SPIE. OPTICAL SYSTEMS DESIGN

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2015 OPTICAL SYSTEMS DESIGN.

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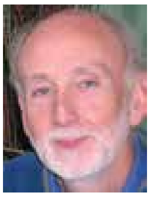

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SPIE. OPTICAL SYSTEMS DESIGN

9626-1, Session 1

Frits Zernike and microlithography *(Invited Paper)*

David M. Williamson, Nikon Research Corp. of America (United States)

Most optical designers are familiar with Zernike aberrations and coefficients, if only from reading Born and Wolf. However, their use in optical design is not widespread, even though they are now available in most modern optical design programs.

It is maybe not widely known that they have been used in the optical design and manufacturing of microlithographic projection optics since their inception in Perkin Elmer's Micralign wafer scanners in the 1970's. This hidden history will be revealed. The story continues to the present day, in the form of Freeform Optics and their application to Exterme UltraViolet microlithographic projection optics.

9626-2, Session 1

Imagery properties of a high-order Fresnel lens: application to cooled and uncooled infrared imaging systems

Tatiana Grulois, Guillaume Druart, Mathieu Chambon, Nicolas Guérineau, ONERA (France); Hervé Sauer, Pierre H. Chavel, Institut d'Optique Graduate School (France) and Ctr. National de la Recherche Scientifique (France)

Huge efforts are currently being made to develop innovative infrared optical systems. In the cooled infrared domain, the target is to develop a camera that is compact, light and able to quickly cool down. For that purpose, we suggest integrating a thin optics inside the dewar and more specifically we focus on studying the potentialities of the Fresnel lens. In the uncooled infrared domain, industrials are interested in designing cheap infrared cameras for low-cost imagery applications. We consider that the use of a thin optics design made of a Fresnel lens can be a breakthrough in lowering the cost of thermal infrared cameras.

Fresnel lenses are not traditionally used for broadband imagery applications because of their chromatic properties. The key element of our design strategy is the use of a high-order Fresnel lens which exhibits much less chromatism than a traditional Fresnel lens that would work in the first order.

The issue is that traditional optical design software do not model precisely the true behaviour of high-order Fresnel lenses. In particular, the Fresnel surface type from the Zemax software only considers an ideal infinitely thin component. It contains no information on the individual discontinuities of the Fresnel lens profile. It does not take into account the true optical path of the light that goes through the real sawtooth-shaped component. Moreover, it only considers pure geometrical optics quality assessments and does not take into account the effect of diffraction orders. So, the default potentialities from optical design software do not permit to model the diffractive properties of a Fresnel lens taking into account the effect of every diffraction order.

For the foregoing reasons, we have developed a novel diffractive model to describe the effect of the real shape Fresnel lens. We have implemented a Zemax user defined surface that describes precisely the profile of a given Fresnel lens with a given etching depth. We have also written a Zemax macro which traces a defined number of rays through the system up to the exit pupil and associates to each ray an optical path length. For each ray on the exit pupil we calculate the optical path length difference between the real wavefront and the ideal spherical wavefront converging on the image point. Then we estimate the square modulus of the 2D Fourier Transform of the complex amplitude of the generalized pupil function, whose phase is deducted from the optical path difference in the exit pupil mentioned above. By this way we obtain the distribution of diffraction light in the image plane of our system, corresponding to the well-known PSF. The absolute value of the Fourier Transform of the PSF then gives the MTF which is an important quality feature for optical design. This model will be explained in details in this presentation.

We have designed, manufactured and characterized two prototypes for both cooled and uncooled infrared imagery applications. Experimental measurements will be shown and will be compared with the theoretical performances calculated from our model. Experimental images will also be presented.

9626-3, Session 1

Direct design of a two-surface lens including an entrance pupil for imaging applications

Yunfeng Nie, Fabian Duerr, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

A multi-fields optical design method aiming to calculate two high-order aspheric lens profiles simultaneously with an embedded entrance pupil is proposed in this paper. The Simultaneous Multiple Surfaces design method in two dimensions (SMS2D) is used to provide a better understanding of how N surfaces allow perfect coupling of N ray-bundles. In contract to this perfect coupling, our multi-fields design approach is based on the partial coupling of multiple ray-bundles. This method allows calculating the optical path lengths (OPL) during the process, directly building connections between different fields of view. Both infinite and finite conjugate objectives can be designed with this approach. Additional constraints like surface continuity and smoothness are taken into account to calculate two smooth and accurate surface contours. Sub-aperture sampling factor is introduced as a weighting function for different fields which allows for a very flexible performance control over a wide field of view. An RMS spot size error function is used to optimize the weighting factor to achieve a very well-balanced imaging performance. As an example, a wide-field lens is designed and analyzed to demonstrate the potential of this design method. The impact of different weighting functions for the sub-aperture sampling is evaluated accordingly. It's shown that this design method provides an excellent starting point for further optimization of the surfaces coefficients and initial design parameters: resulting in a very good and well-balanced imaging performance over the entire field of view.

9626-4, Session 1

Efficient simulation of autofluorescenec effects in microscopic lenses

Herbert Gross, Olga Rodenko, Friedrich-Schiller-Univ. Jena (Germany); Moritz Esslinger, Friedrich-Schiller-Univ Jena (Germany); Andreas Tünnermann, Friedrich-Schiller-Univ. Jena (Germany)

The use of fluorescence in microscopy is a well known technology today. Due to the autofluorescence of materials of optical system components, very often the contrast of the images is degraded. This can be a limiting factor in the performance of the systems. The material parameter of the usual selected glasses are quite different in their properties generating fluorescence. Therefore in reality it make sense to take corresponding effects in the design of objective lenses regarding the material selection into account. The calculation of autofluorescense usually is performed by brute force methods as volume scattering with nonsequential raytrace and can be modelled with commercial optical design tools in a straightforward manner. Unfortunately small false light contributions are able to disturb the imaging conditions. The efficiency of calculations in this case is extremely low and a huge number of rays must be calculated to get accurate results for the autofluorescence effects. In conventional simulations of illumination setups or stray light effects, the concept of important sampling helps a lot to reduce computational effort. The idea is to calculate only those rays, which have the chance to reach the target surface. A similar idea is used here to accelerate the calculation.

In the case of autofluorescence the excitation light is converted into the wavelength shifted fluorescence light in the volume of the lenses. The conversion can be considered to be an inelastic scattering process with isotropic characteristic. Therefore the probability of the light to reach the detector can be extremely small. In the proposed method this reduction factor is calculated by simple means to high accuracy analytical. The main idea is to discretize the lens volume into slices and compare the illuminated phase space domain with the corresponding acceptance domain of the detector in every z-plane. The boundaries of the domains in the phase space are determined by simple tracing the limiting rays of the light cone of the source as well as the pixel area under consideration. The small overlap of both domains can be estimated quickly by geometrical considerations. It is important to take the correct photometric scaling into account and to discretize the lens volume properly. This procedure needs some approximations, but according to the investigations, the errors coming from these simplifications are rather small and can be accepted under real conditions. The improvement in run time is in the range of 104. This gives the opportunity to take autofluorescence effects in the lens design optimization during the material selection process into account. It is shown with some practical examples of microscopic lenses, that the results are comparable with those of the brute force methods. The limitations and approximations are discussed. In particular it is shown that by exchanging some glasses the fluorescence background can be reduced considerably and that the location of the components relative to the field plane is of great importance.

9626-5, Session 1

Tolerancing the impact of mid-spatial frequency surface errors of lenses on distortion and image homogeneity

Kristina Uhlendorf, Karin Achilles, Dennis Ochse, JENOPTIK Optical Systems GmbH (Germany)

During the polishing of high-precision surfaces of optical element the usage of small polishing tools can lead to typical mid-spatial frequency surface errors that are not considered with standard tolerancing tools but might have a major impact on image performance criteria like wavefront error, distortion or even image homogeneity and should therefore be taken into account.

Youngworth [1] presented an analytical approach to get simple estimates for the effects of mid-frequency errors on the modulation transfer function depending on the position of the surface in the optical systems or the ratio of actual beam size to amplitude and frequency of the surface error. With our approach we are addressing a wider field of image criteria like distortion, rms wavefront error and image homogeneity and we have realized a tolerancing tool within Zemax, which makes the usage more convenient. For this we have developed a Zemax user-defined surface which allows us to formulate rings and spines as well as any combination of both. Both types are presenting typical polishing errors of small tools used by magneto-rheological as well as ion beam finishing machines. Furthermore we are able to set amplitude and frequency of these surface errors easily. This gives us a quite flexible and easy to use description of mid-spatial frequency errors.

Depending on the position of the optical surface within the system, the effects of the investigated surface errors are yielding in different image degradations. A mid-spatial frequency error on the surface close to the pupil will mainly yield in the worsening of wavefront error and MTF, where the same error on a surface close to the field will have impact on distortion and image homogeneity.

In our talk we will discuss besides the implementation of our approach in Zemax the results of the tolerancing for different types of optical systems, and will discuss the effect on distortion and image homogeneity in more detail. Furthermore we will discuss the relation between pupil and field sampling in Zemax and discuss the conclusion how to get reliable results from this tolerancing approach.

[1] Youngworth, R.N., Stone, B.D., 'Simple estimates for the effects of mid-spatial-frequency surface errors on image quality', Applied Optics, Vol.30, No. 13 (2000), p. 2198

9626-6, Session 2

Predicting polarization performance of high-numerical aperture inspection lenses

Stephan Fahr, Jan Werschnik, Matthias Bening, Kristina Uhlendorf, JENOPTIK Optical Systems GmbH (Germany)

Along the course of increasing through-put and improving signal to noise ratio in optical wafer and mask inspection, demands on wave front aberrations and polarization characteristics are ever increasing. The system engineers and optical designers involved in the development of such optical systems will be responsible for specifying the quality of the optical material and the mechanical tolerances. Among optical designers it is well established how to estimate the wave front error of assembled and adjusted optical devices via sensitivity or Monte-Carlo analysis. However, when compared with the scalar problem of wave front estimation, the field of polarization control deems to pose a more complex problem due to its vectorial nature. Here we show our latest results in how to model polarization affecting aspects. In the realm of high numerical aperture inspection optics we will focus on the impact of coatings, stress induced birefringence due to non-perfect lens mounting, and finally the intrinsic birefringence of the optical material.

Usually optical lens coatings are required to allow for high transmission for unpolarized light at specified wavelengths for the angles of incidence present at the considered surface. We will show how to additionally evaluate the polarization characteristics of optical coatings via polarization ray trace. These insights help us already to optimize our coating designs and technologies to meet present demands.

In order to build optical systems which can withstand standard shock loads, the mechanical parts are usually loaded with stress, i.e. due to screws. Hence, the task of the mechanical engineers is not just to translate optical tolerances such as lens tilt or lens decenter into mechanical tolerances; it is extended to decouple the lens mount from the lens in such a way, that the latter is not affected by stresses or deformations. By combining polarization ray tracing with mechanical structural simulation via finite element analysis where realistic outer forces are applied, we are able to optimize our lens mounts concerning resulting surface deformation and stress induced birefringence.

Moreover, even the best commercially available optical material is already tainted with intrinsic birefringence. Here we will show how to translate parameters provided by the glass supplier into a polarization budget, which is necessary for specifying the glass which should be purchased.

With all these tools at hand, we have a more complete understanding of the optical performance of our assembled optical systems. Moreover, we are able to coherently develop optical systems meeting demanding wave front criteria as well as high end polarization specifications.

9626-7, Session 2

Non-sequential modeling of commercial dichroic beamsplitters using Zemax

Alberto Asensio Campazas, Marcos X. Alvarez Cid, AIMEN - Asociación de Investigación Metalúrgica del Noroeste (Spain)

In this paper we describe a novel methodology for modeling the coating of commercial dichroic beamsplitters based on Zemax optical design software operating in non-sequential mode. The key aspect of this approach is a software routine that automates the generation of the coating definition files, provided data delivered by the manufacturer is available. Different formats are accepted: spreadsheets, text files and graph plots.

In order to assess the validity of the coating characterization, a multispectral system was simulated and tested in laboratory. The estimated efficiency of the camera sensors and intensity irradiance were obtained. A comparison of the simulated and experimental results is presented, showing the good performance of the simulation in terms of low cost and error close to real performance, which enables a suitable method for fast prototyping.

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9626-8, Session 2

Array projector design for projection on arbitrarily curved screen surfaces

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The array projector is a new and innovative possibility to project patterns onto arbitray shaped surfaces [1]. The array projector is an array of tiny projectorlets, each consisting of condensor lens, which realizes Kohler illumination, a buried micro-slide and a projection micro-lens on both sides of a common glass substrate. For moving images the slides can be replaced by a micro-imager.

In contrast to single-aperture systems the illuminance of the image is raised by only increasing the lateral extent of the projector while keeping the length constant. Thanks to the setup - analogous to a fly's eye condenser – we obtain a very compact design with homogenization of illumination.

While the optical setup seems simple, an efficient multi-channel slide design poses a challenge. The images to be projected are presented as arbitrarily curved CAD-objects. Because of its complexity, the first attempt was a backtrace implemented into a CAD-program, with the individual projectorlets modelled as pinhole cameras. The chief rays of the image points were traced backwards through each array channel onto the slide plane and connected with their corresponding partner, to form lines. With this principle one can trace the slides for several applications like the projection on perpendicular, as well as tilted and curved surfaces. The array projector operates typically at f/3 and projects up to 15° field of view (FOV). Enhanced f/# and/or FOV specs require more complex optical systems – like buried apertures and/or stacked optical wafers or additional bulk-optical components - and imply the consideration of aberrations and asymmetric distortion.

Since aberrations cannot be considered with the simple CAD backtrace decribed above, we used the commercially available raytracer ZEMAX, working in conjunction with a CAD-program for slide mask generation. This solution was implemented into a ZEMAX-macro, controlling the raytrace and the mask CAD-file reading and writing processes. The macro imports the CAD data of the graphics to be projected, generates field points at the right z-coordinate. This guarantees the compability of the mask-data calculation for curved screen geometries. In the next step the centroid coordinates of the assigned points in the slide plane are calculated and written to the mask CAD-file. After generation of mask CAD raw data, a clean-up for erroneously written lines and introduction of individual micro-slide boundaries are carried out with CAD tools.

An often mentioned requirement is an equal illumination level for all points of the image plane. Especially for tilted and curved image surfaces, this causes a serious problem. A simple approach to achieve such an equalization is a channel-wise, partial closing or apodization of the slide apertures. From a forward raytrace simulation of the raw illumination pattern at the image plane, the specs for this closing are identified and the implemented into the mask CAD file with customized CAD tools.

[1] Marcel Sieler et al., "Microoptical array projectors for free-form screen applications", OPTICS EXPRESS Vol. 21, No. 23, p. 28702-9.

9626-9, Session 2

Nano-optical concept design for light management

Martina Schmid, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Freie Univ. Berlin (Germany); Gauri Mangalgiri, Sotirios Tsakanikas, M. Song, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Patrick Andrae, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Freie Univ. Berlin (Germany); Guanchao Yin, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Wiebke Riedel, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany) and Freie Univ. Berlin (Germany); Phillip Manley, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany)

Controlling light propagation and absorption for efficient use of irradiance is of high interest for various applications. One example is thin-film solar cells, where incomplete light absorption introduces the need for light management. Enhanced absorption can be achieved by either prolonging the path length of the light by scattering it into large angles – ideally larger than the angle of total reflection - or by locally enhancing the electromagnetic field. Nanostructures can provide the required large-angle scattering and high near fields. With this idea in mind, but for a much wider range of applications in general, we will investigate in detail the scattering and near fields of nanoparticles and nanorods.

Mie theory solves Maxwell's equations for the scattering and absorption of a plane wave incident to a spherical object [1]. Although it is only valid for a single particle in a homogeneous surrounding, it provides us valuable insight into the physics of scattering and absorption. We extend the simulations from nanospheres to core-shell nanoparticles and nanorods. Besides the far-field scattering we also quantify the near fields and map the distributions of the electromagnetic fields.

These calculations allow us to tune the nanostructure properties for the respective application. A proper engineering can however only be done if realistic material and structural properties are taken into account. Therefore, we use input parameters according to the experiment and compare the results to ensure the validity of our approach. In particular, we focus on ZnO nanorods grown by electrodeposition and on Ag nanoparticles obtained by thermal growth. These are promising structures for efficient scattering and high near-field enhancement and have already shown potential for improving photovoltaic devices [2,3].

The gap between highly complicated experimental structures and simplified theoretical models will be bridged by full 3D solutions to Maxwell's equations using the finite-element method.

[1] C.F. Bohren, D.R. Huffman "Absorption and scattering of light by small particles", John Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore (1998).

[2] W. Ohm, W. Riedel, Ü. Aksünger, M. D. Heinemann, C. A. Kaufmann, J. Lopez Garcia, V. Izquierdo, X. Fontané, T. Goislard, M. Ch. Lux-Steiner, S. Gledhill, An overview of technological aspects of Cu(In,Ga)Se2 solar cell architectures incorporating ZnO nanorod arrays, Phys. Stat. Solidi A 212, 76 (2015).

[3] M. Schmid, R. Klenk, M.Ch. Lux-Steiner, M. Topic, J. Krc „Modeling plasmonic scattering combined with thin film optic", Nanotechnology 22, 025204 (2011).

9626-10, Session 2

Generation and control of radially self-accelerating beams

Christian Vetter, Toni Eichelkraut, Marco Ornigotti, Alexander Szameit, Friedrich-Schiller-Univ. Jena (Germany)

When optical Airy beams became popular in 2007 [Phys. Rev. Lett. 99, 213901 (2007)], they released a still ongoing avalanche of new investigations that rendered this first small subject into an entirely new field of research. Just recently, this field expanded from optics to other fields of physics like laser-assisted plasma generation [Science 324, 229 (2009)], the structuring of electron-beams [Nature 494, 331 (2013)] and particle manipulation [Nature Photonics 2, 675 (2008)] . So far however, most studies concern self-acceleration schemes similar or identical to those of Airy beams meaning that the beam trajectories obey a curved but in-plane movement. In contrast, we report on a new class of optical beams that follow a radial self-acceleration scheme [Phys. Rev. Lett. 113, 183901 (2014)]. Consequently, those beams continuously evolve on spiraling trajectories while maintaining amplitude and phase distribution in their rotating rest frame. We provide a detailed insight into the theoretical origin and characteristics of radial self-acceleration and prove our findings experimentally.

For deriving a rotating solution to the full scalar Helmholtz equation, we start our analysis from the most general mode expansion in cylindrical coordinates, meaning that no assumptions on the input field are made.

In essence, that is a superposition of fundamental eigenmodes given in terms of diffraction-free Bessel waves. From that we derive conditions to obtain a rotating, diffraction-free and shape-invariant solution. Our findings show, that only a discrete set of Bessel waves with particular relations between the spatial frequencies provides the desired features. Moreover, since our derivation follows merely from first principles and mathematical considerations it proves, that the presented set is complete and thus no other solution exists that fulfills the given conditions.

The fact that our beams can be represented by a discrete superposition of properly scaled Bessel functions enables a straight forward experimental implementation. Two commonly known methods to generate (finite energy and thus approximated) Bessel waves in the lab are the use of axicons (i.e. conical lenses) or the Fourier transformation of a ring-shaped intensity pattern by means of a conventional thin lens. Since radially self-accelerating beams consist of multiple Bessel waves, the latter approach is recommended as those waves can be generated simultaneously by creating several concentric rings in the spatial frequency domain.

While the theoretical derivation led to multiple constraints on the initial mode expansion to achieve the final solution, amplitude and absolute phase of each spectral component do not show any constrain whatsoever. Therefore, each additional Bessel wave provides two parameters that allow for tailoring the rotating intensity profile to suit any given application. Using computational methods such as genetic optimization algorithms, the search for a desired beam shape can be automated and the best possible solution within a high-dimensional parameter-space can be found.

In conclusion we have demonstrated an entirely new kind of self-acceleration scheme that leads to rotating, diffraction-free and shape-invariant beams that can be implemented very easily in existing setups and are highly customizable to suit any desired application.

9626-11, Session 2

Alternative Depth of Field approach avoids blur circle and respects pixel pitch

Norbert Schuster, Umicore Electro-Optic Materials (Belgium)

Modern thermal imaging systems apply more and more uncooled detectors. High volume applications work with detectors which have a reduced pixel count (typical between 200x150 and 640x480). This shrinks the application of modern image treatment procedures like wave front coding. On the other hand side, uncooled detectors demand lenses with fast F-numbers near 1.0. Which are the limits on resolution if the target to analyze changes its distance to the camera system? The aim to implement lens arrangements without any focusing mechanism demands a deeper quantification of the classical depth of field problem.

The traditional RAYLEIGH approach to evaluate the depth of focus is based on the un-aberrated Point Spread Function and delivers a first order relation. Here, neither the actual lens resolution neither the detector impact is considered.

Classic Depth of Field approach supposes a certain allowed blur as circle of confusion. Traditionally, this blur depends only on detector diagonal. The article defines the blur as a function of the lens MTF and of imaging device.

The Depth of Field approach presented here is based on the lens specific Through Focus MTF at the Nyquist frequency of the detector. Also the impact on the camera-SNR is considered.

The lens specific Through Focus MTF considers also the detector area. The condition, that the Through Focus MTF at the Nyquist must be higher than 0.25, defines a certain depth of focus.

This symmetrical depth of focus is transferred in the object space by paraxial relations. It follows a general applicable depth of field diagram which could be applied to each lens realizing a lateral magnification range -0.05...0. Hyperfocal distance, shortest and farthest distance at different sharp distances are easily to find using this general diagram. Variables to introduce are only the focal length and the depth of focus.

The deducted relation of the Diffraction-Limited-Through-Focus-MTF counts for all wavelengths. It becomes particular interesting in the thermal infrared where lens performances are often near to the diffraction limit. Practical examples and pictures are related to this wavelength range.

The approach is applied to different commercially available lenses, and the practical consequences for efficient use of lenses are deduced. Pictures illustrate the depth of field for different pixel pitches and pixel counts.

9626-12, Session 2

Research of aberration properties and passive athermalization of optical systems for infrared region

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Infrared optical systems are widely used for surveillance, military, ecological and many other purposes. Their usual working temperature is situated in range from -40 up to +60 Celsius degrees. Image quality of such systems should be stable over the whole working temperature range. Due to temperature dependence of properties of optical materials, lens housing and other mechanical parts it is a very difficult task to keep the required system stability.

There are several compensation methods of the most considerable thermal aberration - thermal defocus. Among these methods are active and passive ways of thermal compensation. The passive compensation ways are the most attractive because complicated mechanical parts or devices are not required. One of the ways is to find such a combination of optical materials for particular housing materials that provides passive correction of thermal defocus.

The method of designing of IR systems based on simple ideas was proposed a few years ago. During designing we can choose a set of optical powers that eliminates field curvature in the system. The next step is a proper designing way of components to correct spherical aberration and coma in each component separately. For materials in IR these aberrations are not significant, that is why components should be rather simple. Astigmatism is corrected in the whole system and as a result the system is free of all monochromatic aberrations. This method does not include chromatic aberration correction and analysis of thermoaberrations. The work is aimed at developing and improving of the IR system design methods.

The analysis of thermoaberrations starts with analysis of possibilities of chromatic and thermal defocus correction in two and three component systems. These components might be applied in previously developed method. Formulas for calculations of components with chromatic and thermal defocus correction are presented. Also research results of thermal defocus correction possibilities and examples of designed systems with different characteristics are given. Results of the work can be helpful for designers to find optimal material combination for further designing of thermostabilized systems working in IR region.

9626-13, Session 2

Modeling, simulation, and analysis of birefringent effects in plastic optics

Achyut Adhikari, Nanyang Technological Univ. (Singapore)

Birefringence in plastic optics is one of the prevalent issues, which can affect imaging and non-imaging aspects. Birefringence or double refraction is typically not covered in imaging applications due to low incidence in many applications. However with increasing use of coherent ,LED sources and need for precision imaging, this effect is being increasingly considered. Birefringence effects are usually modeled using Jones and Mueller matrix but suitable mathematical formulation is still lacking regarding birefringent effects in design and wavefront aberration of optical elements. In this experiment, the effect of birefringence on imaging characteristics of plastic optical components is studied. The study is approached from three aspects. First, the incorporation of birefringence in the optical design methodology. Software such as Zemax which is widely used for designing optics haven't considered much on effects of birefringence in imaging. Hence the need to incorporate birefringence aspects in optical design will be investigated. Second, the cause and measurement of birefringence is vital in fabrication of optical elements. Polarimetry is used for this as a simple tool for birefringence measurement. However improvement of sensitivity and extracting information useful to the design needs to be explored. Finally some case studies of effects of birefringence will be investigated. This study will focus on plastic optics fabricated using injection molding or 3D printing. Plastic optics are being increasingly used in many applications and are more susceptible to birefringence effects. Of course the results of the study can be used for traditional glass optics where the birefringence effects become significant in applications such as lithography.

Modelling of Birefringent material such as calcite, quartz are done, simulation of the experiment on software and on real time is done to observe the errors associated with the experiment. Mathematical model is made for the birefringent material, its effects during imaging. Different birefringent material molded micro plates were used made up of different materials exhibiting varying properties like Polystyrene, polypropylene and cyclic olefin copolymers.

The mathematical modelling of birefringence was done by jones matrix method whereas image intensity value is obtained by fourier transformation method. Image degradation due to birefringence is calculated and analyzed by statistical approach, which is square proportional to the contrast and intensity of the material.The suitable mathematical relation regarding effective parameter contributing birefringence need to be well identified, hence innovative measures for reducing birefringence will be carried out.Modulation Transfer Function (MTF), Point spread Function (PSF), wavefront error and polarisation changes will be compared and explored theoretically with that of simulation on software and on real experiment. Improvement of sensitivity on polarimeter and extracting useful information from different plastic optics like micro plates, channels , lenses and so on. Damage detection , material deformation and image degradation will be explored much. Damage detection by birefringence on using UltraViolet(UV) laser mark is the ongoing experiment which is expected to get useful information. The suitable mathematical relation regarding effective parameter contributing birefringence is devised.

9626-14, Session 3

Reducible complexity in lens design
(Invited Paper)

Zhe Hou, Florian Bociort, Technische Univ. Delft (Netherlands)

One of the most significant challenges in the lens design process is the presence of many local minima in the optimization landscape. Therefore, we still face today the well-known obstacle that when the complexity of the design task increases the designer gradually loses the ability to solve the problem by an effort of intellect.

A non-expert may be surprised that, despite of the fact that the number of local minima increases rapidly with the number of components, it is still possible to successfully design systems as complex as, for instance, lithographic objectives. The fact that successful complex systems exist may therefore be a hint that the lens design landscape has some hidden beneficial properties that help the designers in their efforts.

The purpose of this talk is both theoretical and practical. We first discuss a surprising feature of the design landscape that can facilitate the lens design process: many local minima in the design landscape of a problem with a given number of lenses are closely related to minima in the design landscape of simpler problems. We present a simplified mathematical model of this property that we also see as a step towards a more general mathematical model of the lens design landscape as a whole. For discussing this property, in addition to local minima other critical points in the landscape must also be considered.

Based on this property, practical methods to efficiently explore the design landscape by rapidly switching between neighbouring minima will be discussed. If optimization converges to an undesirable minimum, it must be restarted with a starting point outside the basin of attraction of the old minimum. We show that points on the boundary between the basins of attraction of neighbouring local minima can be obtained in a computationally efficient way from simpler systems with one lens less. The simpler systems are obtained by eliminating one lens from the old undesirable minimum. By successively inserting and removing lenses in optimized systems we can navigate through the landscape and obtain new local minima. The process is systematic and does not involve randomness. We show examples where the landscape is simple enough to be studied in sufficient detail. We find there that the majority of the local minima that have been detected with other methods, including the most interesting solutions, can be easily found with the present switching method. The new type of methods is applicable for systems of arbitrary complexity.

In order to understand the potential and the limitations of this type of methods, the behaviour of critical points needs to be examined in detail. When design parameters change, critical points can separate or merge, in a way that closely resembles phase transitions. We show that information about the phase transitions can be obtained from simple one-dimensional analyses. The practical strategy for switching between neighbouring minima depends on whether for the given design parameters we are below or above the phase transition point.

9626-15, Session 3

The limitations of using M-squared for input beam characterization in simulation software

David M. Hasenauer, Bryan D. Stone, Synopsys, Inc. (United States)

The M-squared parameter is often utilized for defining laser beam quality. It describes the variation of the far field divergence and beam size of a “real” propagated optical beam, compared to that of an ideal Gaussian beam, of the same wavelength and waist size. Its chief benefit is that it is easy to measure, and if the primary metric of interest is limited to the far field divergence angle and beam size, it provides a convenient way to quantify a beam.

While M-squared is a common metric for characterizing a beam, it does not uniquely determine a beam’s parameters. Disparate factors can modify a beam, including aberrations, non-Gaussian amplitude or phase envelopes, and/or partial spatial coherence. The different factors can result in beams with similar or identical M-squared values, but with very different far-field and near-field intensity and/or phase distributions. As a simple example, consider a beam with a Gaussian amplitude envelope, but whose wavefront is not spherical. As the amount of asphericity in the wavefront increases, the M-squared value changes from one (exactly spherical) to larger values. Similarly, if a beam has a precisely spherical wavefront, but the amplitude envelope deviates from a Gaussian, the M-squared value will also vary from one (for a Gaussian envelope) to larger values as the envelope deviates more from that of a Gaussian.

The situation is yet more complicated when the beam is propagated through optical systems that can introduce additional aberrations. For example, consider two beams that have the same non-unity M-squared value. Further, say that one of the beams has an ideal Gaussian envelope (but imperfect wavefront) and the other beam has an imperfect Gaussian envelope (but ideal wavefront), it is possible that a system optimized for focusing the aberrated beam (for example) will perform differently when focusing the beam with the non-Gaussian envelope.

A beamlet-based propagation algorithm is used to explore how different sources of error can result in different beam behavior for input beams with similar M-squared values. The near field and far field amplitude and phase profiles for different inputs beams are compared. Each input beam is characterized by a similar, non-unity M-squared value, but with different “error” mechanism to generate the non-unity M-squared profile. Additionally, it is shown that the use of M-squared is insufficient to characterize an input beam to an auxiliary optical system; the characteristics of the focused spot (for example) can change significantly depending on which factors contribute to the non-unit M-squared value.

9626-16, Session 3

Partial coherent light with discontinuous surfaces using Wigner functions

Minyi Zhong, Herbert Gross, Friedrich-Schiller-Univ. Jena (Germany)

The Wigner-distribution function is a useful tool to analyze partial coherent light. Particularly the propagation of light in optical systems can be described by the Wigner function, while including effects of coherence and diffraction. Here we concentrate on discontinuous optical surfaces where diffraction effects can be dominant, such as gratings, Fresnel lenses and lens arrays.

To calculate the change of the Wigner function in optical systems, we treat the optical surfaces as thin phase elements in one dimension. A Wigner function describes signals in space vs. spatial frequency, resembling position vs. angle in geometrical optics. Therefore the ABCD-matrix method can be used to model the paraxial propagation of partial coherent light. This propagation can be computed efficiently with a shear transformation.

However, the implementation of the Wigner function in practice requires careful consideration. For example, a highly convergent or divergent beam requires many sampling points. To overcome this drawback, we apply a method to remove the parabolic wavefront from the beam, transforming it into a quasi-collimated beam without losing physical effects or computational accuracy.

We discuss a Fresnel lens as a first example with partial coherent light. The Wigner function vividly visualizes the essential effects such as the focal shift and multiple foci. Besides, we obtain insight into how a groove profile influences the optical performance of a Fresnel lens. For instance, a linear groove profile increases the depth of focus.

With the groove width in the range of the wavelength, a Fresnel lens acts similar to a blazed phase grating. The diffraction effect heavily depends on the coherence degree of the light and the optical path difference. In the general case of arbitrary groove depths, multiple diffraction orders occur, and they are clearly separated in the Wigner function. These additional diffraction orders lead to more than one focus in the image space.

As another example for Wigner functions, we analyze a lens array for beam homogenizing. Wigner functions distinctly present the beam-shaping contribution of individual lenslets. Their diffraction effects only influence the homogenized beam profile slightly. Often two lens arrays are placed in sequence to reduce the sensitivity to the incident beam angle. In this case diffraction affects the homogenized beam even less.

In conclusion, the Wigner function offers a convenient approach to analyze the design of components where diffraction effects are important.

9626-17, Session 3

Aberration modelling of thermo-optical effects applied to wavefront fine-tuning and thermal compensation of Sodern UV and LWIR optical systems

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As a manufacturer of optical systems for space applications, Sodern is faced with the necessity to design optical systems which image quality remains stable while the environment temperature changes. Two functions can be implemented: either a wavefront control or the athermalization of the optical system.

In both cases, the mechanical deformations and thermal gradients are calculated by finite-element modeling with the IDEAS NX7 software. The data is then used in CODE V models for wavefront and image quality evaluation purposes. Two cases are presented: one of a UV beam expander in which a wavefront control is implemented and one of an athermalized IR camera.

The beam expander is used on the ATLID lidar developed by Airbus Defense & Space France and Germany for the EarthCARE satellite, element of the ESA (European Space Agency) Living Planet Programme. The beam expander is required to have a wavefront defocus fine-tuning capability of +/-50nm RMS. As the thermal equilibrium time constants are very long, this adjustment is achieved by thermal control. Material properties and thermal mapping must thus be well known in order to perform optical analysis of the system performances.

In order to perform this analysis in parallel with the opto-mechanical development, the thermo-optical modelling is done step by step in order to start before the mechanical design is completed. Each step then includes a new modelling stage leading to progressive improvements in accuracy.

The first step is to choose the materials of the beam expander. A uniform temperature distribution is used at this stage to select the optical and structural materials. Wavefront sensitivity to thermal variations is then computed to obtain the temperature range to be used for the thermal control. The second step is to use a nodal model to calculate the thermal variations from one element to the other. As the first order properties are still sufficient to describe the wavefront defocus variation, they are still used for the final material choice. The third step is done with the detailed mechanical model, a thermal mapping using FEM is established and coefficients worked out with CODE V in order to get the optical performances directly from the thermal calculation macro functions.

In a final step, ray-tracing is performed with the detailed thermal mapping. Optical Design software can simulate all thermal effects: deformations of shape, refractive index variations, thermal expansion of glasses and of mechanical parts.

The second example of thermal analysis is the athermalization of an infrared camera for Earth observation. The thermal environment present in an LWIR system is usually complex including hot areas next to cold parts such as detectors cryostats. The thermal equilibrium creates refractive index gradients within the lenses. At this stage the simulation of the axial gradients, radial thermal gradients and all non-symmetrical thermal variations requires data transfers between mechanical CAD and optical design software. The effect of the index gradients shape on the defocus and aberrations are studied to select the optical materials leading to the lens athermalization. The defocus being cancelled out, we characterized variations of the aberrations depending on temporal variations of gradients.

The purpose of this paper is to present the steps that have led to the final STOP (Structural, Thermal Optical) analysis. Using incremental accuracy in modeling the thermo-optical effects enables to take them into account very early in the development process to devise all adjustment and test procedures to apply when assembling and testing the optical system.

9626-18, Session 3

Chromatic variation of aberration: the role of induced aberrations and raytrace direction

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The design and optimization process of an optical system contains several first order steps. The definition of the appropriate lens type and the fixation of the raytrace direction, for example tracing a photo lens from the object to the sensor (in the real light direction) or starting the raytrace at the sensor up to the photo object (inverse light direction), are some of them. The latter can be understood as a hidden assumption rather than an aware design step. This is usually followed by the determination of the paraxial lens layout including the calculation of the total focal length, the Helmholtz-Lagrange Invariant of the system, the pupil position, the total track length and the working distance. This preliminary paraxial frame of the design is calculated for the primary wavelength of the system. It is obvious that for this primary wavelength the paraxial calculations are independent of raytrace direction. Today, most of the lens designs are specified not to work only for one wavelength but in a certain wavelength range. Considering such rays of other wavelengths one can observe, that depending on the direction there will already occur differences in the first order chromatic aberrations, i.e. the axial color aberration and the lateral color aberration, and additionally in the chromatic variation of the third order aberrations.

The reason for this effect are induced aberrations emerging from one surface to the following surfaces by changing the ray heights. It can be shown that the total amount of surface-resolved first order chromatic aberrations and the chromatic variation of the five primary aberrations can be split into an intrinsic part and an induced part. The intrinsic part is independent of the raytrace direction whereas the induced part is not. In literature the monochromatic induced aberrations of 5th order have already been discussed in detail. In the case of induced chromatic aberrations influences can be observed already for the 1st and 3rd order of aberrations.

Hence in this contribution, an analytical discussion and analysis of these effects will be presented on simple theoretical lens examples by putting emphasis on axial color, lateral color and spherochromatism.

In practice, relevant systems being strongly influenced by induced chromatic aberrations and their reversibility are designs like microscopic lenses or wide angle projection and photo lenses. For these optical designs with either large numerical apertures or large fields higher orders of aberrations become dominant and the compensation of them is only achieved by using many lenses over large distances. Therefore, induced aberrations in general becomes more and more performance-relevant in those systems. For this reason the described effects of induced aberrations and their consequences on such a design example of practical interest will be pointed out in conclusion.

9626-19, Session 3

Fast evaluation of surface sensitivity on ghost

Beate Boehme, Carl Zeiss AG (Germany)

Real optical systems are often suffering from false light caused by ghosts. In particular single reflections are critical, they typically occur in applications like reflected light illumination microscopy, confocal distance sensing systems or laser systems. The degradations of performance can be bright spots or overall contrast reduction of the images. Thus in these systems the suppression of first order reflections is important.

State of the art optical design software supports ray trace based ghost image analysis. The automatic generation of reflex light paths is provided, but for systems with a large number of surfaces the analysis of all ghost light paths is time-consuming. Conventional Monte Carlo based non sequential raytrace is used to evaluate the ghosts, it sums up the reflections of all surfaces simultaneously. To achieve high accuracy and low noise at the detector a huge number of rays is necessary in the calculation. This results in long computational time, especially if the distinction of surface influences needs multiple calculations.

In this paper a fast method is proposed for the calculation of ghosts. For each surface the ghost light path is calculated with paraxial and real ray trace. The ghost diameter and the corresponding illumination NA are calculated in the image space. Usually the distance of the reflex focus to the image is used as criterion to access the importance of a ghost. Here we use the etendue of the ghost ray bundle, it is compared with the signal light and listed for all surfaces generating a ghost. The accuracy of the calculations can be estimated by considering the results of paraxial and marginal ray trace. So in one step a surface contribution of reflex intensities as well as an estimation of total flux of reflected light is obtained. If the physical effect of ghost imaging is considered, there are two main aspects, that determine the relevance of a ghost. First, the residual reflection of the corresponding surface coating determines the relative power of the ghost, secondly the geometrical constellation of solid angle and size of the ghost image influences the perturbation in the image. For an incoherent addition of ghost light thus in one step the total ghost intensity as well as the surface sensitivities are obtained. Due to the fact, that only a few rays have to be calculated, the method is rather fast. As a consequence the optimization of an optical system in the design phase allows to include ghosts and corresponding actions to avoid critical ghosts like surface bending, tilt or decentering.

In the proposed method, some assumptions and approximations are made. Therefore a careful analysis is made to compare the results with more rigorous methods and to assess the limitations and approximations. Some practical example systems are considered to prove the validity of this fast method together with non sequential calculations. The usefulness of the fast tool is evaluated.

9626-20, Session 4

Emerging trends and applications of light field imaging and display *(Invited Paper)*

Gordon Wetzstein, Stanford Univ. (United States)

Light field imaging has emerged as one of the most popular computational imaging approaches. In this talk, we will discuss the state of the art in light field cameras, light field microscopes, and also light field displays. Light field displays facilitate a wide range of unconventional applications in projection systems, vision assessment and correction, and wearable displays.

9626-21, Session 4

Computational imaging: the improved and the impossible *(Invited Paper)*

Andrew R. Harvey, Univ. of Glasgow (United Kingdom); Andy P. Wood, Qioptiq Ltd. (United Kingdom); Guillem Carles, Paul Zammit, Univ. of Glasgow (United Kingdom); Nick Bustin, Qioptiq Ltd. (United Kingdom)

While the performance of imaging systems is fundamentally limited by diffraction, the design and manufacture of practical systems is intricately associated with the control of optical aberrations. Traditional optical design typically aims for a compact point-spread function (PSF) across an extended field of view in the presence of chromatic aberrations and imperfect manufacture. In the design of computational imaging systems, a more pertinent criterion is the overall system PSF, or modulation-transfer function (MTF), and the optical PSF is only an intermediate measure of the transfer of information via the detector to post-detection digital recovery of a high-quality image. This is closely related to transmission of information through an imperfect communication system: it is the recovery of high fidelity information at the output that is the prime concern.

Hybrid computational imaging, involving optimisation of antisymmetric pupil-plane phase functions, yields an extended PSF and approximately defocus-invariant MTF enabling image recovery for an extended depth-of-field. Reduced sensitivity to defocus-related aberrations enables simplified lens design (for example high numerical-aperture imaging with a singlet or a single-element zoom lens). Image-replication artifacts due to strong phase effects can significantly degrade image quality, however the use of complementary imaging and recovery kernels can enable their eradication as will be demonstrated in the presentation.

The resolution of many practical systems is limited, not by diffraction or optical aberrations, but by the finite size of detector pixels and so recorded images are aliased. In such circumstances high-angular resolution may be maintained using an array of shorter-focal length lenslets, typically with an array of lenses of total width equal to the width of the detector array and this limits angular resolution. Higher resolution, using an optical aperture much wider than the detector array, requires more complex optical designs. The consequent distortion and a space-variant PSF, can be incorporated into the recovery of the final image to yield a high-resolution super-resolved image. Angular resolution may also be maintained by super resolving the images recorded by an array of independent cameras, exploiting randomisation of image aliasing to improve image recovery. An alternative to the design and manufacture of optics of increasing complexity to achieve increasing field of view is to provide local correction of a primary lens by a segmented correction element over a small field of view followed by computational image reconstruction. In this case the PSF exhibits multiple separated main lobes, but high-quality image recovery is nevertheless possible, with a much more compact and lower cost lens than could be achieved by traditional optical design.

These so-called computational imaging approaches have strong analogy with conventional communication systems: for example: in hybrid imaging, optical coding and digital decoding with spatial dispersion of optical spatial frequencies is equivalent to the function of an electronic MODEM; multi-aperture imaging is similar to the sub-Nyquist sampling of band-limited temporal frequencies routinely used in high-frequency digitisation; and image recovery for the multi-valued PSF of multiscale imaging is redolent of the use of a Rake receiver to combat multi-path effects in cluttered free-space communication. Digital communication systems routinely combine these coding and decoding techniques to maximise information transmission through imperfect channels to enhance system performance, robustness and logistics. Computational imaging offers the potential to provide the same overall system benefits for imaging. In some cases simplification of optics is possible but with the quid pro quo of more complex digital processing.

