrane were fabricated and a systematic increase to the surface area was observed which is highly useful in many sensing and storage applications. As an application using our hot-embossing technique, improved capacitors with higher surface area and higher capacitance is successfully fabricated and tested. A detailed analysis of the embossing process using different fabrication parameters is also presented.

8973-20, Session 5

Laser micromachining of oxygen-reduced graphene-oxide films

Dogan Sinar, George K. Knopf, The Univ. of Western Ontario (Canada); Suwas Nikumb, National Research Council Canada (Canada); Anatoly Andrushchenko, The Univ. of Western Ontario (Canada)

Non-conductive graphene-oxide (GO) inks can be synthesized from inexpensive graphite powders and deposited on functionalized flexible substrates using inkjet printing technology. Once deposited, the electrical conductivity of the GO film can be restored through laser assisted thermal reduction. Unfortunately, the inkjet nozzle diameter (~40 µm) places a limit on the printed feature size. In contrast, a tightly focused femtosecond pulsed laser can create precise micro features with dimensions in the order of 2 to 3 µm. The smallest feature size produced by laser microfabrication is a function of the laser beam diameter, power level, feed rate, material characteristics and spatial resolution of the micro-positioning system. Laser micromachining can also remove excess GO film material adjacent to the electrode traces and passive electronic components. Excess material removal is essential for creating stable oxygen-reduced graphene-oxide (rGO) printed circuits because electron buildup along the feature edges will alter the conductivity of the non-functional film. The controlled ablation of GO film and the underlying substrate material will also increase mechanical bendability and stretchability. A study on the impact of laser ablation on the GO film and the substrate are performed using a 775nm, 120fs pulsed laser. The average laser power was 25mW at a spot size of ~ 5 µm, and the feed rate was 1000-1500mm/min. Several simple microtraces were fabricated and characterized in terms of electrical resistance, surface topology, and mechanical flexibility. The smallest feature produced was a 2.67µm wide track line using a 10X objective lens and +/-1 µm resolution positioning table.

8973-21, Session 5

Laser assisted and hermetic room temperature bonding based on direct bonding technology

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A novel method for laser assisted room temperature bonding of two substrates is presented. The method enables the packaging of delicate structures and/or finished (MEMS) devices, as there is no need for a high temperature annealing process. This also allows the bonding of two substrates with non-matching thermal expansion coefficients.

The basis of the presented technology is the ability to create a direct pre-bond between to substrates. These can be two glass substrates, of which one has a thin film metal coating (e.g. Cr. Ti, Ta, Au…), or a silicon-glass combination. After (aligned) pre-bonding of the two wafers, a laser (e.g. a Nd:Yag laser) is used to form a permanent bond line on the bond interface, using the metal layer as a light absorber (or the silicon, in the case of a glass-silicon combination). The permanent bond line width is in the order of 10-50µm.

The use of a laser to form the permanent bond ensures a hermetic sealing of the total package; a distinctive advantage over other, more conventional methods of room temperature bonding (e.g. adhesive bonding). He-leak testing showed leak rates lower than 1x10-9 mbar l/s. This meets the failure criteria of the MIL-STD-883H standard.

An added functionality of the proposed method is the possibility to create electrical circuitry on the bond interface, using the laser to modify the metal interlayer, rendering it electrically non-conductive. Biocompatible packages are also possible, by choosing the appropriate interlayer material. This would allow for the fabrication of implantable packages.

8973-22, Session 5

Design and fabrication of sub-wavelength annular apertures on fiber tip for femtosecond laser machining

Yen Chun Tung, Ming-Han Chung, I Hui Sung, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

Adopting optical technique to pursue micromachining must make a compromise between the focal spot sizes the depth of focus. The focal spot size determines the minimum features can be fabricated. On the other hand, the depth of focus influences the ease of alignment in positioning the fabrication light beam. A typical approach to bypass the diffraction limit is to adopt the near-field approach, which has spot size in the range of the optical fiber tip. However, the depth of focus of the emitted light beam will be limited to tens of nanometers in most cases, which posts a difficult challenge to control the distance between the optical fiber tip and the sample to be machined optically. More specifically, problems remained in this machining approach, which include issues such as residue induced by laser ablation tends to deposit near the optical fiber tip and leads to loss of coupling efficiency. We proposed a method based on illuminating femtosecond laser through a sub-wavelength annular aperture on metallic film so as to produce Bessel light beam of sub-wavelength while maintaining large depth of focus first. To further advance the ease of use in one such system, producing sub-wavelength annular aperture on a single mode optical fiber head with sub-wavelength focusing ability is detailed. It is shown that this method can be applied in material machining with an emphasis to produce high aspect ratio structure. Simulations and experimental results are presented in this paper.

Conference 8974: Advanced Fabrication Technologies for Micro/Nano Optics and Photonics VII

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Part of Proceedings of SPIE Vol. 8974 Advanced Fabrication Technologies for Micro/Nano Optics and Photonics VII

8974-1, Session 1

Liquid deposition photolithography for the fabrication of three dimensional gradient index micro-optics *(Invited Paper)*

Robert R. McLeod, Adam C. Urness, Michael C. Cole, Univ. of Colorado at Boulder (United States)

One photon diffusive photopolymers enable self-developing three dimensional (3D) refractive index patterning of up to cm thick solid volumes for the fabrication of micro-optics. However, one photon absorption in solid, thick materials does not yield complete control of the 3D refractive index distribution due to diffraction and the required development time for index features measuring 100's of microns in diameter or larger. We present a fabrication method and photopolymer formulation that can efficiently create multi-cubic mm optical devices with programmable, gradient index of refraction with arbitrary feature size and shape. We demonstrate index contrast of 0.1 and transverse feature size ranging from 150 nm to 6 mm and axial feature size ranging from 1 micron to 10 mm. Devices are fabricated by repetitive layering of a self-developing photopolymer structured by projection lithography. The process has the unusual property that total fabrication time for a fixed thickness decreases as the number of layers is increased, reducing the fabrication time for high axial resolution micro-optics. We demonstrate the process by fabricating thick waveguide arrays and gradient index lenses.

8974-2, Session 1

Raman micro-spectroscopy on cross-linked polymer nanowires formed by 2-photon fabrication

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

Raman micro-spectroscopy is one of the ideal techniques to evaluate molecular structure of nano-sized samples without destruction. We utilized this technique to understand dynamics of structures formed by 2-photon fabrication (2PF) in molecular level. Polymer nanowires were formed by 2PF, and polymerization degree and molecular orientation of the nanowires were analyzed. A variety of the nanowires with different diameters were made of cross-linked poly-methylmethacrylate (PMMA). The nanowires' diameter ranges from 100 nm to 1000 nm. And we conducted Raman micro-spectroscopy of the nanowires by focusing incident light to surface of the wires. Obtained Raman spectra were processed on background subtraction by polynomial fitting and normalization by a reference peak. We focused on a clear peak at 815 cm-1 for polymerization degree analysis on the nanowires. This peak is peculiar to C-O-C deformation vibration of PMMA, and intensity of the peak grows larger along polymerization of methylmethacrylate (MMA). By comparing the intensity of this peak among each nanowire's diameter, we found there was wire diameter dependence on the intensity. Secondly we utilized polarization Raman micro-spectroscopy to analyze molecular orientation of the nanowires, and focused on a peak at 555 cm-1. This peak is also peculiar to PMMA and assigned to C-C-C skeletal deformation mode. We investigated intensity change of the peak along polarization angle on each nanowire. And finally we found the peak intensity had polarization angle dependence in the case of thin nanowires. This result indicates polymer molecules can align to longitudinal direction in case of thin nanowires.

8974-3, Session 1

Mechanisms of nanoparticles formation using DLW and thermal annealing in a phosphate glass

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Since the theoretical advances in recent years in metamaterials field, many groups have shown interest in patterning metals in three dimensions (3D) in transparent media such as glasses or polymers. This is particularly challenging when structures much smaller than the diffraction limit need to be textured for infrared or optical applications. Herein, we describe how near-infrared (NIR) femtosecond (fs) excitation of localized electronic states in Ag-doped phosphate glasses can activate structural rearrangements that influence the aggregation of nucleation centers. Consequently we define how the thermal post-development induces kinetics of Ag nanoparticles (NP). Our strategy aims to address the problem of controlling nano-assembly processes of metal NP patterns in fully inorganic and chemically stable hard materials. We emphasize on the mechanism of silver clustering which is initiated by oxido-reduction under NIR fs excitation. The fs nonlinear absorption by multiphoton interaction followed in time by cumulative effects with high repetition rate promotes structural rearrangements and Ag diffusion confinement. Those centers are available for growth of metal NP through thermal post development. Importantly, we performed the correlative evolution of extinction and fluorescence emission properties during the annealing process within the laser-modified areas, following the localized conversion of clusters into NP. The micro-fluorescence mapping of the femto IR-induced modifications shows that the process is restricted within the three-photon interaction volume of the focused NIR laser beam. The stability of the photo-induced modifications makes it possible to design new metal patterning approaches for the fabrication of three-dimensional metal structures for enhancing plasmonic applications.

8974-4, Session 1

Femtosecond laser processing of silver-containing glass with optical vortex beams

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Silver-containing phosphate glasses are good candidates for femtosecond direct laser writing (DLW). We have demonstrated that 3D structuring in this glass at the TW/cm2 level leads to localized intense fluorescence emission, associated to silver cluster production.

Combining the DLW technique with the use of a complex light field endowed with single or multiple optical phase singularities we demonstrate original vortex-assisted laser/matter interaction. Complex sub-wavelength spatial distributions of laser-induced linear and nonlinear optical properties were achieved. More precisely, tight focusing of a charge two optical vortex beam and optical "quadrupole" led to micron-scale structures with inner sizes and distances of a few hundreds of

nanometers. We also prove that DLW is driven by the spatial intensity distribution of the tailored laser beam, independently from its phase distribution or from both the magnitude and sign of topological charge of the optical vortex.

We equally demonstrate the existence of a perennial laser-induced buried static electric field being correlated to the intensity profiles of the engineered beam, but with distinct spatial distribution to that of silver clusters. Correlative microscopy of fluorescence (linear optical response from silver clusters) and electric-field induced second harmonic generation (non-linear optical response from space charge separation) provide additional understanding of the processes at play during DLW, with the silver clusters being stabilized by the laser-induced buried electric potential modification. Vortex-assisted DLW thus appears as a very promising approach to tailor both fluorescent and SHG nonlinear responses below the diffraction limit for photonics applications.

8974-5, Session 2

UV-curable hybrid polymers for optical applications: technical challenges, industrial solutions and future developments *(Invited Paper)*

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Since the early 2000, industry has shown a considerable interest in the use of micro optical devices [1]. The availability of suitable polymers as optical materials plays a crucial role to satisfy the requirements such as excellent transparency, defined refractive index, non-yellowing etc. Additionally, the strongly increased demand as well as the rising diversity of optical applications such as camera lenses, LED's, waveguides, etc. have constantly pushed the expectations of the optical performance of these polymer materials. In this context, UV-curable hybrid polymers [2], i.e. inorganic-organic materials obtained by sol-gel chemistry, have been widely used for various applications [3].

Besides application motivated specifications, the technical compatibility to various micro- and nanofabrication technologies of the polymers is also an essential aspect to be considered for the development of advanced polymer materials. In addition to conventional UV-lithography, also (nano)imprinting and ink-jet printing have been established as innovative alternatives for direct patterning of micro optical components and devices.

In this contribution, we report on the development of innovative hybrid polymer materials which due to their tailored composition are adapted to fulfill the requirements of both the optical performance as well as the state-of-the-art patterning techniques. Furthermore, these non-toxic materials exhibit a high thermal, mechanical and chemical stability as well as a high UV-sensitivity, low roughness and nanopatterning capabilities. This enables an easy and fast processing with reliable and reproducible results for industrial large-scale productions of micro optical components and devices. The demonstration of recent material innovations will be complemented by current R&D activities.

[1] R. Voelkel, J. Duparre, F. Wippermann, P. Dannberg, A. Brauer, R. Zoberbier, M. Gabriel, M. Hornung, S. Hansen, R. Suess, Proc. MOC'08, Conf. On Micro-Optics, Brussels (2008).

[2] UV-curable hybrid polymers (ORMOCER®s) for micro optics based on a license granted by the Fraunhofergesellschaft zur Förderung der Angewandten Forschung in Deutschland e.V.

[3] C. Sanchez, B. Julian, P. Belleville, and M. Popall, J. Mater. Chem. 15 (2005), 3559-3592.

8974-6, Session 2

A novel route for fabricating printable photonic devices with a high refractive index

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The nanopatterning of high refractive index optical films promises the development of novel photonic nanodevices such as optical integrated circuits or imaging sensors. As a first step, we report here for the first time the fabrication of printable photonic circuit fabricated by direct imprinting of inorganic films with high refractive index.

Hybrid organic/inorganic printable materials were developed for crack free films with high transparency. Printed nanophotonic devices with sub-10 nm resolution were achieved in a single UV-imprinting step by applying low pressure [1]. The optical properties of the printed nanostructures can be tuned over a wide range of values; a refractive index higher than 2.1 and an extinction coefficient close to zero was achieved in the visible wavelength range. The proposed approach promises to drastically simplify the fabrication of photonic devices and the development of novel nanophotonic structures, which are very difficult to achieve by conventional nanofabrication processes. We will present and discuss the optical properties of the first printable planar lightwave circuits.

Our technology opens an original route for fabricating novel printable photonic devices at low cost and high throughput.

References:

[1] C. Pina-Hernandez, V, Lacatena, G. Calafiore, S. Dhuey, S. Cabrini, C. Peroz, Nanotechnology 24 (2013) 065301.

8974-7, Session 2

Silk fibroin: a new resist for eco-friendly photolithography

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In micro/nano-fabrication, lithography technique is the basic essential to generate arbitrary patterns the users want. However the chemicals involved in lithography such as resists and developers contain toxic substances to human body and natural environment. Here we demonstrate all water based direct photolithographic patterning onto a silk fibroin film, a noble biological and easily available natural polymer. With no involving chemicals except "only water", chemical properties of silk fibroin make it possible double-faced patterning (positive/negative tone). We have not added any initiator material for the purpose. The dose threshold of the silk resist is comparable to the well-known commercial resist. And the nanopatterns with resolution limits (under micron for photolithography) are successfully achieved. Additionally the ability to easily dope silk with either inorganic or organic dopants provides augmented utility by allowing innumerable combinations of the functionalized resist to be generated. Using this approach, we demonstrated the nanophotonic structure (photonic crystal) doped with green fluorescence protein (GFP) to enhance fluorescent emission. The silk fibroin-GFP material system demonstrates the ability to bring

together biology and technology, by co-locating a protein-based substrate and a natural fluorescent protein and manufacture a photonic system with this mixture. Along with the fabrication aspect of the silk resist, biocompatibility and ease of biofunctionalization of nanostructured biological polymers will open opportunities for unattainable device applications, such as bioresorbable integration of photonic structure within living tissue or functional activation through biochemical activity.

8974-8, Session 2

Fabrication of SU-8 based nanopatterns and their use as a nanoimprint mold

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As an emerging technology, nanoimprint lithography (NIL) draws more attention due to its low cost, high throughput and print resolution, which are critical for nanomanufacturing of complex three-dimensional (3D) nanostructures for applications in optics and photonics. However, the fabrication of NIL molds with nanoscale features has become a bottleneck for NIL development. In this research, SU-8, a widely used photoresist and permanent structural material, was patterned by focused ion beam (FIB) milling and tested as a NIL mold material. The lack of backscattered electrons in FIB process is thought to enable the fabrication of nanoscale features in SU-8 mold with smaller feature size, when compared to e-beam lithography (E-Beam). The effects of ion beam current, milling time and SU-8 crosslink density on feature quality was studied systematically. Subsequent thermal-NIL and UV-NIL experiments were performed using a patterned SU-8 mold. It was found that both pattern profile and filling ratio depend highly on NIL processing pressure, temperature and physical properties of SU-8. Film mechanical properties resulting from hardening during photocure were specifically investigated in this work. As a comparison, SU-8 molds fabricated by E-Beam patterning were also utilized in the NIL process.

8974-9, Session 3

Self-assembly via condensation of polymer liquid nanolenses for wide-field nanoparticle and virus imaging

Euan R. McLeod, Patrick Huang, Muhammed Veli, Shiv Acharya, Wei Luo, Aydogan Ozcan, Univ. of California, Los Angeles (United States)

Many fields of science and engineering require the ability to detect, localize, and size individual nanoparticles, including, for example, metallic particles or viruses. These tasks are often performed using electron microscopy, even though it can be time-intensive, costly, and/or not readily available in all locations.

Here we present a method of fabricating self-assembled liquid polymer nano-lenses that makes it possible to optically image nanoparticles over an extremely large field-of-view, which can routinely reach, e.g., >0.2 cm^2. The method is based on condensation of polyethylene glycol to form nano-lenses with desired sizes and optical properties on a planar substrate with previously adsorbed nanoparticles. In contrast to our previous liquid-phase method of forming such lenses [1], the new vapor-phase condensation method presented here enables the detection of smaller (<50 nm) particles and is more compatible with surface functionalization. Using this new method, we have imaged gold nanoparticles, specifically-captured streptavidin-functionalized beads, and viruses.

To image these nanoparticle-nano-lens assemblies, we use a lens-free digital holographic on-chip microscopy approach. Here, a partially-coherent light source illuminates the sample, which is positioned <1 mm away from a CCD or CMOS sensor, where an in-line hologram is recorded. Iterative holographic reconstruction techniques are then used to reconstruct the original object. This method provides a field-of-view about 300 times larger than a 40X objective lens, diffraction-limited resolution at 0.8-0.9 numerical aperture, high sensitivity to phase objects, as well as a cost-effective and field-portable device architecture.

[1] Onur Mudanyali, Euan McLeod, et al., Nature Photonics, 7, 247-254 (2013).

8974-10, Session 3

Array of nano/micro polymer lenses for subwavelength optical lithography

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Poly(ethylene glycol) (PEG) is an useful and common material in bio-engineering applications, because PEG can be acquired in broad range of molecular weights with low-cost. In this study, PEG was used as a tool for nanofabrication. Herein, a simple method for making nanoscale lenses from PEG was developed by using dip-pen nanolithography (DPN) with high substrate and pattern registration and excellent shape control. Moreover, subwavelength scale, ~100 nm in width, features of photoresist were obtained by using the PEG lens arrays phase-shift photomask.

8974-11, Session 3

Micro-optics fabrication by mask-based and mask-less mixed lithography process towards 3D optical circuits

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Toward three-dimensional optical-electrical mixed circuit, a flexible, scalable, and CMOS compatible fabrication methods are highly anticipated. In the circuit for which active optical components, lasers and photo detectors are discretely integrated with passive planer optical circuits, an efficient coupling of light between active and passive optics are needed. For example surface grating structure, or alternatively by 45 degree surface micro mirrors can be used for the packaging with vertical cavity surface emitting lasers. Although the fabrication of such a 45 degree mirrors is feasible by anisotropic wet etching of Silicon substrate, a direct laser writing of a mirror structure by using a maskless lithography tool (MLT) and thick photosensitive buffer coat material, by a tightly focused and scanned UV laser (wavelength 355nm), is attractive due to its completely CMOS compatible nature. Since the planer light circuit is fabricated by a physical mask-based lithography, for the mask and the muscles mixed lithography process, alignment of a virtual mask to the physical alignment mark is crucial. In this work, we fabricated optical circuit with micro mirror-based coupler by mask-based and maskless combined process. The substrate prepared by mask-based lithography contains both of the pre-exposed yet undeveloped waveguide structures and an island region, is aligned to MLT by detecting a physical mark. The exposure dose profile is precisely aligned to the island region within 1 micro meter accuracy. The slope angle accuracy is inspected by cross sectional scanning electron microscope and a Linnik interferometer, and is less than 1 degree.

8974-12, Session 4

Planar chalcogenide glass mid-infrared photonics *(Invited Paper)*

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Chalcogenide glasses, namely the amorphous compounds containing sulfur, selenium, and/or tellurium, have emerged as a promising material candidate for mid-infrared integrated photonics given their wide optical transparency window, high linear and nonlinear indices, as well as their capacity for monolithic integration on a wide array of substrates. Exploiting these unique features of the material, we demonstrated high-index-contrast, waveguide-coupled As2Se3 chalcogenide glass resonators monolithically integrated on silicon fabricated using optical lithography and a lift-off process. The resonators exhibited a high intrinsic quality factor of 2 ? 105 at 5.2 ?m wavelength, which is among the highest values reported in on-chip mid-IR photonic devices. We have also demonstrated what we believe to be the first waveguide photonic crystal cavity operating in the mid-infrared. The devices were fabricated from Ge23Sb7S70 chalcogenide glass on CaF2 substrates by combing photolithographic patterning and focus ion beam milling. The waveguide-coupled cavities were characterized at 5.2 ?m wavelength, and a loaded quality factor of ~ 2,000 was measured near the critical coupling regime.

8974-13, Session 4

Photonic crystal resonant surfaces *(Invited Paper)*

Thomas F. Krauss, Annett B. Klemm, Daan Stellinga, Graham Triggs, The Univ. of York (United Kingdom); Emiliano Rezende-Martins, Univ. of St. Andrews (United Kingdom)

Guided mode resonances are excited in photonic crystals for out-of-plane illumination. Tailoring these resonances allows us to create large area biosensors, diffractive lenses with high numerical aperture and diffractive surfaces for light trapping in photovoltaics.

8974-14, Session 4

Talbot lithography an alternative for contact lithography for sub-micron features

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Periodic submicron and nanostructures, like WDM gratings, wiregrid polarizers, photonic crystals and patterned sapphire substrate (PSS), find many applications in photonics and lighting industry (LED). Still manufacturing of submicron and nanostructures on full wafer scale remains expensive. Contact photolithography in mask aligners is possible, but has several disadvantages such as contamination, breakages and short mask lifetime. Electron beam lithography is well suited, but a slow serial process. Interference lithography needs to modify the optical configuration for different printing patterns. Nano imprint method does offer a large production low cost solution, but there remain several issues due to contamination which prevents very high throughputs and short lift time of the stamp. Stepper lithography is a promising photolithographic technologies, but has large upfront cost which acts as an entry barrier.

Talbot lithography is an inexpensive way to obtain sub-micron periodic structures in non-contact in a mask aligner. In this paper we discuss the salient features of Talbot lithography in mask aligners. We present theoretical limits in terms of feature sizes, fill factors, and distance to mask. We also discuss practical limitations in yield and reproducibility due to variation in the optical illumination, flatness and absolute distance to the mask. The theoretical and practical limits are put in context by contrasting them with contact photolithography.

Using SUSS' MicroOptics patented MO Exposure Optics (MOEO) for illumination we show that non-contact Talbot photolithography can give micron and sub-micron features enabling fabrication of plasmonic structures for applications such as optical filtering and PSS.

8974-15, Session 4

Efficient fabrication of complex nano-optical structures by E-beam lithography based on character projection

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The functions of nano-optical elements are typically based on specially designed sub-wavelength structures whose fabrication requires high-resolution and high-quality lithographic techniques. Electron-beam lithography using the Variable Shaped Beam (VSB) writing principle is a suitable and very flexible fabrication technique to address these needs. It is based on an exposure with extended geometrical primitives like rectangles or triangles of flexible size. However, the complexity of the nano-optical pattern increased over the years from simple 1D structures like gratings, over 2D structures (e.g. for plasmonic antennas) to 3D meta-materials. In case of periodic pattern as they are found in most optical elements like photonic crystals or meta-materials, the VSB writing principle can be further extended by a so called character projection where complex exposure pattern are coded in a stencil mask and exposed with a single shot. Resulting shot-count and thus writing time reductions can be in the order of about 100...10000. The realization of numerous kinds of elements on larger areas becomes possible only with such a highly parallel writing strategy. However, in order to maintain the flexibility for generating arbitrary pattern a huge number of diaphragms needs to be addressable within a single exposure job. This is realized in a Vistec SB350 OS E-beam writer by a specially developed diaphragm stage offering to combine more than 250 different exposure characters by computer control.

The significantly extended exposure capability with this automatic diaphragm stage is demonstrated by different nano-optical elements such as effective refractive index structures, plasmonic antennas, and micro-structured polarizers.

8974-16, Session 4

Rapid prototyping of coupled photonic cavities by focused ion beam/ photolithography hybrid technique

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A hybrid photolithography and focused ion beam (FIB) patterning of

coupled photonic cavities is reported. This technique is used for rapid prototyping of nanophotonic devices, where previously mass-produced devices by conventional lithography steps, such as photolithography, projection lithography or nano/micro-imprinting can be customized by a versatile approach on a focused ion beam microscope. This requires accurate positioning of the FIB pattern relative to the pre-patterned devices and minimal drift during the writing phase. Various fabrication parameters that mimic process variability can be studied and the obtained experimental results compared with numerical simulations of the fabricated devices. This allows the calibration of the simulation models for more accurate design to manufacturing predictability. As a proof of concept, the experimental optimization of the localized modes in a photonic molecule formed by placing two one-dimensional photonic crystal cavities on a nanowire coupler is reported. The effects of different photonic crystal geometry, material removal depth and rate, sidewall profile and roughness, patterning drift on the performance of the photonic molecule resonator are investigated. These fabricated photonic molecule devices can be used as refractive index sensors with measured sensitivities on the order of 400 nm/RIU in a sensing volume as low as 18 femtoliters. The dimensions of the fabricated devices and the understanding of their optical behavior on environmental influence open the door for near-field optical spectroscopy of single bacterial specimens.

8974-17, Session 5

On-chip polarizer on image sensor using advanced CMOS technology *(Invited Paper)*

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The structures in advanced complementary metal-oxide-semiconductor (CMOS) integrated circuit technology are in the range of deep-submicron. It allows designing and integrating nano-photonic structures for the visible to near infrared region on a chip.

In this work, we designed and fabricated an image sensor with on-pixel metal wire grid polarizers by using a 65-nm standard CMOS technology. It is known that the extinction ratio of a metal wire grid polarizer is increased with decrease in the grid pitch. With the metal wire layers of the 65-nm technology, the grid pitch sufficiently smaller than the wavelengths of visible light can be realized. The extinction ratio of approximately 20 dB has been successfully achieved at a wavelength of 750 nm.

In the CMOS technologies, it is usual to include multiple metal layers. This feature is also useful to increase the extinction ratio of polarizers. We designed dual layer polarizers. Each layer partially reflects incident light. Thus, the layers form a cavity and its transmission spectrum depends on the layer position. The extinction ratio of 19.2 dB at 780 nm was achieved with the grid pitch greater than the single layer polarizer.

The high extinction ratio is obtained only red to near infrared region because the fine metal layers of deep-submicron standard CMOS process is usually composed of Cu. Thus, it should be applied for measurement or observation where wide spectrum is not required such as optical rotation measurement of optically active materials or electro-optic imaging of RF/THz wave.

8974-18, Session 5

Dual-modes sensing platforms with silicon and metal nanonet structures fabricated using nanosphere lithography

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Electrical biosensing using silicon nanowire electronics and optical biosensing with plasmonic nanostructures have been important research topics in the fields of Nanophotonics and Biophotonics for the last few years. Both techniques have been developed to a status that can be used in current biosensing applications. However, each technique exhibits its own limitation and cannot not be completely solved within its own research discipline. Therefore, a single device that can perform both the electrical and optical sensing of chemical or bio-species will help a lot for the advancing of both technologies.

In this study, fabrications of silicon nanonet membrane field-effect transistor are demonstrated based on oxygen plasma-treated Nanosphere Lithography (PT-NSL). Cr nanonets are first fabricated on top of silicon-on-insulator substrates after Cr deposition and nanosphere lift-off. Silicon nanonet membrane can be obtained after wet silicon etch using the Cr nanonets as the etch mask. After fabricating the connecting electrodes to the silicon nanonet membrane, the nanonet membrane can be used as a electrical sensing platform. It is also possible to fabricate a metal nanonet membrane on top of the silicon membrane. The metal nanonet membrane can be used as optical sensing platforms. The dual-modes sensing platforms will pose several important advantages over a single-mode operation since we can eliminate the limitation from the single-mode detection. Electrical and optical properties of the devices will also be presented. Further improvements of the proposed design will lead to novel sensing platforms.

8974-20, Session 5

High-precision transfer printing of ultra-thin AlInGaN micro-light-emitting diodes onto polymeric substrates

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Mechanically-flexible optoelectronic/photonic devices have been the focus of great interest recently because they have the potential to enable applications not accessible to rigid device formats. A possible way to achieve a flexible or conformable photonic platform is to use the transfer-printing technique, where thin inorganic optoelectronic structures are transported onto non-native (e.g. plastic) substrates. However, to fully capitalize on the capabilities offered by the technology and in turn to enable the flexible devices of the future, it will be important to transfer-print structures with very high (nano) positioning accuracy and wide area scalability . Here, we report the transfer-printing of ultra-thin GaN structures with ~150-nm placement resolution for the fabrication of flexible GaNLED arrays.

LEDs (150x150 µm2 and below) were fabricated from a GaN epitaxial structure grown on Silicon (111). The Si substrate was under-etched, yielding 2µm-thin devices suspended by sacrificial anchors. Devices were then transfer-printed onto a mechanically-flexible PET/PDMS substrate, using a modified dip-pen nano-patterning system, to form a 16x16 LED array. LED-printing was executed using pre-set coordinates to demonstrate an automated process with accurate control of the spacing between elements (150 nm ±14 nm, limited by the LED side-wall roughness). The emission of the elements in the array was centered at 486 nm with an optical output power of up to 80 µW (355 mW/cm2) per LED at a 20 A/cm2 current density. The turn-on voltage of the LEDs was close to 3V on boththe native and non-native substrate. Further advances in device formats as well as their applications will be discussed.

8974-21, Session 5

A compact snapshot multispectral imager with a monolithically integrated, per-pixel filter mosaic

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The adoption of spectral imaging by industry has so far been limited due to the lack of high speed, low cost and compact spectral cameras. Moreover most state-of-the-art spectral cameras utilize some form of spatial or spectral scanning during acquisition, making them ill-suited for analyzing dynamic scenes containing movement. This paper introduces a novel snapshot multispectral imager concept based on optical filters monolithically integrated on top of a standard CMOS image sensor. It overcomes the problems mentioned for scanning applications by snapshot acquisition, where an entire multispectral data cube is sensed at one discrete point in time. This is enabled by depositing interference filters per pixel directly on a CMOS image sensor, extending the traditional Bayer color imaging concept to multi- or hyperspectral imaging without a need for dedicated fore-optics. The monolithic deposition leads to a limited spectral crosstalk and a high degree of design flexibility. In turn, this enables systems ranging from application-specific, high spatial resolution cameras with 1 to 4 spectral filters, to hyperspectral snapshot cameras at a medium spatial resolutions and filters laid out in cells of 4x4 to 6x6 or more. Through the use of monolithically integrated optical filters it further retains the qualities of compactness, low cost and high acquisition speed, differentiating it from other snapshot spectral cameras. Our prototype demonstrator camera can acquire multispectral image cubes of 272x512 pixels over 16 bands in the spectral range of 600-1000nm at 340 cubes per second for normal machine vision illumination levels.

8974-23, Session 6

Structural colour of porous dielectrics processed by direct laser write technique

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We report realization of structural colour in photonic crystal structures fabricated by femtosecond direct laser write (DLW) lithography in photoresist. 3D photonic crystals with woodpile architecture were fabricated by femtosecond DLW technique in Zr containing hybrid organic-inorganic photoresist, and optical reflectivity of the fabricated samples was investigated in the visible and near-infrared spectral ranges. The samples were found to exhibit bright, clearly visible structural colour controllable by the photonic crystal lattice period and the dielectric filling ratio, with visible spectral reflectivity peaks seen at a wavelengths far shorter than those corresponding to the fundamental photonic stop gaps in the structures. These observations can be attributed to dispersion of higher-frequency photonic bands located well above the fundamental, lowest frequency, photonic stop gap. This circumstance facilitates easier and faster DLW fabrication of materials with structural colour by alleviating the requirement to scale down the photonic crystal lattice period below the optical wavelength scale. The fabricated structures may be exploited for optical environmental sensing and imaging in the future.

8974-24, Session 6

Uniaxial alignment of single-wall carbon nanotubes induced in two-photon lithographically fabricated polymer micro/nano-structures

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Single wall carbon nanotubes (SWNTs), which consist of a rolled-up single layer graphene with a 1 nm diameter cylindrical shape, exhibit remarkable mechanical, electrical, thermal, and optical properties. The intrinsic characteristics make them ideal candidates as advanced filler materials in composites, leading to a wide range of applications such as MEMS and photomechanical actuators. In our previous research, we demonstrated 3D micro fabrication of SWCNT/polymer composite by using two photon polymerization (TPP) lithography. Our method allows one to fabricate arbitrary 3D micro structures, and SWCNTs are uniformly distributed throughout the whole structures. Here, we present TPP lithography induces uniaxial alignment of SWCNTs in polymer structures. Polarized micro Raman spectroscopy is used to elucidate the orientation direction of SWCNTs in structures with high spatial resolution. The G-band peak intensity significantly varies in intensity as a function of angles between the polarization of incident light and nanowire axis. The G-band intensity becomes largest when the polarization of the laser beam is parallel to the nanowire axis, while it becomes smallest when the polarization is perpendicular. This result clearly indicates that the SWCNTs are uniaxially aligned inside the wire. We also show that SWCNTs are more aligned in thinner nanowires, probably due to the higher spatial confinement and volume shrinkage of polymer. The alignment would further improve properties of the composite such as mechanical and electrical properties.

8974-25, Session 6

Processing and properties of arsenic trisulfide chalcogenide glasses for direct laser writing of 3D micro-structures

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Arsenic trisulfide (As2S3) is an infrared (IR) transparent (620 nm to 11 ?m) material with direct applications in IR sensors, photonic waveguides, and acousto-optics. As2S3 may be thermally deposited to form glassy films of molecular chalcogenide (ChG) clusters. It has been shown that linear and multi-photon exposure can be used to photo-pattern thermally deposited As2S3. Photo-exposure cross-links the film into a network solid. Treating the photo-patterned material with a polar-solvent removes the unexposed material leaving behind a structure that is a negative-tone replica of the photo-pattern. In this work, nano-pillar arrays were photo-patterned in As2S3 films by multi-photon direct laser writing (DLW) and the resulting structure, morphology, and chemical composition were characterized and correlated with the conditions of the thermal deposition, patterned irradiation, and etch processing. FT-RAMAN was used to characterize the chemical structure of photo-patterned material, and near infrared ellipsometry was used to measure the effective refractive index of nano-pillar arrays. Optical and physical characterization including structure size, effective refractive index, scatter, and surface adhesion of nano-scale features was related to the processing conditions.

8974-26, Session 6

Titania woodpiles with complete three-dimensional photonic bandgaps in the visible *(Invited Paper)*

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The 1987 proposal of complete photonic bandgap (cPBG) materials by Eli Yablonovitch and Sajeev John has spurred enormous experimental efforts to fabricate such materials. Despite these efforts, photonic crystals with a cPBG in the visible part of the electromagnetic spectrum have remained elusive until recently. Since direct-laser-writing (DLW) optical lithography allows for the fabrication of almost arbitrarily shaped three-dimensional (3D) geometries it presents an appealing approach. However, the necessary resolution, feature sizes and refractive-index contrast for a 3D cPBG have to be attained.

In this work, we meet all of these three challenges. We use stimulated-emission-depletion (STED) inspired DLW lithography to obtain polymer woodpiles with rod distances of 310 nm. Next, we employ an adaption of our previously introduced silicon-double-inversion procedure to titania: 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, the rod-dimensions are then fine-tuned using another ZnO ALD step, leading to a rod width of 103 nm. We then apply another inversion step using titania ALD. Finally, the ZnO is etched out selectively, leaving behind a titania woodpile. The refractive index of the ALD-grown titania is measured to be 2.48 which is sufficient to open a cPBG.

Good agreement between angle- and polarization resolved transmission spectra and their theoretical counterparts provide evidence for a cPBG centered around 700 nm.

