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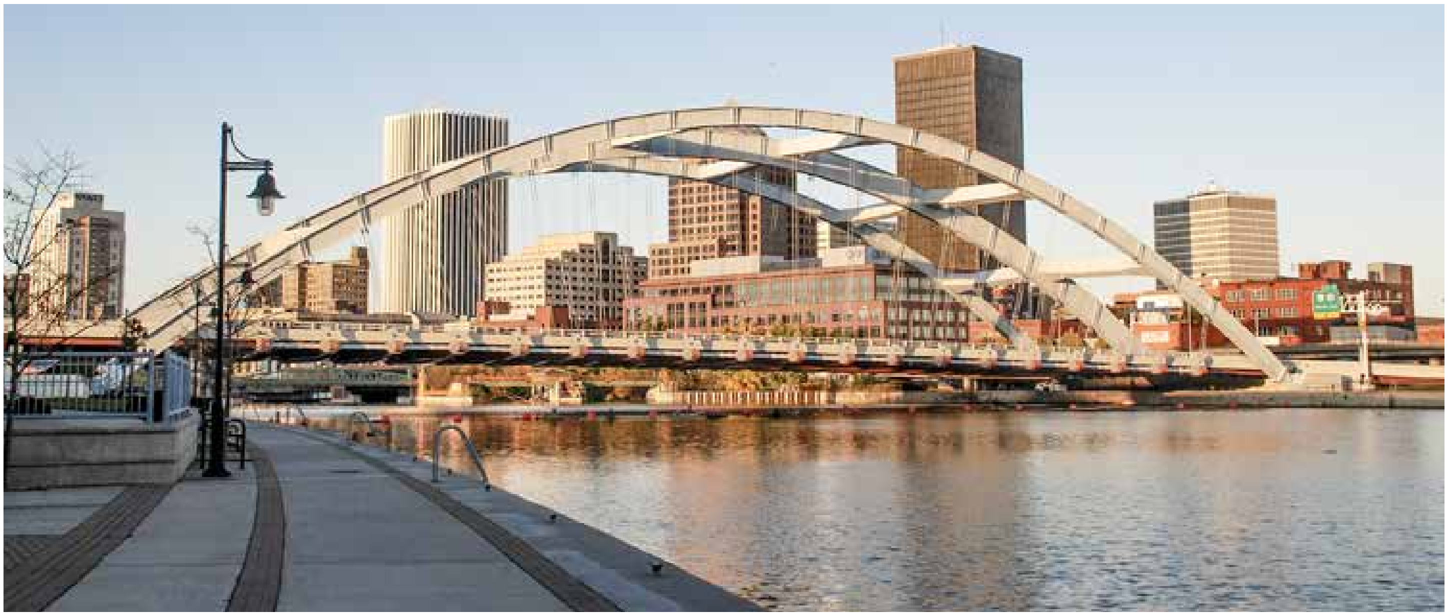

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Contents

Conference 10448: Optifab 2017

Monday - Thursday 16–19 October 2017

Part of Proceedings of SPIE Vol. 10448 Optifab 2017

10448-1, Session 1

Analysis and optimization of surface profile correcting mechanism of the pitch lap in large-aperture annular polishing

Huifang Zhang, Shanghai Univ. (China); Minghong Yang, Xueke Xu, Lunzhe Wu, Shanghai Institute of Optics and Fine Mechanics (China); Weiguang Yang, School of Materials Science and Engineering, Shanghai University (China); Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

The surface figure control of the conventional annular polishing system is realized ordinarily by the interaction between the conditioner and the lap. The surface profile of the pitch lap corrected by the marble conditioner has been measured and analyzed as a function of kinematics, loading conditions, and polishing time. The surface profile measuring equipment of the large lap based on laser alignment was developed with the accuracy of about 1μm, and the pressure meter array were used to detect the pressure distribution at the conditioner/lap interface. The conditioning mechanism of the conditioner is simply determined by the kinematics and fully fitting principle, but the unexpected surface profile deviation of the lap emerged frequently due to numerous influencing factors including the geometrical relationship, the pressure and friction distribution at the conditioner/lap interface, and the viscoelastic relaxation of lap. Both factors are quantitatively evaluated and described, and have been combined to develop a spatial and temporal model to simulate the surface profile evolution of pitch lap. The simulations are consistent with the experiment for a wide variety of polishing conditions. This study is an important step toward deterministic full-aperture annular polishing, providing a beneficial guidance for the surface profile correction of the pitch lap.

10448-2, Session 1

APS 3D: a new benchmark in aspherical polishing

Dan Gauch, Schneider Optical Machines Inc. (United States); Dalibor Mikulic, Christian Veit, Schneider GmbH & Co. KG (Germany)

The new APS 3D Polishing system yields better surface quality, significant reductions in cycle time and a better slope error while eliminating the need for a skilled optician. The system determines the optimum speeds, feed rates and polish pressures to achieve a deterministic process based on the required quality parameters input by the operator. The critical properties of the polishing pad are embedded in the barcode and automatically uploaded into the machine reducing the likelihood of operator error. Calibration and set up is performed via intuitive menus that guide an unskilled operator through the required steps, performing all the necessary calculations and adjusting settings as needed. The software automatically verifies that the correct tooling is being used to for the defined lens geometry. The process flow is always the same to ensure consistent quality and no failures: 1. Measuring, 2. Simulating, 3. Scanning, 4. Polishing, 5. Measuring and 6. Fine polishing. The results can be observed in the bokeh of photographs. Bad bokehs demonstrate a non-uniform circle as well as structures in the picture which are related to the lens. Through APS 3D polishing we are able to minimize this structure and achieve a good bokeh with uniform circles and no visible structures. Form accuracies of 0.5 microns can be easily achieved in a single iteration, while 0.05-0.1 microns PV are achievable through multiple iterations. The software accurately predicts the finished surface quality before processing begins so parameters can be adjusted up front to reduce processing times

10448-3, Session 1

Novel high-NA MRF toolpath supports production of concave hemispheres

Chris Maloney, Christopher M. Supranowitz, Paul Dumas, QED Technologies, Inc. (United States)

Many optical system designs rely on high-NA optics, including lithography and defense systems. Lithography systems require high-NA optics to image the fine patterns on a photomask, and many defense systems require the use of domes. The methods for manufacturing such optics with large half angles have often been treated as proprietary by most manufacturers due the challenges involved. In the past, many high-NA concave surfaces could not be polished with MRF™ due to collisions with the hardware underneath the polishing head. By leveraging concepts that were developed to enable freeform raster MRF capabilities, QED Technologies has implemented a novel toolpath to facilitate a new high-NA rotational MRF mode. This concept involves the use of the B-axis (rotational axis) in combination with a 'virtual-axis' that utilizes the geometry of the polishing head. Hardware collisions that previously restricted the concave half angle limit can now be avoided and the new functionality has been seamlessly integrated into the software. This new MRF mode overcomes past limitations for polishing concave surfaces to now accommodate full concave hemispheres as well as extend the capabilities for full convex hemispheres. We discuss some of the previous limitations, and demonstrate the extended capabilities using this novel toolpath. Polishing results are used to qualify the new toolpath to ensure similar results to the 'standard' rotational MRF mode.

10448-4, Session 1

Ultrasonic grinding of optical materials

Michael J. Cahill, Michael J. Bechtold, Edward Fess, Thomas Stephan, Rob Bechtold, OptiPro Systems (United States)

Hard ceramic optical materials such as sapphire, ALON, Spinel, PCA, or Silicon Carbide can present a significant challenge in manufacturing precision optical components due to their tough mechanical properties. These are also the same mechanical properties that make them desirable materials when used in harsh environments. Slow processing speeds, premature tool wear, and poor surface quality are common results of the tough mechanical properties of these materials. Often, as a preparatory stage for polishing, the finish of the ground surface greatly influences the polishing process and the resulting finished product.

To overcome these challenges, OptiPro Systems has developed an ultrasonic assisted grinding technology, OptiSonic, which has been designed for the precision optics and ceramics industry. OptiSonic utilizes a custom tool holder designed to produce oscillations, in microns of amplitude, in line with the rotating spindle. A software package, IntelliSonic, is integral to the function of this platform. IntelliSonic can automatically characterize tooling during setup to identify and select the ideal resonant peak which to operate at. Then, while grinding, IntelliSonic continuously adjusts the output frequency for optimal grinding efficiency while in contact with the part. This helps maintain a highly consistent process under changing load conditions for a more precise surface. Utilizing a variety of instruments, tests have proven to show a reduction in force between tool and part by up to 50%, while increasing the surface quality and reducing tool wear. This paper will present the challenges associated with these materials and solutions created to overcome them.

10448-5, Session 1

Innovative processing of meter-class optics

Matthias Pfaff, OptoTech Optikmaschinen GmbH (Germany)

The drive for high resolution display systems also drives manufacturing technologies. For fabricating large screens, it requires large optical components with cylindrical surfaces in high end quality. The special challenge is the extraordinary size of up to 2m length. Since these geometries are unlike any others, it requires a special approach for both, grinding and polishing.

Also the increased request for high-end systems raises new challenges in grinding, polishing and figuring of 1m class optics, alongside with handling such large optics.

OptoTech developed a range of grinding and polishing machines for fabricating Meter-class optics.

The concept is based on

- 5Axis Grinding Machine: Shaping of cylindrical surface
- UPG 2000 Ultra Precision Generator: High End Grinding & Correctional Grinding
- MCP 2000 Polishing Machine: Power Polishing & Correctional Polishing and figuring
- ZPM 2000: Smoothing.

This paper introduces the processes, the tooling and the machines they are based on.

10448-6, Session 1

Etching hard brittle optical materials by masked ion beam

Yun Li, Taotao Fu, Jia Xin, Tingwen Xing, Institute of Optics and Electronics, Chinese Academy of Sciences (China)

The fabrication of small size aspheric optical surface, which made of hardbrittle materials, usually uses optical cold processing, such as grinding and polishing. However, it is difficult to achieve the ideal requirements of the surface accuracy and roughness due to the factors such as tool size, surface profile and the material properties and so on.The ion beam figuring technique has advantages to process the hard brittle materials and special surfaces because of its non-contacted magnetron sputtering mechanism. But by using the normal ion beam figuring method to shaping the aspheric surface often leads to mid-frequency error and with poor efficiency. In order to solve this problem, the masked ion beam figuring method is used to etch the one-dimension structure on the plat surface which made of hard brittle material. The results show that the expected surface profile is acquired and meanwhile mainlykept the original roughness and mid-frequency. It provides a possible way forfabricating small size aspheric optics which made of hard brittle materials.

10448-7, Session 2

New surface smoothing technologies for manufacturing of complex shaped glass components

Sebastian Henkel, Anne-Marie Schwager, Jens Bliedtner, Kerstin Götze, Ernst-Abbe-Hochschule Jena (Germany); Edda Rädlein, Technische Univ. Ilmenau (Germany); Christian Schulze, Ernst-Abbe-Hochschule Jena (Germany); Martin Gerhardt, Michael Fuhr, Effgen-Laport Schleiftechnik (Germany)

The production of complex glass components with 2.5D or 3D-structures involves great effort and the need for advanced CNC-technology. Especially the final surface treatment, for generation of transparent surfaces, represents a time-consuming and costly process. Conventional polishing methods using loose grain quickly reach their limits for these workpieces. Manufacturing results are hardly reproducible due to numerous influencing factors.

The ultrasonic-assisted grinding procedure is used to generate arbitrary shaped glass components and freeform-surfaces. The special kinematic principle, containing a high-frequency tool oscillation, enables efficient manufacturing processes. Significant reductions over 50 % of tool wear and decreases in grinding forces can be observed. The good quality of the produced surfaces allows for application of novel smoothing methods, which provide considerable advantages compared to classic polishing. The possibility is shown, to manufacture transparent surfaces with low roughness down to Rq = 10 nm for fused silica, during an ultra-fine grinding process that uses new resin-bond diamond grinding tools. Grinding as well as ultra-fine grinding can take place in the same machine in one setting, meaning an efficient and precise manufacturing possibility. In addition to this technology, investigations of CO2-laser polishing are carried out. In this thermal process the workpiece surface is slightly melted up. High polishing rates and a roughness down to Rq < 4 nm are possible.

Experiments and comparisons regarding the applicability of these special manufacturing procedures are carried out, considering selected component geometries. The investigations focus on surface quality (roughness, shape accuracy) of the workpieces, as well as economic aspects.

10448-8, Session 2

Controlling material removal rate and surface quality in femtosecond laser processing of optical materials

Lauren L. Taylor, Joshua C. Frechem, Rochester Institute of Technology (United States); Hainian Han, Chinese Academy of Sciences (China) and Rochester Institute of Technology (United States); Jing Xu, Thomas R. Smith, Michael Pomerantz, John C. Lambropoulos, Univ. of Rochester (United States); Jie Qiao, Rochester Institute of Technology (United States)

Femtosecond lasers can enable ablation-based, precision material removal with negligible thermal effects. Owing to tight focusing, tunable pulse energy/repetition rate, and fast scanning speeds, femtosecond laser processing can be used for high-speed fabrication of small, complex optical components, such as freeform optics, which may not be achievable by conventional polishing tools. In order to achieve precision material removal, laser processing parameters must be optimized to mitigate thermal effects including material melting, pileup, and oxidation. We have constructed numerical thermal and two-temperature models to simulate the rise in surface temperature of silicon and germanium during multi-pulse femtosecond laser processing and predict optimized laser fluence, repetition rate, and scanning speed to achieve thermally-controlled processing. Matrices of optimized parameters were implemented experimentally to quantify the effect of laser parameters on the rate, depth, and uniformity of material removal. Controlled point and line processing of silicon and germanium using optimized parameters will be presented. Surface quality, material composition, roughness, and subsurface damage will be analyzed and compared to conventional grinding and polishing techniques.

10448-9, Session 2

Beam shaping for efficient femtosecond laser processing of optical glass

Michael Seiler, Lin J. Schubert, Ernst-Abbe-Hochschule Jena (Germany); Christian Schindler, Carl Zeiss Jena GmbH (Germany); Jens Bliedtner, Ernst-Abbe-Hochschule Jena (Germany)

Manufacturing optical elements is a process that must efficiently output optics with narrowly defined specifications, like surface quality and shape accuracy. The conventional process consists of different iterative grinding and polishing steps. The aim of conventional grinding is to achieve a polish-able surface quality and to reduce polishing time. Therefore, the shape accuracy and the induced sub surface damage (SSD) of the optical element have to be optimized.

Due to the benefits of ultra-short pulse laser radiation like non thermal ablation and high fluence, the femtosecond laser process is investigated for optics manufacturing. Implementation of such technologies opens up new processing possibilities in the field of optical glass.

In this paper, the experiments are focused on the ablation process with an optimized top hat profile to achieve higher productivity in comparison to a classical Gaussian profile. For this reason a femtosecond laser system with a maximum average output power of 20 W is applied. During the laser ablation process the resulting surface depends on various input parameters. In order to establish an optimized ablation procedure, the influence of pulse energy, line overlap, and pulse overlap are analyzed. The experiments are performed for different optical materials such as fused silica and N-BK7. The SSD, surface roughness (RMS), and removal rate are evaluated through various characterization techniques. Based on the achieved results, the dependency on the applied beam profile is demonstrated. Furthermore, the efficiency and the constraints in the optical figuring process are discussed.

10448-10, Session 2

Novel lubrication strategies for lapping, grinding, and polishing of optical substrates

Joshua Cobb, Niraj Mahadev, Chemetall Precision Microchemicals (United States)

Lubrication strategies for the machining of glass and other optical substrates are investigated with the aim of increasing material removal rate, improving post-operation surface finish, and minimizing the subsurface damage of brittle substrates. The effect of various surfactants and other additives on the performance of a glass machining coolant are discussed. High performance optical coolant Tech Cool Microcut 86 was developed using these principles and product introduced to glass grinding/lapping markets, resulting in improved removal rates on this substrate as well as markedly improved surface finish on the machined part.

10448-11, Session 2

The broad utility of Trizac diamond tile

John Gaglairdi, Vincent Romero, Bruce A. Sventek, Lijun Zu, 3M Co. (United States)

TDT has been effectively used on a broad range of materials that include glasses, sapphire, SiC, Si, ZrO2, LiTaO3, and flooring materials. Expected removal rates and finish are shown for various grades of TDT and process conditions used. Pad wear rates are shown to be optimal, around 0.2 μm/min, tuned through either 1) the flow rate for easier-to-grind materials such as glass or 2) the conditioning particle concentration for harder-to-grind materials. This TDT pad wear rate is the key variable for obtaining proper CoO. Finally, the type of lubricant and concentration used can have a significant impact on the removal rate, finish and TDT lifetime.