9626-22, Session 5

Optical lead flint glasses: key material in optics since centuries and in future

Peter Hartmann, SCHOTT AG (Germany)

About 350 years ago a new kind of glass types was invented for decorative purposes such as drinking glasses, bowls and vases. It needed more than 70 years until the capability of these lead flint glasses was discovered to improve the performance of optical systems markedly. Color correction enabled images with resolution more than ten times better than earlier systems opening the view of researchers for new fields in the micro and macro world. Within the next 150 years the progress in optical glass production concentrated on improving quality especially homogeneity, characterization of its properties and achieving larger lenses.

The introduction of glass types with considerably different compositions in the 1880s led to complementation of the glass program but not to a replacement of the lead flint glasses. Their outstanding optical properties together with their favorable melting behavior kept them being workhorses in optical systems design.

One of the outstanding properties of lead flint glasses is their capability of being cast in large volumes. The size development reached a summit by the end of the 19th century with the lenses of the largest refracting telescopes. Their use as radiation shielding glasses since the second half of the 20th century led to even bigger castings of up to two tons of weight.

In the 1990s the other outstanding property made lead flint glass types playing an important role in microlithography. Transmissive optics working with the mercury i-line needs crown and flint glass for dispersion correction of the comparatively broad i-line. The flint glasses had to have utmost transmission in the near UV to reduce thermal lensing as far as possible. This combination of requirements on dispersion and transmission could be fulfilled only by using lead flint glasses. It remains valid in fluorescence microscopy. Here the trend goes to an ever broader spectral range extending from the IR into the UV allowing diffraction limited resolution for many fluorescence light bands simultaneously.

These outstanding properties of the lead flint glass types caused SCHOTT to keep them in the glass program and not to replace them completely as other glass companies have done. The improvements of the last two decades with respect to homogeneity and transmittance underline their suitability for future extreme quality optics with applications in medical and general research and in astronomy for large beam shaping and atmospheric dispersion correction.

9626-23, Session 5

Characterization and measurement results of fluorescence in absorption optical filter glass

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Optical filter glasses (absorption filters) have the advantages of nearly angle independent filter characteristics, strong blocking, and avoiding back reflections by absorbing the unwanted light according to the filter curve. One application of optical filter glass is spectroscopy. Here the incident light is separated from the measurement signal (light) by an optical filter. By using e.g. a longpass filter glass GG435, the incident light is absorbed if its wavelength is below about 435 nm. But this absorbed light can lead to (self) fluorescence of the used filter glass. Thus the filter glass itself re-emits fluorescence light at a different wavelength compared to the incident (excitation) light. This fluorescence light can be disturbing for the measurement of the signal. In order to obtain an optimized optical design the fluorescence properties of the glasses must be known. By knowing the emission spectra and the excitation spectra one can design a system with a good signal-to-noise ratio. This effect of self-fluorescence is often not considered. Almost all materials exhibit more or less significant fluorescence.

We will present our measurement set-up for fluorescence measurements of optical filter glass. This set-up was used to obtain fluorescence measurement results for different optical filter glasses. For the first time we present results of the amount of fluorescence for different optical filter glasses. The effect of excitation wavelength on the fluorescence level for the same filter glass type will be studied for 2 wavelengths: 365 nm and 488 nm excitation. The 488 nm excitation can only be studied if the filter glass is absorbing at that wavelength. E.g. GG435 is not absorbing at 488 nm and so no fluorescence results are possible. Besides other factors, fluorescence depends on impurities of the raw material of the glass melt. Due to fluctuations of the raw material used for the glass production the fluorescence of the same filter glass type will fluctuate for different melting campaigns. Thus, results from different melting campaigns will be shown for the same filter glass type. Finally all measurement data are summarized in a single parameter. This single parameter is the integral value of the fluorescence spectrum at a certain excitation wavelength compared to a standard glass (optical glass SF1 – according SCHOTT TIE-36, available for download). With the help of this single parameter a comparison of different filter glass types can be summarized and compared to each other which will be shown for the first time for optical filter glasses.

The shown measurement results will enable users of optical filter glass to estimate the amount of fluorescence depending on different filter glass types and to estimate the influence of different glass melting campaigns. In addition the impact of excitation wavelength on the fluorescence level can be estimated were 2 excitation wavelengths were used: 365 nm and 488 nm (where applicable).

9626-24, Session 5

Diffractive optics with high Bragg selectivity: volume holographic optical elements in Bayfol HX photopolymer film

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The field of micro-optics is becoming more and more attractive due to its ability to enable complex wavefront transformations in a compact and flat design. Especially diffractive optical elements with their microstructures in the size of the wavelength of light, do not show aberrations introduced by edge effects known in Fresnel lenses which are refractive. Uses of diffractive optical elements (DOE) are known and many manufacturing techniques have been developed – from diamond turning over lithography to holographic exposure. Replications techniques of those surface structures are based on a mechanical imprinting step of a metalized master into thermoplastic films or if even higher precisions are needed by liquid resin (wet) embossing techniques. Major drawbacks of those micro-optical devices are related to their limitations in their optical functions, difficulties to achieve high diffraction efficiencies and a need to protect their surface corrugation from marring.

For a long time volume Holographic Optical Elements (vHOE) have been discussed as an alternative, but were hampered by a lack of suitable materials. They provide several benefits over DOEs like high diffraction efficiency due to their ability to reconstruct only a single diffraction order, freedom of optical design by freely setting the replay angles and adjusting their bandwidth by a selection of the vHOE's thickness. Additional interesting features are related to their high selectivity providing transparent films for off-Bragg illumination. The resolution of recording materials is a key parameter as well, so shorter (e.g. blue) wavelength based gratings or complex wavefront interference patterns can be recorded as well. vHOEs can be multiplexed, so several optical functions can be combined in the same film leading to even further advanced schemes from multifunctional optics to compensation methods of commonly known color aberrations in diffractive optics.

Manufacturing of a volume Holographic Optical Element is done by an interference exposure, i.e. a pure photonic process. No wear and tear of the embossing tool is occurring while there are several means to create temporal stable fringe patterns that are transformed into a refractive index pattern – a phase hologram.

In this paper we report on our newly developed photopolymer film technology (Bayfol® HX) that uniquely requires no post processing after holographic exposure. We explain the governing non-local polymerization driven diffusion process leading to an active mass transport triggered by constructive interference. Key aspects of the recording process (exposure time & dosage) and their impact on index modulation formation is discussed. The influence on photopolymer film thickness on the bandwidth is shown. A comparison between coupled wave theory (CWT) simulation and experimental results is given.

There are two basic recording geometries: reflection and transmission vHOEs. They differ by their spatial frequency and their principal dependence of refractive index modulation to diffraction efficiency as predicted by CWT. We explain consequences of how to record them properly and discuss in more detail the special challenges in transmission hologram recording. Here beam ratio and customization of photopolymer film properties can be applied most beneficially to achieve highest diffraction efficiency.

9626-25, Session 6

Overview on surface representations for freeform surfaces *(Invited Paper)*

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Freeform surfaces are a new and exciting opportunity in lens design. The technological boundary conditions for manufacturing surfaces with reduced or no symmetry are complicated and recently the progress in understanding and controlling this kind of components is ready for use in commercial products. This type of component with larger functionalities is needed to correct more compact systems with the desired quality. Nearly all procedures of classical design development are changing, if these more generalized conditions are valid. The mathematical description of the surfaces, the optimization algorithms and their convergence, the initial design approaches, the evaluation of performance over the field of view, the data transfer in the mechanical design software and the manufacturing machines, the metrology for characterization of real surfaces and the return of the real surfaces into the simulation are affected. In this contribution, in particular an overview on possible mathematical formulations of the surfaces is given. The needs for more than one description, the benefits and shortcomings of the known solutions are discussed.

Due to the higher complexity of the surface shapes and of the technological realization, there are several aspects, that should be kept in mind. One of the requirements on the descriptions is a good performance to correct optical aberrations. Due to the more sensitive behavior of the light path on the slope of a surface rather than the position, it is beneficial to construct the formula of a freeform surface as an expansion, that is slope orthogonal according to the famous idea of Forbes, that was first established for circular symmetric aspheres. One more point, that must be considered is the symmetry of the shape itself and of the boundary. Traditional more or less polar oriented or cartesian based representations are used. After fabrication of real surfaces, there are typical deviations seen in the shape. First more localized deformations are observed, which are only poorly described by mode expansions. Therefore a need in describing the surface with localized finite support is seen. This problem can be solved by using radial shifted base functions. For a fit of the low spatial frequency errors of a surface, a system of space orthogonal functions has the best performance. Secondly the classical diamond turning grinding process with a local material removal typically shows a regular ripple structure. These midfrequency errors are hard to describe with expansion approaches, therefore special mathematical approaches are necessary to describe this kind of perturbation. In conclusion, at least four different types of surface descriptions are necessary to support all steps of the development chain. These approaches should be diversified to the symmetry of the surface shape and the boundary. For all these cases it would be the best to have formulations, that only need a few expansion terms, are fast and robust in calculation, allow for conversions without loosing accuracy and are fast in raytrace calculation.

9626-26, Session 6

Optical design through optimization using freeform orthogonal polynomials for rectangular apertures

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Interest in optical systems that use freeform surfaces is rapidly increasing with the development of new manufacturing techniques. With the investigation of novel applications new issues constantly appear. During past years different studies showed various benefits in using the orthogonalized representations of aspheric or freeform shapes, but they were all oriented towards the traditional circular aperture designs. Since freeform surfaces tend to be used in a non-conventional optical systems, like off-axis systems or high aspect ratio systems, a study of non-circular apertures is of potential relevance.

First non-circular aperture shape that one can be interested in due to tessellation or various folds system is the rectangular one. This paper covers the comparative analysis of a simple local optimization of one design example using different orthogonal representations of our freeform surface for the rectangular aperture.

A very simple single surface off-axis magnifier is chosen as a starting system. Different design approaches for similar systems with circular apertures have been presented previously, however, here we are going to use the design through optimization approach, in order to analyze the behavior of our “rectangular aperture” system when using different types of orthogonal polynomials to represent the mirror surface. We use a toroid as a starting surface that is fitted to different polynomials. By analyzing the optimization behavior and the system performance after the optimization we can choose the optimal shape for our rectangular aperture design.

4 different types of surface representations are compared – general x-y polynomial, Forbes freeform, Legendre and a new calculated Legendre type polynomial orthogonal in gradient, all 10th order. Each of these systems have >15mm eye clearance, 3mm pupil (with 3x3mm rectangular aperture stop), 24 degree diagonal field of view (9.56º X semi-field, and 7.2º Y semi-field) and a 14.7º mirror tilt angle. Distance from the mirror vertex to the image plane is around 13mm, and the image plane has a rectangular aperture of 4.8mm by 3.6mm. Each system has 17 field points, and besides the surface coefficients the only variables are image plane tilt and defocus. The only constraint used in all of the systems is the focal length of 14.25mm. We also have to make sure that the image plane doesn’t interfere with the ray path between the eye and the mirror. During the optimization, we are tracing 140 rays across the pupil.

In order to better understand the behavior of our system depending on the surface description that we use, two different comparisons are done. In the first case we use all default field weights, in order to better compare the progress of the merit function versus optimization cycles. Second comparison is done by weighting the fields to obtain the best performance. In both cases we found the design of new calculated polynomial orthogonal in gradient to exceed the ones that use “defined inside a circle” polynomial, and in the second comparison it yields around 20% gain in the average MTF across 17 field points.

9626-27, Session 6

Performance comparison of polynomial representations for optimizing optical freeform systems

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Optical systems can benefit strongly from freeform surfaces, however the choice of the right representation isn`t an easy one. Classical representations like X-Y-Polynomials, as well as Zernike-Polynomials are often used for such systems, but have some disadvantage regarding their orthogonality, resulting worse convergence and reduced quality in final results compared to newer representations like the Q-Polynomials by Forbes. These are orthogonal in slope, which is a huge benefit for optimization convergence. Additionally the basic symmetry of the system (near or far from rotational-symmetry) and the aperture shape (circular, rectangular or complete different) can be important factors in determining the suitable description. Therefore in this work we investigated the properties of performance optimization for three typical optical systems, using different polynomial representations.

The first system is a Three Mirror Anastigmat (TMA); a classical reflective system with remaining plane-symmetry in x. Due to this the number of used parameter is reduced. We optimized only the second mirror near the pupil as a freeform, as well as the image distance. A simple spot-criterion for improved resolution is defined with a fixed F-number.

The second system is a Head Mounted Device (HMD), which is again plane-symmetric in x, but refractive. The freeform is here defined near the image plane as the last surface. The main goal of this optimization is to correct distortion, as well as resolution.

The last system is a complete symmetry-free modified Yolo-telescope with increased size of field and aperture. The third mirror is the freeform surfaces and should be optimized again with a simple spot-criterion.

The different support of tilt and defocus in each of the surface representations is still under investigation. Therefore for a better comparison of the results, neither of them was part of the optimization in the three test-systems.

The results to compare are amongst others the number of varying parameter of the surfaces and resulting radial and azimuthal orders, corresponding spot respectively distortion (for HMD) and number of iteration steps. Additionally the non-rotational part of the freeform surface was of interest.

The investigated surface descriptions offer support for circular or rectangular aperture, as well as different grades of departure from rotational symmetry. The basic shapes are for example a conic or best-fit-sphere and the polynomial set is non-, spatial or slope-orthogonal. These surface representations were chosen to evaluate the impact of these aspects on the performance optimization of the three test-systems. Additionally the use of certain symmetry-groups was analyzed.

Freeform descriptions investigated here were amongst others XY-Polynomials, Zernike in Fringe representation, Q-Polynomials by Forbes, as well as a 2-dimensional Chebyshev-description and a self-developed slope-orthogonal representation for rectangular aperture called Freeform-Polynomials.

As a result recommendations for the right choice of freeform surface representations for practical issues in the optimization of optical systems can be given.

9626-28, Session 6

Investigation of TMA systems with different freeform surfaces

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Three mirror anastigmats (TMA) are telescopic optical system with only plane symmetry, that allow for good image quality without any central obscuration. If the bending angles of the axis are made large to achieve a small size of the system, the field size is increased and the numerical aperture is enlarged, the performance of this kind of system is going down due to aberrations. Therefore in the correction with only 3 surfaces more degrees of freedom are obtained by using freeform surfaces. Additional problems now occur in the manufacturing of the mirrors and the adjustment and alignment. To reduce these complexities two constraints are fixed from the viewpoint of realization. Firstly the two mirrors M1 and M3 are fabricated in one piece to get rid of one dimension of adjustment. Secondly it is preferred to define a common axis of the mirrors, which simplifies the question of changing coordinate reference. Furthermore of course freeform surfaces cause additional cost. Therefore it is attractive to use off-axis used aspheres and to come to an acceptable performance with the smallest number of freeform surfaces.

In this study, for a particular specification the most relevant options for correction are investigated and discussed. To get better conditions for comparison, distortion correction is not considered here, which usually is also important for TMA imaging systems. Different types of freeform surfaces are considered to evaluate their potential. For the off-axis aspheres, Q-polynomials of Forbes are selected. The mild version is orthogonal in slope and thus a good performance is expected. The conventional XY-polynomials are regarded, although it is well known, that due to the lack of orthogonality their performance is poor. Furthermore Zernike polynomials are used, they are orthogonal in space on a circular shape. It is assumed, that they are a good solution in particular for the pupil of the system, which is located on the mirror M2. Last but not least, a new kind of freeform surface is developed and tested in this special system. It is slope orthogonal on a rectangular domain.

In the performed case study, some general results are found. It is seen, that the correction of spherical aberration and coma is best corrected in the pupil with the M2 and to select the Zernike representation with remaining x-symmetry is one of the best ways to do this. The use of the new polynomials also gives good results. Furthermore it is found, that the M1 and M2 are quite beneficial to be modelled as off-axis aspheres of the Q-type and a general freeform surface at these locations is only of limited help. In conclusion, a combination of two Q-aspheres and a Zernike surface at the M2 is one of the most favorable combinations. More detailed results show the differences for the various surface types considering the computational time and the speed of convergence.

9626-29, Session 6

Using the 3D-SMS for finding starting configurations in imaging systems with freeform surfaces

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In the classical lens design a complex optical imaging system is typically derived from an existing start design, whose performance is already close to the aimed specifications. In a multi-variable optimization process, the desired system design is then reached within several iterations. In the still young field of freeform optical systems, the absence of rotational symmetry comes along with a higher variety in possible system geometries. Therefore larger computational effort during the optimization is needed and good starting points are favorable. In contrary to the large possible variety of freeform system geometries, the number of approved systems to start with is still small. Hence the generation of starting systems for non-symmetric lens and mirror designs will be helpful. We investigate the possibility to generate starting systems of freeform optical systems with the help of the Simultaneous Multiple Surface Method (SMS).

The SMS is widely known for the generation of illumination optics [1] and has in general been approved for a small number of imaging applications. This method offers the possibility to generate starting systems with high

numerical apertures, which contain at least two perfectly imaged field points for one wavelength. Using two auxiliary points [2], the classical 3D-SMS determines discrete infinitesimal small surface segments of two optical surfaces by coordinates and normal directions. In one specific plane the auxiliary points also form an ideal image.

Basing on this we developed an approach to get smooth surfaces for the initial design in optimization. The discrete segments, which are derived from the SMS, are fitted in location and normal directions by assuming a Zernike mode expansion. The parameters of this surface can serve now as variables for the final optimization procedure, which can be formulated for a larger number of field points and several wavelengths. For using this method, the tool for performing the SMS algorithm must be coupled with the design software. Therefore in the case of generalized systems special care must be taken to transfer all data properly. Further the position of the auxiliary points, which are used for the 3D-SMS are investigated with regards to their influence onto the image quality in the object and image plane.

On the basis of a specific imaging example, which is not rotational symmetric, we investigate the potential of such a starting system, which is retrieved from the outcome of the classical 3D-SMS for a system with arbitrarily defined image planes. After transfer of the derived starting design to the ray tracing program, its behavior in optimization and performance is evaluated by the number of iteration cycles and achieved image quality over the field. For evaluation, the results are compared with conventional starting design approaches. The properties of the method considering speed of convergence, number of terms in the expansions and the final performance are discussed in detail.

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9626-31, Session 7

Surface contributions to total wavefront aberrations

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Optical systems that do not have axial symmetry are since long the field of study in optical design. The application of freeform elements in such systems increases the number of variables available in correction. That creates a potential for control of higher order wavefront aberrations. It is nevertheless not trivial to determine where to place a freeform element to be used most effectively. To answer that question it is very helpful to understand how aberrations arise with propagation through the system. Particularly what is the contribution of each surface to the total wavefront deformation.

That problem has been extensively studied for systems with axial symmetry where paraxial quantities can be unambiguously determined. The surface contributions to wavefront aberrations are then defined with a help of entrance and exit reference spheres. Those spheres are centered upon an ideal intermediate image location with a radius measured to the center of the intermediate pupil. Following these definitions the complete system is divided into modules where an exit pupil of one surface is at the same time the entrance pupil of the next one. From surface contributions, defined in such a way, we can further separate the intrinsic part and extrinsic part. The intrinsic aberration is introduced upon perfect incoming wavefront, whereas extrinsic part results from aberrations acquired before the considered surface.

Breaking of axial symmetry causes difficulties in unambiguous determination of ideal intermediate image plane and so is true for intermediate pupils. That creates a demand for formulating new concepts. Hence a more general approach has been proposed. In this approach each object point is considered individually with a chief ray treated as a 'local' optical axis. Thus, determination of image plane is studied separately. Different methods for finding the intermediate image locations are considered. Those locations are then the centers of reference spheres. Radii of reference spheres are determined by measuring the distance from the center to the intersection of the chief ray with the surface. In this case exit reference sphere of respective surface does not cover with the entrance reference sphere of the next one. Hence it is required to study deformation of wavefront as it propagates in free space. Another aspect is to find a way for separating intrinsic and extrinsic parts. These is done by considering different grids on reference spheres. First ideal ray bundle is traced from the intermediate image point to determine the intrinsic part. Then rays from distorted grid on entrance reference sphere are traced to calculate the complete surface contribution. Wavefront deformations acquired with both methods are then compared and analyzed.

The method is verified on the example of an on-axis system. Results are checked against those obtained by using classical methods based on paraxial quantities and total optical path differences. Benefits are then presented by application to the off-axis system.

9626-32, Session 7

Diffraction effects in laser beam shaping systems

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Laser-based acceleration concepts for protons and ions recently came into the focus of intense scientific research and applications. The focusing of a high-intensity laser pulse (I>1018 W/cm2) on a specially designed target leads to a relativistic laser-plasma interaction. The interaction process introduces collective charge separation, resulting in a strong electric field of more than 1012 V/m. This provides the acceleration mechanism, where ions are accelerated within a few micrometers to energies of several MeV/u. Thereby, the ions velocity distribution is strongly influenced by the field distribution of the laser spot on the target. To obtain an unidirectional and quasi mono-energetic ion beam, a flat-top field distribution of the focused laser beam is optimal. This can only be achieved, by using a beam-profiling system that reshapes the incident laser beam into an Airy-shaped field distribution in the far field.

Here, we report on the design of a free-form optical system, used to reshape an incident laser beam into an Airy-like field distribution in the far-field. As the system has to withstand high-intensity laser radiation, a layout based on a mirror system is mandatory. It is well known that, in general, two mirrors are sufficient to reshape the high-intensity laser beam into a desired field distribution in amplitude and phase. Therefore, roughly spoken, the first mirror reshapes the intensity distribution, while the second mirror corrects the phase of the beam. In the considered case of shaping an Airy-like field distribution, two problems arise: On the one hand, to shape the rings of zero intensity, corresponding to the roots of the Airy-function, strong curvature peaks on the first mirror are necessary. On the other hand, the alternating phase between these rings can only be achieved with grooves on the second mirror. Both aspects raise the question, if the used geometric optical modelling approach is still valid. To investigate the influence of diffraction effects, our design study is essentially accompanied with wave-optical simulations of the entire structure. We find influences of diffraction in the Airy-like field distribution in the far field and ascertain their influence on the focal field distribution. As a consequence, we find a degradation of the flat-top focal field in the range of a few percent, which cannot be avoided. Moreover, we assess alignment sensitivities of the system, which in turn are found to be very critical and hence of major importance for the overall performance of the system. Therefore, the technological realization of the system is challenging.

9626-33, Session 7

Optical design with freeform surfaces at NASA GSFC

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Optical surfaces without rotational symmetry have been shown to enhance system performance and reduce volume in optical designs. This can greatly benefit CubeSat and other small satellite mission concepts for space-based optical instruments that are severely volume constrained. This paper discusses the application of Zernike and XY Polynomial surface profiles for specific NASA instruments and the subsequent performance and volume improvements achieved. New software tools are also

discussed which more efficiently evaluate the manufacturability of these exotic surfaces.

9626-34, Session 7

Describing freeform surfaces with orthogonal functions

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In optical design with freeform surfaces, there are several requirements on the description of the surface: It should use only few parameters, be suitable for optimization – i.e. it is fast to compute and the optimisation algorithms should work effectively with them, it should be able to fit surface data and be able to include surface manufacturing errors. In this talk we focus on the optimisation properties and provide examples demonstrating them. A set of functions describing a surface is typically good for optimisation if its parameters have orthogonal contributions to the merit function. Depending on the merit function – RMS spot size or wave front error – and the position of the surface in the system – close to the pupil or far from it, different surface types can have merit orthogonal parameters.

Recently G. Forbes [1] proposed a set of polynomials which are orthogonal with respect to their slope on a circular aperture in order to describe freeform surfaces. This description yields good optimisation results, as the impact of the surface on the optical performance is given by its slope. However the recursive computation algorithm presented by Forbes is very difficult to implement with all of its advantages into optical design software.

We will present the results of the implementation of a different but much easier to use set of slope orthogonal polynomials first known from the calculation of the Gaussian moment [2]. They are constructed as linear combinations of Zernike polynomials that have orthogonal contributions to it. As Zernike polynomials are a well-known and widely used set of orthogonal polynomials to describe the optical wavefront of rotational-symmetric systems it is no surprise that these surface functions are also useful for optimising wavefront of an optical system incorporating freeform surfaces, especially if they are used close to the system pupil.

Using the slope orthogonal description based on linear combinations of Zernike polynomials has several advantages: They are fast to compute, easy to convert when changing the merit function, already well known in the optical community and they cannot be any closer to the aberrations that you want to correct with a freeform surface.

Furthermore we will present an orthogonal surface representation on a rectangular aperture which is based on Chebyshev polynomials separated into x- and y-coordinates. These polynomials are very easy and very fast to compute. The Chebyshev surface description is sag orthogonal but the Gramian matrix with respect to the slope is also sparse. This description is very convenient when the aperture has a very high aspect ratio, or when designing a system with a rectangular pupil. But one can also obtain good optimisation results for systems with circular pupil.

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9626-35, Session 7

Optical tolerancing of structured mid-spatial frequency errors on free-form surfaces using anisotropic radial basis functions

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Freeform optical surfaces have been recognized as important addition in a modern optical design. Significant part in the design process of free-from surfaces belongs to tolerancing of structured surface errors in mid-spatial frequency range [1]. Mathematical representation techniques based on expansions of Radial Basis Functions independently and together with global polynomial representations have been verified in the context of free-form optics [2]. Recently, we studied the expansion using anisotropic RBFs as means to represent general freeform surfaces [3]. Particularly, we explored strategies for optimal choice of RBF shape parameters and the novel Fibonacci grid for placement of RBF nodes as important aspects for efficient use of RBF based representation [4].

We investigate optical tolerancing method for free-form surfaces described with the global polynomial and local RBF expansion. We expand our method further by incorporating hierarchical decomposition of the surface with suitable placement of nodes with anisotropic RBFs and RBFs with spatially varying shape parameter. We apply this expansion both on the different sub-apertures and the different resolution levels of surface description. First step, free-form surface is represented with the global polynomial (e.g. Zernike and Forbes Q-polynomials). Second, perturbation (error of the surface) is modeled as a bounded departure, calculated directly and beyond the thin-skin approximation, represented as linear combination of anisotropic RBFs with multilevel decomposition of the surface under consideration. General representation of surfaces based on RBF and global polynomial representations are independently implemented as User Defined Surfaces in Zemax. Sensitivity and Monte Carlo analysis are performed with the customized metrics implemented as our own software extensions using User Defined Operands in Zemax and with the help of Matlab.

Our new method enables study of general structured surface errors in mid-spatial frequency range with direct access to wide range of possible forms: from global ripple (sinusoidal) error type to localized Gaussian bump errors and other arbitrary types of structured surface perturbations. With our method, we can keep computational cost low in tolerancing analysis and use intrinsic flexibility of RBF based surface representations.

Further, the correlation between the calculated MTF and PSF and different features in mid-spatial frequency range is investigated as performance criterion for the tolerancing analysis. We applied our analysis on several examples from patent and scientific literature such as: high-performance imaging objective involving high-order spheres and free-form lenses in the layout, compact mobile phone camera objective and three-mirror anastigmatic telescope with the free-form mirrors.

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9626-36, Session 7

Wide field-of-view bifocal eyeglasses

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Purpose: Presbyopia affects a large part of the population (most people above the age of 45). When vision is affected by amentropia in addition to presbyopia, a solution based on eyeglasses, implies the use of segmented focal regions (bifocal or trifocal lenses) or progressive addition surfaces (PALs). However, both options have the drawback of reducing the field-of-view for each power position (far, near or intermediate object locations), which restricts eye-head movements in natural vision. To avoid this serious limitation we propose the optical design of bifocal power-adjustable lenses ensuring a wide field-of-view for every viewing distance.

Methods:

The optical system, based on the Alvarez principle, comprises two lenses for each eye. The lenses have a planar and a free-form surface and are arranged with their planar surfaces in contact, so that the incoming light is only refracted by two surfaces. The non-planar surfaces to be designed can be third order polynomials that are described by nine terms. Eye movements during convergence for near or intermediate object distances are considered, which makes the design problem particularly challenging because the optical axis changes for each configuration. Spherical refraction correction is considered for different eccentric gaze directions covering a field-of-view range up to 45º. The merit function was optimized following a cascade approach where different surface parameters where optimized at successive steps.

Results:

We designed three optical systems. The first one provides – 3 D for far vision (myopic eye) and -1 D for near vision (+ 2 D Addition). The second one provides a +3 D addition with –3 D for far vision. Finally the last system is an example of reading glasses where for the first relative position the optical power is +1.5 D and for the second relative position the power is +2.5 D (+1 D power adjustment).

For the last example an acceptable vision (optical error below 0.25 D) is an ellipse around the central viewing direction and having major and minor axes of approximately 45º. For the +3 D and + 2 D addition examples the optical window of acceptable quality is slightly reduced to an ellipse having major and minor axes of approximately 30º.

Conclusions: We have presented a new way of designing bifocal wide field-of-view eyeglasses. For each object location the power is adjusted by moving transversely two lenses, one with respect to the other, in such a way that the typical field of-view available when looking through conventional monofocal eyeglasses is achieved. This technology represents a breakthrough over conventional bifocal lenses where the desired power is usable in only half part of the visual field.

9626-37, Session 7

Alvarez lens systems: applications and theory

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We consider using the Alvarez lens concept in systems to perform refocus and zoom functions in conventional optical systems. The Alvarez pair are a good example of freeform surfaces that are used to imprint a deformation into the propagating wavefront. In addition, we try to better understand the paraxial theory of each freeform component in building up to a composite lens system. This is meant to add understanding to the standard first order theory that takes the thin lens approximation as a starting point. In fact, revisiting the first order theory leads to the idea that Gaussian optics has to be complemented by a non-gaussian optics approach. Demonstrable examples are given in the long wave infrared (LWIR) and the medium wave infrared (MWIR). For the LWIR example, a simple refocus is achieved by a perturbative movement of the Alvarez pair. For the MWIR example, a field of view change is performed by a non-perturbative movement of two Alvarez pairs. The nature of this pair leads to a very different constraint as compared with performing axial lens movements. An inherent feature of the Alvarez pair is the SO(2) symmetry breaking due to both the finite air gap between the cubic surfaces and the transverse movement of the pair. This has implications for the wavefront at the image plane. Having developed the first order theory one can better understand misalignment tolerances and how these produce certain wavefront aberrations. Most notably, misalignments lead to simple expressions in terms of the Zernike polynomials. The fact that cubic surfaces can be fabricated in IR materials leads to the possibility of an IR equivalent of the visible 'liquid lens', where now curvature variation is affected by the Alvarez concept. Finally there are some implications for diffraction integrals that are of interest, in particular in calculating pupil functions and ultimately performance measures.

9626-82, Session PTues

Lightweight design and finite element analysis of primary mirror for the space telescope

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In order to satisfy the strict requirements of the lightweight ratios and high dimensional stability for space mirror, the design method of lightweight structure and the flexible supporting structure of the primary mirror is proposed. Subsequently, the surface deformations of two different lightweight structures for primary mirror are discussed for analyzing the influence of the mirror weight on its surface. Finally, the finite element models for primary mirror assembly are built for calculating the surface deformation caused by different gravity orientations and various thermal environments. It is proved that the weight, stiffness and surface accuracy of the structure design for primary mirror can meet the engineering requirement.

9626-83, Session PTues

A tunable integrated system to simulate colder stellar radiation

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In the last years, a lot of extrasolar planets have been discovered in any direction of the Galaxy. More interesting, some of them have been found in the habitable zone of their host stars. A large diversity of spectral type, from early types (A) to colder ones (M), is covered by the planetary system host stars. A lot of efforts are done in order to find habitable planets around M stars and indeed some habitable super earths were found. In this framework, "Atmosphere in a Test Tube", a project started at Astronomical observatory of Padova, simulates planetary environmental condition in order to understand how and how much the behavior of photosynthetic bacteria in different planetary/star scenarios can modify the planet atmosphere. The particular case of an habitable planet orbiting a M dwarf star is under study for the time being. The irradiation of an M star, due to its lower surface temperature is very different in quality and quantity by the irradiation of a star like our Sun. We would like to describe the study of feasibility of a new kind of tunable led stellar-light simulator capable to recreate the radiation spectrum of M type stars (but with the potential to be expanded even to F, G, K star spectra types) incident on the planet. The radiation source is a multiple LED matrix coupled with a 3-halogen lamp core cooled by means of liquid cooling technology. In order to endow it with modularity this device will be composed by a mosaic of circuit boards arranged in a pie-chart shape, on the surface of which will be welded the LEDs. This concept is a smart way in order to replace blown out pieces instead of changing the entire platform as well as implement the device with new modules suitable to reproduce other type of stars. The device can be driven by a PC to raise or lower the intensity of both each LED and the lamp, in order to simulate as close as possible a portion of the star spectrum. The wavelength intervals overlap the limits of photosynthetic pigment absorption range (280-850 nm), while the range of the radiation source will be between 365 nm and over 1200 nm. The reason why we chose a higher outer limit is that M stars have the emission peak at about 1000 nm and we want to study the effects of low-light radiation on bacterial vitality. The innovative concept behind this radiative source is the use of the LED components to simulate the main stellar absorption lines and to make this a dynamic-light. Last but not least the use of LED is crucial to keep the device compact and handy. This device could help us to better understand the link between radiation and NIR-photosynthesis and could find applications in the field of photo-bioreactors as a test bench for the choice of the wavelength to be used in order to maximize the production rate. Other fields of application are the microscopy light sources field and the yeasts growth sector.

9626-85, Session PTues

Progress on the prevention of stray light at the 2.4-m Thai National Telescope

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The 2.4-m Thai National Telescope (TNT) is the main instrument of the Thai National Observatory located on the Doi Inthanon, Thailand's highest mountain. The first astronomical images obtained at the TNT suffered from stray light problems: halos over bright stellar images spread over few arcminutes in the focal plane, and the images taken during observations in bright moon conditions were contaminated by high levels of stray light. We performed targeted investigations to identify the origin of these problems.

In a first time, we analyzed the irradiance distribution of defocused stellar images by placing some masks of different lengths on the TNT primary mirror. We concluded that the halo around the bright stellar images was due to the chamfer and the wavefront error at the mirror edge. We thus installed an annular mask along the edge of the primary mirror that suppressed the bright halo. Then, we quantified the performance improvement by observing the double star Sirius and measuring the signal level around the most brilliant star Sirius A before and after the installation of the mask.

In a second time, we identified the contributors to the stray light by placing a pinhole camera at the TNT focal plane. We concluded that the main contributors were: the baffle that surrounding the M3 folding mirror and the tube placed inside the instrument fork between the M3 and the M4 folding mirrors. We thus designed, manufactured and installed a new baffle to remove these telescope structure areas from the camera pixel views. The final design of the baffle comprises 21 diaphragms and is painted with an ordinary black paint. This baffle was manufactured at the NARIT mechanical workshop by using our Computer Numerical Control machine. The optical and mechanical designs, the procurement, the manufacturing and the installation on the telescope structure were performed in less than 8 months, between May and November 2014.

We assessed the improvement on the performance by measuring the variation of the stray light signal provided by a detector placed at the TNT focal plane before and after installing the baffle in the telescope structure. First, we measured this stray light signal while observing a sky region located at the respective angular distances ?? = 5 degree and ?? = 10 degree from the first quarter moon limb. Then, we measured the stray light signal while observing a sky area located near the zenith with the telescope spiraling around the azimuthal axis during the same night. The results demonstrate a significant rejection of the stray light by the baffle and an improvement of the stability of the signal provided by the detector.

In this paper, we describe our investigations and we present the improvement in quantitative terms.

9626-86, Session PTues

Optical and mechanical design and characterization of the new baffle for the 2.4-m Thai National Telescope

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The first astronomical images obtained at the 2.4m Thai National Telescope (TNT) during observations in bright moon conditions were contaminated by high levels of light scattered by the telescope structure. We identified that the origins of this scattered light were the M3 folding mirror baffle and the tube placed inside the fork between the M3 and the M4 mirrors. Indeed, during the observations these objects were systematically illuminated by some external sources and scattered light directly toward the detector. We thus decided to design and install a new baffle.

The development of this baffle comprised optical, mechanical and planning challenges. The optical challenge consisted of designing a baffle with a good straylight rejection performance that induces a minimum vignetting. The mechanical challenge was to design a baffle which comply with optical requirements and which can be easily installed and adjusted in few minutes. The planning challenge was to design, manufacture and install the baffle in less than 8 months. This, in order to get the telescope ready to operate in November 2014 that is the beginning of the dry and observing season in Thailand.

In a first step, we calculated the optical and mechanical inputs needed to define the baffle optical design. On the one hand, we calculated the beam diameter between M3 and M4 mirrors for an extend source located at infinity and which dimensions covered the TNT specified Field Of View (FOV). On the other hand we assessed the maximum dimensions of the vanes and the maximum length of the baffle. This, by measuring the available space for installation/operation and by applying the required margins for mechanical design and manufacturing feasibility.

In a second step, we defined the number, the position and the diameter of the vanes to remove the critical objects from the detector's FOV by using a targeted method. Then, we verified that the critical objects were moved away from the detector's FOV by tracing rays backwards from the detector toward the telescope structure. Finally, we assessed the maximum vignetting by calculating the flat-field signal with the TNT ZEMAX model. By using this method, we quickly converged to a baffle that comprises 21 vanes and rejects efficiently the stray light by inducing a vignetting lower than 10% over the current TNT useful FOV.

In a third step, we designed and manufactured the baffle. The mechanical design is made of 21 sections and comprises an innovative mechanism for the adjustment of the baffle position and orientation. This mechanism consists of 6 long screws that adjust independently 2 set of 3 lock-in parts placed at 2 different places along the baffle. The orientation and position are thus adjusted by rotating the screws. The baffle installation and adjustment is performed in less than 20 minutes by 2 operators.

In a fourth step, we installed and characterized the baffle by using a pinhole camera. We quantified the performance improvement and we identified the baffle areas at the origin of the residual stray light signal. Then, we compared the simulated and the measured "flat field" signals to confirm the vignetting level. Finally, we performed targeted on-sky observations to test the baffle in real conditions.

9626-87, Session PTues

The polarization smoothing design for improving the spatial spectrum distribution of focal spot

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Polarization smoothing is a technique for reducing speckle pattern contrast on target by overlaying two uncorrelated speckle patterns with orthogonal polarizations in inertial confinement fusion research and it reduces focal spot contrast by a factor of 1/sqrt(2). The improvement of focal spot contrast with traditional polarization wedge for polarization smoothing is aimed at some special spatial frequency and lack of effects in physics experiments. To improve the spatial spectrum of polarization smoothing, a new method is proposed; in which the two orthogonal polarization states are separated by the angle distribution differences between beam direction angle and uniaxial crystal optic axis, the angle can induce the optical phase differences between "o" and "e" light. Theoretical analysis and numerical simulation is developed to analyze the new method. The results show that based on the viable control of beam random polarization state on near field, besides the reduction of the focal spot contrast by 1/sqrt(2), the new method can improve the spatial spectrum distribution of focal spot.

9626-88, Session PTues

A wide-spectrum fluorescence spectrometer design for laser-induced fluorescence lidar

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It is well known that the fluorescence phenomenon can provide information in addition to what obtained by absorptive or reflective spectroscopy. But if we want to facilitate remote fluorescence recordings, the fluorescence detection techniques need to be combined with the ranging capability of a lidar system, and now such fluorescence lidar has been used in the areas such as vegetation monitoring, historical monuments protection, water pollution measurement and so on. In order to obain more spectral characteristics, a double wavelength laser-induced fluorescence lidar based on the gating theory is assemblied and presented, the system consists of a 266nm&355nm laser transmitter, a 15cm receiving telescope, a fluorescence spectrometer containing a intensified CCD (ICCD) detector, and some optical elements such as mirror and optical fibre. The backscattering signals excited by the laser were collected by the telescope, and then delivered to the fluorescence spectrometer by the optical fibre, the signals in spectrometer were diffracted by diffraction grating and focused to the ICCD detector. The ICCD detector can be time gated to accept only light with the right delay, thus suppressing ambient light. The fluorescence spectrometer which is a key component in fluorescence lidar is introduced in detail, including initial optical parameter calculation, design method, simulation result and spectral calibration.The spectral range and spectral resolution of fluorescence spectrometer is wide(290nm - 650nm) and high(1.6nm), avoiding high backscattering strength of the laser by notch filter, eliminating overlap spectrums of different diffracting orders by a special filter. Finally, the fluorescence lidar is used to collect fluorescence signals of several common oils and the test result is presented in the paper. The performance and reliability of the designed fluorescence spectrometer is stable and high, supplying a good path to build fluorescence database and carry out material identification research based on the fluorescence method.

9626-89, Session PTues

Light-sheet microscopy with high resolution: an optical design for an illumination system for oil immersion

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Light sheet microscopy denotes an illumination technique in microscopy, where the image field of the microscope is illuminated from the side, perpendicular to the direction of observation[1]. It is easy to implement for samples with water-immersion, as there are a lot of objective lenses available that can be used for illumination or for imaging. For oil-immersion, it is much more difficult to implement, as you need a long working distance for the illumination optics. Available optical systems either have a very short working distance (e.g. oil-immersion objective lenses from Zeiss, etc.), or generate a relatively thick light sheet (>4µm) for a homogeneous illumination of a large field of view (e.g. the Ultramicroscope from LaVision Biotec). However, there is a high-interest in imaging with oil immersion, as certain oil-like substances can make biological samples completely transparent, and this allows for anatomical investigations deep inside isolated intact organs or whole-mount samples.

In this paper we present our design of a light-sheet illumination optical system with a ~ 1µm illumination thickness, a long working distance through the immersion oil (~12mm), and with a zoom system allowing for moving the focus-spot of the light-sheet laterally through the field of view. This illumination optics enables the acquisition of fluorescence images in 3D with isotropic resolution of below 1 micrometer of whole-mount samples with a size of 1-2 mm diameter.

Technically, we designed the system by using cylindrical lenses for the generation of the light-sheet, and a spherical lens system for aberration correction, and for controlling the focus position of the light-sheet in the image field by using a focus-tunable lens. We were facing several challenges during the computational simulation: The typical characterization methods for aberrations are mostly applied for circular symmetrical systems. The conventional aberration analysis function implemented in Zemax, such as the Seidel's diagram and the Zernike coefficients, can not be applied directly to analyze the aberrations of a system of cylindrical lenses.