We also find a strong modification of the titania fluorescence.

8974-22, Session 7

Direct laser writing with a spatial light modulator *(Invited Paper)*

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We will report on our recent progress on direct laser writing with a spatial light modulator.

Direct laser writing (DLW) has been widely adopted in nanophotonics, in particular to generate three-dimensional (3D) structures at micro and nano scales. However, there are a few challenges in 3D DLW. First, the effect of the mismatch of refractive indices between the immersion medium of a high numerical-aperture objective and the bulk material where a 3D micro/nano-structure is fabricated becomes a dominant factor to determine the functionality of the devices. The fabrication speed is significantly affected by the operation with a single focal spot. We show how these two issues can be overcome with a spatial light modulator. As a result, 3D DLW can be operated in high refractive-index nonlinear media and its fabrication speed can be increased by two orders of magnitude.

8974-27, Session 7

STED-inspired dip-in optical lithography of 3D chiral polarizers for visible and telecom wavelengths

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Direct-laser-writing optical lithography can be seen as a sophisticated version of 3D printing with sub-micrometer resolution in all three spatial dimensions. Photosensitive material is polymerized via nonlinear absorption of a tightly focused laser beam. The technique used to be limited by optical aberrations (i) and the diffraction limit (ii). To overcome (i), we have recently introduced dip-in optical lithography allowing for 3D structuring of large volumes without depth-dependent optical aberrations. Depletion optical lithography inspired by stimulated-emission depletion (STED) microscopy has been introduced as a 3D fabrication route beyond the diffraction limit (ii).

Here, for the first time, we combine both concepts to fabricate 3D nanostructures for photonics. For depletion of the photoinitiator ITX we employ an inexpensive continuous-wave (cw) laser diode at 639-nm wavelength. The measurements of both the exciting Gaussian focus at 780-nm wavelength and the depleting bottle-beam focus are in very good agreement with theory. Fiber-coupling of the depletion laser leads to very stable operation and highly reproducible results.

To demonstrate the performance of the STED-inspired lithography setup, we have fabricated 3D chiral polymeric layer-by-layer twisted woodpile structures with a lattice constant reduced by more than a factor of 2 compared to our earlier results. Instead of 24 layers, we have fabricated as many as 102 layers. The fabricated photonic twisted woodpile structures serve as dual-band polarizers for circular polarization at visible and telecom wavelengths. To further investigate our approach, we have measured the fabricated structures using polarization-sensitive spectroscopy. The spectroscopic results agree well with scattering matrix calculations.

8974-28, Session 7

Quantifying the proximity effect by active point-spread-function engineering

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Direct Laser Writing is an established technique for the fabrication of almost arbitrary three-dimensional structures in photosensitive materials via two-photon absorption [1]. Above a photoresist-specific intensity threshold the crosslinking density of the polymers is high enough to withstand the development process leading to the final structure. The feature size of these structures may almost arbitrarily be reduced by lowering the intensity in the focal volume. However, the two point resolution is much more challenging to increase since the proximity effect leads to undesired polymerization at close feature separations [2]. Hence, a detailed knowledge about the different physical mechanisms driving the proximity-effect and their relative strength is highly desired.

Here, we propose simultaneous multi-foci exposures to study photoresist-specific polymerization processes [3]. We use a spatial-light-modulator to generate different focus patterns. These patterns are calculated such that different physical mechanisms leading to the proximity-effect may be separated and characterized in their time and spatial dependence.

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

[2] Active aberration- and point-spread-function control in direct laser writing, Waller et al., Optics Express 20, 24949-24956 (2012)

[3] Multi foci with diffraction limited resolution, Waller et al., (submitted to Optics Express)

8974-29, Session 7

Three-dimensional ultrafast laser processing of diamond

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We investigate methods for three dimensional structuring using an ultrashort pulsed laser in single crystal CVD diamond. The interaction of the laser with diamond lattice leads to a permanent structural modification, which is highly localized at the focus through non-linear optical processes. The laser written structures can consist of range of phases from a disrupted diamond crystalline structure through to amorphous carbon or graphite. Severe spherical aberration caused by the refractive index mismatch between the diamond and the objective lens immersion medium leads to compromised fabrication below the diamond surface. Distortion of the focus leads to a reduction in spatial precision and a reduction in efficiency. We implement adaptive optical methods to compensate the aberrations to ensure optimum fabrication performance, both in terms of spatial resolution and consistent material modification at different depths. The nature of the structural modification is analysed for both surface and subsurface laser fabrication using a range of techniques including Raman microscopy, atomic force microscopy, optical profilimetry and electrical characterisation. The etching of laser-modified regions to generate three-dimensional photonic structures is explored. We also discuss methods of parallelization of the laser writing process in order to increase fabrication throughput.

8974-30, Session PTue

Random micro-lens array illumination device manufactured by ultra-precision machining

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Micro-lens arrays can be performed as diffusing illumination devices in substitution for the rough surfaces fabricated by electro-discharge machining or sandblasting. These arrays provide an advantage on obtaining higher transmittance, while the beam divergence angle of the arrays can be easily controlled. With these characteristics, a micro-lens array can be used as an exit pupil expander which focuses an intermediate image for a head-up display. However, non-uniform intensity pattern, due to the periodic structure of the array acting as a diffraction grating, is observed at the expanded pupil when an incident light is coherent. In this research, we modify the periodicity with specifying the optimal position and depth of the individual micro-lenslet precisely and utilize diamond turning process for ultra-precision machining with nanometer resolution. A micro-lens array with an appropriate beam divergence angle and higher intensity uniformity is achieved.

8974-31, Session PTue

Fabrication of defects in periodic photonic crystals using a phase-only spatial light modulator

David George, Jeffrey R. Lutkenhaus, Bayaner Arigong, Univ. of North Texas (United States); Hualiang Zhang, Univ of North Texas (United States); Usha Philipose, YuanKun Lin, Univ. of North Texas (United States)

Here we present single exposure holographic fabrication of defects on two dimensional photonic crystal structures in negative photoresist using a spatial light modulator (SLM). A phase pattern is obtained from the beams that form the desired interference pattern and displayed on a phase-only SLM. The resulting first order beams at the fourier plane are used to recreate the interference pattern. The defects are created in the phase pattern in one of the two following ways. A void-type defect is produced by replacing the phase of each of the interfering beams with a constant value at the points where the defect is desired. And an inverse pattern defect can be made by adding another beam with a pi phase shift relative to each of the interfering beams at the points where the defect is desired. Through these methods it is possible to fabricate arbitrary shaped defect structures in photonic crystals through a single exposure process, thus improving cost effectiveness and simplifying the fabrication process of integrated photonics

8974-32, Session PTue

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

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

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

8974-33, Session PTue

Fiber inline quarter-wave plate fabricated by femtosecond laser irradiation: modeling and experiment

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Micro-photonics devices fabricated by the flexible femtosecond (fs) laser direct-write technique have attracted much research interest in recent years. These micro devices are commonly made by two methods: one is fs laser ablation and the other is fs laser inscription. Due to the well-known advantages of all-glass optical fibers such as compactness, large bandwidth, immunity to electromagnetism, passiveness, and remote operation, many researchers are focusing onto these micro-photonics devices associated with optical fibers. Besides, an extremely important property of the optical fiber micro devices--polarization state of the optical fiber--needs to be considered urgently in some application areas. Many kinds of polarization maintaining micro optical fiber devices have been widely used for polarization control in precision fiber-optic sensors and instrumentations.

This paper reports a fiber inline stress-induced birefringent quarter-wave plate fabricated by femtosecond laser (fs) irradiation. A series of symmetric stress regions were formed at optimal distance on both sides along the fiber core. Polarization state changed gradually from ±45° linear polarization on the equator to circular state in the poles along the longitude of the Poincaré sphere during the fabrication process. Moreover, theoretical results about stress distributions and stress induced birefringence distributions were analyzed by finite element method as well. The fiber inline quarter wave plate is particularly well suited for integrated optical communication systems or micro-photonics polarization maintaining applications and devices.

8974-34, Session PTue

Computational modeling and experimental study on fiber inline Michelson interferometer fabricated by femtosecond laser ablation

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Assembly-free all-glass optical fiber inline micro sensors have been well demonstrated of physical and chemical measurement in recent years. Due to their advantages of high melting point (1100°C), compact size, light weight, immunity to electromagnetic interferences (EMI), corrosion resistance, and flexibility of directly embedding into the system structure. Examples of all glass micro optical fiber sensors fabricated by femtosecond laser can be mainly categorized into two types- Index modulation based resonators (Long period fiber grating or fiber Bragg grating) and micro interferometer based sensors (Fabry-Perot or Mach-Zehnder interferometer). Such glass optical fiber sensors can be the solution of high temperature sensing application as well as gas or solution refractive index (RI) sensing application surviving and operating in harsh environment.

This paper reports a new fiber inline Michelson interferometer (FIMI) fabricated by micromachining a step structure at the tip of a standard single mode optical fiber using femtosecond laser ablation technique. The step structure splits the fiber core into two reflection paths and produces an interference signal. A fringe visibility up to 18 dB was obtained. Temperature sensing (50-1000 °C) was demonstrated using the fabricated structure. A comparison of computational and experimental results presented good agreement in the RI sensing range when the FIMI was in use. The simple structure and reflection-based signal interrogation of the proposed device makes it mechanically robust and easy to be deployed in real applications.

8974-36, Session PTue

Manufacturing techniques of large-area optical elements with micro/nano structures on both surfaces

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Recently, there is a growing need for manufacturing of the large-area optical thin film with a new function caused by complicated structures of micro and nano scale. Injection molding, one of the most popular techniques, is well-suited for manufacturing complicated and precise shapes at a relatively low cost. However, it is difficult to achieve low birefringence, high aspect ratios and uniform surface replication over a large area. Thermal and ultra-violet light imprinting is suitable for performing high-definition transfer. However, it demands a long cycle time for forming structures and it decreases the productivity. We report the example that worked on the production technology development of large-area optical elements which is formed the micro/nano structures on both surfaces with extremely low birefringence good at productivity. The mold was designed so that can avoid strain caused by the thermal expansion of metal and keep the high accuracy of relative position of both sides and optimized by three-dimension unsteady heat conduction analysis. As a result, it became able to produce the optical element at a low cost in good productivity.

8974-37, Session PTue

Holographic fabrication of photonic crystal templates using spatial-light-modulator-based phase mask method

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In this work, we present a method of holographically fabricating photonic structures in photosensitive polymer using a phase pattern displayed on a spatial light modulator (SLM) as a programmable phase mask. The phase pattern was chosen to be hexagonal, with each hexagon comprised of 6 symmetrically arranged equilateral triangles. Each triangle in a hexagon is shaded with a different gray level, corresponding to a different phase. Six beams with different phases were generated and interfered to holographically fabricate photonic crystal templates in photosensitive polymer. Blocking two of the generated beams at the Fourier plane allowed the formation of compound photonic crystal templates, and changing the gray level of the triangles in the displayed phase pattern allowed control of the phases of one or more of the beams, thus changing the interference pattern. By using the phase pattern on the SLM as a tunable phase mask, different photonic crystal templates can be fabricated.

8974-38, Session PTue

Miniaturized optical fiber Fabry-Perot interferometer fabricated by femtosecond laser irradiation and selective chemical etching for refractive index sensing

Lei Yuan, Hongbin Wu, Cong Wang, Yanping Yuan, Kaihu Zhang, Zhitao Cao, Sumei Wang, Beijing Institute of Technology (China)

Miniaturized optical fiber Fabry-Perot interferometer (FPI) cavity has attracted tremendous interest in recent years. Owing to its advantages of small size, in-line reflection structure, fast response time, corrosion resistance and high sensitivity, such Fabry-Perot interferometer is particularly attractive for refractive index (RI) sensing application involving harsh environments. In the past few years, various methods have been adopted to fabricate the FPI cavities, especially using femtosecond laser ablation technique to form an artificial air gap inside the optical fiber. However, the cavity surface quality, the mechanical strength and the fabrication efficiency are still issues with respect to this advanced micromachining technique.

This paper presents an assembly-free optical fiber Fabry-Perot interferometer cavity for refractive index sensing. The realization of such interferometer cavity combined with inlet/outlet channels in a standard single mode fiber prepared by ultrafast femtosecond laser irradiation and subsequent selective chemical etching in HF solution. The ipsilateral inlet/outlet channels are vertical to the FPI cavity to realize the injection of the sensing samples. Such device can work as a fiber tip based chemical or biological RI sensor with the unique advantages of robustness, easy for fabrication and potentially low cost.

8974-40, Session PTue

High-temperature sensor-based on microcavity Michelson interferometer fabricated by femtosecond laser

Hongbin Wu, Lei Yuan, Sumei Wang, Zhitao Cao, Beijing Institute of Technology (China)

Optical fiber sensors have attracted increasing research interests for

their low power consumption, immunity to electromagnetism and broad applications in monitoring temperature, refractive index (RI), pressure and strain. The fiber inline Michelson interferometer is a kind of reflective type fiber sensor, with advantages of small size and sensitive to RI and temperature. The light transmitted forward and then reflected back from the cleaved end face, two lights coupled in the same fiber. The sensing structure is more compact than transmissive type fiber sensor.

In this paper, a high temperature sensor Michelson interferometer in a common single-mode optical fiber is fabricated by the method of ablating a microcavity. A femtosecond laser is used to fabricate a microhole on the center of a fiber end, then a microcavity is formed by splicing the ablated end face with a normal one. A transmission loss of 16 dB is observed in room temperature. The interferometer is used to detect high-temperature in the range of 300-1000? with a high sensitivity is achieved with good linearity in the whole range. This new Michelson interferometer is insensitive to external refractive index (RI).

8974-41, Session PTue

Fabrication of the nanoimprint template with periodic structures

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As one of the most promising nanostructure processing technologies, nanoimprint lithography (NIL) has the advantages of high-resolution, low-cost and large-scale production. However, one of the most critical steps of the realization of the NIL is the fabrication of the nanoimprint template. This is because the ultimate resolution of the patterns fabricated by NIL is primarily determined by the resolution of the template. Therefore, the template fabrication is considered as the greatest challenge for NIL.

To overcome the disadvantages of high-cost, low-efficiency and the difficulty in the realization of the high aspect ratio structure in the fabrication of nanoimprint template with periodic structures by E-beam lithography, the holographic lithography - ion beam etching is adopted to fabricate the nanoimprint template with periodic structures. The accurate control of the high aspect ratio of the profile is achieved by the optimization of the holographic lithography and the choice of the appropriate parameters of ion beam etching. There are two major challenging steps of this method: the holographic exposure and development and the ion beam etching. The former one is to make the photoresist mask; and the second step is to transfer the photoresist mask to the quartz. The experiment indicates that titled rotation of the ion beam etching combined with reactive ion beam etching can achieve the accurate control of the high aspect ratio structure. Two types of nanoimprint template have been fabricated: the period of 250nm and the groove depth of 380nm; the period of 600nm and groove depth of 1400nm, respectively.

8974-42, Session PTue

Fiber inline taper-based Michelson interferometer fabricated by CO2 laser irradiations

Hongbin Wu, Lei Yuan, Sumei Wang, Zhitao Cao, Beijing Institute of Technology (China)

Fiber inline interferometers have attracted considerable research interests in the past few decades because of their compactness, easy to fabricate and convenient operation in many applications. Different types of interferometers have various advantages and sensing fields. The fiber inline Michelson interferometer operates in the reflection mode, showing high sensitivity and broad detecting range. It is suitable for the detection of temperature and refractive index.

In this paper, a fiber inline Michelson interferometer is fabricated by CO2 laser irradiations on a single-mode fiber. The laser irradiations melted the local part of the fiber, making this section of fiber become thinner than the sections on both sides. The thinner section caused optical path difference (OPD) between the core and the cladding. The light coupled from the core mode to the cladding mode in this area. Different interferometer lengths (10, 20, and 40 mm) are observed with different interference spectra. The best fringe visibility can reach 35 pm/?. The interferometer can also be used to detect external refractive index with good spectra.

8974-43, Session PTue

Co-molding of nanoscale photonic crystals and microfluidic channel

Chloe E. Snyder, Maurya Srungarapu, Anand Kadiyala, West Virginia Univ. (United States); Gary Eurice, Univ. of Maryland, Baltimore County (United States); Yuxin Liu, Jeremy M. Dawson, West Virginia Univ. (United States)

Co-molding of microfluidic channel and nanoscale photonic crystal (PhC) structures provides a solution to complex co-integration of sensor and transducer elements in lab-on-chip systems used for rapid, point-of-care diagnostics. This paper presents a method of performing co-molding using a polymer molding process. The nanoscale PhC lattice and microfluidic channel master molds are fabricated in silicon. Using this silicon master mold, the nanoscale photonic crystal structures are then fabricated in polymer such as PDMS (polydimethylsiloxane) or epoxy. Photonic crystals with features that are ~100 nm in diameter and with ~200 nm pitch are etched into silicon to achieve a feature height of ~100 nm. The photonic crystal structures are on a ~20 ?m deep and ~150 ?m wide ridge within the finished mold. This complex structure is used for molding in PDMS. The finished structure is fabricated within epoxy due to the rigidity displayed after curing. Attempts using titanium-oxide nanopowder to increase the refractive index of the polymers to above 1.3 will be discussed.

8974-44, Session PTue

Refractive index insensitive asymmetrical optical fiber Mach-Zehnder interferometer for temperature sensing

Hongbin Wu, Lei Yuan, Sumei Wang, Zhitao Cao, Beijing Institute of Technology (China)

Inline Mach-Zehnder interferometers (MZIs) have received great interest for many detecting applications. There exist many advantages for this type of sensors including simplicity, compactness and relatively simple fabrication process. A number of structures have been designed to fabricate a MZI fiber sensor. The fiber inline Mach-Zehnder interferometer is usually used to sense external refractive index and temperature because of its high sensitivity and good working condition in harsh environment.

In this paper, an asymmetrical MZI is proposed which is constructed by concatenating a fiber taper and a ultra-abrupt taper in a single-mode fiber (SMF). CO2 laser is used to fabricate the first fiber taper. Then fusion splicing machine is used to fabricate the ultra-abrupt taper. The distance L between the two tapers is set to be different (5mm, 20mm, 35mm) and then different transmission spectra are achieved. The fringe visibility can be 14dB in spectrum. It can be found from the test that, the MZI fiber sensor is sensitive to temperature while less sensitive to external refractive index. It means that it is a RI insensitive fiber sensor.

8974-45, Session PTue

Temporal growth of gold nanorod aggregates through local surface plasmon-assisted two-photon polymerization

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

Local surface plasmon resonance (LSPR) is an oscillation mode of free electrons in nano-sized metal particles, which plays an important role to focus, accumulate, and transfer the energy of light within a nanoscale volume smaller than the wavelength of the light itself. We have previously reported a novel method to create three dimensional gold nanorod (AuNR) aggregates microstructures by means of LSPR-induced photo polymerization cooperating with optical gradient force. In this presentation, we will show experimental evidences indicating the mechanism in detail of the formation of aggregates during laser irradiation into nanorod-dispersed photopolymer. AuNRs, of the diameter and length are 20 nm and 65 nm, exhibit resonant wavelength at 770 nm as a longitudinal mode of LSPR. By shining femtosecond laser emitting at 780 nm onto AuNRs dispersed in methyl methacrylate (MMA) with photo-initiator, cross-linked PMMA layer surrounding AuNRs with a thickness of ~10-20 nm is formed due to two-photon photopolymerization reflecting the LSPR. We observed growth of AuNR aggregates by changing the exposure time of the laser. We also investigated the time evolution of the geometries of the LSPR-induced polymer layer onto a single AuNR. We compared with a numerical simulation of the formation and the perturbation of the local field distribution of LSPRs by the change of surrounding dielectric constants. From these experimental and numerical results, we will discuss the dynamics of the growth of femtosecond laser-induced gold nanorods aggregates.

8974-46, Session PTue

Two-photon lithography for single-wall carbon nanotube/polymer composite nanofabrication

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

Single wall carbon nanotubes (SWNTs), which consist of a rolled-up single layer graphene with a 1 nm diameter cylindrical shape, exhibit remarkable mechanical, electrical, thermal, and optical properties. The intrinsic characteristics make them ideal candidates as advanced filler materials in composites, leading to a wide range of applications such as MEMS and photomechanical actuators. We have reported on a novel method of 3D micro fabrication of single wall carbon nanotubes (SWCNTs)/polymer composite by means of two photon polymerization (TPP) lithography. Our method allows one to fabricate arbitrary 3D micro structures. In this presentation, we will discuss spatial resolution of the fabrication, polymerization reaction with the presence of SWCNTs, and some properties of fabricated structures. The spatial resolution as a function of laser intensity was investigated by fabricating nanowires, and we found the minimum spatial resolution was around 200 nm. Moreover, we found that the spatial resolution for the composites was higher than that for the resin without SWCNTs, probably because the incident photon was absorbed and dissipated by SWCNTs. We also proved that the polymerization reaction of the photo-resin proceeded smoothly even in the presence of SWCNTs by comparing Raman spectra between before and after polymerization. The fabricated structures were investigated by Raman microscopy that enables to visualize distribution of SWCNTs in the structures. SWCNTs were uniformly distributed throughout the whole structures, even in a few hundreds nm thick nanowires.

8974-47, Session PTue

Size-gradient two-dimensional photonic crystal fabricated using laser holographic lithography

Hyunho Jung, Hanbit Kim, Heonsu Jeon, Seoul National Univ. (Korea, Republic of)

Laser holographic lithography (LHL) process is known to be capable of fabricating highly periodic submicron patterns on a large area at high throughput and low cost. Here we introduce a novel method to fabricate size-gradient photonic crystal (PC) patterns using the LHL technique. Since the exposure intensity is one of the main factors that determine the feature size, we varied gradually the spatial intensity distribution of input beam along one direction to obtain a pattern with constant periodicity but gradually changing feature sizes. In order to fabricate a size-gradient two-dimensional (2D) PC structure with square lattice, sample was exposed twice in a two-beam interference setup; sample was rotated by 60 ° or 90 ° before the second exposure, depending on the desired PC pattern. When the intensity distribution varies from 1 to 0.6 across sample, we found that the air-hole radius of the resultant PC pattern varies over ?r = 0.15a , where a = 600 nm is the lattice constant of PC. Such a wide variation in the air-hole size can produce a large gradation in photonic band structure; for example, our theoretical calculations based on plane-wave expansion method show that the lowest band-edge wavelength at the gamma-point varies from about 1500 nm to 1600 nm when an InGaAsP PC slab with square lattice pattern is assumed, covering the entire low-loss optical communications wavelength range. Therefore, such size-gradient PC patterns should be useful for novel PC-based devices, such as tunable lasers and variable filters with a wide tuning or variation range.

8974-49, Session 8

One step lithography-less silicon nanomanufacturing for low cost, high-efficiency solar cell production

Yi Chen, Univ. of Illinois at Urbana-Champaign (United States) and Effimax Solar, Inc. (United States); Logan Liu, Univ. of Illinois at Urbana-Champaign (United States)

To improve light absorption, previously various antireflection material layers were created on solar wafer surface including multilayer dielectric film, nanoparticle sludges, microtextures, noble metal plasmonic nanoparticles and 3D silicon nanostructure arrays. All of these approaches involve nanoscale prepatterning, surface-area-sensitive assembly processes or extreme fabrication conditions; therefore, they are often limited by the associated high cost and low yield as well as the consequent industry incompatibility. In comparison, our nanomanufacturing, an unique synchronized and simultaneous top-down and bottom-up nanofabrication approach called simultaneous plasma enhanced reactive ion synthesis and etching (SPERISE), offers a better antireflection solution along with the potential to increase p-n junction surface area. High density and high aspect ratio anechoic nanocone arrays are repeatedly and reliably created on the entire surface of single and poly crystalline silicon wafers as well as amorphous silicon thin films within 5 minutes under room temperature. The nanocone surface had lower than 5% reflection over the entire solar spectrum and a desirable omnidirectional absorption property. Using the nanotextured solar wafer, a 156mm ? 156mm 18.1%-efficient black silicon solar cell was fabricated, which was an 18.3% enhancement over the cell fabricated by standard industrial processes. This process also reduces silicon loss during the texturing step and enables tighter process control by creating more uniform surface structures. Considering all the above advantages, the demonstrated nanomanufacturing process can be readily translated into current industrial silicon solar cell fabrication lines to replace the costly and ineffective wet chemical texturing and antireflective coatings.

8974-50, Session 8

Antireflective glass surface patterned by rolling mask lithography

Boris Kobrin, Joseph Geddes III, Joseph Perez, Oliver Seitz, Jonathan Wassei, Ian McMackin, Rolith, Inc. (United States)

A growing number of commercial products such as; displays, solar photovoltaic surfaces, light emitting diodes (LED), even automotive and architectural glass are driving demand for glass with high performance surfaces that offer anti-reflective, self-cleaning, and other advanced functions. State-of-the-art coatings do not meet the desired performance characteristics and/or cannot be applied over large areas in a cost-effective manner. Replicating surface structures found in nature (e.g. moth eye, lotus leaf, and others) by nano-patterning has proven to achieve the desired optical performance. However, until recently, producing the required surface modifications over large areas (>300 mm) and at low cost has been problematic. Conventional photolithography is expensive and limited to standard wafer sizes. Developed by Rolith, Inc. RML is a photolithographic process where a resist-coated substrate is exposed by UV illumination transmitted through a cylindrical mask as it rolls across the substrate. “Rolling Mask Lithography” (RML), has the potential to provide high-resolution lithographic nano-patterning over large areas at low cost.

Rolith will report on significant improvements in the application of RML to production of anti-reflective surfaces. An optical surface can be made antireflective by texturing with a nano-scale pattern that reduces the discontinuity in the index of refraction between the air and the bulk optical material. An array of cones, similar to the Moth eye structure performs this way. Substrates were patterned using RMLTM and etched to produce arrays of cones with an aspect ratio of 3:1, resulting in a decrease in reflectivity from a previously obtained by authors 0.8% to ≤ 0.1%.

8974-51, Session 8

Emission-enhanced plasmonic substrates fabricated by nano-imprint lithography

Bongseok Choi, Masanobu Iwanaga, Hideki Miyazaki, Kazuaki Sakoda, Yoshimasa Sugimoto, National Institute for Materials Science (Japan)

We have fabricated well-designed plasmonic substrates for light-scattering enhancement such as SERS (surface enhanced Raman scattering), based on nano-imprint lithography.

The fabrication was conducted in excellent precision; the deviation between the quartz mold including pillars of 100 nm to 500 nm diameters and the transcript pattern on SOI substrates was suppressed within 1 nm.

The plasmonic substrates were obtained by metal deposition on the patterned SOI substrates, forming stacked complementary structure. We already reported that the plasmonic substrates have a series of well-defined plasmonic resonant modes. Recently, the plasmonic resonances have been experimentally found to be useful for enhancement of SERS signals, and are able to detect particular Raman band selectively. The feature is suitable for rapid screening in molecular sensing.

By the nano-imprint lithography, we produced the plasmonic substrates of 1 cm square dimension, making the substrates very practical for sensing application.

8974-52, Session 8

Thermal emitter performance as a function of lithographic quality

Adam M. Jones, College of Optical Sciences, The Univ. of Arizona (United States) and Sandia National Labs. (United States); Shanalyn A. Kemme, A. Robert Ellis, Sandia National Labs. (United States); Robert A. Norwood, College of Optical Sciences, The Univ. of Arizona (United States)

We explore the fabrication tolerance of a plasmonic structure designed to produce highly directional emission in the long wavelength infrared. The structure consists of an array of square posts suspended above a conducting ground plane in a metal-insulator-metal configuration. The emission wavelength, bandwidth, and efficiency of the array are dependent on the geometry of the posts thus resulting in a fabrication-critical device. We numerically evaluate the impact of the spatial frequency fidelity of the mask pattern printed in the resist material on device performance and relate the resulting performance data to lithographic tolerance in the fabrication process. We then compare the expected performance of several lithography techniques and discuss the suitability of each for fabricating structures of this nature. Specifically discussed are ebeam lithography, contact lithography, and projection lithography with additional information provided regarding defocus in the projection lithography system and the impact of reflective notching caused by the presence of the ground plane. Analyzing the device in this way enables intelligent estimation of the performance of the final product and enhances the probability of successfully fabricating a desired structure, which ultimately results in a reduction in resources required to develop a working prototype.

8974-53, Session 8

Wafer-level micro-structuring of glassy carbon

Loïc E. Hans, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Karin Prater, Cédric Kilchoer, Ecole Polytechnique Fédérale de Lausanne (EPFL) (Switzerland); Toralf Scharf, Hans Peter Herzig, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Andreas Hermerschmidt, HOLOEYE Photonics AG (Germany)

We introduce a process that achieves high-resolution micro-structures of glassy carbon to be used in the fabrication of diffractive optical structures. The approach is based on photolithography and reactive ion etching on four-inch wafers and is appropriated to mass production. The process includes steps such as spin coating of a 2.5 ?m-thick photoresist layer on the glassy carbon substrate, followed by vacuum contact UV-lithography. We apply reactive ion etching by mixing different gases (SF6 and O2). We observed that adding SF6 provides a smooth surface and avoids micro-masking effects, which is essential to realize high-quality optical diffractive elements. We determine the etch rate of glassy carbon as a function of the ratio between the gases. For acceptable surface quality, a selectivity of 5:1 is obtained at a typical glassy carbon etch rate of 110 nm/min. On the wafer, we realized diffractive structures with a lateral feature size of 5 ?m and a depth of a few hundred nanometers on surfaces from 5 to 18 mm diameter. The fabricated binary gratings can be used for applications such as beam-splitting. We characterize the sample with phase shifting interferometry and scanning electron microscopy. The measured rms roughness is less than 20 nm.

Glassy carbon has interesting properties such as high thermal conductivity, surface inertness and significant hardness. These properties make it an ideal candidate to be used as a master for replication, especially for molding in glass with high glass transition temperature, such as fused silica.

8974-54, Session 9

Integrated design and nanofabrication of genetically engineered subwavelength optical nanostructures and metamaterials *(Invited Paper)*

Theresa S. Mayer, Lan Lin, Seokho Yun, Zhihao Zhang, Jeremy A. Bossard, Douglas H. Werner, The Pennsylvania State Univ. (United States)

Heterogeneous integration of dissimilar materials into 2 and 3-dimensional subwavelength nanostructures provides new opportunities to realize advanced materials and devices with unique optical properties. For example, multilayer optical metamaterials can be engineered to have customized refractive index, absorption, and broadband dispersion. Single-layer dielectric coatings can provide wavelength-specific reflection and transmission response. Constituent materials with tunable dispersion can be integrated to create reconfigurable optical components. This presentation will provide an overview of a versatile and highly integrated design and nanofabrication approach that has been used to create subwavelength nanostructures that are engineered to meet performance targets required for future optical devices or systems. The approach combines robust nature-inspired optimization with full-wave electromagnetic simulation to adaptively search a large parameter space and find nanostructure geometries that most closely satisfy the performance targets, while also meeting specified top-down nanofabrication design rules and incorporating measured dispersion properties of each constituent material. Nanofabrication process flows and design rules will be described for several different metallo-dielectric and all-dielectric nanostructures, including wavelength-selective mirrors, zero-index metamaterials, multiband and broadband absorbers. The measured optical properties of the nanofabricated devices will be compared to the theoretically predicted response, with a focus on optical property uniformity over large cm-scale device areas. The presentation will conclude with a perspective on the future outlook for high-throughput manufacturing of subwavelength nanostructures on planar and curved substrates.

8974-56, Session 9

Optomechanical cantilever device for displacement sensing and variable attenuator

Peter A. Cooper, Chris Holmes, Lewis G. Carpenter, Paolo L. Mennea, James C. Gates, Peter G. R. Smith, Univ. of Southampton (United Kingdom)

An optomechanical dual cantilever device has been fabricated with applications as a displacement sensor and variable attenuator. The device is based on silica glass waveguides on a silicon substrate. A novel fabrication approach using a precision dicing saw is used, which has benefits in terms of cost, fabrication time and energy consumption compared to cleanroom based lithography techniques. The silica cantilevers contain integrated optical waveguides and Bragg gratings fabricated using a Direct UV Writing process. The cantilevers are deflected out of plane by thin film stress effects, providing a suitable geometry for use in sensing. Displacement causes both cantilevers to move simultaneously resulting in variable coupling due to the angular alignment of the waveguide modes. Using a developed ratiometric approach based on fitting to Gaussian apodized Bragg gratings, the measured displacement is independent of fluctuations in light source power as well as insensitive to detector noise. The device is optically interrogated at a wavelength band around 1550nm. As a sensor the device has a sensitivity of 0.8 dB/micron and can be accurately modelled using fiber optic coupling misalignment theory. When operating as an attenuator, a suppression ratio of over 25dB can be obtained. If combined with integrated optical components such as X-couplers, multiple double cantilever arrays can be placed on the same chip for distributed sensing. As the device is purely electromechanical, it is uneffected by EM noise. We will report detailed fabrication procedures as well as optical characterization of the device, including the performance metrics of the displacement sensor.

8974-57, Session 9

Application of rigorously optimized phase masks for the fabrication of binary and blazed gratings with diffractive proximity lithography

Lorenz Stürzebecher, Friedrich-Schiller-Univ. Jena (Germany); Frank Fuchs, Torsten Harzendorf, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Stefan Meyer, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Uwe D. Zeitner, Friedrich-Schiller-Univ. Jena (Germany)

Gratings with binary and blazed profiles and periods in the low micron and sub-micron range define a class of microstructures with a huge application potential. We present a mask based photolithographic fabrication method for these demanding grating geometries. It combines the advantages of electron beam lithography and holographic exposure, which are superior homogeneity, high resolution and pattern flexibility on one hand, and a fast, large aerial exposure with the option for smooth profiles on the other hand. This is accomplished by the use of an electron beam written phase mask which contains a very homogeneous pattern of small diffractive features and is used for a full-field exposure in a proximity mask aligner. The key for the beneficial use of the technology is the proper design of the phase mask surface profile which can have a binary or multilevel geometry. Since the patterns to be exposed are periodic, this is also the case for the phase mask which allows calculating their physical light transmission with exact methods like rigorous coupled wave analysis. An optimization algorithm has been developed which can find mask geometries that synthesize a desired complex aerial image in the proximity distance of choice. Aerial images offering e.g. high resolution features, phase shifts, and tilted propagation directions can be realized that way. This technology has been successfully used to fabricate e.g. binary gratings of very high quality with a period of 800 nm as well as blazed gratings with a period of 3 µm.

8974-58, Session 9

Mode-splitting of a non-polarizing guided mode resonance filter by substrate overetching effect

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

We investigate substrate overetch effect on resonance properties of sub-wavelength titanium oxide (TiO_2) Guided Mode Resonance Filters (TiO_2-GMRFs). The TiO_2-GMRF is designed and fabricated to possess non-polarizing behavior which is strongly dependent on fused silica (FS) substrate overetch depth. The non-polarizing behavior very often deviates due to inaccurate etching depth profiles owing to different surface chemistries of etchants and complicated processes involved. At resonance, both TE- and TM-modes have same propagation constants that led to the same geometrical parameters of the grating, however, taking into account an overetch substrate effect results in a degeneration of both modes. Such an effect of substrate overetch on degeneracy of both modes are studied theoretically and experimentally. The TiO_2-GMRFs are designed by Fourier Modal method (FMM) based on rigorous calculation of electromagnetic diffraction theory at a designed wavelength of 850 nm. The TiO_2-GMRFs are fabricated by Atomic Layer Deposition (ALD), Electron Beam Lithography (EBL), and Reactive

ion Etching (RIE) that are subsequently characterized structurally by Scanning Electron Microscopy (SEM). The optical characterization of TiO_2-GMRFs is studied by a spectroscopic ellipsometer. Several TiO_2-GMRFs on FS substrate are fabricated by gradually increasing the overetch depth and measuring the performance in terms of extent of TE- and TM-mode-splitting. A close agreement between the calculated and experimentally measured resonance wavelength spectral shift is obtained, however, the magnitudes of measured spectral shifts are greater than theoretically calculated ones. Furthermore, all the TiO_2-GMRFs are heat treated at 350 °C for 7 hours to change the phase of TiO_2 material from amorphous to crystalline (anatase) and remeasure the optical spectra of all under studied samples. The TiO_2-GMRFs do not reveal significant spectral changes after the heat treatment process; this may be attributed to a change in the surface chemistry by the redeposition of the reaction by-products on the grating lines.