10448-12, Session 2

Impact of slurry pH on material removal rate and surface quality of polished fused silica

Melanie Redien, Cedric Maunier, Bertrand Remy, Karine Poliakoff-Leriche, Jérôme Néauport, Commissariat à l'Énergie Atomique (France)

Cerium oxide is for a long time a choice abrasive for fused silica polishing. Among others, it is used to manufacture large optical components for megajoule-class high power lasers, which require excellent surface quality to withstand high nanosecond fluences and accurately focus the laser beams on the target. The good removal rate and surface quality obtained with cerium oxide are attributed to cerium-water-silica chemical affinity. So, one of the ways to improve the polishing process is the chemical engineering of the slurry. And one of the easiest parameter to set is pH.

In this work, we have selected 2 commercial cerium oxide slurries and studied their performances for fused silica polishing at different pH. We have characterized the slurries for size distribution and chemical properties. Then fused silica samples have been polished by widely varying the pH of the slurries, while the other process parameters were kept constant. The material removal rate and the surface quality (roughness, defects density, size and morphology) have been recorded for each sample and compared considering slurry pH.

We observed that depending on the abrasive reference, MRR continuously varies with pH or exhibits a saturation behavior. Roughness is relatively constant and doesn't seem to be very pH dependent over the whole range. And while the defect density can vary with pH, the size and shape of the surface defects doesn't seem to be very influenced by it.

Those results are discussed and as far as possible, compared to the literature.

10448-13, Session 3

Large MRF capabilities at Harris

James T. Mooney, Harris Corp. (United States)

No Abstract Available

10448-14, Session 3

New high-precision deep concave optical surface manufacturing capability

François Piché, Corning Research and Development Corp. (United States); Chris Maloney, QED Technologies, Inc. (United States); Steven J. VanKerkhove, Corning Research and Development Corp. (United States); Christopher M. Supranowitz, Paul Dumas, QED Technologies, Inc. (United States); Keith J. Donohue, Corning Research and Development Corp. (United States)

This paper describes the manufacturing steps necessary to manufacture hemispherical concave aspheric mirrors for high-NA systems. The process chain is considered from generation to final figuring and includes metrology testing during the various manufacturing steps. Corning Incorporated has developed this process by taking advantage of recent

advances in commercially available Satisloh and QED Technologies equipment. Results are presented on a 100 mm concave radius nearly hemispherical (NA = 0.94) fused silica sphere with a better than 5 nm RMS figure. Part interferometric metrology was obtained on a QED stitching interferometer. Final figure was made possible by the implementation of a high-NA rotational MRF™ mode recently developed by QED Technologies which is used at Corning Incorporated for production. We also present results from a 75 mm concave radius (NA = 0.88) ULE™ sphere that was produced using sub-aperture tools from generation to final figuring. This part demonstrates the production chain from blank to finished optics for high-NA concave asphere.

10448-15, Session 3

Precision production: enabling deterministic throughput for precision aspheres with MRF

Chris Maloney, QED Technologies, Inc. (United States); Navid Entezarian, Thorlabs, Inc. (United States); Paul Dumas, QED Technologies, Inc. (United States)

Aspherical lenses offer advantages over spherical optics by improving image quality or reducing the number of elements necessary in an optical system. Aspheres are no longer being used exclusively by high-end optical systems but are now replacing spherical optics in many applications. The need for a method of production manufacturing of precision aspheres has emerged and is part of the reason that the optics industry is shifting away from artisan-based techniques and towards more deterministic methods. Not only does Magnetorheological Finishing (MRF) empower deterministic figure correction for the most demanding aspheres but it also enables deterministic and efficient throughput for series production of aspheres. The new Q-flex MRF platform was designed to support batch production in a simple and user friendly manner. Thorlabs routinely utilizes the advancements of this platform and has provided results from a batch of aspheres as a case study. We have developed an analysis notebook to evaluate necessary specifications for implementing quality control metrics. MRF brings confidence to optical manufacturing by ensuring high throughput for batch processing of aspheres.

10448-16, Session 3

Evolving rocket optics applications drive manufacturing advances

Brian W. Myer, James Perdue, Kevin Bartlett, Jessica Nelson, Optimax Systems, Inc. (United States)

Improvements to sensing hardware and image processing for airborne optical systems have inspired designers to propose new optics and windows which may be any of: more precise, conformal/freeform and multi-functional. Manufacture of these optics has required innovations in machining, polishing and metrology. The performance requirements and manufacturing methods demand more from conventional optical materials, while also driving development of new formulations with tailored optical and mechanical properties. We describe innovations in manufacturing and adaptations for optical materials selected for end-use performance, though some such materials may present unusual challenges related to their composition, how they are produced, and/or the design geometry. Our desire is to share some observations with the optical designer, who may be able to incorporate some tips into parts “designed for manufacture.”

10448-17, Session 3

Applying MRF to errors caused by optical and opto-mechanical assembly

Christopher A. Hall, QED Optics (United States); William J. Messner, QED Technologies, Inc. (United States); Michael A. DeMarco, QED Optics (United States)

Optical system designers are well-versed in optimizing the performance of a system. The impact of the optical and opto-mechanical assembly, however, poses a significant challenge to attaining the modelled performance in practice. The system engineers are tasked with designing tooling, fixtures and procedures that minimize such impacts, employing well known modeling and analysis techniques. Despite these efforts the resulting system performance often exhibits errors that can be directly related to the assembly process. In the face of lost system performance, the optical designer can compensate with more stringent component and alignment specifications. Alternatively, at the risk of a more complex design, she can consider active compensation, or the addition of compensation components. Yet another path is correcting the components after assembly to regain the original optical performance. MRF is well known for its ability to produce state of the art optical components, lenses, mirrors, etc. In this paper we will explore and demonstrate its application to correcting errors induced by various assembly techniques by reviewing several examples, their respective challenges and the results of the post assembly corrections.

10448-18, Session 3

Novel process for production of micro lenses with increased centering accuracy and imaging performance

Christian Wilde, P. Langehanenberg, T. Schenk, TRIOPTICS GmbH (Germany)

For modern production of micro lens systems, such as cementing of doublets or more lenses, precise centering of the lens edge is crucial. Blocking the lens temporarily on a centering arbor ensures that the centers of all optical lens surfaces coincide with the lens edge, while the arbor’s axis serves as reference for both alignment and edging process.

This theoretical assumption of the traditional cementing technology is not applicable for high-end production. In reality cement wedges between the bottom lens surface and the arbor’s ring knife edge may occur and even expensive arbors with single-micron precision suffer from reduced quality of the ring knife edge after multiple usages and cleaning cycles. As a consequence at least the position of the bottom lens surface is undefined and the optical axis does not coincide with the arbor’s reference axis!

In order to overcome this basic problem in using centering arbors we present a novel and efficient technique, which can measure and align both surfaces of a lens with respect to the arbor axis with high accuracy and, furthermore, align additional lenses to the optical axis of the bottom lens. This is accomplished by aligning the lens without mechanical contact to the arbor. Thus the lens can be positioned in four degrees of freedom, while the centration errors of all lens surfaces are measured and considered. Additionally the arbor’s reference axis is not assumed to be aligned to the rotation axis, but simultaneously measured with high precision.

10448-19, Session 4

Fabrication of free form optics with DLP based 3D printing

Mohammadreza Riahi, Yasaman Honarmand, Milad Rahimzadeh, Sarah Akbari, Somayeh Pourgholami, K.N. Toosi Univ. of Technology (Iran, Islamic Republic of)

3D printing is a fabrication technique that is rapidly growing these days. Utilizing this technique, a 3D part with almost any complex geometry can be fabricated layer by layer. Different techniques are already used for 3D printing but, the DLP (Digital Light Processing) 3D printing technique is one of the most accurate and fastest of them. In this technique a video projector with a DMD chip (digital micromirror device) is used to project the image of each layer with UV light on a UV cure resin from the bottom of a transparent non-sticking vat as shown in figure 1. This process continues until the whole part is built.

Since by 3D printing any desired shape can be fabricated, it might be a perfect choice for fabrication of free form optics

In this article, we used DLP 3D printing technique to 3D print a lens array structure just as an example But any other desired shape can be fabricated .

Since the surface quality of the as printed lenses is poor, a series of molding and thermal finishing are performed to replicate a transparent and polished lens array. The fabricated lenses are good for lighting application.

For fabrication of a lens array, a model is designed in a software. The model is sent to the 3D printer and a lens array structure is 3D printed as shown in figure 1-a. As seen in this figure, the printed part is not transparent and it's surface quality is poor as well. So we have to replicate the lens array with a transparent material and do some action to finish the surface of lenses.

10448-20, Session 4

Simple scattering analysis and simulation of optical components created by additive manufacturing

Manuel Rank, André Horsak, Andreas Heinrich, Hochschule Aalen (Germany)

Additive manufacturing of optical elements is known but still new to the field of optical fabrication. In 3D printers the parts are deposited layer by layer approximating the shape defined in optics design enabling new shapes which cannot be manufactured using conventional methods. But the layered structure also causes surface roughness and subsurface scattering which decrease the quality of optical elements. Using coatings or fluid jet polishing the surface of the additive manufactured parts are smoothened but also the shape is deviated. As this work focuses on the scattering of 3D printed parts the samples are analyzed for roughness using a white light interferometer. But the analysis also includes shape measurements utilizing stripe projection. Together with scattering measurements using a robot based photogoniometer the optical effects for 3D printed parts are quantized, processed and feed back into the optics simulation to improve the design considering the characteristics of the real sample. Therefor the total scattering is split up into surface contributions and subsurface scattering using index matching techniques to isolate the effects from each other.

The purpose of the presentation is to give a detailed insight into additive manufacturing of optical elements summarizing shortly available printing technologies, materials and current possibilities for rework. The main part deals with the scattering analysis for surface and subsurface scattering. The presentation is completed showing the design process using the results from the analysis for optics simulation resulting in 3D printed optical component which is then compared to the optic design and simulation.

10448-21, Session 4

3d printed optical components with compositional and structural gradients

Rebecca Dylla-Spears, D. T. Nguyen, J. F. Destino, N. Dudukovic, W. Chen, E.B. Duoss, Mark A. Johnson, Michael C. Rushford, William A. Steele, Christopher M. Spadaccini, Tayyab I. Suratwala, T. D. Yee, Lawrence Livermore National Lab. (United States)

The ability to customize the structure or composition of an optical element to meet a designer's needs shows promise for reducing cost, size, weight, and power of optical systems by enabling previously unrealizable configurations. 3d printing of glass optical components offers a novel method to achieve such structures and compositions. Using a direct ink writing (DIW) technique, we have successfully printed low density green bodies to the desired shape from specially formulated silica-containing pastes. Then using conventional heat treatment techniques, the green bodies have been converted to full density, optically homogeneous glass. The 3d printed silica-based glass components have material and optical properties that rival conventionally prepared optical grade fused silica. In addition, glass optics that contain tailored gradients in composition have been achieved by blending separate inks inline at the print nozzle and directly depositing the desired material composition at the desired location within the green body. Finally, 3d printing structurally tailored components to yield stiff, lightweight reflective elements or optical supports is described.

10448-22, Session 4

Current use and potential of additive manufacturing for optical applications

Matthew J. Brunelle, Ian Ferralli, Rebecca Whitsitt, Kate Medicus, Optimax Systems, Inc. (United States)

Additive manufacturing, or 3D printing, has become widely used in recent years for the creation of both prototype and end-use parts. Due to the layerwise method in which parts are created, the flexibility of additive manufacturing is unparalleled and has opened the design space to enable features like undercuts and internal channels which cannot exist on traditional, subtractively manufactured parts. This flexibility can also be leveraged for optical applications. This paper will outline the current use of 3D printing in the optical manufacturing process at Optimax. Several materials and additive technologies are utilized, including polymer printing through fused deposition modeling, which creates parts by depositing a softened thermoplastic filament in a layerwise fashion. Stereolithography, which uses light to cure layers of a photopolymer resin, will also be discussed. These technologies are used to manufacture functional prototypes, fixtures, sealed housings, and other components. Additionally, metal printing through selective laser melting, which uses a laser to melt metal powder layers into a dense solid, will be discussed due to the potential to manufacture thermally stable optical-mechanical assembly frameworks and functional optics. Examples of several additively manufactured optical components will be shown.

10448-23, Session 4

Additive manufacturing of glass lenses using fiber-fed laser-melting process

Edward C. Kinzel, John Hostetler, Douglas A. Bristow, Missouri Univ. of Science and Technology (United States); Jonathan T. Goldstein, Air Force Research Lab. (United States); Robert G. Landers, Missouri Univ. of Science and Technology (United States)

This paper presents the Additive Manufacturing (AM) of simple convex glass lenses using a fiber-fed process. Glass fiber with a diameter of 1 um is fed into a laser generated melt pool. A CO2 laser beam is focused on the intersection between the filament and the work piece. The laser energy at ?=10.6 ?m is directly absorbed by phonon modes in the silica and locally heats the glass above the working point. The laser beam is stationary and the work piece in positioned on a heater which is moved by numerically controlled stages. The process is monitored by a pyrometer and observed in-situ with a spectrometer. By carefully controlling the process parameters (laser power, scan speed, and feed rate), complex, bubble free shapes can be deposited, including trusses and free form optics. It is also possible to locally reflow the glass to create optically smooth shapes. The paper demonstrates the creation of very simple spherical lenses of different radii by depositing multiple layers of glass followed by a reflow passes of the laser, which smooth layer-to-layer variations by heating the glass to the point that it can minimize its surface energy. The resulting spherical lenses are tested using a beam profiler and compared to paraxial optical relationships. While not diffraction limited, the ability to deposit arbitrary transparent glass shapes is an important first step toward 3D printing free form optics.

10448-25, Session 5

Freeform Optics: current challenges for future serial production *(Invited Paper)*

Christian Schindler, Thomas Köhler, Eckhard Roth, Carl Zeiss Jena GmbH (Germany)

One of the major developments in optics industry recently is the commercial manufacturing of freeform surfaces for optical mid- and high performance systems. The loss of limitation on rotational symmetry enables completely new optical design solutions – but causes completely new challenges for the manufacturer too. Adapting the serial production from radial-symmetric to freeform optics cannot be done just by the extension of machine capabilities and software for every process step. New solutions for conventional optics productions or completely new process chains are necessary.

As a worldwide operating company ZEISS did identify emerging applications that require high precision freeform surfaces. In our presentation we classify them by market potential and required accuracy. One focus is on wavefront manipulators based on Alvarez plate type freeforms with high requirements that may be of interest for a great variety of applications. Due to the variable refractive power, the Alvarez plates can be used as optics in diffraction limited universal wave front manipulation. Their low temperature sensitivity make them preferable over comparable solutions basing on other technologies like pressure or electro dependent fluid lenses or approaches based on liquid crystal.

The challenges for that type of freeform are a high diameter to thickness aspect ratio in combination with tight tolerances and demanding material properties. Form tolerances span from form error over waviness to roughness limitations. Most common manufacturing techniques have to be improved to reach that goal in serial production. In addition a holistic approach for the whole process chain, including grinding, polishing, smoothing and figure correction, is necessary. We describe mechanical achievements and process improvements in ultra-precision grinding and deterministic polishing. Furthermore we discuss new tool approaches for large-aperture smoothing specifically built for mid-spatial frequency removal. Since each step includes tactile or interferometric testing also the measurements have to be adopted for efficient analysis. We conclude with a look on process chains apart from classical ones like Laser based manufacturing and precision glass molding.

10448-26, Session 5

Concept for a new approach to realize complex optical systems in high volume *(Invited Paper)*

Heinrich Grüger, Jens Knobbe, Tino Pügner, Michael Leuckefeld, Peter Reinig, Sebastian Meyer, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

We have invented a groundbreaking new approach [DE102016221303.2] for the fabrication of photonic systems, especially such with off-axis optics, using planar mounting in combination with a novel folding approach. Up to now volume production has been optimized for on-axis lens based optical systems. Chromatic aberration limits the usage or spectral range of these systems. Applying mirrors instead of lenses may help to suppress chromatic aberrations. But the assembly of reflective optics, often in an off-axis configuration is complex. Up to now most tools for volume production apply stacking of components in planar technology. Off-axis systems are typically assembled by more or less manually alignment of the components, which is not in favor for high-volume / low cost production.

With our novel approach we apply a planar substrate featuring preprocessed bending lines. After placing the components with a high accuracy planar tool, the sides of the substrate are folded and the optical path is generated automatically. This concept is not limited to rectangular shapes. Even the so called "W-configuration" of a Czerny-Turner spectrometer can be folded in that way.