We solved these problems by changing the non-circular symmetrical components to circular symmetrical in Zemax. In this case we can use conventional aberration theories to analyze the system, and use the standard build-in optimization procedures. We then discuss the fidelity of this approximation: At the center of the focus line (the on-axis point), the simulation of such a modified system will predict identical results as a non-modified system. Apart from the center position of the focus line, other aberrations such as coma can broaden the focus line, and Petzval-curvature also bends the focus line. These aberrations can be predicted by our methods presented in the paper, by splitting the cylindrical surface into small regions in which the ray bending is the same as that of spherical surfaces. The circular lens approximation is a good description for the used 1mm center region of the focus line, as we have an almost collimated illumination of the cylindrical lens, with a ray divergence of below 0.2 degree.

[1] Dodt et al. Nat Methods, 2007. 4(4): p. 331-6.

9626-90, Session PTues

Opto-mechanical door locking system

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We present an Opto-Mech Door Lock which is a secure and simple optical system comprising a coherent light source and a photodiode sensor. The fundamentals of the Lock and Key mechanism (fixed patterns to unlock), have been modified such that the Key comprises a Laser module enclosed in a cylindrical enclosure that slides perfectly into the slot provided on the Lock. The laser is pulsed at a fixed encrypted frequency encoded specifically for that locking system using an Arduino Atmega 328. The casing of the Key is designed in such a way that the circuitry of the pulsed laser will only be powered when the Key is inserted properly into the Lock. The Lock includes a photo-sensor that will decrypt the signal by converting the detected pulses of light into its corresponding electrical signal. The Lock also includes a feedback system carrying the digital information regarding the decrypted frequency code. This information received from the decryption circuit is then compared with the stored information; if found to be a perfect match, a signal will be sent to the servo to unlock the mechanical lock or to carry out any other operation.

The proposed technique has lots of potential application in security systems for residential and safe houses and can easily replace the traditional locks which formerly used fixed patterns to unlock. This system can also be used to keep a log of the users entering the facility by encoding specific user information in the key. The major advantage of this proposed coherent light based opto-mechanical door lock (CLOD) over conventional ones is that it no longer relies on a hard imprinted pattern to perform its task thus making it impossible to tamper with.

9626-91, Session PTues

New technologies of optical instruments for small earth observation satellites

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Presently small optical remote sensing satellites are playing an important role in the Earth observation system, and the related technologies are greatly developed during the past twenty years. In this paper, several new technologies adopted in optical instruments of small remote sensing satellites are proposed to solve the problem that optical systems cannot fulfill the requirements of high resolution and wide swath at the same time due to strong constraints of small satellites in size and weight. These new technologies includes: freeform surfaces that can realize wide field imaging; long focal and wide-field-of-view optical system; optical metal mirror that can realize lightweight, compact size and athermal design; fined bands that can realize multi-spectral imaging; TDI-CMOS detector with large array, small pixel, low power consumption, high enviromental

adaptability and radiance resistance; high-precision radiometic calibration technology. And these new technologies adopted in optical instruments of small satellites will provide more and more useful remote sensing images for agriculture, forestry, disaster monitoring and forecasting.

9626-92, Session PTues

Imaging spectroscopic reflectometer based on pellicle beamsplitter

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Imaging spectroscopic reflectometry is a technique suitable for measurements of optical parameters(thickness, refraction index and index of extinction) of non-uniform thin films along their surface. It is usually assumed that gradients of these non-uniformities are reasonably small. In practise we can encounter thin films preparation technologies (e.g. the deposition by a single capillary plasma jets at atmospheric pressure) which produce non-uniform thin films with high gradients of non-uniformities in optical parameters. A new design of an imaging spectroscopic reflectometer provides the possibility to successfully measure such non-uniformities along relatively large areas of a thin films surface. The specialized low cost apparatus was developed to accomplish a higher resolution of surface imaging at the cost of reduction of spectral range usable. The whole concept of the imaging spectroscopic reflectometer was designed to achieve higher light throughput using only prefabricated optical components. This implies shorter measurement times and lower demands on an imaging camera used. The imaging spectroscopic reflectometer mentioned above was realised as a compact device with easy calibration and handling. Its calibration can be performed without need of any disassembling the instrument. Any monochromator with its output into an optical fibre can be used as a source of light. The potentialities of the device are demonstrated using samples with high gradients of thickness along their surfaces. The samples were prepared by the aforementioned plasma jet technology. The significant improvement in the resolution of thin films interference pattern images was observed in comparison with the same images obtained by means of an older self-made imaging spectroscopic reflectometer we utilized so far. On the other hand the necessary reduction of the spectral range did not limit the optical characterization of the films studied.

9626-93, Session PTues

Optical system for an ultra-high-speed framing camera without ghost images

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High-speed photography is an effective method for studying high-speed moving objects, but it differs fundamentally from ordinary photography because of its high time resolution, which facilitates the tracking and recording of rapidly changing processes. Thus, rapid changes in many physical, chemical, and biological processes can be analyzed by high-speed photography, such as vibrations, shells, flying spark discharges, explosions, and chemical reactions. Therefore, high-speed photography has a wide range of applications in fields such as physics, biology, and medicine.

Ultra-high-speed optical camera systems are the most commonly used types of high-speed photography equipment. However, the design of the optical systems employed in ultra-high-speed photoelectric framing cameras readily leads to the formation of a ghost image in the vicinity of the image plane due to the large surface and complex structure, which can affect the images sharpness and contrast, thereby interfering with target recognition. In order to address the problem of ghost images, we identified the key component responsible for ghost images, i.e., the image intensifier in the optical system, and we used a fiber optic panel to further optimize the design of the image intensifier, thereby overcoming the problem of ghost images, but also improving the image quality.

We conducted a high-voltage spark discharge experiment using a prototype developed by the Institute of Fluid Physics, CAEP. An image shows the presence of ghosts. The structure of the image intensifier in this system comprises a glass panel input window and a photocathode coated with metal film. When the light reaches the cathode surface, a considerable amount is reflected, which arrives at the photocathode repeatedly to generate multiple reflections in the glass panel input window, thereby forming a ghost image. Based on this analysis, we produced an optimal design for the image intensifier, where a fiber panel was used as the input window. The fiber panel comprised a large number of dense and fine light pipes, with an optical fiber based on the principle of total reflection to transport the optical image. The characteristics of the optical fiber ensured the independence of the light transmitted between each of the fibers, and thus the stray light phenomenon did not occur. Therefore, the fiber panel made of a large number of optical fiber optical did not produce stray light rays during the optical image transfer process, thereby avoiding ghost formation in an effective manner.

In a further experiment, a high-voltage spark discharge was captured by an ultra high-speed photoelectric framing camera that contained our optimized optical system and the experimental results demonstrate that the image obtained lacked ghosts. This system can be used in ultra-high speed photography experiments at the nanosecond time scale because the photographs obtained include no ghost images, which facilitates the accurate identification and interpretation of targets.

9626-94, Session PTues

Research and design for focusing device of secondary mirror

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The position of optical focal plane for a space remote sensing instrument will be changed in severe launching process and complex working thermal environments, which affects the imaging quality of the remote sensing instrument seriously. based on traditional R-C optical systems designed a new type of initiative thermal controlling focusing device, which was driver by the change of thermal according to the basic concepts of thermal expansion properties, the apparatus selectively adjusting the position of the secondary mirror to compensate for the amount of defocus, analysis the main factors of affecting the accuracy of focusing device, and using finite element analysis software for simulation data, while the device for the corresponding experimental verification according to the actual working environment .The results showed that the focusing device designed to meet the required displacement precision 0.001mm, shaking volume requirement 15".

9626-95, Session PTues

Polymer hybrid materials for planar optronic systems

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Polymer hybrid materials for planar optronic systems

Planar optronic systems made entirely from polymeric functional materials on polymeric foils are interesting architectures for monitoring and sensing applications. Key components in this regard are polymer hybrid materials with adjustable optical properties. These materials can then be processed into optical components such as waveguides for example by using embossing techniques. However, the resulting microstructures are often found to be vulnerable as even low mechanical or thermal stress quickly leads to a degradation of the microstructures accompanied by an often complete loss of function.

A good way to increase the thermal and mechanical stability of polymers is to connect the individual chains to a polymeric network. Various groups use a stable cladding with embossed grooves for the waveguide core material which is often a UV-curable epoxy resin [1, 2]. Swatowski et al. cast films for core, bottom and top cladding and pattern the waveguide structure by lithography or direct laser writing [3]. Our approach uses precursor polymers which carry thermally or photochemically reactive groups. Upon excitation these groups form reactive intermediates such as radicals or nitrenes which then insert into adjacent C-H-groups. If both

reactants originate from different polymer chains, these two chains are crosslinked with each other. The refractive index of the polymer can be adjusted by mixing in inorganic nanoparticles.

This material is then patterned by soft lithographic procedures and the waveguide structure are generated by a stamp [4, 5, 6]. A PDMS stamp is filled with our waveguide core material e.g. poly(methylmethacrylate) (PMMA), which is modified with a few molecular weight percent of our thermal cross-linker styrene sulfonylazide (SSAz) and hot embossed it onto a foil substrate e.g. PMMA. In this one-step hot embossing process polymer ridge waveguides are formed and crosslinked simultaneously. Due to the crosslinking by C-H-insertion into neighboring polymer it is possible to combine initially incompatible polymers for core and substrate foil. The stability of the waveguide structures is also increased substantially as already shown for DVD nanostructures [7].

We will describe the synthesis of the polymer hybrid materials and present the results of the thermal and mechanical stability tests as well as solvent resistance test for different crosslinking units attached to selected polymers. The process and the parameters of the hot embossing process will be presented along with the results of the waveguide analysis.

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9626-96, Session PTues

Effects of satellite platform's vibrations on the image quality of a remote sensing payload: system level design and challenges

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Image motion due to satellite platform vibrations often limits the resolution and performance of remote sensing payloads, especially for the missions with high resolution objectives. Vibration blurs the incoming energy and degrades the overall payload's ability to detect the target with proper quality. Effects of Linear and high frequency vibrations on the overall MTF are known exactly in closed form but the low frequency vibration effect is a random process and must be considered statistically. It should be considered in system level payload design to know whether or not the overall MTF is limited by the vibration blur radius. The maximum resolvable spatial frequency of the camera (and hence the minimum pixel size) may be limited by the vibration effects. Here we fully analyzed different vibration effects and have specified the allowable image motion. If the vibrations of satellite platform are more severe than the allowed quantity, a stabilization system method must be considered in the system level payload design procedure.

In this paper we have considered the effects of a single and double frequency harmonics of low frequency vibration on the Modulation Transfer Function. Because of its random effects, the majority of this paper deals with the statistical analysis of its blur radius to find the probability of taking images with a pre-defined MTF budget. Finally we proposed a trade-off analysis among the vibration MTF, effective F/#, relative exposure time (with respect to the vibration period), detector pixel size, and some mission requirements.

9626-97, Session PTues

Multi-wavelength laser system designed for material processing

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Many industrial applications require a different wavelength than the output from commercially available lasers. For example, most materials have higher absorptions at shorter wavelengths than the fundamental near-infrared output of typical solid-state lasers. Nonlinear optical devices, such as harmonic generators, provide the means of extending the spectral range of solid-state Nd-laser to the visible and ultraviolet spectrum. The multi-wavelength laser system includes an optional harmonic generation units, which enables easy switching of output wavelength.

The standard technique for frequency doubling uses a single nonlinear crystal located in the fundamental output beam of the pulsed Nd-laser. Selection of the output wavelength (fundamental or second harmonic) is usually performed by rotating the half-wave plate installed in front of the nonlinear crystal. Depending on the processed material, the wavelength can be switched between a wavelength of 1.06 ?m and a wavelength of 0.53 ?m.

It should be noted that switching wavelength leads to changing the parameters of the laser radiation, such as: the output pulse energy and spatial beam characteristics. In the present paper most attention has been concentrated on the beam characteristics of the fundamental and second-harmonic radiations at the workpiece surface.

From the theoretical treatment it follows that the second harmonic beam diameter inside the nonlinear crystal depends on the conversion efficiency and the beam diameter of the Gaussian-shaped fundamental radiation. The typical diameters of the second harmonic beam D2 are in the range of 0.7D1 to 1.0D1, where D1 and D2 are the diameter of the fundamental and the second harmonic beams, respectively. For high conversion efficiency (approaching 100%), the beam diameter of the second harmonic wave coincides with the diameter of the fundamental wave D2 = D1. For low conversion efficiencies (< 20%) D2 ≈ 0.7D1.

Theoretical and experimental investigations have shown that the fundamental and second harmonic beams are collinear and propagate coaxially through the optical elements of laser workstation. In a typical design, the laser beam is first expanded, to reduce divergence, and then it passes through a lens and is focused onto the workpiece. The second harmonic beam has a smaller diameter compared to a fundamental laser beam at any point along the optical axis of the laser system. Calculations have shown that the ratio of the diameters lies in the range of 0.7 to 0.5.

For the same set of optical elements, the frequency-doubling efficiency determines the relation between the beam sizes on the workpiece. The results obtained show that the diameter of the second harmonic beam focused on the workpiece surface is smaller than that of the fundamental radiation, the ratio is in the range of 1 to 0.7. Considering appropriate changes of the focused spot size and assuming frequency-doubling efficiency of 50-70%, we find that the fluence per pulse of the second harmonic radiation ranges from 0.5 to 1.4 of the fundamental radiation fluence at the workpiece surface. The Rayleigh range of the second harmonic beam is 2 times larger or equal than that of the fundamental beam with the same waist radius in case of high conversion efficiency, and in case of low conversion efficiency, respectively.

The considerations presented in this work are especially useful in the design of a multi-wavelength laser system.

9626-98, Session PTues

Maximum allowable low-frequency platform vibrations in high resolution satellite missions: challenges and look-up figures

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Performance of high resolution remote sensing payloads is often limited due to satellite platform vibrations. Effects of Linear and high frequency vibrations on the overall MTF are known exactly in closed form but the low frequency vibration effect is a random process and must be considered statistically. It should be considered in system level payload designing to know whether or not the overall MTF is limited by the vibration blur radius. Usually the vibration MTF budget is defined based on the mission requirements and the overall MTF limitations. With a good understanding of harmful vibration frequencies and amplitudes in the system preliminary design phase, their effects could be removed totally or partially. This procedure is cost effective and let designer to just eliminate the harmful vibrations and avoids over-designing.

In this paper we have analyzed the effects of low-frequency platform vibrations on the payload's modulation transfer function. We have used a statistical analysis to find the probability of imaging with a MTF greater or equal to a pre-defined budget for different missions. After some discussions on the worst and average cases, we have proposed some "look-up figures" which would help the remote sensing payload designers to avoid the vibration effects. Using these figures, designer can choose the electro-optical parameters in such a way, that vibration effects be less than its pre-defined budget. Furthermore, using the results, we can propose a damping profile based on which vibration frequencies and amplitudes must be eliminated to stabilize the payload system.

9626-99, Session PTues

Automation design of cemented doublet

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Systems of two cemented lenses are widely used in telescopes, as collimator's objective, as components in lens relay (inverting) systems in spyglasses and as components in more complicated systems. It is well known that cemented doublet has enough parameters to correct longitudinal chromatic aberration, spherical aberration and coma, but correction of all three aberrations is possible only with proper glass combination. Glass combination is also responsible for residual aberrations which are defined by higher order aberration. There are some methods for choosing glasses. One of them is glass selection using special tables based on the third aberration theory. This method is known as Slusarev's methodology and Trubko's tables. This methodology is based on lookup tables that allow calculating doublet radiuses by given value of third-order coma, spherical aberration and chromatic aberration by specific algorithm. Usually using this method designer can calculate the system. If the aberration correction is not good enough the process should be repeated with other glass combination. This calculation is automated in this work.

Algorithm and program for automated cemented doublet synthesis are presented in this paper. The input parameters for algorithm are desired values of third-order coma, spherical aberration and chromatic aberration of cemented doublet. The program calculates few pairs of optical glasses corresponding to specified value of chromatic aberration and then calculates radiuses of surfaces for each pair of glasses corresponding to specified third-order coma and spherical aberration.

The resulted third-order aberrations and real aberrations on the edge of the lens are calculated for obtained radiuses. Several doublets can be analyzed in result table and the chosen one can be imported into Zemax. The calculated cemented doublet parameters can be analyzed and optimized in optical system design software.

The program allows to make first step of optical system design fast and simple. It allows to design not only the system which is free of the third-order spherical aberration, coma and axial color, but obtain necessary value of aberration for compensation of aberrations in another part of optical system. Possibility to automatically choose optical glasses, which is influence to chromatic aberration correction and aberration correction in general, is especially important.

Examples of automatic calculation of cemented doublet and compensation of aberrations in another part of optical system are presented in the paper.

9626-100, Session PTues

Influence of aspherical surfaces description on aberration correction

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Aspherical surfaces are widely used in optical systems of various applications. Optical design tools (Zemax, CODE-V and others) offers different types of aspherical surfaces equations to be used in designs, but it is always a question how properly choose what coefficients and what number of coefficients should be used.

The usage of all possible variables or all possible aspherical coefficients as correction parameters during automatic correction of an optical system is not the best way to obtain good design result. Choosing of the optimal number of aspherical coefficients is a question of experience or many trials for inexperienced designer.

One of the ways for reasonable balancing of the aberration is usage of step-by-step correction. The first step is correction of the third-order aberrations. The second step is correction of the fifth-order aberrations and so on. It can be shown that conic constant affects only the third-order aberration. In particular, it can be clearly observed in mirror systems. When higher order aberrations are presented in optical system we should use aspherical equation with higher order coefficients.

It can be shown that with a special type of aspherical equation where the profile is described by dependence of the quadratic height from the z-sag each coefficient in that equation affects the only one aberration order. Unfortunately, such type of equation is rather rarely used in optical design tools. Special procedure can be developed for approximation of this equation to the common equation. The routine calculates aspherical coefficients for the most widely used type of an even asphere equation and finds a deviation of the initial surface from the approximated. Thus user can decide to use more coefficients or keep the number.

The presented routine helps to find the coefficients in aspherical equation that responsible for the each aberration order and helps to find out the optimal number of aspherical coefficients for correction during optimization.

Examples of aberration correction using different types of aspherical surfaces equations are presented in the paper.

9626-101, Session PTues

Analysis of ghost images in a compound prismatic combiner for head-up-displays

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Systems of augmented reality are widely used not only in military application but and in civil application. Providing a sufficient size for the pupil zone, which is the area where the user's eye could be located, may be implemented in different ways. One of the ways is using an objective with a large exit pupil. The other way is to multiply (duplicate) the pupil using a beam-splitting with special coating or elements, for example with semi-transparent layers. The last method is very attractive because it can provide the most compact schemes.

The compound prismatic combiner which uses waveguide principle is considered and analyzed in the work. It was shown in previous work that the angles of the entrance prism and layers should be chosen in certain limits to provide beam passing through the structure due to total internal reflection. Layers inside the combiner structure have special beam-splitting coatings. Beam is partially reflected by the layer and goes to the observer, the rest part of the beam goes through the layer and travels along the structure.

It can be shown that for each field angle the dark (blind) zones will appear. For the axial beam analytical expressions which define the dark zone size are obtained, for non-axial beam and for all field angles this property was demonstrated using modelling. For field beams situation may arise when the same field rays are reflected additionally by side faces and only after the additional reflection travel to the appropriate layer. Thus the ghost images may appear. Dark zones size and brightness of the ghosts are dependent on the combiner's parameters, so we can find optimal case as compromise between the dark zone size and ghost image. Different cases of layers angles and combiner thickness are considered in the work. Analysis of the ghosts brightness is implemented, and optimal locations of the observer's eye and optimal structure parameters are found from the point of view of minimizing ghosts for the system with the smallest blind zone sizes.

9626-102, Session PTues

Development and optimization of conversion and polarization optics in optical scheme of high-resolution fiber-fed echelle-spectrograph for the Large Azimuth Telescope

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The report describes the development and optimization of optical scheme of the pre-slit part of the spectrograph. This part provides separation of the beam into two beams by a polarimetric analyzer for polarimetric studies, and feeds these beams into two optical fibers which transfer the light from the pre-slit part to the spectrograph's slit.

The instrument is intended for a variety of astronomical programs from search for exoplanets to studies of stellar magnetism. Therefore it is necessary to organize different regimes of observations and different waveguide channels, including two polarimetric ones. All these channels are assembled in the suspended part and provide different regimes. Requirements to conversion and polarimetric optics are that the resultant image quality, efficiency and stability should be as high as possible.

The spectrograph consists of the transportable, suspended (pre-slit) part, fiber waveguide channel, and spectrograph, located stationary in a special room outside of the telescope. The pre-slit part is intended to be periodically installed at the primary focus of the 6-m telescope. This part provides formation of the beams and organizes all necessary services for different regimes of the spectrograph. The fiber channel consists of two individual waveguide channels of 53 m length to transport the light to the spectrograph's slit to be dispersed there by wavelengths and projected onto a CCD of large format. In contrast to slit spectrographs installed directly at telescopes, fiber-feed spectrographs can be installed out of the moving parts of the telescopes and be therefore highly stable.

The spectrograph should provide two basic regimes: spectropolarimetric, and traditional spectroscopy. For the spectropolarimetric regime was designed spectropolarimetric analyzer consisting of a beam-splitter and retarding phase-shifting plates (quarter-wave and half-wave plates). For the beam-splitter the Wollaston or Savarr plates. It was necessary to optimize the analyzer in order to work at F/30 exit beam (transformed from F/4 from the telescope). In the same time the system should be as simple and efficient as possible. The resultant two exit channels should completely be separated to have maximum diamteres 1.2 mm each.

After comparison of the two systems with two types of the beam-splitters was chosen the case with thin Wollaston plate. Despite the fact that this system gives weaker image quality, it provides much more efficient and simple design. Small angle between the separated beams ? = 0,517 ° compensated by a large trailing segment, which allows one to separate polarized beams at the required distance of 4 mm. Such a configuration allows the only optical scheme to operate in different modes. The analysis of each of the spot diagrams of the polarized beams for the final version of the system has shown that the original optical scheme does not require significant adjustments or revision. This is an important advantage. As well of the advantages is a small thickness of the polarizer, which provides minor light losses due to absorption and easy installation of all service optics in the converging beam. The main drawback of the system is chromatism that gives the spot diameter of about 1.7 mm. It is however partially neutralized by passing light through the fiber.

9626-103, Session PTues

Heat generation and thermo-mechanical effect modelling in longitudinally diode-pumped solid state lasers

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Thermal management in solid state laser is a challenge to the high power laser industry's ability to provide continued improvements in device and system performance. In this work an investigation of heat generation and thermo-mechanical effect in a high-power Nd:YAG and Yb:YAG cylindrical-type solid state laser pumped longitudinally with different power by fibre coupled laser diode is carried out by numerical simulation based on the finite element method (FEM). Impact of the dopant concentration on the power conversion efficiency is included in the simulation. The distribution of the temperature inside the lasing material is resolute according to the thermal conductivity. The thermo-mechanical effect is explored as a function of pump power in order to determine the maximum pumping power allowed to prevent the crystal's fracture. The presented simulations are in broad agreement with analytical solutions; provided that the boundary condition of the pump induced heat generation is accurately modelled.

9626-104, Session PTues

Design and optimization of some optical parts for a high resolution echelle-spectrograph at the 6-m Russian telescope BTA

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Design and optimization of some optical parts for a high resolution echelle-spectrograph at the 6-m Russian telescope BTA.

I present my update to the cross-disperser and projecting camera for a project of high-resolution echelle-spectrograph for the 6-m Russian telescope BTA. In original design of the instrument these two parts contained some weakness which made them to be expensive and difficult in construction. Due to these problems I simplify the cross-disperser toward classic grism with profiled diffraction groves and recalculate projecting camera. The new grism and camera should provide optimal distribution of echelle spectral orders projected on 60x60 mm CCD-matrix with distance between orders of 700 microns. Each of the orders is displaced by a polarimetric analyzer into two suborders which should be separated by 80 microns between each other. The resultant PSF spot size must be about 15x15 mm (the CCD's pixel size). The entrance diameter of the camera should not exceed 250 mm.

The work has been carried out to assess the capabilities of glass from catalogs of different companies. The evaluation criteria were the following: the absorption coefficient of glass in the working range of 400-750 nm; the refractive index and dispersion coefficient as parameters influencing the distance between the order of the spectrum; cost and manufacturability of the workpiece and the possibility of creating the grating on the material. The glass PBM2Y from Ohara has been finally chosen as material for grism. Refraction angle of about 40 ° and a diffraction grating frequency of 200 lines / mm were then determined. This allowed one to revise and improve the projecting camera. The red branch projecting camera of the spectrograph UVES was chosen as to be adopted to the working range of wavelengths. For this purpose the most suitable glasses with maximum transmission coefficient in the working wavelengths were chosen with characteristics similar to the original ones. As a result of optimization of the modified camera, the PSF characterizing 80% of the light energy within 15 microns are has been reached. This area corresponds to the CCD's pixel size of 15x15 microns. This discrete allows to achieve required spectral resolution R = 100 000. Vignetting was also reduced by changing the angle of the collimators and dimensioning input slits.

The new solution has been obtained with good result for the devices under discussion. The use of more transparent glasses has increased their efficiency. The grism provides light losses at 400 nm wavelength less than 4%. The camera's losses are not higher than 30% in the blue, and up to just 10% at 750 nm. Resultant vignetting is 5%. Total efficiency of the spectrograph is raised from 5.5% to 7.4% at 400 nm, and from 10% to 14% at 500-600 nm wavelengths. This result corresponds to the best examples of this type of spectrographs.

9626-105, Session PTues

Modeling of interferometer scheme for chirped fiber Bragg grating recording

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Fiber Bragg gratings (FBG) nowadays are used widely in different optical applications such are optical communication links, multiplexors, sensors, etc. Meantime, if FBG operate in a spectral range wider than 0,5 nm they should have a variable modulation period (chirping) of the order of decades of nanometers for the dispersion compensation. Recording of such a small structure on an optical fiber is a complex process. We consider a modified Talbot interferometer scheme with a special UV laser source, phase mask and a cylindrical lens (CL) for the chirped FBG recording. Computer modeling is necessary to find the chirping dependencies related to optical and geometrical parameters of the interferometer scheme and its elements.

The modeling was performed using Zemax software in the non-sequential mode. Optimal modeling parameters were found as a compromise between the computation speed and accuracy.

The interferometer model validity was evaluated for uniform FBG operating at wavelengths of 1300 and 1550 nm, certain UV laser sources, and mirror tilts. It was shown that the modeling accuracy did not exceed 10%.

Chirping dependencies were studied for the interferometer scheme with a positive CL (f '=50, 70, 100, and 500 mm) located on the symmetry axes of the interferometer that both beams pass it through or just in one of the ray path. CL were shifted in transversal and longitude directions. Position of the interference area was determined each time. The applied software did not allow calculating the period structures directly, so it may be performed manually only. To overcome it a special computer tool has been developed and applied to process the chirping dependencies from irradiance data obtained from Zemax modeling.

The modeling has shown that application of a short-focus positive CL (f '<100 mm) allows achieving the chirping from zero till hundreds of nanometers, whereas a long-focus CL gives a weak chirping. Considerable chirping may be distinguished if a CL is located in one of the interferometer paths. Combination of positive and negative CL in the interferometer scheme provides an expanded recording area.

9626-106, Session PTues

A study of modulation transfer function of digital image system via microscanning technique

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Normally, MTF works linearly with analogue detector like traditional film. Unfortunately, modern digital systems work discretely. Therefore, the measurement of MTF of digital systems willbe not valid because of obey of linearity so that we have to correct MTF for digital systems. Besides, inadequate sampling and different phases will introduce phase effects and aliasing effects respectively, which can distort the image distortion so as to fail to measure real modulation transfer function. In this paper, the application of micro-scanning experiment (Microscanning) will be employed to eliminate the aliasing effects for accurate measurement of real modulation transfer function of digital system. In this experiment,telecentricand non-telecentriclenses are used to observe the change of aliasing effect reduction on lens axis images and off-axis images via Microscanning technique in this experiment.

9626-107, Session PTues

Optical systems modeling of the laser and broadband light focusing for two channels of pump and probe scheme

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Two optical systems modeling of laser and broadband radiation focusing, that is necessary for realization of the pump and probe method, was carried out in this work. Modeling was utilized to construct experimental setup for transmission spectra measuring of studied sample by probe nanosecond broadband radiation (coumarin photoluminescence) depending on the intensity of the nanosecond laser pump pulses.

The particular attention was given to the optical system modeling of focusing of the probe broadband coumarin radiation.

It is necessary to realize focusing of broadband coumarin radiation (a rectangular shape source) for the probe beam formation. The source shape is determined by optical system peculiarities of setup probe channel. An additional restriction is imposed by the necessity of performing correlation between the size of the pump beam and probe beam, for which the pump beam should completely cover the probe beam. The decrease of the probe beam diameter and its transformation into an axisymmetric form allow to reduce the pump beam diameter several times, and hence to significantly increase its intensity. Therefore an anamorphic optical system that consists of a cylindrical lens forming an axially symmetric parallel beam and a positive lens focusing the radiation in a given spot diameter has been utilized.

Laser beam focusing has been realized in order to form the pump beam that required for the excitation of sample. Laser beam focusing is necessary to increase the intensity of the radiation exciting a sample. In this case a simple optical system consisting of a single biconvex lens was used.

Modeling allowed us to obtain the basic geometrical parameters that define the structural scheme of the experimental setup and the best image planes for the two channels have been determined.

Aberration analysis of the considered optical systems was not conducted because the scattering spot diameter was chosen as the main quality criterion.

9626-108, Session PTues

Parametric synthesis of optical systems composed of thin lenses by using the plane-parallel plate aberration properties

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The construction of the optical system based on the use of aberration properties of plane-parallel plate was reviewed. The aberration properties of the system built by adding to thin plano-convex lens a plane parallel plate located in the converging beam of rays are determined.

The third order coma aberration of image does not depend on the position of the entrance pupil when the spherical aberration is corrected. In the research optical system the center of the entrance pupil is located in front focus of the optical system, because in this case a plane-parallel plate doesn't add a coma aberration on the image formed by the lens.

Keeping the relative aperture and focal length of the optical system constant, aplanatic system was placed between the plano-convex lens and a plane-parallel plate. If aplanatic system is a system consisting of k aplanatic meniscus, we obtain an optical system, which is equivalent to a plano-convex lens.

We drew a circle specified radius with the center at the axis point of the paraxial image, located on a plane surface equivalent lens, the equivalent lens was divided into two. Discarding the second lens, we obtain an optical system with nearly perfectly spherical aberration correction. The focal length of the obtained system in n times more than focal length of the original system. To keep the image scale we can add to a single lens the aplanatic meniscus of the same material (with the same index of refraction).

Such optical system, whose design is simple, can be used in devices working in the infrared spectrum. Considered system can be supplemented plane-parallel plate of small thickness. Using the "sag" (angle alpha) of the lens and the thickness of the plate as the adjustable parameters we can achieve very advanced aplanatic correction of aberrations in a such system.

As a result of execute research, the possibility of constructing the optical system with an aplanatic correction of aberrations representing generally combination of the thin lens (base member) with an aplanatic meniscus and plane-parallel plate is shown.

9626-109, Session PTues

Analysis of the quality of the image formed by the zoom-lens optical system based on the use MATLAB and ZEMAX

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Theoretical foundations and mathematical formalism of parametric synthesis of zoom-lens optical system previously developed formed the basis for the development of software for the analysis of the quality of the image formed by the zoom-lens optical system. The software is built with the ability to import data using the dynamic data exchange between Zemax and MathLAB.

The initial data for work are: the range of change image magnification (or focal length), the design parameters of the optical system, the size of the field of view, the position of the aperture stop.All data except the range of the focal length change can be obtained from the description of the optical system formed by the software Zemax.

The possibility research multiconfiguration systems and individual configurations of the one system is implemented in this work. In the first case there is analysis of the image quality and change the settings for the whole range of magnifications, and the results are presented as the dependence of the characteristics of a linear magnification. In the case research of selected configurations the image quality analysis takes place at the same time for several configurations and the results for each configuration are presented at the same time on a graph or in a table. This is a great difference between developed software and Zemax and is very comfortable to compare multi configuration systems and several configurations of the one system.

Calculation of components parameters is carried regardless of the system configurations number. Calculated parameters are focal length, position of the principal planes of the components of the optical system, a linear magnification for the component without moving, etc. The function of the tracing rays calculation of the in Zemax is used for this calculation. However, the increase of the developed software functional and the addition of paraxial rays tracing calculation through the test optical system are possible.

The results of the software can be presented in a table or graph that shows the dependence of the image quality characteristics depending on the magnification or the focal length of zoom-lens optical system. This representation allows to make a quantitative analysis of the the optical zoom-lens system quality in the whole range of its focal length.

9626-110, Session PTues

Beam shaping of supercontinuum pulses

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A basic recipe for shaping spectrally and temporally partially coherent broadband pulsed fields like supercontinuum pulses is discussed. To shape these pulsed beams, shaping element designed using the optical map transform method is used [1]. The spatial profiles show a high quality flat-top region and the time integrated intensity profile is also of high quality flat-top shape. The spatiotemporal target field distribution is shown to bend, which is of practical importance in time-resolved experiments in ultrafast optics [2].

Spectrally broadband light pulses like supercontinuum pulses have gained many applications, for example in imaging, bio-medical science, telecommunication, etc [3,4]. Supercontinuum pulses are spatially highly coherent but spectral coherence swings between two extremes fully coherent and incoherent, which makes these pulses partially coherent [5]. Taking the spectral coherence as a parameter, the effect of beam shaping is observed in space-frequency and space-time domains. The beam shaping elements used in this study are designed by the map transform method for the central frequency of the spectrum. Both refractive free-form elements and diffractive beam shaping elements are discussed. For sufficient accuracy, an ensemble of some 1000's spectral domain electric fields E are taken, which correspond to individual simulated supercontinuum pulses. The coherent mode expansion technique [6] in space-frequency domain is used to describe supercontinuum coherent modes and their weights. For fully coherent case, only one coherent mode is enough to describe the whole quasicoherent part [6]. We assume that the beam is spatially fully coherent (which is very nearly the case for supercontinuum light generated in microstructured fibers [3,4]) profile is fully coherent and vary the spectral coherence. We study the effect of spectral coherence and its effect on temporal coherence. We show that a time integrating detector sees the same intensity for partially coherent shaped pulses as a frequency-integrating detector sees for stationary light. Hence, if time integrals are measured, the beam shaping element works in the same way for stationary and pulsed light.

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9626-111, Session PTues

Distortion definition and correction in off-axis systems

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Off-axis optical configurations are becoming more and more used in a variety of application, in particular they are the most preferred solution for cameras devoted to planetary and small solar system bodies (i.e. asteroids and comets) study. Off-axis designs, being devoid of central obstruction, are able to guarantee better PSF and MTF performance, and thus higher contrast imaging capabilities with respect to classical on-axis designs. In particular they are suitable for looking at extended targets with intrinsic low contrast features, or at scenes where a high dynamical signal range is present.

Classical distortion theory is able to well describe the performance of the on-axis systems, but it has to be adapted for the off-axis case.

A proper way to deal with off-axis distortion definition is thus needed together with dedicated techniques to accurately measure and then remove the distortion effects present in the acquired images.

In this paper, a review of the distortion definition for off-axis system will be given. In particular the method adopted by the authors to deal with the distortion related issues (definition, measure, removal) in some off-axis instruments will be described in detail.

9626-112, Session PTues

Objectives for a spectral optical coherent tomography with a diffractive optical element

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An optical coherent tomography (OCT) allows to scan in a depth of an object without a destruction. It has been carried out in an interferential microscope according to the scheme of academician V.P. Linnik by removing the mirror in a reference channel of the interferometer. However, a mechanical scanning is slowly. We'll be able to replace the mechanical scanning with spectral if we use a laser with a tunable wavelength and a special objective, which has a large longitudinal chromatic aberration in an object channel of the interferometer, in this scheme. Changing of a wavelength within a spectral range of radiation produces interference pictures of an equal chromatic order. This picture contains information about heterogeneity of an investigated environment. When we use the tunable laser, which radiates in the spectral range from 1260 to 1360 nm, we won't be able to create a lens objective with the large longitudinal chromatic aberration (1mm). Transparent in a visible spectral range optical glasses have an insufficient difference of coefficients of dispersion. It's the reason of impossibility to receive a necessary value of the longitudinal chromatic aberration. Glasses for an infrared region of spectrum can't be used in the microscope's an objective because they cut visible region of the spectrum. An adjustment and a quality control of an assembly are carried out visually.

So decision was made to replace the lens system with a single diffractive optical element (DOE). In this case, DOE was used for increasing of the longitudinal chromatic aberration and not for reduction of this one. The objective should create an instantaneous image of a monochromatic light in the necessary spectral range. Lateral images from additional wavelengths of the high-orders of diffraction will be absent, so a contrast of an image won't decrease. The single diffractive optical element can perfectly correct a spherical aberration. Unfortunately, DOE has a large value of a deviation from the condition of isoplanatism which won't be able to eliminate. Because a law of tangents have to be carried out for correction of the spherical aberration, but a coma will be correct if a law of cine is carried out. When the numerical aperture sin?'= 0,4 the deviation from the condition of isoplanatism is 9%, that is unacceptable.

To sum up, the objective for spectral optical coherent tomography should be created from a diffractive optical element and a lens part. This objectives and a method for their creation will be presented.

9626-113, Session PTues

Design of a cost-effective laser spot tracker

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The basis of guided systems consists of detection, decision making and controlled actuation. The sensitivity of the detection affects the whole system performance. Taking into account the price per unit, the most convenient detection in the sense of precision can be achieved with a laser spot tracker. This study deals with a military grade, high performance and cost-effective laser spot tracker for a guided system. Since the system to be designed is expected to be a military grade system there are many constraints regarding volume and cost. Also the environmental conditions which the system needs to endure is very strict. Some of these conditions are as follows; mechanical strength of the window, resistance to humidity and ability to operate at a wide range of temperature.

The aim is to develop a system with a field of view of ±15° that will detect proportionally at a distance of 3 kilometers from the target and give the line-of-sight angle of the target as an output, in which the target is designated with a 1064 nm wavelength Nd:YAG laser from 3 kilometers and where the field of view and detection range parameters are set as the design criteria of the study. The study basically consists of the system design, modeling and analyzing on a computer environment, producing and the conducting performance tests of the whole system.

The system consists of 3 optical components. A protective window is needed to isolate the system from environmental conditions as well as have enough mechanical integrity to endure a pressure caused by aerodynamic flow. A band-pass filter is required to narrow the spectrum of light entering the system in order to eliminate unwanted wavelengths, thus reducing the noise. Optics are also needed to focus the laser beam into a spot on the four quadrant detector. In order to reduce cost and increase reliability a single lens is required. However a single lens to perform a high accuracy focusing brings about the need for an aspheric lens. The final part of the system is a four quadrant detector which is the main component of all laser spot trackers.

ZEMAX is used for the base optical system design and modeling as well as thermal analysis and tolerance analysis. Matlab is used for radiometric calculations to aid the optical design in terms of range and power. The protective window is designed using aerodynamic flow inputs. The filter specifications are determined and produced accordingly. And the aspheric lens is designed according to the system requirements. However taking into account the cost of a custom lens, a lens which is most alike the designed lens is chosen and the system is optimized for this lens.

After the design is proved the system is assembled and tested using a pulsed laser diode collimator. The field of view angles are simulated as the detector output is analyzed. Finally the system performance is analyzed and compared to the system requirements.

9626-114, Session PTues

Comparison of optical design methods of freeform surfaces for imaging applications

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Optical systems based on freeform optical components offer many advantages over conventional systems in imaging applications, e.g. superior image quality, compact and lightweight designs. There are a few well established manufacturing method that can be used for the generation of freeform surfaces with low surface form error and low surface roughness, such as diamond turning, nickel plating and post-polishing. Metrology is evolving rapidly, although developments are still needed in order to verify the manufactured surface with the necessary accuracy. Optical design methods of freeform surfaces are also lagging behind, many algorithms address non-imaging applications, but in the field of imaging (image-forming) only a few exists and works with various limitations. We compare the available techniques in optical design of freeform surfaces for imaging and explore the advantages, disadvantages and boundary conditions of the different methods. We also intend to identify the most useful concepts and investigate how they can be embedded into commercially available optical design software.

9626-115, Session PTues

Three-component zoom systems for transformation of Gaussian laser beams

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Lasers are currently being widely used in numerous areas of science and engineering. In a variety of cases (e.g. cutting, welding, laser marking, laser micromachining, scanning and annealing of materials etc.), a smooth change in the parameters of a laser beam is required, which can be best achieved by using an optical system with continuously adjustable properties (e.g. focal length) – the zoom systems. It is widely recognized that a beam coming out of a laser is not homocentric but Gaussian and for its transformation by an optical system the equations that apply are different from those for the transformation of a homocentric beam by an optical system. Thus, it is not possible for the equations for computation of zoom systems for homocentric light beams to be valid for zoom systems for transformation of Gaussian beams.

The aim of the present contribution is to perform a theoretical analysis of paraxial properties of the three-element zoom systems for the

transformation of circular Gaussian beams. It is required from the optical system that the distance between a beam waist of the incoming Gaussian beam (object waist) and beam waist of the output Gaussian beam (image waist) do not change during the change of the magnification of the system. Relations enabling the computation of the paraxial parameters of a three-element zoom optical system are derived and applied on an example of a zoom optical system with continuously adjustable magnification. It is shown that the kinematics of the optical system for the transformation of a Gaussian beam differs from the kinematics of the optical system for the transformation of a classical beam and the application of classical zoom systems for the transformation of laser beams is thus not possible. With lasers generating Gaussian beams with different parameters, it would be necessary to design a special zoom system for each type of laser. However, practically it is possible to design a zoom system for Gaussian beams with specific parameters and the adjustment to another Gaussian beam is achieved by a suitable optical system. Using the derived equations it is possible to solve a number of other issues transforming the Gaussian beam such as beam expansion etc.

9626-116, Session PTues

Miniature the size of integrated sphere by three-lens design to measure the total light flux of wafer-level LED in a multichannel LED measuring system

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At each stage of the light emitting diode (LED) production, the use of measuring devices to measure the properties of the LED in electricity, radiometry, photometry and colorimetry is required. The method of measuring the LED luminous flux, for example, is to place the LED inside an integrating sphere, which is connected to a photodetector. Once the power is on and lights up the LED, the light emitted from the LED scatters uniformly all over the inner surface of the integrating sphere and the illuminance on the inner surface of the integrating sphere is detected by the photodetector in order to measure the total luminous flux of the LED.

When the LED production is still at its wafer stage prior to cutting the LEDs apart, a pair of test needles is used to transmit electricity to the electrodes of the LED chip as a means to light it up. However, due to the size of the LED wafer, the measuring process is conducted with the LED sitting outside the integrating sphere instead of within thereof. The light emitted by the LED, which resides outside the integrating sphere, enters the integrating sphere through an opening on the integrating sphere and a photodetector then intercepts the light, which has been uniformly scattered inside the integrating sphere, for calculation.