Conference 8975: Reliability, Packaging, Testing, and Characterization of MOEMS/MEMS, Nanodevices, and Nanomaterials XIII

Monday - Tuesday 3 –4 February 2014

Part of Proceedings of SPIE Vol. 8975 Reliability, Packaging, Testing, and Characterization of MOEMS/MEMS, Nanodevices, and Nanomaterials XIII

8975-101, Session PLEN

Electrostatic nano electromechanical switches (NEMS) for energy-efficient digital systems

Roger T. Howe, Stanford Univ. (United States)

Micro- and nano-fabricated sensors and actuators have become commonplace in recent years and have transformed the interfaces between the physical world and the Internet. Nano electromechanical switches (NEMS), by contrast, are intended for augmenting the performance of digital systems at the core of information technology. This talk will summarize recent research in NEMS, with a focus on designs using electrostatic actuation. At Stanford, we have developed processes for fabricating lateral (in-plane) electrostatically actuated multi-terminal switches above CMOS. Given the performance characteristics of NEMS, we identified a promising system application—implementing the programmable routing in field-programmable gate arrays (FPGAs). I will review the fabrication challenges, contact phenomena, and scaling of lateral NEMS, as well as their micro-encapsulation and potential applications in sensing systems.

8975-1, Session 1

Development of wireless, battery-free microgyscope based on one-port SAW delay lines and double resonant antenna *(Invited Paper)*

Kee-Keun Lee, Ajou Univ. (Korea, Republic of)

Wireless, battery-free gyroscope was developed by employing a one-port surface acoustic wave (SAW) reflective delay line, a SAW resonator, and an antenna. Two SAW devices with different center frequencies were simultaneously activated by one antenna with double resonant frequencies. At a wireless testing, the developed gyroscope showed clear reflection peaks with high S/N ratio in both time and frequency domain. On rotation of the device, large shifts of the reflection peaks were observed due to a secondary wave interference effect caused by Coriolis force depending on the spinning rate. The measured sensitivity and linearity of the gyroscope were 1.35 deg/(deg/s) and 0.99, which are the promising values for our target applications. The temperature and vibration/shock effects, multi-axis measurements, sensor's hermetic sealing effects were also characterized.

8975-2, Session 1

Design and fabrication of net flux radiometers for Mars exploration

Linh Ngo Phong, Canadian Space Agency (Canada); Christian Proulx, François Châteauneuf, INO (Canada)

We report on the design and fabrication of an experimental net flux radiometer as part of a wireless network of meteorological sensors for the acquisition of surface data of Mars. The radiometer makes use of four separate detectors to measure simultaneously: (i) global solar radiation; (ii) ground reflected solar radiation; (iii) sky emitted infrared radiation; and (iv) ground emitted infrared radiation. To perform measurements in the broad spectral range from 0.2 to 42 um, goldblack coated microbolometric detectors of 100 um pitch were fabricated for use in custom packaged pyranometers and pyrgeometers. Each detector was placed at the center of an optically coated dome which acted as a bandpass filter and provided a directional response close to the cosine characteristics. The ability to modify the pyrgeometer field of view was further achieved by incorporating a baffle into the dome. The output signal from each detector was integrated and digitized to 18 bits using dedicated readout electronics. For field measurements, the net flux radiometer was integrated into a sensor node structure together with a power and wireless communication unit. The typical responsivity and response time of the detector were measured to be respectively 400 kV/W and 50 ms. Under certain conditions, the radiometer exhibited a resolution better than 0.1 W/m2. The effects of the operating parameters and the instrument signatures are presented and discussed.

8975-3, Session 1

Low spring index, large displacement shape memory alloy (SMA) coil actuators for use in macro- and micro-systems *(Invited Paper)*

Brad Holschuh, Dava Newman, Massachusetts Institute of Technology (United States)

Shape memory alloys (SMA) offer unique shape changing characteristics that can be exploited to produce low-mass, low-bulk, large-stroke actuators. We are investigating the use of low spring index (defined as the ratio of coil diameter to wire diameter) SMA coils for use as actuators in morphing aerospace systems. Specifically, we describe the development and characterization of minimum achievable spring index coiled actuators made from 0.3048 mm (0.012") diameter shape memory alloy (SMA) wire for integration in textile architectures for future compression space suit applications. Production and shape setting of the coiled actuators, as well as experimental test methods, are described. Force, length and voltage relationships for multiple coil actuators are reported and discussed. The actuators exhibit a highly linear ($R2 > 0.99$) relationship between isometric blocking force and coil displacement (isometric test length - fully coiled length), which is consistent with current SMA coil models; and SMA coil actuators demonstrate the ability to produce significant linear forces (i.e., greater than 8N per coil) at strains up to 3x their initial (i.e., fully coiled) length. Discussions of both the potential use of these actuators in future compression space suit designs, and the broader viability of these actuators in both macro- and micro-systems, are presented.

8975-4, Session 1

MEMS tactile display: from fabrication to characterization *(Invited Paper)*

Norihisa Miki, Keio Univ. (Japan) and Japan Science and Technology Agency (Japan); Yumi Kosemura, Hiroaki Ishikawa, Junpei Watanabe, Keio Univ. (Japan)

We report fabrication and characterization of MEMS-based tactile display that can display users various tactile information, such as Braille codes and surface textures. The display consists of 9 micro-actuators that are

equipped with hydraulic displacement amplification mechanism (HDAM). We developed a liquid encapsulation process, which we termed as Bonding-in-Liquid Technique (BiLT), to manufacture the HDAM. HDAM encapsulates incompressible glycerin in a cavity that has different opening areas between the top and the bottom with largely deformable polymer membranes. In BiLT, the membrane was bonded to the cavity with a UV-curable resin in glycerin, which prevented interfusion of air bubbles and deformation of the membrane during the bonding. HDAM successfully amplified the displacement generated by piezoelectric actuators by a factor of 6. The micro-actuators were characterized and were verified to satisfy the required specifications for the tactile display, i.e., the actuators could successfully stimulate the tactile receptors in our fingertips. The display achieved a vibrational Braille code display, which required lower voltage to display the codes to users than a static one. It could also virtually produce "rough" and "smooth" surfaces, by controlling the vibration frequency, displacement, and the actuation periods of an actuator until the adjacent actuator was driven. However, even when these parameters are identical, the display does not necessarily provide same tactile feeling to different users. Therefore, we introduced a sample comparison method to characterize the system that involves the users. First, we prepared samples whose mechanical properties are known. We displayed a surface texture to the user by controlling the parameters and then, the user selects a sample that has the most similar surface texture. By doing so, we can correlate the parameters with the mechanical properties of the sample as well as can find the sets of the parameters that can provide similar tactile information to many users. The preliminary results with respect to roughness and hardness will be presented.

8975-6, Session 2

Characterization of gallium nitride microsystems within radiation and high-temperature environments

Heather Chiamori, Minmin Hou, Caitlin A Chapin, Ashwin Shankar, Debbie G Senesky, Stanford Univ. (United States)

Gallium nitride (GaN) is a ceramic, semiconductor material that is stable within high-radiation, hightemperature and chemically corrosive environments. In this presentation, a review of the advancements in GaN manufacturing technology such as the growth of epitaxially deposited thin films, micromachining techniques, nanostructure synthesis and high-temperature metallization is presented. In addition, the compelling results of fabricating and operating micro-scale GaN-based sensors and electronics within radiation environments and elevated temperatures are shown. The presentation will close with future directions GaN-based microsystems technology for propulsion, space exploration and military applications.

8975-7, Session 2

Submicorradian deflection and stress metrology for fabrication of MEMS and optoelectronic structures

Peter Walecki, Sunrise Optical LLC (United States)

We report two approaches to measurement of wafer stress and curvature: long arm scanner and modified auto-collimator design.

In the long arm scanner configuration, the laser beam is impinging measured surface and its deflection is measured using 2D sensor. The analysis of deflected beam provides the deflection angle, and allows us to find normal vector to the surface with micro-radian accuracy. The scanning measurement yield field of normals to the surface, and allows reconstruction of the entire surface. Similar commercial tools measure only radial component.

In case of semiconductor stressed wafers we show results where application of generalized Stoney equation is used to calculate all lateral stress tensor components, unlike most commercial tools which provide only scalar value.

Finally we present results of measurements using new small (1.5 kg and (LxWxH) 200 mm x 100 mm x 75 mm) proprietary electro-optic auto-collimator probe providing the sub-micron reproducibility of the measured deflection.

8975-8, Session 2

Improved test setup for MEMS mechanical strength investigations and fabrication process qualification

Tobias Bandi, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland); Xavier Maeder, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland); Alex Dommann, EMPA (Switzerland); Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Antonia Neels, Ctr. Suisse d'Electronique et de Microtechnique SA (Switzerland)

Microfabrication using single crystal silicon allows for a unique combination of high material quality, low material density, high Young's Modulus and resistance to fatigue accessible to a wide range of mechanical applications and a broad range of geometries. However, the quality of the crystal in a finished MEMS device is influenced by the fabrication processes, especially DRIE and dicing, which leave characteristic damage (defects, cracks, dislocations…) in the material and affect the mechanical stability. Specially designed mechanical tests can be used to assess the resistance of micro-structures to monotonic and cyclic loading. By characterization of the failure distributions, micromechanical tests support the qualification and optimization of fabrication and die separation processes.

We report on the development progress of a micromechanical test bench for reliability assessment of microstructures. The instrument induces a displacement-controlled deformation in 4-point, 3-point and 2-point bending as well as tensile testing geometries and custom-made chucks for testing of specific specimen geometries. This allows quantifying the failure distribution in test structures and functional devices. Moreover the versatility of the mechanical test setup allows reproducing the strain conditions and sample properties, size, volume-to-surface area and fabrication processes as close as possible. In-situ testing in combination with high-resolution x-ray diffraction measurements was used to investigate strain distributions and defects in micron-sized silicon devices. The advantages and limitations of the test geometries and the analytical models of the strain distribution and the failure probability are discussed, illustrated with examples.

8975-9, Session 2

Investigation of a novel approach for the cross-linking characterization of SU-8 photoresist materials by means of optical dispersion measurements

Christopher Taudt, Tobias Baselt, Westsächsische Hochschule Zwickau (Germany); Edmund Koch, Technische Univ. Dresden (Germany); Peter Hartmann, Westsächsische Hochschule Zwickau (Germany)

The increase in efficiency and precision in the production of semiconductor structures under the use of polymeric materials like SU-8 is a crucial point to secure the technological innovation within this industry. The manufacturing of structures on wafers demands high quality of materials, tools and production processes. In particular, deviations in the materials parameters (e.g. cross-linking state, density or mechanical properties) will lead to subsequent problems like a reduced lifetime of structures and systems. Especially problems during the soft and post-exposure bake process can lead to an inhomogeneous distribution of material properties.

This paper describes a novel approach for the characterization of SU-8 material properties before and after crosslinking based on the measurement of optical dispersion within the material. Therefore a white-light interferometer was implemented. In particular the setup consists of a supercontinuum white-light source, a Michelson-type interferometer and a spectrometer. The investigation of the dispersion characteristics is carried out by the detection of the equalization wavelengths for different temporal states in a range from 400 to 1000 nm. The measured time delay due to dispersion ranges from 3.3 to 6.8ps/mm.

For evaluation purposes SU-8 bulk material was characterized in the described setup regarding its dispersion characteristics. Furthermore a modified laboratory setup could be implemented where the measurement of on-wafer SU-8 layers is possible. Using this setup a space resolved dispersion measurement of a wafer was achieved.

The novel measurement approach allows a fast and high-resolution material characterisation for SU-8 microstructures which is suited to be integrated in production lines.

8975-10, Session 2

Measuring Young's modulus using a self-mixing laser diode

Ke Lin, Yanguang Yu, Jiangtao Xi, Yuanlong Fan, Huijun Li, Univ. of Wollongong (Australia)

Young's modulus is a useful quantity for proper evaluation of mechanical properties in materials. The Young's modulus for a specific material can be obtained by retrieving the resonant frequency from the vibration of the material excited by the external forces. In this paper, we present a novel approach for determining the Young's modulus by using a self-mixing laser diode (SMLD). The SMLD system is a new emerging sensing technology which can be used for metrological measurement, including vibration measurement. The SMLD system can achieve high measurement accuracy with an extremely simple and inexpensive set-up, thus can be directly proposed for the determination of Young's modulus. In order to accurately determinate the Young's modulus, this work builds an SMLD based vibration sensing system which consists of a LD, a micro-lens and an external target. With a small portion of light backscattered or reflected by the target reentering the LD inside cavity, both the amplitude and frequency of the LD power are modulated. This modulated LD power is referred as a self-mixing signal (SMS) which is detected by the photodiode (PD) packaged in the rear of the LD. The external target is the tested sample which is in damping vibration excited by a singular elastic strike with an impulse tool. The vibration information from the tested sample is carried in the SMS. Advanced data processing in frequency-domain is applied on the SMS, from which the resonant frequency of the vibration can be retrieved, and hence Young's modulus is calculated. The proposed method has been verified by both simulation and experiments.

8975-11, Session 2

Wafer-level radiometric performance testing of uncooled microbolometer arrays

Denis G. Dufour, Patrice Topart, Bruno Tremblay, Christian Julien, Louis Martin, Carl Vachon, INO (Canada)

This paper reports on a turn-key semi-automated test system to perform on-wafer testing under vacuum of microbolometer arrays. The system allows for testing of several performance characteristics of ROIC-fabricated microbolometer arrays including NETD, SiTF, ROIC functionality, noise and FPA operability, both before and after microbolometer fabrication. The system can also be used to perform semi-automated on-wafer measurements of microbolometer test structures, to evaluate responsivity, response time and thermal conductance. The system accepts wafers up to 8 inches in diameter and performs automated wafer die mapping using a microscope camera. Once wafer mapping is completed, a custom-designed quick insertion 8-12 µm AR-coated germanium viewport is placed and the chamber is pumped down to below 1X10-5 Torr, allowing for a direct comparison to package level NETD performances. The probe card is electrically connected to an INO IRXCAM camera core, a versatile system that can be adapted to many types of ROICs using custom-built interface PCBs. We currently have the capability for testing 384x288, 35 µm pixel size and 160x120, 52 µm pixel size FPAs. For accurate NETD measurements, the system is designed to provide an F/1 field-of-view of two rail-mounted blackbodies as viewed through the germanium window by the die under test. A master control computer automates the alignment of the probe card to the dies, the positioning of the blackbodies, image acquisition using IRXCAM, as well as data analysis and storage. NETD and microbolometer pixel performance measurement precision was validated using dies measured by the automated probing system that were then packaged and re-measured using our standard, calibrated radiometric test-bench systems.

8975-25, Session 2

Measurements of thermal conductivity of La0.95Sr0.05CoO3 nanofibers using MEMS devices

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Thermoelectric oxide nanofibers prepared by electrospinning are expected to have reduced thermal conductivity when compared to bulk samples. Measurements of nanofibers' thermal conductivity is challenging since it involves sophisticated sample preparation methods. In this work, we present a novel method suitable for measurements of thermal conductivity of a single nanofiber. A microelectro-mechanical (MEMS) device has been designed and fabricated to perform thermal conductivity measurements on a single nanofiber. A special Si template was designed to collect and transfer individual nanofibers onto a MEMS device. Pt was deposited by Focused Ion Beam to reduce the effective length of a prepared nanofiber. A La0.95Sr0.05CoO3 nanofiber with a diameter of 140 nm was studied and characterized using this approach. The measured thermal conductivity of a nanofiber was determined to be 0.7 W/m•K, which is 23% of the value reported for bulk La0.95Sr0.05CoO3 samples.

8975-13, Session 3

Heterogeneous MEMS device assembly and integration

Patrice Topart, Francis Picard, INO (Canada); Samir Ilias, INO (Canada) and INO (Canada); Christine Alain, Claude Chevalier, Bruno Fisette, Jacques Paultre, Francis Généreux, Mathieu Legros, INO (Canada); Jean-F Lepage, Christian Laverdière, RDDC (Canada); Lin Phong, CSA (Canada); Jean-sol Caron, Yan Desroches, INO (Canada)

In recent years, smart phone applications have both raised the pressure

for cost and time to market reduction, and the need for high performance MEMS devices. This trend has led the MEMS community to develop multi-die packaging of different functionalities or multi-technology (i.e. wafer) approaches to fabricate and assemble devices respectively. This paper reports on the fabrication, assembly and packaging at INO of various MEMS devices using heterogeneous assembly at chip and package-level. First, the performance of a giant (e.g. about 3 mm in diameter), electrostatically actuated beam steering mirror is presented. It can be rotated about two perpendicular axes to steer an optical beam within an angular cone of about 60° with an angular resolution of 1 mrad and a response time of 300 ms. To achieve such angular performance relative to mirror size, the microassembly was performed from sub-components fabricated from 4 different wafers. To combine infrared detection with inertial sensing, an electroplated proof mass was flip-chipped onto a 256x1 pixel uncooled bolometric FPA and released using laser ablation. In addition to the micro-assembly technology, initial performance results of packaged devices will be presented. To realize a broadband radiometer from wavelengths of 0.25 to 50 ?m for the ESA earthcare satellite, the hybrid integration of a VOx based-uncooled bolometric detector with a CMOS read-out was employed. The assembly process will be presented. Finally, to simulate a 3072 pixel uncooled detector for cloud and fire imaging in mid and long-wave IR, the staggered assembly of six 512x3 pixel FPAs with a 50 micron alignment precision will be reported.

8975-14, Session 3

Contact resistance evolution of lightly loaded, highly cycled, micro-contacts

Christopher Stilson, Ronald A. Coutu Jr., Air Force Institute of Technology (United States)

Reliable microelectromechanical systems (MEMS) switches are critical for developing high performance radio frequency circuits like phase shifters. Engineers have attempted to improve reliability and lifecycle performance using novel contact metals, unique mechanical designs and packaging. Various test fixtures including: MEMS devices, atomic force microscopes (AFM) and nanoindentors have been used to collect resistance and contact force data. AFM and nanoindentor test fixtures allow direct contact force measurements but are severely limited by low resonance sensors, and therefore low data collection rates.

This paper reports the contact resistance evolution results and fabrication of thin film, sputtered and evaporated gold, micro-contacts dynamically tested up to 3kHz. The upper contact support structure consists of a gold surface micromachined, fix-fix beam designed with sufficient restoring force to overcome adhesion. The hemisphere-upper and planar-lower contacts are mated with a calibrated, external load resulting in approximately 100µN's of contact force and are cycled in excess of 106 times or until failure. Contact resistance is measured, in-situ, using a cross-bar configuration and the entire apparatus is isolated from external vibration and housed in an enclosure to minimize contamination due to ambient environment. Additionally, contact cycling and data collection are automated using a computer and LabVIEW.

8975-15, Session 3

Combined dielectric spectroscopy and laser-induced photocurrent approach to study the degradation of organic solar cells

Olena Kozlova, Siegfried G. Bauer, Markus C. Sharber, Reinhard Schwödiauer, Matthew White, Thomas Stokinger, Johannes Kepler Univ. Linz (Austria)

Solar energy becomes increasingly popular as a clean source of renewable energy. While organic electronics offers new solutions for photovoltaics, stability of organic solar cells is still a key issue preventing them from entering large-scale markets. In this work we address the degradation of organic solar cells using impedance spectroscopy and current voltage (I-V) measurements. Local degradation is investigated employing the laser-beam-induced current (LBIC) technique. Impedance spectroscopy measures the dielectric characteristics of solar cells and gives access to such important physical parameters as charge carrier concentrations and mobility. I-V curves allow for the overall estimation of the efficiency and the fill factor of solar cells. The LBIC method consists of irradiation of a solar cell with a focused laser beam and consequential measurement of the light-induced current. LBIC allows for discovering defects and regions of high and low efficiency, and also the monitoring of degradation processes by observing the evolution of these regions. By combining the three methods it is possible to look at organic solar cell degradation from different points and follow different aspects: analysis of the impedance measurements allows for a better understanding of the chemical processes taking place in the solar cells, I-V characterizations give an idea about the overall evolution of the solar cell performance and LBIC locates regions where degradation starts. In particular we pay attention to reversible and irreversible degradation processes. We study and compare several P3HT:PCBM solar cells to understand the reasons and speed of degradation. Work partially supported by ESTABLIS.

8975-16, Session 3

Studies on the dynamics of vacuum encapsulated 2D MEMS scanners by laser Doppler vibrometry

Joachim Janes, Ulrich Hofmann, Fraunhofer-Institut für Siliziumtechnologie (Germany)

2D MEMS scanners are used for e.g. Laser projection purposes or Lidar applications. Electrostatically driven resonant torsion oscillations of both axes of the scanners lead to Lissajous trajectories for Laser beams reflected from the micro mirror. Wafer level vacuum encapsulation with tilt glass capping ensures high angular amplitudes at low driving voltages additionally preventing environmental impacts. Applying Laser Doppler Vibrometry, the effect of residual gas friction, squeezed film damping and internal friction on 2D MEMS scanners is analyzed by measuring the Q-values associated with the torsion oscillations. Vibrometry is also used to analyze the oscillatory motion of the micro mirror and the gimbal of the scanners. Excited modes of the scanner structures are identified giving rise to coupling effects influencing the scanning performance of the 2D MEMS mirrors.

8975-17, Session 3

Evaluation of silicon tuning-fork resonators under space-relevant radiation conditions

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Hermetic packaging is essential for many microelectromechanical systems (MEMS), establishing a suitable and stable atmosphere inside the cavity. Constant pressure levels ensure optimum damping of moving structures and extend lifetime by hindering degradation caused by ingress of humidity and contaminants. However, the duration over which stable conditions can be maintained is limited by leakage, diffusion through materials, and by outgassing. The qualification of the packaging method is challenging for microsystems because the acceptable leak rate decreases with the size of the cavity. In this work we report on the

pressure dependency of damping in silicon tuning fork resonators used for leak rate assessment in MEMS packages. The resonators operate at 150 kHz and possess Q-factors in the range of 1000 to 20000. The pressure-sensitivity of the resonators has been characterized by measurements of the resonance frequency and the quality factor in dependence of the air pressure in the range of 10^(-2) mbar to 1 bar. Over the full pressure range the results match very well with theoretical models of air-damping in MEMS micro-resonators which were adapted to account for the tuning fork geometry. Besides the application as pressure-sensors in MEMS cavities, silicon based tuning fork resonators are also candidates for time-keeping and electronic filter applications. Therefore the detailed understanding of the air-damping to assess the performance under specific pressure conditions is essential.

8975-18, Session 3

HALT to qualify electronic packages: a proof of concept

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Explored a proof of concept of Highly Accelerated Life Testing (HALT) technique to assess and optimize electronic packaging designs for long duration deep space missions in a wide temperature range (–150oC to +125oC). HALT is a custom hybrid package suite of testing techniques, such as extreme temperatures varies from -160oC to +200oC and dynamic shock step processing 0g and up to 50g acceleration. HALT testing used in this study implemented repetitive multiple-axis vibration on the test vehicle components to precipitate workmanship defects rapidly and/or manufacturing defects combines with thermal cycling related weak links of the designs. This study is to reduce the product development cycle time for improvements to the packaging design qualification. A test vehicle has been built using advanced electronic package designs and surface mount technology processes which are considered useful for a variety of JPL and NASA projects. For the first time, We have explored a proof of concept of Highly Accelerated Life Testing (HALT) technique to assess and optimize packaging designs for long duration deep space missions in a wide temperature range (–150oC to +125oC). The HALT technique has been explored to predict reliability, failure mechanism and survivability of selected advanced packages (surface mount packages such as ball grid arrays (BGA), plastic ball grid arrays (PBGA), very thin chip array ball grid array (CVBGA), quad flat-pack (QFP), microleadframe (MLF) packages, several passive components, etc.) for long duration deep space missions in a shorter test duration.

Test articles were built using advanced electronic package designs that are considered useful in various NASA projects. All the advanced electronic packages are daisy-chained independently to monitor the continuity of the individual electronic packages. Continuity of the daisy chain packages was monitored during the HALT testing using a special data logging system put together for this study. We were able to test the boards to up to 50g shock levels and temperatures of +125oC to -150oC. The HALT system can deliver 50g shock levels at room temperature, but the highest g levels are lower than it can deliver especially at the hot and cold temperatures extremes tested. Several tests were performed by subjecting the test boards to various g levels, test durations, and the hot and cold temperature levels. Several packages have shown the signs of continuity problems. These packages include plastic ball grid array, ball grid array, micro-lead-frame (MLF), quad flat packs which have shown the sign of failures. PBGA package was completely open where as others have shown the signs of continuity variations. The failure of PBGA has occurred within 10 hours of normalized accelerated test duration. The PBGA package has failed during the thermal cycling of -185oC to +125oC after 711 thermal cycles (or 959 cycles of -150oC to +125oC, extrapolated from the test data using Coffin-Manson relationship). Each thermal cycle took around 2.33 hours and a total test time to fail PBGA is 2237 hours (or ~3.1 months) due to thermal cycling alone. Accelerated technique required only 12 hours to fail which indicates that there is an acceleration of ~186 times (more than 2 orders of magnitude) to fail the same PBGA component if it were tested independently. This acceleration process will save significant time and resources to predict the life of the component in a given environment. In summary, one can determine the life of the PBGA component in less than 12 hours of testing instead testing for 3.1 months. Further studies are in progress

to make systematic study of various components, constant temperature range for both the tests. Therefore, one can estimate the number of hours to fail in a given thermal and shock levels for a given test board physical properties.

8975-5, Session 4

Electrothermally tunable MEMS filters

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MEMS resonators have potential application in the area of frequency selective devices (e.g., gyroscopes, mass sensors, etc.). In this work, design of electro thermally tunable resonators is presented. SOIMUMPS process is used to fabricate resonators with springs (beams) and a central mass that can be electrically tuned. When voltage is applied, resistance of the springs increases due to degradation in mobility because of Joule heating. Mechanically, the spring starts softening and therefore the resonant frequency decreases. So for a given structure, one can set the exact resonant frequency by changing the applied voltage. Coupled thermal effects result in non-uniform heating. It is observed from measurements and simulations that some parts of the beam become very hot and therefore soften more. Consequently, at higher voltages, the structure (equivalent to a single resonator) behaves like coupled resonators and exhibits peak splitting. In this mode, the given resonator can be used as a band rejection filter. This process is reversible and repeatable. Comprehensive FEM simulations are carried out integrating the electrical and thermal models. For the designed structure, it is experimentally shown that by varying the voltage from 1 to 16V, the resonant frequency could be changed by 28%.

8975-19, Session 4

The mechanical properties and stabilities of pristine, and hydrogenated and fluorinated silicine under tension

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A first principles study has been performed to systematically evaluate the mechanical properties and stabilities of pristine, hydrogenated and fluorinated silicene (H-silicane and F-silicane) under tension. The uniaxial tension in the armchair (AC) and zigzag (ZZ) direction and the biaxial tensile strain are considered. The calculated results have shown that the deformation, failure behavior and the ultimate strength are anisotropic. The hydrogenation and fluorination reduces the ultimate strengths in all tree deformed directions. Nevertheless, the ultimate strain was increased after hydrogenation and fluorination. Therefore, the hydrogenation and fluorination increase the toughness. The phonon calculations based on the finite differences method confirm stabilities of the silicene, H- and F-silicane. The Poisson ratios of three materials in the armchair and zigzag directions all exhibit monotone decreasing changes with increasing strain, except that the Poisson ration of pristine silicene in the zigzag direction increases with increasing strain. The tensile strains decrease the important parameter that is buckling height, as expected, but in a complex function. The second- and third-order elastic constants are determined by least-squares fit to the first principles calculations. Our results can help to understand the effect of hydrogenation and fluorination of silicene on its mechanical properties and provide some useful data for the experiments.

8975-20, Session 4

Effective data processing in the frequency-domain based self-mixing approach for measuring alpha factor

Yan Gao, Yanguang Yu, Ke Lin, Jiangtao Xi, Univ. of Wollongong (Australia)

The Alpha factor, also known as the linewidth enhancement factor, is one of the fundamental parameters for semiconductor lasers (SLs) as it characterizes many properties of the SLs, such as the responses to the electrical injection and the optical injection. Due to the great importance of alpha factor in research analysis and application design, the high accuracy of the experimental alpha measurement is required. The optical feedback self-mixing interferometry (OFSMI) based method for the alpha measurement is one of the popular approaches in the past twenty years due to its easy implementation and inexpensive, self-aligned experiment set-up. This paper proposes an effective data processing method applied in the frequency-domain based self-mixing approach for alpha factor measurement. The alpha value is estimated from the complex frequency spectrum of the feedback phase signal in an OFSMI system. However, some of the estimated results with large deviation are found in the experimental estimation due to the noises in practice. The work presented in the paper is twofold. Firstly, the errors of alpha estimation are analyzed. Secondly, the algorithm using distance-based outlier removal is proposed for optimizing the estimation results of alpha. The results show that the estimation accuracy of alpha can be achieved to 0.67% and 0.73% for the optical feedback level in the OFSMI system.

8975-21, Session 4

Optical properties of plasmonic nanoantenna arrays based on H-shaped nanoparticles with extended arms

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In this study, we present the optical properties of a plasmonic nanoantenna array based on H-shaped gold nanoparticles with extended arms, which can be used for infrared detection applications. Plasmonic nanoantennas operating at the infrared and visible region provide an unique way to capture, control and manipulate light at the nanoscale through the excitation of collective electron oscillations known as surface plasmons [1,2]. The unit cell of proposed antenna consists of one H-shaped nanostructure and two extended arms located on the lateral sides of this nanostructure. We will demonstrate the proposed antenna has a dual band spectral response and the locations of the resonance frequencies can be adjusted by changing the geometrical dimensions of both the H-shaped nanoparticles and the extended arms. Theoretical calculations of the reflectance spectra of the nanoantenna array are performed by using simulation software, which utilizes Finite Difference Time Domain (FDTD) method [3]. The results of the simulations state that the first-order mode comes from the H-shaped particle and the second order mode originates from the extended arms. In order to show the sensing capacity of the structure, the effect of the dielectric medium on the resonance frequency is also determined. The results show that the proposed antenna can be utilized for infrared sensing applications.

References:

1. F. Wang and Y. R. Shen, "General properties of local plasmons in metal nanostructures," Phys. Rev. Let., Vol. 97, 206806, 2006.

2. A. Haes and R. P. Van Duyne, "A unified view of propagating and localized surface plasmon resonance biosensors", Anal. Bioanal. Chem., Vol. 379, 920, 2004.

3. Lumerical FDTD, www.lumerical.com, 2013.

8975-22, Session 4

A new release technique using methodologies for reliability in the fabrication process of MEMS devices

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MEMS parallel plates capacitor structures are widely used in microelectromechanical systems (MEMS) as sensors, actuators, mirrors and antennas, amongst many applications. In this paper, is taken account an evaluation through the deviation indicators using methodologies of the reliability in the fabrication process in two perspectives: the design of the MEMS structures, identifying, examining and determining the critical parts of the mechanical elements of design and evaluating yield improvement used in the fabrication process determining the thickness of the film, the combination of the materials and the deposition technique to achieve more movement (reducing stiction and adhesion), as well as, large range of capacitance produced by the effects of residual stress gradients. Finally, we present a novel release technique for MEMS devices with a high yield, simple and avoiding curdle, stiction and collapse effects.

8975-23, Session 4

Acoustic and optoelectronic nature and interfacial durability of modified CNT and GnP-PVDF composites with nano-structural control

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Nano- and hetero-structures of modified carbon nanotube (CNT) and Graphene nano Platelet (GnP) can control significantly piezoresistive and optoelectronic properties in Microelectromechanical Systems (MEMS) as acoustic actuators. Interfacial durability and electrical properties of modified CNT and GnP embedded in poly(vinylidene fluoride) (PVDF) nanocomposites were investigated for use in acoustic actuator applications. Modified GnP coated PVDF nanocomposite exhibited better electrical conductivity than neat and modified CNT due to the unique electrical nature of GnP. Modified GnP coating also exhibited good acoustical properties. Contact angle, surface energy, work of adhesion, and spreading coefficient measurements were contributed to explore the interfacial adhesion durability between neat CNT or plasma treated CNT and plasma treated PVDF. Acoustic actuation performance of modified GnP coated PVDF nanocomposites were investigated for different radii of curvature and different coating conditions, using a sound level meter. Modified GnP can be a more appropriate acoustic actuator than CNT cases because of improved electrical properties. Optimum radius of curvature and coating thickness was also obtained for the most appropriate sound pressure level (SPL) performance. This study can provide manufacturing parameters of transparent sound actuators with good quality practically.

8975-12, Session PTue

Quantitative thermal characterization of microelectronic devices by using CCD-based thermoreflectance microscopy

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A thermoreflectance microscopy (TRM) system has emerged as a non-destructive and non-contact tool for a high resolution thermal imaging technique for micro-scale electronic and optoelectronic devices. Quantitative imaging of the temperature distribution is necessary for elaborate thermal characterization under operating conditions, such as thermal profiling and performance and reliability analysis. We introduce here a straightforward TRM system to perform quantitative thermal characterization of microelectronics devices. The quantitative imaging of the surface temperature distribution of a poly-silicon micro-resistor is obtained by a lock-in measurement technique and calibration process in the conventional CCD-based widefield microscope. To confirm the quantitative thermal measurement, the measured thermal information is compared to that obtained with an infrared thermography (IRT) system. In addition to quantitative surface temperature distribution, the sub-micron defects on microelectronic devices can be clearly distinguished with the thermoreflectance images, which are hardly perceptible with a conventional widefield microscopy system. The thermal resolution of the proposed TRM system is experimentally determined by measuring standard deviation values of thermoreflectance data with respect to the iteration number. The spatial and temperature resolutions of our system are measured ~ 400 nm and ~ 50 mK, respectively. We believe that quantitative imaging in the TRM system can be used for improvement of microelectronic device and integrated circuit (IC) design.

8975-24, Session PTue

Certain properties of multi-phase anisotropic systems

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The approach is developed for calculation of «effective» electrical, thermal, galvanomagnetic and mechanical properties of anisotropic multi-phase systems basing on the model of orderly orientated inclusions with variable 3D –configuration [1]. The model allows receiving simple algebraic equations for the properties depending on the several impacts (e.g. electrical, thermal, and magnetic fields as in Hall effect and Nernst-Ettingshausen effects) orientated along the different axes of coordinate [2]. Some powerful relations may be obtained using the model, for example, the relation between Seebeck effect on the one hand and thermal and electrical conductivities on the other hand for two-phase systems with arbitrary anisotropy [1]. The using of the present model as well as other ones is considered for real systems. The widely used simplest approximation for inclusions configuration as randomly distributed spheres of identical sizes was shown to be insufficient for correct estimations of electrical and mechanical properties of some multi-phase systems. The using of the model for isotropic systems is discussed. Applications of the approach for consideration of thermo-electrical and mechanical properties in several real systems are presented.

The work was done within RAS Program (Project no. 01.2.006 13394), by UD RAS as part of Program “Matter at high energy densities” of the Presidium of RAS (project 12-P-2-1004).

References:

[1] Shchennikov V.V., Phys. Met. Metallogr., 67(1), 93-96 (1989).

[2] Shchennikov V.V., Ovsyannikov S.V., Vorontsov G.V., Shchennikov V.V. Jr., Phys. status solidi B, 241(14), 3203-3209 (2004).