For a first trial and proof of concept a camera device has been realized from a 3D printed substrate. An entrance window, two spherical mirrors, an aperture stop and a detector array have been assembled using planar technology. Afterwards the substrate was folded and fixed. This working principle was proven to be successful. Future applications like spectrometers for mobile phones [Pügner et al., Applied Spectroscopy 2016, Vol. 70(5) 734–745] or multispectral cameras for autonomous driving vehicles will benefit from this approach.

10448-28, Session 6

Tolerancing aspheres based on manufacturing knowledge

Sven Wickenhagen, Sebastian Kokot, Ulrike Fuchs, asphericon GmbH (Germany)

A standard way of tolerancing optical elements or systems is to perform a Monte Carlo based analysis within a common optical design software package. Although, different weightings and distributions are assumed they are all counting on statistics, which usually means several hundreds or thousands of systems for reliable results. Thus, employing these methods for small batch sizes is unreliable, especially when aspheric surfaces are involved. Later is mainly due to the sub-aperture polishing process, which differs fundamentally from manufacturing spherical surfaces. Since the use of aspheric surfaces in optical design offers many advantages concerning optical function, weight and size reduction there is a need for reliable ways of tolerancing those surfaces as well. Fortunately, it was possible over the last years to establish high precision serial manufacturing of aspheric lenses. Therefore, a considerable large amount of aspheres were produced in large batches of up to several thousand pieces. Due to the cause of manufacturing at asphericon, every single one of them was measured with respect to several different parameters. This huge database with an incredible amount of information was used to investigate the correlation between the given tolerance values and measured data sets. The resulting probability distributions of these measurement data sets were analyzed aiming for a robust optical tolerancing process. Among standard tolerances as center thickness and radii of curvature, surface form deviations like RMS slope tolerance are discussed and a statistic is set up. Above this, the batch to batch variation is analyzed.

10448-29, Session 6

The importance of understanding manufacturing distributions in simulating manufactured performance of optical systems

Mark C. Sanson, Corning Incorporated (United States)

Manufactured system performance analysis routines are built into several optical design software programs. These programs have limited abilities to change the probability distribution function of the tolerances. At Corning Incorporated, Advanced Optics, in-house analysis software is used which allows the distribution function of different tolerances to be customized. These simulation tools are capable of accurately modeling the distribution functions from the internal optical fabrication capabilities of Corning. This case study demonstrates the change in performance outcomes due to distribution functions and the importance of knowing the manufacturing distribution functions of the optical fabrication house used.

10448-30, Session 6

Integrating optical, mechanical, and test software (with applications to freeform optics)

Victor L. Genberg, Gregory J. Michels, Sigmadyne, Inc. (United States); Brian Myer, Optimax Systems, Inc (United States)

When major design, analysis and test software can share data better products are created. Comparison of test and analysis results improves the understanding and confidence in both. This paper describes recent advances to SigFit, a useful tool in interfacing finite element (FE) analysis with optical design codes and with interferometric testing software. Finite element analysis is very useful in the support of optical design, fabrication and testing. The FE analysis can be used to optimize test supports, determine mechanical tolerances based on optical performance, investigate anomalies in test results, and provide 'back-out' arrays to simulate 0g performance.

10448-31, Session 6

Efficient production of mounted lens objectives using alignment turning

Christian Buss, TRIOPTICS GmbH (Germany)

Increasing demands for single lenses and lens systems influence in particular their production technology. It has become unfeasible – both technologically as well as financially – to manually adjust lenses in pre-assembled objectives. The common process of manually correcting for astigmatism and coma are limiting factors if tilt and air gaps need to be controlled with accuracies in the micron range.

The effective solution for the production of small and high quality lens systems is the assembly of lenses mounted in sub-cells and adapted with alignment turning. The alignment turning process relies on an automatic alignment chuck to align the optical axis of a mounted lens to the spindle axis of the machine. Subsequently, the mount is cut with diamond tools on a lathe with respect to the optical axis of the mount. Software controlled integrated measurement technology ensures highest precision. In addition to traditional production processes, further dimensions can be controlled in a very precise manner, e.g. the air gaps between the lenses. Using alignment turning simplifies further alignment steps and reduces the risk for errors.

This contribution describes the recent progress in efficient manufacturing of small and precise lens systems, explains the measurement technology behind the process, presents the used alignment turning technique itself and outlines strengths and limitations of this method.

10448-32, Session 6

Twyman effects in thin curved optics

John C. Lambropoulos, Univ. of Rochester (United States)

It is well known, since Twyman's work in early 20th century, that grinding produces a compressive state of stress. When the other surface is polished, for example, the residual stress results in the bending of a thin flat plate so that the ground surface becomes convex. Such effects are important in thin optics, with aspect ratio of about 1:25 or thinner.

The picture is entirely different when curved optics are considered: Examples are thin cylinders, ogives, aspheres, deep hemispheres, or thin curved lenses with variable thickness. For such thin, curved optics, the deformation now consists of two coupled components: A membrane-like stretching, and bending occurring near the free edges of the optic (in a concentrated "boundary layer.") The boundary layer accounts for the manner that the optic is supported. The stretching deformation is easily characterized; bending near the optic edge is much more involved.

I will describe several approaches describing the coupling of stretching and bending in thin curved optics. One approach is by finite element methods, requiring extensive modeling capabilities and careful model debugging. The other approach, based on the principle of minimum potential energy (PMPE) is approximate but can lead to rapid solutions that can be made to be highly accurate by judicious choice of expansion terms in the normal and tangential deflections of the optic middle surface. These two approaches will be compared, thus elucidating some unexpected features of Twyman-like effects due to the optic curvature in relation to its thickness and extent.

10448-33, Session 7

Analysis of the application of poly-nanocrystalline diamond tools for ultra precision machining of steel with ultrasonic assistance

Marius Doetz, Olaf Dambon, Fritz Klocke, Fraunhofer-Institut für Produktionstechnologie IPT (Germany); Benjamin Bulla, Karl Schottka, David J. Robertson, son-x GmbH (Germany)

Ultra-precision diamond turning enables the manufacturing of parts with mirror-like surfaces and highest form accuracies out of non-ferrous, a few crystalline and plastic materials. Furthermore, an ultrasonic assistance has the ability to push these boundaries and enables the machining of materials like steel, which is not possible in a conventional way due to the excessive tool wear caused by the affinity of carbon to iron.

Usually monocrystalline diamonds tools are applied due to their unsurpassed cutting edge properties. New cutting tool material developments have shown that it is possible to produce tools made of nano-polycrystalline diamonds with cutting edges equivalent to monocrystalline diamonds. In nano-polycrystalline diamonds ultra-fine grains of a few tens of nanometers are firmly and directly bonded together creating an unisotropic structure. The properties of this material are described to be isotropic, harder and tougher than those of the monocrystalline diamonds, which are unisotropic. This publication will present machining results from the newest investigations of the process potential of this new polycrystalline cutting material.

In order to provide a baseline with which to characterize the cutting material cutting experiments on different conventional machinable materials like Cooper or Aluminum are performed. The results provide

information on the roughness and the topography of the surface focusing on the comparison to the results while machining with monocrystalline diamond. Furthermore, the cutting material is tested in machining steel with ultrasonic assistance with a focus on tool life time and surface roughness. An outlook on the machinability of other materials will be given.

10448-34, Session 7

Micro-laser assisted machining: the future of manufacturing silicon optics

Deepak Ravindra, Micro-Laser Assisted Machining Technologies, LLC (United States); Sai Kumar Kode, Chris Stroshine, Micro-Laser Assisted Machining Technologies (United States); Donald E. Morrison, Mike Mitchell, Rochester Precision Optics LLC (United States)

A wide range of materials including metals and alloys, ceramics, glasses, semiconductors and composites are manufactured to meet service requirements to a given geometry, accuracy, finish and surface integrity. Metals and alloys in general are easier to machine because of their high fracture toughness, low hardness, non-directional bonding, low porosity, large strain to fracture and high impact energy. Non-metals, on the other hand, such as ceramics, semiconductors and optical crystals are characterized by covalent or ionic bonding, limited slip systems for plastic deformation, high hardness and low fracture toughness. It is due to these major differences that ceramics, semiconductors and optical crystals are considered more challenging to machine.

In this paper an innovative and novel technique termed micro-laser assisted machining (?-LAM) will be analyzed for machining optical grade Silicon (Si). The goal of this study is to evaluate the value propositions of the ?-LAM technology such as extended tool life, increased productivity and improved part quality during the manufacture of Si optical lens.

Mono-crystal Si is hard, strong, inert and lightweight. It also has good optical properties, wide energy bandgap and high maximum current density. This combination of properties makes it an ideal candidate for the optic and opto-electronic industries. Manufacturing Si without causing surface and subsurface damage is extremely challenging due to its high hardness, brittle characteristics and poor machinability. Current limitations for machining optical Si include the high cost of processing and low product reliability. The cost is mainly due to expensive tools that wear out rapidly, long machining time, low production rate and the manufacturing of satisfactory surface roughness, figure and form.

In this context, developing a cost effective method to achieve a flawless surface in ultra-fine machining of these materials has become a challenge. The real challenge is to produce an ultra-precision surface finish in these nominally brittle materials at low machining cost by reducing the tool wear, machining time with increased production rate. Initial efforts performed by Bifano et al. demonstrated the possiblity of machining brittle materials by controlled infeed rates as small as several nanometers. This early work was based on grinding certain brittle materials (germanium, Si, silicon carbide, etc), including an analytical and experimental investigation, was focused on defining the infeed rates necessary for ductile regime grinding. In order to develop a suitable process, ductile regime machining, considered to be one of the satisfactory precision machining techniques, has been continuously studied in the last two decades. Laser assisted micro/nano machining is another important development in this direction.

Past research has demonstrated that ductile-regime machining of these materials is possible due to the high pressure phase transformation (HPPT) occurring in the material caused by the high compressive and shear stresses induced by the single point diamond tool tip. To further augment the ductile response of these materials, traditional diamond turning is coupled with a novel micro-laser assisted machining (?-LAM) technique.

The patented μ-LAM technology directly heats and thermally softens the workpiece material, in the chip deformation and generation zone, increasing the material's ductility. The fundamental concept of this process is illustrated in Figure 1. Improved ductility that results from reduced material hardness allows for easier chip formation, decreased brittleness and ultimately higher material removal rates, i.e. better tool performance and increased productivity, which leads to lower manufacturing costs.

The focus of this paper is to evaluate the machinability of optical grade Si via the ?-LAM process. Machining parameters such as the depth of cut, cross feed, cutting speed and laser power are optimized in order to make the manufacturing process more efficient. A 25mm diameter concave diffractive lens will be machined using the laser assisted machining process and the following will be evaluated:

- Surface finish (roughness)
- Surface aesthetics (spokes, brittle bands, etc.)
- Form accuracy or irregularity tolerance
- Tool life (based on number of parts)
- Productivity (pushing the machining parameters to enhance production)

The lens requirement is as follows:

Irregularity Tolerance < 0.5 FRINGE

Roughness < 10 nm Ra

Surface Quality 60-40

Aesthetics No spokes

No grey or brittle bands

The machining tests were performed on an AMETEK Precitech Nano-X Ultra diamond turning lathe with a 15 picometer positional accuracy feedback system. The Nano-X diamond turning lathe is designed for the production of optical lenses, optical mold inserts and mirrors as well as small precision mechanical components. Figure 2 shows the μ-LAM system mounted and setup on the Nano-X to machine optical Si. The μ-LAM system's tool post, termed Optimus T+1, replaces the existing tool-post where it is a simple bolt-on system that takes less than 60 minutes to retrofit.

The Optimus T+1 is coupled to a 1064nm YAG laser via a fiber optic cable and collimated lens. The diamond tool is optically transparent to the wavelength of the laser and fabricated to perform as a focusing lens that directs the beam to the tool's cutting edge radius

A total of 12 Si diffractive lens were machined in order to evaluate the viability of the laser assisted machining process. Table 1 shows the machining parameters used for the finishing pass.

No. of Parts RPM Depth Feed Laser Power

12 5000 10 μm 10 mm/min 20%

10448-35, Session 7

UPC 300 ultra precise fast tool freeform machining system with integrated metrology for corrective machining

Frank Niehaus, Stephan Huttenhuis, Schneider GmbH & Co. KG (Germany); Dan Gauch, Schneider Optical Machines Inc. (United States)

The need for increasingly complex optics and the demand for freeform optics with ultra-high precision specifications is growing rapidly for numerous applications such as LED illumination, telescope optics, night vision sensors, augmented reality, or head-up displays. Achieving the required accuracies in freeform manufacturing still demands very long machining times, high production costs, a need for experienced, highly skilled operators as well as numerous manual interventions, tying up valuable resources while machining a small number of parts.

he newly released, compact UPC 300 diamond turning system increases efficiency by utilizing fully integrated optical measurement features, high accuracy long stroke fast tool, an advanced software package with built in tool path calculation and analysis as well as corrective machining functions.

The unique axes configuration of the UPC 300 has been specially designed to optimize fast tool machining reducing process times and thermal influences, with the fast tool mounted perpendicular to the X-slide. Therefore, any dynamic forces generated by the fast tool motion do not have to be compensated for by the linear motor of the underlying axis

The integrated optical measurement probe is able to characterize freeform surfaces contact free for quality assurance or for corrective machining. The corrective machining process produces a 5-fold improvement in form accuracy over the original measurement. For an aluminum mirror, overall form error is less than 200nm PV, focusing on the important center portion of the workpiece, over a diameter of 100 mm the form accuracy deviation is below 100 nm.

10448-36, Session 7

Aspheric optics fabrication by single point diamond turning: some issues

Ramagopal V. Sarepaka, Siva Sakthibalan, Somaiah Doodala, Rakesh Singh Panwar, Rajendra D. Kotaria, Optics & Allied Engineering Pvt. Ltd. (India)

The demands on advanced instrumentation have propelled precision optical system developers to aim at achieving near theoretical performance (in terms of resolution, photonic intensity on image plane etc), under system budgets of weight, volume and foot-print. These requirements can only be met by deploying innovative optical surfaces (aspheric, torics, freeforms etc.) with holistic advancements in optical design, fabrication, assembly and testing. While these novel surfaces offer design and performance advantages, their fabrication (mostly by SPDT) and characterization present unique challenges in system development and resource optimization. This calls for a deep insight of all involved issues of precision optical system development.

This presentation deliberates on some major issues involved in Single Point Diamond Turning (SPDT) for optical material processing for the desired optical surface quality, viz: diamond tool selection & geometries, tool positional logistics, design and dynamics of fixtures deployed, machining parametric optimization, optimal machining conditions, work-piece handling (pre-during-post SPDT), material characteristics, tool wear and its effect on surface quality, machining protocols, error correction techniques deployed, profile errors due to thermal energy generated during precision machining, and corresponding profile compensation correction.

SPDT being a multi-variate process, its outcome in terms of the surface quality (Form, Figure and Finish) will be severely affected (individually and collectively) by all process parameters. The objective of this study is to adopt a deterministic approach of precision surface generation of desired optical quality. Hence, this discussion provides a better starting point for the practioners of ultra-precision machining for the development of novel precision optical surfaces.

10448-37, Session 7

Effect of cutting parameters on surface roughness in ultra-high precision turning of a contact lens polymer

Muhammad Mukhtar Liman, Khaled Abou-El-Hossein, Odedeyi P. Babatunde, Nelson Mandela Metropolitan Univ. (South Africa)

Contact lens manufacture requires high accuracy and surface integrity. Surface roughness is generally used to measure the index quality of a turning process. It has been an important response because it has direct influence toward the part performance and the production cost. Hence, choosing optimal cutting parameters will not only improve the quality measure but also the productivity. This research work is therefore aimed at developing a predictive surface roughness model and investigate a finish cutting conditions of ONSI-56 contact lens polymer with a monocrystalline diamond cutting tool. In this work, natural log transformed surface roughness prediction model is developed using a Box–Behnken design (BBD) with response surface methodology (RSM). The effects of feed rate, cutting speed and depth of cut were investigated. Analysis of variance (ANOVA) showed that the transformed quadratic model effectively interpreted the experimental data with coefficients of determination of $R2 = 0.89$ and adjusted $R2 = 0.84$.