Due to the spatial distribution of the light emitted from LED, the further distance between the integrating sphere and the LED is, the opening on the integrating sphere needs to be bigger for flux measurement, and the bigger the integrating sphere is needed therefore. According to the design principle, the area of the opening on the integrating sphere shall be less than 5% of the inner surface of the integrating sphere. Therefore, the diameter of the integrating sphere currently adopted by industry for measuring the luminous flux of the LED at its wafer stage reaches 2 inches or larger.

There are several LED dies on one wafer when the LEDs production is at its wafer stage. Being able to measure multiple LEDs on the same wafer simultaneously can increase the measuring efficiency dramatically. However, the size of the integrating sphere is comparably large, thus making it impossible to place multiple integrating spheres above a wafer to measure several LEDs simultaneously. As a result, the efficiency of inspecting the optical properties of LEDs during wafer level is difficult to improve.

Because of the reasons just mentioned, our study was design a light collecting element for minimize the size of the integrating sphere, and we can achieve to measure several LEDs simultaneously.

In this study, we use two commercial optical software, one for three-lens design about collecting most energy, and the other one is for stray light analysis. We can minimize the size of the element by optical simulation and efficiency optimization. After design process, we have a prototype to validate this design.

9626-117, Session PTues

Optimization model for UDWDM-PON deployment based on physical restrictions and asymmetric user's clustering

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UDWDM PON is a leading technology oriented to provide ultra-high bandwidth to final users while profiting the physical channels' capability. One of the main drawbacks of UDWDM technique is the fact that, due to the close spectral proximity among channels, the non linear effects become stronger and more relevant in the data transmission as well as in the deployment optimization problem restrictions. On the other hand, the geographic distribution of users in a provided region is asymmetric in most cases. Traditional approaches for PON optimal deployment do not take into account fiber limitations as restrictions in the problem and do not take into account a differentiated user´s clustering. This work proposes a model for the optimal deployment of this type of networks taking into account the fiber length limitations imposed by physical restrictions in the fiber's data transmission as well the users' asymmetric distribution. The proposed model employs the data transmission related effects in UDWDM PON, mainly the Four Wave Mixing (FWM) effect, as restrictions in the optimization problem and also takes into account the user's asymmetric clusterization employing a k-means algorithm and the subdivision of the users region through a Voronoi's geometric partition technique.

Then, considering the fact that the Euclidean Minimum Spanning Tree (EMST) is a subset of the Delaunay Triangulation (which is the Voronoi's dual graph), and considering fact that a Delaunay Triangulation is a planar graph which connects the clusters' centroids, it is possible to evaluate the minimum weight of the fiber links as an heuristic problem which can be resolved in almost linear time: O(n log n).

9626-118, Session PTues

Effects of temperature variations on the performance of a space imaging system baffle

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All the star trackers must be composed of a baffle system to removes stray lights intensity. The baffle is designed to mount in front of the optical system. The performance of a star tracker is often limited by the stray light level on the detector. According to the space conditions, the baffle may deflect due to the temperature variation during the mission. Sun heat flux imposed to the baffle from one side and heat radiates from baffle to the space in all sides. In our case, the baffle is fixed to the satellite structure by four titanium screw. A finite element model has been used to modeling the baffle and temperature distribution and deflection is obtained in worst cold and hot conditions. Results show that in worst cold condition, baffle is deflected symmetrically whereas in hot case, deflection is not symmetric and the side exposed to the sun light is elongated. Using ray tracing methods along with Monte Carlo algorithm, the baffle efficiency is obtained and compared for both cases. Results show that baffle deflections is not so extreme to force us to cover it with the MLI.

9626-120, Session PTues

Speed correction of the inertial navigation system based on a novel vehicle-mounted laser Doppler velocimeter

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In order to improve the accuracy of the vehicle inertial navigation system (VINS), an idea of using a novel vehicle-mounted laser Doppler velocimeter to make speed correction for the navigation system was proposed. The measured true speed over ground was used to correct the parameter of velocity of VINS discontinuously. The basic principle of measuring the vehicle's speed with laser Doppler technique was expounded and the optical frame of the system was designed based on the technique of multipoint layer-type. The Doppler signal was processed by the technique of tracking filter and digital autocorrelation. Results of experiment showed that the background signal and some noises out of the passband were removed by a tracking filter, and the residual noise was restrained by a digital autocorrelator so that the signal-to-noise ratio and the detection sensibility of the system were greatly improved. The speed measurement accuracy of the vehicle-mounted laser Doppler velocimeter was good to 0.2% from 0 to 50m/s. After speed correction, the accuracy of VINS improved nearly 3 times. So it was available to put this kind of LDV in use for the inertial navigation system (INS). Future detailed attention to the optical system would enable three-dimensional velocity and faster motion to be measured.

9626-121, Session PTues

Research on multipoint layer-type laser Doppler self-velocimeter

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An idea of using multipoint layer-type laser Doppler self-velocimeter (LDV) to offer velocity for vehicle navigation system was proposed, because the accelerometer had the error term generated by overload. The principle of measuring its own velocity with laser Doppler was expounded while multipoint layer-type LDV was designed. And Doppler signal was processed with the technique of tracking filter and digital autocorrelation. The result of theory and experiment showed that: multipoint layer-type LDV solved the problem that dual-beam LDV can not measure the velocity while out of focus; background signal and part of noise in the passband were restrained by tracking filter, and residual noise was removed by digital autocorrelator so that the signal-to-noise and sensibility of the system was raised. Comparing with Global Position System (GPS), the relative accuracy of the system was about 2%.

9626-122, Session PTues

Lens auto-centering

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In a typical optical system, optical elements usually need to be precisely positioned and aligned to perform the correct optical function. This positioning and alignment involve securing the optical element in a holder or mount. Proper centering of an optical element with respect to the holder is a delicate operation that generally requires tight manufacturing tolerances or active alignment, resulting in costly optical assemblies. To optimize optical performance and minimize manufacturing cost, there is a need for a lens mounting method that could relax manufacturing tolerance, reduce assembly time and provide high centering accuracy.

This paper presents a patent pending lens mounting method developed at INO that can be compared to the drop-in technique for its simplicity while providing the level of accuracy close to that achievable with techniques using a centering machine (usually <5um). This innovative auto-centering method is based on the use of geometrical relationship between the lens diameter, the lens radius of curvature and the thread angle of the retaining ring. The auto-centering principle and centering test results performed on real optical assemblies are also presented.

In addition to the low assembly time, the high centering accuracy and the environmental robustness, the INO auto-centering method has the advantage to relax lens and barrel bore diameters as well as lens wedge tolerance. The use of this novel lens mounting method significantly reduces manufacturing and assembly costs for high performance optical systems. Large volume production would especially benefit from this advancement in precision lens mounting technique resulting in a drastic cost reduction.

9626-123, Session PTues

Athermal spectrometer optics of for space telescopes

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Space-borne astronomical telescopes have essential advantages on ground-based telescope in many points: space-borne telescopes are free from air turbulence and thermal background cause by the air, wide wavelength coverage, high stability, and so on. For the wide wavelength coverage, optics consisting of mirrors is often useful rather than lens optics. For realizing high stability optics, it is important to avoid influence of thermal deformation. Indeed, cryogenic instruments are popular for various space-borne telescopes. One of solution is athermal optics. We present optics made of fully aluminum. A collimating mirror in the optics is made of aluminum machining and its surface figure is parabolic. A focusing mirror is also made of aluminum but with free-formed surface figure. The free-formed surface is necessary to use wide area of a 2 D array detector and formed by fine controlled machining. Surface roughness of both mirrors is in the order of nm rms. The optical bench and mirror support structures are fabricated with same aluminum. Various spectral dispersion devices are able to install the collimated beam with 5 mm diameter in the optics. The optics are compact, light, and simple. These properties are suitable to apply to space-borne telescopes. A chamber for cryogenic tests are also presented. Whole the optics are able to be installed the chamber and cooled to 5 K by mechanical cryo-cooler. No cryogen (e.g., liquid Nitrogen, liquid Helium) is necessary. Performance stability of the optics through cooling from ambient temperature to 5 K is studied.

9626-124, Session PTues

Design and optimization of single grating x-ray differential phase contrast imaging system with free-form and micro-optics-channeled detector array

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A grating-based Talbot-Lau interferometer enables differential phase contrast imaging employing a low brilliance X-ray source. An absorption grating along with an extended source creates array of partially incoherent line sources. Each line source generates Talbot images of phase grating. An object distorts phase front or fringe of Talbot image and it is detected by another absorption grating. The modality has been actively researched in medical imaging community. Recently Such an X-ray phase imaging for aviation security becomes of interest because it measures index of refraction, along with absorption, that enables discriminating hazardous materials inside a luggage. A higher and polychromatic X-ray source is needed so that X-ray penetrates deeply into the luggage.

The imaging system is not achromatized, however used with a polychromatic source. Therefore, understanding how spectrum contributes to signal formation is crucial to maximize signal. First, we analyzed theoretical limit of performance of grating-based system by physical optics model. Interestingly, the optimum design energy that maximize signal contrast is relatively independent to X-ray photon

spectrum, and is about 40KeV. Whereas, the field-of-view (FOV) is severely limited by the high-aspect-ratio gratings which would prevent the technology from being used in field. The result suggests that a grating-less sources and detectors are ideal ones to utilize the higher X-ray photon while increasing the FOV. We designed a grating-less X-ray detector array with free-form micro optics having an extended depth-of-focus. The micro optics is jointly optimized with grating-less source. The grating-less design provides comparable signal level while not limiting the FOV.

9626-125, Session PTues

Analytical new method to generation of nonlinear optical pulses in wave guides and analysis of its stability

Antônio Carlos Amaro de Faria Júnior, Univ. Tecnológica Federal do Paraná (Brazil)

We have developed a analitical method based on the general theory of modulation Whitham [1] where the variational method is a particular case, to generate Optical Solitons. We show the equivalence of the solutions of the Nonlinear Schrödinger Equation (NLS) and the solutions derived from the method proposed here, demonstrating that these solutions lead to the Optical Solitons. We analyze the stability of these solutions and developed a new method to check the Optical Solitons of stability from the method proposed in this paper. We show that the Optical Solitons obtained from a Lagrangian density can propagate through a waveguide such as an optical fiber, and are equivalent to Solitons Opticos guided by an optical fiber generated by the NLS. To analyze the stability of system solutions we have expanded the Lagrangian density and from the expanded Lagrangian we obtain the system equations of motion and restrict the solutions that have oscillating behavior when disturbed. Thus obtain a self-value equation whose spectrum is positive indicating that the solutions with the characteristics of reproducing the NLS solutions are stable. This method can be used and implemented computationally for linear stability analysis of any optical system or any NLS solution. Another important aspect of our research has been the discovery of a relationship between the Lagrangian of optical system and the an optical pulse propagating through a waveguide. In theory, we can deform the Lagrangian (through an deformation to its kinetic term) to generate other solutions that behave like Optical Solitons propagating through Wave guides. Another important aspect of this relationship is the fact that the optical system Lagrangian describe the geometry of the waveguide and the interaction of light with its constituents. In the model we propose at work it is possible to establish a relationship between two different solutions of the NLS mapping solution into another solution of (1 + 1) dimensions (a temporal dimension and another space). We have demonstrated that this relationship is also obeyed by Optical Solitons in (1 + 1) dimensions. This relationship can have many applications such as mapping the characteristics of the interactions of a solution in another solution that presents a behavior opposite profile. We make a simulation in which the profile of the Optical Soliton beam propagation is mapped into another solution that does not presents the characteristics of an optical soliton, however, this mapping between the two solutions preserves the properties of both. Another feature of the method developed in this study is the possibility of description of Quantum Scatterings in waveguides such as optical fibers, from an solution from a appropriate Lagrangian describing an optical system. In this sense Quantum Scatterings as the Raman and Brillouin in waveguides could be treated by this method proposed in the work.

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9626-126, Session PTues

Nonlinear and non-Hermitian optical systems applied to the development of filters and optical sensors

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In this work we present a method of investigation of nonlinear optical beams generated of non-Hermitian optical systems [1]. This method can be applied in the development of optical filters and optical sensors to process, analyze and choose the passband of the propagation modes of an optical pulse from an non-Hermitian optical system. Non-Hermitian Optical Systems can be used to develop Optical Fiber sensors that suppress certain propagation modes of optical pulses that eventually behave as quantum noise. Such systems are described by the Nonlinar Schrödinger-like Equation with Parity-Time (PT) Symmetric Potential:

where ? is proportional to the electric field envelope and z is a scaled propagation distance. were investigated in 2008 [2]. V(x) and W(x) are the real and imaginary components of PT symmetric potential. There are optical fiber sensors that due to high laser intensity and frequency can produce quantum noise, such as Raman and Brillouin scattering. However, the optical fiber, for example, can be designed so that its geometry suppress certain propagation modes of the beam. We apply some results of non-Hermitian optical systems with PT symmetry to simulate optical lattice by a appropriate potential function, which among other applications, can naturally suppress certain propagation modes of an optical beam propagating through a waveguide. In other words, the optical system is modeled by a potential function in the Nonlinear Schrödinger-like Equation that one relates with the geometric aspects of the wave guides and the optical beam interacting with the waveguide material. The result are the quantized propagation modes that can be used in the design and development of waveguides where certain beam propagation modes can be suppressed. We present in this paper new models and new solutions of eq. (1) describing a particular optical system characterized by a beam propagating through a waveguide. We analyze the energy spectrum of new models investigated and prospect some applications of the method developed in this study to the development of optical filters based on the suppression of certain modes of propagation of the optical beam. We also analyze the development of optical fiber sensors based on optical pulses of high intensity and high frequency. A optical fiber sensor can be designed to select certain propagation modes of the optical beam, by bandwidth method presented in this paper. Therefore we present an application of a filter designed to choose the passband wavelength related to the geometrical aspects of the wave guide described by the potential function of Eq. (1).

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9626-127, Session PTues

Near-to-eye displays with embedded eye-tracking by bi-directional OLED microdisplay

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Near-to-eye (NTE) projection is the major approach to “Smart Glasses”, which have gained lot of traction during the last few years. Micro-displays based on organic light-emitting diodes (OLEDs) achieve high optical performance with excellent contrast ratio and large dynamic range at low power consumption, making them suitable for such application. In state-of-the-art applications the micro-display typically acts as a purely unidirectional output device. With the integration of an additional image sensor, the functionality of the micro-display can be extended to a bidirectional optical input/output device, aiming for implementation of eye-tracking capabilities in see-through (ST-)NTE applications to achieve gaze-based human-display-interaction.

9626-128, Session PTues

Optical design and stray light analysis for the JANUS camera of the JUICE space mission

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The JUICE (JUpiter ICy moons Explorer) satellite of the European Space Agency (ESA) is dedicated to the detailed study of Jupiter and its moons. Among the whole instrument suite, JANUS (Jovis, Amorum ac Natorum Undique Scrutator) is the camera system of JUICE designed for imaging at visible wavelengths. It will conduct an in-depth study of Ganymede, Callisto and Europa, and explore most of the Jovian system and Jupiter itself, performing, in the case of Ganymede, a global mapping of the satellite with a resolution of 400 m/px. The optical design chosen to meet the scientific goals of JANUS is a three mirror anastigmatic system in an off-axis configuration. To ensure that the achieved contrast is high enough to observe the features on the surface of the satellites, we also performed a preliminary stray light analysis of the telescope. We provide here a short description of the optical design and we present the procedure adopted to evaluate the stray-light expected during the mapping phase of the surface of Ganymede. We also use the results obtained from the first run of simulations to optimize the baffle design.

9626-38, Session 8

Design and fabrication of ultra-wide-angle lens with stitched aspheric surface *(Invited Paper)*

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A novel ultra-wide-angle lens is proposed and designed for obstruction-free panoramic imaging, which consists of a catadioptric objective and an embedded central lens. Unlike the traditional catadioptric lens with a mirror in the front of the system, the central view of this new panoramic imaging system is not blocked. Our design produces a field of view of 270° in elevation and 360° in azimuth without any blind angles. Furthermore, this kind of lens can be attached to a mobile phone by means of a small restructuring. A description method for a stitched aspheric surface is introduced and used in the design, and a MACRO is developed in CODE V. The surface is composed of several annular areas, but its sectional profile is a curve of continuous first-order derivative, which makes it easier to fabricate and test. By using this new stitched aspheric surface, the image performance of the ultra-wide-angle lens is balanced and improved.

9626-39, Session 8

Zoom lens design for projection optics

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The optical design of zoom lenses for projection applications is a task which has to take many different aspects into consideration. The optical designer has to achieve a demanding specification with respect to monochromatic and polychromatic aberrations across a significant magnification range.

Besides the requirements on image quality there are usually numerous constraints deriving from fixed mechanical interfaces that already have an impact in the very early design stages of the paraxial and monochromatic design.

It has been proven essential to also include cost targets in the figure of merit during the design work.

This paper will outline a systematic process for projection zoom lenses design.

A solid specification of the design task in terms of magnification range, image quality therein, mechanical and cost requirements is necessary as starting point.

Paraxial considerations are helpful to gain insight into the design problem and choose the appropriate zoom design type for further design work.

Intermediate designs, which are only monochromatically corrected, proofed invaluable while considering mechanical design requirements.

As soon the basic design requirements are fulfilled it makes sense to correct chromatic aberrations.

Outstanding color correction requires extensive use of expensive glasses for secondary color correction.

In order to find an ideal compromise between potential cost of an optical design and image quality achieved therewith, we employ tools to identify cost drivers as well as tools to simulate the perceived imaging performance.

Together these tools also enable us to efficiently discuss specifications that drive cost without aiding perceived image quality.

9626-40, Session 8

MEMS based retina scanner for mobile applications

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In the past few years there has been a growing interest in technologies for reliable authentication. This is especially true for mobile applications where some requirements can be very demanding. Among different biometric methods available the human retina is considered to be one of the most secure biometric identifiers. However, compared with other biometric features like fingerprints or the iris it is more difficult to get data of the retina for authentication purposes. This is due to the fact that the retina is an inner part of the eye. To image the vascular structure of the retina several special apparatus were developed in the past. One of them is the laser based retina scanner. These systems are strongly related to medical applications where such a device is known as a scanning laser ophthalmoscope (SLO).

However, the existing technology is not well suited for mobile applications. Most of the available systems are relatively large and sensitive instruments, not designed to be carried around. In order to address mobile applications in the future a small and robust device is needed.

Based on a MEMS scanning mirror developed at Fraunhofer IPMS a portable and robust retina scanner with an integrated projection system has been designed and built. The system consists of two lasers as light sources with beam shaping optics, the MEMS scanner, a custom designed eyepiece and a detector along with driving electronics. The full field of view is 30° x 30° which makes it possible to scan a retinal area from the center (macula) to the optic nerve. To obtain a good image contrast the scanning is done in the near infrared at 830 nm.

For the applications of interest additional requirements arise. Since the system is intended for use under different ambient light conditions it has been designed for a minimal eye pupil diameter of 1.7 mm, which corresponds to a situation in broad daylight. Furthermore, the free distance between the eye and the first lens of the retina scanner has been set to 40 mm so that persons wearing glasses do not have to take them off.

Due to the small size of the MEMS scanner the outline of the whole system could be kept very compact. The opto-mechanical setup measures 11 cm x 10 cm x 6 cm.

In order to provide the user with additional information and to reduce the eye's movements during scanning a laser projection system has been integrated. It works at a wavelength of 635 nm and can simultaneously project monochrome images onto the retina.

The system has been designed for a near diffraction limited performance

for the retina scanner as well as the projector. To this end the beam shaping optics and the eyepiece were optimized separately with commercially available optical design software. The demonstration system has been characterized and first images were made using standard USAF test charts. The results are in good agreement with the optical design data and show an adequate performance for mobile authentication purposes.

9626-41, Session 8

Curved detectors developments and their impact on optical system design

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The emergence of curved detectors, first proposed by Ko et al in their Nature paper, certainly represents the major disruptive technology for imaging systems that will come up in a near future. As explained by Rim et al or Dumas et al, such breakthrough devices have a very high potential impact on the performance of optical systems and their design, compactness and cost. The curvature of focal plane arrays leads to a drastic simplification of the optical systems by directly correcting the field curvature in the focal plane of wide field instruments, cameras, telescopes. It results in an increase of transmitted flux and a reduction of the exposure time by a significant factor. Less optics means less misalignments and instrumental errors, less integration and calibration time, less dependence to the environmental condition: the simpler the merrier. We present the work done so far in collaboration between the CEA-LETI and the CNRS/LAM on two main parts: the development of the devices and their performance, and the work done on optical design optimisation making use of these revolutionary components. We will first focus on the specific case of cameras and then open the discussion to (i) astronomical instrumentation, and (ii) the emergence of new optical functionalities offered by these flexible and versatile concepts.

9626-42, Session 8

Wide-angle lens miniaturization through foveated imaging

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In the recent years, there have been many improvements in optics miniaturization, including wide-angle lenses. As a result, they are now being integrated into various miniature systems such as endoscopic and inspection probes. The large amount of information that a wide-angle lens can collect in one capture, without the need for movement or high processing power, can be a great advantage over scanning techniques. However, the design of a miniature wide-angle lens (full field of view of 180°) is not a simple task, especially when the goal is to reduce its size even further. In order to correct aberrations that are issue from the large field of view, many lenses are necessary. Moreover, the amount of distortion is usually very high for those kinds of designs.

It has been reported that distortion can be used as a design parameter in order to control the local magnification of the image across the field of view. The local focal length, defined as the variation of the image height per degree, is a suitable tool that permits this control. Typically, the magnification will slowly decrease with the field of view, leading to a compressed image on the sides. A more aggressive control of the distortion can be used to enhance the quality of the information present at the center of the image at the expense of the sides. This usage of distortion leads to a foveated design. Since many applications using wide-angle lens don't need the same quality of information across the entire field of view, the design of a foveated wide-angle lens is a promising way to release some constraints, thus allowing greater miniaturization of the lens. By carefully adjusting the resolution across the field of view and focusing on the region in the center of the image, less care can be given to correcting defects issue from the edge of the field. This sort of compromise could, for example, allow a reduction of the number of lenses in the system.

The present paper explores the effect of the control of distortion toward foveated imaging on a wide angle lens. The goal is to assess its potential for allowing the simplification of the system. In order to achieve this objective, a miniature wide-angle lens is modified into different foveated designs, each of them with different targets. The starting design is a state of the art commercial miniature wide-angle lens (Thibault et al. "Design, Fabrication and Test of Miniature Plastic Panomorph Lenses with 180° Field of View," Classical Optics 2014, paper IM2A.3, 2014). The conditions in which the system can be reduced are then analyzed. Finally, the results and findings are discussed.

9626-43, Session 8

Dual-band infrared lenses design

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Problems of designing dual band lenses were considered. The main problem is color correction in two spectral bands simultaneously because of dispersion issues between two bands for all optical materials. For example, if we have Germanium – ZnSe, in LWIR we will have Germanium working as a crown, and ZnSe working as a flint. But in MWIR we will have ZnSe working as a crown, and Germanium working as a flint. Another challenge is designing the lens with a few optical elements as possible. Because of low transmission of most infrared material in MWIR and LWIR, we have to minimize number of elements to keep working f/number high. It results in complication of design dual band lenses compared with single-band lenses design.

Dual band lenses design methods using two and three optical materials were discussed. In case, when we use only two materials, we can have only approximate solution of axial chromatic equations. To have an accurate solution, we should use three optical materials. All two- and three- material combinations in MWIR and LWIR bands for most used materials have been investigated. F/number of single components in infrared lenses has limitation because of high f/number of an overall lens. In the agreement with this fact, we have provided a criterion for selection of good combinations. The most powerful component must have f/number less than 4, and other components f/numbers must be less than 2. In this case, we can split the most powerful component into two lenses.

The results of calculations were tabulated. Also, Seidel coefficient S4 was determined for all combinations. If we design a separate lens, we should pick combinations with the least value of S4. And if we design a lens, that will be a part of a complicate optical system, we can pick a combination with a huge S4 value to compensate image curvature of the rest parts of the system. Manufacturability of all material combinations has been analyzed, and the best combination was obtained. Various designs for the best combinations have been produced. It was designed for 50 mm aperture, f/number 2 and one degree angular field. Also, image quality and tolerance sensitivity analysis of these designs was made, so we also provided a criterion for selection of good designs for the same material combination.

9626-44, Session 8

A study of optical design of high ratio zoom optics with intermediate optics and liquid optics

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Recently, image quality is strongly demanded due to newly developed high quality optomechanics products. In past, the optical designer is almost working for the national defense so that new technologies are not able to reveal quickly. Thank to the semiconductor technology, the lens designer can work for the entertainment and medical instrument as well. Some kind of lens designs have been developed for astronomical telescope [1-2], mobile lens [3-4], pinhole camera [5-6] and medical endoscope [7], etc.; especially in optomechanics system. For the lens design, the first step is to build a lens layout with constant effective focal length (EFL) according to the different specification. The advantages are that the lens designer can effectively predict the image quality then make the best image quality during simulation. However, this kind of lens has a

limitation for catching the various sense images at the various distances, which complicate the zoom lens developments. The zoom lens is to design the multiple EFLs on a lens system to acquire the object images that the distance of object varies [8-9].

9626-45, Session 9

Lens-mount stability trade-off: a survey exemplified for DUV wafer inspection objective lenses *(Invited Paper)*

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The stability of optical elements is an essential part of the tolerance budget of an optical system and insofar an important constraint in the design of optical systems.

Exploiting the exact knowledge of lens-mount stability – to be more precise the stability of the lens within the mount – generally allows to avoid or minimize the number of compensators. This keeps system complexity and cost low, since it reduces the number of adjustment cycles, which are accompanied by additional measuring devices and time. Occasional actuators within the system might also be rendered dispensable.

For many mounting principles the stability benchmark is based on previous systems or information gathered by elaborated testing of complete optical systems.

While going to the limits of optical system design, these experiences are not sufficiently precise and tend to be not transferable when scaling of the optical elements is intended. Testing assembled optical systems alone does not give a direct link to the impact of single lens-mounts. This is inconvenient for a particular optimization of the mounting. In addition, measures intended to increase the, as usually understood, positional stability will often affect other optical properties in a not appreciated manner.

This contribution discusses the influences of different optical mounts concepts on the stability using the example of HNA / DUV inspection lenses. A method to investigate the positional stability is presented for selected mounting examples typical for inspection lenses.

9626-46, Session 9

The use of low departure aspheric surfaces in high quality wide angle lenses

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It is well known that an aspheric surface is preferred to a sphere in terms of aberration correction. A single aspheric surface can produce perfect geometric imagery for a monochromatic point source. Today aspheric optical designs are commonplace, many being mass produced by molding of glass or plastic. For smaller volumes, aspheric surfaces must be individually produced using single point diamond turning or sub-aperture grinding and polishing. These smaller volumes are often seen in high performance camera lenses such as those used in cinematography.

Two or more aspheric surfaces are often necessary when such lenses are used with modern digital cameras that have large arrays with small pixels, in order to address aperture and field dependent aberrations. To achieve the required levels of correction, these aspheric surfaces frequently have departures from best fit sphere of up to a few millimetres. Use of such surfaces are accompanied by a number of consequences; high cost metrology, very tight opto-mechanical tolerances and image artifacts due to the sub-aperture grinding and polishing process.

Designs with such high departure aspheres lead to a number of manufacturing, assembly, and quality challenges. Typical surface metrology requires use of computer generated holograms (CGH) with associated cost and penalty to schedule. There are several interferometers on the market that leverage different technologies to measure aspheres without the use of a CGH. Typically these interferometers can measure rotationally symmetric, non-reversing aspheres with departures of up to about 2000 waves. There are varying limitations which must be considered when designing aspheres to be tested using such interferometers. The shape, size, slope and departure of the asphere need consideration. In addition, there are limitations to the hardware of the interferometer including mechanical interferences, availability of transmission spheres and the resolution of the sensor.

These surfaces, depending on the location in the lens relative to the stop, require very accurate alignment and therefore tight tolerances. Residual surface structures left by sub-aperture grinding and polishing even at the hundredth of a wave level can give rise to unwanted artifacts in the internal structure of out-of-focus (bokeh) image areas.

Previous work examined the use of aspheric surfaces with departures of less than 15μm from best fit sphere concluded that advantages may be gained in standard, and telephoto lens designs, but was not successful when applied to wide angle lenses. In this work, the authors examine the problem related to wide angle lenses in more detail, and explore the potential benefits of low departure aspheric surfaces, as applied to wide angle lenses in particular.

We review the number, placement, and nature of aspheric surfaces in some in-house designs as well as some other well-known wide angle lens design forms, and look at the potential to re-design with an increased number of lower departures aspheric surfaces. Revised designs are examined from a performance, manufacturing and cost perspective, paying particular attention to testing, mechanical alignment tolerances, and out-of-focus image artifacts (Bokeh).

9626-47, Session 9

Design of deterministic diffusers for head-up-display applications

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Each pixel of a Head-up-display (HUD) screen should scatter incident light of an image into a certain angular spectrum (eyebox) to ensure that light from each screen position is reaching an observer located in a specified area. To realize high image contrasts and high efficiencies, typically a customized scattering lobe must be realized. Therefore the design of two different kinds of deterministic diffractive diffuser structures, namely diffractive optical elements and grating cells arrays are introduced. On the one hand grating cells arrays subdivide a HUD pixel into several cells by (virtual) apertures. Each cell locally deflects the incident light into a single angular direction. An array of different cell structures then finally realizes the required diffusion cone. On the other hand a HUD pixel which consists of a diffractive optical element can be used to scatter the incident light in all necessary directions at once. Mayor differences between the two approaches from the design, simulation accuracy and the application point of view are discussed in detail. Finally we show the practice-oriented design and fabrication process of a semi-transparent reflective HUD for white light.

9626-48, Session 9

Polarization sensitive detection of diffusely reflected circularly polarized light for optical diagnostics of biotissues

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Early detection of cancer is extremely important for the successful treatment. However, during early cancer onset it is quite difficult for clinicians and pathologists to differentiate between tissues that could be neoplastic versus normal tissue that is unlikely to become neoplastic. Currently, the gold standard and most widely used methodology for precise cancer diagnosis is histological analysis that utilizes exhaustive microscopy investigation. However, despite best laboratory practices the rate of conclusive diagnosis by histological analysis for a range of cancers, including cervical, prostate, bladder, skin and oral cancer, is only 65-75%. For example, only 70% of prostate cancer cases are detected during the

initial biopsy.

We introduce a development of optical setup for diagnostics of biological tissues by using circularly polarized light. In the experiment the vertical polarized light from a laser diode (LQC639-30C, Newport, USA, 639 nm, 30 mW) is directed towards the tissue sample at 55° from the normal. The light is then altered by a quarter wave plate into a state of right circular polarized and/or right elliptically polarized, and focused onto the sample by a lens. Incident circularly or elliptically polarized light is propagated through the medium and undergoes multiple scattering events before being collected by the detector. Diffusely backscattered light is collected at a distance d from the point of incidence and is then passed through a polarimeter to measure state of polarization. The source detector separation as well as the angle of detection can be varied to influence the sampling volume. To assess the optimal source-detector separation and angles of incidence and detection, the Monte Carlo code developed in house has been extensively used for the actual parameters of the experimental system.

Finally, multiple measurements were performed in a scanning approach on a human lung metastasis of thymic carcinoma embedded in paraffin wax. These samples had a variety of tissue structures present, including both healthy and cancerous tissue previously classified by the pathologist. To visualize and compare the polarization state of the detected radiation the Poincaré sphere was used. The cancerous and healthy tissue samples have shown that their scattered polarization states are clearly distinguishable from one another. It is noticeable that the polarization state of the backscattered light from the cancerous samples is located mostly on the upper regions of the northern hemisphere, while the healthy tissues correspond to lower latitudes. We believe that the proposed approach would enable the creation of a new tool helping the pathologists in their diagnostic decisions.

9626-49, Session 9

Hyper-hemispheric lens distortion model for 3D-imaging SPAD-array-based applications

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Simple omnidirectional panoramic lenses have the typical draw-back effect to obscure the frontal view, producing the classic "donut-shape" image in the focal plane. We realized an omnidirectional lens where the frontal field is make available to be imaged in the focal plane, by means of a frontal optics, together with the panoramic field, producing then a FoV of 360 deg in azimuth and 260 deg in elevation; it have then the capabilities of a fish eye plus those of a panoramic lens: we call it hyper-hemispheric lens. We built and test an all-spherical hyper-hemispheric lens. This all-spherical panoramic lens suffer for the typical issues of all very wide angle lenses: there is a large distortion at high view angles. The fundamental origin of the optical problems resides on the entrance pupil shift at large angle, where the paraxial approximation is not more valid: chief rays angles on the object side are not preserved passing through the optics preceding the aperture stop (fore-optics). This effect produce an anamorphic deformation on the focal plane, with the focal length changing along the elevation angles. Tracing the rays appropriately require some effort to the optical designer. It has to be noted here as both the anamorphism and image distortion are not source-point-aberrations: they are present also in well corrected optical lenses. Anamorphic distortion may be partially corrected using aspheric surface. We show here the way in which we correct for anamorphism our original all-spherical hyper-hemispheric lens by design an aspheric surface inside the optical train.

9626-50, Session 9

Handheld probes and galvanometer scanning for optical coherence tomography

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As part of the ongoing effort of the biomedical imaging community to move Optical Coherence Tomography (OCT) systems from the lab to the clinical environment and produce OCT systems appropriate for multiple types of investigations in a medical department, handheld probes equipped with different types of scanners need to be developed. These allow different areas of a patient's body to be investigated using OCT with the same system and even without changing the patient's position. This paper reviews first the state of the art regarding OCT handheld probes. Novel probes with a 1-D galvanometer-based scanner developed in our groups are presented. Their advantages and limitations are discussed. Aspects regarding the use of galvoscanners with regard to Micro-Electro-Mechanical Systems (MEMS) are pointed out, in relationship with our studies on optimal scanning functions of galvanometer devices in OCT. These scanning functions are discussed with regard to their main parameters: profile, theoretical duty cycle, scan frequency, and scan amplitude. The optical design of the galvoscanner and refractive optics combination in the probe head, optimized for various applications, is considered. Perspectives of the field are pointed out in the final part of the presentation. Selected references: [1] Duma V.-F.*, Rolland J. P., and Podoleanu A. Gh., Scanning in Optical Coherence Tomography: Review and Perspectives – submitted; [2] Demian D., Duma V.-F.*, Sinescu C., Negrutiu M. L., Cernat R., Topala F. I., Hutiu Gh., Bradu A., and Podoleanu A. Gh., Design and testing of prototype handheld scanning probes for optical coherence tomography, J. of Eng. in Medicine 228(8), 743-753 (2014). [3] Duma V.-F.*, Lee K.-S., Meemon P., and Rolland J. P., Experimental investigations of the scanning functions of galvanometer-based scanners with applications in OCT , Appl. Opt. 50(29), 5735-5749 (2011). [4] Duma V.-F., Optimal scanning function of a galvanometer scanner for an increased duty cycle, Opt. Eng. 49(10), 103001 (2010).

9626-51, Session 9

Electronic holographic device based on macro-pixel with local coherence

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Holography has been regarded as the most ideal technique for 3D display because it records and reconstructs both amplitude and phase of object wave simultaneously. Nevertheless, many people think that this technique is not suitable for commercialization due to some critical problems. First, it needs an enormous amount of data since holographic display uses interference phenomena with the modulator. In holographic display, the space-bandwidth product is proportional to the product of field of view (FOV) and screen size and there is a trade-off between them. Therefore, the amount of data is important for large FOV and screen size. Second, holographic displays are usually very complex and bulky and the size can be a practical problem for commercialization. Third, it has eye-safety problem resulting from using coherent light source such as lasers.

In this paper, we propose an electronic holographic 3D display based on macro-pixel with local coherence. Here, the incident wave within each macro-pixel is coherent but the wave in one macro-pixel is not mutually coherent with the wave in the other macro-pixel. This concept provides amazing freedom in distribution of the pixels in modulator. The relative distance between two macro-pixels doesn't change the interference pattern in observation space. Also it is possible to make the sub-pixels in a macro-pixel compact in order to enlarge the FOV. In other words, this idea is expected to reduce the amount of the data. In addition, the thickness of the system can be downsized since the coherence is required within the only small area. It means that we don't need large aperture lens for collimation of the incident wave. In our system, the micro lens will be assigned to each macro-pixel for collimation. If the collimation lens has a given numerical aperture, it is natural that its length decreases according as the diameter of the aperture decreases. Last, we expect that this design will be better from the point of view of eye-safety since the modulated wave doesn't have global coherence.

We planned our experiments by two steps. In phase 1, the initial device will be design with commercial liquid crystal (LC) panel as spatial light modulator (SLM) and additional micro-lens array is attached for control the coherence of the light source. For this experiment, the LC has eight-micron pixel-pitch and the distribution of the pixels is uniform. Therefore, it is improper for macro-pixel idea its pixel pitch is relatively big and diffraction angle is too small. But it is useful to confirm the feasibility of our idea. In phase 2, a chrome mask is used as the substitute of the modulator. Even though the chrome mask modulates the optical wave in binary amplitude, it has advantage to organize the distribution of the pixels as we want.

We think that the macro-pixel idea is a practical solution in electronic holography since it can provide reasonable FOV and large screen size with relatively small amount of data. In future, we plan to suggest an ideal structure of the modulator and realize it.

9626-52, Session 10

Spectrometry: photon sorting with the speed of light *(Invited Paper)*

Henri Vink, James Day, Jean Baptiste Volatier, TNO Science and Industry (Netherlands)

The field of spectrometry is a long-existing and ever-changing one. The application area extends from optical communication to, health- and environmental monitoring, possible extraterrestrial life detection and a long list of other topics. TNO is playing a leading role in several of these areas, always using state of the art designs and components.

In this talk an overview is given of the state of the art of several key components of a spectrometer:

telescope, slit, collimator, disperser and imager. Each of these functions is discussed taking into account the ever pushing progress in the manufacturing and design capabilities of the industry.

Examples of recent progress are the move from a two-mirror spherical telescope for (the pushbroom space-based daily global coverage spectroscopy instrument) OMI to a two-mirror freeform telescope for TROPOMI , and the design and manufacturing of super-gratings showing very little straylight. Other interesting design approaches which are covered are the use freeform mirrors in all reflective spectrometers and the use of deliberately decentered lenses for aberration correction.

Finally cross-over cases of lessons learned in one application to a different one are addressed.

9626-53, Session 10

Performance of silicon immersed gratings: measurement, analysis, and modelling

Michiel Rodenhuis, Tonny H. M. Coppens, Phillip P. Laubert, Paul J. J. Tol, Aaldert H. van Amerongen, SRON Netherlands Institute for Space Research (Netherlands)

The use of Immersed Gratings offers advantages for both space- and ground-based spectrographs. As diffraction takes place inside the high-index medium, the optical path difference and angular dispersion are boosted proportionally, thereby allowing a smaller grating area and a smaller spectrometer size. Short-wave infrared (SWIR) spectroscopy is used in space-based monitoring of greenhouse and pollution gases in the Earth atmosphere. On the extremely large telescopes currently under development, mid-infrared high-resolution spectrographs will, among other things, be used to characterize exo-planet atmospheres. At SRON Netherlands Institute for Space Research, we have designed and built immersed gratings for both space- and ground-based instruments, examples being the TROPOMI instrument for the European Space Agency Sentinel-5 precursor mission and the METIS (Mid-infrared E-ELT Imager and Spectrograph) instrument for the European Extremely Large Telescope.

The transparency of Silicon at infrared wavelengths means that production methods from the semiconductor industry can be applied to the fabrication of immersed gratings at these wavelengths. At SRON we have developed an immersed grating fabrication process whereby a Silicon wafer into which the grating pattern has been etched is directly bonded to a Silicon prism. The grating pattern is etched in the monocrystalline Silicon wafer using lithography. By aligning the facets of the V-shaped grooves with the crystal lattice, the shape and surface roughness of the grooves can be controlled very precisely. The angle at which the wafer has been cut with respect to the lattice orientation determines the blaze angle of the grating.

Three key parameters govern the performance of an immersed grating:

1) The wavefront error (WFE), which directly affects the optical quality of the science beam delivered to the detector. Typically, the requirement is to provide diffraction limited spectroscopy meaning the WFE must be kept to an absolute minimum. On immersed gratings, the WFE is a function not only of the tolerances on the prism and wafer polishing but also on the uniformity of the grating groove pattern. Thus, measuring the WFE yields information on the quality of the grating fabrication process.

2) Grating (polarized) efficiency, which is mainly controlled by optimizing the cross-section of the grooves. Both for ground-based astronomical low-light spectroscopy, and in space based remote sensing applications the efficiency must be maximized as the cost driving system size is governed by the throughput.. Measurement of the grating efficiency is therefor an essential validation of the design and fabrication of an immersed grating.

3) Scattered light, which originates from micro-roughness of the entrance and grating surfaces but also from small-scale errors on the groove positioning. Additional scattered light may be caused by chosting from spurious internal reflections, in particular from light diffracted into non-nominal grating orders. Again, characterization of the scattered light from the immersed grating through measurement of the bi-directional reflectance distribution function (BRDF) is an essential step in the verification of the grating performance.

In this paper we present the measurement of these key performance parameters of the immersed gratings we have developed in terms of the equipment and methods used and the results obtained. We also detail our efforts in developing a theoretical framework for describing these measurements.

9626-54, Session 10

Optical design and development of a monolithic, fully-integrated miniature spectrometer for injection moulding fabrication

Matthias Haupt, Ulrich H. P. Fischer-Hirchert, Mladen Joncic, Hochschule Harz (Germany)

Optical simulation software based on the ray tracing method offers easy and fast results in imaging optics. This method can also be applied in other fields of light propagation, e.g. nonimaging optics. In this paper a miniature spectrometer designed and developed by means of ray tracing will be discussed. Compared to the classical optical design, requirements for optimal design of this element differ particularly with regard to the spatial separation of the different wavelengths and the complete transmission of light to achieve the best signal-to-noise ratio.

The basis of the presented element is a Rowland spectrometer. But for the complete guidance of light that emerges the entrance split the design of this element has to be changed fundamentally, especially when a high numerical aperture of the light beam is taken into account. A monolithic approach is presented with a blazed grating based on an aspheric mirror to suppress most of the aberrations. The grating is analysed for different diffraction orders and the best possible efficiency. On the exit of this element the light must be guided into different photo diodes with different effective areas. In general, the element should be designed in a way that it can be produced with a mass production technology like injection moulding in order to offer a reasonable price. The paper will

describe the development of this miniature spectrometer step by step by means of ray tracing simulations.