Conference 8976: Microfluidics, BioMEMS, and Medical Microsystems XII

MOEMS-MEMS
SPIE Photonics West

Sunday - Tuesday 2 –4 February 2014

Part of Proceedings of SPIE Vol. 8976 Microfluidics, BioMEMS, and Medical Microsystems XII

8976-1, Session 1

Scalable production of sub µm functional structures made of non CMOS compatible materials on glass

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Biophotonics applications often require non-CMOS compatible -materials to be patterned with sub µm resolution. Whilst the mass production of sub µm patterns is well established in the semiconductor industry, semiconductor fabs are limited to using CMOS compatible materials on silicon. On the other hand expensive lab scale methods like E-Beam direct-write exist for R&D of non CMOS-materials . Our goal was to enable the biophotonics community to evolve technologies using sub µm patterns from the lab through to a marketable product.

Using equipment from the semiconductor industry we have implemented a fully automated (carrier-to-carrier) manufacturing line for processing 200mm wafers that enables the mass production of consumables with sub-µm patterns.

The automated line allows manufacturing consumables for biophotonics in substrate materials like D263 glass or fused silica and layer/coating materials like Cr, SiO_2, Cr_2O_5, Nb_2O_5, Ta_2O_5 and with some restrictions even gold. The applied processes (lift-off and RIE) offer a high degree of freedom in the design of the consumable (e.g. curved and / or chirped gratings, regular and irregular dot- or well- patterns also in combination with waveguides). Using equipment and processes from the semiconductor industry offers a high level of reproducibility and scalability.

8976-2, Session 1

Modeling particle flow and blockages in microfluidic channels supported by periodic posts

Mahyar Mehran, Jorden A. L. Bryer, Bonnie L. Gray, Glenn H. Chapman, Simon Fraser Univ. (Canada)

One common problem with microfluidic systems is the accumulation of particles and fluid bubbles inside chambers and other structures, which causes distortion in fluid flow potentially leading to device or system failure. Microchannels and chambers that utilize a “cathedral-ceiling” arrangement, whereby the tops of the channels are supported by periodic posts, have been suggested to improve defect tolerance over arrays of parallel channels through the provision of multiple paths during localized blockage formation. This paper builds on our prior investigations through development of a modified Monte Carlo method for modeling the fluid dynamics and blockage formation based on the likelihood of blockages forming in areas of high particle traffic but which have low flow. Our COMSOL model generates a large number of randomly (normal) distributed sets of particle streamlines. Coordinates along these streamlines are cross-examined to find the lowest flow areas, which are deemed likely points for blockage formation. Models generated by MATLAB then determine which areas of the microchannel are most likely to be obstructed based on particle population. This process is iterated as blockages form, creating new streamline patterns, which in turn indicate placements for new blockages. This semi-automated method has enabled us to predict where the particles may accumulate and how this progressive blockage formation will change system pressure and flow. Preliminary results support the findings of significantly increased lifetime expectancy of microchannels with periodic posts compared to arrays of parallel microchannels, while also providing greater insight into where blockages may form in the cathedral-ceiling type geometry.

8976-3, Session 1

Selective structuring of thick SU-8 layers on fused silica by femtosecond laser ablation for medical applications

Tamara Pacher, Fachhochschule Vorarlberg (Austria); Adrian Prinz, Sony DADC Austria AG (Austria); Stefan Partel, Johann Zehetner, Fachhochschule Vorarlberg (Austria); Victor V. Matylitsky, High Q Laser, a Newport Corp. Brand (Austria); Sandra Stroj, Fachhochschule Vorarlberg (Austria)

We present our latest results in the field of selective ablation with ultrashort laser pulses. Aim of this work was to develop a structuring process based on femtosecond laser ablation for the fabrication of a master for molding a fluidic chip. Laser pulse durations of around 400 fs yield well defined ablated structures with almost no heat load to the remaining material. The fabrication based on selective ablation needs a suitable resist-substrate system which provides a sufficiently large processing window where the resist can be completely removed without damaging the underlying substrate material. In this work we used a wafer of fused silica spin coated with an approx. 100 µm thick layer of SU-8 for generating the microstructure. One possible application of this process is rapid prototyping and mastering in the field of microfluidics and biochips, respectively. As an example structure we fully processed a microfluidic device which can be used in life science and diagnostic applications. It is a bio-inspired microsystem that reconstitutes the critical functional alveolar capillary interface of the human lung. This micro device reproduces complex integrated organ-level responses to bacteria and inflammatory cytokines introduced into the alveolar space [1].

[1] D. Huh, et. al., Reconstituting Organ-Level Lung Functions on a Chip, Science 328, 1662 (2010), DOI: 10.1126/science.1188302

8976-4, Session 1

Micro-porous drilling in natural rubber latex using femtosecond laser for drug release application

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In the last years the interest in exploiting laser processing of materials has been growing due to its versatility to applications in different fields, from metal cutting to medical applications. When femtosecond laser pulses are focused into a material, the intensity is enough to induce multi-photon absorption and, consequently, structural changes in the material. In this work, we present a femtosecond laser micro-drilling method to produce micro-porous in Natural Rubber latex (NRL) membranes for drug release applications. To produce the porous we used 150-fs laser pulses at 775 nm from a Ti:Sapphire system, operating at 1 kHz repetition rate. The samples were micro-drilled by focusing the laser beam onto the sample surface, under nitrogen flux, using an f= 20 cm lens (beam waist size at the focus of ~20 µm), while computer controlled scanning mirrors scan the laser beam onto the sample surface. We are able to produce distinct porous densities onto the membranes to investigate its drug delivery capability. No collateral thermal damage and no cracks in the surrounding porous area were observed by SEM. Our results reveal an increase in the drug adsorption and release with porous density, indicating this approach to develop controllable drug delivery

systems. The authors acknowledge FAPESP, CNPq, CAPES and the Air Force Office of Scientific Research (FA9550-07-1-0374) for financial support and Andre Romero for technical assistance.

8976-5, Session 1

Design and analysis of a hot embossing machine and the effects of tool wear and accuracy of resin replication on high aspect ratio microfluidic features

Khanh H. Nguyen, Brian W. Anthony, Massachusetts Institute of Technology (United States)

Hot embossing is a growing technology proven to be capable of reproducing micro-scale features on thermoplastics and can be an effective process for rapid prototyping microfluidic devices with high aspect ratio micro features. Advantages of this manufacturing process can include tooling flexibility, fast production time, low capital cost and a vast selection of production materials. A greater understanding on the micro feature transferring capabilities and use limits of tools are needed so that hot embossing may advance to becoming a practical technique for producing microfluidic parts. This work focuses on both the design and analysis of a hot embossing system and a brass tool to replicate an existing functional high aspect ratio micro feature onto Polymethyl methacrylate (PMMA). The aspect ratio of features ranged from 10:1 to 4,000:1. Optimal embossing parameters used a pressure of 3.5kN, hold time of 12 minutes, tool temperatures of 140oC and substrate temperature of 130oC to produce parts that filled shoulder heights and widths up to 97% and 90%, respectively. The wearing of features on the metal tool ware also characterized for purposes of understanding the limits on tool use and was found that a maximum range of +/-3μm in dimensional change existed. Gains in tool dimensions were then mainly attributed to the deposition of embossed materials onto the tool. The study further determined a method for creating usable resin tool copies that exhibited a replication accuracy of less than 2% , on average, for micron size features.

8976-6, Session 2

OSTE: a new material system for labs-on-chip *(Invited Paper)*

Tommy Haraldsson, Carl Fredrik Carlborg, Wouter van der Wijngaart, KTH Royal Institute of Technology (Sweden)

We present OSTE, a polymer platform, adapted for rapid prototyping of labs-on-chip but at the same time having material and processing properties compatible with large scale production. The new polymer platform is based on off-stoichiometry thiol-ene (OSTE) chemistry and is a rapidly UV-curing system allowing for tunable mechanical properties (rubbery-like to thermoplastic-like), tunable surface chemistry (built in molecular surface anchors that can be used for direct and permanent surface modification) and a low-temperature direct bonding process not requiring any surface activation or glues. The material features a novel direct photolitography mechanism, but can also be micropatterende by standard soft lithography micropatterning or precision machining. We will demonstrate packaging of biofunctionalised photonic and QCM sensors, bonding to spotted protein and DNA-microarrays and wafer-level integration and bonding.

8976-7, Session 2

Design, measurement analysis, and process optimization of hot embossing system for high aspect ratio microfluidics

Nicholas Ragosta, Viren Kalsekar, Brian W. Anthony, Massachusetts Institute of Technology (United States)

A hot embossing machine was designed and built for the purpose of prototyping a critical feature of their microfluidic network. The machine was designed for an embossing area of 6 square inches, and was found to have a maximum positional repeatability of 43 microns. The purpose of this research was to find the capabilities of the system used for hot embossing and optimize the process for maximizing the performance. The system was validated for alignment, measurement procedure and the process control. The measuring procedure was analyzed to find the best possible metric which could serve as a response variable for the performance of the process. The 'Fill ratio' of height and width were chosen as metrics for the experimental design which had precision to tolerance ratios of 0.44 and 0.33 respectively. An analysis of the factors affecting the hot embossing process was carried out using experimental design and the optimal parameters were identified. The tool temperature, pressure and the holding time were the most significant in that order. The Cp for the process with respect to the height fill was found to be 4.71 and for the width fill ratio was found to be 1.97. Using the optimal parameters the process variation of six standard deviations was found to lie within the specification limits.

8976-8, Session 2

Rapid bonding of polydimethylsiloxane (PDMS) to various stereolithographically (STL) structurable epoxy resins using photochemically cross-linked intermediary siloxane layers

Elisabeth Wilhelm, Christiane Neumann, Kai Sachsenheimer, Kerstin Länge, Bastian E. Rapp, Karlsruher Institut für Technologie (Germany)

Most prototyping processes in microfluidics rely on either PDMS replication by casting or stereolithography from 3D digital data. However, these techniques cannot be combined to set up multiple materials stacked devices with different material properties as it is necessary for some microfluidic systems e.g., valves or actuators. As described in literature PDMS devices can be connected to other PDMS devices by plasma or corona induced bonding. However, this technique cannot be used to bond other materials because not all materials (e.g., epoxy resins) can be oxidized by plasma treatment; a requirement for this bonding technique. Silanization techniques, which are used to create a siloxane similar surface via surface modification, appear to be an alternative to enable bonding of PDMS devices to other materials. Unfortunately most of these methods are based upon heat treatment or immersion of the components in solvents which deform the STL components. We suggest a new silanization strategy based on a photoinduced cross-linking reaction. According to the surface properties of the STL epoxy resin (e.g., amount of free reactive groups) 3-glycidoxypropyltrimethoxysilane or dimethoxydimethylsilane with triarylsulfonium hexaflourantimonate as photoacid generator are used to coat the surface. Maximum bond strengths between 69 kPa and 689 kPa (depending on the epoxy material) were determined by ISO-conform tensile testing. These results are comparable to those reported for PDMS/PDMS bonds. Furthermore we tested the hydrolytic stability of the bond in long-term experiments, achieving more than 40 hours leak tightness.

8976-9, Session 2

Rapid prototyping of multiphase microfluidics with robotic cutters

Zidong Li, Zhengtuo Zhao, Fu-Jiou J. Lo, Univ. of Michigan-Dearborn (United States)

Microfluidics devices offer novel techniques to address biological and biomedical issues. Standard microfluidics fabrication uses photolithography to pattern channels on silicon wafers with high resolution (micron scale). In these lithography, a lot of procedures are required, including substrate pretreatment, coating, soft bake, exposure, post-exposure bake, and developing, which take at least half the day for thick channels. On the other hand, we have prototyping applications with features on the sub-millimeter scale (>200 µm). With a versatile robotic cutter (Pazzle Inspiration), many devices can be rapidly fabricated via etch mask or soft lithography options to form these prototypes. The total procedures take only 10's of minutes. And including preparing and curing PDMS (polydimethylsiloxane), only several hours are required to go from initial idea to usable device. Using this technique, a range of up to 4 different designs were conceived, fabricated, and tested in a typical work day, with only simple CAD design changes in between. Furthermore, we developed a safe and facile way to use the cuttings as etch masks for glass microfluidics, with etch depths down to 60 µm. We also use the cuttings to form patterned PDMS membranes with soft lithography. With these techniques, we can achieve low cost, simple prototyping of gas and liquid microfluidics before stepping up to full resolution lithography. This allows not only a moderate increase in prototyping turn around but also opens doors to small scale labs that want to investigate both glass and PDMS microfluidics without first investing and training in photolithography.

8976-10, Session 3

Magnetic microbeads for sampling and mixing in a microchannel *(Invited Paper)*

Peter J. Hesketh, Drew Owen, Matt Ballard, Wenbin Mao, Alexander Alexeev, Georgia Institute of Technology (United States)

Detection of low concentrations of bacteria, viral particles and parasites in food samples is a challenging process [H. P. Dwivedi, L. A. Jaykus, Critical Reviews in Microbiology, Vol. 37, pg. 40 (2011)]. The separation of the target from the food matrix is a key step that needs to be carried out with highly specific capture of the target onto a mobile phase. This can subsequently be separated and concentrated for detection. The capture of the target can be more effectively carried out with efficient mixing. We present a simple microfluidic system capable of controlled transport of rotating magnetic beads among soft magnetic patterns. An external permanent magnet attached to a motor provides a magnetic field, which can be rotated at different speeds while magnetizing the NiFe disks in the channel. We have demonstrated the capacity to capture particles from flow with rotating M-280 beads in this device. We developed a computational model for the microchannel with rotating magnetic beads that drive the fluid. To examine the effect of beads on mixing and capturing of target solutes, we introduced tracer particles that are suspended in the fluid. Our tracer particles diffuse through the fluid based on the magnitude of their diffusion coefficient and also convected by the fluid as it is driven by the rotating magnetic beads. As the fluid in the microchannel mixes, the particles are also mixed, allowing more of them to approach the magnetic beads, and ultimately to be captured.

8976-11, Session 3

High aspect ratio magnetic nanocomposite polymer cilium

Mona Rahbar, Hsiu-Yang Tseng, Bonnie L. Gray, Simon Fraser Univ. (Canada)

This paper presents a new approach for fabricating an active mixer based on stirring by artificial cilia. A new and simple fabrication method has been developed in order to create high aspect ratio cilia mixers. As the cilia are fabricated directly in the mixing chamber, the fabrication process is easily integrated with complex microfluidic systems.

Rare earth permanent magnetic powder, was used to dope polydimethylsiloxane (PDMS), resulting in a highly flexible permanent magnetic nanocomposite polymer (M-NCP) of much higher magnetization than ferromagnetic polymers previously reported. This M-NCP was then used to create high aspect ratio cilia that can be actuated using miniature electromagnets to achieve a high range of vibration.

In order to fabricate the artificial cilia, the reaction chamber was filled with melted Poly(ethylene-glycol). Micro-needles with a diameter of 120?m were inserted into the chamber and then M-NCP was poured over the needles and the needles were slowly pulled out. The vacuum created as the result of the evacuating needle drew the M-NCP into the holes. Then the sample was allowed to cure at room temperature. In the last step, the PEG mold was dissolved in 60°C water. The cilia were actuated at different frequencies and amplitudes in order to characterize its mixing effect. It was shown that a cilium mixer reduces the mixing time by about 10 times over passive diffusion.

To date, many approaches have been attempted to make cilia mixers. In most case either the complication of the fabrication technique or the actuation methods can limit their practicality. In contrast, the proposed fabrication is very simple and doesn't require access to equipments such as DRIE and sputtering machine. Also, the actuation method achieves high range of actuation using relatively low voltage. The simplicity of the fabrication and actuation techniques, as well as its high mixing performance, makes it practical for use in complex microfluidic applications.

8976-12, Session 3

A chemically inert, multichannel chip-to-world interface to connect microfluidic chips

Christiane Neumann, Elisabeth Wilhelm, Thomas Duttenhofer, Leonardo Pires, Bastian E. Rapp, Karlsruher Institut für Technologie (Germany)

Within the last decades more and more microfluidic systems for applications in chemistry, biology or medical science were developed. All of them need a connection between the chip and its environment e.g., pumps. Numerous concepts for such interconnections are known from literature but most of them allow only a small number of connections and are neither chemically inert nor contamination free. We developed a chemically inert, reusable, multichannel Chip-to-World-Interface (CWI) based on a force fit connection comparable to hollow screws such as used at high-performance liquid chromatography. The CWI can be used to connect chips, made of different materials e.g., glass, polydimethylsiloxane or epoxy polymers, with up to 100 thermoplastic tubes. The dimensions of the CWI and the number of connections can be individually adapted depending on the chip dimensions but the pitch between the tubes is fixed. Due to the design of the CWI the fluid is only in contact with the chip and the tubing material, thus leading to a contamination free and zero dead volume interconnect. Using tubes of polytetrafluorethylene (PTFE, Teflon®) even enables probing with organic solvents like dimethylformamide, dichlormethane or tetrahydrofurane during several hours without leakage or corrosion of the CWI. During experiments the CWI with 100 connections resisted pressure up to 630 kPa (6.3 bar) and sustained flow rates higher than 4 ml/min.

8976-13, Session 3

Confinement of single macromolecules in free solution using a hydrodynamic trap

Melikhan M. Tanyeri, Istanbul Sehir Univ. (Turkey)

High precision control of micro- and nanoscale objects in aqueous media is an essential technology for nanoscience and engineering. However, confinement and fine-scale manipulation of macromolecules and nanoparticles remains a significant challenge. Currently, particle trapping methods based on acoustic, electrokinetic, magnetic and optical fields are utilized, but these methods are limited to trapping particles with specific material properties and bulky micron-scale dimensions. Recently, we developed a new microfluidic method that allows for fine-scale manipulation and positioning of single micro- and nanoscale particles in aqueous solution (Nano Letters (2013), Lab Chip (2011), Applied Physics Letters (2011)). Using this method, micro and nanoscale objects are confined at the stagnation point of a planar extensional flow generated at a microchannel junction. We demonstrated trapping and two-dimensional manipulation of particles with size ranging between 100 nm – 10 ?m with a positioning precision as small as 180 nm. This method offers key advantages over existing confinement methods such as isolation of a single particle from a crowded solution and active control over the surrounding medium of a trapped object. Furthermore, unlike the existing methods such as optical or magnetic traps (where force scales with volume), the microfluidic trapping force scales linearly with particle radius, which promises to enable facile trapping of macromolecules and small nanoparticles (<50 nm) in free solution. Here, we explore the feasibility of trapping individual macromolecules such as globular proteins (~ 5 nm in diameter) in free solution using this flow-based confinement method. Using Brownian dynamics (BD) simulations, we show that macromolecules with radius of gyration as small as 5 nm are effectively confined using the microfluidic trapping method. We further determined the key parameters for effective confinement of macromolecules in free solution.

8976-14, Session 3

Microfluidics on liquid handling stations (µF-on-LHS): a new industry-compatible microfluidic platform

Jörg Kittelmann, Carsten P. Radtke, Ansgar Waldbaur, Karlsruher Institut für Technologie (Germany); Christiane Neumann, Karlsruhe Institute of Technology (Germany); Jürgen Hubbuch, Bastian E. Rapp, Karlsruher Institut für Technologie (Germany)

Various concepts have been described for connecting and operating microfluidic chips with peripheral fluidic infrastructure and instruments. However in industry, computer controlled liquid handling stations (LHS) are an established standard and high-throughput screening (HTS) methods in microwell plate format utilizing LHS have become widely established in lead discovery as well as up and downstream process development. Suggesting a new (microfluidic) platform is therefore usually met with a certain degree of resilience as it must prove an added-value compared to the well-known standard.

Instead of trying to replace the microwell plate based screens on LHS, we suggest combining microfluidics with LHS in a standardized and generic format which we termed Microfluidics on Liquid Handling Stations (µF-on-LHS). This combined approach allows microfluidics integration into standardized screening systems to exploit the full potential of fluid physics at micrometer scale and industry compliant HTS capable screening equipment. For µF-on-LHS, we developed a molding tool which is suitable for low-cost disposable chips replication using any room-temperature curing polymer (such as polydimethylsiloxane). To interconnect µF-on-LHS compatible microfluidic chips and LHS, the molding tool defines connector interfaces that enable connection to the pipetting needles of the LHS. This allows the usage of various LHS dispenser heads for on-chip sample flow control. The molding tool features space for an exchangeable insert which defines the microfluidic channel networks, thus by simply changing this replication master, a new chip can quickly be created.

Thus, µF-on-LHS allows running virtually any microfluidic chip design on a fully automated fluid handling device.

8976-15, Session 4

Paper analytical devices for detection of low-quality pharmaceuticals *(Invited Paper)*

Abigail Weaver, Marya Lieberman, Univ. of Notre Dame (United States)

The problem of low quality pharmaceuticals has been intractable in the developing world, despite the fact that it is a “solved problem” in most of the developed world. Sophisticated instrumentation and regulatory vigilance reduce the prevalence of fake drugs in the US to under 1%. However, most of the people in the world live in countries where these protections are not in force, due to the expense of the technological infrastructure and problems with governance. To attack this problem, we are designing inexpensive, instrument-free analytical devices that can detect very low quality drugs--those where the API has been replaced with a substitute drug or an inert filler. Our prototype paper test cards use 12 color tests for analysis of pharmaceutical dosage forms. An internal lab study showed that the test cards can detect various beta lactam antibiotics, first-line TB medications, and a range of binders and fillers with sensitivity and selectivity over 95%. Formulations in which active pharmaceuticals were replaced by substitute APIs or inert fillers were detected with generally >90% sensitivity and >95% selectivity. A field test of 235 samples of acetaminophen, ampicillin, and amoxicillin samples collected from pharmacies in western Kenya showed no samples contained substitute ingredients or suspicious fillers; of the 35 samples that have been analyzed so far by HPLC, all agree with the test card results, although about 8% of the samples were substandard (>15% variation in API content from label). Later studies at the FDA’s forensics office showed that the paper test cards could detect adulterated or falsified drugs that FDA and customs officials had collected in the US and Mexico. Surprisingly, excellent results were obtained even for drug classes for which the test cards were not optimized, including Oxycontin, Cialis, Levitra, Viagra, Tamiflu, and Lipitor.

8976-16, Session 4

Laser patterning for paper-based fluidics

Collin L. Sones, Ioannis Katis, Ben Mills, Matthias Feinaeugle, Robert W. Eason, Medya Fouad Namiq, Morten Ibsen, Univ. of Southampton (United Kingdom)

Paper-based microfluidics is a rapidly-progressing inter-disciplinary technology driven by the need for low-cost alternatives to conventional point-of-care diagnostic tools. For transport of reagents/analytes, such devices often consist of interconnected hydrophilic fluid-flow channels demarcated by hydrophobic barrier walls that extend through the thickness of the paper. Fabrication approaches include photolithography, ink-jet etching/printing, flexographic printing, screen printing, wax printing, plotting, paper-cutting, and laser treatment of the paper used.

Here, we present a laser-based fabrication procedure that uses photo-polymerisation of a negative hydrophobic photoresist to produce the fluidic channels required. A cellulose paper (Whatman Grade 1) was soaked with the liquid resist, heated at 100C for 1 hour to harden the resist, and then illuminated by focussed nanosecond pulses (?=266nm, 20Hz, 5mJ pulse energy). Computer-controlled 3-axis stages were used to move the paper relative to the laser focus, in such a way as to polymerise cm long lines, with widths of order ~100µm (although wider lines are possible by using a larger beam). During development in 1-propanol, all un-polymerised regions were removed, whilst the

polymerised structures remained in the paper. Analysis showed that the structures directed the flow of the water and hence the sample could function as a microfluidic device. For this work, the total fabrication time for ~10 channels was on the order of ~few minutes, but this time was ultimately limited by the speed of the translation stages and available laser power, indicating that this rapid, flexible, laser-patterning procedure could possibly be used to produce devices on a commercial-scale.

8976-17, Session 4

Electrical manipulation of biological samples in glass-based electrofluidics fabricated by three-dimensional femtosecond laser processing

Jian Xu, Katsumi Midorikawa, Koji Sugioka, RIKEN (Japan)

Electrical control of biological objects in microfluidic chips such as on-chip dielectrophoresis, electro-orientation, electro-rotation, and electro-stretching is very useful for many biological and medical applications, e.g. tissue engineering. To achieve this, monolithic integration of microelectric components into microfluidic chips is necessary. However, conventional microfabrication strategies such as planar photolithography processes combined with metal deposition techniques require complex procedures due to their inherent nature of two-dimensional fabrication.

In this paper, we apply a three-dimensional laser processing strategy to fabricate a monolithically integrated electrofluidic microchip. The microfluidic structures with three-dimensional configuration are first fabricated in photosensitive glass by femtosecond laser direct writing followed by thermal treatment and successive chemical etching. Then, by using the same laser, the microelectric components based on conductive metal microstructures with high adhesion and high chemical stability are integrated into the fabricated microfluidic structures by the two-step procedures consisting of the laser direct-write ablation followed by electroless metal plating. Compared with the conventional techniques, our new technique provides a simple and flexible way for the fabrication of functional electrofluidics.

To demonstrate the application of such electrofluidic chips, the electro-orientation of bio-objects with asymmetric shapes in the microfluidic channels is presented. By designing and integrating different shapes and number of microelectrodes at the different sites in proper microfluidic channels, the orientation direction of aquatic microorganisms such as Euglena gracilis can be well controlled at an arbitrary angle. Moreover, in-channel manipulation of biological objects by three-dimensionally controlling the electrical fields is realized. In addition, the control of the movement of biosamples such as electrotaxis by using the same chip is demonstrated.

8976-18, Session 4

Uniform algal growth in photo-bioreactors using surface scatterers

Syed S. Ahsan, Cornell Univ. (United States); Brandon Pereyra, Binghamton University (United States); David Erickson, Cornell Univ. (United States)

Algal growth is highly dependent on light intensity. In conventional photo-bioreactors and raceway ponds, this manifests itself in shading effects where only small cross sections of algae receive the optimal light intensity for growth conditions. In this work, we present a scheme with a unique scatterer design to integrate within photo-bioreactors for algal fuel production. In the envisioned scheme, light is coupled into waveguides in each stack of a multi-stack reactor. The waveguides are enhanced with surface scatterers that were fabricated out of SU-8 pillars (5 x 5 x 2.4 μm) to deliver the light to the algae. The scatterers were characterized with SEMs and some revealing FDTD simulations were also performed. Angular scattering measurements with multiple light inputs and at different points on the waveguide revealed varying angular scattering profiles. To integrate over all multiple scattering angles, shallow channel dye experiments with Alexa 680 were conducted to simulate a thin biofilm on the scattering waveguide. From a uniform distribution of SU-8 pillars, the extinction coefficients of the system could be calculated and used to design a gradient distribution of SU-8 pillars that would achieve uniform scattering intensity with total photon usage being approximately 87% for glass thickness #1.5 for a 4 cm reactor. Finally, single-stack photo-bioreactors were also built to characterize the uniformity of algae growth integrated with the surface scattering waveguides.

8976-103,

Bio-integrated and bio-inspired optical microsystems

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

Recent advances in materials and fabrication techniques enable construction of high performance optical microsystems that can flex, bend, fold and stretch, with ability to accommodate large (>>1%) strain deformation, reversibly and in a purely elastic fashion. Such systems open up new engineering opportunities in bio-inspired device design and in intimate, multifunctional interfaces to biology. This talk summarizes two examples: (1) hemispherical digital imagers that incorporate essential design features found in the arthropod eye and (2) injectable, cellular-scale light emitting diodes for wireless control of complex behaviors in animal models, via the techniques of optogenetics.

8976-20, Session 5

Labs, cells, and organs on chip *(Invited Paper)*

Albert van den Berg, Univ. Twente (Netherlands)

The recent rapid developments in microfluidics technologies has enabled the realization of miniaturized laboratories. These Labs-on-a-Chip will play an important role in future medicine, both in point-of-care devices for drug or biomarker monitoring, as well as in early diagnostic devices. We developed a pre-filled ready-to-use capillary electrophoresis platform for measuring ions in blood. It is used to monitor lithium in finger-prick blood of manic-depressive patients, but can also be used for measuring calcium in blood for prevention of milk fever, or for measuring creatinine in blood or sodium in urine for early detection of ESRD. Another device was developed for analyzing male fertility by determining sperm concentration and motility in semen. It appears that the same device can be easily adapted to detect the presence of cells in milk, a good indicator for the presence of mastitis. Finally recent developments of organs on chip, in the form of a Blood Brain Barrier (BBB) chip and atherosclerosis chip will be presented.

8976-21, Session 5

Femtosecond laser fabricated micro fluorescence-activated cell sorter for single cell recovery

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Manipulation, sorting and recovering of specific live cells from samples containing less than a few thousand cells is becoming a major hurdle in rare cell exploration such as stem cell research or cell based diagnostics. Moreover the possibility of recovering single specific cells for culturing and further analysis would be of great impact in many biological fields ranging from regenerative medicine to cancer therapy.

In recent years considerable effort has been devoted to the development of integrated and low-cost optofluidic devices able to handle single cells, which usually rely on microfluidic circuits that guarantee a controlled flow of the cells. Among the different microfabrication technologies, femtosecond laser micromachining (FLM) is ideally suited for this purpose as it provides the integration of both microfluidic and optical functions on the same glass chip leading to monolithic, robust and portable devices.

Here a new optofluidic device is presented, which is capable of sorting and recovering of single cells, through optical forces, on the basis of their fluorescence and. Both fluorescence detection and single cell sorting functions are integrated in the microfluidic chip by FLM.

The device, which is specifically designed to operate with a limited amount of cells but with a very high selectivity, is fabricated by a two-step process that includes femtosecond laser irradiation followed by chemical etching. The capability of the device to act as a micro fluorescence-activated cell sorter has been tested on polystyrene beads and on tumor cells and the results on the single live cell recovery are reported.

8976-22, Session 5

Microfluidic devices for cell culture and handling in organ-on-a-chip applications

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For many problems in system biology or pharmacology, in-vivo-like models of cell-cell interactions or organ functions are highly sought after. Conventional stationary cell culture in 2D plates quickly reaches its limitations with respect to an in-vivo like expression and function of individual cell types but even more so in the case of multitype cell clusters. Microfabrication technologies and microfluidics offer an attractive solution to these problems. The ability to generate flow as well as geometrical conditions for cell culture and manipulation close to the in-vivo situation allows for an improved design of experiments and the modeling of organ-like functionalities. Furthermore, reduced internal volumes lead to a reduction in reagent volumes necessary as well as an increased assay sensitivity. In this paper we present a range of microfluidic devices designed for the co-culturing of a variety of cells, namely hepatic cells. The influence of substrate materials and surface chemistry on the cell morphology and viability for long-term cell culture has been investigated as well as strategies and medium supply for on-chip cell cultivation. Chips with integrated membranes for experiments with counterflowing media have been designed and realized using injection molding in a standard microscopy-slide format. Experiments show a high cell viability and proliferation over extended periods of time.

8976-23, Session 5

Separation of biological cells in a microfluidic device using surface acoustic waves (SAWs)

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In this study, a surface acoustic wave (SAW)-based microfluidic device has been developed to separate heterogeneous particle or cell mixtures in a continuous flow using acoustophoresis. The microfluidic device is comprised of two components, a SAW transducer and a microfluidic channel made of polydimethylsiloxane (PDMS). The SAW transducer was fabricated by patterning two pairs of interdigital electrodes on a lithium niobate ($LiNbO3$) piezoelectric substrate. When exciting the SAW transducer by AC signals, a standing SAW is generated across the cross-section of the channel. Solid particles immersed in the standing SAW are accordingly pushed to the pressure-node arising from the acoustic radiation force acting on the particles, referring to the acoustic particle-focusing phenomenon. The amplitude of acoustic radiation force highly depends on the properties of the particle, resulting in different acoustic responses for different types of cells. A numerical model, coupling the piezoelectric effect in the solid substrate and acoustic pressure in the fluid, was developed to provide a better understanding of SAW-based particle manipulation. Separation of two types of fluorescent particles has been demonstrated using the developed SAW-based microfluidic device. An efficient separation of E. coli bacteria from peripheral blood mononuclear cell (PBMC) samples has also been successfully achieved. The purity of separated E. coli bacteria and separated PBMC were over 95% and 91%, respectively, obtained by a flow cytometric analysis. Conclusively, the developed microfluidic device can efficiently separate E. coli bacteria from biological samples, which has potential applications in biomedical analysis and clinical diagnosis.

8976-24, Session 5

A newly designed optical biochip for a TDM-POCT device

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The continuous measurement of therapeutic drugs and metabolites is a strong requirement coming from physicians in many clinical areas. In transplanted patients, the continuous monitoring of the immunosuppressants is essential both in the first period immediately after the transplantation and in stable conditions, in order to determine the right dosage which is within a very narrow therapeutic window, different from patient to patient. NANODEM (NANOphotonic Device for Multiple therapeutic drug monitoring) is a European FP7 project, started at the end of 2012, with the ambitious objective of developing a novel therapeutic drug monitoring point-of-care-testing (POCT) device for the automatic measurement of immunosuppressants and related metabolites in transplanted patients. The design of a novel optical biochip will be presented. The core of the biochip consists of two polymeric parts, a ZEONEX® slide and a ZEONOR® foil, bonded each other. The ZEONEX® slide is properly shaped as a comb with a microfluidic multi-channel array with the related inlet and outlet. The ZEONOR® foil is used as a covering thin film at the bottom of the ZEONEX® slide and, due to its higher refractive index, it is able to guide the optical signal – coming from an external light source – by total internal reflection. In such a way, the guided light excites, by evanescent field, the fluorescent sensing-layer immobilized onto the fluidic channels. Thanks to a proper shape of the ZEONEX® slide and because of the anisotropy of the fluorescence, the emitted fluorescence is mainly coupled inside the plastic chip and driven toward photodetectors placed on top of the chip. Competitive assays for the detection of tacrolimus and cyclosporin A are implemented immobilizing their derivative on the ZEONOR® surface of the micro-channels.

8976-27, Session 6

Design and fabrication of tri-axial capillary needles in flow focusing for microencapsulation of multiple drugs and imaging agents

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Biodegradable microcapsules encapsulating multiple drugs, genes and imaging agents have gained extensive interests in many diagnostic and therapeutic applications. Traditional microencapsulation methods are limited by their low encapsulation efficiency, low production rate, and difficulty to form a multi-layer core-shell structure. Tri-axial electrospray and flow focusing are emerging microfabrication techniques with the potential to overcome these limitations. However, practical application of these techniques in fabricating drug-loaded biodegradable microcapsules is still challenged by instability of the concentric flow and residue obstruction in the needle. In order to overcome these technical challenges, we have designed a new type of tri-axial metallic capillary needles that can be readily cleaned, assembled, and aligned. With these tri-axial needles, we have successfully produced microcapsules with outer shell, middle layer, and inner core. The triple-layer microcapsules were collected and observed by laser scanning confocal microscopy (LSCM). Compared with the tri-axial needles we used before, the new design enables reliable encapsulation of multiple drugs and imaging agents in biodegradable microcapsules with the enhanced size distribution, increased productivity, and improved drug-loading efficiency.

8976-28, Session 6

Pathology in a tube, step 1: fixing, staining, and transporting pancreatic core biopsies in a microfluidic device for 3D imaging

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A minimally-invasive diagnosis of pancreatic cancer is accomplished by obtaining a fine needle aspirate and observing the slurry cells under conventional optical microscopy. As an unavoidable artifact, native tissue architecture is lost making diagnoses uncertain and staging invasiveness impossible. One solution is the preparation of core biopsies (CBs) within a microfluidics device that are subsequently imaged in 3D. CBs (L = 1-2 cm, D = 0.4-2.0 mm) obtained from pig pancreas were formalin-fixed and optically cleared with FocusClear®. In bright-field at 40x, light transmission through the ordinarily opaque CBs was increased 4-15x. As a result, islet structures were easily identified 250-300 µm beneath the tissue surface. Typically, biospecimen preparation is time intensive and requires precise handling since CBs are delicate, thus fixative, absorptive stain and FocusClear® diffusion were done slowly and manually. To significantly speed-up specimen processing, we developed a microfluidic device consisting of a main circular channel (L = 5 cm, d = 700 µm) used for fixing and transporting the CB and two feed channels (L = 2 cm, d = 1200 µm) employed for staining, which together made an "H" geometry. Extra space between the CB and channel wall provides a key feature not traditionally employed in microfluidic devices. At low flow rates (0.5-1 mL/min), CBs can be fixed and stained, while the specimen remains stationary. By switching quickly to a higher flow rate (5 mL/min), we can precisely overcome adhesion and transport the specimen within the channel towards the imaging platform for 3D pathology.