10448-38, Session 8

Effect of precision glass molding on index of refraction in new and conventional chalcogenide glasses

George P. Lindberg, Jamie L. Ramsey, Blair L. Unger, John Deegan, Robert Benson, Rochester Precision Optics, LLC (United States)

The precision glass molding (PGM) process is known to induce a drop in the index of refraction of the molded glasses. It has been shown that this drop is much larger in the chalcogenide materials. In this paper we report on the effect of the PGM process on the index of refraction in various available chalcogenide glasses, both import and domestic. We also look at the same material from various vendors.

10448-39, Session 8

Precision glass molding of sensor/MEMS structures

Alois Kasberger, Christian Wistl, Maximilian Hasenberger, Raimund Förg, Technische Hochschule Deggendorf (Germany)

Due to growing demand for ever smaller becoming components and structures by the industrial market, new concepts for an efficient production of these micro parts must be considered. Precision glass molding is an eligible process for high volume production of optical and micro components made out of glass. Those reduced structure sizes results in fundamental new processes for molding and tooling of high precision molds. Beyond a structure size of 500μm common machining processes like milling, grinding or turning fasten reach their limits. So this purpose alternative processes such as in semiconductor industries established etching methods, need to be applied for the moldmaking. Also the strategies in the molding process need to be modified to those orders of magnitude. The present report deals with the development of micro glass molding processes for structures down to tens of micrometer range.

The potential of precision glass molding as process for imprinting smallest structures down to two digit micron range will be demonstrated on different basic geometries like quadrangles or cylinders and spheres.

10448-42, Session 9

Fabrication and correction of freeform surface based on Zernike polynomials by slow tool servo

Yuan-Chieh Cheng, Ming-Ying Hsu, Wei-Jei Peng , Wei-Yao

Hsu, Instrument Technology Research Ctr. (Taiwan)

Recently, freeform surface widely using to the optical system; because it is have advance of optical image and freedom available to improve the optical performance. For freeform optical fabrication by integrating freeform optical design, precision freeform manufacture, metrology freeform optics and freeform compensate method, to modify the form deviation of surface, due to production process of freeform lens ,compared and provides more flexibilities and better performance.

This paper focuses on the fabrication and correction of the free-form surface. In this study, optical freeform surface using multi-axis ultra-precision manufacturing could be upgrading the quality of freeform. It is a machine equipped with a positioning C-axis and has the CXZ machining function which is also called slow tool servo (STS) function. The freeform compensate method of Zernike polynomials results successfully verified; it is correction the form deviation of freeform surface. Finally, the freeform surface are measured experimentally by ultra-accuracy 3-D profilometer (UA3P), compensate the freeform form error with Zernike polynomial fitting to improve the form accuracy of freeform.

10448-43, Session 9

Precision asphere and freeform optics manufacturing using plasma jet machining technology

Thomas Arnold, Georg Böhm, Hendrik Paetzelt, Leibniz-Institut für Oberflächenmodifizierung e.V. (Germany)

Atmospheric Plasma Jet Machining is a non-conventional deterministic sub-aperture surface processing technique that employs a local chemical etching process for material removal. It was shown to have great technological potential for the manufacturing and correction of precision optical surfaces made preferably from fused silica, ULE®, silicon, or silicon carbide.

A plasma based processing chain suitable for freeform generation or surface correction comprises high-rate plasma etching for freeform generation (removal rate 1-30 mm?/min), bonnet polishing for smoothing, plasma fine correction (removal rate 0.01-1 mm?/min) to achieve minimal surface figure error and a post-polishing step utilizing a soft tool. Since plasma jets are not only a source of reactive species but also of heat, the chemical reaction during processing depends on the resulting local surface temperature distribution. A coupled model involving finite elements for temperature field analysis and sophisticated dwell time calculation algorithms has been developed to simulate the complex interplay of surface heating and material removal. With it, the convergence of the etching process is significantly increased. Sub-aperture polishing on freeforms suffers from inhomogeneities in material removal depending on local surface curvatures. An analytical approach has been chosen to estimate the material removal during polishing and appropriate measures have been undertaken to preserve the plasma-generated surface shape. By combination of the processing steps and applying the theoretical modeling fast and efficient precision freeform manufacturing aiming at residual errors of less than 30 nm PV becomes possible.

10448-44, Session 9

Computer aided manufacturing for complex freeform optics

Frank L. Wolfs, Edward Fess, Dustin Johns, Gabriel LePage, Greg Matthews, OptiPro Systems (United States)

Recently, the desire to use freeform optics has been increasing. Freeform optics can be used to expand the capabilities of optical systems and reduce the number of optics needed in an assembly. The traits that increase optical performance also present challenges in manufacturing. As tolerances on freeform optics become more stringent, it is necessary to continue to improve methods for how the grinding and polishing processes interact with metrology.

To create these complex shapes, OptiPro has developed a computer aided manufacturing package called PROSurf. PROSurf generates tool paths required for grinding and polishing freeform optics with multiple axes of motion. It also uses metrology feedback for deterministic corrections. ProSurf handles 2 key aspects of the manufacturing process that most other CAM systems struggle with. The first is having the ability to support several input types (equations, CAD models, point clouds) and still be able to create a uniform high density surface map useable for generating a smooth tool path. The second is to improve the accuracy of mapping a metrology file to the part surface. To perform this OptiPro is using 3D error maps instead of traditional 2D maps. The metrology error map drives the tool path adjustment applied during processing. For grinding, the error map adjusts the tool position to compensate for repeatable system error. For polishing, the error map drives the relative dwell times of the tool across the part surface. This paper will present the challenges associated with these issues and solutions that we have created.

10448-45, Session 9

Shape measurement of freeform surfaces using experimental ray tracing

Tobias Binkele, Daniel Vassmer, David Hilbig, Friedrich Fleischmann, Thomas Henning, Hochschule Bremen Univ. of Applied Sciences (Germany)

To use its proven abilities in gradient based surface measurement of aspherical lenses in transmission, we adapted the principle of experimental ray tracing (ERT) to measure the gradient field of specular freeform surfaces. In this work we present a new application for ERT and propose a setup for this application.

Using gradient based measurements improves the efficiency of the used channel capacity of a measurement. Also, the measurement can be performed relatively and must not be performed absolutely. This leads to a higher accuracy of the measurements compared to direct height measurements. Additionally, most of the common measurement techniques are using lenses. These lenses may introduce deviations to the results that cannot be traced back to its source. In this work we propose a new measurement technique to measure freeform optics without any optical component between the device under test (DUT) and the measuring sensor. For this, we introduce a narrow laser beam under a certain angle into the measurement system. After being reflected from the freeform surface, the direction and the position of the ray on the CCD sensor are detected. By moving the DUT, the whole surface is investigated. From knowledge about the direction of the beam introduced into the measurement system and the directions of the reflected beams for the known surface positions, the gradient field of the surface is determined. Common surface reconstruction methods can be applied to these data.

By numerical simulations and experimental measurements, the potential of this concept has been verified and compared.

10448-46, Session 9

Metrology for the manufacturing of freeform optics

Todd Blalock, Brian W. Myer, Ian Ferralli, Matthew J. Brunelle, Tim Lynch, Optimax Systems, Inc. (United States)

Recently the use of freeform surfaces have become a realization for optical designers. These non-symmetrical optical surfaces have allowed unique solutions to optical design problems. The implementation of freeform optical surfaces has been limited by manufacturing capabilities

and quality. However over the past several years freeform fabrication processes have improved in capability and precision. But as with any manufacturing, proper metrology is required to monitor and verify the process. Typical optics metrology such as interferometry has its challenges and limitations with the unique shapes of freeform optics. Two contact metrology methods for freeform metrology are presented; a Leitz coordinate measurement machine (CMM) with an uncertainty of ± 0.5 µm and a high resolution profilometer (Panasonic UA3P) with a measurement uncertainty of ± 0.05 µm. We are also developing a non-contact high resolution technique based on the fringe reflection technique known as deflectometry. This fast non-contact metrology has the potential to compete with accuracies of the contact methods but also can acquire data in seconds rather than minutes or hours.

10448-47, Session 9

Enhanced resolution and accuracy of freeform metrology through Subaperture Stitching Interferometry

Christopher M. Supranowitz, Chris Maloney, Paul E. Murphy, Paul Dumas, QED Technologies, Inc. (United States)

Recent advances in polishing and metrology have addressed many of the challenges in the fabrication and metrology of non-rotationally symmetric surfaces, and the manufacture of these surfaces is possible today. However, achieving the form and mid-spatial frequency (MSF) specifications that are typical of visible imaging systems remains a challenge. Metrology capable of resolving MSFs is critical for monitoring and optimizing fabrication processes, as well as assuring conformance to final specification.

Multi-axis (3D) profilometers or coordinate measuring machines (CMM) are attractive for freeform metrology, due to the wide range of parts they can measure, but they often have insufficient lateral resolution and accuracy for high-precision applications. Instead, interferometric metrology is highly desirable for these applications, but the capability is currently quite limited for freeforms.

QED has recently developed prototype software that extends its subaperture stitching interferometry (SSI) technology to enable interferometric measurements of freeform surfaces without null optics. Just as it does for planos, spheres, and aspheres, SSI technology provides accurate, high-resolution measurements of freeform surfaces, which is necessary in order to meet the tightening specifications on these types of optics.

QED has obtained preliminary measurement results on several freeform surfaces using prototype software on QED'S ASI (Aspheric Stitching Interferometer). We will show these measurement results, including repeatability and cross-test data, and discuss the benefits of SSI technology over other techniques.

10448-48, Session 10

From optics testing to micro optics testing

Christian Brock, Ralf Dorn, Johannes Pfund, OPTOCRAFT GmbH (Germany)

Testing micro optics, i.e. lenses with dimensions down to 0.1mm and less, with high precision requires a dedicated design of the testing device, taking into account propagation and wave-optical effects. In this paper, we discuss testing principles based on Shack-Hartmann wavefront technology for functional testing in transmission and for the measurement of surface shape in reflection.

As a first example of more conventional optics testing, i.e. optics in the millimeter range, we present the measurement of the optical aberrations of a camera lens, and discuss the corresponding point spread function and modulation transfer function. By repeating the measurement at different wavelengths, information on chromatic effects is retrieved.

A task that is often tackled using Shack-Hartman wavefront sensors is the alignment of collimation optics in front of an optical fiber. In case of a micro-optical collimation unit with a beam diameter of ca. 1mm 1/e?, we need adapted relay optics for suitable beam expansion and well-defined imaging conditions. In this example, we will discuss the alignment process and effects of the relay optics magnification, as well as typical performance data.

Oftentimes, micro optics are fabricated not as single pieces, but as mass optics, e.g. by lithographic processes. Thus, in order to reduce tooling and alignment time, an automated test procedure is necessary. We present an approach for the automated testing of wafer- or tray-based micro optics, and discuss transmission and reflection measurement capabilities. Exemplary performance data is shown for a sample type with 30 microns in diameter, where typical repeatabilities of a few nanometers (rms) are reached.

10448-49, Session 10

Asphere cross testing: an exercise in uncertainty estimation

Paul E. Murphy, QED Technologies, Inc. (United States)

Aspheric surfaces can provide substantial improvements to optical designs, but they can also be difficult to manufacture cost-effectively. Asphere metrology contributes significantly to this difficulty, especially for high-precision aspheric surfaces. With the advent of computer-controlled fabrication machinery, optical surface quality is chiefly limited by the ability to measure it. Consequently, understanding the uncertainty of surface measurements is of great importance for determining the quality of optical surface that can be made.

We measured sample aspheres using multiple techniques: profilometry, null interferometry, and subaperture stitching. We also obtained repeatability and reproducibility (R&R) measurement data by retesting the same aspheres under various conditions. We highlight some of the details associated with the different measurement techniques, especially efforts to reduce bias in the null tests via calibration. We compare and contrast the measurement results, and obtain an empirical view of the measurement uncertainty of the different techniques. We found fair agreement in overall surface form among the methods, but meaningful differences in reproducibility and mid-spatial frequency performance.

10448-50, Session 10

Advancements in non-contact metrology of asphere and diffractive optics

Scott DeFisher, OptiPro Systems (United States)

Advancements in optical manufacturing technology allow optical designers to implement steep aspheric or high departure surfaces into their systems. Measuring these surfaces with profilometers or CMMs can be difficult due to large surface slopes or sharp steps in the surface. OptiPro has developed UltraSurf to qualify the form and figure of steep aspheric and diffractive optics. UltraSurf is a computer controlled, non-contact coordinate measuring machine. It incorporates five air-bearing axes, linear motors, high-resolution feedback, and a non-contact probe. The measuring probe is scanned over the optical surface while maintaining perpendicularity and a constant focal offset. Multiple probe technologies are available on UltraSurf. Each probe has strengths and weaknesses relative to the material properties, surface finish, and figure error of an optical component. The measuring probes utilize absolute distance to resolve step heights and diffractive surface patterns. The non-contact scanning method avoids common pitfalls with stylus contact instruments. Advancements in measuring speed and precision has enabled fast and accurate non-contact metrology of diffractive and steep aspheric surfaces. The benefits of data sampling with two-dimensional profiles and three-dimensional topography maps will be presented. In addition, accuracy, repeatability, and machine qualification will be discussed with regards to aspheres and diffractive surfaces.

10448-51, Session 10

Spectrally controlled interferometry for measurements of flat and spherical optics

Chase Salsbury, Artur G. Olszak, Äpre Instruments, LLC (United States) and College of Optical Sciences, The Univ. of Arizona (United States)

Conventional interferometry is widely used to measure spherical and flat surfaces with nanometer level precision. Typical configurations use lasers to produce high fringe visibility in the entire measurement space. While convenient, laser interferometry often creates problems with multiple reflections from the back surface of the investigated parts.

Herein we describe a new method of isolating the measurement surface by controlling spectral properties of the source (Spectrally Controlled Interferometry - SCI). Using spectral modulation of the interferometer source enables formation of localized fringes where the optical path difference is non-zero. As a consequence it becomes possible to form white-light like fringes in common path interferometers, such as the Fizeau. The proposed setup does not require mechanical phase shifting, resulting in simpler instruments and the ability to upgrade existing interferometers. The fringe formation and phase shifting are controlled electronically allowing a new level of flexibility in the measurement process.

A major benefit of SCI is the ability to attenuate multiple beam interference for both flat or spherical parts. In the paper we present basics of the SCI supported by results of measurements of optical flats and lenses where back reflections are particularly difficult to remove. Fast alignment of the parts is addressed by the system's ability to switch between high coherence (non localized) fringe formation and low coherence (localized) measurement modes. The proposed setup can be a very attractive extension to conventional interferometry and in many cases remove cumbersome part preparation.

10448-52, Session 10

Surface characterization protocol for precision aspheric optics

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In Advanced Optical Instrumentation, Aspherics provide an effective performance alternative. The aspheric fabrication and surface metrology, followed by aspheric design are complementary iterative processes for Precision Aspheric development. As in fabrication, a holistic approach of aspheric surface characterization is adopted to evaluate actual surface error and to aim at the deliverance of aspheric optics with desired surface quality.

Precision optical surfaces are characterized by profilometry or by interferometry. Aspheric profiles are characterized by contact profilometers, through linear surface scans to analyze their Form, Figure and Finish errors. One must ensure that, the surface characterization procedure does not add to the resident profile errors (generated during the aspheric surface fabrication).

This presentation examines the errors introduced post-surface generation and during profilometry of aspheric profiles. This effort is to identify sources of errors and is to optimize the metrology process. The sources of error during profilometry may be due to: profilometer settings, work-piece placement on the profilometer stage, selection of zenith/nadir points of aspheric profiles, metrology protocols, clear aperture – diameter analysis, computational limitations of the profiler and the software issues etc.

At OPTICA, a PGI 1200 FTS contact profilometer (Taylor-Hobson make) is used for this study. Precision Optics of various profiles and shapes: Spherical-Aspheric, Aspheric-Aspheric, Bi-Convex, Bi-concave, Positive Meniscus, Negative Meniscus are studied, with due attention to all possible sources of errors during characterization, with multi-directional scan approach for uniformity and repeatability of error estimation.

This study provides an insight of aspheric surface characterization and helps in optimal aspheric surface production methodology.

10448-53, Session 11

SUN: A fully automated interferometric test bench aimed at measuring photolithographic grade lenses with a sub nanometer accuracy

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SUN is a test bench developed by Safran Reosc to measure spherical or aspherical surface errors of litho-grade lenses with sub-nanometer accuracy. SUN provides full aperture high resolution interferometric measurements. Measurements are performed at the center of curvature using high precision transmission spheres (TS), and Computer Generated Holograms (CGH) for aspheres, in order to light the surface at normal incidence. SUN can measure lenses with diameter up to 350mm and a radius of curvature varying from 20 to 2000 mm.