9626-55, Session 10

Fluorescence imaging spectrometer optical design

Alessio Taiti, Peter M. Coppo, Enrico Battistelli, SELEX ES S.p.A. (Italy)

The optical design of the FLuORescence Imaging Spectrometer (FLORIS), studied for the Fluorescence Explorer (FLEX) mission, is discussed.

FLEX is candidate for ESA's 8th Earth Explorer opportunity mission. FLORIS is a pushbroom hyperspectral imager foreseen to be embarked on board of a medium size satellite, flying in tandem with Sentinel-3 in a Sun synchronous orbit at a height of about 815 km. FLORIS will observe the vegetation fluorescence and reflectance within a spectral range between 500 and 780 nm. Multi-frames acquisitions on matrix detectors during the satellite movement will allow the production of 2D Earth scene images in two different channels, called HR and LR, with spectral resolution of 0.3 and 2 nm respectively.

A common fore optics is foreseen to enhance by design the spatial co-registration between the two spectral channels, which have the same ground spatial sampling (300 m) and swath (147 km). An overlapped spectral range between the two channels is also introduced to simplify the spectral co-registration.

The ESA-funded phase A-B1 study has been devoted to demonstrating the system feasibility and a breadboard activity is on-going

Three cooled back-sided illuminated CCDs and a thermally stabilized optical bench are used to guarantee the required SNR and the stability accuracy (spectral and radiometric) between two consecutive on board calibrations. For absolute radiometric calibration a dedicated Lambertian diffuser, illuminated by the sun light, has been implemented, while spectral calibration is obtained by observing the atmospheric or the sun absorption lines (vicarious technique).

A compact opto-mechanical solution with all spherical and plane optical elements is proposed, and the most significant design rationales are described.

A dual Babinet scrambler is placed in front of the telescope in order to reduce the polarization degree of the incoming light inside the optical channels .A camera lens is used to image a ground scene onto a double slit. The radiation is then guided and dispersed onto the detectors by the two grating spectrometers (HR and LR), each consisting of a modified Offn?r configuration with unitary magnification, whose performances are improved by the addition of spherical lenses. The design approach foresees no aberration compensation between telescope and spectrometers.

Proper anti-reflection coating, surface roughness, contamination level and grating manufacturing process have been selected to reduce spatial and spectral stray-light, which have direct impact on the fluorescence measurement accuracy within the O2 absorption bands. The saw tooth profiles of the grating grooves allow to achieve high efficiency and low polarization sensitivity.

The operative spectral region is selected by a band pass filter, placed at the telescope level and obtained as a combination of a Low Pass and a High Pass dichroic. Out of band stray-light is mitigated by using two additional filters, one for each channel, coated on two folding mirrors that are part of the double slit assembly.

The developed design is robust, stable vs temperature, easy to align, showing very high optical quality along the whole field of view. The system gives also excellent correction for transverse chromatic aberration and distortions (keystone and smile).

9626-56, Session 10

ELOIS: an innovative spectrometer design using a free-form grating

Coralie De Clercq, Vincent Moreau, Jean-François Jamoye, Pierre Gloesener, Carlo Flebus, AMOS Ltd. (Belgium)

For hyperspectral applications, grating-based spectrometers are of special interest due to the high spectral resolution and optical throughput that can be achieved. The classical spectrometer designs are 1:1 systems. For these systems the achievable signal to noise ratio is limited by the slit width/pixel pitch combination. One way to increase the signal to noise ratio of a spectrometer without increasing the global instrument size is to design an instrument with a magnification power of less than one. With a smaller magnification, the entrance slit is wider and a larger amount of light is collected while the image is smaller and compatible with typical detector size and pixel pitch.

We presents an innovative spectrometer design with 2:1 magnification and high image quality and radiometric performances. This spectrometer called ELOIS (for Enhanced Light Offner Imaging Spectrometer) is designed with a grating atop a free-form surface. The use non-rotationally symetric surfaces offer additional freedom for designing compact and well-corrected instruments. Nevertheless, most of the available manufacturing techniques, such as direct ruling, holography, lithography or e-beam writing, are typically applicable on simple shape of the grating surface, such as flat or spherical surface.

AMOS demonstrated the feasibility of the Free Form Grating (FFG), i.e. a ruled grating on a surface without any rotational symmetry, using cost-effective approach for manufacturing blazed grating by Single Point Diamond Turning (SPDT).

9626-57, Session 10

Design of a MEMS scanning grating spectrometer for NIR applications integrated to mobile phones

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

Numerous NIR applications from food analysis e.g. quality parameter measurements to medical related like blood glucose measurements and many other more attract a broad attention. Future generations of mobile phones might serve this request, ideally by a spectral analysis system integrated into the device. Computation power, data access and easy to use software applications are already available. The miniaturized low cost multi-purpose NIR spectrometer is still missing. Much work has been invested to different approaches. MEMS scanning grating technology offers the advantage to work with a single detector element. Up to now miniaturization was intended to reduce the volume, recently 2.1 ccm which equals the volume of a sugar cube have been reached. Nevertheless to fit into a mobile phone device a flat device will be required. Thus the next design will be optimized for only 6 mm thickness. It will apply the same MEMS device used before including scanning grating with drive and position sensor as well as both slits. The optical bench will be optimized. Besides this the demand on the optical components of the spectrometer setup and the accuracy requirements for the assembly will be reduced. The electronics have been realized on a printed board, further miniaturization potential lies within chip scale integration of readout, drive and communication circuitry. The software has been transferred to an Android platform on a regular mobile phone and was demonstrated successfully.

9626-58, Session 11

Photon handling on femtosecond ultrafast beamlines *(Invited Paper)*

Luca Poletto, Fabio Frassetto, Paolo Miotti, IFN-CNR Padova (Italy)

The developments in laser technology over the last thirty years lead to the generation of laser pulses as short as few femtoseconds , providing a unique tool for high-resolution time-domain spectroscopy. While femtosecond optical lasers have offered unique insights into ultra-fast dynamics, the structural arrangement and motion of nuclei are not directly accessible from measured optical properties. This gap has been filled by the availability of femtosecond sources in the extreme-ultraviolet (XUV) and soft X-rays spectral region, such as high-order laser harmonics

(HHs) and free-electron lasers.

In my talk, I will discuss the main topics related to the optical design of table-top ultrafast beamlines with femtosecond or sub-femtosecond resolution for the generation and use of HHs. After the generation through laser-gas interaction, the photon beam has to be conditioned and handled. The talk will be focused on two main issues: 1) beam monochromatization and 2) beam focusing.

The available techniques to realize XUV ultrafast tunable monochromators using gratings will be discussed. The different available grating geometries and some practical realizations will be presented. The main issue to be faced when designing a monochromator is the preservation of the ultrashort duration of the pulse after the monochromatization. The different solutions adopted in some existing beamlines for HHs will be presented.

Furthermore, the problems related to the design of the focusing section of the XUV ultrafast beamline will be discussed. The effects of the focusing properties on the ultrashort duration of the pulse will be considered, namely the focal aberrations due to the optical design. The influence of the actual surface finishing of the mirrors on the temporal response of the beamline will be also discussed. Finally, some optical solutions for XUV ultrafast micro-focusing and results measured on existing beamlines will be discussed.

9626-59, Session 11

Positioning of Littrow mounted gratings in pulse compressors

Galina Kalinchenko, ELI Beamlines (Czech Republic); Stepan Vyhlidka, ELI Beamlines (Czech Republic) and Charles Univ. in Prague (Czech Republic); Daniel Kramer, ELI Beamlines (Czech Republic); Alexander Lerer, Southern Federal Univ. (Russian Federation); Bedrich Rus, ELI Beamlines (Czech Republic)

The development of chirped pulse amplification (CPA) lasers toward multi-PetaWatt power imposes more and more demands on all elements of a laser system. Grating pulse compressors are an imperative part of CPA lasers. In order to compress a several kilo-Joule pulse down to 10 - 30 femtosecond duration, all the compressor optics needs to be high-reflective over broad spectral band. To make the spectral band of compressor gratings wider, laser designers began to consider Littrow mounted grating setups. The problem of Littrow setup is that diffracted beam reflects straight back to the source. A good solution to avoid straight back reflection was found by scientists from Washington State University in 1993. In their stretcher, the reflections from the grating are at Littrow angle and disperse the beam in the horizontal plane with slight vertical deviation, so that the input and output beams are slightly displaced. The same technique was recently chosen by Vulcan 10 PW project designers for their compressor. They call it off-plane setup.

The main goal of our study is to find the optimal off-plane configuration. There are two ways to displace input and output beams at Littrow configuration. The first way is to turn the grating by a small angle about the axis perpendicular to grating grooves and parallel to the grating plane (the same way as it had been done in 1993), we call it pitch. The second way is to slightly rotate the grating grooves in the grating plane, we call it roll. Here we investigate and compare pitch and roll grating setups for diffraction gratings designed for s-polarized incident beam. All the simulations have been done by two methods: numerical Fourier Modal Method in LightTrans Virtual Lab and semi-analytical Volume Integral Equation Method.

As a start condition we consider a plane s-polarized wave (E vector is parallel to the grating grooves) hitting the grating at Littrow angle. For roll rotation the incident wave does not change polarization. The situation is more complicated for pitch tilt. This case can be considered as a change of start conditions: i) the incident wave here is acquiring some p polarization, and, as a consequence, the amplitude of electric vector for s polarization is getting smaller; ii) the angle of incidence is changing; iii) the polarization vector is gaining some roll angle. P-polarized light does not reflect into – 1 diffraction order as good, as s-polarized light. Though, we can consider p-polarized portion of light as an energy lost. This energy leak to p-polarization makes the main difference between roll and pitch configurations.

We found dependencies of diffraction efficiency on off-plane angle for roll and pitch tilts. The simulations were performed for binary metal coated and all-dielectric diffraction gratings. It is shown that the energy of laser pulse compressed by Littrow-roll configured gratings is 2 to 5% higher than for Littrow-pitch configured ones.

9626-60, Session 11

Optical design and performance of F-Theta lenses for high-power and high-precision applications

Vladimir Yurevich, Laser Ctr. (Russian Federation); Viacheslav A. Grimm, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Andrei Afonyushkin, Konstantin Yudin, Sergey G. Gorny, Laser Ctr. (Russian Federation)

F-Theta lenses are widely used in the remote laser processing. Nowadays a large arsenal of commercially available systems is offered. Nevertheless, optical design and processing performance basics remain poorly understood by regular users. Laser power scaling requires attention to thermally induced phenomena and ghost reflections. This considerably complicates optimization of the system in the optical configuration and primary aberration correction, even during preliminary design. Thus, accuracy of the system becomes dependent on the laser power.

Engineering and simulations show that the value of the combined parameter including field size, focused waist size and processing speed is virtually constant for a typical configuration of commercial F-Theta lenses. A number of the best of our systems demonstrate how this invariability violation in order to reach record performance by improving one of parameters worsens others. Caustic shapes formed by different F-Theta lenses in presence of residual design and thermally induced aberrations of variable strengths were experimentally studied. It was found that the focused beam shape distortion in presence of a sum wave aberration of few tenths of wavelength rms is sufficient for considerably altering the process performance. Experiments in remote laser cutting and 3D processing of thin-section metals, crystals and ceramics were conducted using the beams formed by F-Theta lenses with different magnitudes of design and thermally induced aberrations. It was revealed that in high-precision applications the material removal rate determining commercial processing speeds is inversely related to the rms magnitude of wave aberration introduced by all components of the system.

Experimental setup included F-Theta lenses with EFL ranging from 5.4 to 400 mm at 1064±20 nm. It resulted in processing beam diameters from 4 to 120 um with the Strehl ratio better than 0.95 (typically 0.97-1.0) over the square field ranging from 2x2 to 300x300 ??2. It allowed using these systems as aberration-free analogues in the case of low power. In a number of trials aberrations were introduced into F-Theta lenses by altering the orientation and airspacings of the components. Rms magnitudes of the introduced primary aberrations and thermally induced aberrations were defined on the ground of the Strehl ratio calculated as the ratio of the maximum waist intensity produced by the aberrated system to the maximum waist intensity produced by its diffraction-limited analogue. Thermally induced aberrations were evaluated by combining the heating and small-signal probe beams in the bulk of the lens. Beam caustics were measured by a beam analyzer. Commercial single mode QCW and Q-switched fiber lasers and Q-switched Nd-doped DPSSLs with average power ranging from 10 to 150 W were used as the laser machines. Scanning systems included high performance galvo motors and enhanced SiC mirrors. For the trials, the scanning programs were deliberately organized to maximally exclude formation of stationary thermal field in the lens.

Detailed simulations, measurement results and discussion concerning optical design and performance of F-Theta lenses for high-power and high-precision applications are presented.

9626-61, Session 11

Design and alignment methods of stretchers and compressors: key devices of high-power laser systems

Ivan V. Yakovlev, Institute of Applied Physics (Russian Federation) and N.I. Lobachevsky State Univ. of Nizhni Novgorod (Russian Federation)

Considerable progress has currently been attained in the creation of petawatt and multipetawatt laser systems. Their unique properties allow expecting breakthrough in fundamental science and astrophysics, power engineering and new technologies, biology and medicine, etc.

A large variety of ultrahigh-power lasers with femtosecond or picosecond pulse duration, laboratory-scale systems or "monsters" covering an area of hundreds of square meters, all these systems are based on the chirped pulse amplification (CPA) technique.

This technique based on amplification of pre-stretched in time ultra-short pulses allows reaching petawatt and even multipetawatt peak power laser pulses after compression. Due to CPA, the load on the optical elements of the laser system reduces significantly during amplification, which prevents unwanted nonlinear effects and decreases the probability of breakdown of optical materials.

Controlled stretching of ultra-short pulses and subsequent compression to their original duration occur, respectively, in the stretcher and compressor due to the dispersion of diffraction gratings used in these optical devices. Stretchers and compressors are the key elements of high-power CPA laser systems addressed in this presentation.

Quite a number of stretchers and compressors have been developed in the history of creating high-power laser systems. A wide variety of designs, original technical solutions, know-how and, finally, the elegance and beauty of these devices will be presented.

Even more diverse are methods of compressor alignment, as with power enhancement, the transverse size of the beams and, hence, the precision alignment requirements increase also. Incorrect adjustment of the compressor leads to residual phase dispersion in the laser pulse, reducing of the intensity contrast per pulse and appearance of pre-pulses that destroy the target before the arrival of the main pulse. There arises residual uncompensated angular dispersion (angular chirp), leading to pulse front tilt. This, in turn, results in a decrease of radiation intensity in the focus due to the increase of the effective pulse duration.

So, special attention will be paid to the methods of matching the dispersion characteristics of the stretcher and compressor, as well as to the accuracy and alignment methods of these devices.

Overview of modern high-power laser systems, problems associated with a limited size of diffraction gratings, as well as their resistance to laser radiation will be discussed as well.

Also, we will focus on the history of the development of the optics of ultra-short high-power pulses and creation of laser sources of such radiation.

9626-62, Session 12

Spaceborne lasers development for ALADIN instrument on board ADM-Aeolus ESA Mission *(Invited Paper)*

Alberto Cosentino, Alessandro D'Ottavi, Paolo Bravetti, Enrico Suetta, SELEX ES S.p.A. (Italy)

ALADIN TxA is the first worldwide All-Solid-State, Compact, UV-laser Transmitter Assembly for the novel spaceborne Doppler Wind Lidar, the ALADIN Instrument, which is the core of the ESA ADM-Aeolus mission.

The TxA optical architecture is that of a MOPA, medium energy, pulsed, frequency tripled, tunable, almost single transverse and single longitudinal mode Nd:YAG laser with 50 Hz PRF and a three years in-orbit lifetime.

A brief resume of the design, together with the qualification approach and the main performance results obtained by the two flight models are presented. The major technological challenges faced during the program development and the lessons learnt for future space All-Solid-State lasers will complete the paper.

9626-63, Session 12

Modeling of optical aberrations due to thermal deformation using finite element analysis and ray-tracing

Tobias Bonhoff, Lasse Büsing, RWTH Aachen Univ. (Germany); Jochen Stollenwerk, Peter Loosen, Fraunhofer-Institut für Lasertechnik (Germany) and RWTH Aachen Univ. (Germany)

Thermal lensing in optical systems for laser beam guiding and shaping can lead to a significant focal shift and a degradation of the focal beam distribution. Especially when utilizing multi-kW lasers with a high brilliance, thermal effects have to be taken into account to achieve a stable process. Moreover, the quality of an in process monitoring might be diminished by thermally induced aberrations.

Absorption of laser energy in the bulk material and the coating leads to an inhomogeneous heating of the optical components and causes a locally varying refractive index. In addition, surface deformations and thickness variations due to thermal expansion influence the optical behavior. A compensation of these thermo-optical effects requires a precise modeling. Since commercially available ray-tracing software such as ZEMAX® can only model homogeneous temperature variations, combining the advantages of Finite Element Analysis (FEA) and ray-tracing is reasonable.

In previous publications, an interface between the FEM software ANSYS® and ZEMAX has been presented. The thermal analysis is performed in ANSYS and the discrete temperature data are approximated into a continuous function, which is implemented into the optical simulation to evaluate the local change in refractive index. To take full advantage of this feature, it is extended to model the thermally induced surface deformation and change in thickness. In dependence on the lens curvature, the mounting and the thermal load, the lens does not only expand in axial but also in radial direction. For a precise modeling, also the radial deformation has to be taken into account. The ray-tracing requires a continuously differentiable function for the surface sag. Thus, based on the nodal displacement from the FEA and the unaffected surface sag, an effective axial displacement is calculated and approximated using even polynomials. These polynomials are added as an additional sag to the surface in ZEMAX which can be spherical, conical or aspherical.

This enhanced feature enables a precise thermal analysis of various applications. Besides high power applications such as laser cutting or Selective Laser Melting, it is feasible for low power applications where plastic lenses are used. Compared to optical glass, plastic features a 100 times larger thermal expansion and a high absorption so that thermal expansion cannot be neglected. A first simulation reveals that plastic lenses already show severe aberrations for optical powers below 5 W whereas comparable aberrations occur for optical glass in the range of several 100 W.

9626-64, Session 12

Modular optical design for flexible beam shaping of a top-hat profile

Ulrike Fuchs, asphericon GmbH (Germany)

An increasing number of applications, for example laser material processing, ask for top-hat intensity distributions. Even focusing leads to smaller spot sizes when the incoming beam has a top-hat instead of a Gaussian beam profile. Since most laser source offer a beam profile, which is close to Gaussian, a common beam shaping design task is to create a top-hat distribution out of this. This can be done in two ways, either employing diffractive optical elements (DOE) or refractive optical elements. Unfortunately, the first kind is very sensitive to changes in wavelength and variation of the entrance beam distribution. Refractive optical beam shaping elements on the other hand are much less sensitive and can be described as aspheric surfaces. All the same, matching beam diameters from the source used for the beam shaping element is mandatory, whereby a high wavefront quality is required as well.

Nevertheless, researches and customers have found various limitations when using standard systems, e.g. Galilei telescopes. Some of them are complicated in adjustment and limited to very small diameters for the incoming beam (1/e?). Additionally, one often would like to have a system that can be adapted to the wavelength used without varying the magnification.

A monolithic beam shaping solution, which is based on the usage of only one aspheric component, will be presented. To ensure a matching incoming beam diameter the aspheric beam shaping elements are compatible to our monolithic beam expansion systems, which are designed for four basic wavelengths (532, 632, 780 1064nm) and allow for a remarkable input aperture of up to 14.7mm. If various magnification levels (1.5x, 1.75x, 2.0x) are combined with each other in a cascade, one can achieve 230 possible overall enlargements, which ensures an optimal adaption. Above that, experimental data on the performance of cascades with up to five monolithic elements with diffraction-limited wavefronts will be shown. This high level performance is the foundation for the successful combination with beam shaping elements. Additionally, a fiber collimation package is presented, which allows for plug and play perfection and, when used with a standard single mode fiber, for a high repeatability in alignment accuracy and outgoing beam diameter.

Overall, we will present an optical design analysis for the refractive aspheric beam shaping element with respect to sensitivity in wavelength changes and varying input beam profiles and diameters. Thereby, the main focus lies on the feasibility of the aspheric shape. Thus, only surface shapes that can be manufacture either by diamond turning or grinding and polishing processes are taking into account during optical design process. This analysis will be concluded with an outlook on experimental results of its performance and sensitivity behavior. For later one, the dependency on wavelength changes is of main interest. Nevertheless, an analysis of the generated beam profiles for changing incoming beam profiles will be presented as well.

9626-65, Session 12

A miniaturized laser illumination module

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A miniaturized laser illumination module

A.T. Winzer, J. Freitag, P. Dannberg, M. Hintz, J. M. Schädel, H.-J. Freitag

We present the design and the first experimental results for a miniaturized laser illumination module fabricated on wafer level. For the first time, a mass production capable technology produces miniaturized laser modules for narrow and high quality laser beams for macroscopic sensing applications. The module has dimensions of 700 µm x 700 µm x 1.4 mm and forms a light spot of 300 µm in diameter at 30 mm distance. This corresponds to a divergence angle of about 1°. The light output is linearly polarized in a plane 45° inclined to the module edge. We manufactured modules with emission wavelengths of 670 and 850 nm.

Our newly developed manufacturing process is based on glass wafer technology with up to 20'000 modules per wafer. One side of the wafers will be functionalized optically and on the other side opto-electronicallym, i.e. it carries the light source and its electrical contacts. Glass as a wafer material has the advantages of being mechanically stable up to high temperatures, it is can be coated, possesses a very high planarity and precise thickness. The wafer side for the electrical contacts is coated by a gold based thin film metal system which is lithographically patterned with µm resolution. A high laser beam quality and a precise focus are achieved by an UV polymer molding process on the optics side of the wafer. The polymer material used is stable at metal soldering temperatures and thus compatible with the following technological steps. Lenses and spacer layers are positioned by a mask aligner to the metallisation pattern on the adjacent wafer side. This ensures good centering to the optical axis for the finished modules. We use vertical surface emitting laser diodes (VCSEL) as light sources. They provide good initial beam quality with a stable power output and a linear polarization. The VCSEL chips are flip chip bonded onto the patterned metal side soldering by a state of the art automated die bonder. Visual alignment and feature detection allow for good centering in this process. Before dicing into individual modules, each unit is tested for beam quality and polarization in an automated process to ensure quality and traceability of the modules. We show particular design and technology considerations against defocusing and decentering due to inevitable production tolerances.

Due to the stable output of polarized light, one application of the module are miniaturized polarimeters for measuring the concentration of carbohydrates in chemical or biological solutions, like the blood sugar level in the body or the concentration of fermentation products in biogas plants. Another application is a polarized reflectance sensor for measuring the thickness and the refractive index of dielectric coatings. This sensor may be integrated into coating machines for automated quality testing or automated process adjustment.

9626-66, Session 13

Pupil imaging space based lidar design

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The design concept for a 1.5 meter diameter dual wavelength LIDAR system is presented. The pupil imaging design has a 1.5 meter pupil diameter and a 200 micron detector. The F/10 Cassegrain front end is followed by a reflective aft-optic assembly and two F/1 refractive lenses for final imaging. This design incorporates some unique features such as a bore sight monitor that does not steal light from the science detector, a wedged dichroic beam splitter and a clam-shell Mersenne relay for quick magnification in a short distance. Model layout, performance details, material selection, and estimated mass and volume will be discussed.

9626-67, Session 13

Opto-mechanical design of the MTG FCI spectral separation assembly

Francois Riguet, Emmanuel Brousse, Jean-Louis Carel, Justine Cottenye, David Harmann, Marc Joncour, Houssine Makhlouf, Daniel Mouricaud, Meihdi Oussalah, Jacques F. Rodolfo, REOSC (France)

The Spectral Separation Assembly (SSA) is a key component of the Flexible Combined imager (FCI), an instrument that will be onboard Meteosat Third Generation (MTG). It splits the input beam coming from the telescope into five spectral groups, for a total of 16 channels, from 0.4 to 13.3 µm. It comprises a set of four dichroics separators followed by four collimating optics for the infrared spectral groups, which feed the cold imaging optics. The visible spectral group is directly imaged on a detector.

This paper will present the optical design of the assembly, the mechanical mounting of the optical components, and the coatings developed for the dichroics, mirrors and the lenses.

The various technical challenges of this system will be tackled, from the tight packaging constraints to the required high levels of transmission, as well as the implementation of specific adjustment and compensating devices. The demanding wavefront error specification is also one of the main characteristics, with levels as low as lambda/50 for some channels. Moreover, the various optical materials used on several spectral ranges leaded to the design of 22 different types of coatings, from dichroics to mirrors, along with anti-reflective coatings.

To assess the overall performances, REOSC had to accomplish a complete set of simulations, including the impact of thermal gradients on WFE and line of sight, stray-light using the BSDF of each component as well as ghost images due to the residual reflectivity of lenses, or the tolerancing of the coating stacks to predict the final transmission.

9626-68, Session 13

Ring-field TMA for PRISMA: theory, optical design, and performance measurements

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PRISMA (PRecursore IperSpettrale della Missione Applicativa) Hyperspectral Payload is an Electro-Optical instrument developed in Selex ES for the dedicated ASI (Italian Space Agency) mission for Earth observation. The instrument is composed of a high spectral resolution spectrometer optically integrated with a medium resolution panchromatic camera fed by common path fore-optics.

The performance requirements for this mission in terms of Signal-to-Noise Ratio and optical resolution are stringent and have led to an optical instrument design that is based on a reflective, un-obscured fore-optic telescope, consisting of a Ring-Field Three Mirror Anastigmat (Ring-Field TMA), a two channel prism dispersion based spectrometer (VNIR and SWIR), and a Panchromatic Camera. To limit the overall envelope, a common optical bench accommodates the Ring-Field TMA on the upper side and the spectrometer with its entrance slit and the panchromatic camera on the opposite side. The image plane of the Ring-Field TMA is coupled to the spectrometer entrance slit via two folding mirrors arranged in an "Optical Trombone" configuration.

The Ring-Field TMA contains three mirrors (two conics and one conic with some higher order correction). Exceptional performance has been achieved in this Ring-Field TMA by not only introducing 3rd order astigmatism to balance the 5th astigmatism at the ring field zone as is traditional in an Offner-type design but, additionally, 3rd order coma has been controlled to align the balance of the linear and field cubic coma terms at the same ring field zone.

Full-field displays were used based in field dependent Zernike polynomials to guide the alignment of the ring zones for the dominant aberration fields. The predicted wavefront performance of the Ring-Field TMA design over the field of view of the instrumentation will be highlighted. The analysis demonstrates that the optical design of the Ring-Field TMA is excellent for this application. The telescope delivers excellent image quality across the corrected ring zone that is wide enough to accommodate the rectangular format spectrometer slit along the instrument field of view.

An assembly and alignment procedure for the Ring-Field TMA has been developed from the results of the sensitivity and tolerances analysis. The tilt and decenter sensitivity of the design form is nearly exclusively determined by 3rd order binodal astigmatism and therefore the sensitivity analysis is based on quantifying the response of the astigmatic nodal sensitivity as a function of perturbation. The nodal position is linear with perturbation, which greatly simplifies the decisions on alignment compensators. Based on this procedure, the manufactured mirrors of the Ring-Field TMA have been aligned at Selex ES and as will be reported the preliminary results in terms of optical quality are in good agreement with the predicted as-built performance, both on-axis and in the field.

9626-69, Session 14

Integrated modeling for NASA's WFIRST Mission

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NASA's WFIRST mission includes science goals for exoplanet exploration, dark energy research and galactic and extragalactic surveys. This paper describes the optical modeling portion of the current observatory-level integrated modeling effort, which couples the telescope with the science instrumentation and models performance changes due to structural-thermal-optical effects, as well as flight dynamics.

9626-70, Session 14

Optical alignment of the SPICE EUV imaging spectrometer

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SPICE is a high resolution imaging spectrometer operating at extreme ultraviolet wavelengths, 70.4 – 79.0 nm and 97.3 - 104.9 nm. It is a facility instrument on the ESA Solar Orbiter mission. SPICE will address the key science goals of Solar Orbiter by providing the quantitative knowledge of the physical state and composition of the plasmas in the solar atmosphere, in particular investigating the source regions of outflows and ejection processes which link the solar surface and corona to the heliosphere. By observing the intensities of selected spectral lines and line profiles, SPICE will derive temperature, density, flow and composition information for the plasmas in the temperature range from 10,000 K to 10MK.

The optical components of the instrument consist of an off axis parabolic mirror mounted on a mechanism with a scan range of 8 arc minutes. This allows the rastering of an image of the spectrometer slit, which is interchangeable defining the instrument resolution, on the sky. A concave toroidal variable line space grating disperses, magnifies, and re-images incident radiation onto a pair of photocathode coated microchannel plate image intensifiers, coupled to active pixel sensors.

For the instrument to meet the scientific and engineering objectives these components must be tightly aligned with each other and the mechanical interface to the spacecraft. This alignment must be maintained throughout the environmental exposure of the instrument to vibration and thermal cycling seen during launch, and as the spacecraft orbits around the sun. The built alignment is achieved through a mixture of dimensional metrology, autocollimation, interferometry and imaging tests. This paper shall discuss the requirements and the methods of optical alignment.

9626-72, Session 14

Recent developments in the design and verification of crystalline polarization scramblers for space applications

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Monitoring the composition of the Earth's atmosphere for technical and scientific purposes is a major goal of space observation satellites which embark spectro-imagers. With the improving accuracy of space borne instruments, excellent radiometric accuracies are required. Unfortunately, the response of the spectro-imager varies with the polarization state of the incoming beam, because of polarization sensitivity of the grating, mirror coatings, etc. As the incoming polarization state is impossible to predict beforehand, depolarization of the incoming beam is needed to obtain the required radiometric accuracies.

Depolarization is achieved by using a so-called polarization scrambler in a dual Babinet arrangement. Dual Babinet polarization scramblers have the advantage of using crystalline materials. These materials are intrinsically transparent over extended wavelength ranges, from the UV to the IR, a requirement for today's spectro-imagers. As a Dual Babinet polarization scrambler creates a multiple spot pattern, depolarization is achieved at the expense of the imaging quality of the spectro-imager. Thus, depolarization is in essence limited by the acceptable image quality degradation.

The design of a polarization scrambler requires the ability to perform fast calculations of the performances, in order to scan the space of available solutions and perform tolerancing. Commonly available software (e.g. Matlab, Code V, ...) do have the ability to compute such performances, but are too slow for such purposes. Computation times of the order of 1 second for each Müller matrix are common. Performances to be

computed also require a fine wavelength sampling, of the order of 0.1 nm. As a consequence, computing the full performances of just one design requires a sizeable amount of time. Monte Carlo simulations are intractable .

Because interpreted code, as used by Matlab, is slower than compiled code, Sodern has developed software means to compute Müller matrices in the order of the millisecond, which is fast enough to perform Monte-Carlo simulations with thousands of configurations in just a few hours.

Verification of the performances is another challenge. Required performances such as polarization sensitivity and relative spectral accuracy are routinely in the 0.1% range. This is particularly challenging for relative spectral accuracy.

A specific bench has been built for verification of the performances. Its design is based on the synchronous detection of a reference path and of the measurement path. This design has been selected for its intrinsic high signal to noise ratio. All radiometric error sources must still be identified so that they are either eliminated through the design of the test bench or accounted for by calibration. Radiometric error sources include partial polarization of the beam caused by the monochromator, beam size difference between the reference path and the measurement path, partial coherence effects, etc.

9626-73, Session 14

Very high stability systems: LMJ target alignment system and MTG imager test setup

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Most of space instruments and research facilities require test equipment with demanding opto-mechanical stability. In some specific cases, when the stability performance directly drives the final performance of the scientific mission and when feasibility is questionable, specific methods must be implemented for the associated technical risk management. In present paper, we will present our heritage in terms of methodology, design, test and the associated results for two specific systems : the SOPAC-POS(1) and the MOTA(2), generating new references for future developments. From a performance point of view, we will emphasis on following key parameters : design symmetry, thermal load management, and material and structural choices. From a method point of view the difficulties arise first during design from the strong coupling between the thermal, mechanical and optical performance models and then during testing from the difficulty of conceiving test setup having appropriate performance level. We will present how these limitations have been overcome.

SOPAC-POS(1) is the target alignment system of the LMJ, Laser Mega Joule, the French inertial confinement fusion research center. The stability requirement directly comes from the inertial fusion principle itself, which requires a very accurate positioning of the Deuterium-Tritium target with respect to the laser beams in order to obtain the energy concentration required for the fusion to occur. The SOPAC-POS stability is consequently a key contributor. The SOPAC-POS is based on 6 custom tele-microscopes mounted on the LMJ spherical vacuum chamber (internal diameter : 10m). These 6 systems are imaging the shadow of the target at the center of vacuum vessel, from several points of view, enabling to define its position with multilateration algorithms. In present paper we will present the main design choice, theoretical simulations and specific qualification activities which have enable to demonstrate by test the system performance in 2014 after 10 years of research and development activities, achieving 1µm stability @ 6m during hour periods.

MOTA(2) is an Optical Ground Support Equipment aiming at qualifying by tests the Flexible Combined Imager (FCI). FCI is an instrument for the meteorological satellite MTG-I, a programme of and funded by the European Space Agency and under prime contractorship of Thales Alenia Space. MOTA stability is required by the MTF measurement process based on Knife Edge Function (KEF) measurements, which requires a high line of sight stability during the displacement of the knife edge. The presented design will allow to get better than 0.2 µrad stability for hour periods despite important thermal load generated by the optical sources (QTH lamps and hot black bodies). Such a stability is expected thanks to an opto mechanical and thermal design, optimized to operate under vacuum conditions.

9626-74, Session 14

Design and analysis of an active optics system for a 4-m telescope mirror combining hydraulic and pneumatic supports

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AMOS has developed a hybrid active optics system that combines hydraulic and pneumatic properties of actuators to support a 4-m primary mirror. The mirror is intended to be used in the Daniel K. Inouye Solar Telescope (DKIST, formerly the Advanced Technology Solar Telescope) that will be installed by the National Solar Observatory (NSO) atop the Haleakala volcano in Hawaii. The mirror support design is driven by the needs of (1) minimizing the support-induced mirror distortions under telescope operating conditions, (2) shaping the mirror surface to the desired profile, and (3) providing a high stiffness against the wind loads. In order to fulfill these requirements, AMOS proposes an innovative design that consists of 118 axial actuators and 24 lateral actuators. The axial support is based on coupled hydraulic and pneumatic actuators. The hydraulic part is a passive system whose main function is to support the mirror weight while offering a high stiffness against wind loads. The pneumatic part is actively controlled so as to compensate for low-order pupil aberrations (mainly astigmatism, coma, 3rd-order spherical, trefoil and quatrefoil) that are generated by the mirror support itself or by any other elements in the telescope optical chain. The lateral actuators have only a pneumatic part whose supporting force is continuously adjusted to compensate for the mirror lateral weight.

The performances of the support and its adequacy with the requirements are assessed with the support of a comprehensive analysis loop involving finite-element, thermal and optical modellings. In particular, the active corrections of the mirror surface are directly incorporated in the mirror finite-element model. These analyses result in reliable support performances predictions that take into account realistic operational scenarii. Critical contributions that impact the mirror support performances are identified. They arise from (1) the nominal support print-through (i.e. the results of the optimization of the location of the support points), (2) the deviations of the mirror dimensions from nominal values, (3) the mirror mount errors that are generated during the integration of the axial and lateral supports, (4) the environmental parameters (i.e. temperature, gravity and wind) and (5) the performance of the active optics control system. Except for the latter contribution that is related to the intrinsic performance of the active optics control system, all the other contributions can be (at least partially) corrected by the active optics system. When including all these contributions in the analysis loop, the expected mirror deformations are computed and expressed in terms of RMS Surface Figure Error. The active optics correction forces that are necessary to maintain the predicted mirror SFE are evaluated, and the ability of the actuators to correct for low-order aberrations is provided.

9626-75, Session 15

Wavefront curvature sensing in a 2.5m wide-field telescope: design, analysis, and implementation for real-time correction of telescope alignment

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In the framework of the design and manufacturing of a wide-field 2.5m telescope for the Observatorio Astrofisica de Javalambre (OAJ), AMOS has developed a novel wavefront sensing system that allows for real time correction of the alignment of the telescope without perturbing the acquisition of science images. The system is based on the wavefront

curvature sensing (WCS) technique in which the wavefront of the telescope is reconstructed from the measurement of the intensity of two out-of-focus images of a star. The WCS system takes advantages of the zones in the focal plane that are not covered by the science detectors. Four pairs of adjacent detectors are installed in these areas: one detector lies at +1 mm from the science focal plane and the other one at -1 mm. Four pairs of out-of-focus images are therefore available for reconstructing the telescope wavefront error. The nominal wavefront error is computed right after telescope final alignment such that any deviations from these initial performances are tracked and corrective actions can be implemented (e.g. M2 hexapod motions) so as to optimize the telescope optical quality.

The wavefront reconstruction technique and the associated corrections of the telescope alignment have been modelled and analyzed so as to validate the proposed approach before its implementation in the telescope. To this aim, a bespoke coupled Zemax-Matlab model has been developed by AMOS. The model allows to (1) simulate the acquisition of out-of-focus images, (2) reconstruct the telescope wavefront error from the images, (3) compute the corrective motions to be implemented in the telescope and (4) assess the efficiency of the corrections of the telescope alignment. In particular, the implementation of the algorithm for the wavefront error reconstruction is described and validated by comparison with wavefront error maps that are obtained with other methods. The justification of the wavefront sensing approach, its robustness against several sources of errors, as well as the selection of the appropriate equipment for its implementation in the telescope are discussed on the basis of this combined model.

9626-76, Session 15

VNIR, MWIR, and LWIR source assemblies for optical quality testing and spectro-radiometric calibration of earth observation satellites

Eric Compain, Philippe Maquet, Pierrick Leblay, Eric Gavaud, Julien Marque, Wilfried Glastre, Maxime Corteze, Pierre Sugranes, Stephanie Gaillac, Hervé Potheau, Bertin Technologies (France)

This document presents several original OGSEs, Optical Ground Support Equipment, specifically designed and realized for the optical testing and calibration of earth observation satellites operating in a large spectral band from 0.4µm to 14.7µm. This work has been mainly supported by recent development dedicated to MTG, Meteosat Third Generation, a programme of and funded by the European Space Agency and under prime contractorship of Thales Alenia Space dedicated to the next generation of meteorological satellites. The improved measurement capabilities of this new satellite generation has generated new challenging requirements for the associated optical test equipment. These improvements, based on design and component innovation will be illustrated for the MOTA, the GICS and the DEA OGSEs. MOTA and GICS are dedicated to the AIT, Assembly Integration and Test, of FCI, the Flexible Combined Imager of the imaging satellite MTG-I. DEA OGSE is dedicated to the AIT of the DEA, Detection Electronics Assembly, which is part of IRS instrument, an IR sounder mounted on MTG-S satellite.

From an architectural point of view, the presented original designs enable to run many optical tests with a single system thanks to a limited configuration effort. Main measurement capabilities are optical quality testing (MTF based mainly on KEF measurement), Line of Sight (LoS) stability measurement, straylight analyses, VNIR-MWIR-LWIR focal plane array co-registration, and broadband large dynamic spectro-radiometric calibration. In order to fulfill these measurements capabilities with the required level of performance, following improvements have been implemented: (1) source selection is optimized to cover the high dynamic of earth radiances, it uses specific integrating spheres with multiple QTH lamps for the VNIR, and water or LN2 cooled blackbodies for the MWIR and LWIR to obtain IR apparent temperature in the 200K – 520K range; (2) optimized optical sources and system design enable to obtain radiance uniformity up to 99% and temporal instability <0.2% in VNIR, MWIR and LWIR to enable state of the art MTF measurement; (3) MWIR and LWIR high definition target plates are implemented in a dedicated architecture that enables to overcome intrinsic high emissivity material limitations in terms of spatial definition, the presented architectures have typically 1-5µm resolution capabilities together with higher than 0.95 apparent emissivity; (4) Improved 2D translation stages, with very high regularities features (<100nm @ 2?) have been optimized for demanding KEF measurements; (5) new radiometric standard transfer procedure have been developed for long term, operational, satellite calibration in representative vacuum and thermal environment. This procedure results in a very limited calibration uncertainty degradation with respect to national metrology institutes capabilities, offering satellite optimum measuring accuracy.

Depending on the AIT phase of the satellite, these source assemblies are operated at atmospheric pressure or under secondary vacuum. In operation, they are associated with an opto-mechanical projection system that enables to conjugate the image of the source assembly with the focal plane of the satellite instruments. These conjugation systems are usually based on high resolution, broadband collimator, and are optionally mounted on hexapod to address the entire field of the instruments.

9626-77, Session 15

ATLID receiving spatial and spectral filtering units: design and associated performances

Pierrick Leblay, Maxime Vaché, Diego de Saint Seine, Bertin Technologies (France); Julien Archer, Philippe Berlioz, Airbus Defence and Space (France); Eric Compain, Bertin Technologies (France)

ATLID is one of the key instrument of EARTHCARE, a program of and funded by the European Space Agency and under prime contractorship of Airbus Defence and Space. ATLID is dedicated to the understanding of aerosol and clouds contribution to earth climate. It is an atmospheric LIDAR that measures the emitted 355nm ultraviolet laser which is backscattered by the atmosphere. The molecules and the particles have different optical signature and can consequently be distinguished thanks to polarization analyses and spectral filtering of the backscattered signal. The following optical units of ATLID receiver chain directly contribute to this function : After ATLID afocal telescope, the CAS-OA, the Optical Assembly of the Co Alignment Sensor, sample and image the beam on the CAS sensor in order to optimize the alignment of transmitting and receiving telescopes. Then, the beam goes through the BF, the Blocking Filter which has two filtering function: (1) spatial with the BF-ORE, which is a Kepler afocal spatial filtering module that defines the instrument field of view and block the background and straylight out of the useful field of view; (2) spectral with the BF-EFO, the Entrance Filtering Optic, which is a very narrow band filter with a high rejection factor. It is this filter that enable to distinguished narrow backscatter signal from particles from broad backscattered signal from air molecules. The BF-EFO also adjust the orientation of the linear polarization of the input beam. After filtering and polarization adjustment, the beam is injected in several optical fibers and transported to the instrument detectors. This last transport function is done by the FCA, the Fiber Coupler Assembly.

This paper will present the flight models of the previously described units, detail the opto-mechanical design, and review the main achieved performances with a focus on following main specific characteristics:

(1) the spectral filtering capabilities of the BF-EFO, <0.70 nm (FWHM), transmission >0.90, rejection < 10-4 over [320–420] nm;

(2) the line of sight stability of the BF-ORE <50 µrad in a very compact design;

(3) the test setup implemented to limit BF-ORE magnification uncertainty < 0.1%;

(4) the UV laser induced contamination control plan, with end of life contamination level requirements < 1mg/m? for molecular and 50 ppm for particulate contamination.