8976-29, Session 6

Passive flow regulators for drug delivery and hydrocephalus treatment

Eric Chappel, Dimitry Dumont-Fillon, Selma Mefti, Debiotech SA (Switzerland)

Passive flow regulators are usually intended to deliver or drain a fluid at a constant rate independently from pressure variations. New designs of passive flow regulators made of a stack of a silicon membrane anodically bonded to a Pyrex substrate are proposed.

A first design has been built for the derivation of cephalorachidian fluid (CSF) towards peritoneum for hydrocephalus treatment. The device allows draining CSF at the patient production rate independently from postural changes. The flow rate is regulated at 20 ml/h in the range 10 to 40 mbar. Specific features to adjust in vivo the nominal flow rate are shown.

A second design including high pressure shut-off feature has been made. The intended use is drug delivery with pressurized reservoir of typically 100 to 300 mbar.

In both cases, the membrane comprises several holes facing pillars in the Pyrex substrate. These pillars are machined in a cavity which ensures a gap between the membrane and the pillars at rest. The fluid in the pressurized reservoir is directly in contact with the top surface of the membrane, inducing its deflection towards Pyrex substrate and closing progressively the fluidic pathway through each hole of the membrane. Since the membrane deflection is highly non-linear, FEM simulations have been performed to determine both radial position and diameter of the membrane holes that ensure a constant flow rate for a given range of pressure.

8976-30, Session 7

Actively transporting virus like analytes with optofluidic plasmonic sensors for rapid and ultrasensitive biodetection *(Invited Paper)*

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Binding of analytes in solution to surface-immobilized receptors is of great importance for rapid and precise detection of biomolecules. Research shows that the binding event is not simply controlled by the chemical reaction between analytes and receptors, but also depends on the availability of the analytes in the sensing area. The latter factor is directly related to the analyte delivery mechanism. In conventional biosensing systems, the sensor performance is limited by inefficient analyte transport especially when detecting analytes with larger sizes such as viruses and cells due to their low diffusivities. In this article, we present an actively controlled optofluidic system that merges actively controlled fluidic and plasmonic nanosensors on the same platform to address this fundamental analyte transport problem. With virus like analytes, we show that the sensing response time is reduced by an order of magnitude from 4 hours to 30 minutes as compared to the conventional fluidic scheme. A dynamic range spanning 7 orders of magnitude from 10^3 to 10^9 particles/mL is quantified, corresponding to a concentration window relevant to clinical diagnostic and drug screening. In addition, the virus like analytes are captured and detected intact without being damaged, so that the samples could be further studied. This lab-on-a-chip fluidic detection system, by offering superior analyte delivery efficiency, significant reduced sensing response time and minimized sample volume, could have profound implications in wide range of biological and clinical applications.

8976-31, Session 7

Parallel optical sorting of biological cells using the generalized phase contrast method

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Optical forces are used to fixate biological cells with optical tweezers where numerous parameters and phenomena can be studied. Optical beams carry a small momentum which generates a weak optical force, but on a cellular level this force is strong enough to allow for manipulation of biological cells in microfluidic systems exclusively using light.

We demonstrate an optical cell sorter that uses simultaneous manipulation by multiple laser beams using the Generalized Phase Contrast method (GPC). The basic principle in an optical sorter is that the weak radiation force of the optical beam can push the biological cell from one microfluidic flow to another. The serial optical sorter with only a single laser beam has been demonstrated by others. Due to the weak nature of the optical forces the throughput, the number of sorted cells per second, is not high compared with other competing methods. By using multiple laser beams it is possible to multiply the throughput several times, and such laser beams can be synthesized with the GPC method. We also claim that the parallel approach can give higher purity and yield of the sorted cells.

The microfluidic system for parallel optical cell sorting is different from that of the serial optical cell sorter. However, the microfluidic systems for optical cells sorters all rely on the same basic principles. In our presentation we will demonstrate how the principles are adapted for parallel optical sorting with multiple laser beams.

8976-32, Session 7

Combining dual wavelength optical trapping in a microfluidic channel with simultaneous micro-Raman spectroscopy and motion detection

Penelope F. Lawton, John M. Girkin, Christopher D. Saunter, Durham Univ. (United Kingdom)

Since their invention by Ashkin, optical tweezers have demonstrated their ability and versatility as a non-invasive tool for micromanipulation. One of the most useful additions to the basic optical tweezers system is micro-Raman spectroscopy, which permits highly sensitive analysis of single cells or particles. We report on the development of a dual laser system combining two spatial light modulators to holographically manipulate multiple traps (at 1064nm) whilst simultaneously undertaking Raman spectroscopy using a 532nm laser. We can thus simultaneously trap multiple particles and record their Raman spectra in turn, without perturbing the trapping system. The dual beam system is built around micro-fluidic channels where crystallisation of calcium carbonate occurs on polymethylmethacrylate (PMMA) and polystyrene beads. The setup is designed to simulate at a microscopic level the reactions that occur on items in a dishwasher, where permanent filming of calcium carbonate on drinking glasses is a problem. Our system allows us to monitor crystal growth on trapped particles in which the Raman spectrum and changes in movement of the bead are recorded simultaneously. Due to the expected low level of crystallisation on the bead surfaces this allows us to obtain results quickly and with high sensitivity. The long term goal is to study the development of filming on samples in-situ with the microfluidic system acting as a model dishwasher.

8976-33, Session 7

Microfluidic optomechanics with viscous liquids

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Whispering gallery mode optical- and mechanical- resonators individually have been explored as platforms for sensing nanoparticles and bioanalytes in fluids. We develop a platform to bridge optomechanics and microfluidics, and enable parallel sensing. We optically excite mechanical vibrations in our microfluidic resonator which interact with liquids inside. By confining liquids inside the resonator, acoustical radiation losses are substantially reduced, compared to submerging mechanical resonators in liquid. This also allows evanescent light coupling which eliminates unnecessary acoustical damping. Here, we report optomechanical vibrations with water and viscous solutions inside the resonator, ranging from 20 MHz to 140 MHz. Excited oscillations lasted longer than 35 seconds without external feedback since the optomechanical vibrations are a self-sustained process. Changing the fluid inside the resonator causes shifts in resonance frequency due to the large overlap between the mechanical mode and liquid core. We measure shifts in resonance frequency while changing the concentration of sucrose solution of the capillary liquid. Starting at 27.2 MHz for a water core, the mechanical resonance frequency increases with sucrose concentration. We measure a maximum mechanical frequency of 28.6 MHz with a 45% w/w sucrose solution inside (~viscosity 3 times higher than blood). Additionally, a 30.2 MHz vibration is measured with air inside. The device showed mechanical quality factor of 2172 with water inside the resonator, which is comparable to other optomechanical devices operating in air. The interaction of mechanical mode with liquid capillary core in this device could extend optomechanics into study of non-solid phase of matter.

8976-35, Session 7

Monolithic optoelectronic chip for label-free multi-analyte sensing applications

Ioannis Raptis, Eleni Makarona, Panagiota Petrou, Sotirios E. Kakabakos, Konstantinos Misiakos, National Ctr. for Scientific Research Demokritos (Greece)

The existing technological approaches employed in the realization of optical sensors still face two major challenges: the inherent inability of most sensors to integrate the optical source in the transducer chip, and the need to specifically design the optical transducer per application. We have introduced a unique Optoelectronic chip that consists of a series of light emitting diodes (LEDs) coupled to silicon nitride waveguides allowing for multi-analyte detection. Each optocoupler is structured as Broad-Band Mach-Zehnder Interferometer and has its own excitation source and can either have its own detector or the entire array can share a common detector depending on the targeted. The light emitting devices (LEDs) are silicon avalanche diodes biased beyond their breakdown voltage and emit in the VIS-NIR part of the spectrum. The optoelectronic chip is fabricated by standard silicon technology allowing for potential mass production in silicon foundries. The integrated nature of the optoelectronic chip and the ability to functionalize each transducer independently allows for the development of miniaturized optical transducers tailored towards multi-analyte tests. The platform has been successfully applied in bioassays and binding in a real-time and label-free format and is currently being applied to ultra-sensitive food safety applications. In this work, the recent advances in the design and implementation of the optoelectronic chip are presented along with results in the real-time detection of biomolecules in certain case studies.

8976-36, Session 8

Capillary-driven microfluidic chips with evaporation-induced flow control and dielectrophoretic microbead trapping *(Invited Paper)*

Yuksel Temiz, Jelena Skorucak, Emmanuel Delamarche, IBM Zürich Research Lab. (Switzerland)

This work reports our efforts on developing simple-to-use microfluidic devices for point-of-care diagnostic applications with recent extensions that include the trapping of micrometer beads using dielectrophoresis (DEP) and the modulation of capillary-driven flow using microheaters for evaporating minute amounts of liquids.

A key strength of capillary-driven microfluidic chips is their simplicity of use. However, such chips are typically passive and do not easily allow for in-situ flow control. It is also difficult to integrate reagents in microfluidic chips for bio-analytical assays. Here, we design microfluidic chips that include loading pads, reaction channels, capillary pumps, vents, etc, and pattern a metal layer for effecting DEP and creating a microheater at the end of the flow path. DEP serves the purpose of trapping microspheres coated with receptors and analytes in specific areas of the chip for detection of a fluorescent signal. The microheater can be actuated once the chip is filled so as to create a small flow as needed by assay conditions. The microheater also alleviates from using large capillary pumps.

The chips are composed of a glass substrate that is selectively metallized with Pd and covered/sealed with patterned dry film resists. This creates native hydrophilic surfaces having electrodes for DEP and lines of Pd for resistive heating. Finally, we combined the chip fabrication with a new, effective and high-throughput chip singulation technique in which glass layers are pre-diced. We informally call this process “chip-olate” since the singulation of the ready-to-use chips is as easy as breaking a chocolate bar.

8976-37, Session 8

Real-time PCR in microfluidic devices

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A central method in a standard biochemical laboratory is represented by the polymerase chain reaction (PCR), therefore many attempts have been performed so far to implement this technique in lab-on-a-chip (LOC) devices. PCR is an ideal candidate for miniaturization because of a reduction of assay time and decreased costs for expensive bio-chemicals.

In case of the “classical” PCR, detection is done by identification of DNA fragments electrophoretically separated in agarose gels. This method is meanwhile frequently replaced by the so-called Real-Time-PCR because here the exponential increase of amplificates can be observed directly by measurement of DNA interacting fluorescent dyes.

Two main methods for on-chip PCRs are available: traditional “batch” PCR in chambers on a chip using thermal cycling, requiring about 30 minutes for a typical PCR protocol and continuous-flow PCR, where the liquid is guided over stationary temperature zones. In the latter case, the PCR protocol can be as fast as 5 minutes.

In the presented work, a proof of concept is demonstrated for a real-time-detection of PCR products in microfluidic systems. This could be shown for both operation methods described above. Protocols for on-chip Real-Time-PCR as well as the respective microfluidic devices for sensitive monitoring of fluorescent on-chip amplificate signals have been designed and tested. It is expected that during the next future microfluidic Real-Time-PCR systems will develop to competent analysis systems with respect to performances, reliability, and robustness, which will represent adequate alternatives to the currently available Real-Time-PCR systems.

8976-38, Session 8

Disposable pen-shaped capillary gel electrophoresis cartridge for fluorescence detection of bio-molecules

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We introduce a novel and cost-effective capillary gel electrophoresis system for highly efficient, high speed, high throughput bio-molecules analysis.

The CGE system has been integrated with dual excitation and emission optical-fibers with micro-ball end design for fluorescence detection of bio-molecules separated and detected in a disposable pen-shaped capillary gel electrophoresis cartridge. The high-performance capillary gel electrophoresis (CGE) analyzer has been optimized for glycoprotein analysis type applications. Using commercially available labeling agent such as ANTS as an indicator, the capillary gel electrophoresis-based glycan analyzer provides high detection sensitivity and high resolving power in 2-5 minutes of separations. The system can hold total of 96 samples, which can be automatically analyzed within 4-5 hours. This affordable fiber optic based fluorescence detection system provides fast run times (4 minutes vs. 20 minutes with other CE systems), provides improved peak resolution, good linear dynamic range (3 orders of magnitude) and reproducible migration times, that can be used in laboratories for high speed glycan (N-glycan) profiling applications. The CGE-based glycan analyzer will significantly increase the pace at which glycoprotein research is performed in the labs, saving hours of preparation time and assuring accurate, consistent and economical results.

8976-39, Session 8

Rapid detection tuberculosis using droplet-based microfluidics

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We describe the use of droplet microfluidics for the rapid diagnosis of Tuberculosis (TB) based on the encapsulation of cells in a large number (10^6) of picoliter droplets each containing a fluorogenic probe. Tuberculosis (TB), caused by Mycobacterium tuberculosis (Mtb), is one of the deadliest infectious diseases with ~1.1 million deaths in 2011. Fortunately, TB is curable with a treatment success rate of 85%. The biggest challenge is in the prompt diagnosis of TB. Delayed diagnosis has serious consequences, both in patient prognosis and disease spreading to others fueling an epidemic. Traditional methods such as acid-fast smear and culture of Mtb are either insensitive or slow. TB diagnosis will benefit from more rapid methods to detect Mtb, ideally at the point of care (POC). In this work, we use E. coli expressing BlaC, a natural enzyme expressed by Mtb, as our first demonstration of principle. The probe is a cell-permeable substrate designed to be cleaved specifically by BlaC to generate a fluorescent product. If cells expressing BlaC are present inside a drop, the probe is cleaved to render the droplet fluorescent. Counting the number of drops that are fluorescent allows us to quantify the initial concentration of cells. The use of small droplet sizes accelerates the increase in fluorescence intensity. We also show that the probe is specific to BlaC only, but not other forms of beta-lactamase.

8976-40, Session 9

Optofluidic jet waveguide for Raman spectroscopy

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An optofluidic jet waveguide for Raman spectroscopy is reported. In this device a micro-channel is used to produce a high speed liquid stream acting at the same time, as the solution to analyse and as an optical waveguide. The liquid waveguide, exploiting total internal reflection, is able to effectively collect the Raman signal produced by the chemical compound under analysis opportunely excited by means of a laser source. Using a self-aligned configuration, the liquid jet is directly coupled with a multimode optical fiber collecting the Raman signal towards the detection system.

The waveguiding nature of the liquid waveguide enables high Raman signal collection and the device configuration allows strong reduction of the background as no confining walls are used to contain the solution to analyse. The performances of the system have been successfully tested on ethanol water solutions.

8976-41, Session 9

Opto-mechanical manipulation of chemical reactions on the nanoscale with optofluidic nanotweezers

Dakota O'Dell, Xavier Serey, David Erickson, Cornell Univ. (United States)

Chemical reactions are often described as a progression along an abstract reaction coordinate in a reaction energy diagram. For reactions where the relevant reaction coordinate is the separation between the reactants, electromagnetic potentials offer an attractive way to locally manipulate these energy landscapes in a precise and controllable manner. The evanescent field from a waveguide generates an electromagnetic force that only spans tens of nanometers, but has been used previously to attract and trap nanoscale protein molecules. Applying this local force along a reaction coordinate could radically alter the corresponding chemical reaction by biasing the reaction towards one of several possible pathways or by modifying the activation energy. In this paper, we show that the adsorption of proteins onto carbon nanotubes can be controlled with opto-mechanical forces on an optofluidic chip. Silicon photonic waveguides are used to deliver 1550 nm laser light to multi-walled carbon nanotubes, which greatly amplify the electric field intensity near their surfaces due to their metallic properties. Immunoglobulin proteins are shown to adsorb to the nanotube surface only when the optical power input exceeds a critical threshold, suggesting that the adsorption reaction is being driven opto-mechanically. This reaction diagram is also modeled through a DLVO theory which was extended to account for electromagnetic potentials. The predictions made by the analytic theory are then explored by probing the potential barrier height under a variety of experimental conditions. Our optofluidic technique offers a fundamentally novel method to investigate energy landscapes and manipulate chemical reactions locally on the nanoscale.

8976-42, Session 9

Development of a novel configuration for a MEMS transducer for low bias and high resolution imaging applications

Tahereh Arezoo Emadi, Douglas A. Buchanan, Univ. of Manitoba (Canada)

A novel MEMS transducer for high resolution imaging applications is developed and characterized. This transducer is fabricated by employing a sacrificial technique and operates on the basis of creating electrostatic force between its electrodes. Unlike conventional MEMS transducers, this device benefits from a novel configuration where a stack of two polysilicon membranes vibrate simultaneously with respect to a fixed bottom electrode. The presence of an additional deflectable membrane results in a more robust structure. The transducer driving voltage is chosen in such a way that the deflection of one membrane influences the other membrane, resulting in higher vibration amplitude and therefore higher power level. Comparison is made between this novel transducer and conventional transducers fabricated with the same technique and with similar dimensions, thicknesses and materials. The resonant frequency of the transducers is determined by performing impedance measurements on devices with membrane radii ranging from 30um to 55um and as fabricated gap of 0.75um. The device spring constants are extracted from the shifts in their resonant frequencies at different bias voltages. It was observed the proposed transducers undergo a significantly larger spring constant variation, relative to conventional devices, when the DC bias voltage increases from 20V to 40V. For the 55um radius transducers, this amounted to an increase of 12.6% compared to 7.6% for the conventional device. This demonstrates the larger membrane deflection amplitude of these transducers which enhances the device sensitivity, resolution, as well as power generation capability.

8976-43, Session 9

Research and development on the construction of 2D light-driven droplet manipulation platform based on light modulation of TiOPc impedance

Yi-Chen Chen, Ho-Tsung Chen, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

In recent years, microfluidic devices are gaining popularity. For 25 micrometer to 100 micrometer channel width, 1 mm/sec to 1 cm/sec transportation speed can be achieved within today's typical microfluidic devices. To further facilitate the use and to improve the efficiency of fluidic transport, we utilized the opto-eletrowetting phenomena to develop new digital microfluidic devices. The newly developed configuration included adopting the photosensitive electrode material TiOPc (titanyl phthalocyanine) to create the electrowetting on dielectric (EWOD) mechanism. With this new development, the electric potential on the surface of TiOPc could be comprehensively changed and defined spatially by illuminating spatially distributed light beam patterns. Detailed discussions on matching the impedance of photosensitive and dielectric materials in our device were also presented. It will be shown that our newly developed devices can work at two modes, optoelectrowetting and optoelectronic tweezers respectively. Each of these modes operated at specific operating frequencies. Moreover, different light intensities influence the surface wettability gradient of TiOPc so as to construct the route for autonomous motion droplet. To quantify the effect of the light intensity on TiOPc and to explore its applications, we tried to control the polarized droplets in our EWOD devices by using different light intensities. The experimental results clearly demonstrated that the relationship of light intensity and electrowetting phenomena can provide us with a feasible platform to construct optofluidic chip with potential autonomous manipulation of samples for point-of-care home medical detection applications.

8976-44, Session 9

Real-time multi-analyte label-free detection of proteins by white light-reflectance spectroscopy

Panagiota Petrou, Georgios Koukouvinos, National Ctr. for Scientific Research Demokritos (Greece); Dimitrios Drygiannakis, Dimitris Goustouridis, Ioannis Raptis, ThetaMetrisis S.A. (Greece); Konstantinos Misiakos, Sotirios E. Kakabakos, National Ctr. for Scientific Research Demokritos (Greece)

Label-free optical sensors thanks to their advantages over the labelled ones, are considered ideal for biomedical analysis applications. In this work we introduce a label-free detection approach based on White Light Reflectance Spectroscopy offering the advantages of low cost, multi-analyte detection and high detection sensitivity. The compact optical setup consists of a VIS-NIR light source, a spectrometer and a reflection probe and is combined with a reaction cell composed by an open compartment made of polydimethylsiloxane with embedded fluid inlet and outlet tubing, and a top cover glass slide. The sensor is a Si piece with 1-micron thick thermal SiO2 film and functionalized with the recognition biomolecule e.g., antibody. The incident light is directed vertically to the surface where the biomolecular reaction takes place and the reflected interference spectrum is recorded. By monitoring the shift in the recorded interference spectrum the course of biomolecular reaction can be also monitored in real-time. By creating arrays of different biomolecules onto the sensing surface and employing a simple x-y stage, multi-analyte determinations of up to seven different reactions bands were already demonstrated with excellent repeatability and with limited alignment needs. An immunoassay for the determination of C-reactive protein (CRP), a biomarker related to acute inflammatory incidents, is used as demonstrator with a detection limit of 10 ng/mL. Regeneration of antibody coated sensing areas for up to 20 times without loss of immobilized antibody reactivity is also presented. In conclusion, the proposed sensor is characterized by low cost, high assay sensitivity and, reliability.

8976-45, Session 10

Integrated neurotransmitters and electrical signal sensing and stimulations using neurons-on-a-chip system *(Invited Paper)*

Sam Kassegne, Pieter van Niekerk, Jaco van Niekerk, Zach Achen, San Diego State Univ. (United States)

Integrated circuits and silicon microfabrication technology have recently been used to fabricate the so-called ‘neurons-on-a-chip’ system where neuron cells are cultured and then their biophysical properties including electrical characteristics investigated.

In this work, we report on the application of microfluidics in sorting and trapping neural stem cells and then allow them to form synaptic connections in preparation for not only electrical characterization but also electrochemical monitoring of neurotransmitters. A combination of microfluidics platform and microfabricated microelectrode arrays could offer a fast and reliable simultaneous, decoupled detection of neurotransmitters like dopamine and serotonin along with monitoring electrical signals. The integrated microfluidics and multi-site microelectrode array will have separate electrodes for sensing electrical and electrochemical signals - but all integrated on a single chip (Figure 1). This simultaneous sensing of ECoG electrical signals as well as electrochemical detection of neurotransmitters like dopamine and serotonin could find powerful use in DBS (deep brain stimulation) where the effect of application of electrical input (voltage) on the response of neurons could be monitored real-time. The array nature of the electrodes will also provide a key advantage of simultaneous and de-coupled detection of several neurotransmitters.

8976-46, Session 10

Label-free Electronic Detection of Target Cells

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We previously introduced a novel, label free and real time electrical impedance biosensor, called the nanoneedle biosensor. A nanoneedle biosensor structure consists of four thin-film layers, two conductive layers with an insulator layer in between. A protective oxide layer is fabricated above the top electrode and underneath of the bottom electrode to prevent the exposure of conductive electrodes to the solution. Various thicknesses and geometrical designs of the sensor were fabricated and tested. The utility of this sensor for label-free bio sensing was demonstrated and the electrical response of nanoneedle for various types of biological agents was studied. The sensor behavior was fully characterized in the presence of proteins and nucleic acids and all the affecting mechanisms on the behavior of the sensor were fully analyzed. The utility of this sensor for affinity-based biosensing was demonstrated by using biotinilated BSA and Streptavidin. We also will discuss the in vitro electrical detection of Vascular Endothelial Growth Factor (VEGF) for cancer diagnosis using anti-VEGF modified nanoneedle biosensor. Impedance changes of the sensor for various VEGF concentrations as a function of time was measured. Our demonstration of label-free and real-time detection of VEGF with this sensor can be envisioned to allow for point-of-care cancer diagnosis.

8976-47, Session 10

On the sensitivity improvement of a miniaturized label-free electrochemical impedance biosensor

Yi-Ching Kuo, Shin-Ting Chou, Pei-I Tsai, Guan-Wei Li, Chih-Ting Lin, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

Development of point-of-care (PoC) biosensors continues to gain popularity due to the demand of improving the cost performance in today’s health care. As cardiovascular disease (CVD) induced death remains on the top 3 death causes for most Asian countries, this paper is to present a high-sensitivity PoC biosensor for the detection of CVD biomarkers.

To meet the PoC biosensors requirements, which include characteristics as small size, low cost, and ease of operation, we adopted electrochemical methods as the basis of detection. The 4-aminothiophenol (ATP) was adopted as the bio-linkers to facilitate the antibody-antigen interaction. A more stable three-electrode configuration was miniaturized and laid out onto a biochip. A microfluidics subsystem based on opto-piezoelectronic technology was also integrated to create the microfluidic biochip system. To improve the detection sensitivity associated with the reduction in biochip size, electrochemistry simulation was used to investigate several potentially effective means. We found that the electric field on the edge near working electrode (WE) and counter electrode (CE) was higher, which was verified by using atomic force microscopy (AFM) to measure the surface potential. With the successful verification, we explored the configuration, i.e., lengthened the edge of WE and CE without changing the areas of WE and CE and the gap between this two electrodes, so as to evaluate the possibility of improving the measurement efficiency in our newly developed biochips. Detailed design, simulation and experimental results, improved design identified, etc. will all be presented in detail in this paper.

8976-48, Session 10

Monolithic cell counter based on 3D hydrodynamic focusing in microfluidic channels

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Hydrodynamic focusing is a powerful technique frequently used in microfluidics that presents a wide range of applications since it allows focusing the sample flowing in the device to a narrow region in the center of the microchannel. In fact thanks to the laminarity of the fluxes in microchannels it is possible to confine the sample solution with a low flow rate by using a sheath flow with a higher flow rate. This in turn allows the flowing of one sample element at a time in the detection region, thus enabling analysis on single particles.

Femtosecond laser micromachining is ideally suited to fabricate device integrating full hydrodynamic focusing functionalities thanks to the intrinsic 3D nature of this technique, especially if compared to expensive and complicated lithographic multi-step fabrication processes. Furthermore, because of the possibility to fabricate optical waveguides with the same technology, it is possible to obtain compact optofluidic devices to perform optical analysis of the sample even at the single cell level, as is the case for optical cell stretchers and sorters. In this work we show the fabrication and the fluidic characterization of extremely compact devices having only two inlets for 2D (both in vertical and horizontal planes) as well as full 3D symmetric hydrodynamic focusing. In addition we prove one of the possible application of the hydrodynamic focusing module, by fabricating and validating (both with polystyrene beads and erythrocytes) a monolithic cell counter obtained by integrating optical waveguides in the 3D hydrodynamic focusing device.

8976-49, Session 10

Nitric oxide (NO) release by vascular endothelial cells grown in microchannels of different sizes

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Dysfunction of the vascular endothelium, the cellular monolayer lining the inner surface of blood vessels, plays a critical role in the development of atherosclerosis. Atherosclerosis lesions develop preferentially in arterial regions where endothelial cells (ECs) are round, whereas regions of elongated ECs are largely protected. The basis of the correlation remains unknown. We have previously demonstrated that culturing ECs in microchannels of different sizes allows elongation of the cells to various degrees. We are interested in determining if microchannel-induced EC elongation regulates cell function.

A key function in ECs is the release of the potent vasodilator nitric oxide (NO). Abnormalities in NO release are considered as a manifestation of endothelial dysfunction. In this paper, a system is presented, which enables in vitro detection of NO released from ECs cultured in microchannels. The system consists of arrays of PDMS microchannels of a given width. The number of channels in each array is controlled to yield a constant cell culture surface area (75 mm2): for instance, 30 100 micron-wide channels vs. one 3 mm-wide channel. The microchannel surfaces are collagen-coated and ECs are cultured to confluence within the channels. A cell scraper is used to scrape extraneous cells cultured between channels, and NO measurements are made 24 hrs later. A chemiluminescence-based sensor system (NOA 280i, Sievers NO Analyser) is utilized to measure sample NO. Initial results show that NO concentrations averaging 500 nM above baseline medium values can be measured from our microchannel samples. We are currently comparing data sets to see if a difference can be detected among signals derived from channels of different widths.

8976-50, Session PTue

High precision innovative micropump for artificial pancreas

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The concept of artificial pancreas, which comprises an insulin pump, a continuous glucose sensor and a control algorithm, is a major step forward in managing diabetes for type 1 patients.

The stability of the control algorithm is based on short-term precision micropump to deliver rapid-acting insulin and to specific integrated sensors able to monitor any failure leading to a loss of accuracy.

Debiotech's MEMS micropump, based on the membrane pump principle, is made of a stack of 3 silicon wafers. The pumping chamber comprises a pillar check-valve at the inlet, a pumping membrane which is actuated against stop limiters by a piezo cantilever, an anti-free-flow outlet valve and a pressure sensor. An additional sensor downstream the outlet valve is mainly dedicated to occlusion detection. The micropump inlet is tightly connected to the insulin reservoir while the outlet is in direct communication with the patient skin via a cannula.

To meet the requirement of a pump dedicated to close-loop application for diabetes care, in addition to the well-controlled displacement of the pumping membrane, the high precision of the micropump is based on specific actuation profiles that balance effect of pump elasticity in low-consumption push-pull mode and to detection algorithms that allow determining any loss of accuracy larger than 5% due to air bubble, leakage or overpressure. Finally the system is able to determine, even at rest, the maximum rate of out-of-stroke over or underdelivery due to abnormal conditions of pressure in the reservoir.

8976-51, Session PTue

Optofluidic prism refractometer

Sergio Calixto-Carrera, Areli Montes-Perez, Guillermo Garnica, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

Instruments used to measure the refractive index of different materials like gases, liquids or solids are called refractometers. They rely on different physical principles like interferometry or total internal reflection (TIR). Here we present a refractometer based on an optofluidic configuration that uses a hollow right triangle prism. The prism is made in a silicone block of about 13mm x 13mm x 9mm (height). Prism has an apex angle of 45o and measures about 9 mm x 9 mm x 13 mm and 8 mm height. Optical configuration resembles a classical spectrometer. Light coming from a He – Ne laser is introduced by one side of the silicone block. After light traverses some of the silicone block it is refracted at the hypotenuse of the prism. Then it travels through the liquid in the prism and is refracted in the second surface of the prism or cathetus. Finally it leaves the silicone block in the last surface of it. Beam angular movement is done by changing the liquid in the hollow prism. Light beam has a diameter of about 3 mm and has a Gaussian intensity profile. By placing a 105/125 optical fiber in the output beam we can detect the profile of the beam as it moves when the liquid in the hollow prism is changed. Thus, we can obtain a calibration curve of Intensity vs. Refractive Index. To know the refractive index of a liquid we inject it in the hollow prism and read the intensity of light out coming from the optical fiber.

8976-52, Session PTue

Optical characterization of Jerusalem cross-shaped nanoaperture antenna arrays

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Recent advances in nanofabrication and computational electromagnetic design techniques have enabled the realization of metallic nanostructures in different shapes and sizes with adjustable resonance frequencies. To date, many metamaterial designs in various geometries with the use of different materials have been presented for the applications of surface plasmons, cloaking, biosensing, and frequency selective surfaces [1-4]. Surface plasmons which are collective electron oscillations on metal surfaces ensure that plasmonic nanoantennas can be used in many applications like biosensing at infrared (IR) and visible regions. The nanostructure that we will introduce has a unit cell that consists of Jerusalem cross-shaped nanoaperture on a gold layer, which is standing on a suspended SiNx membrane. The proposed nanoaperture antenna array has a dual band spectral response. In this study, we will present the sensitivity of the resonance characteristics of Jerusalem cross-shaped nanoaperture antenna arrays to the changes in substrate parameters and metal thickness. We will demonstrate that two resonance frequency values can be adjusted by changing the thicknesses of the dielectric substrate and the metallic layer. Numerical calculations on spectral response of the nanoantenna array are performed by using Finite Difference Time Domain (FDTD) method [5]. The results of the simulations specify that resonance frequencies and the band gap vary by the change of substrate and metal thicknesses. These variations is a sign of that the proposed nanoantenna can be employed for microfluidics and biosensing applications.

References:

1. Y. R. Padooru, A. B. Yakolev, P.Y. Chen and A. Alù, “Line-source excitation of realistic conformal metasurface cloaks”, J. Appl. Phys., Vol. 112, 104902, 2012.

2. F. Wang and Y. R. Shen, “General properties of local plasmons in metal nanostructures,” Phys. Rev. Let., Vol. 97, 206806, 2006.

3. A. Haes and R. P. Van Duyne, “A unified view of propagating and localized surface plasmon resonance biosensors”, Anal. Bioanal. Chem., Vol. 379, 920, 2004.

4. Y.P. Kathuria, “Frequency selective IR-filter produced by using EB-lithography”, Applied Surface Science, Vol. 253, Issue 19, 7826, 2007.

5. The numerical simulations are carried out using a finite-difference-time-domain package, Lumerical FDTDTM, www.lumerical.com, 2013.

8976-53, Session PTue

Thermally induced light-driven microfluidics using a MOEMS-based laser scanner for particle manipulation

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One key challenge in the field of microfluidics and lab-on-a-chip experiments for biological or chemical applications is the remote manipulation of fluids, droplets and particles. These can be volume elements of reactants, particles coated with markers, cells or many others. Light-driven microfluidics is one way of accomplishing this challenge.

In our work, we manipulated micrometre sized polystyrene beads in a microfluidic environment by inducing thermal flows. Therefore, the beads were held statically in an unstructured microfluidic chamber, containing a dyed aqueous solution. Inside this chamber, the beads were moved along arbitrary trajectories on a micrometre scale.

The experiments were performed, using a MOEMS (micro-opto-electro-mechanical-systems)-based laser scanner with a variable focal length. This scanner system is integrated in a compact device, which is universally applicable to various microscope setups. The device utilizes a novel approach for varying the focal length, using an electrically tuneable lens. A quasi statically driven MOEMS mirror is used for beam steering.

The combination of a tuneable lens and a dual axis micromirror makes the device very compact and robust and is capable of positioning the laser focus at any arbitrary location within a three dimensional working space. The developed device, which will be presented in detail, constitutes a valuable extension to manually executed microfluidic lab-on-chip experiments.

8977-102,

Tailoring light for optically-guided nano- and microassembly: from bio-hybrid robots to droplet cages

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With the utilization of holographic beam shaping techniques in optical tweezers, complex trapping configurations based on tailored light fields have been realized to overcome current challenges in applications in fluidic and biomedical systems. Holographically generated higher-order light modes, for example, can induce highly structured and ordered three-dimensional optical potential landscapes allowing optically-guided assembly of nanocontainers or bio-hybrid nano robots, and can be used as a tool to explore the inner cell, paving the way to optically-assisted analysis of diseases.

Tailored light fields can also be implemented to induce non-optical forces. Optoelectronic tweezers take advantage of dielectrophoretic forces to trap microstructures in an adaptive and flexible, massively parallel way. Photophoretic trapping makes use of thermal forces and by this means is perfectly suited for trapping absorbing particles in dynamic light cages or to guide droplets. Hence the combination of holographically tailored light fields with complementary dielectrophoretic and photophoretic trapping provides a holistic approach to novel optical nano- and microassembly scenarios of bio-hybrid or fluidic matter.

8977-1, Session 1

MEMS endoscopes for advanced biomedical imaging *(Invited Paper)*

Ki-Hun Jeong, Hyeon-Cheol Park, Kyungwon Jang, KAIST (Korea, Republic of)

Medical endoscopy has been widely used as the primary optical method for clinical in vivo diagnosis. Conventional white light endoscopy is currently limited to the reflection imaging from tissue surface with low spatial resolution. Advanced optical imaging techniques for optical biopsy, which can offer immediate diagnostic information, have been of much interest for clinical applications such as optical biopsy or imaging guided surgery. Miniaturizing optical imaging systems is still challenging, particularly in developing advanced endoscopes due to tough spatial restrictions. Recently, Optical MEMS techniques enables compact endoscopes with high speed and high resolution under clinical safe operations. Side and circumferential viewing endoscopes have been intensively studied and demonstrated for cardiology and gastroenterology. On the other hands, forward viewing endoscopes would be the most easily adapted on a conventional endoscope. However, these are generally far fewer in number due to the lack of forward scanning units. In this work, we will introduce some recent development of MEMS enabled endoscopes for forward endoscopic imaging. The MEMS lens scanner, which consist of two commercial aspheric glass lenses laterally mounted on two resonating electrostatic MEMS scanner, has been fully packaged and combined with Lissajous scanning based 3D SD-OCT system. Compact 3D stereoscopic imaging endoscope based on a single aperture and a single detector was also demonstrated by using parallel plate rotation system. A thin transparent plate in front of a single camera was rotated by using bimorph MEMS actuator to obtain binocular disparities within a limited space of the endoscope catheter. A novel combination of MEMS and advanced optical imaging modalities will provide new directions for advanced endoscopic diagnosis.