SUN provides absolute measurements thanks to a special calibration procedure, which allows cancelling most non-axisymmetric bias from the measurement, together with a dedicated calibration of the axisymmetric errors of the TS and CGH. Performance better than 1nm RMS MSE was proven for all types of surface.

SUN measurement sequence is fully automated. Although SUN requires a thorough work for lens alignment, it can after that perform measurements on a 24H/7 days basis without any assistance. This ability is decisive for reducing noise contribution in the error budget. Thanks to dedicated tools and proven methods, measurements can be made to validate the theoretical gravity map and quantify the error made for the metrology error budget. Thus, when the lens holding is compatible, gravity free performance can be determined.

10448-54, Session 11

Test bench for alignment and optical quality measurement of large-field of view objective

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We present a metrology bench used to help alignment and control objective sub-assemblies on axis first; to qualify completely objectives off axis (MTF, OPD, distortion, field curvature) in a second time. This bench is completely adapted for fish eye lens tests.

Fish eye objectives have a wide field of view, typically larger than 180° and fast numerical apertures (better than F/2). These lenses introduce by principle distortion. This point is a limitation of standard MTF benches when measuring MTF at the field of view edges.

We propose an alignment and test bench which answers above limitations. The same instrument is able to both speed up objective lens alignment and characterize them in their full-field when the alignment is finished. It is based on the measurement of the wave front transmitted by the objective.

In order to help objective alignment, the first algorithm "DesignPro" compares in real time the measured wave front with the optical design of the optics under test. Each sub-assemblies can be tested and controlled up to few microns of spherical aberration.

When the objective is aligned, it is qualified in terms of optical quality over its full field of view. The MTF is deduced from the wave front and intensity measurement after they are back-propagated from the measurement plane to the objective exit-pupil. This last step is crucial since diffraction theory requests using the OPD in the exit pupil plane to accurately evaluate the objective MTF.

We characterized the bench according to the ISO 5725 standard. Its precision was tested with commercial lenses whereas trueness was assessed with calibrated lenses. The accuracy on MTF was found to be below 2% over the whole field of view.

10448-55, Session 11

Centering steep aspheric surfaces

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Finding the optical axis of an aspheric surface is an essential part of making an aspheric lens because the center of curvature, or optical axis, of the second side must lie on, or be coincident with, respectively, the optical axis of the first side for maximum optical performance. Looking at the center of an aspheric surface and measuring the tilt and coma as a function of decenter is an obvious means of determining centration, but many aspheric surfaces are relatively spherical over the part of the lens aperture that can be viewed with commercially available optics and there is too little coma to make a useful measurement of decenter.

We describe an alternative method of viewing a small patch of the aspheric surface near the edge of the clear aperture where the asphericity is greatest while the lens is rotated about an axis close to coincident with the optical axis of the surface. By tracking the reflected light image when using an autostigmatic microscope, or using an interferometer to measure the low order Zernike coefficients, as the lens is rotated both the tilt and decenter of the surface can be determined.

The relationship between the image motion and Zernike coefficients is described for both tilt and decenter of the surface as well as the means of separating the relative amounts of tilt and decenter are given. These methods of determining tilt and decenter seems to work for all aspheric surfaces we have tried.

10448-56, Session 11

Automated asphere centration testing with AspheroCheck UP

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With aspheres being incorporated in optical designs across all industry fields, there is high demand for fast and flexible metrology solutions for aspheric lenses. While many systems support measuring the surface topography, the process is limited to a specific design or based on a time-consuming scanning process. Centration measurement with such systems requires additional probes or the inclusion of external reference surfaces in the measurement process. In this paper, we present AspheroCheck UP, a highly automated lens testing system based on the well-established AspheroCheck principle. The paraxial centering errors of both optical surfaces are measured in reflection using a focussing autocollimator. This centration measurement is combined with a fully motorized, non-contact distance sensor that measures the aspheric surface run-out. All three measurements can be performed in parallel during a single rotation of the sample, greatly reducing overall measurement time. The sensor can also be used for the measurement of outer diameter, flange and/or interlock surfaces and even double-aspheric lenses. A five-axis motorized table enables the automatic alignment of the optical axis of the sample to the rotation axis. This significantly reduces setup time and allows for fully automatic testing without user interaction, ensuring both high measurement accuracy and high repeatability independent of the operator. A full cycle time of less than 1 minute including loading and unloading is possible, enabling applications in both R&D and production environments. In addition to supporting ISO and Q-type polynomial surfaces, the system supports most other rotationally symmetric surface types, including Fresnel and diffractive surfaces.

10448-57, Session 12

Tailored complex degree of mutual coherence for plane-of-interest interferometry with reduced measurement uncertainty

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A problem of interferometers is the elimination of parasitic reflections. Parasitic reflections and modulated intensity signals, which are not related to the reference surface (REF) or the surface under test (SUT) in a direct way, can increase the measurement uncertainty significantly.

In some situations standard methods might be used in order to eliminate reflections from the backside of the optical element under test. For instance, match the test object to an absorber, while taking the complex refractive index into account, can cancel out back reflections completely. This causes additional setup time and chemical contamination. In some situations an angular offset might be combined with an aperture stop. This reduces spatial resolution and it does not work if the disturbing wave field propagates in the same direction as the wave field, which propagates from the SUT. However, a stack of surfaces is a problem.

An increased spectral bandwidth might be used in order to obtain a separation of the plane-of-interest from other planes. Depending on the interferometer used, this might require an optical path difference of zero or it might cause a reduction of the visibility to $V < 0.5$.

Contrary to these methods, a tailored complex degree of mutual coherence can be used. High visibility is obtained for a single plane-of-interest. Wave fields of interest are shifted against each other. The reduction of the measurement uncertainty, as well as the embodiment of a modified interferometer, will be discussed.

10448-58, Session 12

Absolute surface form measurement of large flat optics based on oblique incidence method

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With the development of optoelectronic technique, large flat mirror is widely used in optical systems like high-end optical lithography system, astronomical telescope, inertial confinement fusion and so on. The high accuracy requirement prompts the development of components processing to a kind of extreme direction. Therefore, a step forward of optical interferometric testing is also needed. At the present stage, the mainstream interferometric testing method is based on a given reference flat. If the surface quality of test optics is close to or even better than that of the reference surface, an absolute measurement method is necessary in order to perform accurate charaterization. In this paper, a test method based on oblique incidence is proposed in the interferometric measurement process. Three sets of wavefront data are achieved through cavity interference measurement with a Fizeau interferometer and one oblique incidence measurement. An iterative algorithm is applied to retrieve the matrix of transmission flatness and reference flatness. Both simulation and experiment is done in order to verify the effectiveness of the method. The proposed method can not only calibrate the reference flat error of large aperture interferometer, but also provide the absolute measurement method for large rectangular optical components applied in high power laser systems.

10448-59, Session 12

Measurement of a concave spherical mirror with sub-50 pm repeatability by 3D nanoprofiler using normal vector tracing

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High accurate mirrors are needed for synchrotron radiation, X-ray free electron laser sources, extreme ultraviolet lithography in fabrication of semiconductor devices and digital video instruments as consumer products. It is necessary to measure various optical components with uncertainty of nanometer level. We developed a non-contact 3D nanoprofiler that measures normal vectors of the mirror surface using straightness of laser beam, five-axis numerically controlled stage which consists of two pairs of goniometers and one linear stage and quadrant photo diode (QPD). Five-axis stage makes laser beam which reflects from mirror surface return to photosensitve surface of QPD and optical path length of the laser beam constant. Then we calculate the coordinates and normal vectors of mirror surface from the encoder output of five-axis stage, signal of QPD (relative position of reflected laser beam against the center of QPD) and optical path length. From these coordinates and normal vectors, the mirror surface shape is calculated by reconstruction algorithm based on least-square fitting. In this report, we introduce a measurement of a concave spherical mirror with radius of curvature of 1000 mm. The repeatability of this measurement were less than 50 pm.

10448-72, Session Posters

Non-conventional optomechanical choppers: analysis and design of novel prototypes

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Optical choppers are widely used in laser systems – for light modulation and/or attenuation. In their most used well-known configuration, they are built as a rotational wheel with windows, which transforms a continuous-wave laser beam into a series of impulses with a certain frequency and profile. We present the analysis and design we have completed for the classical chopper wheels (i.e., with windows with linear margins) – for both top-hat and Gaussian laser beams. Further on, the novel chopper wheels configurations, with outward or inward semi-circular (or with other non-linear shaped) margins of the windows is presented - with analytic functions and simulations for both top-hat and Gaussian beams, in order to deduce their transmission functions (i.e., the time profile of the laser impulses generated by the device). Finally, the novel choppers with shafts we have patented are presented, and the prototypes of all the above configurations are compared, with regard to their performances. Selected References: [1] Duma V.-F., Theoretical approach on optical choppers for top-hat light beam distributions, J. of Opt. A: Pure and Appl. Opt. 10, 064008 (2008). [2] Duma V.-F., Optical choppers with circular-shaped windows: Modulation functions,Communications in Nonlinear Science and Numerical Simulation 16, 2218-2224 (2011). [3] Duma V.-F., Prototypes and modulation functions of classical and novel configurations of optical chopper wheels, Latin American J. of Solids and Structures 10(1), 5-18 (2013). [4] Duma V.-F., et al., Optical modulator with rotation movement, Romanian Patent RO 126505/2016. [5] Duma V.-F., Demian D., Optical modulator, has solid rotating shaft with some through slots of well-defined profiles, Romanian Patent RO129610-A0/2015.

10448-73, Session Posters

Optical properties of Ge-Sb-Se chalcogenide glasses

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The results of the refractive index, and Vis-NIR absorption wavelength of the chemically stoichiometric glass is the minimum, and the transmittance and optical band-gap reach a maximum at the glass with the chemically stoichiometric composition have deduced in optical properties. The transition threshold occurred as MCN (mean coordination number) is 2.40 and 2.67 that is not found after a careful analysis of their refractive index (in Fig.1), transmittance (in Fig.2), and optical band-gap (in Fig.3). Proving again that the chemical order rather than that the topological order is a main factor in determining optical properties of Ge-Sb-Se glasses. The optical band gap as a function of the Ge concentration and the MCN in Ge-Sb-Se glasses(in Fig.4).

10448-75, Session Posters

High precision processing CaF2 application research based on the magnetorheological finishing technology

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Single crystal calcium fluoride ?CaF2? is the excellent transparent optical material having extremely good permeability and refractive index from 120nm wavelength ultraviolet range to 12?m wavelength infrared range and widely used in the applications of both infrared optical systems (IR), short wavelength optical systems (DUV), as well as high power UV laser systems for various advanced optical instrument. Nevertheless, the characteristics of CaF2 material, including lower fracture toughness and hardness, low thermal conductivity as well as high thermal expansion coefficient, result in that the conventional fabrication techniques usually exposed to lots of problem, such as sub-surface damage, scratches, dig and so on. Single point diamond turning (SPDT) is a prospective technology for manufacture the brittle material, but the residual surface textures or artifacts of SPDT will cause great scattering losses. Meanwhile, the roughness also falls far short from the requirement in the lithography systems. So, the advanced processing technologies for obtaining the shape accuracy, roughness, surface flaw at the same time need to put forward. In this paper, the authors investigate the Magnetorheological Finishing(MRF) technology for the high precision processing. We finish the surface accuracy below RMS ?/100 and roughness about Rq 0.4nm on the concave aspheric CaF2 from original surface figure 0.8? and roughness 15nm after the SPDT processing. The studying of the MRF techniques makes a great effort to the calcium fluoride material processing level for the state-of-the-art optical lithography systems applications.

10448-76, Session Posters

An optimized method to calculate error correction ability of tool influence function in frequency domain

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Extreme optical fabrication projects, known as high-power laser systems, large astronomical telescopes and nano-lithograph systems, make special requirement for different spatial frequency errors. Different spatial frequency errors will have seriously influence on image quality of optical system. The situation is quite serious for middle spatial frequency errors, which always lead to small-angle scattering or flare that reduces the contrast of the image. Computer-controlled optical surfacing (CCOS) technology has been entrenched in optical manufacturing as amain method to fabricate optical surfaces. CCOS technology achieves a target material removal by spatially distributing and accumulating tool influence function (TIF) on the work-piece surface. The characteristics of TIF will have an important influence on the convergence of CCOS process and the final surface figure. Traditionally, the material removal volume and distribution of TIF in space domain are the focuses of research. While quantitatively investigating the error correction ability of TIF in frequency domain is also quite essential for CCOS to restrain different spatial frequency errors. An optimized method to calculate error correction ability of tool influence function (TIF) in certain polishing conditions will be proposed based on smoothing spectral function. The basic mathematical model for this method will be established in theory. A set of polishing experimental data with rigid conformal tool is used to validate the optimized method. The calculated results can quantitatively indicate error correction ability of TIF for different spatial frequency errors in certain polishing conditions. The comparative analysis with previous method shows that the optimized method is simpler in form and can get the same accuracy results with less calculating time in contrast to previous method.

10448-77, Session Posters

Multi-wavelength large optics wave front error metrology bench

William Boucher, Etienne Homassel, Benoit Wattellier, PHASICS S.A. (France)

We present an optical metrology instrument for measuring both transmitted and reflected wavefront error (TWE and RWE) of coated or uncoated optics over a diameter of 5 inches. Depending on the coating transmittance and reflectance, the measurements have to be done at different wavelengths.

Interferometer is a standard instrument to measure the TWE and RWE of uncoated optics. But in the case of coated optics (bandpass filters for example) measurement of TWE is not possible because the optics may not transmit the interferometer laser light.

The chosen solution is based on a quadriwave lateral shearing interferometer (QWLSI) wave front sensor. QWLSI is an achromatic technique, meaning that it measures OPD at any wavelength without any need for recalibration at specific wavelengths. Consequently, various sources at different wavelengths can be used with the same instrument and metrology bench. In addition, QWLSI measures the derivative of phase contrary to interferometer that measures phase. Therefore QWLSI has by design a better WFE dynamic range for TWE and RWE measurement. Moreover accuracy (below 15nm RMS) and repeatability (below 2nm RMS) is perfectly adapted to optical metrology measurement.

The optical solution is a standard double pass configuration composed of a collimator and a beam expander to adapt the size of beam at the aperture of wavefront sensor. We use LED sources to avoid any noise due to interferences within the optics, which occur with coherent light. We can use different wavelength between 400nm and 1100nm. We can optimize the longitudinal chromatic aberration by moving a lens on the beam expander.

We characterized the bench according to the ISO 5725 standard for different wavelengths. Its precision was tested with different samples (filters and mirror). The precision on TWE was found to be below 2nm RMS.

10448-78, Session Posters

Precision lens assembly with alignment turning system

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The poker chip assembly with high precision lens barrels is widely applied to ultra-high performance optical system. ITRC applies the poker chip assembly technology to the high numerical aperture objective lenses and lithography projection lenses because of its high efficiency assembly process. In order to achieve high precision lens cell for poker chip assembly, an alignment turning system (ATS) is developed. The ATS includes measurement, alignment and turning modules. The measurement module is equipped with a non-contact displacement sensor (NCDS) and an autocollimator (ACM). The NCDS and ACM are used to measure centration errors of the top and the bottom surface of a lens respectively; then the amount of adjustment of displacement and tilt with respect to the rotational axis of the turning machine for the alignment module can be determined. After measurement, alignment and turning processes on the ATS, the centration error of a lens cell with 200 mm in diameter can be controlled within 10 arcsec. Furthermore, a poker chip assembly lens cell with three sub-cells is demonstrated, each sub-cells are measured and accomplished with alignment and turning processes. The lens assembly test for five times by each three technicians; the average transmission centration error of assembly lens is 12.45 arcsec. The results show that ATS can achieve high assembly efficiency for precision optical systems.

10448-79, Session Posters

Cheap and fast measuring roughness on big surfaces with an imprint method

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Roughness, shape and structure of a surface offer information about the state, shape and surface characteristics of a component. Particularly the roughness of the surface dictates the subsequent polishing of the optical surface. The roughness is usually measured with a white light interferometer, which is limited by the size of the components. Using a moulding method, of surfaces that are difficult to reach, an imprint is taken and analysed in regard to roughness and structure. This moulding compound method is successfully used in dental technology. In optical production, the moulding compound method is advantageous in roughness determination in inaccessible spots or on large components (astrological optics).

The “replica method” has been around in metal analysis and processing. Film is used for taking an impression of a surface. Then, it is analysed for structures. In optical production, compound moulding seems advantageous in roughness determination in inaccessible spots or on large components (astrological optics).