9626-78, Session 15

3MI OPD optical design: concept and performances

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Umberto Bruno, Fabio Belli, Giuseppe Bove, Alberto Caruso, Luciano Calamai, SELEX ES S.p.A. (Italy); Ilias Manolis, European Space Research and Technology Ctr. (Netherlands); Demetrio Labate, SELEX ES S.p.A. (Italy)

The Multi-Viewing, Multi-Channel, Multi-Polarisation Imager (3MI) is an imaging radiometer for the ESA/Eumetsat Meteorological Operational satellite programme - Second Generation (MetOp-SG). Based on the heritage of the POLDER/PARASOL instrument, 3MI is designed to collect global observations of the top-of-atmosphere polarised bi-directional reflectance distribution function (pBRDF) in 12 spectral bands, by observing the same target from multiple views using a pushbroom scanning concept. The image data is ultimately used to measure, among many others, the Earth's tropospheric aerosol distribution, the Earth radiance budget, the cloud properties (including height, phase and type), land surface and ocean colour.

The 3MI Optical Module Unit (OMU) consists of two wide field of view (FOV) telecentric lenses, one operating in the VNIR range (400-920 nm) and the other in the SWIR range (900-2150 nm). A filter wheel with two concentric sets of filter stacks rotates between the two lenses and the detectors, allowing observations in 9 spectral bands in the VNIR and 3 in the SWIR. Among these, 6 bands in the VNIR and 3 bands in the SWIR are observed in 3 different linear polarisation directions, i.e. at 0, +60 and -60 deg.

In order to mitigate any technological risks associated with the 3MI instrument development, an Elegant Breadboard (EBB) of representative form, function and performance to the 3MI VNIR optics was foreseen in the frame of the Optics Pre-Development (OPD) activity.

The optical design and the performance results of the EBB are presented, from the top level requirements flow-down to the optical design solution and concept adopted. The large FOV and throughput uniformity, the extended VNIR spectral range, combined with the demanding polarisation and stray-light requirements are the main design drivers.

The design concept is based on a Galilean telescope coupled to a focusing group. The aperture stop, placed in between, is located in such a way that the system is telecentric in image space. The system exhibits a fine control of the entrance pupil size as a function of the FOV, low distortion and correction of lateral chromatic aberration.

Polarisation related performances are achieved by low polarisation sensitivity and low retardance anti-reflection coatings, as well as by a proper selection of glass material properties.

9626-79, Session 15

Image irradiance distribution in the 3MI wide field of view polarimeter

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In order to mitigate any technological risks associated with the 3MI instrument development, an Elegant Breadboard (EBB) of representative form, function and performance to the 3MI VNIR optics was foreseen.

The demanding challenge of the EBB is represented by the polarisation and image irradiance fall-off (throughput uniformity) requirements.

In a generic optical system, the image irradiance fall-off is function of: target radiance distribution and polarisation, entrance pupil size and optical transmittance variations across the field of view (FOV), distortion and vignetting. In most applications these aspects can be considered as independent; however, when high image irradiance uniformity is required, they have to be considered as linked together. This is particularly true in case of a wide FoV polarimeter as 3MI is.

In order to properly account for these aspects, an irradiance fall-off analytical model has been developed in the frame of 3MI Optics Pre-Development (OPD). It is shown how it is possible to control the shape of image irradiance distribution acting on optical design parameters (e.g. distortion and entrance pupil size variation with FoV). Moreover it is discussed the impact of polarization performances on irradiance fall-off, and how it is possible to tailor all parameters in order to meet the requirement.

9626-80, Session 15

ATLID beam steering mechanism and derived new piezoelectric based mechanisms for optical applications

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In Space & Defence (as well as many others fields), there is a trend for miniaturisation in active optics requiring new actuators. As onboard place and available electric power is becoming increasingly limited, these new actuators need to offer high output energy to mass ratio. Applications also often require the ability to withstand high vibrations and shocks levels, as well as vacuum compatibility for space applications.

A new generation of small and smart actuators such as piezoelectric (piezo) actuators, are resolving this trend, thanks to their capacity to offer high energy density and to support both extreme and various requirements.

One example of such mechanisms is ATLID Beam Steering Mechanism (BSM) for the EarthCare satellite for which first flight models has just been delivered. It consists in a 2-axis pointing mechanism ("Tip Tilt"), , mounted on a bracket including front end conditioning for position sensors. The base of the BSM is two stiff push-pull pairs of APA60SM® piezoelectric actuators with improved high stability strain-gage sensors. This space mechanism aims at bending a pulsed high energy UV laser beam with a very high stability and resolution.

Derived from the BSM is an XY piezoelectric translation stage. Though the combination of the improved strain gages sensors and high dynamic APA® piezoelectric actuators, this stage can provide both fast (ms) and accurate (<µm) displacements of a see-through payload. This stage is notably used for micro-scanning and line of sight stabilisation, allowing IR camera resolution enhancement or shake compensation.

A last new mechanism, still based on the same core technology, is a piezoelectric motor that can achieve much larger displacement, typically in the range of 1cm to 20cm. This motor combines the high resolution, high dynamic capacity of the APA® actuators with the stepping accumulation of a motor. The resulting actuator is able to provide large displacement while preserving very high resolution capability for optical elements positioning.

This paper first presents the BSM mechanism and its requirements, the technologies involved in the design and the validation campaign results. Secondly, a derived XY piezoelectric positioning stage based on the same APA® and associated Strain Gage sensing technology is presented with its associated performances. Finally , a new piezoelectric motor based on the APA® technology, which allows the combination of long stroke while maintaining high resolution positioning of optical elements, is presented with experimental performances.

9626-81, Session 15

Impact of aberrations on the measurement of the solar diameter with the SODISM instrument

Francois Riguet, REOSC (France); Mustapha Meftah, LATMOS (France); Fabien Pradal, REOSC (France)

PICARD was successfully launched in June 2010 and observed constantly the sun, producing more than one million images during its 3-year mission. SODISM (Solar Diameter Imager and Surface Mapper) is one of three instruments onboard, whose main goal is to measure the solar limb and its spectral dependence from the middle ultraviolet to the near infrared.

The very high accuracy (a few milli-arcseconds) needed to measure the solar limb with its spatial and temporal variations makes the instrument very sensitive to small aberrations, and especially to small temperature gradients in the front window of the telescope. A small deformation of the PSF will induce a displacement of the limb position and an enlargement of its width. Depending on the introduced aberrations, the measured limb may eventually show a profile that is trefoil-shaped, compared to a perfect circle.

In this paper, we will present the impact of various parameters on the solar limb measurement, from simple displacements of mirrors to complex thermal gradients. A complete scenario has been constructed from these simulations, leading to a model that describes the actual limbs obtained with SODISM. It appeared that a combination of focus (giving larger limb profiles) and trefoil (leading to a trefoil shape) as a thermal gradient in the window were giving results very similar to what was meaured. Moreover, the evolution of of this gradient, along with a nominal defocus, explained the temporal evolution of the meaured limb.

Some other simulations have been conducted to explain the evolution of transmission observed during the mission. The conclusion is that a simple layer of carbon-like contaminant on the inner face of the window, whose thickness was progressively increased, explained with a very good correlation the evolution of transmission a different wavelengths.

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9627-1, Session 1

Recent developments in the field of optical coatings *(Keynote Presentation)*

Norbert Kaiser, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The following topics will be addressed: Specific demands and development directions in applications of optical coatings, such as space and astro-optics, XUV-BEUV-EUV optics, and high-power and ultraprecision optics for DUV to IR. Design coatings with specific requirements, characterization, and optimization of optical layer properties, understand virtual coatings for design and process optimization. Evaluation of different techniques for antireflection of surfaces. Identification of basic structure-related film properties. Discussion of industrial needs in optical coating technologies vs. performance and costs. Discussion of international trends.

9627-2, Session 1

History of optical coatings in Jena *(Invited Paper)*

Helmut Bernitzki, JENOPTIK Optical Systems GmbH (Germany)

No Abstract Available

9627-3, Session 1

Broadband antireflection coatings for optical lenses with extreme curvature *(Invited Paper)*

Ulrike Schulz, Friedrich Rickelt, Peter Munzert, Norbert Kaiser, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Direct plasma etching is a powerful method for producing antireflective (AR) nanostructures on organic layers and substrates. Normally, the structure depth achievable by a single etching step is limited to approximately 100 nm. The AR performance is excellent in the visible spectral range for normal light incidence on planar substrates therefore. A more sophisticated application is a curved lens in which the AR function is maintained throughout the visible spectral range and over an extended range of incident light angles. Based on theoretical knowledge, it is widely accepted that interference stacks have limitations that cannot be overcome with currently available compact thin-film materials and that a gradient layer of sufficient thickness would provide the best possible AR performance for wideband or wide-angle AR applications. In this work, multiple inorganic and organic layers are used to build up AR coatings with a decreasing effective index from the substrate side to the surrounding air. By depositing and etching of organic layers step-by-step a broadband antireflective performance can be achieved. Experimental results will be presented together with the simulation of the optical properties. In particular, the behavior on inclined surfaces can be improved markedly by applying multilayer systems containing of more than one structured layer.

9627-4, Session 2

Design and pre-production analysis of optical coatings *(Invited Paper)*

Alexander V. Tikhonravov, Lomonosov Moscow State Univ. (Russian Federation)

Nowadays optical coating engineers have in their disposal efficient general purpose design techniques that allow them to design coatings with required spectral properties in a very short time. So a formal designing of an optical coating with excellent target spectral characteristics is not a problem anymore. It is however more difficult and more time-consuming task to find coating design that meets a number of additional practical requirements along with the requirement of a good approximation of specified target characteristics. Quite often there are additional requirements to the thicknesses of design layers that are connected with monitoring techniques used for coating production. In recent years there was an essential progress in the development of special purpose design techniques aimed at designing of coatings with various demands to the thicknesses of their layers. Modern design approaches allow one to obtain a series of promising coating designs and the choice of the most practical design from this series becomes more and more important. For this choice one can use a pre-production analysis that evaluates the influence of possible production errors on various coating designs. Various forms of pre-production analysis are also tightly connected with monitoring techniques used for coating production. For the production of complicated coatings direct optical monitoring techniques are often used. Such techniques cause correlation of errors in thicknesses of subsequent coating layers. In this case the most reliable form of pre-production analysis is computational manufacturing of optical coatings, i.e. computer simulation of deposition and monitoring processes.

9627-5, Session 2

Design and production of three line antireflection coatings for visible and far infrared spectral regions

Valeryi Zhupanov, Viktor Fedoseev, Federal State Unitarian Enterprise “Scientific Research Institute Luch” (Russian Federation); Michael K. Trubetskov, Max-Planck-Institut für Quantenoptik (Germany) and Lomonosov Moscow State Univ. (Russian Federation); Tatiana V. Amotchkina, OptiLayer GmbH (Germany) and Lomonosov Moscow State Univ. (Russian Federation); Alexander V. Tikhonravov, Lomonosov Moscow State Univ. (Russian Federation)

Production of multilayer coatings with several distant working spectral regions presents serious challenges even at the modern state-of-the-art in optical coating technology. Typically such problems require application of all major thin film software tools including design, characterization, and reverse engineering. In the present work we consider design and production of an antireflection coating with three narrow low reflection zones in the vicinities of the wavelengths of 0.546, 1.06 and 11.0 micrometer. Along with these main requirements there are also additional demands for the reflectance maxima in the visible and far infrared spectral regions.

For the production of the required coating, we apply a version of broad band monitoring (BBM) that we refer to as quasi-direct BBM. Basically, this is a direct BBM in the sense that monitoring is performed directly on the coating to be manufactured. At the same time our monitoring spectral region of 1300-2300 nm is noticeably different from the spectral regions where target requirements are specified. This causes additional challenges for the successful application of quasi-direct monitoring systems. In the first turn, this is the requirements of very accurate determinations of wavelength dependencies of refractive indices in wide spectral regions.

For the production of our coating we use ZnSe as a substrate material and ZnS/YbF_3 as layer materials. The substrate material is strongly absorbing below 480 nm and an accurate determination of its optical parameters requires using various combinations of reflectance and transmittance measurements and applying sophisticated thin film models that are available in OptiLayer thin film software. Verification of substrate and thin film material refractive indices is further performed using results

of reverse engineering of the coating with a special periodic structure that is specifically deposited for this purpose.

Theoretical design of the antireflection coating with the above specifications is not a difficult task. However it is much more challenging problem to find a practical design that can be reliably manufactured using the chosen quasi-direct BBM. In order to select such a design, we apply a combination of various modern design approaches and computational manufacturing experiments simulating real production runs. Based on the results of these experiments a special 8-layer design is found to be the most practical one.

In the course of the coating production we apply a special stabilization procedure aimed at raising the accuracy of BBM layer thickness control. This procedure has been successfully applied in some of our previous works related to coating production with BBM thickness control. It is based on taking into account wavelength positions of monitoring signal extrema. Thickness control with taking into account correspondence of these positions to theoretically predicted extrema positions at the ends of layer depositions is especially important for several first coating layers when the monitoring signal in BBM spectral region does not have well-pronounced interference features yet.

Due to the careful application of the mentioned software tools, the produced three line antireflection coating meets all required specifications.

9627-6, Session 2

Simulation in thin film technology *(Invited Paper)*

Marcus Turowski, Marco Jupé, Henrik Ehlers, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

Recent progresses in thin film technology resulted in an increase in purity, a reduction of particle contamination, and a precision in layer thickness on the atomic scale. The state of the art technology allows to manufacture optical coatings with losses in the range of few ppm in the near infrared wavelength range and components with high power handling capability. With respect to the demands on optical coatings, a multiplicity of coating techniques have been developed, but even when considering only one selected coating method, a large variety of technical implementations and modifications can be found in the production field. Nevertheless, the fundamental processes of the thin film nucleation are not understood in detail, and the optimization of coating processes is still based on empirical experience concerning the correlation between thin film properties and process parameters. In the course of the rapid development of modern photonics the quality requirements on optical coatings have reached a level, which will not be achievable by the present empirical optimization strategies in near future. This indicates the need for more sophisticated optimization concepts based on modelling of deposition processes on a fundamental theoretical level. Such novel simulation approaches offer the possibility to investigate in the influence of the process parameters on the resulting film properties individually. Consequently, a significant narrowing of the process parameter space may be achieved prior to the implementation of a specific deposition process facilitating coating production with improved flexibility and economy.

In order to support the experimental endeavors to realize high quality optical coatings, a large number of different simulation techniques are applied in thin film technology. These methods are often related to the design of complex layer systems for specific laser applications and to optical monitoring concepts, where pre- and post-processing simulations gain of importance. Furthermore, the different processes taking place during the coating manufacturing are also covered by numerous simulation techniques. For instance, the material transport in the vacuum chamber is investigated by plasma and flux simulations, the thin film growth is typically described by classical atomistic simulation techniques, and the optical properties of the coating materials can be modeled using ab-initio quantum mechanical calculations. Not least considering high power laser applications, the interaction of the laser irradiation with dielectric materials can be determined by solving rate equation models, and absorption as well as the laser damage threshold can be predicted by numerical approaches.

The present contribution is focused on the investigation of thin film growth in dependence of characteristic process parameters. A multi scale model approach is discussed with the target to correlate specific production parameters with the resulting structural, optical and electronic film properties of the coatings. Finally, a concept is introduced, that combines plasma and thin film growth models to a "virtual PVD coater".

9627-7, Session 2

Supercomputer modeling of the ion beam sputtering process: full-atomistic level

Fedor V. Grigoriev, Alexei V. Sulimov, Igor V. Kochikov, Olga A. Kondakova, Vladimir B. Sulimov, Alexander V. Tikhonravov, Lomonosov Moscow State Univ. (Russian Federation)

The atomistic modeling method of the ion beam sputtering (IBS) process, oriented at supercomputers calculations is presented. Corresponding algorithm is organized as a sequence of identical molecular dynamic steps. On each step several groups of the deposited atoms are injected into the modeling box and interact with the substrate and film forming new chemical bonds. The method was implemented for the simulation of the SIO2 thin films growth. For the calculation of the interatomic potential energy the original force filed DESIL has been elaborated. It provides high computational efficiency and is capable of describing all major structural properties of bulk fused silica dioxide and silica dioxide thin films.

Our model includes substrate modeling, modeling of the source of deposited atoms, a special way for taking into account chemical reactions in the deposition chamber, temperature variations, angular and energy distributions of deposited atoms, various types of boundary conditions and various statistical ensembles accounting for environment of modeling volume. The deposition process is organized as a sequence of molecular dynamic cycles when deposited atoms interact with the substrate and earlier deposited layers and form new Si-O chemical bonds. The atomic flow density is chosen so that subsequent interactions of deposited high-energy atoms with film surface could be considered as independent events.

The elaborated method has been implemented in the frame of KUVALDA code; simulations were performed on the Lomonosov supercomputer of Moscow State University. For MD modeling KUVALDA exploits one of the most effective standard MD software packages GROMACS.

Atomistic modeling of thin film deposition processes was performed for the film thickness up to 40 nm (number of the atoms one millions). The dependence of thin film density on film thickness has been investigated. It was shown that film density exceeds the density of fused silica substrate for 0.1-0.2 g/cm^3. Thickness of interface layer between thin film and substrate is about 1-2 nm. The dependence of film density on film thickness has been investigated and it has been shown that density variations of about 0.1-0.2 g/cm^3 are still possible in rather deep film layers that are located at distances of 10 nm beyond the film surface.

Two approaches for calculating optical parameters of thin films have been investigated. The first one is based on quantum-mechanics considerations while the second one utilizes the macroscopic electrodynamic considerations that establish relations between optical parameters of thin film and thin film density. It has been found that the with the current state-of-art in quantum-mechanics calculations the second approach allows to obtain results that are in better agreement with the existing experimental data. Based on the obtained results for thin film density dynamics, the dynamics of thin film optical properties has been studied.

9627-8, Session 3

Optical characterization of high index metal oxide films for UV/VIS applications, prepared by PIAD *(Invited Paper)*

Olaf Stenzel, Steffen Wilbrandt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Oxide coatings have been prepared by PIAD by means of a Leybold Syrus pro 1100 deposition system. Focus was placed on tantalum pentoxide, hafnium oxide, and zirconium oxide films. The samples have been characterized by means of spectrophotometry. In situ spectrophotometry has been performed using an OptiMon process spectrophotometer operating in transmittance. Ex situ spectrophotometry included absolute measurements of transmittance and reflectance using self-developed VN-accessories, designed for use in the GPOB of commercial Perkin Elmer double beam dispersive spectrophotometers.

Coating characterization was focused on the determination of refractive index and extinction coefficient of the films in the VIS/UV spectral regions, as well as the geometrical film thickness. Most of the films investigated appeared to be optically homogeneous. Weak refractive index gradients have been quantified in terms of the Schröder approximation, where necessary. For the homogeneous layers, further optical characterization was performed in terms of spectra fits by means of a multi-oscillator model. In situ spectrophotometry was used to obtain information about the shift of the coatings. Measurements of the coating stress as well as EDX characterization have further been performed to complete the picture.

Results are presented which provide information about the correlation between deposition parameters (Assistance, choice of working gas, and the like) and the optical properties of the films. Correlations between optical (see Fig.1) and non-optical (stress, EDX-results) properties are further presented and discussed in terms of classical models. Reproducibility issues are discussed, too.

9627-9, Session 3

Multilayers and optical constants of various fluorides in the far UV

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Several fluorides are among the materials in nature that keep their transparency down to the shortest possible wavelength. This property makes them almost the only choice for multilayer coatings tuned in the ~100-150-nm wavelength range of the far ultraviolet (FUV). FUV multilayers are required for various fields of application, such as space instrumentation for astrophysics, solar physics and atmosphere physics, as well as plasma diagnostics, synchrotron radiation, spectroscopy, etc. In order to design the desired multilayer, accurate optical constants of the materials are required, which have been mostly lacking.

Measurements of the optical constants of thin films of MgF2, LaF3, and CeF3 will be presented covering not only the FUV but extending to a broad range from 40 to 950 nm. Fluoride thin films were deposited by evaporation onto substrates at 250?C. The measured optical constants were further extended with literature data and extrapolations in order to obtain self-consistent sets of data using the Kramers-Krönig analysis.

The obtained optical constants were used to design narrowband reflective multilayer coatings. Measurements will be presented on multilayer coatings peaked at a wavelength as short as ~120 nm.

9627-11, Session 3

Mid-infrared optical coatings with improved transparency for 3 to 6um spectral region using sputtered silicon and oxide films

Desmond R. Gibson, Shigeng Song, Univ. of the West of Scotland (United Kingdom)

Mid infrared optical coatings are commonly designed & manufactured using typically electron beam evaporated films of Silicon and Silicon Monoxide. However the transparency of these coatings is limited by optical absorption in the films when producing coatings for wavelengths beyond 4um approximately. This work reports improvements in mid infrared (3 to 6um) filter transparency achieved by exploiting recent advances in plasma assisted pulsed DC magnetron sputtering technology. Sputtered silicon compound films have been used to demonstrate efficient optical coatings for gas sensing applications at wavelengths between 3 to 6um. This process technology allows a new selection of film materials to be used in design of mid infrared filters, with transmission and thermal drift characteristics which are enhanced compared with conventional evaporated coatings. The spectral location of the optical coatings is controlled by a non-optical method, which avoids the complex optical monitoring configurations normally required. Durable filters are obtained without elevated process temperature, which would otherwise be required in conventional evaporation processes. This avoids heating filter substrates which may be sensitive to thermal cycling effects. Examples optical coatings for use in non-dispersive infrared gas sensors are demonstrated.

9627-48, Session 3

Optical and mechanical properties of infrared thin film at cryogenic temperature

Fabien Pradal, Rémi Lhuillier, Daniel Mouricaud, REOSC (France)

For the most demanding infrared applications, fine knowledge of performance of system under operational temperature is required. Management of thin film spectral and mechanical behavior at cryogenic temperature is a key factor to improve infrared system performances.

Reosc recently investigated models and methods to anticipate, measure and control effects of low temperature on coated optical components. Solutions have been developed in order to maximize highest performances under operational conditions.

Effects of temperature on spectral transmission and flatness have been studied.

This work has been applied to narrow band pass filters and dichroic coatings working from 55K to 90K.

Measurements show satisfying correspondence with model.

On the basis of model prediction, process and design have then been adapted to improve performances at operational temperature. It has been applied to manufacturing of optics for MTG satellites and IASI NG instrument.

9627-70, Session 3

Frequency tripling mirror based on optical interference coatings

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As a consequence of the demanding phase matching conditions, direct third harmonic generation (THG) processes in solids are commonly limited to relatively small conversion efficiencies. Therefore, most frequency conversion concepts to the third harmonic are based on an efficient second harmonic generation (SHG) followed by a sum frequency generation (SFG) of the fundamental wave with the second harmonic.

In the present contribution, a new approach towards efficient direct THG processes in dielectric layer structures is proposed. In fact, frequency tripling processes in single layers have been subject of many research activities dedicated for example to the characterization of short pulses, ultrafast spectroscopy, or fundamental research in noninstantaneous polarization decay phenomena. Most of these studies rely on the detection and evaluation of the third harmonic signal transmitted by the sample without considering interference effects in the layers. However, interference effects may be employed to significantly increase direct third harmonic generation efficiencies in reflection and transmission geometries. Major effects contributing to this improvement are based on electric field enhancements optimized by the design of the structure and an effective compensation of the phase mismatch. The present study is focused on these phenomena in coating sequences consisting of alternating layers of hafnia and silica. After a brief general review on THG processes, the fundamental principle of third-order nonlinear optical processes in dielectric coating materials will be presented. A mirror design algorithm, that takes into account THG, will be introduced and applied to layer stacks of HfO2 and SiO2. Designs with layer numbers from 1 up to 25 layers for maximum THG in reflection geometry will be described. The layer systems were produced by ion beam sputtering under broad band monitoring control with a zone target of Hafnium and Silicon. Third harmonic signals from this frequency tripling mirror were generated using a Ti:sapphire laser oscillator (800 nm, 50 fs, 100 MHz). TH signals produced by the layer stacks were 104 to 105 times stronger than those predicted and measured for single layers of HfO2. Single pulse conversion efficiencies of 1% - 2% have been observed for a stack of 25 layers. The experiments also indicated evidence of laser incubation, which is known from studies of laser damage phenomena in HfO2-coatings.Such laser conditioning effects should be minimized in further research efforts. Extrapolation of the observed conversion scaling suggests efficiencies in the range from 10% - 15% at power levels well below the damage thresholds of the employed materials. Hence, nonlinear optics in dielectric layer systems may be considered as a promising new direction for optical interference coatings.

9627-12, Session 4

HfO2 layers deposited using e-beam from metallic hafnium

Martijn E. A. Brouwer, TNO (Netherlands); Ronald R. Willey, Willey Optical, Consultants (United States)

Hafnium oxide (HfO2) is a commonly used high refractive index material used for optical coatings. Its main benefits are its good UV transparency (down to 225nm) and its high laser damage threshold. When deposited using e-beam evaporation, HfO2 granules are the commonly used source material. This deposition process has a number of disadvantages, which are related to the physical properties of HfO2. It does not melt during deposition since its melting temperature is higher than the temperature achieved during evaporation. This causes the formation of irregular holes in the grains, especially during long coating runs. This effect, called "tunneling", changes the distribution of the vapour, which in turn affects the tooling factor. This is a source of errors in the deposition process.

A second disadvantage is that small particles are emitted from the solid material, a process called spitting. These particles limit coating durability and the laser damage threshold. Careful pre-melting can limit, but not prevent it.

These disadvantages can be avoided by depositing HfO2 from a metallic hafnium source. The metal melts, thus forming a smooth surface from which the vapour emanates. Due to absence of water and mechanic stress in the source material, spitting is avoided. This process has been mentioned by Willey. The challenge is to achieve stoichiometric films to avoid absorption in the coatings. Ion assistance is used to achieve full oxidation of the metal.

In this paper we present results of optimisation of the deposition process for metallic hafnium. We show measurements of the absorption spectrum and give wavelength dependent values of the absorption coefficient. To demonstrate that the process is suitable to manufacture "real" optical coatings we have deposited a short pass filter with a cut-off wavelength at 310nm. The absorption of this coating is measured and compared to the absorption of a coating produced by reactive evaporation without ion assistance from hafnium oxide.

9627-13, Session 4

Properties of transparent organic-inorganic composite coatings prepared by ion beam sputtering of PTFE and Al2O3

Melanie Gauch, Henrik Ehlers, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

Coatings with optical and protective functions on glass substrates are widely used in industry. For the production of coatings with the similar functionality on flexible substrates like polymer foils, new materials are needed. The commonly used oxides and nitrides have excellent optical properties and are mostly resistant against environmental influences. For example they are widely used as protection against UV-light, moisture and can improve the scratch resistance of surfaces. However their mechanical stress may distort the substrate properties or even lead to cracking. Therefore, coatings with low stress, good optical, and protective properties are needed for flexible substrates. Composite materials combining the durability of oxides with the flexibility of polymers could fulfill these requirements.

In addition, flexible substrates like polymer foils are sensitive to temperature. Therefore, a low temperature coating technique has to be used. Ion Beam Sputtering (IBS) of composite materials consisting of two oxides is a well-known technique for the production of high quality optical coatings with tailored properties. Because of the separated ion generation, the temperature of the substrates does not exceed critical values during the sputtering process. The combination of IBS with polymers is rarely used. However, it is possible to use polytetrafluoroethylene (PTFE) as target material for the production of fluorocarbon coatings with low mechanical stress and a low refractive index around 1.38. This material can provide enhanced protection against water and UV, but the mechanical stability and scratch resistance need improvement.

In this study, the mixing of PTFE and oxides employing a zone target in an IBS-process is investigated. From former measurements it is known that sputtering of PTFE in an oxide atmosphere leads to a lower deposition rate and a deterioration of the optical quality compared to the sputtering process of PTFE with pure argon. But this effect is extenuated in dependence of the amount of metal in the coatings.

For the production of composite coatings, IBS from a zone target of PTFE and Al2O3 was employed. The composition of the sputtered coatings depends on the target position in relation to the ion beam. Different materials are used as substrates such as fused silica, PMMA, and KBr. Energy-Dispersive X-ray spectroscopy and Fourier Transform Infrared spectroscopy measurements were performed for investigations in the molecular structure and the contents of aluminum, oxygen, fluorine, and carbon in the sputtered coatings. The variation of the refractive index in dependence of the chemical composition was studied. Furthermore, a change from compressive to tensile stress in dependence of the composition was observed.

9627-14, Session 4

Reduce the stress of multilayers by SiOxCy plasma polymer film

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The large stress causes films cracking or wrinkling and resulted the thin films peeling, so that reduced the yield and stability of the optical thin films production. How to reduce the stress of thin films has become a very important issue. There are many ways to eliminate the stress of thin films, such as coating on both sides of the substrate, choosing the thin film materials and substrate. How to coat flexible polymeric films effectively and reduce the stress of multilayer optical films is the aim in this study. SiOxCy plasma polymer film was deposited by plasma polymerization process used a mixture source gas by hexamethyldisiloxane(HMDSO) and oxygen. Growing different properties of SiOxCy thin film by four parameters are the flow of oxygen and HMDSO, plasma beam current (Ii) and anode voltage (Vd). The transmittance of thin films was measured by Hitachi U4100 spectrometer. The thin film composition and structure has been investigated by X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared (FTIR) spectroscopy. Analyzing the stress of thin films was investigated by phase shift interferometer. The multilayers layers were deposited in an electron-beam gun (e-gun) coating system. Ta2O5 be high-index and SiO2 be low-index materials with refractive indices of 2.2 and 1.45, respectively. The composition structure, optical properties, proportion of elements and films stress of the coated polymer films were investigated by changing the flow of HMDSO, the flow of oxygen, beam current and anode voltage.

The flexibility of the SiOxCy plasma polymer film was reduced the stress of multilayers. In this study, HMDSO monomer was lysed by plasma polymerization, and then the plasma polymer films was coated. The average transmittance of the deposited films is above 90%. When the Linear/Cage ratio increases, the stress decreases from - 0.267GPa to 0.029GPa. The stress of the SiOxCy plasma polymer film was turned from compressive stress into tensile stress by increased the flow of HMDSO and decreased the beam current. It proved that we can control the Linear/Cage ratio effectively and predicted the plasma polymer films stress by changing parameters. The stress of the multilayers and SiOxCy plasma polymer film was 0.06 GPa and -0.067GPa, respectively. Finally, the multilayers were coated on the precoated SiOxCy plasma polymer film shown that the stress of the multilayers was reduced 70 % form 0.06GPa to 0.018GPa.

9627-15, Session 4

Combined deposition of optical interference coatings and wear resistant Diamond Like Carbon (DLC) in a novel box coater

Silvia Schwyn Thöny, Rico Benz, Andreas Frigg, Evatec Ltd. (Switzerland)

The substrate as well as coating materials used for infrared optics often suffer from a limited durability and can easily be damaged. Thus, front lenses, which have to withstand the harsh requirements of an external part, need a special protection layer. The most suitable coating for this application is diamond like carbon (DLC). Not only IR optics benefit from DLC, but also handheld devices such as high end cell phones, tablets and gaming devices.

DLC layers are made of amorphous hydrogenous carbon (a-C:H) having the optimal mixture of extremely hard SP3 (diamond) and soft SP2 (graphite) bonds. The combination of these bonds results in an extremely durable and hard layer. The index of refraction of DLC is in the range of 1.7 - 1.9, which is a good optical match to high-index substrates used in infrared optics such as Silicon and Germanium. In combination with the low absorption in the IR part of the spectrum this results in excellent single wavelength antireflection coatings. Broadband antireflection coatings can be obtained by an optical coating design combining IR materials and DLC.

So far, state of the art components are manufactured in a two step process. A multispectral coating, such as a broadband antireflection coating is deposited in a standard box coater, whereas the DLC is deposited in a second step in a separate coating chamber. There are many ways to produce DLC coatings such as plasma enhanced chemical vapor deposition (PECVD), magnetron sputtering and arc-evaporation with a variety of precursor gases.

The new approach reported in this paper combines physical vapor deposition (PVD) of the multi spectral coating and PECVD deposition of the DLC coating in one and the same box coater deposition system. This offers a wide number of advantages, starting from superior film quality due to the uninterrupted vacuum, and ranges to reduced process cost due to a shorter process time and the elimination of substrate handling between processes.

The PECVD process in the box coater was enabled by using an Inductively Coupled Plasma (ICP) source and the appropriate process gases like methane, butane or acetylene. A stringent safety concept had to be put in place to handle the flammable or explosive process gases. Furthermore, we will show how the DLC process was optimized by using in-situ optical and stress measurements as well as ex-situ abrasion and adhesion testing and spectrophotometric measurements. These investigations resulted in establishing process conditions for coatings with excellent hardness, withstanding the wiper test, perfect adhesion to silicon, germanium and glass, which are virtually absorption-free in the wavelength regions of 3 5 and 8-12 μm. In a second step the DLC will be optimized as part of a broadband antireflection coating centered at 4μm. We will show the results for adhesion, abrasion and spectral performance of this antireflection coating.

9627-16, Session 4

Lamination of chemical incompatible optical polymer layers

Raimund Rother, Anne-Katrin Schuler, Claas Müller, Oswald Prucker, Jürgen Rühe, Holger Reinecke, Univ. of Freiburg (Germany)

Lamination is a well-known process to form multilayers of compatible polymers. To obtain stable multilayers of chemical incompatible polymers, it is necessary to apply an intermediate layer. Otherwise, optical polymers with different polarity block the interdiffusion of polymer chains across the polymer boundary, and therefore no lamination is possible. In integrated optics, there is an increasing need for multilayers composed of different optical polymers, for devices with long term stable and smooth optical boundaries.

To take up this challenge, a process needs to be developed that does not rely on entanglement of polymer chains to form a stable multilayer like the conventional lamination process. We developed a process that uses a thin layer of chemical modified PMMA that is able to chemically bond to any C-H-containing surface it is applied to instead of conventional entanglement. We named this process “reactive lamination process”.

This reactive lamination process is performed in three steps. In a first step, a solution of the reactive PMMA is spray coated on the surface of a polymer substrate (foil) to form an intermediate layer. In a second step, a second polymer foil incompatible to the first one is laminated on top of the spray coated PMMA layer. In the last step, a stable multilayer stack is formed after an activation that allows the functionalized polymer layer to form chemical bonds with both neighboring polymer foils. Activation depends on the type of reactive PMMA and can be either thermal or optical.

The advantage of this new process is the accessibility of stable multilayers of a multitude of polymer materials that no longer need to be miscible in each other and therefore can have a wider range of optical properties without the need of special additives. A further important benefit is the insolubility of the interconnected polymers – therefore a stable interface between any two C-H-bond-containing polymers can be realized that will not disappear with time because no interdiffusion is possible.

To obtain high-quality optical devices by reactive lamination, it is very important to generate homogeneous layers of the functionalized PMMA with a defined shape. We consider spray coating to be an appropriate technique, because it is suitable for substrates of any size and shape in contrast for example to spin coating and allows a better control of layer thickness in comparison to dip coating.

The paper focuses on the development of a spray coating process with reactive PMMA to obtain optical multilayer devices. We establish a new spray coating process for different applications by applying a controlled low amount of reactive PMMA solution onto a substrate. To evaluate the bonding stability, defined dots with a diameter from 1 mm up to several centimeters were used as intermediate layer. Polymer dots with both a sharp or diffuse boundary are possible. Highlights of the new coating process are: the high precision in dot positioning, the accurate volume control allowing the smallest possible amounts of reactive PMMA solution and the consistent good and reproducible substrate coating.

9627-17, Session 5

Interference coatings for high energy lasers operating at wavelengths in the 1-2 μm range *(Invited Paper)*

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We have recently demonstrated a diode pumped chirped pulse amplification system producing Joule-level pulses of picosecond pulse duration at repetition rates of 100 Hz [1,2]. The development of this type of lasers which have numerous scientific and technological applications motivates our work in interference coatings for operation in the 1-2 μm wavelength range. Interference coatings were designed using a combination of metal-oxides, and were grown by ion beam sputtering.

Results will be presented on 1 μm coatings based on Ta_2O_5/SiO_2 in which by modifying the top few layers it is possible to achieve a laser damage fluence 2x that of a quarter wave Ta_2O_5/SiO_2. Results will also be presented on interference coatings designed with metal oxides for 1.6-2 μm operation. At-wavelength testing of the laser damage performance of these coatings showed they can withstand fluences of 7 J/cm2, a value similar to that of the high quality infrared fused silica substrates when tested with a train of pulses of 2 picosecond duration.

9627-18, Session 5

Production of optical components by novel phase separating IBS process

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During the last decades, Ion Beam Sputtering (IBS) was developed to a coating process with superior quality. Actually, absorption losses below 1 ppm can be achieved and film thickness precisions of few atomic layers are realized. Nevertheless, new photonic technologies impose continuously increasing demands on optical components challenging the established processes including even advanced ion beam sputtering (IBS). In general, the reduction of contamination of the optical surface by particles is one of the outstanding problems. These particles can be generated in different phases of the manufacturing, and the reduction is a technological challenge. The only solution is the precise analysis of each production step and its dedicated optimization. Especially for complex optical components with a high number of layers and a huge total coating thickness, the genuine coating process often contributes the major sources for particle contamination. This may apply especially to ion sputtering processes, where the debris produced during sputtering on the target surface is suggested to find its way to the growing layer. Before this background, the present study considers a novel coating process, which specially separates the sputtering process and the thin film growth on the sample surface. In detail, the process applies a magnetic plasma guiding to transport the coating material from the target to the substrates. Actually, different guiding concepts are applied in the study. The main difference between the concepts is the geometry of the guiding device. In pre-studies, a linear set-up was used to investigate in the fundamental functioning. The final set-up includes a curved separator which masks the direct line of view between the target and the substrates. Generally, only ions of the deposition material components are guided by the magnetic field to the substrate. In contrast to this, heavy debris particles follow a linear ballistic trajectory and are not able to reach the substrates via the curved coil.

In the present contribution both, fundamental studies and experiments close to applications are presented. The fundamental understanding of the guiding process, the influence of the sputtering and the separator parameter are discussed. Furthermore, the influence of the guiding on the deposition rate and on the layer quality is investigated. Finally, some demonstrator optics are presented, which illustrate the properties and advantages of the plasma guiding at the different sections of the guiding system. The effect of the guiding concept on different atomic species will be discussed and applied for the deposition of a dielectric mirror using a fixed zone target position in the sputtering process. In this experiment the necessary contrast between high and low refractive index is generated only by the variation of the polarization and the magnetic field strength of the separator.

In conclusion, the separation of coating material can be considered as a promising novel approach for a significant reduction of the particle contamination in IBS-coatings with advantageous effects on their optical losses and the power handling capability.

9627-19, Session 5

High performances optical coatings with dual ion beam sputtering technique

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We present hereafter the results on the manufacturing of complex optical coatings done with dual ion beam sputtering technique (DIBS). Such technology uses a first ion beam gun for sputtering a target and a second one for compacting the sputtered material. The density of the deposited layer is very close to the bulk material and enables the coatings to be nearly insensitive to environmental parameters. This technology is well adapted to severe environments as it allows the production of very dense layers and high quality coatings.

The use of an in-situ optical monitoring system in visible and near infrared range (up to 2500nm) permits to reach severe spectral specifications and to have a good agreement with the theoretical designs.

In this paper, we will focus on some complex optical functions that have been manufactured with DIBS technique: narrow band-pass filters and wide band filters including large blocking range with more than 100 layers and 25 μm total thickness, antireflection coatings which reach very low values of reflectivity in the near infrared spectral domain for wide angular ranges, and also metal-dielectric absorbing coatings.

We will also give an analysis of the cosmetics performances of the deposited layers, which shows the high quality of the coatings even with functions with large total thickness.

Many experimental results of qualification tests in temperature, humidity, thermal vacuum, radiations,… are presented and show the reliability of these multidielectric components in space or cryo-vacuum environment.

9627-21, Session 6

PACA2M magnetron sputtering optical coatings for large dimension

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In this paper, we will present recent achievements done with our large dimension magnetron sputtering coating machine that has been implemented by CILAS company in its premises in Aubagne. Such equipment called PACA2M (PulvérisAtion CAthodique de 2M) is an inline coating system that has been designed to ensure uniform coating on large optical components, up to 2 meters by 2 meters, 40 centimeters thick and to 1.5 ton weight.

We will see how its wide variety of configurations based on seven 2.5 meters-long planar magnetrons, that may be powered in various modes (RF, MF, DC, ..) allows us producing complex optical functions such as multilayer dielectric mirrors, antireflective coatings and protected or enhanced metallic mirrors from ultraviolet to infrared applications. Moreover, an all-fibered broadband optical monitoring system developed in collaboration by Institut Fresnel is installed on this industrial machine and allows extremely accurate monitoring carried out on samples and fine characterization directly on components.

Many spectral measurements and cosmetic results will be given that show that this equipment is well adapted for producing large optical components with high quality for various applications in the fields of industry, space or astronomy. In particular, PACA2M coating machine can be used for space application to produce in a same batch all the required models as it is possible to simultaneously coat flight models, qualification witnesses and spare models.

The stability of the performances in severe environmental conditions compatible with space environment will be illustrated with qualifications tests and characterizations.

9627-22, Session 6

Recent developments in precision optical coatings prepared by cylindrical magnetron sputtering

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Cylindrical targets give the opportunity to improve the process stability of magnetron sputtering processes although reactive deposition might be a challenge. Sputtering from metal doped oxide targets in connection with an oxidizing plasma source unlocks the full potential: The process can be driven in mid-frequency mode and the plasma source ensures fully stoichiometric films with low losses.

During the last years different developments for oxide cylindrical targets have been undertaken. In the tube geometry new manufacturing methods are required that ensure these properties.

In the present paper we show examples of coatings using tantalum oxide and zirconium oxide as high index materials. New sputter targets have been utlized and single films as well as complex optical filters have been deposited. The results are accompanied by performance measurements in terms of uniformity over 200 mm glass wavers as well as carrier to carrier and batch to batch.

9627-23, Session 6

High efficiency RF-plasma source with increased energy range

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The manufacture of interference coatings with plasma ion assisted deposition (PIAD) is state of technology in nowadays box coaters. The application of a RF-powered plasma source in combination with e-beam or thermal evaporation allows the production of thin films with excellent optical properties and low absorption from UV to NIR.