8977-2, Session 1

A high-resonance-frequency MEMS Fabry-Perot tunable filter with applications in high speed swept-source optical coherence tomography (OCT) imaging

Vaibhav Mathur, Peter Whitney, Mark Kuznetsov, AXSUN Technologies Inc. (United States)

We present design, performance modeling, and initial characterization of a high-resonance-frequency MEMS Fabry-Perot tunable filter with applications in high speed swept-source optical coherence tomography (OCT) imaging. The Fabry-Perot (F-P) filter consists of fixed and movable-membrane silicon micro mirrors assembled together with a precision bonding technique. Resonance frequency and damping characteristics of the movable-mirror membrane are critical for producing F-P filter with high repetition rate and high duty cycle wavelength tuning waveforms. We describe the finite element analysis (FEA) studies of the electro-mechanical response of the movable tethered membrane. We also explore the effect of damping on the resulting filter response waveform and duty cycle. Initial characterization results from laser vibrometry and expected enhancements of using such a filter in a swept-frequency OCT laser source are also described.

8977-33, Session PTue

Efficient grating simulation for general incident beam

Site Zhang, Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany); Jani Tervo, Univ. of Eastern Finland (Finland)

Fourier modal method (FMM) is known as a powerful technique in simulations of periodic micro-structures, e.g., gratings. For an arbitrary plane wave incidence, the Rayleigh coefficients for both reflected and transmitted field can be calculated with FMM efficiently. When dealing with a beam incidence, FMM together with plane wave decomposition can still solve this question. However the needed computational effort increases with the increasing number of plane wave components in angular spectrum domain. To solve this problem, we put forward an approach which integrates interpolation technique into the method above. For most diffractive thin elements, the complex Rayleigh coefficients distribution is a smooth function. In this case several well-selected plane wave components are enough to represents the diffraction property of the beam. We analyze the selected components with FMM while we use cubic interpolation to obtain the results of the rest. Besides the general approach, another efficient approach for especially divergent incident beam is also presented in this article. It enables a parallel FMM analysis which calculates a set of plane wave components in one computational loop.

8977-34, Session PTue

Parabasal thin element approximation for the analysis of the diffractive optical elements

Huiying Zhong, Friedrich-Schiller-Univ. Jena (Germany); Site Zhang, Friedrich-Schiller-Universität (Germany); Frank Wyrowski, Muhammad Ahmad, Friedrich-Schiller-Univ. Jena (Germany); Hagen Schweitzer, LightTrans VirtualLab UG (Germany)

Efficient diffraction design and analysis of 2D diffractive optical elements is still a challenging task. The design of diffractive optical elements (DOEs) can be handled very efficiently by using iterative Fourier transform algorithm (IFTA) which takes optimized advantage of available phase and amplitude freedoms in DOE design. The rigorous approach for analysis of diffractive optical elements is using Maxwell solvers e.g. finite element method (FEM) but they require much numerical effort and often impractical to use. On the other hand the conventional thin element approximation (TEA) works well but its application is limited to normal illumination case only. Therefore, we have developed an extend model, which is referred to as Parabasal thin element approximation (Parabasal TEA). This technique is based on local plane wave approximation (LPWA) and local interface approximation (LIA). With this technique, parabasal oblique incident beam through general diffractive optical element can be traced. Finally we will get an equidistantly sampled target field by a numerically efficient procedure.

8977-35, Session PTue

120° silicon double mirrors for the use in a micro optical gyroscope

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In this work a new concept for the realization of a micro RLG was developed. It allows minimization of the influence of misalignment errors by the use of double mirrors. As a consequence, measurement errors can be minimized. The idea being pursued to improve the design robustness to alignment errors is the use of double mirrors with an angle between its two mirrors that is intrinsically defined by silicon crystallography and with a total reflection angle that is robust against misalignment. Here, the angle error that occurs either during installation or due to thermal stress can be limited to an error that arises and can be detected during production. This error can be compensated by the Sensor. The principle of the double mirror is tolerant to small vertical axis errors in the installation and still leads to constant reflection angles

The development of 120 ° double mirrors for use in a MOEMS RLG is described. Starting with the layout, all major processing and manufacturing steps of the mirror elements will be described. For the fabrication of these mirrors (100) silicon wafers are used, which are tilted by 5.3 ° in the (110) plane and, therefore, achieve an etching flank of 60 °by KOH wet chemical etching. A 33% KOH solution with addition of isopropanol is used to obtain uniform and smooth etched sidewalls. Two structured wafers are connected by silicon direct bonding and then cut into small mirror elements to mount them in the RLG.

8977-3, Session 2

Micro-scanning mirrors for high-power laser applications *(Invited Paper)*

Thilo Sandner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Simon Kimme, Fraunhofer-Institut für Photonische Mikrosysteme (Germany) and Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik (Germany); Thomas Grasshoff, Ulrich Todt, Harald Schenk, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

In this paper we will present two novel micro scanner devices especially developed for high power laser applications, e.g. for fast and precise beam guidance inside a novel handheld laser instrument for laser surgery. The miniaturized scanning system consists of two different MEMS mirrors. A first scanning mirror, which has a mirror aperture of 5mm x 7,1mm, is based on the electrostatic, resonant / linear LinScan technology developed by Fraunhofer IPMS. It was optimized for an efficient laser cutting process with fast beam guidance. The second magnetically driven mirror, with a mirror plate of 6mm x 8mm, enables two-dimensional static deflections up to ± 3° and thus allows for a static correction of the laser beam position. This mirror combination is intended for high power laser applications, where fast and dynamic beam guidance with compact, handy instruments is required. As an example, researchers from the Fraunhofer Institute for Laser Technology ILT are evaluating the Fraunhofer IPMS technology to develop a handheld laser instrument for the laser cutting of cranium bone, where a high-energy ps-laser with large repetition rates allows for the laser treatment of bone and hard tissue without the usual accompanying thermal problems (tissue carbonization). Here, the pair of MEMS scanners was illuminated by a ps-laser (15ps, 10kHz) of 20 W continuous power and 3mm beam diameter with a wavelength of 532nm. In order to be able to use micro scanners at such high laser powers and with a power density greater than 100 MW / cm?, we have created large mirrors with apertures greater than 5 mm as well as highly reflective and robust optical coatings which have a high laser damage threshold and a high optical planarity of < ? / 10. To achieve this, high reflective micro mirrors with dielectric Bragg coatings which are compensated for stress and thermal effects were developed. Both MEMS devices were successfully tested with a high power ps-laser at 532nm up to 20W CW. However, the novel micro scanning mirrors - suitable for high laser power – also show a high potential for industrial laser applications such as laser marking systems.

8977-4, Session 2

Two-dimensional scanning using two single-axis, low-voltage, PZT-resonant micromirrors

Shanshan Gu-Stoppel, Joachim Janes, Hans-Joachim Quenzer, Ulrich Hofmann, Wolfgang Benecke, Fraunhofer-Institut für Siliziumtechnologie (Germany)

Micromirrors are entering different fields because of shrinking dimensions and decreasing power consumption. The micromirrors dedicated for laser-projection must simultaneously fulfill the requirements of large tilting angle and high resonant frequencies, which is determined by the drivers and structures of micromirrors. The used leverage mechanical amplification applying PZT drivers result in large tilting angles at low power while high frequencies are defined by the suspensions.

The most 2D laser-projections are based on biaxial micromirrors, which leads to the small chip size but encounters crosstalk and interference of the parasitic modes. Therefore, the motivation for this work is to show the combination of two independent resonant micromirrors for 2D scanning, whose aperture size, tilting angle and the respective frequencies are specified for laser-projection.

This paper presents designs and fabrication process of two single-axis PZT micromirrors with 1 mm diameter and 1.4 mm x 4 mm apertures, whose frequencies are 60 kHz and 16 kHz respectively. These micromirrors reach large optical scan angles of up to 40° driven by 10 V rectangular pulses and show high Q-factors of about 1000. The investigation on the long-term stability of a PZT driver has detected more than 100 Billion cycles stable running of the micromirror. The combined results of experimental diagnostics and FEM analyses give rise to new designs iteratively leading to larger deflection and appropriate frequencies, which are currently fabricated.

8977-5, Session 2

Analysis of capacitive sensing for 2D-MEMS scanner laser projection

Thomas von Wantoch, Christian Mallas, Ulrich Hofmann, Joachim Janes, Bernhard Wagner, Wolfgang Benecke, Fraunhofer-Institut für Siliziumtechnologie (Germany)

Typical applications for resonantly driven vacuum packaged MEMS scanners including laser projection displays require a feedback signal for closed-loop operation as well as high accuracy angle synchronization for data processing. A well known and widely used method is based on determining the angular velocity of the oscillating micromirror by measuring the time derivative of a capacitance.

In this work we analyze a capacitive sensing approach that uses integrated vertical comb structures to synchronize the angular motion of a torsional micromirror oscillating in resonance. The investigated measurement method is implemented in a laser display that generates a video projection by scanning a RBG laser beam. As the 2D-micromirror performs sinusoidal oscillations on both perpendicular axes a continuously moving Lissajous pattern is projected. By measuring the displacement current due to an angular deflection of the movable comb structures an appropriate feedback signal for actuation and data synchronization is computed. In order to estimate the angular deflection and velocity a mathematical model of the capacitive sensing system is presented. In particular, the nonlinear characteristic of the capacitance as a function of the angle that is calculated using FEM analysis is approximated using cubic splines. Combining this nonlinear function with a dynamic model of the micromirror oscillation and the analog electronics a mathematical model of the capacitive measurement system is derived. To evaluate the proposed model numerical simulations are realized using MATLAB®/Simulink®and are compared to experimental measurements.

8977-6, Session 2

Tunable external cavity quantum cascade lasers (EC-QCL) an application field for MOEMS-based scanning gratings

Jan Grahmann, Harald Schenk, André Merten, Michael Fontenot, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Ralf Ostendorf, Daniela Bleh, Joachim Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

NIR spectrometers have made strong progress in recent years, providing compact, portable and affordable analytic systems. But for many applications in the chemical, pharmaceutical and the food industry, in situ process information is required and the analysis time must be short for real time inline process monitoring. This can partially be provided nowadays by spectroscopic analysis in the VIS/UV/NIR range. However the strongest absorption lines of substances relevant in the mentioned fields of application are in the MIR-wavelength range of 3µm – 12 µm. In this range analytical methods like FTIR- and Raman spectroscopy are used and there is still a strong need for the MIR range to follow the development of cost effective, fast and portable systems in the shorter wavelength range.

The use and development of a MOEMS scanning grating as wavelength selective element for a Quantum Cascade Laser operated in an external cavity Littrow configuration allows the development of a very compact tunable laser source, providing high power spectral density in the MIR range for spectral analysis. Combined with the stronger absorption lines for the relevant chemical bindings in this wavelength range, sensitivity increases and the unambiguous identification of substance becomes easier.

The challenge for the MOEMS scanning grating is to provide high diffraction efficiency over a possibly large wavelength range, a large diameter of up to 5mm, as well as a frequency of 1 kHz and large mechanical deflection angles. The required optical grating depths require an adapted technological approach to integrate the optical grating technology into the process flow for MOEMS scanners.

8977-7, Session 2

High-speed focus control capability of electrostatic-pneumatic actuation of MEMS deformable mirrors

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MEMS deformable mirrors are versatile elements for optical focus control. Electrostatic-pneumatic actuation of deformable mirrors offers relatively large membrane stroke to increase the optical focus range. Moreover this novel actuation method maintains high speed focus control with either positive or negative focus. The MEMS mirrors consist of two membranes suspended over two sealed cavities. One membrane serves as the deformable mirror and the other one as the pneumatic actuator. The membranes are made of photoset epoxy SU-8. The cavities, which are on opposite sides of the silicon substrate, are connected through small air channels A cryogenic silicon etch is used to create those high aspect ratio air channels. In this paper the focusing speed of electrostatic-pneumatic actuated mirrors is investigated. The speed of focusing is dependent on membrane tension, membrane size, air channel configuration and the size of the backchamber. The volume of the backchamber as well as opposing pneumatic force for electrostatic actuation can be controlled by applying voltage to the pneumatic membrane so that air damping of the mirrors is under electronic control as well. The frequency response and step response of the mirrors are reported. The 3 mm diameter mirrors with 5 mm diameter actuator membrane achieve 30 kHz bandwidth with electrostatic actuation and 5 kHz with the pneumatic actuation. The bandwidth for pneumatic actuation of the mirror is limited by the actuator membrane motion. When the mirror size is equal to the actuator, pneumatic and electrostatic actuations show similar bandwidth. The settling time of the step response for both electrostatic and pneumatic actuation is less than 100 µs.

8977-8, Session 2

Wafer-level vacuum-packaged two-axis MEMS scanning mirror for pico-projector application

Ulrich Hofmann, Frank Senger, Joachim Janes, Christian Mallas, Fraunhofer-Institut für Siliziumtechnologie (Germany); Vanessa Stenchly, Fraunhofer Institut fur Siliziumtechnologie (Germany); Thomas von Wantoch, Fraunhofer-Institut für Siliziumtechnologie (Germany); Hans-Joachim Quenzer, Manfred Weiss, Fraunhofer Institut fur Siliziumtechnologie (Germany)

Hermetic wafer level packaging of MEMS scanning mirrors effectively protects the MEMS device against contamination already at the step of fabrication but also after integration into the final application. By integration and activation of a thin film getter the MEMS mirror operates in its own miniature vacuum environment and thereby experiences lowest damping enabling high scan frequencies at large scan amplitudes and at very low power consumption. High Q-factors are achieved that enable to realize high resolution biaxial scanning mirrors at minimum chip size which is advantageous for all pico-projector display applications. On the other hand resonant operation of both axes of a high-Q scanning mirror can cause disturbing flicker image artifacts depending on the frequency ratio of the two scan axes. This paper reports on concept fabrication and characterization of an improved MEMS mirror design to avoid such artifacts.

8977-36, Session 2

Rapidly analyzing parametric resonance and manufacturing yield of MEMS 2D scanning mirrors using hybrid finite-element/behavioral modeling

Sandipan Maity, Susan Liu, Coventor, Inc. (United States); Stephane Rouvillois, Gunar Lorenz, Coventor, SARL (France); Mattan Kamon, Coventor, Inc. (United States)

Nonlinear dynamics of electrostatically actuated MEMS scanning mirrors

require reduced order models to predict transient scanning behavior when driven in parametric resonance. These reduced models are either handcrafted, which limits their accuracy to that of simple analytic relationships, or are extracted from finite-element simulations, which limit their applicability to a single set of design dimensions, making design iterations laborious.

Behavioral-modeling environments of the past decade have helped by providing component libraries for common MEMS structures such as beams and combs. However, such environments struggle to meet the needs of ever-changing design architectures in MEMS.

In this paper, we present a hybrid modeling approach that combines finite elements with behavioral modeling to overcome these shortcomings. As an example, we show, using Bernoulli beam elements can lead to errors in modeling of mirrors with thick SOI suspension structures (~30um). By using finite elements that include warping, the correct behavior is captured with only a few more degrees of freedom. Since the order is still low, parametric resonant behavior can still be simulated. As another example, large scanning angle mirror design requires accurate electrostatic comb force computation when the comb fingers no longer overlap. Analytic models are difficult in this regime but numerical quadrature combined with analytic conformal-mapping techniques can accurately capture these electrostatic forces. The model is validated against measurement on a previously fabricated scanning mirror.

Finally, because the model is of low-order and expressed in terms of variable design parameters, not fixed values, statistical manufacturing yield analyses are now feasible.

8977-9, Session 3

A robust design and fabrication of micro-machined electro-absorptive optical modulator for 3D imaging *(Invited Paper)*

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A time-of-flight (TOF) based three dimentional (3D) image capturing system and its enhanced optical modulating device are presented. The 3D image capturing system includes 850nm IR source (typically compact Laser diodes) and high speed image modulator, so called optical shutter. The optical shutter consists of multi-layered optical resonance cavity and electro-absorptive layers. The optical shutter is a solid-state controllable monochrome filter which modulates the monochrome IR image to extract the phase delay due to TOF of the IR light. This presentation especially addresses robustness issues and its solutions when operated under practical enviroments such as ambient temperature variation and existence of sun light (e.g. outdoors). The wavelength of Laser diode varies substantially depending on the ambient temperature, which degrades the modulation efficiency. To get a robust operation, the bandwidth of transmittance of the optical shutter is drastically improved with a novel coupled Fabry-Perot resonance cavity design to cover the wavelength range of the Laser diode. Also, to suppress the interference of Solar irradiance to IR source, a novel driving scheme is applied, in which IR light and optical shutter modulation duties are timely localized, i. e. 'bursted'. Suggested novel optical shutter design improvement and burst driving scheme enable capturing of a full HD resolution of depth image under the realistic usage environment, which so far tackles the comerciallization of 3D sensors. Design, fabrication, characterization of the optical shutter, 3D capturing system prototype and image test results are presented.

8977-10, Session 3

Next generation miniature simultaneous multi-hyperspectral imaging systems

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MOEMS based Fabry-Perot tunable infrared filter array uses electrostatic actuation for Etalon gap tuning. The Etalons are made up of fixed and spring mounted movable mirrors which are metal plated and act as the electrodes in the electrostatic control system. The Fabry-Perot tunable array (FPTA) has 16 elements in a 4 x 4 configuration. When coupled to a 1024 x 1024 pixel element focal plane array give 256 x 256 pixel based resolution. Each Etalon in the FPTA is tuned to a different quiescent frequency between 1 and 4 microns thus allowing simultaneous spectral imaging each frame of the camera.

Coupling the MOEMS based FPTA with a lenslet array and a fore-optic collimator will give simultaneous multispectral imaging of the same target in the field of view. Then tuning the Etalon gap each frame will fill in the spectral bands between the quiescent wavelengths thus allowing hyperspectral imaging in less than 1 second over the SWIR and MWIR bands in a single sensor.

The concept design of the FPTA along with the fundamental processing techniques used to manufacture the MOEMS device will be presented. Conceptual system architecture will also be presented.

This work is being sponsored by an SBIR program with the US Army. It is anticipated that this technology can be used for both defense and commercial applications in the area of gas imaging and analysis, IED threat detection, chemical and biological warfare agent detection, medical and chemical imaging just to name a few.

8977-11, Session 3

MEMS-based miniature FT-IR engine with built-in photo-detector

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A MEMS FT-IR engine is developed as a key device for Fourier-Transform Infrared Spectrometer which consists of a Michelson interferometer, an optical fiber groove for incident light and a photo-detector. All these elements except for the photo-detector are monolithically fabricated by MEMS technology based on Silicon. The optical elements such as a beam splitter, a fixed mirror and a moving mirror compose the Michelson interferometer, which are formed by DRIE (Deep Reactive Ion Etching) and aligned simultaneously with high degree of precision. The vertical side walls are utilized as optical surfaces so that the incident light path is located in parallel with the Silicon substrate. The moving mirror is driven by an electro-static MEMS actuator. The photo detector is placed above an angled mirror which is formed by the wet etching exposing the Silicon crystal plane at the end position of light path. All the elements including the photo detector are hermetically covered by a lid of Silicon in the vacuum chamber by using a surface activate bonding technology. In order to reduce the cost, wafer level process and separation of each chip by a laser dicer after all assembly processes are introduced.

The following characteristics of the FT-IR engine are obtained from an experimental result on the conditions of 14 x 16 x 1 mm in size, 0.01% in optical coupling loss, 30cm-1 in resolution of wavenumber and 25dB in SNR in a range from 6000 to 8500 cm-1.

8977-12, Session 3

A new generation of MEMS middle-infrared spectrometers

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Mid infrared spectroscopy has been developed to a powerful and essential method of material analysis, with a steadily increasing number of industrial and scientific application fields. The so called spectral fingerprint range enables identification of chemical compounds by their unique spectral pattern. To provide a suitable miniaturized and portable MIR spectrometer solution at an affordable price, an existing MEMS NIR spectrometer module has been expanded in its wavelength range.

The developed spectrometer belongs to the category of scanning grating spectrometers. Main component is a fast oscillating micro mirror which moves sinusoidal with high mechanical precision enabling a high stability of according wavelength axis. This is supported by a highly precise optical tracking of the actual motion. Mono-crystalline silicon guarantees a long-life operation with no wear even under harsh environmental conditions. Spectral signal acquisition is realized by using a TE-cooled MCT single element detector assisted by low noise trans-impedance amplifier. With the help of integrated logic components a data pre-processing takes place, such as averaging, offset subtraction, detector transfer characteristic correction and noise shaping. Due the compact and flexible setup, the spectrometer is suitable for the use in various applications, such as process control in chemical industry, gas mixture analysis or liquid verification. The portability of the device opens up new application possibilities in mobile environment.

In this paper the advances of the promising technology and its specific applications will be described. Advanced performance issues and reliability test results of the device be reviewed in detail.

8977-13, Session 3

MEMS Fabry-Perot interferometer with Si-air mirrors for mid- and thermal infrared

Mikko Tuohiniemi, Antti Näsilä, Altti Akujärvi, VTT Technical Research Ctr. of Finland (Finland)

We recently introduced a surface micro-machined tuneable Fabry-Perot interferometer (MEMS-FPI, MFPI) for the thermal infrared (TIR) range around 10 µm. The benefits of the device included the single-wafer manufacturing process and the wide, millimetre-range optical aperture. The TIR-range operation was enabled by Si/air thin-film mirrors so that a solid bi-layer structure was avoided. We reached a 1 % relative peak width and 30 % tuning range.

Next, similar MEMS structure will be exploited at the middle infrared (MIR) near 4 µm. We demonstrate a 'CO2-range' MFPI, which already has proven commercial potential in CO2 detection with earlier MEMS solutions. We target at two-fold improvement of the resolution, i.e. the transmission peak width, as compared with the published wide-aperture MFPIs. We expect a peak-width variation below 20 % over a 30 % tuning range. The improved performance will serve the future CO2 monitoring markets in the interior air conditioning as well as in the automotive.

We now introduce the MFPI structure and manufacturing aspects that enabled the TIR range and which are now exploited for improving the performance at the MIR range. The implications of the shorter wavelength on the design are highlighted. We present the measured results for the key performance indicator, the transmission spectrum of the MIR MFPI. The tuning performance of the final device is predicted by comparing these measurements with the results of the TIR version. The results of both the earlier TIR and the new MIR version are reflected against the simulation predictions.

8977-14, Session 4

High-speed 32?32 MEMS optical-phased array *(Invited Paper)*

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Optical phased arrays (OPAs) with fast response time are of great interest for various applications such as displays, free space optical communications, and lidar. Existing liquid crystal OPAs have millisecond response time and small beam-steering angle. Here, we report on a novel 32?32 MEMS OPA with fast response time (<4 microseconds), large field of view (±2°), and narrow beam divergence (0.1°). The OPA is composed of high-contrast grating (HCG) mirrors which function as phase shifters. Relative to beamsteering systems based on a single rotating MEMS mirror, which are typically limited to bandwidths below 50 kHz, the MEMS OPA described here has the advantage of greatly reduced mass and therefore achieves a bandwidth over 500 kHz. The OPA is fabricated using deep UV lithography to create submicron mechanical springs and electrical interconnects, enabling a high (85%) fill-factor. Each HCG mirror is composed of only a single layer of polysilicon and achieves >99% reflectivity through the use of a subwavelength grating patterned into the polysilicon surface. Conventional metal-coated MEMS mirrors must be thick (1-50 microns) to prevent warpage arising from thermal and residual stress. The single material construction used here results in a high degree of flatness even in a thin 300 nm HCG mirror. Beamsteering is demonstrated using both binary and analog phase patterns and is accomplished with the help of a closed-loop phase control system based on a phase-shifting interferometer that provides in-situ measurement of the phase shift of each mirror in the array.

8977-15, Session 4

Newly developed broadband plasmonic absorber for uncooled infrared detectors

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In this paper, we introduces a floating plasmonic absorber having multiple resonances in metallic nanostructures and broadband absorption characteristics by adjusting Drude relaxation rate of metal, which can absorb infrared in a relatively small resonator. This plasmonic broadband resonator capable of capturing light with a large optical cross-section area is able to substantially enhance the performance of micro-bolometer (response time, noise equivalent temperature difference, pixel size and so on) due to the significantly reduced thermal mass and conductance. Firstly, to integrate plasmonic absorber with micro-bolometer, various kinds of plasmonic absorbers which have combinations of short and long dipole resonators were designed and simulated using CST microwave studio. Then the mean crystalline size of metal was optimized by changing the deposition condition in order to adjust Drude relaxation rate and the absorption characteristics of absorber were measured by Fourier transform infrared spectroscopy in the 8 ~ 14 ?m wavelength range. The measurement results show that 1.62 times of broadening in bandwidth was obtained by decreasing the crystalline size from 5.73 nm to 3.18 nm while maintaining the maximum absorption at resonant wavelength of 10 ?m within 93 ~ 95%. Comparisons between measurements and CST microwave studio simulations show similar spectral absorption trends. Based on these results, 12 ?m micro-bolometer pixels integrated with plasmonic broadband Ti absorber are designed and fabricated. The optimized Ti resonators with multiple resonance and small crystalline size

absorb 98 % of the unpolarized radiation in the 8 ~ 14 ?m spectral range on the average.

8977-16, Session 4

Three-dimensional collimation of in-plane-propagating light using silicon micromachined mirror

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Collimation of free-space light propagating in-plane with respect to the substrate is an important performance factor in micro-optical bench systems. This is usually carried out by the integration of micro lenses into the system or the use of lensed fibers, which increase the cost of fabrication/assembly in addition to limiting the wavelength working range of the system imposed by the dispersion characteristic of the lenses. In this work we demonstrate single-mode optical fiber light collimation using silicon micromachined three-dimensional curved mirror. The three-dimensional curvature of the mirror is controlled by a process combining deep reactive ion etching and isotropic etching of silicon. The produced surface is astigmatic with out-of-plane radius of curvature that is about one half the in-plane radius of curvature, where the latter is 300 ?m. Having the incident beam in-plane and inclined with an angle of 45 degrees with respect to the principal axis, the reflected beam is maintained stigmatic with about 4.25 times reduction in the beam diffraction angle in free space and about 12-dB reduction in propagation losses, when detected with a limited-aperture. This fiber-mirror configuration has a strong potential to replace the lensed fibers widely used in MOEMS systems with the advantage of producing monolithically integrated systems with wider spectral response.

8977-17, Session 4

Analog of electromagnetically induced transparency in coupled one-dimensional photonic crystal cavities

Feng Tian, Guangya Zhou, Yu Du, Fook Siong Chau, National Univ. of Singapore (Singapore); Jie Deng, A*STAR Institute of Materials Research and Engineering (Singapore)

Typical electromagnetically induced transparency (EIT) is a quantum interference effect that permits the propagation of light through an otherwise opaque atomic medium, and extreme dispersion is also created within this transparency "window". Interference effects similar to the EIT in atomic medium also occur in various photonic resonant devices, such as interference between two coupled resonators, interference between two coexisting resonant modes in a single resonator, metamaterial analog of EIT (split ring resonators and plasmonic bars), and optomechanical analog of EIT. In this paper, we first demonstrate the EIT-like effect in the double-coupled one-dimensional photonic crystal (1D-PhC) cavities. As well known, when two identical 1D-PhC cavities couple together, individual order resonance for single cavity will be split into a pair of resonances (odd and even modes). The resonant wavelength of even mode is longer and shifts faster with the gap change between the cavities than that of odd mode. Here, we design the coupled 1D-PhC cavities with a selected even order mode close to the next order odd mode. A nanoelectromechanical systems (NEMS) comb drive is integrated to finely adjust the gap width between the cavities, and then the two resonances are precisely shifted to superimpose and an EIT-like effect is formed. Although the device is the coupled cavities, different from previous works that are the interferences of resonances from respective resonators, the EIT-like effect demonstrated here is the interference between the supermodes from different orders. The EIT-like effect in a single cavity has been realized in a pilydimethylsiloxane (PDMS)-coated silica microtoroid, in which thermal-optic tuning is utilized to align the two resonances. Here the NEMS tuning is first adopted in the resonance alignment for the EIT-like effect.

8977-18, Session 4

Nano-scale optical actuation based on coupled one-dimensional photonic crystal cavities

Feng Tian, Guangya Zhou, Yu Du, Fook Siong Chau, National Univ. of Singapore (Singapore); Jie Deng, A*STAR Institute of Materials Research and Engineering (Singapore)

Previously, lots of interactions of nano-optics and mechanics are studied by the nanoelectromechanical system (NEMS) actuators based on the electrostatic force, while nanoscale all-optical circuits driven by optical forces have broad applications in future communication, computation, and sensing systems. In this paper we propose and verify an actuator based on the bipolar optical forces existing in the double coupled one-dimensional photonic crystal cavities (1D PCCs). Due to their high quality (Q) factors, resonance modes in the 1D PCCs are capable of generating much larger forces than waveguide modes and different symmetry of modes can produce attractive or repulsive forces. The designed device consists of two pairs of double coupled 1D PCCs, one pair is used as engine and the other pair is used as displacement sensor. As we known, there is thermo-optic effect accompanying the optical forces, and the decoupling method have been invented, in which the relations of resonance shift versus gap change and resonance shift versus temperature are separately calibrated in advance. Although the driving and sensing pairs of cavities are separated in our configuration, the heat induced by the pump light can distribute through the whole device. Here, a device with the fixed gap is fabricated as a reference to decouple the thermo-optic and optomechanical effects. The experimental results demonstrate that the optomechanical actuator proposed here is energy-efficient and useful for the potential reconfigurable all-optical circuits.

8977-19, Session 4

A bi-material microbeam based thermal actuator for out-of-plane rotation

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The thermomechanical response and deflection pattern of a bi-material microbeam depends on its geometry and the stacking order of its materials. In a typical bi-material microbeam where the top metal layer completely covers the underlying polysilicon layer, a temperature increase causes the structure to bend up. Alternatively, by reversing the stacking order of materials, the opposite thermomechanical response can be achieved. Recently, it has been shown that by partially patterning the top metal layer, the thermomechanical response of the beam can be tuned to concurrently achieve both bending up and down without the need of altering the stacking order of materials. In this paper, this tunable thermomechanical response observed in bi-material microbeams is further expanded by proposing a new scheme for the patterning of the top metal layer to selectively deliver out-of-plane rotation or the up and down bending of the beam. To support this new design scheme, a systematic approach based on numerical modeling and thermal loading experiment is developed. This approach is then used on a set of polysilicon microbeams measuring 300 µm long and 20 µm wide, on top of which a 60 µm long gold strip is deposited. The results show that by locating the gold strip at about 16% of length distance from the fixed end, a pure out-of-plane rotation can be achieved at a point located 27% along the length of the microbeam. The new scheme is used in a

micromirror to deliver a rotation of 0.7 degree for 175 °C temperature increase.

8977-20, Session 5

Holographic display with a FPD-based complex spatial light modulator *(Invited Paper)*

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We demonstrate a holographic image reconstructed by a FPD-based complex spatial light modulator (SLM) which comprises a phase SLM and a sheet of beam combiner. A complex SLM which modulates amplitude and phase independently is necessary for a better image quality with reducing conjugate images and the two-phase encoding method is one of the most practical candidates for complex SLM.

The proposed complex SLM is presented in a phase-only LCD panel which can be manufactured in a conventional LCD process and it was used for generating different phases. The PAL (Parallel-Aligned nematic liquid crystal Layer) mode is used to modulate phase without the amplitude change. The film-type beam combiner consists of a conventionally fabricated prism and a grating using a conventional fabrication process. The beam combiner plays a vital role to merge two phases and to adjust the direction of them.

The complex hologram fringe using an angular spectrum method was decomposed to a pair of phase values and 3D image is reconstructed in optical experiments. The optically reconstructed image are fromed in a spatial field and de-focuse effect are mesured. In this paper, the holographic image by the proposed complex SLM is verified by the experimental and simulation work in a monochromatic reconstruction. This complex SLM can be scaled up and it is promising candidates for a large-size holographic display.

8977-21, Session 5

Fast one-dimensional light modulator for mask-less lithography in the ultra-violet spectral range

Jan-Uwe Schmidt, Ulrike A. Dauderstädt, Martin Friedrichs, Thomas Hughes, Thomas Ludewig, Dirk Rudloff, Tino Schwaten, Daniela Trenkler, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Ingo Wullinger, GLOBALFOUNDRIES Dresden Module One LLC & Co. KG (Germany); Michael Wagner, Fraunhofer-Institut für Photonische Mikrosysteme (Germany); Per Askebjer, Climeon AB (Sweden); Andreas Bergstrom, Peter B. Bjoernangen II, Tord Karlin, Micronic Mydata AB (Sweden)

We discuss design, technology, characterization and application results of a fast, reliable and field-tested one-dimensional spatial light modulator (SLM) developed for maskless lithography applications in the ultraviolet (UV) spectral range. The SLM comprises 8192 (8k) pixels, each containing hundreds of single-axis electrostatic tilt submirrors. All mirrors within a „pixel“ are connected to the same address electrodes. The SLM actuators are monolithically integrated on a silicon substrate and consist of 3 metal layers (electrodes, springs, mirror) to achieve a high optical fill factor and stable mechanical performance. An excellent global chip planarity and a mirror planarity at the level of a few nm are routinely obtained. During the packaging process, the SLM electrodes are wire bonded to printed circuit boards arranged to both sides of the SLM interfacing to an external electronics supplying analogue driving voltages. This enables a modulation of tilt angles in the MHz range, matching state-of-the-art high power quasi-CW UV lasers. The resulting SLM-module has been successfully integrated in Micronic Mydata's novel LDI 5s Series laser direct imaging (LDI) system. Initially this system will be used for production of advanced electronics substrates. The optical system images the SLM to a line focus comprising 8k spots (one per SLM pixel). Benefiting from continuously adjustable tilt angles and diffractive intensity control, the intensity of each spot in the line can be set instantaneously to the desired gray-level (no time multiplexing). By scanning the intensity-modulated line across the resist on the exposed substrate panel, sub-10 micrometer line/space features can be written at high speed.

8977-22, Session 5

Speckle reduction technique for embeddable MEMS-laser pico-projector

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The paper presents a novel technique for speckle reduction in MEMS-scanning laser projection system. The solution enables is based on a non-moving part fully embedded in the optical engine. In terms of characterization, the speckle contrast ratio measurement was done using state-of-the-art standard in this field (c.f. Stijn Roelandt and co. paper), meeting both the theory data in terms of fully developed speckle contrast ratio for both non-scanning system and MEMS-scanning system (CR = 0.7). The paper describes in details the technique and the design of the developed solution, which is based on light beam separation and recombination specific design, enabling both the speckle reduction in each of the displayed pixels without impacting any other features of the projector, such as always-in-focus, color gamut, beam collimation, alignment and divergence.

In terms of size, the solution fits in a 5mm thick optical engine package. The solution was implemented in a complete MEMS-laser projection system, having 20 lumens brightness and 2cc complete optical engine volume, including the anti-speckle solution. The measurement results show speckle reduction of 60% and a resulting speckle contrast ratio close to 10%.

For the first time, an embeddable anti-speckle solution for MEMS-scanning laser projection system that do not degrade other key features of the projection is demonstrated, then providing a suitable solution for embedded projection system into next generation mobile devices.

8977-23, Session 5

Large array of 2048 tilting micromirrors for astronomical spectroscopy: optical and cryogenic characterization

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Multi-object spectroscopy (MOS) is a powerful tool for space and ground-based telescopes for the study of the formation and evolution of galaxies. This technique requires a programmable slit mask for astronomical object selection.