In preliminary trials, different glass samples with different roughness levels were manufactured. Imprints were taken from these samples (based on DIN 54150 „Abdruckverfahren für die Oberflächenprüfung”).

The objective of these feasibility tests was to determine the limits of this method (smallest roughness determinable / highest roughness). The roughness of the imprint was compared to the roughness of the glass samples. By comparing the results, the uncertainty of the measuring method was determined.

The spectrum for the trials ranged from rough grind (0,8 ?m rms), over finishing grind (0,6 ?m rms) to polishing (0,1 ?m rms).

10448-80, Session Posters

The study of sub-surface damage distributions during grinding process on different abrasion materials

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The grinding process is the primary technology for shape generation on glass optics. The higher material removal rate (MRR) of the grinding process leads to deeper sub-surface damage (SSD) on lens surface. The SSD must be removed by following lapping and polishing processes to ensure the lens quality. However, these are not an easy and an efficient process to remove the SSD from ground surface directly for aspheric surfaces with tens to hundreds microns departure from best-fit-sphere (BFS). An efficient fabrication procedure for large aspheric departure on glass materials must be considered. We propose 3-step fabrication procedures for aspheric surface with larger departure. First step is to generate a specific aspheric surface using cross grinding process with less than 10 um SSD. Second step is to remove SSD and keep the aspheric form by using Zeeko polisher with higher MRR pad. Final step is to figure and finish the aspheric surface by using QED MRF machine. In this study, we focus on the 1st step to investigate the depth of SSD and surface roughness after cross grinding process on different abrasion materials including synthetic silica, S-NPH2, S-PHM52, and calcium fluoride (CaF_2). A tilted polishing process is used to expose the SSD layer on the ground surface. The characteristic of SSD would be observed after etching by Keyence VK 9700 laser confocal microscope.

10448-81, Session Posters

Manufacturing of three dimensional silicate moldings by selective laser beam sintering

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The efficient production of complex glass components is often not possible with classical manufacturing methods. In order to obtain glazed three-dimensional quartz glass moldings, the alternative method of selective laser beam sintering (SLS) is investigated.

Using synthetic and natural silica powders enables an additive production by SLS. Particle-diameters in the range of 19…78 ?m and spheroidal and vitrified particle-shapes allow to manufacture green bodies. For this purpose, an experimental set up as well as material-specific scan and parameter concepts are developed. A high component quality can be achieved by combining a hull-and-core scan strategy with a 180° scan field rotation each sintered layer. Also a bidirectional beam guide and a material-specific parameter concept is needed. The absorption of CO_2 laser radiation and the heat conduction of the powder are supported by the process-dependent plasma and the preheating of the building platform. Component densities of ?R = 65 % and surface roughness of Ra = 32.21 ?m are achieved. Subsequently a glassy, opaque molded body is produced by temperature-pressure-sintering. The component density increases to ?R = 96 % with a shrinkage of 16%. In order to use the glazed molded body as glass fiber preform, polishing of the shell surface is necessary. Surface roughnesses of Ra = 10.4 nm can be realized by laser beam polishing.

Basically, SLS is an alternative method to the classical isostatic pressing of glass powder. In particular, an increase in efficiency with regard to the producible component geometry of the green bodies can be achieved.

10448-82, Session Posters

Optical characterisation of hydroxide catalysed bonds applied to phosphate glass

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We apply the Hydroxide Catalysis Bonding (HCB) technique to phosphate glass and measure the reflectivity and Light Induced Damage Threshold (LITD) of the newly formed interface.

HCB is a room temperature, high performing process which was designed for astronomical research glass assemblies and played a key role in the detection of gravitational waves, a breakthrough in contemporary science. The bonds have numerous assets including mechanical strength, stability, no outgassing and resistance to contamination which are of high interest in the precision optics industry. However only little research has been done on their optical properties and mostly on silica based materials.

In this paper, we use HCB to bond phosphate glass at room temperature with the goal of designing composite components for solid state laser gain media. We change the solution parameters to identify how they influence the final properties of the bonds: The LIDT at 1535nm in long pulse regime and the reflectivity at 532 nm are investigated. The measurement of the incidence dependent reflectance allows estimating the thickness and refractive index of the bond in a non destructive process. The best performing set of parameters yields a LIDT of 1.4 GW/cm^2 (14 J/cm^2) and a reflectivity below 0.03% which makes it suitable for use in high power lasers. The bond thickness is derived both from Scanning Electron Microscopy and the reflectivity measurements and is in the range of 50-150 nm depending on the parameters. Finally, the bonds survive cutting and polishing which is promising for manufacturing purpose.

10448-83, Session Posters

Development of a fully integrated and injection-moldable miniature spectrometer for low-cost applications

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In most cases optical simulation software is based on the ray tracing method. This offers easy and fast results in imaging optics. However, ray tracing can also be applied in other fields of light propagation, such as non-imaging optics for the designing of optical sensor or metrology elements.

In this paper, the development of a miniature spectrometer by means of ray tracing is demonstrated. The basis of the element presented is a Rowland spectrometer, that is optimized in crucial points, e.g. the shape of mirror and grating, to transmit the maximum amount of light. The classical Rowland spectrometers exhibit a flat design in one dimension leading to a bad signal-to-noise ratio, especially for high numerical aperture sources. Therefore, this spectrometer is designed to transmit the

complete amount of light in the sagittal and tangential plane.

Further on, a monolithic approach is presented with a blazed grating, based on an aspheric mirror to spectrally separate and focus light on the image layer. The aspheric mirror is designed in such a manner, that most of the aberrations are suppressed. In general, the element should be devised in a way that makes its assembly with mass production technology possible, for example through applying injection molding. This would, in turn, generate a reasonable end price. The paper will give an introduction to the fields of application for miniature spectrometers, and will describe, step by step, the development of this fully integrated monolithic miniature spectrometer by means of ray tracing simulation.

10448-84, Session Posters

Sub-nanometer precision surface shape measurement of optical flat and sphere

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High-accuracy interferometeric surface metrology is constantly gaining importance, not only in the classical area of optical fabrication, but also for new application such as semiconductor and lithography lens. Requirements for the measurement resolution in the subnanometer range have become quite common. This includes not only the repeatability or reproducibility but also the absolute measurement accuracy, in which both the slowly varying shape error and the medium-to-high spatial frequency waviness of the surface under test, is important. Result of the testing contain the reference surface errors and test surface errors in the high-accuracy Phase shifting interferometeric which test the relative phase between the two surface. The test accuracy can be achieved by removing the error of reference surface. In the laboratory, we have obtained the plane shape(D=103.9mm) of rms 0.286nm, sphere shape(F2.3,D=274.5mm) of rms 0.323nm. In the thousand level cleanroom, we establish a good environment system. Long time stability, temperature controlled at 22°±0.02°.The humidity and noise are controlled in a certain range. The lens are polished by the ion figuring machine. High and Middle spatial- frequency errors (Filter wavelength 5mm) of flat and sphere are controlled at RMS 0.154nm. The repeatability of the interferometer is less than RMS0.1nm (point to point subtraction). The rotation-shift absolute testing method is used. We also obtained other flats and spheres which the RMS shape between 0.3nm - 0.5 nm. The reproducibility is between RMS 0.2-0.3nm(Remove the lens, point to point subtraction).

10448-85, Session Posters

Newly patented process enables low-cost solution for increasing white light spectrum of LEDs

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A newly patented process for completing the spectral light array emitted by LED bulbs provides a low-cost method for producing better human centered lighting (HCL). This process uses non-luminescent colorant filters, filling out the jagged LED spectral emission into a full, white light array. While LED bulbs have the distinct economic advantages of using less energy, producing less heat and lasting years longer than traditional incandescent bulbs, the persistent metameric failure of LED bulbs has resulted in slower, and sometimes reluctant, adoption of LED lighting by the residential, retail and architectural markets. Adding missing wavelengths to LED generated bulbs via colorant filters increases the aesthetic appeal of the light by decreasing current levels of metameric failure, reducing the 'flatness', 'harshness', and 'dullness' of LED generated light reported by consumers. LED phosphor-converted light can be successfully tuned to "whiter" white light with selective color filtering using permanent, durable transparent pigments. These transparent pigments are selectively applied in combination with existing manufacturing technologies and utilized as a final color-tuning step in bulb design. The quantity of emitted light chosen for color filtering can be adjusted from 1% to 100% of emitted light, creating a custom balance of light quantity with light quality. This invention recognizes that "better light" is frequently chosen over "more light" in the consumer marketplace.

10448-86, Session Posters

Enhanced measuring range with aspheric transmission spheres

Anna Möhl, Sven Wickenhagen, Ulrike Fuchs, asphericon GmbH (Germany)

The demands on optical metrology such as Fizeau interferometers increase rapidly. A significant portion of these demands are directly connected with the optical components, especially the transmission sphere. Typically, a Fizeau lens design consists exclusively of several spheres. There is an increasing need for larger measuring ranges as well as higher NA of these Fizeau lenses. One critical aspect of this tendency is, that the lower the F/# and the larger the radii of curvature that can be measured, the bigger and heavier become the transmission spheres, since more lenses are needed to ensure the measuring range. To overcome this tendency, aspheric designs were developed and manufactured successfully. Some selected results will be presented. Launching a design of a F/0.55 Fizeau lens, that includes one or more aspheric surfaces, there are several advantages. The transmission sphere becomes significant more light-weight (0.57 kg without mechanics). Above that, the aperture diameter could be increased simultaneously up to 34 mm, which is nearly a factor of two compared to spherical designs, while keeping the wavefront quality the same. Besides all design characteristics, a crucial point to consider, is the manufacturability in serial production of the lenses. Especially, the surface form deviations of the aspheres are of most interest in this case. This design was incorporated straight into manufacturing. The aspheric surface is of superior quality having a measured RMSi = 8 nm, RMS?S (7µrad/1/0.1)) over a diameter of 102 mm. Thus, high NA Fizeau lenses with overall superb features are presented.

10448-87, Session Posters

Diffraction effect control in measuring off-axis aspheric on axis by using computer-generated holograms

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Testing the free-form surface by using Computer-generated holograms is popular nowadays, which is a null method providing high-precision test in the aspheric mirror manufacturing. By transferring the off-axis aspheric to the on-axis position can greatly reduce the difficulty in designing the CGH phase. However, the phase quantization normally creates more than one diffraction, which bringing disturbing light to the CCD camera. This paper analyzed the filtering effect by adding tilt-frequency phase to the CGH plate whiling measuring the off-axis aspheric mirror on axis. An approximate expression to describe the distribution of the disturbing-order light is presented, which coincides with the results in optical designing softwares.

10448-88, Session Posters

Glass molding of 3mm diamter aspheric plano-convex lens

Hayoung Sung, Myung Sang Huh, Giljae Lee, Geunman

Ryu, Dongguk Kim, Suncheol Yang, Osong Medical Innovation Foundation (Korea, Republic of)

The many industries and research fields have demands for small scale optical systems. To satisfy the demands, many studies are conducted and the miniaturization technologies have been developed. The optical lens is directly related to the optical systems and a key component for the miniaturization. So the aspheric surface which can replace multi-spherical lenses is applied to the optical lens. And fabrication methods to reduce the diameter of the lens have been developed. The glass molding process (GMP) is an attractive method to fabricate aspheric lens among the lens manufacturing processes. Because the GMP has advantages of productivity, repeatability and so on. In this study, a 3mm diameter aspheric plano-convex lens was fabricated using the GMP. The GMP was divided into heating, pressing, annealing and cooling. And the process was conducted using a commercial glass molding machine. Mold tools consist of an upper and a lower mold insert, an inner and an outer guide. The aspheric and the flat surfaces of the mold inserts were coated with ta-C to prevent the sticking of the glass to the mold. The surfaces of molded lens were measured by white interferometry and surface profilometer. The height and the diameter were measured using optical microscopy. As results, the aspheric surface of the lens was 5.1187 ? in Ra and 0.242 ? in Pt. And the flat surface was 2.6697 ? in Ra and 0.13 ? in Pt. The height and the diameter were 1.935 mm and 3.002 mm respectively.

10448-89, Session Posters

A MWIR catadioptric optically passive athermal lens with chalcogenide glasses

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Compared with the visible lens, the infrared lens has many advantages,such as passive detection, high detection accuracy, good disguise, easy observation and clarity character of image. when temperature changes,many parameters for lens also change,for example curvature radius, thickness, aspheric coefficient,refractive index,aperture,distance,and so on,which result in the image performance become worse,so the thermalization is a key technology for infrared lens ..The temperature influence of parameters in infrared lens are analyzed.Benefitting from chalcogenide glasses less low temperature coefficient of refractive index and optically passive athermal method,a compact catadioptric MWIR athermal lens is presented.The wavelength is 3.7?4.8?m?effective focal length is 73.3mm?field of view is 4.24°?F? is 1.5 and cold shield efficiency is 100?. The total length is just 64.4mm.The design results indicate that the image quality from -40? to 60? have little changed, which testify the validity of the method.

10448-90, Session Posters

Measurement of strongly curved surfaces by multi-beam experimental ray tracing

David Hilbig, Jan Schulze, Friedrich Fleischmann, Thomas Henning, Hochschule Bremen Univ. of Applied Sciences (Germany)

Experimental ray tracing (ERT) is a proven method for transmission testing of various optical components providing a wide range of optical performance parameters from a single measurement. In this work, we demonstrate how this technique can be enabled for testing strongly curved specular surfaces in reflection with an emphasis on increased dynamic range.

In ERT, the the surface under test (SUT) is scanned by a beam of light. The direction of the reflected beam is detected from intersection with two parallel imaging planes yielding a surface gradient.

Optical surface profilers are limited in their dynamic range with respect to maximum measurable surface slopes and curvatures. The emitted light must re-enter the aperture of the sensor after reflection from the surface under test. Strong surface curvatures pose a serious problem unless the measurement probe is guided tightly following the surface profile. This requires an elaborate motion system with highly accurate position feedback whose complexity depends on the intricacy of the surface shape.

To overcome such limitations, the proposed method applies multiple test beams combined in a specific arrangement ensuring that at least one reflected beam will always intersect the image sensor. Knowing the direction of the individual test beams with respect to the camera coordinate system is the essential point in the implementation.

We give a thorough introduction to the working principle and demonstrate suitable alignment and calibration strategies. Furthermore, we discuss the limitations of the method and present selected surface measurements of mirrors and aspherical lenses.

10448-91, Session Posters

Breakthrough for cost-effective mass production of precision optics

Andreas Rack, Harald Liepack, Jörg Weber, Clement David, Solayer GmbH (Germany)

To address the continuously increasing requirements and challenges in coating high-precision optical layers, Solayer has built a unique production tool. The new AVIOR M-300 is specifically designed to guarantee a safe and reliable production of optical filters, mirrors, polarizers etc. with market-leading film uniformity and characteristics.

A unique combination of a sputter-up configuration along with dual rotary magnetrons offers unrivaled competitive benefits with regard to high process stability, reduced particle count, minimal service time and lowest cost of ownership.

AVIOR M-300 is capable to handle up to 12 substrates per run with a diameter of up to 300 mm and a weight of up to 7 kg per piece. For a flexible production, carrier systems for various substrate sizes are available, e.g. 56 x ø150 mm or even more.

Equipped with an in-situ deposition growth control, calibration and test runs are not needed even for stack designs of several hundred layers. Deposited films are stoichiometric, amorphous, smooth and very dense with cutting-edge absorption and scattering.

The fully automated load-lock type coater holds up to 4 different target materials. This design offers a benchmarking variety of dielectric films as well as metallic and mixed coatings without material exchange or any service.

Using CARS or METAMODE sputtering process, the system is capable of coating sophisticated layer stacks with market-leading thickness uniformities down to ±0.2 % and deposition rates of 1.2 nm/sec. The tool has a superior long-term process stability over the complete target lifetime of up to 3 months.

10448-92, Session Posters

Freeform optics manufacturing

Greg Matthews, James Ross, Jake Gemballa, OptiPro Systems (United States)

As optical systems get more complex and compact the use of freeform components is becoming ever more present. With their nontraditional geometry freeform optics can not only improve image quality over a greater field of view but they can also reduce the physical space requirements of the optical components in a system. On top of increased performance conformal shapes can match the shape of platform they reside on to reduce drag while still maintaining optical functionality. As the demand for these shapes increases manufacturing and metrology techniques need to be developed to achieve the specifications as well reduce the cost of fabrication. On top of those challenges the optical tolerances used for traditional optics are not always relevant or practical to an optic with a freeform prescription.