The LION300, a single-grid, RF-powered plasma source had been introduced earlier. With a water-cooled body of 300 mm diameter, the ECWR-type source operates at RF-power loads up to 6500W, inductively coupling the radio frequency of 13.56MHz.Through an auto-matching network, directly mounted to the source, a portion of the RF-power is capacitive coupled into the plasma thus allowing the ion energy to be controlled in a broad range.

A new, high-efficiency auto-matching network has been introduced, increasing the RF-source efficiency by approximately 20% and delivering higher ion energies above 1000eV. The new configuration has been applied for the production of "shift-free" UV-IR cut filters with low scattering losses in a standard box coater on a large dome-shaped substrate holder (D=1400mm). Excellent coating results could be achieved at evaporation rates R(SiO_2) > 1.0nm/s, thus significantly reducing the coating time by approximately 20%.

9627-24, Session 6

Nanoporous SiO2 made by atomic layer deposition and atomic layer etching

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Atomic layer deposition (ALD) is a powerful coating technology with applications in electronics, semiconductors, etc. These applications take mainly advantage of the ALD capability to deposit conformal, pinhole-free coatings on complex structured substrates. The second main advantage of ALD, namely to precisely control the composition of thin films at an atomic level has received much less attention. The chemistry of such atomically mixed systems paves the way towards novel material functionalities. In this study, we demonstrate a new simple approach to obtain porous SiO_2 films from ALD Al_2O_3:SiO_2 alloys. Both Al_2O_3 and SiO_2 are well established ALD processes with a good growth control. The thermal deposition windows of the ALD processes for these oxides are compatible so that it becomes very easy to combine them in a single ALD run by alternating the ALD cycles for Al_2O_3 and SiO_2. The composition of the alloys could be varied by adjusting the relative number of Al_2O_3 and SiO_2 cycles during the ALD process. Al_2O_3 was removed from the alloys using wet chemical etching in the phosphoric acid solution (85%, H_3PO_4) at 50°C. Phosphoric acid is a well-known alumina etchant, whereas silica is resistant against it, so that the selective dissolution of the Al_2O_3 resulted in the formation of nanoporous SiO_2 layer with lower refractive index as that of the compact SiO_2 films. The pathway of pore evolution depends critically upon the etching history. Only under a limited set of conditions that depend on the composition, the etching time and etching temperature, we could observe the desired pore evolution in the final SiO_2 films. Layers with refractive index of n=1.38 and porosity of 14% could be prepared by etching of the Al_2O_3:SiO_2 alloys with a ratio of 1cycle:1cycle. By adjusting the ratio of Al_2O_3 and SiO_2 contents, it was possible to increase the porosity and consequently decrease the refractive index of the final silica layers. Increasing the content of the Al_2O_3 in the alloys from 50% (1cycle:1cycle) up to 66.7% (4cycle:2cycle), porous SiO_2 films with a porosity of around 66% and a refractive index of 1.14 at 632.8nm could be achieved. The other alloys with higher content of alumina as in the alloy 4:2 (66.7%) were already unstable in the H_3PO_4 solution and etched away completely. The energy-dispersive X-ray spectroscopy (EDX) measurements showed that the Al was completely removed during the first 30min of etching. The removal of the alumina from the alloys could also be observed with an abrupt decrease of the film thicknesses during the given etching time. Afterwards, the films showed a slight increase of the thickness which was then constant during further etching. The Scanning Electron Microscopy (SEM) images confirmed the increase of the porosity in the final SiO_2 layers with increasing the Al_2O_3 content in the initial Al_2O_3:SiO_2 alloys. These results show the potential feasibility of the ALD to manufacture porous silica layers for applications in optics as low-n layers adding a new contribution to the advancement in the ALD field expanding it into new, wide-ranging applications.

9627-25, Session 6

Plasma-enhanced atomic layer deposition for antireflection coatings using SiO2 as low-refractive index material

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Anti-reflection (AR) coatings are essential to greatly reduce reflection losses and increase the transmission of optical surfaces. Commonly, thin films applied in precision optics are produced by physical vapor deposition (PVD). However, this methods require great technical efforts to meet strict tolerances, e.g. in film thickness. The adaption of an alternative coating technology is needed to comply with the ever-growing requirements on the performance of optical coatings, especially also on curved surfaces.

In this study, the implementation of fundamental optical interference coatings using plasma-enhanced atomic layer deposition (PEALD) is demonstrated. Atomic layer deposition (ALD) is a promising method that is particularly known for excellent scalability of film thickness, high reproducibility and uniform coating of substrates with high aspect ratio. This cycle-controlled deposition technique is based on self-limiting surface reactions. In every ALD cycle the same reaction takes place, hence optical homogeneous films are expectable.

SiO_2 was chosen as low-refractive index material and TiO_2 or HfO_2 were qualified as high refractive index materials. The development of PEALD processes was carried out in an Oxford Instruments OpAL open load reactor that is equipped with three precursor ports. Dielectric films were deposited using the metalorganic precursors tris(dimethylamino) silane [3DMAS], tetrakis(dimethylamino)hafnium [TDMAH] and titanium tetraisopropoxide [TTiP] for SiO_2, HfO_2 and TiO_2, respectively. In all depositions plasma activated oxygen was used as the oxidant in the ALD second half-cycle.

Single layer experiments were done on Si(100)substrates to prove the linear growth behavior of ALD layers that is essential for fulfilling the requirements of exact thickness control. For this purpose, X-Ray reflectometry (XRR) and spectroscopic ellipsometry was used to determine the resulting film thickness dependent on the number of deposited ALD cycles. Furthermore, single layers of the dielectric materials with minimum three quarter wave optical thickness (3QWOT) were deposited on fused silica substrates in order to analyze the transparency, optical homogeneity and the optical constants using spectrophotometry in a wavelength range of 200 to 1100 nm. The dependence of film microstructure and crystallinity on substrate temperature was investigated with scanning electron microscopy (SEM) and X-ray diffraction (XRD) in order to assure amorphous films without any scattering losses in the required spectral range.

The decision of the materials used in AR coatings was finalized after evaluating single layer experiments with respect to primarily optical losses, optical homogeneity but also film growth rates. The coating design of the multilayer was simulated considering the film thickness tolerances and dispersion of single layers. Antireflection coatings were produced on glass substrates and the optical performance was characterized in a broad spectral range using spectrophotometry.

9627-26, Session 6

Complex optical interference filter with stress compensation

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We present hereafter the results on the fabrication of complex optical filters within the Espace Photonique of the Institut Fresnel in close collaboration with CILAS Company. Bandpass optical interference filters, with central wavelengths ranging in near ultraviolet or in the near infrared, were deposited on both sides of glass substrates with a very good congruence with theoretical designs. For these applications, the required functions are particularly complex as they must present a very narrow bandwidth as well as a high level of rejection over a broad spectral range. Moreover, in order to satisfy more and more critical specifications on flatness of the component treated on both faces, the stress induced by the different layers has to be taken in account in the filter design.

All these components were manufactured using Plasma Assisted Reactive Magnetron Sputtering (PARMS) technique offered by the HELIOS machine and monitored in real time with an OMS5000 in-situ optical monitoring, both developed by Leybold Optics. The reproducibility and the stability of this process allowed manufacturing complex filters with more than 120 layers and 25 μm thickness.

To have the best knowledge on the stress parameters of both, high and low, materials, a dedicated study has been performed on single layers with various thicknesses. From the dependence of the radius of curvature on the film thickness for each material, the values of the stress were extracted and implemented in the filter design.

After presenting the coating process and stress measurements, we review the spectral responses of both devices with a focus on some specific parameters, i.e. uniformity, spectral transmission, spectral rejection, deformation. Flatness of the final components is extrapolated from the measurement performed separately on both faces of the device using white light optical profilometry. High transmission, i.e. very low absorption, is also demonstrated for near-UV filters. To be in accordance with demanding requirements concerning cosmetics performances, improvement of the process were implemented and allowed decreasing the number of defects by several orders of magnitude.

9627-27, Session 6

Properties of Nb2O5, Ta2O5, and SiO2 thin films prepared by different deposition techniques

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Optical, mechanical properties and microstructure of Nb_2O_5, Ta_2O_5 and SiO_2 thin films prepared by electric beam evaporation deposition(EB), ion beam assisted deposition(IAD) and ion beam sputtering deposition(IBS) were systematically studied. Ion bombardment process can significantly improve the microstructure and reduce the surface roughness of thin films compared to the results of samples deposited by EB and IAD. The effect of assisted ion energy of ion beam sputtering on the films were investigated. Thin films deposited by IBS present very good optical performance and mechanical performance but higher compressive stress than other deposition techniques.

9627-58, Session PTue

Multiple scale modeling of Al2O3 thin film growth in an ion beam sputtering process

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Thin film growth simulation approaches are a reliable tool to investigate in fundamental mechanisms of layer formation and to support experimental optimization procedures for the realization of high quality optical coatings. Since the computing power increases continuously, it became possible to simulate more complex and larger atomistic systems matching well the structural data of common optical thin films. In order to perform representative calculations, which can be used to improve the resulting layer properties, the underlying parameters of the coating process have to be taken into account in the growth model. Especially, the generation of the coating material, the transport of the material inside the coating chamber, and, as a result, the characteristic energy and angular distributions of the coating material at the substrates define the growth of the thin films. Furthermore, the resulting optical layer properties, e. g. index of refraction, optical bandgap, extinction coefficient, are of particular interest, being the class of properties that is most easily accessible for the coating manufacturer.

In the present contribution, the growth of an Al_2O_3 single layer is studied applying the parameters and geometry of an experimental Ion Beam Sputtering (IBS) coating plant. To perform a full simulation of the entire coating process, starting with the generation of coating material, the modeling of thin film growth and finally, the calculation of the optical properties of the realized thin film structures, several simulation techniques were combined to a multiple scale model approach. The used techniques are working on different time and length scales, and each of them is intended to describe a defined and differentiated physical problem of the complete simulation chain. The simulation methods are merged with adapted interfaces in order to secure the compatibility between each technique. A Direct Simulation Monte Carlo (DSMC) approach is applied to model the transport of the coating material from the location of generation to the substrates. Therefore, the geometry and the process parameters of the existing IBS coating plant are transferred into the DSMC calculations. The resulting characteristic energy and angular distributions of the coating material at the substrates are used in the following to simulate the layer formation with a developed thin film growth approach which is based on classical Molecular Dynamics (MD). From the classically grown films the structural layer properties, e. g. film density, surface roughness, and stoichiometry are derived. Finally, the optical properties are calculated by quantum mechanical simulation techniques on the level of Density Functional Theory (DFT). The determined structural properties are used to prepare small supercells which represent the main input for the DFT simulation. As a result, the imaginary part of the dielectric function is calculated. With the application of the Kramers-Kronig relation, the real part of the dielectric function and in conclusion the frequency dependent index of refraction of the modeled IBS alumina thin film structure can be determined. In order to validate the presented multiple scale approach, the results are compared to the optical properties of an Al_2O_3 single layer prepared with the investigated IBS coating plant.

9627-59, Session PTue

Preparation and characterization of aluminum oxide/aluminum fluoride mixture coatings for applications in the deep ultraviolet spectral range

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Aluminum Oxide (alumina, Al2O3) is one of the choices for mid-index coating materials typically applied in the wavelength range between 7000 and 200 nm [1]. Moreover, because in the Vacuum Ultraviolet/Deep Ultraviolet (VUV/DUV) spectral regions, typical high index oxide materials such as titania, niobia, hafnia, tantala and the like show strong absorption and are therefore not suitable for interference coating design purposes, alumina becomes an interesting candidate for applications as a high index oxide VUV/DUV material [2]. This is particularly relevant for applications at the 193 nm lithography wavelength [3].

A promising approach to prepare mid- to low index UV layers with tailored refractive indices is offered by preparing mixtures of pure UV-materials using PVD techniques. A combination of aluminum oxide and fluoride coating materials in mixture thin films is expected to offer an extension to lower refractive indices, higher optical band gap energies, and potentially higher laser induced damage threshold (LIDT) in the femtosecond regime compared to UV compatible pure oxide mixtures [4].

In the present study, emphasis will be placed on preparation of suchlike mixture coatings by co-evaporation in a PIAD process, while the focus is on the flexibility in optical (refractive index) and mechanical (layer stress) properties offered by these mixture coatings. Particularly, the relation between optical constants and elementary layer content as found by means of EDX is discussed in more detail. Emphasis is further placed on reproducibility issues.

It will be shown, that the mentioned deposition technique allows preparing aluminum oxide/ aluminum fluoride mixture coatings (as verified by EDX) with flexible refractive indices varying between 1.40 and 1.75 in the deep ultraviolet spectral region. At the same time, extinction coefficients vary between less than 1x10-4 and 2x10-3. With respect to the n- and k-values, no remarkable difference can be obtained when comparing Co-PIAD and Co-IBS mixture coatings [5]. As it is established in this study, some of the Co-EBE and Co-PIAD samples tend to appear practically free of mechanical stress because of certain porosity. Those mixtures appear prospective for use in DUV optical coatings with flexible refractive index and low mechanical stress.

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9627-60, Session PTue

Ion beam sputtering for plane and curved optics on 2-meter scale

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Optical coatings are essential for many applications of excimer or frequency converted solid state lasers in industry and science. An increasing demand for larger optics of highest quality, mainly generated by the display industry processing active matrix OLED backplanes, is posing new challenges for substrate and coating suppliers. For the deposition process development principally the coating uniformity, but also the handling and the cleaning steps of optics with one edge length (L) above 1 meter and several kilograms of weight have to be considered. To provide coatings for optics up to 2 meter edge length a new ion beam sputtering (IBS) machine was developed at LASEROPTIK.

This contribution describes an approach to adapt the IBS technology with its highest coating quality for small optics (L≤50mm) to the field of large area deposition (L≥1m). Applying a customized linear drive, the MAXIMA deposition machine is able to coat optics of up to 100kg weight sequential. Experimental results on the uniformity, the spectral characteristics, and the laser damage resistance of dielectric single- and multilayer coatings are presented and compared with the performance of standard IBS thin films. Furthermore the deposition of thin films on convex curved surfaces applying curvature dependent movement profiles is discussed. Finally the run to run stability is evaluated on the basis of concrete coating examples.

9627-61, Session PTue

Morphology and microstructure of cyanine dye J-aggregate film: correlation with absorption, photo- and electroluminescence, and exciton-polariton

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J-aggregate cyanine dyes are a class of absorbing and luminescent materials extensively employed in the polariton-based research. Here we present a systematic study of the DEDOC cyanine dyes J-aggregate films made by layer-by-layer assembly (LBL) and spin-coating processes to establish a correlation between the film structure and the absorption, luminescence, and exciton-polariton properties. From detailed analyses of morphology, optical spectra, and device characteristics, we demonstrate that LBL produces higher degrees of homogeneity and molecular packing quality of J-aggregate films compared to spin-coating process. This consistently correlates with a higher absorption coefficient, more uniform luminescence, a greater electroluminescence quantum efficiency, and stronger exciton-photon coupling of LBL J-aggregate film.

9627-63, Session PTue

Structual and optical performance of Pd/B4C working from 7.5nm to 11nm

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Boron or boron carbide based multilayers are basically selected since the energy is just below boron K absorption edge for operating from 6.7nm to 12.4nm except Mo/Y multilayer. The highest reflectivity exploration was made for a series of material combinations and the Pd/B4C multilayer has the highest theoretical reflectivity from 7.5nm to 11nm based on the practical views. However, the studies and applications of Pd/B4C multilayer are few at the moment. In this paper, the Pd/B4C multilayer

coatings are manufactured by direct current magnetron sputtering. Different base vacuum pressures and different bilayer multilayers were investigated to study the influence of e.g. oxygen and nitrogen in the vacuum. Reactive sputtering with 6% nitrogen was also used to improve the Pd/B4C multilayer interfaces. Grazing incidence X-ray reflectometry at 8keV and transmission electron microscopy (TEM) were used to investigate the multilayer structure. Different models were introduced to fit the hard x-ray reflectivity curves. The at-wavelength reflectivity measurement was carried out at Beijing Synchrotron Radiation Facility. The sructural and optical properties of Pd/B4C multilayers were obtained.

9627-64, Session PTue

Protected and enhanced silver for mirrors: damage mechanisms and how to prevent them

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Thin film coatings are indispensable in order to manufacture mirrors with highest possible reflectivity. The maximum reflectivity can be achieved by all-dielectric coatings; however, the spectral bandwidth of these mirrors is limited. Metal based coatings (Al, Au, Ag) are applied, as they enable a high reflectivity and at the same time a broad spectral bandwidth. Of all metals, Ag provides the highest reflectivity from VIS to IR. Because of the high reflectivity, mirrors with Ag-coatings are the first choice for many applications. This is especially true for optical devices where multi-reflections are necessary.

Silver is a noble metal. However, corrosion activators (S and Cl) in combination with water/humidity can lead to corrosion. During aging, corrosion products like Ag2S and AgCl are formed and reduce the reflectivity. Thus, a protective layer is required to prevent the corrosion and sustain the high reflectivity of the mirror. A protective layer on the mirror front-side influences the optical properties. Therefore transparent dielectric materials like oxides, nitrides or fluorides are commonly applied as protective layers. Sputtering enables deposition of silver and dielectric materials at large and curved substrates. Unfortunately, at harsh environmental conditions, damage of the Ag-coating can occur even in the case of protected Ag. In this contribution we present:

- possible damage mechanisms at protected Ag,
- test methods concerning these damage and
- how to prevent these damages.

The damage mechanisms are based on corrosion activators which permeate the protective layer and subsequently damage the Ag. The permeation is possible due to weak spots in the protective layer. These week spots occur due to porosity, pinholes, particles on the substrate or a rough surface of the substrate. In addition to this already known damage mechanisms, we will describe the particle induced damage mechanism. Hygroscopic air borne particles absorbed on the surface attract water molecules and form a solution. This solution damages the protective layer in a first step, subsequently permeates the layer and finally damages the silver whereby the reflectivity is reduced. It is possible to test the stability of different protection systems concerning these damage mechanisms.

The understanding and the ability of testing concerning these mechanisms enables a systematic improvement. An improved environmental stability can be achieved by combine layers of different materials. The same approach can be used to enhance the reflectivity by use of the interference effect. For many applications, mirrors with a high reflectivity between 350 nm and the IR-range are required. In these cases a UV-enhanced Ag-coating is a suitable option. We present such a coating which offers an enhanced reflectivity (> 95% for wavelength > 350 nm) in the UV-range and an increased environmental stability at the same time.

9627-65, Session PTue

Frequency domain in situ GDD measurement

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During the last years, short pulse lasers have gained of increasing importance especially in ultra-precise material processing. On the way to more power and shorter pulses the demands on the lasers increased rapidly. Today, key elements of many short pulse lasers are chirped mirrors for compensation of dispersion effects induced within the beam path. To achieve these shorter pulses chirped mirrors with very flat broad negative group delay dispersion (GDD) or very precise high negative GDD are needed. This imposes critical demands on coating precision and coating control mechanisms. To deposit these complicated coating designs with more than hundred layers, advanced optical monitoring strategies like broad band monitoring and also single wavelength monitoring are state of the art. These techniques use transmittance or reflection measurements during the coating process to terminate every single layer with a defined optical thickness. One effect, which has to be mentioned in this context, is error compensation. Usually, this is a positive effect of optical monitoring, which compensates e.g. for deviations in optical constants by modification of physical thickness. Furthermore, errors in already deposited layers are corrected by thickness adjustments of following layers. As a consequence, the result will be normally slightly worse than the target specification but better than without compensation effect. In case of chirped mirrors with additionally defined GDD target, this compensation effects can be counterproductive, because variations or inaccuracy in dispersion have a large impact on the GDD and cannot be easily compensated by thickness modifications. Hence, the last layers of chirped mirrors, which normally represent an adjustment of the optical impedance, have an essential influence on the GDD performance of the mirror and are often controlled by classical methods like quartz crystal monitoring or time counting. These methods are not very effective, because many coating iterations will be needed to find a coating parameter set for a satisfactory GDD result. To attain information about the developing GDD especially of these last growing layers, an in situ Fourier-transform measurement system is proposed. The method is based on a Michelson interferometer with a broad band light source and a very fast spectrometer. To our knowledge it can be shown for first time that it is possible to measure the GDD directly on the moving substrates during coating process. With this additional information about the group delay dispersion, novel real time algorithms can be developed to react on deposition errors and to optimize the thicknesses of the last layers of chirped mirror systems.

9627-66, Session PTue

Optimized strategy for IBS-deposition of dielectric filters using broadband optical monitoring and testglass changer

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In the last decade, broadband optical monitoring became a powerful tool in the production of optical thin films and enabled the fast and reliable automated production of complex filter designs in industrial environment. Even the realization of quasi-rugate filters with a very high number of design layers and a high physical thickness has been demonstrated successfully using ion beam sputtering deposition (IBS).

Broadband optical monitoring includes an inherent mechanism of error self-compensation for most designs which limits the size of thickness errors and stabilizes the control of the deposition process. However, apart from this positive influence of error compensation in the same deposition process also a kind of error propagation effect increasing from layer to

layer can inhibit the exact calculation of the termination points of the layers. This in the end limits the accuracy of broadband optical monitoring and also defines a maximum number of layers that can be monitored.

To reduce this error propagation effect, indirect monitoring using several witness samples can be applied. Nevertheless, the selection of the right monitoring strategy for these witness samples or so called testglasses often depends on the experience and preferences of the operator and is chosen subjectively. In this publication, an algorithm to automatically determine an optimized monitoring strategy for a specific design using up to 6 different witness samples will be presented. This algorithm is based on the analysis of the dynamics of theoretical transmission spectra of the used design. A high dynamic signifies a fast change of transmission in the measured spectral range per nm physical thickness and will increase the sensitivity of the optical monitoring. This can reduce the error propagation and finally might also make the calculation of layer termination points more reliable. A testglass changing mechanism installed in an IBS deposition plant allows for an easy exchange of the witness samples during the deposition without venting the coating chamber and will also be introduced.

Beside the effect of error propagation, the sensitivity of optical broadband monitoring is dramatically reduced when a design has to be fabricated with a low index material as starting layer on the substrate. This is a well-known effect in optical monitoring of thin films caused by the low refractive index contrast between substrate and low index material. To overcome this situation and to increase monitoring sensitivity typically a pre-coated testglass with a high refractive index layer is used for indirect optical monitoring. In this publication we will analyze the effect of this pre-layer on the monitoring of the subsequent design layers and propose an algorithm to determine an optimized pre-layer for each specific design. This algorithm is again based on the investigation in the dynamics of theoretical transmission spectra.

To compare different pre-layer configurations and different monitoring strategies, simulations of coating runs using virtual deposition processes are presented. Advantages of the optimized monitoring strategy are discussed. A quasi-rugate filter design is deposited with IBS using the derived optimal monitoring strategies including an ideal pre-layer and multiple testglasses.

9627-67, Session PTue

Precise fabrication of ultra violet dielectric dispersive mirrors

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During the last years, ultra-short pulse lasers gained more and more interest for commercial industrial use. In order to fulfil the demands imposed by these applications, special dispersive optics are required that compensate the dispersion and maintain the temporal profile of the laser pulse. Progress in coating deposition techniques and material studies led to commercial fabrication techniques for high reflective dielectric dispersive mirrors (CMs) covering a wavelength range from the visible (VIS) to the near infrared (IR). For example, dielectric dispersive mirrors are involved in the generation of laser pulses with durations shorter than 2 fs in the visible range. However, fabrication of ultra violet (UV) dielectric dispersive mirrors with high reflection below 350 nm is still challenging for several reasons. Firstly, only a limited number of materials with appropriate optical quality are available in this spectral range. Prominent materials are Hafnium oxide (HfO_2), Aluminium oxide (Al_2O_3) and Silicon dioxide (SiO_2), which suffer from specific problems concerning the reproducibility of dispersion data and optical absorption in the UV-range. These difficulties accumulate in CMs, which are typically composed of many layers to a total thickness of several μm. Secondly, the average layer thickness of CMs scales roughly linearly with the central wavelength, and consequently, the acceptable layer thickness precision has to be improved for the UV-range. In this context, the thickness precision and control approaches single atomic layers in the UV compared to an average absolute layer thickness accuracy of 0.5 nm in the VIS-range. In general, the target group delay dispersion (GDD) is extremely sensitive to deposition errors. A single deposition error in the last layer of about 1nm leads to a total failure of the target GDD.

The present contribution is concentrated on an improved method to fabricate dielectric dispersive mirrors in the UV-range by applying a new phase monitoring system. The developed measurement device monitors the phase of the electric field in-situ during the deposition of the laser system using a fiber based white light interferometer.

The study is initiated by a design synthesis involving most suitable materials, including ternary composites, to achieve optimum reflection and GDD values. Afterwards the best suited design is manufactured with an Ion Beam Sputtering (IBS) process. Ternary composites are sputtered applying a zone target assembly. The first layers of the stack are switched using in-situ broad band monitoring in conjunction with a forward re-optimization algorithm, which also manipulates the layers remaining for deposition at each switching event. To accomplish the demanded GDD-spectra, the last layers are controlled by the novel in situ white light interferometer operated in the infrared spectral range. The desired GDD in the UV is achieved by selecting a design which is characterized by an appropriate GDD target in the IR.

9627-68, Session PTue

Anti-reflective coating corrrection for ultra-low-reflectance large optics

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In order to not degrade the final performances of complex optical systems it is required to limit the overall wasted reflected light coming from all the different surfaces involved. Ultra-low-reflectance coating becomes even a crucial point for high sensitivity experiments such as gravitational wave detectors where a dozen surfaces must not have a total reflectance higher than 0.2% equivalent to a reflectance lower than 100 ppm per surface.

Some tenth of percent is a common value for Anti-Reflection (AR) coating but reflectance below 100 ppm is trickier to achieve. The coating design sensitivity with respect to thickness errors or refractive index error can lead quickly to non-compliant reflectance. Moreover process parameters such as shutter closure time or sensor drift can occur as well and cause additional error.

When an AR coating has failed it is very difficult to recover the low reflectance. In theory adding one or two layers could correct the reflectance but it requires knowing exactly the actual coated stack. That is the aim of the well-known reverse engineering techniques. Spectrometric measurements (T or R) are usually used to retrieve actual thickness of the different layers constituing the coating. These technique work pretty well with small samples but they are more complicated to perform with larger ones (larger than 100mm in diameter)

For large optics (diameter up to 500 mm), we developed a new technique based on reflectance measurements with different polarizations and incidence angles at one wavelength. Thanks to the knowledge of the indexes of refraction measured on monolayers, one can determine the actual thicknesses of the layers by non-linear fitting. The measurements were performed in s-polarized and p-polarized light to discriminate between several solutions. Indeed by analyzing separately each data set we get two families of solutions having equivalent value of the function of merit. In contrast one optimal solution can be determined by taking into account both polarizations. Then a correction based on one or two layers is computed in order to decrease the reflectance.

The method efficiency is demonstrated in the case of a four-layer AR coating designed for zero reflectance at 1064nm and coated onto a 350mm diameter and 200mm thick substrate. The reflectance has decreased from 500ppm to 26ppm thanks to a correcting bilayer. Experimental aspects will also be highlighted during the poster presentation.

9627-69, Session PTue

Multispectral thin film coating on infrared detector

Fabien Pradal, Meihdi Oussalah, Benjamin Portier, Daniel Mouricaud, REOSC (France); Hervé Sik, Sagem (France); Joel Fleury, Patrice Laprat, Sagem SA (France)

High end applications in infrared may benefit from infrared colorimetry. Actual systems are designed using filter wheel, gratings or dichroic components. Those systems are bulky, do not allow real-time acquisition and are sensitive to stray light.

Reosc recently developed technologies to pixelate infrared coating filter at detector level. It allows to design very compact systems, easy to cool down and to significantly reduce ghost images. Optical systems are simplified and can achieve fast acquisition of multi-spectral video.

Simulations using Maxwell Gauss equations have been performed in order to optimize pattern shape and profile. The etching processes of multilayer optical stack have been developed. Finally, a prototype has been manufactured and tested.

This technology opens up new perspectives in the field of infrared filtering.

9627-28, Session 7

Some aspects of absorption and gain *(Invited Paper)*

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Absorption and gain are difficult to define precisely but in the sense we shall use the terms, they represent a failure of the sum of specularly reflected and transmitted light to equal that incident. A greater sum represents gain and a lesser, absorption. Although there is a variety of physical processes that can contribute to these phenomena, their quantitative expression can be achieved through a nonzero extinction coefficient k. In the normal way we encourage gain and discourage absorption, but, recently, an increasing interest in enhancing absorption has emerged. Calculations involving nonzero k are straightforward but understanding the consequences can be a little more difficult. The admittance diagram is mostly used for conventional coatings that are either dielectric or, sometimes, absorbing. However the admittance diagram has much greater potential and can help in these more complex cases and especially in respect of lasers, amplifiers and perfect and coherent perfect absorbers, the latter being essentially linear switches. Normal thin-film calculations start from the light that enters the emergent medium through the rear surface and works backwards to find the conditions at the surface of incidence. Our normal thin-film model is actually capable of much more and it can readily handle a much wider range of conditions. In terms of the admittance diagram, it is simply necessary to open up the second and third quadrants of the complex plane. There the net flow of energy is in the opposite direction and the rules for the loci are a little different from those in the more usual first and fourth quadrants. The quarterwave rule still applies, although dielectric loci are described counterclockwise instead of clockwise, and increasing reflectance implies moving towards the point -y0 rather than moving away from it. The admittance diagram connects an emergent surface admittance to an incident surface admittance. The surface admittance is C/B where C and B are the normalized total tangential magnetic and electric field amplitudes respectively. A useful concept is that of a reversed admittance locus that answers the question of where the locus should start if it is to terminate at a desired point. The admittance locus is, however, is just part of the story. Net inputs and outputs require also a product involving B and C and the implication, therefore, is that both should be known. This is not difficult. The existing model can handle this without problem, but it does add another dimension to the calculations. The most important point is that we do not need to change our model. We simply need to use it in a slightly different way.

9627-29, Session 7

Metal-dielectric absorbers with magnetron sputtering technique

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In this paper, we show how thin film absorbing coatings can be designed with multilayers using both metallic and dielectric materials involving some thicknesses that are very low down to some nanometers. Such multilayers enable to reach a very low level of reflectance and a zero value of transmittance which can be a solution for stray light reduction in optical systems.

After a description of the design steps, we will present the manufacturing of such multilayer stacks using magnetron sputtering technique and we will see how such coating technique is very well suited for production due to its high process reproducibility even for very thin layers required in metal-dielectric absorbers.

Monitoring of such coatings is also presented with the help of a powerful in situ optical system developed in collaboration with Institut Fresnel that allows characterization of in-situ refractive indices of deposited materials and broadband monitoring of the multilayer stack.

Many results will be given on qualification samples, such as environmental tests and spectral characterizations that show the stability of the performances in severe environmental conditions.

At last, we will focus on the spectral and angular scattering behavior of such absorbing coatings and we will present several measurements performed on glass or metallic substrates with different roughnesses.

9627-30, Session 7

2x2-array pixelated optical interference filters

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The need for imaging systems for onboard scientific applications (e.g. for planetology) is becoming of prime interest. Today's CCD scientific cameras do not provide spectral information of the observed scene. Multi-spectral imaging therefore requires the usage of filters wheels which allow achieving the required optical performances but are a heavy and bulky solution that make them non-adapted for space missions.

The goal of this work consisted in developing pixelated filters that could be directly integrated in front of an onboard CCD camera in order to provide with the required spectral information without significantly changing the volume and the weight of the whole system. Also, the central wavelength and the spectral profile of each pixelated filter needs to be adapted to final application requirements.

In this paper, we show the first demonstration of 2?2-array pixelated optical filters with 30 ? 30 ?m2 pixel size. Four bandpass filters centered at 550, 700, 770 and 840 nm and ? 40 nm bandwidth were designed and fabricated. Those filters reject in a broadband from 500 to 900 nm. These filters were then fabricated by a masking technique using lift-off processes with two photoresists in order to secure sharp edges for each pixel. Deposition of the filters was carried out using ion assisted deposition technique. Each filter was obtained by the deposition of about 40 layers and has a total thickness in the range from 3 to 5 microns. A dedicated setup (SPHERE) was also developed in order to characterize the spectral response of each pixel with high spectral (0.5 nm) and lateral (2 microns) resolution. This system uses a white light source coupled with a monochromator. An imaging system allows imaging the source on the pixelated filter which is further imaged on a CCD camera with a 700?450 µm2 field of view. Square core optical fibers associated with a deformable mirror allows obtaining a speckle free and uniform illumination of the pixelated filter. Comparative measurements between witness samples and filters prototypes show that this system has a precision similar to a commercial spectro-photometer and that the pixelated filters have performances comparable to the witness 25 mm aperture filters. This new technology therefore paves a way to the fabrication of multispectral imagers with versatile spectral specifications.

9627-31, Session 7

Angle insensitive color filters

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We propose five kinds of angle insensitive color filters based on compact multilayer structure and two-dimensional (2D) subwavelength gratings using silver and silicon, which maintain the same perceived specular colors for a broad range of incident angles with the average polarization. The transmission/reflection curves at different incidence angles are coincident and the color difference calculated by CIE DE2000 is small up to 45°, even less than 2 for the some filters, within the threshold value of the human visual sense. High refractive index of silicon and outstanding ability of exiting surface plasmon resonance of silver contribute to the incident angle insensitivity of these color filters, while concretely, the spectral filtering feature is attributed to the particular mechanism for these specific structure. These angle insensitive color filters can have enormous potential for diverse applications in display, colorful decoration, anti-counterfeiting and so forth.

9627-32, Session 7

Design, production, and reverse engineering of a double sided innovative thin film laser element

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Most of the modern ultrafast laser systems include thin film optical elements such as dispersive mirrors, chirped mirrors, beamsplitters, output couplers exploited for accurate phase control which is necessary for efficient pulse compression. Design and production of such coatings require using effective numerical design algorithms, stable deposition techniques and high precision thickness control. The situation is even more challenging if, for some reasons, a double-sided thin film element is required. In this case, design, deposition and characterization of two complicated coatings should be interconnected.

In the present work we report about an innovative optical element developed for the multiterawatt few-cycle light wave synthesizer (LWS-20) based on optical parametric amplification. LWS-20 currently produces sub-5-fs, 80-mJ, 18-TW pulses. The required multilayer element had to have an average value of the GDD of +75 fs2 and reflectance exceeding 99% in the spectral wavelength region from 560 to 1030 nm. Also, the element had to have the diameter of 75 mm at a substrate with 15 mm thickness.

The designed dispersive mirror consisted of 68 layers and had total physical thickness of 7658 nm; niobium pentoxide and silicon dioxide were taken as layer materials. Mechanical stresses of DM layers caused the substrate bending that distorts wave front quality resulting in a distorted focus of the laser system. In order to compensate this mechanical stress, the substrate back side was covered by an antireflection coating (AR) providing the lowest possible reflection in the working spectral range and having the total physical thickness close to DM thickness. In addition to this, total thicknesses of Nb2O5 and SiO2 were close to the corresponding total thicknesses of Nb2O5/SiO2 in DM layers. As a result, a back side AR containing 71 layers and satisfying all required specifications was successfully designed with the help of OptiLayer Software.

In order to produce the optical element, two deposition runs were performed using HELIOS machine. First, DM design was deposited on two substrates: Glass B260 of 1 mm thickness and BK7 of 15 mm thickness. In the second run, the back side of the BK7 substrate was covered by AR design. Also, the AR design was deposited on an uncoated Glass B260 substrate. Finally, this procedure resulted in a double-sided multilayer element DM-AR as well as two one-sided samples of DM and AR coatings. Transmittance scans were recorded in-situ after the deposition of each layer of DM and AR coatings on glass substrates. We performed reverse engineering of the samples on the basis of on-line scans.

The spectral characteristics as well as group delay of the DM-AR element were measured. The optical element exhibited excellent spectral properties. We demonstrate the whole design-production chain including design, production and careful post-production characterization of the coating.

9627-33, Session 8

High reflecting dielectric mirror coatings deposited with plasma assisted reactive magnetron sputtering *(Invited Paper)*

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Manufacturing all dielectric mirror coating with reflectivity values of more than 99.99 % is still a challenge to achieve. Losses caused either be transmittance, absorption or scattering have to be maintained well below 100ppm. Increasing the layer number for minimizing the transmittance losses usually increases the scattering by the growth of the roughness. High energy processes are required to minimize or avoid this behavior, but which are a challenge for avoiding unwanted contamination and interface absorption due to unwanted sputtering. As high energy process we used for the preparation of high reflecting dielectric mirrors plasma assisted reactive magnetron sputtering with a Helios 800 system.
The machine was equipped with 3 cathode position for low and high index materials. We used metallic tantalum and hafnium targets for the preparation of the high index, silicon and silica targets for the low index. Metallic targets were powered with mid frequency, whereas the quartz target was sputtered by rf. As substrate we used either super polished fused silica or standard silicon wafer. The optical properties of the substrates we characterized by CRD, Laser calorimetry and spectrophotometric measurements. All combination allowed us to reach reflectivity values above 99.99%, with total deficit levels as low as 36ppm.

9627-34, Session 8

Highly dispersive mirrors for thin-disk oscillator

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Recently, femtosecond high-energy oscillators and amplifiers have become popular tools in research labs and in a number of industrial applications. Pulse energy of femtosecond diode-pumped thin-disk oscillators has increased significantly to µJ levels at MHz-repetition rates and pulse durations have been reduced below 200 fs. Such high energy lasers open new horizons in the femtosecond and attosecond science. Dispersive mirrors constitute key components of these systems, with their performance significantly affecting that of the laser.

We developed and manufactured high-dispersive mirrors (HDM) with record values for the group delay dispersion (GDD) of -10000 fs2

and with wavelength range of 1027-1033 nm. In order to design HDM OptiLayer software was used and a novel robust synthesis technique was applied. The HDM was produced with the magnetron-sputtering (Helios, Leybold Optics). We chose Ta2O5 and SiO2 as materials with high (2.1 @ 1030 nm) and low (1.45 @ 1030 nm) refractive indices, respectively. These materials offer optimum trade-off between low loss and high difference in the refractive indices for the wavelength range around 1030 nm. The fabricated mirrors have reflectance >99.95% and therefore can be used for intra-cavity of disk lasers.

The reflectivity of the manufactured HDMs was measured with a precision loss meter (LossPRO, Novawave Technologies, Inc.) at wavelength of 1030 nm, yielding excellent values. The GDD values measured with the home-build white light interferometer are in a good agreement with theoretical values. The difference between theoretical and measured GDD can be explained by high sensitivity of the HDM design to errors in layer thicknesses and was predicted by the error yield analysis.

Reported mirrors fully cover emission bandwidth of Yb:YAG gain media and have been successfully utilized in the Kerr-lens mode-locked Yb:YAG thin-disk oscillator which yields 200 fs pulses.

For oscillators operated at a negative cavity GDD, the maximum pulse energy that is achievable in the regime of stable operation is proportional to the net magnitude of negative group-delay dispersion. Therefore reported HDMs with -10000 fs2 open the way to a new level of thin-disk oscillator energies.

9627-36, Session 8

Low scattering filter coatings made by plasma-assisted reactive magnetron sputtering

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In multi-spectral instruments, the spectral separation is performed by optical bandpass filters. The demands placed on the filters are, among others, a high transmittance for a certain spectral band and a deep and wide out-of-band blocking, as well as steep spectral edges in the transition zones. Thin-film coatings with large coating thicknesses (up to 20μm) and a high number of layers are necessary to meet the spectral requirements. With increasing coating complexity, more and more light is scattered. Under white light illumination not only the direct transmitted beam of the in-band wavelengths is observed but also scattered light of out-of-band wavelengths can pass the filter. That affects the performance of the instrument as out-of-band light reaches the detector. This effect has been observed for filters used in earth observation and is described in literature as "large angle scatter".

The main reasons for scatter effects are micro-irregularities of surfaces, whereas for low-loss deposition processes the substrate roughness has the largest impact. As the surface structure is reproduced at each layer boundary within the multi-layer stack, complex coatings with several hundreds of layers require well-polished substrate surfaces with rms roughness < 0.5nm. A high-energy process called plasma-assisted reactive magnetron sputtering (PARMS) has been used for deposition. This low-loss process is known to produce highly correlated coatings, in terms of surface micro-structures, and low level of uncorrelated effects such as volume scattering.

Furthermore, the filter orientation as well as the layer sequence of the thin-film design contributes crucially to the level of scattered light. The configuration of a broadband blocking bandpass filter facing the instruments detector and an antireflective coating on the backside of the substrate has been shown to be beneficial. All dielectric, self-blocking coating designs with an optimized layer sequence have been developed in order to avoid a deep penetration of scattered light into the layer stack.

The measurements of scattered light have been performed with a spectrophotometer equipped with an integrating sphere. The filter coatings deposited by PARMS show a significantly reduced level of scattered light as well as an overall improved spectral performance. Compared to coatings deposited by ion-assisted evaporation (IAD), the level of out-of-band scattering could be reduced by more than 2 orders of magnitude to about 0.001%.

9627-37, Session 9

Advances in monitoring of optical thin film deposition *(Invited Paper)*

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The reliability of the production of complex thin film optical filters is highly dependent on a precise deposition control. On the one hand, layer thickness monitoring systems for accurate end-point detection are essential even within stable deposition processes. On the other hand, online monitoring concepts can be applied to further stabilize deposition processes by complementing or replacing open-loop control systems by the implementation of closed-loop control approaches. However, in most cases layer thickness monitoring is in the focus of attention. Based on the task to produce optical filters, optical monitoring systems are naturally advantageous and have become established over decades. Today, indirect monitoring concepts are replaced more and more by direct monitoring solutions that measure optical properties of samples on the moving substrate holder. Also deterministic production strategies based on process and monitoring simulation packages as well as online error correction tools found their way into optical coating industry. Virtual deposition processes are not only applied for the selection of stable multilayer designs but also as an important process development tool for investigating parameter dependencies. Nevertheless, the process control algorithms and the simulation tools have to be further improved, for instance by integrating layer growth models to predict optical and non-optical thin film properties. Another promising approach is the development of optical monitoring systems, which are not limited to the measurement of the transmittance or reflectance of the growing layers. On the one hand, the online-evaluation of simultaneous transmittance and reflectance measurements allows for new process insights. Current optical monitoring systems mostly calculate the layer thicknesses on the basis of fixed predetermined n and k dispersion data. Using a combination of transmittance and reflectance data, more information about n and k can be derived online, e.g. in case of process deviations and layer inhomogeneities. On the other hand, a new monitoring system has been developed, which enables the measurement of the phase information directly on the moving samples being coated. The set-up consists of a Michelson interferometer that has been transferred successfully from the stabilized optical bench to an ion beam sputtering deposition chamber. For instance, this system can be used to monitor the group delay dispersion for depositing advanced femtosecond laser optics.