We are engaged in a European development of micromirror arrays (MMA) for generating reflective slit masks in future MOS, called MIRA. The 100 x 200 µm2 micromirrors are electrostatically tilted providing a precise

angle. The main requirements are cryogenic environment capabilities, precise and uniform tilt angle over the whole device, uniformity of the mirror voltage-tilt hysteresis and a low mirror deformation.

MMA with single-crystal silicon micromirrors was successfully designed, fabricated and tested. They were composed of 2048 micromirrors (32 x 64), capable of a 25°, and fabricated using fusion and eutectic wafer-level bonding. The fill factor, contrast and deformation of the micromirrors at room and cryogenic temperatures were investigated. The results illustrate that the array exhibited a fill factor of 82% (98% along the long slit mode); a contrast of 1000:1; and a surface mirror deformation of 8nm for mirrors tilted at room temperature, and 27nm for mirrors tilted at 162K. These performances demonstrate the ability of such MOEMS device to work as objects selector in future generation of MOS instruments both in ground-based and space telescopes. In order to fill large focal planes (mosaicing of several chips), we are currently developing large micromirror arrays integrated with their electronics.

8977-24, Session 6

MMI-based MOEMS FT spectrometer for visible and IR spectral ranges

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MEMS Interferometers have very strong potential in future healthcare and environmental monitoring applications. Recently, MEMS Michelson interferometers based on using the Silicon interface as a beam splitter BS has been proposed. This allowed having a monolithic integrated FTIR spectrometer on a chip. However silicon BS has high absorption losses in the visible range and high dispersion in the NIR range. For these reasons, we propose in this work, a novel MOEMS interferometer allowing operation over wider spectral range covering both the infrared and visible ranges. The proposed architecture is based on spatial splitting and combining of optical beams using the imaging properties of hollow Multi-Mode Interference MMI waveguide. The proposed structure includes an optical splitter for spatially splitting an input beam into two beams and a spatial combiner for spatially combining the two interferometer beams. A MEMS moveable mirror is provided to produce an optical path difference between the two splitted beams. The new interferometer is fabricated using DRIE technology on an SOI wafer. The movable mirror is metalized and attached to a comb-drive actuator fabricated in the same lithography step, self-aligned on the chip. The novel interferometer is tested as a Fourier transform spectrometer. Red Laser, IR Laser and absorption spectra of different materials are measured with a resolution of 2.5 nm at 635 nm wavelength. The structure is a very compact one that allows its integration and fabrication on a large scale with very low cost.

8977-25, Session 6

On-chip NIR optical spectrometer based on polymeric waveguide and metallic nano-structures

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In this work, we report about optical spectrometry using gold nano-structures printed on top of a polymer based integrated optical waveguide. The optical waveguide is a single mode buried waveguide, having dimensions of 3 x 2.2µm2. It is made from a combination of photo-polymerizable materials and is fabricated by photolithography on a glass substrate. To sense the electric field inside the waveguide, an array of gold nano-couplers composed of thin lines (50 nm thick and 8 µm length) is embedded on top of the aforementioned waveguide and it is produced by E-beam lithography. The array pitch is 2.872 µm and the number of lines 564, which yields in an array length of 1.619 mm. The device is capped with a superstrate to prevent it from dust and destruction. Both waveguide ports are polished and the output port in particular, is plated with a gold layer to assimilate a mirror and hence, it enables the creation of stationary waves inside the structure.

The measurement procedure involves light injection using a single mode fiber carrying both visible light (658 nm) and infrared light (785 nm), for alignment and measurement purposes respectively. Stationary waves generated inside the guide constitute the spatial interferogram which is out-coupled using the nano-couplers. The resulting pattern is imaged by a vision system involving an optical microscope with a digital camera mounted on-top of it. Signal processing, mainly based on Fast Fourier transform is performed on the captured interferometric signal to extract the spectral content of the measured signal.

8977-26, Session 6

Resolution and speed improvements of mid-infrared Fabry-Perot microspectrometers for the analysis of hydrocarbon gases

Martin Ebermann, Norbert Neumann, InfraTec GmbH (Germany); Karla Hiller, Mario Seifert, Technische Univ. Chemnitz (Germany); Marco Meinig, Steffen Kurth, Fraunhofer-Institut für Elektronische Nanosysteme (Germany)

Micromachined tunable Fabry-Perot filters (µFPF) are key elements in a new class of miniature spectrometers and analyzers. Different groups all over the world are working on µFPF for spectral ranges from the visible up to the long wave infrared. In order to achieve a large tuning range, the filters are normally operated in low interferences orders. At the same time the spectral resolution is limited due to a limited effective finesse (typical 20…60). µFPF for the MWIR range, which is mainly of interest for gas analysis, typically achieve a tuning range of about 1.1 µm and an FWHM bandwidth of 60…100 nm. This is sufficient for a variety of applications, whereas for others a higher resolution is needed. This is particularly true for the multicomponent analysis of hydrocarbon gases, because the individual absorption bands are very similar and widely overlapping.

In this paper a higher resolution µFPF is presented, in which the third or fourth interference order is used. Thus a spectral resolution of 18…25 nm in the wavelength range 3.1…3.7 µm can be achieved. The narrowed tuning range is unproblematic for the analysis of hydrocarbons. To measure additional gases in adjacent ranges (e.g. water vapour < 3 µm or CO_2 > 4 µm) a dualband configuration with simultaneous use of different orders can be used. The µFPF is combined with a room temperature operated lead salt photoresistor, which allows for fast tuning and direct acquisition of the spectrum without the need for pulsing or chopping the IR source.

8977-27, Session 6

MEMS Fabry-Perot interferometer-based spectrometer demonstrator for 7.5 µm to 9.5 µm wavelength range *(Invited Paper)*

Jussi H. Mäkynen, Mikko Tuohiniemi, Antti Näsilä, Rami Mannila, Jarkko E. Antila, VTT Technical Research Ctr. of Finland (Finland)

VTT Technical research centre of Finland has developed a MEMS

Fabry-Perot interferometer for the wavelength range from 7.5 µm to 9.5 µm. The device consists of two Distributed Bragg Reflectors (DBR) manufactured with MEMS processing techniques. The distance between the two reflectors can be changed by applying a control voltage that electrostatically pulls the upper reflector closer to the lower reflector. The full width half maximum of the transmission peak is 150nm. This transmission peak can be tuned from 7.5 µm to 9.5 µm by applying a control voltage from 0 V to 30 V.

A laboratory demonstrator has been put together to show the use of this module as a part of a spectral measurement setup. The measurement setup consists of a light source, optical chopper, gas flow cell, ZnSe lenses, Band pass filter, MEMS-FPI, MCT-detector and control electronics. Several gas samples have been measured with the setup and compared against measurement results found in literature. A transmission of an optical filter with known characteristics was also measured to evaluate the performance of the built setup.

The small size of the interferometer module and the use of a single point detector provide a good starting point to build low cost miniaturised spectrometers for the wavelength range from 7 µm to 11 µm.

8977-28, Session 6

MEMS optical tunable filter based on free-standing sub-wavelength silicon layers

Haitham Omran, Ain Shams Univ. (Egypt); Yasser M. Sabry, Ain Shams Univ. (Egypt) and Si-Ware Systems (Egypt); Mohamed Sadek, Khaled Hassan, Si-Ware Systems (Egypt); Mohamed Y. Shalaby, Ain Shams Univ. (Egypt); Diaa Khalil, Ain Shams Univ. (Egypt) and Si-Ware Systems (Egypt)

Optical tunable filters have many applications in optical telecommunications, biomedical optics, atomic studies, and chemical analysis. The involvement of the MEMS technology in tunable filters has the advantages of system miniaturization and low-cost production. MEMS tunable filters with out-of-plane optical axis, with respect to the substrate, are usually formed using high-quality dielectric coating of the wafer top surface, which results in high optical performance but with the expense of difficulty in optical assembly with other optical components. MEMS tunable filters with in-plane optical axis enable the monolithic integration of the whole optical system on-chip. In this work we report a MEMS optical tunable filter based on high-aspect-ratio etching of sub-wavelength silicon layers on a silicon-on-insulator wafer. The etching is used to form Bragg mirrors of successive Si/air layers; with one mirror fixed while the other is moved using a precise comb drive actuator for filter tuning. The reported filter has measured free-spectral and filter-tuning ranges of approximately 100 nm and a finesse of about 20 around a wavelength of 1550 nm, enabled by the use of 1000 nm-thick silicon layers and a balanced tilt-free motion using a lithographically-aligned electrostatic actuator. The average insertion loss of the filter is about 12 dB with a superior wavelength-dependent loss of about 1.5 dB. The filter has an out-of-band to in-band wavelength rejection ratio that is better than 20 dB. The reported filter experimental characteristics and its integrability are suitable for the production of integrated swept sources for optical coherence tomography application and miniaturized spectrometers.

8977-29, Session 7

MEMS infrared approaches to detector-based on nonlinear oscillation and wavelength selective emitter using surface plasmon polariton *(Invited Paper)*

Minoru Sasaki, Shinya Kumagai, Toyota Technological Institute (Japan)

The suspended MEMS structure is suitable for reducing the energy loss due to the thermal conduction. There is the possibility that IR photon energy can be well-controlled to generate some physical effects.

As for the detector, the conventional devices are static (e.g., thermopile). A new method bases on the nonlinear oscillation. The thin film torsional spring exhibits a large hard spring effect when the deflection occurs in the out-of-plane direction of the film. When IR is absorbed, the resonator bends due to the thermal expansion. The torsional spring becomes harder increasing the resonant frequency. The frequency measurement is suited for the precise sensing. The response of the device is measured using the laser (wavelength of 650nm). The resonant frequency is 88-94kHz. Q factor is about 1600 in vacuum (1Pa). The sensitivity is -0.144[kHz/(kW/m2)].

As for the emitter, non-dispersive IR gas sensor is considered. The molecules have their intrinsic absorptions. CO2 absorbs the wavelength 4.2-4.3 m. The major incandescent light bulbs have the broad spectrum emitting IR which is not used for sensing. The energy efficiency is low. The wavelength selectivity near to the band width is required. We proposed a new principle. The grating is placed facing to the heater. SPP is excited carrying IR energy on the grating surface. IR emission is the reverse process of excitation occurring at the output end. FT-IR spectra show SPP related peak having the width of 190nm. When the input power increases from 0.3 to 1.9W, the peak at wavelength of 3.5 m becomes clearer.

8977-30, Session 7

Tunable MOEMS Fabry-Perot interferometer for miniaturized spectral sensing in near-infrared

Anna Rissanen, Rami Mannila, Mikko Tuohiniemi, VTT Technical Research Ctr. of Finland (Finland); Altti Akujärvi, VTT Technical Research Center of Finland (Finland); Jarkko E. Antila, VTT Technical Research Ctr. of Finland (Finland)

Surface-micromachined Fabry-Perot interferometers are MOEMS structures which form the engine of small, robust and massproducible microspectrometers. When combined with detectors and optical light sources, these tunable optical filters enable various optical sensor and instrument combinations for spectroscopic analysis applications. Previously, MOEMS FPI process platforms have been demonstrated for visible (? < 750nm), as well as near- and mid infrared (NIR/MIR) above the silicon substrate transmission range (? > 1.2 µm). In between these remains an optical region, which is of interest due to its suitability for various spectral imaging and sensing applications. This paper presents a novel MOEMS FPI process platform for the range of 0.8 – 1.0 µm. Simulation results including design and optimization of device properties in terms of transmission peak width, tuning range and electrical properties are discussed. Process flow for the device fabrication is presented, with overall process integration and backend dicing steps resulting in successful fabrication yield. The mirrors of the FPI consist of LPCVD (low-pressure chemical vapour) deposited polySi-SiN ?/4-thin film Bragg reflectors, with the air gap formed by sacrificial SiO2 etching in HF vapour. Silicon substrate below the optical aperture is removed by inductively coupled plasma (ICP) etching to ensure transmission in the visible – NIR, which is below silicon transmission range. The

characterized optical properties of the chips are compared to the simulated values. Achieved optical aperture diameter size of the released and diced FPI chips is 2 mm, which enables utilization of the chips in both imaging as well as single-point spectral sensors.

8977-31, Session 7

Planar integrated polymer-based optical strain sensor

Christian Kelb, Eduard Reithmeier, Bernhard Roth, Leibniz Univ. Hannover (Germany)

In this work we present a new type of optical strain sensor that can be manufactured by mems-typical processes such as, e.g., photolithography, and by hot-embossing. The sensor consists of an array of planar polymer-based multimode waveguides whose output light is guided through a measurement area and focused onto a second array of smaller (detection) waveguides, by using micro-optical elements. Strain induced in the measurement area varies the distance between the two waveguide arrays, thus, changing the coupling efficiency to the detection waveguides. This, in turn, leads to a variation in output intensity or wavelength which is detected. The approach aims at high sensitivity and dynamic range for 1D and 2D sensing of strain changes and can also be extended to quantities such as pressure, force, and humidity.

We performed a set of optical simulations in order to identify the optimal sensor layout with regard to either resolution or measurement range or both. Since the initial approach relies on manufacturing polymer waveguides with cross sections between 20x20 µm2 – 100x100 µm2, the simulations were carried out using raytracing models. A prototype of the strain sensor was manufactured by using photolithography and hot embossing and characterized with respect to overall functionality, measurement range and resolution. We also present a setup that allows for easy adjustment, coupling and readout of the prototype sensor. The work towards reduction of cross correlations and development of concepts for calibration will be discussed.

8977-32, Session 7

Mechanically amplified MEMS optical accelerometer with FPI readout

Edward Davies, Imperial College London (United Kingdom); David S. George, AWE plc (United Kingdom); Andrew S. Holmes, Imperial College London (United Kingdom)

Inertial sensors with optical readout are attractive for applications involving hazardous environments due to their immunity to electromagnetic interference and their ability to operate without electrical signals or power. We have developed a silicon MEMS optical accelerometer in which the motion of the proof mass is mechanically amplified prior to transduction using a V-beam mechanism. The output motion of the V-beam is detected using a Fabry-Pérot interferometer (FPI) which is interrogated in reflection mode via a single-mode optical fibre. Mechanical amplification allows the sensitivity of the accelerometer to be increased without compromising the resonant frequency or measurement bandwidth. We have also devised an all-optical method for normalising the return signal from the FPI and measuring the fringe visibility; this is based on photo-thermal actuation of the V-beam structure using fibre-delivered light of a different wavelength. Prototype devices have been fabricated with resonant frequencies above 10 kHz and dynamic ranges of 0.05 to 15 g over a measurement bandwidth of 3 kHz. In this paper we will explore the design trade-offs for devices of this type and compare the performances of devices with different FPI configurations. We will also consider the shock resistance of the devices and present recent work on wafer-scale packaging aimed at improving the robustness against shock.

Conference 8978: MEMS Adaptive Optics VIII

Sunday 2 –2 February 2014

Part of Proceedings of SPIE Vol. 8978 MEMS Adaptive Optics VIII

8978-1, Session 1

FPGA-accelerated adaptive optics wavefront control

Steffen Mauch, Johann Reger, Technische Univ. Ilmenau (Germany); Claudia Reinlein, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Michael Appelfelder, Matthias Goy, Fraunhofer-IOF (Germany); Erik Beckert, Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The speed of real-time adaptive optical systems is primarily restricted by the data processing hardware and computational aspects. Furthermore, the application of mirror layouts with increasing numbers of actuators reduces the bandwidth (speed) of the system and applicable control algorithms. This burden dramatically increases when deformable mirrors with continuous mirror surface and highly coupled actuator influence functions are used.

Moreover, specialized hardware is necessary for high performance real-time control applications. Our approach to overcome this challenge is an adaptive optics system based on a Shack-Hartmann wavefront sensor (SHWFS) with a CameraLink interface. Data processing is based on a high performance Intel i7 Quadcore hard real-time Linux system. Employing a Xilinx Kintex-7 FPGA, an own developed PCIe card is outlined in order to accelerate i.e. the analysis of a Shack-Hartmann Wavefront Sensor. A recently developed real-time capable spot detection algorithm evaluates the wavefront.

The main features of the presented system are the reduction of the latency and the acceleration of computation. Examples are the acceleration of matrix multiplications, which in general are O(n3), via using the DSP48 slices of the FPGA, as well as a novel hardware implementation of the SHWFS algorithm. Further benefits are the Streaming SIMD Extensions (SSE) which intensively use the parallel capability of the processor for further reducing the latency, and increasing the bandwidth of the closed loop. Due to this approach, up to 64 actuators of a deformable mirror can be handled and controlled without noticeable restriction due to computational burdens.

8978-2, Session 1

Focus-tunable Moiré lenses from stacked diffractive optical elements

Walter H. Harm, Stefan Bernet, Monika Ritsch-Marte, Innsbruck Medical Univ. (Austria)

We have experimentally investigated the performance of four different designs of focus-tunable diffractive lenses. The lenses consist of a pair of diffractive optical elements fabricated in thin (0.75 mm) glass slides. The DOEs are designed such that the transmission function of two axially stacked elements corresponds to that of a Fresnel zone lens, with a focal length which can be tuned by a mutual rotation of the elements around their central axis. The principle is similar to diffractive versions of the well-known refractive Lohmann and Alvarez lenses, however there the focal tuning is achieved by a lateral displacement between the stacked optical elements.

Our Moiré DOEs consist of a two-dimensional 16 level (4 bit) structure fabricated by lithography and subsequent etching in a glass plate. The pixel structure has a resolution of one micron, and the maximal etching depth corresponds to a phase shift of one wavelength for 633 nm illumination. The maximally adjustable accommodation range of the assembled flat zoom lenses depends on the aperture of the DOEs, and on the lateral pixel resolution, and is demonstrated to exceed +/- 20 diopters in our prototype lenses. The diffraction efficiency depends on the bit depth of the pixel structure, and on the manufacturing tolerances of each DOE pair, and reaches up to 86% in our prototypes. The point spread function of the focus-tunable lenses for quasi-monochromatic illumination is almost ideal, namely diffraction limited. Using assemblies of two Moiré lens pairs, we demonstrate optical systems like telescopes and microscopes with tunable magnification, which are realized without any axially shifting optical components.

8978-3, Session 1

Testing of thermally-piezoelectric deformable mirror with buried functionality

Claudia Reinlein, Michael Appelfelder, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Nam Gutzeit, Technische Universität Ilmenau (Germany); Sylvia E. Gebhardt, Fraunhofer-Institut für Keramische Technologien und Systeme (Germany); Matthias Goy, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Laser-induced mirror deformation and thermal lensing in optical high power systems shall be compensated by a thermally-piezoelectric deformable mirror (DM). The DM is a unimorph-type deformable mirror with a screen-printed piezoelectric thick-film on the rear surface and a copper layer on the front surface. The mirror substrate is based on LTCC and fixed into the mount. This deformable mirror is piezoelectrically activated by the actuators on its rear surface, and thermally activated mirror by the bimetal set-up inherently formed by ceramic and metallic layers. In our device, the laser-induced thermal lensing can be compensated by heating of the DM as previously described with compound loading.

We experimentally show, the capability of this mirror for wavefront shaping of up to 6.2 kW laser power and power densities of 2 kW/cm? in a developed high power set-up. Therefore, a high power single mode laser (1064nm) with an aperture of 20mm is incident on the deformable mirror. The wavefront of the reflected light is measured and analyzed by a wavefront sensor. Therewith we can also analyze the temporal behavior. Further, we show that the laser-induced defocussing of the membrane is compensated by mirror heating. The piezoelectric stroke of the single actuators only depends on their position on the membrane, and is not affected by the reflected laser power.

8978-4, Session 1

First light with a carbon fiber reinforced polymer 0.4 meter telescope

Christopher C. Wilcox, U.S. Naval Research Lab. (United States); Freddie Santiago, Matthew E. Jungwirth, Sandia National Labs. (United States); Ty Martinez, Sergio R. Restaino, U.S. Naval Research Lab. (United States); Brett E. Bagwell, Sandia National Labs. (United States); Robert C. Romeo, Composite Mirror Applications, Inc. (United States)

For the passed several years, the Naval Research Laboratory (NRL) has been investigating the use of carbon fiber reinforced polymer (CFRP) material in the construction of a telescope assembly including the optics. NRL, Sandia National Laboratories, and Composite Mirror Applications, Inc. have jointly assembled a prototype telescope and achieved “first light” images with a prototype CFRP 0.4 meter aperture telescope. CFRP offers several advantages over traditional materials such as creating structures that are lightweight and low coefficient of thermal expansion

and conductivity. The telescope's primary and secondary mirrors are not made from glass, but CFRP, as well. The entire telescope weighs approximately 10 kg while a typical telescope of this size would weight an order of magnitude more. We present the achievement of "first light" with this telescope demonstrating the imaging capabilities of this prototype and the optical surface quality of the mirrors with images taken during a day's quiescent periods.

8978-5, Session 2

MEMS and the direct detection of exoplanets *(Invited Paper)*

Sandrine J. Thomas, NASA Ames Research Ctr. (United States)

Deformable mirrors, and particularly MEMS, are crucial components for the direct imaging of exoplanets for both ground-based and space-based instruments.

Without deformable mirrors, coronagraphs are incapable of reaching contrasts required to image Jupiter-like planets. The system performance is limited by image quality degradation resulting from wavefront error introduced by multiple effects including: atmospheric turbulence, static aberrations in the system, non-common-path aberrations, all of which vary with time. Correcting for these effects necessitates a deformable mirror with fast response and numerous actuators having moderate stroke. Not only do MEMs devices fulfill this requirement but their compactness permits their application in numerous space- and ground-based instruments, which are often volume- and mass-limited.

In this paper, I will explain coronagraphs and demonstrate their requirement for extremely high Strehl ratios. I then will discuss the different control loops that are required to compensate for the introduced wavefront error and produce the contrasts necessary to detect exoplanets.

As examples, I will discuss a facility instrument for the Gemini Observatory, called the Gemini Planet Imager, that will detect Jupiter like planets and present recent results from the NASA Ames Coronagraph Experiment laboratory, in the context of a proposed space-based mission called EXCEDE.

8978-6, Session 2

Wavefront compensation technique using acquired images for small satellite remote sensing

Norihide Miyamura, Meisei Univ. (Japan)

We are developing an adaptive optics system for earth observing remote sensing sensor. In this system, high spatial resolution has to be achieved by a lightweight sensor system due to the launcher's requirements. Moreover, simple hardware architecture have to be selected to achieve high reliability. Image based AOS realize these requirements without wavefront sensor. In remote sensing, it is difficult to use a reference point source unless the satellite controls its attitude toward a star or it has a reference point source in itself. We propose the control algorithm of the deformable mirror on the basis of the extended scene instead of the point source. In our AOS, a cost function is defined using acquired images on the basis of the contrast in spatial or Fourier domain. The cost function is optimized varying the input signal of each actuator of the deformable mirror. In our system, the deformable mirror has 140 actuators. We use basis functions to reduce the number of the input parameters to realize real-time control. We constructed the AOS for laboratory test, and proved that the modulated wavefront by DM almost consists with the ideal one by directly measured using a Shack-Hartmann wavefront sensor as a reference.

8978-7, Session 2

On-sky wavefront correction with a 2048 actuator MEMS *(Invited Paper)*

Olivier Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States) and The Univ. of Arizona (United States); Frantz Martinache, Nemanja Jovanovic, Christophe S. Clergeon, Garima Singh, Tomoyuki Kudo, Subaru Telescope, National Astronomical Observatory of Japan (United States)

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system was recently upgraded to use a 2048-actuator MEMS deformable mirror (DM). SCExAO is optimized for direct imaging of exoplanets around nearby stars. The DM is used both for fast wavefront correction to achieve high image quality (sharp diffraction-limited image) and to actively remove residual speckles in the scientific camera focal plane, delivering a contrast suitable for detection of exoplanets close to the star. We describe the SCExAO system architecture and present on-sky and laboratory results obtained with both the previous 1024-actuator and the new 2048-actuator deformable mirrors. We also discuss the suitability of MEMS DMs for exoplanet imaging.

8978-8, Session 3

Comparison of closed loop and sensorless adaptive optics in widefield microscopy *(Invited Paper)*

John M. Girkin, Christopher D. Saunter, Cyril J. Bourgenot, Gordon D. Love, Durham Univ. (United Kingdom); Jonathan P. Taylor, Univ. of Glasgow (United Kingdom)

Adaptive optics in microscopy has now established itself as a reliable method of improving image quality at depth in biological samples. The initial interest was focused on beam scanned non-linear microscopy and such systems have now demonstrated improvements in signal of an order of magnitude and even at depths of hundreds of microns enabled diffraction limited imaging. The method is now being applied to widefield microscopy, including optical sectioning using light sheets. In widefield systems there are two options for determining the shape to be placed on the aberration correction device (SLM or mirror) 1) closed loop using a wavefront sensor, 2) sensorless methods based upon an image optimization metric. The presentation will explore the different approaches and provide guidelines on to the selection of the most appropriate method for different imaging situations and samples types. We will demonstrate that the selection of the image metric in optimization based system can play an important role in the speed of optimization but generally does not affect the final resolution achieved. In consideration of closed loop correction results will be presented of systems using both inherent features within a sample (the equivalent of natural guide stars in astronomy) and also beacons introduced into samples (laser guide stars). Closed loop control using both fluorescent and back scattering targets will be shown.

8978-9, Session 3

Accuracy of adaptive optics correction using fluorescence fluctuations *(Invited Paper)*

Joseph Gallagher, Université Grenoble 1 / CNRS (France); Charles-Edouard Leroux, Irene Wang, Antoine Delon, Univ. Joseph Fourier (France)

Fluorescence fluctuation microscopy (FFM) is an ensemble of techniques intended to measure concentration, mobility (diffusion, flow, etc.) and interactions of fluorescent molecules. It relies on the statistical analysis of the fluctuations of the fluorescence signal originating from a limited number of molecules or particles passing through a small observation volume, generally corresponding to the point spread function (PSF) of a confocal microscope. However, the absolute character of these measurements (in terms of number density, constant of diffusion, etc.) relies on the assumption that the observation volume is well quantified. For most biological applications of FFM, the PSF, if not known, should at least remain stable for an accurate comparison of measurements. Optical aberrations can prevent meaningful analysis of FFM measurements. In the case of freely diffusing molecules, the enlargement of the PSF increases both the measured number of molecules and diffusion time, because these quantities depend on the observation volume. We demonstrated the use of an adaptive optics (OA) system to cancel the aberrations due to a refractive index mismatch, using aqueous solutions. We also observed strong optical aberrations when focusing through a single living cell in a control solution, so much that the number of molecules, as measured by FFM, increases up to a factor 7. These aberrations could be efficiently corrected by optimizing the brightness (or fluorescence signal per molecule), thanks to a deformable mirror.

To conclude, FFM makes it possible to perform AO in cases of low image contrast, photon scattering, etc.

8978-10, Session 4

Imaging deep and clear in thick inhomogeneous samples *(Invited Paper)*

Jordi Andilla, Omar E. Olarte, Rodrigo Aviles-Espinosa, Pablo Loza-Alvarez, ICFO - Institut de Ciències Fotòniques (Spain)

Acquisition of images deep inside large samples is one of the most demanded improvements that current biology applications ask for. Another important requirement is to approach the acquisition to the actual living conditions of the biological specimen. This, usually, implies having samples with hard optical properties in terms of imaging. Absorption, scattering and optical aberrations are the main difficulties encountered in these types of samples. Each one of these difficulties produces a reduction on the collected photons to generate an image. Thus, this effect becomes worse when going deep into the sample and reduces dramatically the signal to noise ratio of the image. Adaptive optics has been imported form astronomy to deal with the optical aberrations induced by the sample in order to compensate them and recover part of the lost information. However, the effects of optical aberrations are very dependent on the used technology and the characteristics of the optical setup. Because of that, the expected improvements on the acquisition will be also dependent on these characteirstics.

In this work, we will perform a complete overview of the application of adaptive optics to the biological imaging, from super-resolution to mesoscopic imaging in linear and non-linear modalities. We will try to clarify some of the aspects of the adaptive optics from the perspective of the technique and, finally, we will be able to discuss about the limitations and performances of the correction methods and setups.

8978-11, Session 4

Adaptive optics for in vivo two-photon calcium imaging of neuronal networks

Serge C. Meimon, Jean-Marc Conan, Vincent Michau, ONERA (France); Arnaud Malvache, Institut de Neurosciences Cognitives de la Méditerranée (France)

The landscape of biomedical research in neuroscience has changed dramatically in recent years as a result of spectacular progress in dynamic microscopy. However, the optical accessibility of deep layers (a few 100 microns typically) remains limited, due to volumic aberrations created by the sample inhomogeneities.

Adaptive optics is a technology allowing to precompensate the illumination laser, provided that the wavefront (aberrations) is correctly measured. In in vivo microscopy, such a wavefront sensing is particularly difficult, and has to be done via an ``indirect" measurement based on the observation of the scene itself. A promising demonstration of an indirect in vivo measurement has already been published but it only constitutes a first step towards an optimal use of adaptive optics.

Our goal is to improve this method by using an original idea in terms of indirect wavefront sensing leading to a tomographic measurement of the aberrations, as well as the latest developments in widefield adaptive optics for astronomy. The obtained Adaptive Optics system will be applied to the in vivo two-photon calcium imaging of the hippocampus, aiming at understanding the functional architecture of neuronal networks involved in spatial coding, memory and epilepsy. Such an imaging experiment,featuring a wide field of view (500x500 microns), with a high numerical aperture (ON=1), will require a wavefront correction that evolves with the field.

We present a preliminary system analysis of the Adaptive Optics architecture, based on a direct measurement (in transmission) of the aberrations on brain slices maintained in vitro.

8978-12, Session 4

Adaptive optical two-photon microscopy with direct wavefront sensing using autofluorescent guide-stars

Xiaodong Tao, Andrew P. Norton, Matthew Kissel, Oscar A. Azucena Jr., Joel Kubby, Univ. of California, Santa Cruz (United States)

We demonstrate a direct wavefront sensing method for adaptive optical two photon microscopy. By using a Shack-Hartmann wavefront sensor and an open loop control, the system provides high-speed wavefront measurement and correction. To measure the wavefront in the middle of a Drosophila embryo at early stages, autofluorescence from endogenous fluorophores in the yolk were used as reference guide-stars. The autofluorescent emission following two-photon excitation was collected by a Shack-Hartmann wavefront sensor (SHWS). The measured wavefront error was compensated by a deformable mirror using an open loop control. High-speed and high-performance wavefront measurement and correction are the critical advantages of direct wavefront measurement over other sensor-less adaptive optical systems. The proposed method was tested by live imaging of a Drosophila embryo labeled with green fluorescent protein (GFP) and red fluorescent protein (RFP). The aberration in the middle of the embryo was measured directly for the first time. After correction, both contrast and signal intensity of the structure in the middle of the embryo was improved.

8978-13, Session 4

Optical design of a broadband scanning adaptive optics ophthalmoscope for the mouse eye *(Invited Paper)*

Yusufu N. Sulai, Univ. of Rochester (United States); Alfredo Dubra, Medical College of Wisconsin (United States) and Marquette Univ. (United States)

An adaptive optics ophthalmoscope for simultaneous imaging of multiple retinal layers and/or use of multiple wavelengths needs to be diffraction limited over a range of conjugate planes. This range is dictated by the maximum axial separation of the layers of interest and the longitudinal chromatic aberration across the wavelengths to be used. While in a human eye, this range could be as large as 3 diopters (D), it could be up to 60D in a mouse eye. Furthermore, the mouse eye is about 8 times

shorter than that of the human, which means that a proportionally larger field of view is required to image the retinal structures of the same dimension in the mouse. Lastly, defocus (i.e., spectacle prescription) in a mouse eye could be over twice as large as that of the human. The combinations of these three factors make the optical design of adaptive optics ophthalmoscopes for mice more challenging than for humans. This is mostly due to variations in astigmatism and coma with the conjugate planes. In this work, we discuss the compromises that have to be made to address these problems using off-the-shelf spherical optics and demonstrate the experimental performance by presenting preliminary in vivo retinal images.

8978-14, Session 5

Adaptive optics for superresolution nanoscopy *(Invited Paper)*

Brian R. Patton, Daniel Burke, Fiona Kenny, Maria Frade Rodriguez, Martin Booth, Univ. of Oxford (United Kingdom)

Superresolution microscopes have been able to resolve features on the scale of tens of nanometers and lower. These microscopes - including scanning methods (STED, RESOLFT, etc.) and single molecule switching (SMS) methods (PALM, STORM, GSDIM, etc.) - all suffer from the effects of aberrations that compromise resolution, signal and consequently image quality. Adaptive optics has been demonstrated in a range of diffraction-limited resolution microscope modalities to compensate for system and specimen-induced aberrations. However, the use of adaptive optics in superresolution microscopes presents new challenges. We investigate how aberrations affect the properties of superresolution microscopes and develop new adaptive optics schemes to measure and correct the aberrations. In particular we show aberration correction in 2D and 3D STED microscopes via sensorless image-based feedback schemes. We also show improvement in localization performance in SMS microscopes. The adaptive nanoscopes are used to perform three-dimensionally resolved superresolution imaging through thick (~10 to 50 micrometre) specimens. Significant improvements in resolution and image intensity are achieved. The adaptive correction of specimen-induced aberrations in this manner will extend the application of superresolution nanoscopes to thicker specimens.

8978-15, Session 5

Development and testing of an AO-structured illumination microscope

Matthew Kissel, Oscar A. Azucena Jr., Juan J. Díaz León, Marc R. Reinig, Joel Kubby, Univ. of California, Santa Cruz (United States)

While super-resolution imaging has revolutionized optical microscopy by overcoming the diffraction limit in far field imaging, it has yet to transform dynamic live in vivo imaging through thick tissue, which is of broad interest to the biological research community. Our talk will discuss the development and testing of an Adaptive Optical Structured Illumination Microscope (AO-SIM) that is a novel combination of three different imaging techniques; structured-illumination to double the resolution from 200 nm to 100 nm, tomography to increase the corrected volume, and a woofer-tweeter adaptive optical system that is sufficient for an order of magnitude increase in the depth of correction.

8978-16, Session 5

120nm resolution in thick samples with structured illumination and adaptive optics

Benjamin Thomas, Megan Sloan, Adrian J. Wolstenholme, Peter A. Kner, The Univ. of Georgia (United States)

Linear Structured Illumination Microscopy (SIM) provides a two-fold increase over the diffraction limited resolution. SIM has produced excellent images with 100nm resolution in tissue culture cells in two and three dimensions. For SIM to work correctly, the point spread function (PSF) and optical transfer function (OTF) must be known, and, ideally, should be unaberrated. When imaging through thick samples, aberrations will be introduced into the optical system which will reduce the peak intensity and increase the width of the PSF. This will lead to reduced resolution and artifacts in SIM images. Adaptive optics can be used to correct the optical wavefront restoring the PSF to its unaberrated state, and AO has been used in several types of fluorescence microscopy. We demonstrate that AO can be used with SIM to achieve 100nm resolution through 60µm of tissue by imaging through the full thickness of an adult C. elegans roundworm. The aberrations can be corrected over a 35µm ? 35µm field of view with one wavefront correction setting, demonstrating that AO can be used effectively with widefield superresolution techniques.

8978-17, Session 5

Point spread function optimization for STORM using adaptive optics

Kayvan Forouhesh Tehrani, Peter A. Kner, The Univ. of Georgia (United States)

Single Molecule Localization (SML) Microscopy techniques (STORM, PALM, etc.) require a high Strehl ratio point spread function (PSF) to achieve high resolution, especially in the presence of background fluorescence. The PSF is degraded by aberrations caused by imperfections in the optics, the refractive index mismatch between the sample and coverslip, and the refractive index variations of the sample. The aberrations distort the shape of the PSF and increase the PSF width directly reducing the resolution of SML microscopy. Here we discuss the use of Adaptive Optics (AO) to correct aberrations, maintaining a high Strehl ratio even in thick tissue. Because the intensity fluctuates strongly from frame to frame, image intensity is not a reliable measure of PSF quality, and the choice of a robust optimization metric is critical. We compare different AO optimization methods for use in SML microscopy including genetic and quadratic optimization algorithms and demonstrate the use of a Fourier ring filter based metric that is relatively insensitive to image intensity.