OptiPro Systems has been a pioneer in the field of optics manufacturing and freeform geometry is no exception. We have improved our existing grinding and polishing platforms to facilitate easier fabrication of optics with complex shapes and difficult materials as well created our own software packages specifically tailored to these processes. In this paper we will discuss some of the challenges associated with complex shapes and some of the techniques and technologies we use to overcome them. We will discuss some of the difficulties associated with the qualification and tolerancing of these freeform prescriptions as well as some possible solutions to reduce manufacturing costs while still fabricating effective parts. Examples these difficult shapes will be provided alongside of results and data from processing.

10448-93, Session Posters

Fabrication of advanced glass light pipes for solar concentrators

Yusuf Dogan, Matthew Morrison, Chehao Hu, Robert A. Atkins, Texas A&M Univ. (United States); Mehmet E. Solmaz, Izmir Katip Celebi Univ. (Turkey); Christi K. Madsen, Texas A&M Univ. (United States)

The feasibility of creating fused silica light pipes with advanced geometries like angled facets and tapered cross-sections and combiners with micron-scale precision is demonstrated using femtosecond laser irradiation followed by chemical etching (FLICE). In particular, sub-millimeter dimensions for the width and height are achieved and tapering is accomplished over a wide range of angles in two dimensions. Tapered light pipes with magnification factors up to 7x for homogenizing or concentrating beams were fabricated with a 45°-angled input facet to turn the beam and a straight output facet to couple to a detector. Fabrication parameters were optimized to achieve the lowest roughness and highest surface quality while keeping the deformation minimum. While HF is often used, KOH is preferred as the chemical etchant which has advantages that include less deformation, non-toxic and easy to control. For tapering, control over the laser irradiation path allows us to obtain precise tapering in the horizontal and vertical directions. Vertical and tapered sidewalls are analyzed over a range of spatial wavelengths using atomic force microscopy (AFM) and optical profilometry. Using 1mm thick Corning 7980 fused silica, we demonstrated light pipe lengths up to 25mm and three different 45° and 4° plane tapered 3D shape structures. The accuracy of the angled surfaces is ±0.5° and ±0.04° for 45° and side wall tapered surfaces, respectively. The effective kerf width after etching is measured to be less than 25nm. These results signify that FLICE can enable new 3D optical structures to be fabricated in glass with precisely-controlled dimensions.

10448-95, Session Posters

Study on a magneto-rheological removal process of periodic turning marks

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Single Point Diamond Turning (SPDT) has cost-effectiveness and versatile ability in manufacturing rotationally symmetrical forms, non-rotationally symmetrical forms, micro-patterned surfaces and free forms using Slow Tool Servo (STS) and Fast Tool Servo (FTS) techniques. However, in most cases, SPDT process generates regularly spaced tool-marks on the machined surface, which can act as a source of diffraction and scattering of light. To overcome this weakness, this paper suggests magneto-rheological finishing for the post-treatment of diamond turning process to remove the periodic microstructures with the improvement of the original figure and surface roughness. A workpiece used in experiments is an off-axis aspherical mirror that has the electroless nickel-phosphorus plated surface. The workpiece was processed by SPDT and MRF. Spatial frequency analysis like Fast Fourier Transformation (FFT) and Power Spectrum Density (PSD) were performed for identifying the diamond turning marks on the turned and polished surfaces. The experimental results indicate that MRF can be suitable for removing the repeated micro patterns caused by diamond turning process with the progress of the figure and surface roughness.

10448-96, Session Posters

Material of LAPAN's thermal IR camera equipped with two microbolometers in one aperture

Bustanul Arifin, Andi Mukhtar Tahir, Irwan Priyanto, Indonesia National Institute of Aeronautics and Space (Indonesia)

Besides the wavelength used, there is another factor that we have to notice in designing an optical system. It is a material used which is correct for the spectral bands determined. Basically, due the limitation of the available range and expensive, choosing and determining materials for Infra Red (IR) wavelength are more difficult and complex rather than a visible spectrum. We also had the same problem while designing our thermal IR camera equipped with two microbolometers sharing aperture.

Two spectral bands, 3 - 4 μm (MWIR) and 8 - 12 μm (LWIR), have been decided to be our thermal IR camera spectrum to address missions, i.e., peatland fire, volcanoes activities, and Sea Surface Temperature (SST). Referring those bands, we chose the appropriate material for LAPAN's thermal IR camera optics. This paper describes material of LAPAN's thermal IR camera equipped with two microbolometers in one aperture.

First of all, we were learning and understanding of optical materials properties and all matters of IR technology including its bandwidths. Considering some aspects, i.e., Transmission, Index of Refraction, Thermal properties covering the index gradient and coefficient of thermal expansion (CTE), the analysis then has been accomplished. Moreover, we were utilizing a commercial software, Thermal Desktop/SindaFluint, to strengthen the process. Some restrictions such as space environment, low cost, and performance (durability and transmission), were also cared throughout the trade off the works. The results, graphs, and measurement indicate that the lens of LAPAN's thermal IR camera with sharing aperture is based on Germanium/Zinc Selenide materials.

10448-97, Session Posters

Design of a solar concentrator considering arbitrary surfaces

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Nowadays linear concentrating collectors such as cylindrical parabolic collectors and Compound Parabolic Collectors (CPCs) have found an

important application in the solar energy industry; in particular they have been implemented in solar photocatalytic treatment. Traditionally, photocatalysis tests for emerging materials are implemented simply adding solid reactive samples inside of a pipe glass coil, which is irradiated with a predetermined amount of optical power exposed during certain time lapses by using commercial solar simulators. Under normal conditions these optical devices possess a kind of underneath flat mirror without optimize the reflected light. In order to efficiently redirect the reflected light on the photocatalytic samples placed inside commercial solar simulator, we have designed a small-scale prototype of Cylindrical Cycloidal Collectors (CCCs), resembling a compound parabolic collector.

The prototype consists of six troughs cycloidal, which has been designed considering an exact ray tracing assuming a bundle of rays propagating parallel to the optical axis and impinging on a curate cycloidal surface, obtaining its caustic surface produced by reflection. Properly modifying the parameters of the curate cycloid we have optimized the concentration of light in a similar way as a singlet condenser lenses does. The main idea to design CCCs has been to concentrate the reflected light on a predefined extended area instead of linear concentration as usually is done by using CPCs. Preliminary prototypes have been fabricated using computer numerical controlled milling equipment (CNC). Finally a quantitative comparison between CPCs versus CCCs implemented inside the solar simulator in the photocatalysis process has been studied.

10448-98, Session Posters

Dual band AR coatings of LAPAN's thermal IR camera to enhance system and reduce stray light

Bustanul Arifin, Indonesia National Institute of Aeronautics and Space (Indonesia); Irwan Priyanto, Indonesia National Institute of Aeronautics and Space (Indonesia); Andi Mukhtar Tahir, Indonesia National Institute of Aeronautics and Space (Indonesia)

To accommodate additional mission, Sea Surface Temperature (SST), we decided to change our thermal Infra Red (IR) camera. After considering and discussing, thermal IR camera equipped two microbolometers in sharing one aperture has become our last design since in the beginning of 2017. As a consequence of the new design, several things had to be adjusted with, wherein one of them was anti- reflection (AR) coating for LAPAN's thermal IR camera lens. Utilizing dual bands IR, 3 - 4 μm (MWIR) and 8 - 12 μm (LWIR), that share one aperture has provided a big challenge since it creates a need for high performance in order to increase and enhance the IR system sensitivity. As a result, design of dual band AR coatings is more complex and complicated instead of AR coating for one spectral band. Since our thermal IR camera has been designed to space application, another matter that we have had to concern is stray light problem. This paper describes dual band AR coatings of LAPAN's thermal IR camera to enhance system and reduce stray light.

By doing several trade-off of film thickness, number of layers, refractive index lens materials (coating materials), complexity, transmission, absorptivity, and emissivity, dual band AR coatings of LAPAN's thermal IR camera has been developed without reducing optical and performance. Thermal Desktop/Sinda Fluint was also utilized to clear up the analysis. Graphs and numerical data reports that a dual-band IR camera system will increase the performance and overcome stray light problem.

10448-100, Session Posters

Laser scattering technique to characterize turbulent liquid

Aissa Manallah, Mohamed Bouafia, Malika Lakhal, Univ. Ferhat Abbas Sétif 1 (Algeria)

In this work, an optical method to characterize a turbulent liquid will be presented; it comes to measuring the content of a suspension in a liquid by laser scattering.

A laser beam transmitted through a transparent rectangular cuvette containing the emulsion liquid is imaged using a CCD camera, and the resulting image is processed to calculate the scattering intensity. Thus, a relationship between the concentration of the particles in the liquid and the full width at half maximum (FWHM) of the intensity profile of the scattered laser will be determined.

Furthermore, one does a measure of the contrast of an interference pattern obtained by Mach Zehnder interferometer; the object beam passes through the cuvette containing the turbulent liquid. A correlation between the FWHM determined above and the contrast of the interference figure as a function of the concentration of the emulsion will be established.

10448-101, Session Posters

Spectroscopic enhancement study in Yb3+/Er3+ doped ferroelectric SrTiO3 ceramics

Prasenjit Prasad Sukul, Kaushal Kumar, Indian Institute of Technology (Indian School of Mines), Dhanbad (India)

An evidence of pervoskite oxide host to rare earth dopant combination for solid state lightning application, this work focuses on ferroelectric SrTiO3 which has been turned into a multifunctional material via doping of lanthanide ions (0.5 mol% Er3+/2.0 mol% Yb3+) and subsequently upconversion luminescence was greatly enhanced by changing the crystal structure from cubic to tetragonal phase. The characterization results are well supported by each other, as the phase transformation is clearly visible in XRD patterns (as clear splitting in the peaks). Formation of two different kind of crystal grains(hexagonal cuboid & nano chalk rod) at 1300OC also support the gesture of phase transformation. The intuitive crystal phase transition in the sample causes a great enhancement in upconversion emission (by 20 times). So the giant spectroscopic enhancement in the sample is an advantage over the conventional phosphor. The material gives emission within a wide range visible to NIR bands, especially enhancement of the intense green light (by 5 times) is observed. The transformation of the crystal phase of cubic to tetragonal in the sample can be detected by its emission enhancement. So we can use this optical emission as a tool to detect crystal phase in the sample, which is a novel achievement, to our knowledge.

10448-102, Session Posters

An efficient way to fabricate micro transmission grating inside quartz and PDMS material by femtosecond laser micromachining

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We report fabrication of optical volume grating inside the quartz glass sample using femtosecond laser based micromachining system. An optical volume grating with an area of 1mm x 15 mm x 2 mm thickness can be achieved by this writing method. The wavelength of fs laser system is 775 nm, repetition rate and pulse width of the system is 1 KHz and 100 fs respectively. An embedded quartz micro grating is successfully demonstrated. The distance between two adjacent lines was set to be 3 ?m with grating period 7 ?m and fabricated grating having 143 lines/mm. The maximum diffraction efficiency was examined to be 69.69 % for

632.8 nm. The change in R.I of laser modified region was obtained ~10-4. The experimental results show that the quality of gratings is quite good with the relative error of the change in refractive index (?n) about 15%. The advantages and applications of the fabricated volume and surface gratings are discussed

10448-103, Session Posters

A streak tube multi-spectral three-dimensional imaging system for complex target

Jingya Cao, Shaokun Han, Wenze Xia, Liang Wang, Yu Zhai, Beijing Institute of Technology (China)

This article is intended to discuss complex targets based on the technology of the three-dimensional active imaging detection.The streak tube three-dimensional imaging is one of the imaging methods,which are most promising to be practical,because of its high precision, large field of view and high frame frequency.Using streak tube, range and insensity images are obtained at the same time.We propose a multi-spectral imaging simulation algorithm. The derivation of the main structural parameters is given,and the influence of them for the system are analyzed. In the model of the streak tube multi-spectral imaging system , the laser echo signals of multiple wavelength bands are fed into the photocathode of the same streak tube at the same time by the fiber array. In practice, we choose a target which composed of different materials. And the experiment is carried out for the case of 64?64 pixels. Using two different wavelengths to detect the target separately.By comparing the imaging results of the same target at different wavelengths,it can be concluded that multi-material target correspond to different imaging results.We also change the detecting pixels,especially 32?32 or 128?128. By analyzing the resulting images, the relationship between resolution and pixels is obtained.This study contributes to the development of multi-spectral multi-surface,and it can be extended to hidden or multi-objective studies.

10448-104, Session Posters

An improved three-dimensional non-scanning laser imaging system based on digital micromirror device

Wenze Xia, Shaokun Han, Jingya Cao, Beijing Institute of Technology (China)

Nowadays, there are two main methods to realize three-dimensional non-scanning laser imaging detection, which are detection method based on APD and detection method based on Streak Tube. However, the detection method based on APD possesses some disadvantages, such as small number of pixels, big pixel interval and complex supporting circuit. The detection method based on Streak Tube possesses some disadvantages, such as big volume, bad reliability and high cost. In order to resolve the above questions, this paper proposes an improved three-dimensional non-scanning laser imaging system based on digital micromirror device. In this imaging system, accurate control of laser beams and compact design of imaging structure are realized by several quarter-wave plates and a polarizing beam splitter. The DMD is used to convert laser pulses in temporal domain into laser pulses in spatial domain. The CCD with strong sensitivity for infrared light is used to detect the final reflected laser pulses. The remapping fiber optics is used to sample the image plane of receiving optical lens, and covert it to line light resource, which is used to realize the non-scanning imaging principle. In this paper, we also propose an algorithm which is used to simulate this improved laser imaging system. In the last, the simulated experiment demonstrates that this improved laser imaging system can realize three-dimensional non-scanning laser imaging detection.

10448-105, Session Posters

Design of an ultra-precision CNC chemical mechanical polishing machine and its implementation

Chupeng Zhang, Huiying Zhao, Xi'an Jiaotong Univ (China); Yawen Gu, Xi'an Jiaotong University (China); Xinxing Ban, Chunye Jiang, Xi'an Jiaotong Univ. (China)

To improve the chemical mechanical polishing efficiency and accuracy during the fabrication process of the plane optics, a CMP model and machine tool was developed. Through measuring the runout error of several circles on the polishing plate, a 3D contour plot of the polishing plate surface was established. According to the preston equation and the 3D contour plot, a CMP model which could simulate the material removal of any point on the workpiece was presented. The model indicated the higher motion accuracy could improve the efficiency and accuracy. Then a new CMP machine was designed according to this opinion, and the ultra-precision gas hydrostatic guideway and rotary table as well as the Siemens 840Dsl numerical control system was applied in the new CMP machine. To verify the new machine, a series of detection and machining experiments was conducted. The straightness error of the gas hydrostatic guideway could be less than 1.1?m. The axial runout error of the gas rotary table could be less than ±0.4?m. The surface profile of the experimental workpiece could be less than 0.01?, and the machining efficiency of the new CMP machine could be 4 times as the machining efficiency of the traditional CMP machine. Moreover, the repeatability and stability of the CMP process was improved on the new machine.

10448-106, Session Posters

Optical designs for MWIR and four quadrant detectors by using beam steering methods in missile applications

Doğan Uğur Sakarya, Roketsan A.S. (Turkey)

Beam steering optical arrangement needs less volume envelope for same field of regard than other gimbal approaches. Both for imaging and four quadrant missile applications, volume is critical parameter limiting system performance. Therefore, an conceptual design of beam steering method has been focused on both for imaging and four quadrant missiles. In this study; four different optical designs have been made by using both beam steering and regular method for mid-wave infra-red imaging and four quadrant systems. Optical designs performances have been illustrated in simulation results. By using manufactured risley prisms, some experimental results are conducted to compare simulations results.

10448-107, Session Posters

Four and eight faceted domes effects on drag force and image in missile application

Doğan Uğur Sakarya, Roketsan A.S. (Turkey)

Drag force effect is an important aspect of range performance in missile applications. Depending on the domes geometry, this effect can be decreased. Hemispherical domes have great image uniformity but more drag force has an effect on it. Four and eight faceted domes decrease drag force. However, environment reflections cause noise in system. Also depending on the faceted domes shape, sun and other sources in the environment are deformed in the face of them and these deformed objects result in false target in image. In this study; hemispherical, four faceted and eight faceted domes are compared with respect to drag force. Furthermore, images are captured by using these manufactured

domes. To compare domes effects on images, scenarios are generated and automatic target acquisition algorithm is used.

10448-60, Session 13

Stability requirements for two-beam interference lithography diffraction grating manufacturing

Felix Koch, Dennis Lehr, Tilman Glaser, Carl Zeiss Jena GmbH (Germany)

Reproducible manufacturing especially of large diffraction gratings using two-beam laser interference lithography gives rise to exceptional requirements on the stability of environmental conditions like temperature, air pressure, humidity, vibrations as well as a robust exposure setup using stable components, a highly coherent, frequency-stable laser and high-quality optics. In our contribution, these requirements are reviewed systematically. The influences of atmospheric refractive index, laser frequency fluctuations, and thermomechanical drifts on the exposed dose contrast and hence on profile variations for surface-corrugated gratings are discussed. Moreover, mid-spatial frequency surface-errors of the used optical elements are identified as a main cause for local dose variations. Reasonable specifications for series manufacturing of grating masters are given and real-world measurement data from our holography laboratory is presented to illustrate the interplay between these different influences. This experimental data includes atomic force microscope scans of high-groove density resist gratings, spatially resolved diffraction efficiency measurements, moiré-interferometric measurements of the fringe stability, temperature-, air-pressure and vibration spectrum logs. The results of our analysis are also useful for other holographic manufacturing facilities, including the manufacturing of surface and volume holographic optical elements of any kind.

10448-61, Session 13

Thermal instability of BK7 and how it affects the manufacturing of large high precision surfaces

Michael Hyman, Matthew J. Brunelle, Nohl Schluntz, Michael K. Gregory, Mark Notargiacomo, Gregory Frisch, Jeremiah Triftshauser, Optimax Systems, Inc. (United States)

When manufacturing precision optical surfaces of size it is critical to understand the thermal stability of the substrate material. The material properties associated with thermal homogenization are commonly reviewed and soak schedules are created. These schedules ensure a surface under test is in a stable state and is ready for wavefront measurement with an interferometer. However with some materials such as BK7, soak schedules may not be enough. This paper explains the thermal challenges associated to manufacturing precision optical surfaces when the substrate material is BK7, and how the issue can be easily confused with poor metrology. Throughout the manufacturing of precision optical surfaces, the substrates are exposed to varying heat sources and loads. During the manufacturing of lenses greater than 4 inches in diameter we have observed permanent deformation of the optical surface as a result of exposure to temperatures well below the strain point. While the reasons why the change occurs is not yet well understood the result is well documented and was recently observed during the manufacturing of a 15 inch diameter spherical mirror. We use this lens as a case study highlighting the challenges associated to this phenomenon.

10448-62, Session 13

Commercializing potassium terbium fluoride, KTF (KTb3F10) faraday crystals for high laser power optical isolator applications

Wolfgang Schlichting, Northrop Grumman Corp. (United States); Kevin T. Stevens, Greg Foundos, Alexis Payne, Northrop Grumman SYNOPTICS (United States)

Many scientific lasers and increasingly also industrial laser systems operate in >500W and kW outputpower regime and require high-performance optical isolators to prevent disruptive light feedback into the laser cavity. The optically active Faraday material is the key optical element inside the isolator. SYNOPTICS has been supplying the laser market with Terbium Gallium Garnet (TGG -Tb3Ga5O12) for many years. It is the most commonly used material for the 650-1100nm range and the key advantages for TGG include its cubic crystal structure for alignment free processing, little to no intrinsic birefringence, and ease of manufacture.

However, for high-power laser applications TGG is limited by its absorption at 1064nm and its thermo-optic coefficient, dn/dT. Specifically, thermal lensing and depolarization effects become a limiting factor at high laser powers. While TGG absorption has improved significantly over the past few years, there is an intrinsic limit. Now, SYNOPTICS is commercializing the enhanced new crystal Potassium Terbium Fluoride KTF (KTb3F10) that exhibits much smaller nonlinear refractive index and thermo-optic coefficients, and still exhibits a Verdet constant near that of TGG. This cubic crystal has relatively low absorption and thermo-optic coefficients. It is now fully characterized. Mr. Schlichting will present recent results comparing the performance of KTF to TGG in optical isolators and show SYNOPTICS advances in large volume crystal growth and the production ramp up.

10448-63, Session 13

UV-cured polymer optics

Victor Pinon III, Sandia National Labs. (United States); Freddie Santiago, U.S. Naval Research Lab. (United States); Ashten Vogelsberg, Amelia Davenport, Neil Cramer, Colorado Photopolymer Solutions (United States)

Although many optical-quality glass materials are available for use in optical systems, the range of polymeric materials is limited. Polymeric materials have some advantages over glass when it comes to large-scale manufacturing and production. In smaller scale systems, they offer a reduction in weight when compared to glass counterparts. This is especially important when designing optical systems meant to be carried by hand. We aimed to expand the availability of polymeric materials by exploring both crown-like and flint-like polymers. In addition, rapid and facile production was also a goal. By using UV-cured thiolene-based polymers, we were able to produce optical materials within seconds. This enabled the rapid screening of a variety of polymers from which we down-selected to produce optical flats and lenses. We will discuss problems with production and mitigation strategies in using UV-cured polymers for optical components. Using UV-cured polymers present a different set of problems than traditional injection-molded polymers, and these issues are discussed in detail. Using these produced optics, we integrated them into a modified direct view optical system, with the end goal being the development of drop-in replacements for glass components. This optical production strategy shows promise for use in lab-scale systems, where low-cost methods and flexibility are of paramount importance.

10448-64, Session 13

Brilluoin spectroscopy application for express, non-contact testing of glass and polymer products

Stephan L. Logunov, Corning Incorporated (United States)

The paper will describe application of Brilluoin spectroscopy to obtain Young modulus, stress, and thermal history of different glass parts as well as mechanical properties of polymer coating on optical fibers.

Weak dispersion of mechanical properties of glass on frequencies from static to supersonic allows extraction of mechanical properties of material from supersonic speed of sound derived from Brilluoin spectrum. Stress in glass creates a change in speed of sound due to strain in the material. Although stress effect on speed of sound is quite complicated, in many cases simple empirical relationships allow to either obtain stress values, or extract a thermal history of the glass. This will be demonstrated for ion-exchanged, thermally quenched, and multilayer glasses with different values of CTE (coefficient of thermal expansion).

Polymer materials, on the other hand, show very strong dispersion of mechanical properties when frequency changes from a few Hz to a few GHz. The paper will show that establishment of empirical relationship between Brilluoin frequency and static Young modulus of polymer material solves the dispersion problem. This approach is successfully used on express test of polymer coating mechanical properties for optical fibers.

Overall, Brilluoin spectroscopy, albeit not frequently used in applied research or manufacturing tests, has a lot of potential for the non-contact, non-destructive testing for a wide variety of optically transparent materials. Recent developments on implementations of this approach will be discussed as well.

10448-65, Session 13

Application of speckle shearing interferometry to the evaluation of creep strain in elastomers

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In this paper, authors present a new application of speckle shearing interferometry (shearography) to a phenomenon known as creep compliance, which is an important mechanical property of viscoelastic materials. Two different sealing elastomers were tested in a short-term creep experiment, applying a constant tensile stress to a specimen. An experimental in-plane shearography setup was implemented in order to measure directly the in-plane creep strains produced in the tested object. In order to show the effectiveness of shearography for the assessment of this mechanical property, results were compared to that obtained with an equipment of Digital Image Correlation (DIC). It was demonstrated that shearography can be potentially and successfully applied to the creep analysis of these kind of materials. Finally, advantages and limitations of this measurement method are discussed.

10448-66, Session 14

Novel cleaning strategy for removing paraffin waxes from optical substrates

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In this paper we report a novel cleaning process to remove paraffin and other hydrocarbon waxes from optical substrates, using conventional heating and sonicating techniques in conjunction with proprietary cleaning formulations. The process reported is intended as a safer and more environmentally-friendly alternative to xylenes, hexanes, toluene, and the other aggressive organic solvents conventionally used for this purpose. In laboratory testing, Chemetall Sabre® MicroClean 212XP - a high-boiling, solvent-based formulation designed to dissolve heavy waxes and greasy soils – was observed to successfully debond polished optical blanks bound with a variety of mounting waxes. The demounted substrates were further cleaned with dilute solutions of Chemetall Sabre® MicroClean 31A, an aqueous, free-rinsing cleaner, followed by a final rinse in DI water. AFM analysis was performed & found no evidence of residue remaining on the glass substrates following cleaning.

10448-67, Session 14

Rare earth-based low-index films for IR and multispectral thin film solutions

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Over several decades, the workhorse as low-index film material for IR coating applications - in particular for MWIR and LWIR broadband and laser applications - has been Thorium fluoride. It combines a combination of excellent properties like wide transmittance band, low refractive index, little water uptake during deposition, excellent environmental film durability and high film LIDT at 10.6 ?m, however is unfortunately slightly radioactive. Due to the increasing legal restrictions for radioactive materials, it has been partly substituted for LWIR applications – both broadband and laser - by Ytterbium fluoride, however with considerable limitations in performance.

Theoretical work suggested that alternative modified rare-earth based coating materials have the potential to yield films with optimized film properties to bridge the mentioned performance gap. Experimental work on the coating material side as well as on the deposition process side was done and supported by spectral and analytical film measurements to achieved optimized coating properties by a combination of a tailored starting material geometry with a special type of reactive, assisted evaporation deposition leading to a modified film composition.

10448-69, Session 14

Prospects for the enhancement of PIAD processes by plasma diagnostics

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Plasma ion assisted deposition (PIAD) is a technique employed for the production of high quality multilayer optical coatings. Typical applications are dielectric antireflective coatings, beam splitters or specific spectral filters in various optical components for ophthalmics, imaging or laser equipment.

The key issue of PIAD is the densification of the growing films by precise momentum and energy input from a plasma ion beam. However, limits in repeatability and yield are observed, which are due to process drifts. It is expected that an extension of the operational range of PIAD can be achieved by plasma characterisation and related control schemes.

In this contribution we present results from experiments conducted on a box coater equipped with an electron beam evaporator and an APSpro(Bühler) as the assist-source. In order to access plasma parameters during the deposition process we employ optical emission spectroscopy (OES) and active plasma resonance spectroscopy (APRS) as monitor diagnostics. Data on radiance by OES and electron density by APRS is used to develop novel schemes for plasma based control. The standard approach of keeping constant external parameters like voltages or currents is opposed by operating internal plasma properties. Single- and multilayer deposition experiments based on SiO_2, Al_2O_3, Ta_2O_5 and TiO_2 materials allow for a comparison of conventional and novel control concepts. Here, we focus on layer properties such as refractive index, intrinsic stress and inhomogeneity.

This work is funded by the German Federal Ministry of Education an Research under grant 13N13213.

10448-70, Session 14

Film stress and surface shape control of dichroic beam-spliter (DBS) with polarization maintaining by stress compensation method

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Film Stress and Surface Shape Control of Dichroic Beam-spliter (DBS) with Polarization Maintaining by Stress Matching Method

Dichroic beam-spliter with polarization-maintaining played an important role in the quantum telecommunication test on the Mozi satellite of China. Film stress problem, however, generated by thin film deposition process will result in a phenomenon of surface deformation as well as influence the optical performance of polarization-maintaining DBS, and further influence laser beam shape of the whole optical system.

Several methods can be used to test film stress, such as interferometry method, cantilever method, bending method, x-ray diffraction, raman spectroscopy, etc. Herein, we use interferometry method to characterize the surface curvature change of the DBS. According to the Stoney formula, , film stress possesses linear relationship with the reciprocal value of Rf, which represents the curvature radius of samples after coating.

In this presentation , a polarization-maintaining DBS with an incidence angle of 22.5 degree was prepared by ion beam sputtering method (IBS). Ta_2O_5 and SiO_2 materials were separately deposited as the high refractive index (H) and low refractive index (L) layers. Through optimizing design, a 51 layers with total physical thickness of 9.57?m was adopted. The total physical thickness ratio of Ta_2O_5/SiO_2 was about 0.89. Laser interferometer measurement of the DBS showed that Rf was -1.2?(?@632.8nm) after coating, which indicated compressive stress in the film.

To solve this problem, we designed a complicated anti-reflection(AR) coating with 18 layers in the backside surface. The physical thickness of the AR coating was 4.83?m , with a total physical thickness ratio of Ta_2O_5/SiO_2 of 0.73. The Rf of the primary side changed to -0.35?(?@632.8nm) after the backside coating. Additionally, the transmittance and polarization properties almost kept the same.

10448-71, Session 14

Multilayer coating of optical substrates by ion beam sputtering

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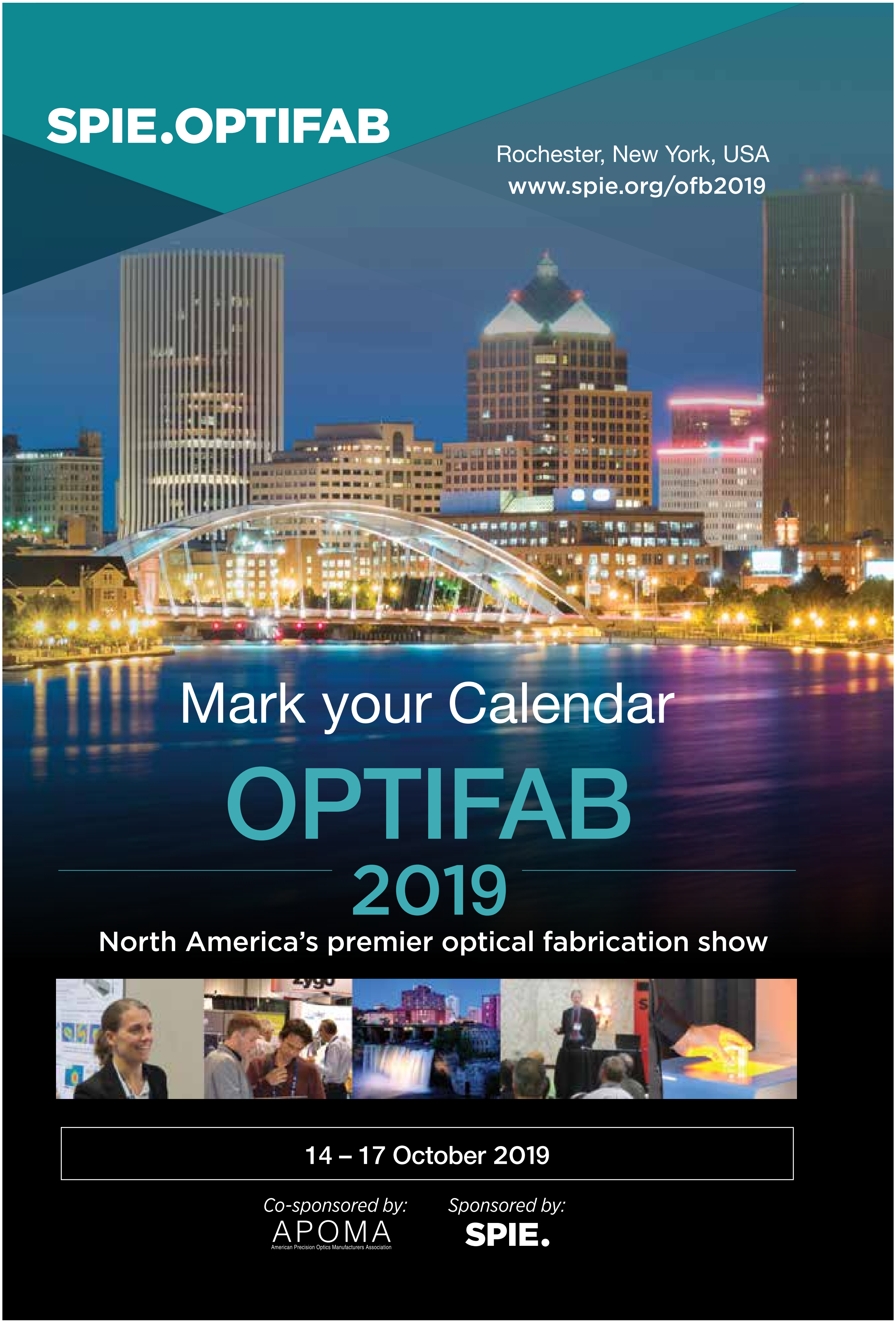
Optical filters and mirrors often are based on periodic layer stacks, which consist of single layers with high and low refractive index. Using ion beam sputter deposition allows significantly higher energies of the particles incident on the substrate, compared to competing processes. Therefore multilayers coated with this deposition process are denser and show a very low roughness, which is required for application which require very low optical losses or a high laser induced damage threshold.

The dual ion beam deposition technology uses a second assist ion beam source in addition to the sputter source to pre-clean the substrate or adjust the layer characteristics, for example. By using an optical measurement system, the optical thickness of the deposited layers may be determined in-situ and therefore corrected while running the process.

The author will present the latest ion beam deposition equipment and the coating results for different applications.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