8978-18, Session 6

Non-invasive optical imaging through scattering layers *(Invited Paper)*

Allard P. Mosk, Elbert G. van Putten, Univ. Twente (Netherlands); Jacopo Bertolotti, Univ. Twente (Netherlands) and Univ degli Studi di Firenze (Italy); Christian Blum, Ad Lagendijk, Willem L. Vos, Univ. Twente (Netherlands)

Imaging through strongly scattering systems is of wide interest in technological and biological settings, and many approaches have been developed to allow imaging despite scattering. In cases where some ballistic light is present, this light can be purified by gated imaging methods such as the very successful optical coherence tomography method. Optical imaging with diffusely scattered light is possible at a low resolution. We present a method to obtain high-resolution images of fluorescent objects using only randomly scattered laser light. Our method combines the optical memory effect, which allows scanning of a speckle pattern, with iterative phase retrieval methods known from astronomy and digital holography. We demonstrate imaging of artificial and natural fluorescent objects obscured from view by a diffuser that transmits no ballistic light. We will discuss the relevance of this result to security applications and high-resolution imaging, achieving resolutions below 100 nm without a direct view of the object.

8978-19, Session 6

Time-reversal optical focusing for biophotonics applications *(Invited Paper)*

Changhuei Yang, California Institute of Technology (United States)

I will discuss our recent work on the use of digital optical phase conjugation and ultrasound tagging to accomplish time-reversal deep tissue optical focusing for fluorescence imaging and other applications.

8978-20, Session 6

Real-time 3D endoscopic imaging through a single multimode optical fiber *(Invited Paper)*

Wonshik Choi, Donggyu Kim, Jungho Moon, Changhyeong Yoon, Korea Univ. (Korea, Republic of)

A multimode optical fiber, although its mode dispersion is detrimental to imaging, is a promising image-guiding tool for endoscopy applications. Due to the large number of modes per unit area, it can carry image information with an order of magnitude or two smaller diameter than the conventional bundled fiber. In recent years, advances have been made to eliminate the effect of mode dispersion by a single multimode fiber. However, a liquid-crystal spatial light modulator (LC-SLM) widely used for compensating the image distortion has set the image acquisition rate too low for practical applications. Here, we present a high-speed fluorescence endomicroscopy system that can take high-resolution and 3D fluorescence images through a single multimode fiber. In our study, we used a digital micro-mirror device (DMD) having an extremely high refresh rate (22,727 Hz) instead of LC-SLM. While the binary control of the DMD has posed difficulty in fine wavefront shaping, we devised an exquisite method to make use of the full degree of the binary control of DMD for measuring the transmission matrix of a multimode fiber. From the measured transmission matrix, we identified a display pattern that would generate a focused spot in both lateral and axial planes at the far side of the fiber. By displaying the patterns at full frame rate of DMD, we achieved near video-rate image acquisition rate (10.3 frames per second) for a typical 47?47 pixels fluorescence image, which is faster than the previous LC-SLM-based techniques by 2 orders of magnitude. With the near-complete elimination of image distortion, the image resolution was diffraction-limited set by fiber numerical aperture. Our study lays a foundation of applying the single-fiber microendoscopy to in-vivo real time imaging or high-speed micromanipulation based on optical guide geometry.

Conference 8979: Emerging Digital Micromirror Device Based Systems and Applications VI

Tuesday - Wednesday 4 –5 February 2014

Part of Proceedings of SPIE Vol. 8979 Emerging Digital Micromirror Device Based Systems and Applications VI

8979-19, Session 1

Massively parallel confocal scanning imaging of the retina

Kari V. Vienola, Boy Braaf, Koenraad A. Vermeer, Rotterdam Ophthalmic Institute (Netherlands); Johannes F. de Boer, Rotterdam Ophthalmic Institute (Netherlands) and Vrije Univ. Amsterdam (Netherlands)

Eyes are constantly in motion even when fixating on a target. Therefore high-speed imaging is crucial for obtaining high quality retinal images. Recently the digital light projection technology has been successfully demonstrated in microscopy and ophthalmic imaging. In both applications, a digital micromirror device (DMD) was used to either project multiple point-sources for sample illumination or to simulate line-scanning by projecting narrow adjacent lines for imaging the retina.

In this project we will present our first results of our novel retinal imaging system. A DMD was used to generate multiple point-sources across the whole field of view (FOV) simultaneously. A high-power light emitting diode was used to homogeneously illuminate the DMD and a total internal reflection prism was placed in front of the DMD to guide the light propagation. A near-infrared CMOS area scan camera with a global shutter was used for detecting backscattered light from the whole FOV.

There are two major advantages of this system over a (line) scanning laser ophthalmoscope. Firstly, retinal information is acquired instantaneously within the whole FOV with one acquisition cycle whereas in raster or line scanning this is not the case. Secondly, motion artifacts are minimal due to the high imaging speed that can be achieved. Any remaining motion artifacts result in slightly blurred images rather than the geometric distortions associated with traditional scanning methods. In our setup, confocality is achieved by sparsely switching mirrors ON, thereby eliminating cross-talk from neighboring mirrors. The final frame is generated by combining several registered sub-sampled images.

8979-21, Session 2

The use of hyperspectral imaging (HSI) in wound healing *(Invited Paper)*

Javier La Fontaine, Lawrence Lavery, The Univ. of Texas Southwestern Medical Ctr. at Dallas (United States); Karel J. Zuzak, Digital Light Innovations (United States)

Objective: A hyperspectral imaging system (HsI), described previously, was utilized to evaluate and monitor wounds and their healing surgery and post-operatively. Briefly, the system consists of a DLP® based spectral light modulator providing active spectral illumination that is synchronized with a digital focal plan array for collecting spectroscopic images that are processed for mapping the percentage of oxyhemoglobin at each detector pixel non-invasively and at near video rates ~8 chemically encode images per second.

Methods: Ten patients were imaged over a period of two weeks and two patients were imaged twice. Patients were taken to the operating room for soft tissue and bone debridement of the foot following and infection. HsI was utilized during surgery by imaging patients before, and after soft tissue and bone debridement of the foot, and -2 days postoperative, HsI images were collected when the patient returned to surgery to have the wound re-debrided, possible closure or treatment with negative pressure wound therapy (NPWT) utilizing V.A.C.® Therapy.

Results: The bases of each wound were measured, and showed to have tissue oxygenation as low as 32.48 %HbO2 prior to amputation. Tissue area that was clinically determined as having poor perfusion was on average 44.59 %HbO2 while areas of good perfusion were 60.65 %HbO2. Wounds that were considered at risk for amputations had a tissue oxygenation of 51.97 %HbO2. Tissue oxygenation was noticed to increase after debridement, and 5 minutes after NPWT treatment. NPWT was noted to improve tissue oxygenation by 6% within 15 minutes, and 18% after 48 hours of continuous use.

Conclusion: The present study suggests the level of tissue health is directly related to tissue oxygenation levels within the micro vasculature. Results show low tissue oxygenation indicating poor tissue health and compared well with standard clinical methods. This technology may assist surgeons in identifying well oxygenated tissue in which is not possible with visual evaluation alone.

8979-22, Session 2

DLP technology application: 3D head tracking and motion correction in medical brain imaging

Oline V. Olesen, Massachusetts General Hospital (United States) and Technical Univ. of Denmark (Denmark); Jakob Wilm, Rasmus R. Paulsen, Technical Univ. of Denmark (Denmark); Liselotte Højgaard, Rigshospitalet (Denmark); Rasmus Larsen, Technical Univ. of Denmark (Denmark)

Motion correction in medical imaging is of increasing importance due to improved scanner resolution and advanced dynamic imaging techniques where patient movement can be confounded with physiological changes.

A tracking prototype system based on Digital Light Projection (DLP) Technology for medical brain imaging is presented. The system, referred to as Tracoline, has successfully been tested for motion correction in Position Emission Tomography (PET) on phantom and human studies. This work describes a complete system from technical design and methods to clinical demonstration. The key component of the Tracoline system is a Pico DLP light projector reengineered to project at near infrared wavelengths to avoid patient discomfort. The system uses the principle of structured light surface scanning to track the patient's head. Partial 3D-surface representations of the forehead are computed from projections of a set of phase-shifted sine patterns. The system returns the relative head pose which is then used for motion compensation in the post-processed image reconstruction. The tracking estimates can alternatively be transmitted to a medical scanner in real time for prospective motion compensation.

The major advantage of the presented system for this particular application is that it does not rely on markers – in contrast to previously published and demonstrated methods. This makes the Tracoline system attractive for clinical use since time consuming and error prone marker attachment is avoided.

A quantitative analysis shows a tracking accuracy of less than 0.3 mm and 0.1°, while in-situ dynamic PET data of a healthy subject shows significant reduction of acquisition artifacts.

8979-23, Session 2

Using DMDs for focusing light through turbid media

Sri Nivas Chandrasekaran, Hans Ligtenberg, Wiendelt Steenbergen, Ivo M. Vellekoop, Univ. Twente (Netherlands)

The holy grail of biomedical optical imaging is to perform optical-resolution microscopy deep inside living tissue. Unfortunately, most biological tissue scatters light. Scattering changes the direction of the light in a random matter and after less than a millimeter all light is diffuse.

Recently it was shown that spatial light modulators (SLMs) can be used to focus light through and inside turbid materials. This technique, called 'wavefront shaping' uses multi-path interference to focus scattered light at a sub-micrometer resolution. The potential of wavefront shaping to image deep inside turbid objects has been demonstrated in proof-of-principle experiments.

A prerequisite for wavefront shaping is that the wavefront must uniquely match the scattering profile of the sample at each moment in time: when the particles in the sample move, the wavefront needs to be updated continuously.

For biological tissue, this requirement means that both the SLM and the rest of the feedback system need to construct a matching wavefront in less than 1 ms.

So far, most experiments were performed with liquid crystal light modulators, which are too slow to keep up with the dynamics of perfused tissue. Since digital micromirror device (DMD) technology is orders of magnitude faster, it holds the promise to bring wavefront shaping to in-vivo applications.

We will demonstrate and compare different algorithms that can be used to focus light through scattering media using a DMD. We discuss the efficiency of intensity-only DMDs compared to spatial phase modulators in terms of focus contrast, resolution, and speed.

8979-24, Session 2

Fabrication of topographic patterns by DMD-controlled photopolymerization and characterization for cellular migration

Nelson Cardenas, Samarendra K. Mohanty, The Univ. of Texas at Arlington (United States)

Spatially-patterned topographic environments are finding applications for cellular confinement and organization for cancer research, and stem cell differentiation etc. Physical confinement constitutes a biophysical stimulus that alters cell morphology and suppresses motility. While photo-polymerization based techniques exist for construction of cell-supportive topographic matrices, these methods require projection masks that are not dynamic and require advanced facility. Here, we report fabrication of topographic structures using a digital micromirror device (DMD) to create dynamic photomasks for crosslinking geometrically specific photopolymers, induced through UV-light initiated polymerization. The resulting structures provide a constrained 3D environment for cellular growth. Control of topographic features of the structured formed by variation in light intensity and exposures was characterized using digital holographic microscopy and AFM. The process is highly reproducible and can be extended to crosslink photo-polymerizable hydrogels for 3D tissue culture. Whole tissue explants or dissociated cells can be encapsulated into the topographic platform for experimental assays such as cellular migration or neurite outgrowth. Moreover, as the protocol can work for many types of hydrogels and cells, the potential applications are both varied and vast. Characterizations of cells in the presence of 3D microstructures were carried out employing several quantitative microscopic techniques.

8979-1, Session 3

Towards superfast 3D optical metrology with digital micromirror device (DMD) platforms

Tyler Bell, Song Zhang, Iowa State Univ. (United States)

This paper presents our decade-long research efforts towards superfast 3D optical metrology using the digital micromirror device (DMD) platforms. Firstly, we will present probably the first-ever high-resolution real-time 3D optical metrology system that we developed using the digital fringe projection (DFP) method: The system could simultaneously acquire, reconstruct, and re-display 3D shape at 30 frames per second with over 300,000 measurement points per frame. We then will present our recent innovations on the digital binary phase-shifting technique that has been demonstrated its merits over the conventional sinusoidal phase-shifting method in terms of measurement speed and simplicity: achieving kHz rate 3D optical metrology without worrying about the nonlinearity of the projection system. This speed breakthrough was enabled the digital-light-processing (DLP) Discovery platform and lately the DLP LighCrafter platform. Yet, we found that the binary defocusing technique is not trouble free: the squared binary method has smaller measurement depth range than the conventional method. To address this challenge, we have developed methods to improve the measurement accuracy without sacrificing the measurement speed, and to increase the measurement depth range without losing the measurement quality. Specifically, this paper will summarize the development of the optimal pulse width modulation (OPWM) and the binary dithering/halftoning techniques for high-quality superfast 3D shape measurement with the binary defocusing method. Principle of each technique will be presented, and experimental results will be shown to verify its performance.

8979-2, Session 3

Comparison of fixed-pattern and multiple-pattern structured light imaging systems

Vikram V. Appia, Pedro Gelabert, Texas Instruments Inc. (United States)

A wide variety of patterns are used in structured light depth imaging. At the highest level of abstraction, these techniques are classified as single fixed-pattern approaches and variable multi-pattern approaches. Depending on the application, there are certain trade-offs for each technique. In prior literature, several attempts have been made to understand the benefits of each approach individually. But quantitative comparison of these different approaches has not been studied.

In this paper, we present a quantitative comparison of a fixed-pattern and multi-pattern structured light system under varying capture environments. For this analysis, we created two ground truth models, with various depth and spatial variations as well as some smooth regions. These models represent the two extremes of depth measurement requirements. We also designed experiments that enable us to make a fair comparison of these two techniques. We fix all system parameters except the exposure time and ambient light levels in the scene. To ensure a fair comparison we reduce the exposure time for each capture in the multi-pattern approach to add up and equal the exposure time of a single capture in the fixed-pattern system. Then we analyze the accuracy of these methods under varying ambient lighting conditions.

We show that multi-pattern approaches can be very accurate in controlled environment in stationary scenes with high SNR, whereas fixed pattern methods are robust to ambient lighting changes. Further, in practical applications, we show that the multi-pattern approach has higher spatial and depth resolution when compared to a fixed pattern system.

8979-3, Session 3

Accurate and simple calibration of DLP projector systems

Jakob Wilm, Technical Univ. of Denmark (Denmark) and Rigshospitalet (Denmark); Oline V. Olesen, Technical Univ. of Denmark (Denmark) and Rigshospitalet (Denmark) and Massachusetts General Hospital (United States); Rasmus Larsen, Technical Univ. of Denmark (Denmark)

Much work has been devoted to the calibration of optical cameras, and accurate and simple methods are now available which require only a small number of calibration targets. The problem of obtaining these parameters for light projectors has not been studied as extensively and most current methods require a camera and involve feature extraction from a known projected pattern.

The projector is usually modeled just like a pinhole camera, with focal lengths; aspect ratio and principle point coordinates. Lens distortion parameters are usually considered important in camera calibration, while they are often neglected in projector calibration methods.

In this work we present a novel calibration technique for DLP Projector systems based on fringe image projection onto a printed calibration target. In contrast to most current methods, the one presented here does not rely on an initial camera calibration, and so does not carry over the error into projector calibration. A radial interpolation scheme is used to convert features coordinates into projector space, thereby allowing for a very accurate procedure. This allows for highly accurate determination of parameters including lens distortion. Our implementation acquires printed planar calibration scenes in less than 2s, and requires 3 scenes at least. This makes our method both fast and convenient. Implementation is particularly easy as currently available camera calibration software is reused for parameter optimization.

We evaluate our method in terms of reprojection errors and structured light image reconstruction quality and show that it compares favorably against currently available software.

8979-4, Session 4

Robust near-infrared structured light scanning for 3D human model reconstruction

Bo Fu, Ruigang Yang, Univ. of Kentucky (United States)

In this paper we present a novel sensing system, robust Near-infrared Structured Light Scanning (IRSL) for three-dimensional human model scanning application. Human model scanning due to its nature of various hair and dress appearance and body motion has long been a challenging task. Previous structured light scanning methods typically emitted visible coded light patterns onto static and opaque objects to establish correspondence between a projector and a camera for triangulation. The success of these methods rely on scanning objects with proper reflective surface for visible light, such as plaster, light colored cloth. Whereas for human model scanning application, conventional methods suffer from low signal to noise ratio caused by low contrast of visible light over the human body. The proposed robust IRSL, as implemented with the near infrared light, is capable of recovering those dark surfaces, such as hair, dark jeans and black shoes under visible illumination.

Moreover, successful structured light scan relies on the assumption that the subject is static during scanning. Due to the nature of body motion, it is very time sensitive to keep this assumption in the case of human model scan. The proposed sensing system, by utilizing the new near-infrared capable high speed LightCrafter DLP projector, is robust to motion, provides accurate and high resolution three-dimensional point cloud, making our system more efficient and robust for human model reconstruction.

Experimental results demonstrate that our system is effective and efficient to scan real human models with various dark hair, jeans and shoes, robust to human body motion and produces accurate and high resolution 3D point cloud.

8979-5, Session 4

High-speed active head tracking system

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

We report on the development of a highly scalable head tracking system capable of tracking many users. Throughout the operating area, a series of high-speed (4 kHz) near-infrared LED-based Digital Light Processor (DLP) picoprojectors provide overlapping illumination of the volume. Each projector outputs a sequence of binary images which encode the position of each pixel within the projected image as well as an identifier sequence for the projector. Overlapping projectors use differing temporal carrier frequencies to allow sensor discrimination and background rejection. Pixel positions from multiple projectors received by each sensor are triangulated to obtain position and orientation.

In many regards this may be considered a time-reversed version of conventional optical tracking systems, in which projectors broadcasting to photosensors replace cameras sensing fiducials. This eliminates the processing bottleneck associated with camera imagery analysis, particularly when the number of users increases. In comparison, our system operates in a manner conceptually similar to the Global Positioning System (GPS) in that angularly encoded beacons (projectors) broadcast to independent IR receivers. This confers many of the same GPS advantages in that each receiver is independent, allowing for any number of users to interact without interference or added computational load. Additionally, multiple overlapping projector footprints can be used to scale the system volume indefinitely.

8979-6, Session 5

Microsecond reconfigurable NxN data-communication switch using DMD *(Invited Paper)*

Pierre-Alexandre J. Blanche, College of Optical Sciences, The Univ. of Arizona (United States); Alexander A. Miles, The Univ. of Arizona (United States); Brittany Lynn, College of Optical Sciences, The Univ. of Arizona (United States); John Wissinger, The Univ. of Arizona (United States); Daniel N. Carothers, Texas Instruments Inc. (United States); Robert A. Norwood, Nasser N. Peyghambarian, College of Optical Sciences, The Univ. of Arizona (United States)

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

We present here the use the DMD as a diffraction-based optical switch, where Fourier diffraction patterns are used to steer the incoming beams to any output configuration. The Fourier diffraction patterns are computer generated holograms that structures the incoming light into any shape in the output plane. This way, the light from any fiber can be redirected to any position in the output plane, and the performance of the switch scales well to high port count. .

We have implemented a single-mode fiber coupled 7?7 switch and demonstrated its ability to operate over the entire telecommunication C-band centered at 1550 nm. The all-optical switch was built primarily with off-the-shelf components and a Texas Instruments DLP7000 with an array of 1024 ? 768 micromirrors. This DMD is capable of switching 100 times faster than currently available technology (3D MOEMS). The switch is robust to typical failure modes, protocol and bit-rate agnostic, and permits full reconfigurable optical add drop multiplexing (ROADM). There is potential to address the growing need for high speed scalable circuit switching for data centers and optical aggregation networks.

The switch demonstrator was inserted into a networking testbed for the majority of the measurements. The testbed assembled under the Center for Integrated Access Networks (CIAN), a National Science Foundation (NSF) Engineering Research Center (ERC), provided an environment in which to simulate and test the data routing functionality of the switch. A Fujitsu Flashwave 9500 PS was used to provide the data signal, which

was sent through the switch and received by a second Flashwave node. We successfully transmitted an HD video stream through a switched channel without any measurable data loss.

We are working on a 30?30 version of the switch using a Texas Instrument DLP9500 with 1920?1080 micro-mirrors. This new version should address the high insertion loss we experience with the first prototype switch, due to the Fourier lens selected. In the presentation we will also present solutions to the problems of chromatic dispersion and diffraction efficiency of such a device.

8979-7, Session 5

Precise holograms using complex light modulation

Michael F. Becker, The Univ. of Texas at Austin (United States); Jinyang Liang, Washington Univ. in St. Louis (United States)

Our objective is to achieve precise wavefront reconstruction using complex modulation of light. The advantage over phase or amplitude modulation individually is that much higher quality reconstructed images are possible. Absent off-the-shelf complex spatial light modulators (SLMs), we have proposed complex modulation by utilizing high precision amplitude beam shaping that uses a digital micromirror device (DMD). Our approach is to image a precisely amplitude-shaped beam onto a phase SLM. Amplitude beam shaping using the DMD can give highly precise beams for low spatial frequency patterns. Higher spatial frequency patterns are accompanied by a predictable increase in RMS error. A second advantage of this scheme is that precise pixel-to-pixel registration of the amplitude pattern onto the phase SLM is not required.

A significant first step was to derive an efficient backwards propagation algorithm for hologram design that did not degrade the reconstructed image by truncating high spatial frequencies or by aliasing. This design routine was demonstrated to be equivalent to an exact Rayleigh-Sommerfeld calculation. Necessary conditions and constraints to use this method will be reported.

Subsequent steps are to simulate and experimentally measure the reconstruction quality. We report that reconstruction fidelity decreases slowly as the spatial bandwidth of the amplitude modulated component decreases. Significant hologram fidelity is not lost due to low-pass filtering the amplitude modulation. We will explore the tradeoff between final reconstruction precision and the bandwidth of the amplitude modulation and the characteristics of the phase-only modulation.

8979-8, Session 5

Micro-mirror arrays for spectroscopic applications

Walter M. Duncan, Charles J. Maxwell, The Univ. of Texas at Dallas (United States)

Visible and Near Infrared (NIR) spectroscopy is used in a number of applications including security, biomedical, military, materials science, and materials processing areas. Visible red and NIR ranges are valuable for in vivo studies because photons in this range have very low potential energy and are hence considered non-invasive. Integrated spectrometers operating in this spectral range can have high performance (i.e. resolution and transmission), low cost, sensitivity (fast and low noise) and can operate under normal environmental conditions (such as temperature, atmospheric gases, pressure and humidity).

In this study the “spectral analysis” sections of both a micro-mirror based adaptive slit plus single pixel detector NIR based spectrometer and pixelated InGaAs array based spectrometer are compared. It should be noted that in either approach, adaptive slit plus single element versus array detector, the spectrometer requires a dispersive element or filter and if it is an active system, a light source is needed to operate. In this work we test, model, and compare the adaptive micro-mirror slit plus single element detector approach to the array detector spectrometer. Within the context of the adaptive micro-mirror slit spectrometer, we are establishing a set of optical requirements, to ideally cover a number of applications. In addition to experimental performance comparisons between the spectrometer approaches, we will report on the performance requirements and environmental issues for these NIR spectrometers.

8979-9, Session 6

High-resolution and energetically efficient lensless imaging system based upon time-varied pinholes array *(Invited Paper)*

Ariel Schwarz, Amir Shemer, Zeev Zalevsky, Bar-Ilan Univ. (Israel)

Imaging systems generally involve tradeoffs between spatial resolution and signal to noise ratio. In a single pinhole based imaging system, the size of the aperture determines the spatial resolution. Up to a certain point, the smaller the aperture, the sharper the image, however, with a small pinhole the number of photons passing through decreases and the uncertainty of the measurements is increased. On the other hand, a larger pinhole allows more photons to pass through, which reduces the relative uncertainty of the measurements, but this comes at the price of degraded spatial resolution.

In this paper we propose a novel method for realizing an imaging system that can enhance the spatial resolution while preserving the energetic efficiency. The imaging system is a lensless configuration in which there is a time varied array of pinholes that is positioned in the aperture plane. The changeable and moving pinholes array is realized using a DLP matrix. This paper presents both numerical simulations as well as experimental results showing the capability of the proposed concept.

8979-10, Session 6

Frequency division multiplexed imaging: a Texas Instruments DMD implementation

Houman Habibkhani, Bahadir K. Gunturk, Martin Feldman, Louisiana State Univ. (United States); Aziz U. Batur, Texas Instruments Inc. (United States)

Recently we proposed frequency division multiplexed imaging (FDMI), which allows capturing multiple images in a single shot through spatial modulation and frequency domain filtering. (The paper received the best paper award in the SPIE International Conference on Digital Photography in 2013.) Spatial modulation is done in such a way that different images or sub-exposures are modulated and placed at different locations in Fourier domain. For example, one image might be modulated with a horizontal grating (black-and-white line pattern) and the other might be modulated with a vertical grating. When we take the Fourier transform of the sum of these two images, we will have replicas of the individual Fourier transforms of the images as sidebands. As long as there is no overlap of the sidebands, we can recover different components by band-pass filtering the multiplexed image. In this paper, we present a Texas Instruments DMD based implementation of FDMI. An image is formed on the DMD chip; pixels are modulated by the micro-mirrors; and the reflected image is captured by a camera. In the first half of the exposure time, we have one type of pattern (spatial modulation); in the second half, we have another type. As a result, we can recover the first and second half sub-exposure images. Such a system could be used in a variety of applications, such as motion analysis and image deblurring. We will provide experimental results with the setup, and discuss possible applications as well as limitations.

8979-11, Session 6

Use of high-radiant flux, high-resolution DMD light engines in industrial applications

Alexandra Müller, IN-VISION Digital Imaging Optics GmbH (Austria); Surinder Ram, Lenzing Technik GmbH (Austria)

Illumination systems and imaging systems of industrial projectors in applications like lithography, 3D printing and so on have special demands that differ in many points from commercial home projection systems. Video projectors or projectors for presentations are optimized to please the human eye. Bright colors and image enhancement are far more important than uniformity of the illumination or image distortion.

On the other hand, a projector designed for use in a specialized field has to be tailored regarding its unique requirements in order to make no quality compromises. We present a light engine that is optimized for lithography and related areas.

The illumination technology of photopolymers has a wide application range in 3D printing, printed circuit board exposure, ID card printing and much more.

The basic principle is to illuminate a photopolymer substrate with an image generated by the DMD, hardening the illuminated areas. Like this slice by slice a 3D object can be formed.

We developed a light engine that emphasizes on

- High uniformity of illumination – for uniform chemical reaction
- High radiant flux – for fast chemical reaction
- Extreme low image distortion – for accuracy of the printed object
- Near telecentricity – for accuracy of the printed object
- Short wave length – for good chemical reactivity
- Very high resolution – for high detail resolution up to the object corners

Only by taking special care about all the necessary key features of the illumination, the highest quality result for the work piece will be achieved.

8979-12, Session 6

Dynamically reconfigurable framework for pixel-level visible light communication projector

Leijie Zhou, Shogo Fukushima, Takeshi Naemura, The Univ. of Tokyo (Japan)

We have developed Pixel-level Visible Light Communication projector (we call it as PVLC projector later) based on the DLP (Digital Light Processing) system before. However, there are some limitations when we applied the system. (e.g. it can only use the data in the memory of the system) In order to eliminate these limitations, we employ HDMI signals from a PC as an input of the system. Because the system (DLP Discovery 4100 Development Kit) has no HDMI signal interface, we designed a HDMI signal receiver circuitry, created a piece of PCB and connected it to the EXP expansion connector on the system board to let the FPGA on the system process the image data which is decoded by the HDMI receiver circuitry. Through controlling the HDMI signal output from the PC, we can implement a dynamically reconfigurable system framework. On the other hand, in order to achieve a high-frame-rate feature of DLP system, we optimized the trade-off relationship between the image resolution and the refresh rate of the HDMI output. A single high resolution 24-bit color image is firstly divided into four 24-bit images, then each divided image is changed into twenty-four consecutive binary frames. However, the higher the image resolution is, the lower the refresh rate of HDMI output will be. Thus, through testing the performance of the system, as a result, we set the refresh rate of digital video signal at 120Hz and the resolution at 1024*768. Consequently, the PVLC projector displays 120*4*24 = 11,520 frames per second. In this paper, we will detail the system framework and the design method of dynamically reconfigurable PVLC projector.

8979-25, Session 6

DMDs for Smart Headlights *(Invited Paper)*

Robert Tamburo, Srinivasa G Narasimhan, Anthony Rowe, Takeo Kanade, Carnegie Mellon University (United States); Eriko Nurvitadhi, Mei Chen, Intel (United States)

The primary goal of a vehicular headlight is to improve safety in low-light and poor weather conditions. The typical headlight however has very limited flexibility - switching between high and low beams, turning off beams toward the opposing lane or rotating the beam as the vehicle turns - and is not designed for all driving environments. Thus, despite decades of innovation in light source technology, more than half of the vehicular accidents still happen at night even with much less traffic on the road.

In this talk, I will describe a new DMD-based design for a headlight that can be programmed to perform several tasks simultaneously and that can sense, react and adapt quickly to any environment with the goal of increasing safety for all drivers on the road. For example, we will be able to drive with high-beams without glaring any other driver and we will be able to see better during rain and snowstorms when the road is most treacherous to drive. The headlights can also increase contrast of lanes, markings and sidewalks and can alert drivers to sudden obstacles. I will lay out the engineering challenges in building this headlight and share our experiences with the prototypes we developed over the past two years.

8979-13, Session 7

Design of a single projector multiview 3D display system

Jason Geng, IEEE Intelligent Transportation Systems Society (United States)

Multiview three-dimensional (3D) display is able to provide horizontal parallax to viewers with high-resolution and full-color images being presented to each view. Most multiview 3D display systems are designed and implemented using multiple projectors, each generating images for one view. Although this multi-projector design strategy is conceptually straightforward, implementation of such multi-projector design often leads to a very expensive system and complicated calibration procedures. Even for a multiview system with a moderate number of projectors (e.g., 32 or 64 projectors), the cost of a multi-projector 3D display system may become prohibitive due to the cost and complexity of integrating multiple projectors.

In this article, we describe an optical design technique for a class of multiview 3D display systems that use only a single projector. In this single projector multiview (SPM) system design, multiple views for the 3D display are generated in a time-multiplex fashion by the single high speed projector with specially designed optical components, a scanning mirror, and a reflective mirror array. Images of all views are generated sequentially and projected via the specially design optical system from different viewing directions towards a 3D display screen. Therefore, the single projector is able to generate equivalent number of multiview images from multiple viewing directions, thus fulfilling the tasks of multiple projectors. An obvious advantage of the proposed SPM technique is the significant reduction of cost, size, and complexity, especially when the number of views is high. The SPM strategy also alleviates the time-consuming procedures for multi-projector calibration. The design method is flexible and scalable and can accommodate systems with different number of views.

8979-14, Session 7

DMD technology enables an optical see-through head-mounted 3D display with true focus cues

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Conventional stereoscopic displays force an unnatural decoupling of the accommodation and convergence cues, which may contribute to various visual artifacts and result inaccurate depth perception. Multi-focal-plane displays render a series of 2D images at carefully placed, discrete focal distances, where each focal-plane renders 3D objects within a depth range centered on it and they together render a volume of 3D space. Using depth-weighted luminance blending technique, a large 3D volume may be rendered continuously using only a few focal planes. Therefore multi-focal-plane displays are capable of rendering correct focus cues and potentially provide higher depth perception accuracy, higher stereoacuity and lower fatigue in stereoscopic displays.

We present a multi-focal-plane display prototype capable of rendering true focus cues for a large volume of 3D space extending from 0 to 3 diopters and a field of view of 40 degrees. In our system, 3D objects of different depths are rendered time-sequentially on 2D focal planes whose focal distances are modulated by a MEMS deformable mirror in synchronization with the depths of the objects being rendered. The enabling technology is the Digital Micromirror Device which provides a very high frame and flexible bit-plane control that allows us to time-multiplex 6 or more focal planes of high resolution color images at a flicker-free speed. With custom designed optics, including a freeform prism eyepiece and a see-through compensator, the system provides high display quality and see-through quality as well as a compact form factor to be implemented into a head-mounted display.

8979-15, Session 7

Control over the DMD for projection display applications

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Digital light processing (DLP) uses a digital micromirror device (DMD) to control light, effectively acting as an array of optical switching elements. DMDs have found wide use as high-speed spatial light modulators for projection applications. This paper describes a novel interface solution that converts objects drawn on the screen of a personal computer (PC) to mirror-copy representations across the DMD micromirror array such that corresponding images of the objects can be projected onto a screen. Continuously, the interface solution checks the PC screen for any new rendering to update the projected identical mirror-copy over the DMD surface. In addition, the user can render a 3D volumetric image by simply drawing the slices of the 3D image over a previously specified number of application windows opened by the interface solution. Then, the interface solution ensures a continuous projection of these slices forming the 3D image with complete control over the projection speed. This interface solution is successfully shown to be applicable to the process of volumetric 3D display through the acquisition of data from a PC screen and subsequent creation and display of 3D image slices which can be assembled into a volumetric image.

8979-16, Session 7

A scalable multi-DLP pico-projector system for virtual reality

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Virtual Reality (VR) environments can offer immersion, interaction and realistic images to users. A VR system is usually expensive and requires special equipments in a complex setup. One approach is to use multi-projector systems, with auto-calibration cameras, to build small and low cost VR systems by using off-the-shelf equipment without decreasing significantly the visual experience. In this paper, we propose a low-cost, scalable and mobile solution for augmented and virtual reality that allows to build systems that projects images onto a variety of screen types such as planar, cylindrical and spherical surfaces. Our prototype is composed by a cluster of pico-projectors that has LED technology for energy efficiency, and assembled in a much smaller footprint. We developed a multi-projector software library, called Fast Fusion, that calibrates all projectors so that uniform images are always shown to viewers. Fast Fusion uses a camera to automatically calibrate geometric and photometric correction of projected images. The current prototype has four TI DLP 2.0 Pico Projectors, with 7 lumens (LED) and DLP 0.17 HVGA Chipset (480x320). These are placed as 2x2 array and the final resolution is up to 900x600 pixels. Our system is scalable for several projectors. Also, we are able to use a non-planar screen and to integrate with a head tracking system (Optitrack with six S250e cameras). Thus, we can calculate the correct viewpoint of the user and the projection. In our analysis, a non-planar screen with multiple DPL-Pico-Projectors plus head tracking can provide high immersion perception to users.

8979-17, Session 7

Integration of real-time 3D image acquisition and multiview 3D display

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The 3D acquisition, display systems will gain effective 3D visualization of the real objects or scenes in the world as the technology progresses in this area. The vivid representation of rendered or captured 3D objects is available to help us observer these 3D objects and scenes in a more familiar way. In this paper, we describe an autostereoscopic-based multiview 3D acquisition and display system to demonstrate both the rendered 3D models and captured scenes. We focus upon the design principle, the hardware and the software architecture of this system. An autostereoscopic screen is firstly set up for the anisotropic display. Secondly, the Client-Server model (C/S model) is applied in our system enabling the multiple capturing and display functions. Considering the size of the image-capture and image-generating equipment we use, we arrange them in an interlaced way and perform correction to unify the captured image and displayed image in each view point. Improved algorithms are also involved so the system operates faster. In terms of transmission between the client and the server PCs, we rearrange and compress the images from each equipment in the capturing array and broadcast the data to client PCs. In addition, synchronization mode is set up to control the capturing and display process in case some of the captured image frames will go ahead of others or fall behind. Finally, a prototype consists of the screen, the capturing array and display array is built with the integration of the real-time acquisition and display functions. Experiments are also performed to ameliorate our system.