In general, modern process control systems have to be flexible with regard to the process environment as well as a wide variety of thin film designs. In particular, there should be no need for any individual design dependent monitoring strategy. Some solutions include hybrid systems based on a combination of different monitoring approaches. In the context of process stabilization in situ monitoring approaches can cover a range from pure error detection to advanced closed-loop control, e.g. to prevent process drifts. On the one hand, already available measurements can be used as input for new control algorithms. On the other hand, previously unused measurement methods can be implemented to stabilize the deposition processes. In this contribution an overview of different monitoring approaches in combination with recent application examples will be given.

9627-38, Session 9

Advanced optical monitoring system using a new developed low noise wideband spectrometer system

Alfons Zöller, Leybold Optics GmbH (Germany); Detlef Arhilger, Michael Boos, Harro Hagedorn, Bühler Alzenau GmbH (Germany)

The monitoring capabilities for the production of optical multilayer coatings in batch type coating systems were improved significantly in the last 15 years. Substantial progress was achieved by introduction of direct intermittent monitoring on the moving substrate holder. Monochromatic and broadband monitoring systems are successfully used for thickness control in production.

A newly developed wideband optical monitoring system (WB-OMS) is based on a fast triggered spectrometer with a high dynamic array detector with low signal noise. It is useful for fast in-situ transmittance measurements on the rotating substrate holder during the deposition. The spectra can be stored and used for re-engineering analysis.

Layer thickness control with monochromatic monitoring strategies can be applied by using a selected single wavelength from the array detector. The high dynamic detector supports the classical turning point monitoring as well as trigger-point cut-offs with online corrected end points.

Alternatively the thickness can be controlled by using a broad spectral range. The function of merit of the measured curve and a calculated spectrum is minimised by fitting the actual thickness. The calculation is based on the commonly used matrix thin film model.

The paper will describe the basic system design and functionalities. Multilayer coatings were performed in a large 1500mm evaporation process with rf-plasma assistance. Deposition rates up to 1.5nm/s were achieved while the substrate holder rotates with 30rpm. This leads to a thickness increment of 3nm per revolution with is the same increment for the measurement. This is a challenging task for accurate thickness control.

The results UV-ir cut filter coatings will demonstrate the performance of the newly developed monitoring system.

9627-39, Session 9

Advanced reflection coefficient monitoring for thin film deposition

Cheng-Han Chiang, Meng-Chi Li, Kai Wu, Cheng-Chung Lee, National Central Univ. (Taiwan)

Optical monitoring techniques for film deposition have garnered considerable attention, particularly for depositing optical thin film filters, which requires controlling a precise thickness and refractive index of each layer. During fabrication, errors can arise from thickness deviation or refractive index variation. Such errors accumulate sequentially by layer and result in spectrum deviations in the final product. Real-time reflection coefficient monitoring is a powerful technique for multilayer interference coatings because of the combination of the reflection amplitude and phase. Real-time fitting and calculation through the broadband transmittance spectrum are performed to obtain the practical thickness of the deposited layer for acquiring the corresponding reflection coefficient value through the known refractive index. Reflection coefficient monitoring exhibits high stability, an excellent error compensation ability, and uniform monitoring sensitivity without deposition termination ambiguity. In this study, we determined the correct refractive index of the deposited film by using the spectrum of previous layers. Combining this method with the reflection coefficient monitoring technique can acquire a higher precision. This paper proposes an optical monitoring method and presents a corresponding experiment show its advantage. A narrow band-pass filter with a specified bandwidth is difficult to achieve but extremely crucial. The performance of a narrow band-pass filter monitored using this method is demonstrated.

9627-40, Session 9

Multi-criteria in situ optical monitoring system

Dragan Stojcevski, Institut Fresnel (France) and CILAS (France); Michel Lequime, Institut Fresnel (France); Catherine Grezes-Besset, CILAS (France)

In situ optical monitoring is a very efficient tool to control the deposition of complex optical interference coatings. However the criterion used to define the turning point of each layer depends on the monitoring scheme and can correspond either to the nulling of the derivative of the stack transmission in case of a monochromatic control or to the minimization of a merit function in case of a broadband optical monitoring. Each scheme nevertheless exhibits specific benefits and drawbacks that are moreover function of the stack formula and it is really difficult to perform a choice that would be optimal in any kind of situation. It is the reason why we developed an in situ dual optical monitoring system allowing a synchronous, real time and high accuracy acquisition of both data, i.e. the transmission at a specified wavelength as well as the transmission spectrum over a large wavelength range (280 nm – 1100 nm). The combined use of a high brightness light source, an optimized routing of the light flux through bifurcated fiber optic bundles and a low noise variable gain photo-receiver allows reaching high signal to noise ratio over a very large range of transmission values. A special attention is given to the study of the influence of the compared spectral resolution of both means. First examples of use will be reported for the manufacturing of high reflectivity quarter-wavelength mirrors, narrow bandpass Fabry-Perot filters and broadband splitters.

9627-41, Session 9

Optical monitoring of high throughput ion beam sputtering deposition

Ove Lyngnes, Veeco Instruments Inc. (United States); Ulf Brauneck, SCHOTT Suisse SA (Switzerland)

Ion Beam Sputtering (IBS) offers a deposition process yielding optical thin films with stable optical parameters, near bulk density, and ppm level optical loss. Historically IBS systems have had a relatively low deposition rate over a smaller substrate fixture resulting in a low production throughput. Recently higher rate systems with larger substrate fixtures have been developed. Maintaining the same process control and film properties in these higher throughput systems offers challenges. In particular, the higher deposition rates make accurate layer control essential. This is most readily achieved by using an optical monitoring system (OMS).

We have deposited multiple optical bandpass, edge filters and notch filters in a high throughput IBS system. The systems were configured with four 333mm diameter planetaries. Both a single wavelength OMS as well as a broadband OMS were used for layer control. Both systems intermittently monitored through a substrate mounted in the middle of one of the planetary fixtures. The coating materials were SiO_2 and Ta_2O_5, both reactively sputtered with assist from a secondary ion source. The deposition rates were ~6 Å/s for the SiO_2 and ~4 Å/s for the Ta_2O_5. Coating thickness uniformity was obtained by using mechanical shadow masks optimized for the planetary fixture.

We demonstrate a wavelength repeatability of less than 0.1% for five subsequent short wave pass filters coated using broad band OMS control. The centering of the coating is also within 0.1% of the design wavelength. We also present results for a multi notch filter coated using the broad band OMS. This type of filter design tends to have thick layers resulting in high frequency ripple that is hard to fit with a broad band model. A control strategy utilizing a mix of a broadband and a single wavelength model is therefore used successfully in the deposition.

Various bandpass filters using turning point control with both single wavelength and broad band OMS has been deposited. A transition steepness from the T=50% point to OD6 in less than 3% is demonstrated on a 10nm bandpass filtered centered at 550nm. It is essential for a high throughput deposition system to yield parts across the whole coating fixture. We have deposited a ~15nm FWHM bandpass filter centered at 830nm on 300mm glass substrates. A 2D mapping of the center wavelength and the FWHM maximum across the wafer shows +/-.05% CWL variation across the central 180mm diameter and +/-0.35nm variation in the FWHM to the edge of the wafer. The variation is resulting from a combination of variations in coating thickness uniformity and thermal distribution across the substrate as well as imperfect averaging of the mechanical fixture rotation.

We have also developed a variation of the standard turning point monitoring that enables us to control filters with narrower bandwidth than the spectral resolution of the OMS system. We demonstrate a 0.8nm FWHM filter centered at 532nm controlled using a broad band OMS with a ~1.5nm FWHM spectral resolution of the spectrometer.

9627-35, Session 10

Depth determination of critical fluence-limiting defects within planarized and non-planarized mirror coatings

Christopher J. Stolz, Justin E. Wolfe, Paul B. Mirkarimi, James A. Folta, John J. Adams, Marlon Menor, Nick E. Teslich, Lawrence Livermore National Lab. (United States); Carmen S. Menoni, Dinesh Patel, Colorado State Univ. (United States)

Multilayer interference optical mirror coatings are fluence-limited by nodular inclusions. Planarization of these defects modifies the geometrically and interference-induced light intensification to increase the laser resistance of mirror coatings. Previous studies using engineered defects on the substrate or buried in the middle of the coating stack have focused only on understanding the improvement in laser resistance. However, real coating defects are distributed throughout the coating. To better understand differences between the critical fluence-limiting defects of both planarized and non-planarized mirror coatings, laser damage pit depths were determined as a function of laser fluence.

9627-42, Session 10

Advanced femtosecond laser coatings raise damage thresholds *(Invited Paper)*

Hans Becker, Diana A. Tonova, Michael Sundermann, Carl Zeiss Jena GmbH (Germany); Lars O. Jensen, Mark Gyamfi, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

Femtosecond lasers, like titanium sapphire, typically generate pulses with a power density of about 1 J/cm2 or above. Refractive optical coatings are used as mirrors, antireflection coatings or dichroics for frequency multiplying. The long-term laser durability of these coatings is currently one of the limiting factors. Increasing the long-term laser durability of optical components and assemblies for femtosecond laser applications is one of the topics within the federal “Ultra Life” project.

Advanced optical thin film design is the key to increase laser durability significantly: either by optimizing the electric field distribution within the coating, or by multi-index or rugate designs. Both ways may be even combined.

The electric field distribution within a thin film stack can be optimized to avoid peak intensities in critical layers using refractive index engineering and/or layer thickness grading. Femtosecond laser mirrors and dichroics for 780 nm and 390 nm were designed and realized at ZEISS and characterized at Laser Zentrum Hannover. Here we present LIDT measurements of electric field optimized mirrors and dichroics, which are almost a factor of three higher compared to standard coating designs. At 780 nm a LIDT of 1.49 J/cm2 has been achieved and at 390 nm 0.58 J/cm2. The experimental results show a proportional dependence of the LIDT with electric field maximum as expected by theory.

Multi-index or gradient/rugate designs offer additional degrees of freedom, and can simplify or even enable challenging designs. They can also help to increase laser durability. Such gradient thin film stacks can be designed ab initio without any start- or index profile approximations using a design software developed at ZEISS. In earlier work a rugate omnidirectional AR coating was designed at ZEISS, realized and characterized in comparison to a classical binary AR design at Laser Zentrum Hannover. The measured femtosecond LIDT of the rugate AR was significantly higher than the binary one.

The authors currently work on further developments and demonstrators. The latest technology development results will be summarized in this presentation.

9627-43, Session 10

The damage characteristics of laser coatings irradiated from crystal-film interface at oblique incident angles

Xinbin Cheng, Zhi Song, Hongping Ma, Zhanshan Wang, Tongji Univ. (China)

The nano-precursors and electric field distributions in the subsurface of Nd: glass slab are two contributing factors that affect the laser-induced damage threshold (LIDT) of high reflection (HR) coatings irradiated from crystal-film interface. Here we first investigate how the electric field distribution varies with oblique incident angle and polarization. Then we discuss how different electric field distributions lead to different damage behaviors of HR coatings. It was found that the discontinuity of P-polarized electric field at the crystal-film interface was the reason that HR coatings had lower LIDT for P-polarization than S-polarization when the proper coating design was used.

9627-44, Session 10

Analysis of energy deposition and damage mechanisms in single layer optical thin films irradiated by IR and UV femtosecond pulses

Dam-Bé L. Douti, Laurent Gallais, Christophe Hecquet, Thomas Bégou, Julien Lumeau, Mireille Commandré, Institut Fresnel (France)

Sputtering techniques are known to produce extremely dense, smooth, stoichiometric and amorphous thin films that are very suitable for laser applications. The LIDT values of these films are close to those that bulk materials can achieve. The laser damage resistance has been investigated mostly in the range of NIR wavelengths, but some results can be found in the literature in IR, visible and UV. Numerical investigations of LIDT in thin films have been made on materials suitable for laser applications. The most applied numerical models are the Single Rate Equation (SRE) and the Multiple Rate Equation (MRE) in which the damage criterion is the critical electron density for creating plasma. On the other hand, ablation studies have been made largely in bulk materials, highly contributing in the ablation techniques. These studies are mostly oriented towards the evaluation of the absorbed energy in the material and the conversion of this energy to mechanical forces that can pull out atoms from the material.

We propose in this work the use of a SRE model and criterion on the absorbed energy, to analyze the laser-induced damage and the ablation thresholds. We present first experimental results of single layers of Nb2O5 and HfO2 tested with a femtosecond Ytterbium laser at the wavelengths 1030nm and 343nm. The initiation of the ablation (damage) is shown to start in the volume of the film, in some cases, with the help of surface profile measurements (interferometric and AFM) and scanning electron microscopy. Then the deposited energy distributions in depth, radial and time are calculated. The experimental results are discussed starting from existing empirical or theoretical models that describe LIDT and ablation thresholds. Comparisons between experimental and numerical results give rise to discussions on the ionization processes involved and the choice of the adjustment parameters which are the effective mass coefficient and the electron relaxation time.

9627-45, Session 10

Polishing and coating of a F1250mm 90° off-axis parabola for PW lasers

Adrien Hervy, Adrien Dussourd, Gilles Chaussat, Daniel Mouricaud, REOSC (France); Gilles Chériaux, Lab. pour l’Utilisation des Lasers Intenses (France); Laurent Gallais, Institut Fresnel (France)

The peak power handling capability of ultra-short pulse lasers is main

concern for new facilities, like those for the French APOLLON 10P, and European Extreme Light Infrastructure (ELI) projects. Indeed, these last generation lasers require complex, large (Ø 1m) and resistant optical components with optimized thin-films coatings. Using on one hand the recent development of high laser resistant broadband high reflective coatings through a joint project with the Laboratoire d'Optique Appliqué and Fresnel Institute, and on the other hand its long time experience with polishing and measuring large and complex optical components, Reosc decided to demonstrate the feasibility of a Ø750mm 90° Off-Axis Parabola (OAP) dedicated to focalize ultra-intense laser beams.

The prototype of the 90° OAP has a concave surface with 19mm of asphérisation for focal length of F1250mm. The OAP is coated with a hybrid Metal/Multi-Layer-Dielectric coating. It provides the a reflectivity up to 98%, an absolute Group Delay Dispersion (GDD) below 100fs? and a Laser-Induced Damage Threshold (LIDT) up to 0.5J/cm, at 15fs and under vacuum. These performances are achieved on the whole surface and on the 200nm spectral range required by the sub 20fs PW-systems.

In this paper we will present the developments required for the polishing, the coating and the measurements of the OAP and we will show the performances achieved on the prototype.

9627-46, Session 10

Ultra-wide dynamic range system for the spectral transmission measurement of complex optical filters

Simona Liukaityte, Michel Lequime, Myriam Zerrad, Thomas Bégou, Julien Lumeau, Claude Amra, Institut Fresnel (France)

Performance requirements applicable to optical filters today become more and more stringent in various fields like earth observation from space, data telecommunications routing or fluorescence confocal microscopy. Efficient deposition machines are now available to achieve very accurate manufacturing of complex optical interference coatings including more than one hundred layers. Nevertheless, the qualification of such components requires an accurate measurement of its optical properties in order to allow a reliable comparison between theoretical and experimental spectral transmission features. Classical spectrophotometric means can be used to perform this control when the transmission levels are comprised between 100% and 0.01%, but the determination of rejection levels greater than 4 in terms of optical density remains difficult and almost inaccurate. We show in this presentation how the SALSA bench (Spectral and Angular Light Scattering characterization Apparatus) developed by our team can be used for extending the range of these rejection measurements up to optical densities of 12 by keeping a spectral resolution better than 2 nm and relative transmission accuracy about 0.1%. In our presentation we will stress the influence of the spectral purity of the light source on the accuracy of such ultra-low spectral transmission levels measurements, detail the result of an in-deep metrological characterization of this new bench and give some wide-range rejection data recorded on complex optical filters including a comparison with theoretical prediction.

9627-47, Session 10

Measurements of angular and spectral resolved scattering on complex optical coatings

Simona Liukaityte, Myriam Zerrad, Michel Lequime, Thomas Bégou, Claude Amra, Institut Fresnel (France)

Due to market demand and technical progresses, a new generation of optical components requires much more sophisticated structures with a great number of layers. These complex structures enable to achieve severe optical performances but, at the same time, enhance light scattering processes.

For these reasons, it is essential to develop a metrological tool which provides an accurate quantification of the spectral and angular behavior of scattering losses, with sufficient angular and spectral resolution.

In order to face this issue, new investigations were performed by our group at Institut Fresnel and led to the development of the new scatterometer SALSA (Spectral and Angular Light Scattering characterization Apparatus). The use of both a broad-band source and a tunable filter allows to accurately select the illumination wavelength and the spectral bandwidth on the whole spectral range of CCD detectivity.

In this paper, we will present the performances of the setup and some experimental results. Moreover, we will show how the management of the spectral dimension leads to the identification of specific signatures.

9627-49, Session 11

Metamaterials for optical coatings *(Invited Paper)*

Anna Krasilnikova Sytchkova, ENEA (Italy)

Metamaterials, and complex materials having plasmonic properties in general, interact with external electromagnetic radiation in a particular way compared to traditional thin films. The reason lays in the physics of such artificial media. Such peculiarity of metamaterials defines the choice of suitable measurement techniques used for their characterization as well as adequate methodology for measurement data interpretation, specific for the case. Here we overview main issues on the physical properties of complex plasmonic materials and methods for their characterization. The modern approaches to modeling of their optical parameters are considered as well. The emphasis on the optical thin film applications is made.

9627-50, Session 11

Glancing angle deposition of silver nanostructures for use in surface enhanced raman scattering

Hin On M. Chu, Shigeng Song, Desmond R. Gibson, Univ. of the West of Scotland (United Kingdom)

Surface Enhanced Raman spectroscopy (SERS), has attracted huge interest in recent years for its potential applications in biomedical sensing and chemical detection. The main issues that affect SERS are the production of reliable rough metal surfaces. Many methods have been investigated to obtain these nanostructured noble metal surfaces, from colloidal lithography for discrete nanostructure arrays to electron beam lithography. The issue with these methods typically involve fabrication expense, difficulty of production, and control & regularity of nanostructures. Oblique Angle Deposition (OAD) is also used to produce noble metal nanostructures on smooth substrates, relying on the random nucleation sites. In this investigation, this issue is overcome by; Ag nanorods grown using OAD onto a pre-patterned polymer template. Our method enables the production of reproducible SERS substrates on large areas and at lower costs as well as control over nanostructure shape. SERS substrates were characterised by using Raman spectroscopy (Trans-1, 2-bis (4-pyridyl)-ethylene (BPE) was used as the Raman probe), scanning electron microscopy (SEM). Observations were compared with simulated local electromagnetic fields calculated using the computational physics program DDSCAT 7.2 with the discrete dipole approximation method. This project focuses on the relation of Ag nanorod length, angles and their effects on the Raman signal intensity. The simulation showed regions of strong electromagnetic enhancement located in gaps between adjacent Ag nanorods. Results indicate supporting data to this simulation, as the 400nm thick film that produced greatest Raman signal enhancement showed greatest consistent gap spacing between adjacent nanorods. The Raman intensities indicate that longer (931 – 1283 nm) nanorods with appropriate gap spacing enhanced the Raman signal best. The greater the Raman enhancement, the more background (such as oil contamination from the vacuum chamber) was diluted. These results present promise for cheap and easy fabrication of SERS substrates on large areas with controllable tuning of Ag nanostructures.

9627-51, Session 11

Volume phase elements in chalcogenide (Ge33As12Se55) thin films

Alexandre Joerg, Michel Lequime, Julien Lumeau, Institut Fresnel (France)

Phase masks are commonly used to control light spatial distribution and pattern it into different shapes such as dots, top-hat, ring... They are generally fabricated by local control of the physical thickness of a glass plates using surface etching techniques associated with a photolithographic process and are today commercially available. However, due to their nature, these optical components are very sensitive to dust or scratches and require a very well-controlled process. In this paper; we propose a new approach for the fabrication of these phase masks and to produce volume phase elements which local phase is controlled by the local modification of the refractive index within the bulk of a photosensitive chalcogenide thin film. Single layers of Ge33As12Se55, a commercial chalcogenide glass known as AMTIR-1 and provided by Amorphous Materials Inc., were fabricated using electron beam physical vapor deposition in a Balzers BAK600 deposition chamber. Spectral dependence of the transmission and the reflection of these layers were fully characterized by spectrophotometry and refractive index dispersion, extinction coefficient dispersion and thickness were determined from these measurement. Due to their strong absorption k>> 0.01 in the visible range, Tauc-Lorentz optical dispersion model derived from Kramers-Kronig relation was used. Photosensitive properties of these layers were also investigated. Photo-induced refractive index change kinetics were characterized, when exposed with a diode laser at 808 nm. Local refractive index variations as large as ~4.10-2 at 1 micron are demonstrated. This giant photosensitivity coupled with a 20 microns thick layer is able to generate phase shift up to 2ϖ between exposed and unexposed zones and therefore can be used for the generation of volume phase elements. To avoid interference losses generated by the single AMTIR-1 layer, multilayer structure consisting of two anti-reflection coatings surrounding the chalcogenide layer were designed. In addition, a custom optical system based on a digital micro device DMD Discovery 1100 from Texas Instrument was assembled in order to allow local exposure of the chalcogenide layer with controlled dosage. Using this system, it is possible to generate various spatial patterns as well as to generate different refractive index variations, and therefore different levels of phase shift in the layer. Using these results, we show the versatility of the proposed method and present the first prototypes of binary volume phase elements that allow, for example, converting Gaussian beams into a higher order TEMnm mode as well as more complex volume phase elements with grey-levels that allow generating, for example, squared top hat beams at the focal plane of a lens.

9627-52, Session 11

High-efficiency embedded transmission grating

Stephan Ratzsch, Ernst-Bernhard Kley, Friedrich-Schiller-Univ. Jena (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Adriana Szeghalmi, Friedrich-Schiller-Univ. Jena (Germany)

Highly efficient transmission gratings are demanded in optical devices or setups e.g. chirped pulse amplification (CPA) system or grating spectrometer. The fabrication of these diffractive optical elements (DOE) benefits greatly from the ongoing technological progress in the fields of lithography and structuring. Consequently, grating designs with a period of few 100 nm are realizable in fused silica substrates.

Usually, highly efficient transmission gratings are mounted in Littrow-configuration. In Littrow-configuration, the 0th and -1st diffraction order will propagate symmetrically. Additionally, dispersive gratings are preferred for compact device layouts. Thus, gratings with a small period are required. However due to the Littrow-configuration, an increasing angle of incidence results from smaller periods. As a consequence, higher Fresnel reflection at the air-grating interface will limit the maximum transmission efficiency of standard gratings.

To achieve higher transmission efficiency, gratings need to be embedded embedded void-free in a high refractive index material. Besides enhanced optical functionality, the embedding increases the mechanically stability of the pattern and provides protection against harmful external contaminants such as corrosive materials, or dust particles.

The embedding of gratings is realized by atomic layer deposition (ALD). Atomic layer deposition based on cyclic, self-limiting surface reactions of the reactants. The deposited layer thickness is only dependent on the chosen number of cycles. Additionally, atomic layer deposition enables conformal coatings on structured surfaces with high aspect ratios (ratio between groove depth and ridge width).

High refractive index contrast between the embedding material and the grating substrate lead to smaller aspect ratios , which put less demands on the structuring. Since titanium dioxide (TiO_2) has one of the highest refractive index among dielectrics and no absorption at the operating wavelength (= 1030 nm), it is an ideal candidate for embedding. The deposition of TiO_2 by thermal ALD and by plasma-enhanced atomic layer deposition (PEALD) has been thoroughly investigated. Generally, plasma-enhanced atomic layer deposition requires lower substrate temperatures and provides layers with a lower contamination level compared to thermal ALD.

This conference paper reports on an embedded grating with a period of 575 nm that has been optimized for TE-polarized light at the wavelength of 1030 nm. The deposition of TiO_2 by PEALD is performed using titanium tetraisopropoxide (TTiP) as metal precursor and plasma activated oxygen as oxidizer at 100°C substrate temperature. The excess ALD layer on top of the grating is removed and an anti-reflective coating is deposited by physical vapor deposition on top of the grating. Finally, we received an embedded grating with transmission efficiency higher than 97% in the -1st diffraction order. In contrast, a standard grating with the same period reaches only a maximum theoretical efficiency of 92.3% at the same wavelength in Littrow-configuration.

9627-53, Session 11

Large-area anti-reflective coatings for backlight of holographic displays by reactive magnetron sputtering

Thomas Goschurny, Daniel Gloess, Hagen Bartzsch, Peter Frach, Kerstin Täschner, Jörn-Steffen Liebig, Fraunhofer-Institut für Elektronenstrahl- und Plasmatechnik (Germany); Hagen Sahm, SeeReal Technologies GmbH (Germany)

Reactive pulse magnetron sputtering becomes increasingly important for the deposition of optical coatings. High deposition rates, excellent environmental stability, dense and smooth films as well as the possibility of upscaling are just some advantages. Optical coatings like edge filters, anti-reflective coatings (AR-coatings), Rugate-filters can be deposited at low cost with very little absorption and scattering losses. With the availability of large sputter sources, even large substrates can be coated uniformly with acceptable productivity.

In this paper, one application for large area precision optical coatings is shown. Anti-reflective coatings for a backlight of holographic displays were deposited using a 24 layer HL-design. To realize a full color holographic display, three lasers with the wavelengths 457 nm (blue), 532 nm (green) and 644 nm (red) are applied as a background illumination. The collimated laser beams strike the backlight at an angle of incidence of 85° and are expanded anamorphic by a factor of at least 10. This widening enables the illumination of the whole display with a coherent plane wave. Thus, a compact backlight unit avoiding conventional laser beam expansion is possible. The AR multilayer with an overall thickness of about 2.4 μm strongly increases the transmittance into the glass substrate for the three target wavelengths at high angles. The transmittance of the s-polarized fraction of the incoming laser beams can be enhanced by the AR coating from about 26% to about 95% at an angle of incidence of 85°. The following deflection into normal direction is achieved by Volume Bragg Gratings (VBG).

For AR multilayer deposition the dynamic in-line coating machine (PreSensLine) with process stations for the low index (SiO_2) and the high index (Nb_2O_5) material was used. Each process station is equipped with two rectangular magnetrons having a target length of 800 mm, which are suitable for coating of substrates with dimension up to 650 mm x 750 mm. The deposition of the AR was accomplished successfully on 28" substrates (400 mm x 300 mm) with a total error lower than +/-1% regarding layer thickness, homogeneity, reproducibility and optical properties all over the substrate. It could be shown that the coating is functional for the illumination of the entire display area with a plane laser wave, which is a precondition for holographic applications.

9627-54, Session 12

Metamaterials and optical filtering functions: a review *(Invited Paper)*

Michel Lequime, Claude Amra, Institut Fresnel (France)

No abstract available.

9627-55, Session 12

Prototyping fishnet metamaterials: alumina-silver-based structures

Anna Krasilnikova Sytchkova, Maria Luisa Grilli, Antonio Rinaldi, Angela M. Piegari, ENEA (Italy); Guohang Hu, Hongbo He, Kui Yi, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

Fishnet metal-dielectric-metal structures have been realized by combination of r.f. sputtering and lithographic technique. First experimental results are presented for Alumina-Silver-based structures for optical coating applications. The metamaterial morphology is what mainly defines the effective optical functions of the engineered medium and is determined by the choice of the manufacturing parameters at each step of the process. The dielectric functions of composing materials and the metal-dielectric interface quality play essential role as well.

9627-56, Session 12

Tunable structural color inspired by Papilio blumei butterfly

Cheng-Chung Lee, Mei-Ling Lo, National Central Univ. (Taiwan)

In this study, the reflectance spectra of the 2D photonic-crystal models for green band and cyan tail are in agreement with the measured results. Besides, the structural color of Papilio blumei butterfly depends on the film thickness, film material (film refractive index) and the size of air hole (effective refractive index). As the thickness of air hole is decreased or the width of air hole is increased, the reflection peak shifts toward shorter wavelength, meanwhile, the hue of color is blue-shift. In addition, the reflectance is enhanced and half-width is wider simultaneously when the width of air hole is increased. It means the color became brighter and saturation is lower. Those phenomena have inspired us to obtain tunable structural color by adjusting the dimension of the photonic crystal structure. Hence, any structural colors can be designed and achieved. The hue, brightness and saturation of color can be manipulated, too. Consequently, the structural color is the useful technology to reflective display application because all colors could be manipulated by adjusting the dimension of structure and the materials can be saving in fabrication process.

9627-57, Session 12

The normal-incidence multilayered diffraction grating for the high-resolution astrophysical extreme ultraviolet spectroscopy

Xiaowei Yang, Dechao Xu, Qiushi Huang, Zhanshan Wang, Tongji Univ. (China)

The high resolution extreme ultraviolet spectroscopy mission based on the normal-incidence multilayered diffraction grating technology, which provides high effective area and spectral resolution, can carry out a survey of local Galactic stellar and white dwarf targets. Compared to grazing-incidence systems, this approach allows previous observatory-class science to be delivered in a low-cost package. The instrument has already been proven in two sub-orbital space flights. However, the multilayer uesd before is periodic one and the working bandpass is limited. In this paper, the spectroscopic properties of a normal-incidence multilayered diffraction grating were similated with three kinds multilayers for the wavelength range between 17.5nm and 25.0nm, which includes lines of Fe VIII to XIII that will be strongest in the cooler (solar like) coronae, plus some weaker lines of O, Si, S and Ar. The highest efficiency at central wavelenth of bandpass can be obtained if the periodic multilayer is adopted. When a double periodic multilayer is used, we can get the arerage highest efficiency in most working wavelength range. The most flat response efficiency can be achieved if we utilized a non-periodic multilayer. The simulation results demonstrated that the choice of the multilayer is dependent on the requirement to the spectroscopy mission and should be considered carefully.

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9628-1, Session 1

Overview of EUV lithography at Carl Zeiss SMT: status and trends in optical coatings *(Invited Paper)*

Hartmut Enkisch, Carl Zeiss SMT GmbH (Germany)

In this presentation the current status of EUV optics development and manufacturing at Carl Zeiss SMT will be reviewed and an outlook on the EUV optics roadmap will be given.

After delivery of the optical trains for ASML's Alpha DemoTools in 2005/06, Carl Zeiss SMT has shipped in 2009/10 the illumination and projection Optics for ASML's NXE:3100 systems.

In 2010 the production of optics with improved specifications for the next generation of EUVL tools with a numerical aperture of beyond 0.3 was started. In addition, a new illumination system has been developed. We will report on the status and trends in optical coatings at Carl Zeiss SMT GmbH.

9628-2, Session 1

Fabrication of mild aspheres for improvement of image quality of highly corrected optical imaging systems *(Invited Paper)*

Roman Feldkamp, Olaf Schmelzer, JENOPTIK Optical Systems GmbH (Germany)

The presentation describes the application of subaperture correction technologies for the fabrication of mild aspheres, which open up the possibility of improving the performance of optical imaging systems (e.g. inspection modules). Beside the illustration of an exemplary application, the presentation will focus on the technology chain necessary for the production of high-precision aspherical optical components, and the characterization of the applied subaperture finishing tools MRF and IBF.

Among other things, the product life cycle of semiconductor inspection systems is determined by the possibility of an evolutionary improvement of the optical performance parameters such as wavefront error or image field curvature. At the end of the life cycle the customer has the choice between a replacement investment and a less expensive redesign of the existing system. Within a joint project with the customer the replacement of a built-in lens with a mild aspherical lens (deviations to the best-fit-sphere < 1 μm) has been identified as an economically reasonable way to increase the system's performance significantly. The design of this asphere is challenging the manufacturing technology, because the asphere has to be fabricated with a surface accuracy known from high-precision spherical surfaces.

At first, classic optics fabrication techniques generate a spherical surface with the best-fit-radius of the asphere. Subsequently, the two subaperture finishing tools MRF (magneto-rheological finishing) and IBF (ion beam finishing) in combination are implemented to realize the asphere's specification. Both technologies are using a tool with a diameter significantly smaller than the workpiece. The removal function can be determined accurately and remains constant during processing. Therefore the fabrication results can be simulated in advance with a convergence rate of about 90%. The tool is moved by a CNC-axis system based on a dwell time control.

Regarding the working mechanism both technologies pursue different philosophies. MRF uses a chemical mechanical removal mechanism. The tool is a magnetorheological suspension composed of aqueous solvent, polishing agent and magnetic powder. The slurry's shape and viscosity can be adjusted by a magnetic field while it is moved over the workpiece by a wheel. The material removal is realized locally by the wheel's movement and the polishing slurry.

IBF is using an ion beam with a Gaussian particle distribution. Atoms are sputtered from the workpiece's surface by accelerated argon ions. Compared to MRF significantly smaller tools with lower removal rates can be used, enabling even more precise results regarding form accuracy. The low removal rates require longer processing times.

Considering that both technologies have different conditions for working efficiently, they can be usefully combined to realize the high demands of the fabrication task. First, a classic polished sphere is aspherized using MRF. The final correction is made by IBF with a small beam diameter.

The project's result will be presented at an example.

9628-3, Session 1

Characterization of Mo/Si mirror interface roughness for different Mo layer thickness using resonant diffuse EUV scattering

Anton Haase, Victor Soltwisch, Frank Scholze, Physikalisch-Technische Bundesanstalt (Germany); Stefan Braun, Fraunhofer IWS Dresden (Germany)

The throughput of EUV lithography systems is presently strongly limited by the available radiant power at the wafer level. Besides increasing the power of EUV sources, also the quality of the optical elements plays a key role. With state of the art multilayer mirrors the main cause of diminished reflectance is surface and interface roughness as well as interface diffusion. Both properties lead to reduced specular reflectance while only the interface roughness causes diffuse scattering. EUV diffuse scatter thus allows to selectively assess the contribution of the interface roughness

The intensity distribution of diffusely scattered EUV radiation provides information on vertical and lateral correlations of spacial frequencies of roughness through the appearance of resonant diffuse scattering (RDS) sheets. The study of off-specular scattering thus serves as a natural tool for the investigation of the roughness power spectral density (PSD) of the interfaces. However, upon near-normal incidence impinging EUV radiation, dynamical scattering contributions from thickness oscillations (Kiessig fringes) lead to Bragg lines which intersect the RDS sheets. This causes strong resonant enhancement in the scatter cross section which we called "Kiessig-like peaks" in analogy to the well known phenomenon of Bragg-like peaks appearing in hard X-ray grazing incidence measurement geometries. Thus for power spectral density studies of multilayer interface roughness, resonant dynamical scattering cannot be neglected. Theoretical simulations based on the distorted-wave Born approximation enable to separate dynamic features of the multilayer from roughness induced scattering. This allows to consistently determine an interface PSD. We have analyzed several magnetron sputtered high-reflectance Mo/Si multilayer mirrors with different nominal molybdenum layer thicknesses from 1.7nm to 3.05nm crossing the Mo crystallization threshold. The results show distinct resonant diffuse scattering from unpolished and ion-polished samples with decreased lateral correlation lengths in the latter case.

Our off-specular scattering measurements at multilayer samples were conducted at the soft X-ray radiometry beamline in the PTB lab at the BESSY II electron storage ring in Berlin. The samples were produced by magnetron sputtering at Frauenhofer IWS, Dresden.

9628-4, Session 1

Roughness characterization of lithography optics for 13.5 nm

Marcus Trost, Matthias Hauptvogel, Sven Schröder, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Torsten Feigl, optiX fab GmbH (Germany); Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The trend towards ever shorter wavelengths in semiconductor optical projection lithography to the next planned wavelength ? = 13.5 nm generates large demand for high throughput, optimal imaging properties, and long-term stability. This leads to challenging requirements on the surface finish because of the strong wavelength dependence of scattered light from interface imperfections (~1/??). In particular the substrate roughness can easily impair the imaging quality and optical throughput as most of the roughness components are replicated throughout the entire multilayer stack. Therefore, characterizing the surface roughness over the entire range of relevant spatial frequencies is of crucial importance.

However, the long measurement times of classical high resolution metrology tools, such as atomic force microscopy, only enable a few isolated measurement positions to be characterized by these techniques. This is in direct contrast to the large sample dimensions with several 100 mm in diameter required for EUV lithography optics. As will be demonstrated, this limitation can be overcome by angle resolved light scattering measurements, which enable a fast and area covering characterization of the relevant roughness. The achieved roughness sensitivity approaches a roughness level comparable to the noise limit of an AFM.

A further aspect which is addressed in the talk is the characterization of grating-like multilayer coatings which are appealing as an optical filtering element for the unwanted infrared radiation in laser produced plasma sources. It will be demonstrated that light scattering measurements can be used to obtain a detailed picture of the surface roughness. Furthermore, a novel approach for reducing the scattered light from multilayer coatings by specifically changing the interference conditions for the individual interfaces is presented.

9628-5, Session 2

Fabrication and testing of STREEGO: a compact multispectral optical payload for earth observation on small satellites *(Invited Paper)*

Massimiliano Rossi, Fabio E. Zocchi, Piet Holbrouck, Ivan Ferrario, Antonio Ritucci, Media Lario Technologies S.r.l. (Italy); Matteo Taccola, European Space Research and Technology Ctr. (Netherlands)

In the framework of an ESA GSTP contract, Media Lario Technologies is developing an optical payload for Earth Observation targeted to small satellites.

In this paper we present a detailed description of the sensor which, by leveraging on aspheric surfaces, bonnet polishing, lightweight materials, an off-the-shelf large format CMOS detector and multispectral filters integrated in the FPA, achieves remarkable image quality with compact volume claim and weight of only 15 kg.

The instrument is based on a three mirror anastigmat (TMA) design with an aperture of 200 mm and an F/number of 6. The payload is designed to provide for the panchromatic channel a ground sampling distance (GSD) of 2.75 m at a reference altitude of 600 km, a field of view of 1° and a nominal MTF greater than 60% at Nyquist frequency with a SNR greater than 100.

9628-6, Session 2

Rapid manufacturing for space applications

André A. M. Hoogstrate, Han J. A. J. Oosterling, TNO (Netherlands)

This paper outlines the potential impact of new manufacturing technology for spacecraft applications. Emerging manufacturing technologies, such as Additive Manufacturing, offers huge opportunities in terms of design freedom, mass reduction, function integration and volume reduction. In the framework of the ESA project “Advanced Manufacturing Methods for Systems-of-Microsystems Nanospacecraft”, three demonstrators with increasing levels complexity have been investigated. The demonstrators include inventory of parts and manufacturing strategies, ranking and selection, redesign, and realization.

The three selected levels of complexity are:

1. part level – an existing part realized with a new manufacturing strategy

2. application level – functionality of a single part, redesigned and optimized for a new manufacturing strategy

3. (sub-)system level – functionality of a (sub-)system, redesigned and optimised for a new manufacturing strategy.

For the part level demonstrator an instrument base-plate has been selected and remanufactured using Additive Manufacturing technologies.

For the application level demonstrator one of the mirrors of the telescope of the recent Tropomi-instrument has been redesigned. The redesign was tailored towards Additive Manufacturing technologies.

For the sub system level demonstrator, the optics-box of a CubSat compliant spectrometer, currently under development at TNO, has been selected. The optics-box has been realized using additive manufacturing technologies, combined with precision lost-wax casting.

This paper discusses the results, evaluation and conclusions of the realisation of these demonstrators and may act as a guideline to include emerging manufacturing technologies in the design of a new generation of space-born instruments.

9628-8, Session 2

The challenge of developing thin mirror shells for future x-ray telescopes

Thorsten Doehring, Manfred Stollenwerk, Hochschule Aschaffenburg (Germany); Laura Proserpio, Anita Winter, Peter Friedrich, Max-Planck-Institut für extraterrestrische Physik (Germany)

Different to visible light astronomy, satellite based X-ray telescopes use mirrors with reflecting surfaces almost parallel to the incoming radiation. Most of these telescopes are based on the

Wolter I optical design, which applies of two subsequent reflections at glancing angles on tube-shaped primary paraboloid and secondary hyperboloid mirrors. Thereby the most important parameters describing an X-ray telescope are collecting area, angular resolution and weight per unit area. To increase the collecting power for X-ray photons of a telescope for a given maximum diameter, several mirror shells are usually combined, resulting in telescope modules of nested mirror shells. The first of such imaging X-ray telescope systems was launched in 1978 on board of the Einstein Observatory, followed by satellite missions like ROSAT, Chandra, and XMM-Newton. However, the previously used mirror technologies are not able to fulfil the requirements of future

X-ray telescopes due to challenging requests from the scientific community. Next generation X-ray observatories are aiming for huge apertures of several meters in diameter, combined with larger effective areas and good angular resolution. In addition they have to be light to meet the stringent mass budgets of rocket launchers.

Consequently new technical approaches for X-ray mirror production are under development in the USA, Japan and Europe. In Europe the technical baseline for ATHENA, the currently planned next generation X-ray observatory of the European Space Agency is the radical new approach of silicon pore optics. This technology is based on commercially available silicon wafers as substrate material for the mirror shells, manufactured by methods of the semiconductor industry to arrays of tiny pore mirror optics, bonded together to larger petals to form a three meter diameter telescope.

NASA´s recently launched NuStar mission uses segmented mirrors shells made from thin bended glasses, successfully demonstrating the feasibility of the slumped glass technology. For risk mitigation also in Europe the hot slumping of thin glasses is being developed as an alternative technology for lightweight X-ray telescopes. Although significant progress has been made for the production of segmented glass mirror shells during the last years, some technical aspects still have to be worked out. The production of several thousands of precise mirror segments will need the industrialization of all process steps. Technical and economic aspects of the intended glass mirror production are studied within the recently started interdisciplinary project INTRAAST, an acronym for “industry transfer of astronomical mirror technologies”. The goals of the INTRAAST project and its work packages to face the challenge of thin mirror shells for future X-ray telescopes are described within this paper. The project is embedded in a cooperation between the Max-Planck-institute for Extraterrestrial Physics in Garching and the University of Applied Sciences in Aschaffenburg. As a first project task the development of low stress coatings for the thin glass mirror substrates have already been started, the corresponding technical approach and first results will be presented.

9628-9, Session 2

Light scattering characterization of IR optical components

Matthias Hauptvogel, Marcus Trost, Sven Schröder, Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Measurements of the Bidirectional Reflectance and Transmittance Distribution Function (BRDF / BTDF) provide essential information on the suitability of optical components for the desired application. Especially in complex optical systems and for high-end applications, knowledge about the scattering properties of the optical elements is fundamental in order to assess their impact onto the optical performance of the system. Optical systems working in the infrared (IR) spectral range are typically used in medical devices, for communication, in safety equipment, or in astronomy and space.

Very often, specifications for optical components are directly derived from computer-based predictions assuming idealized surface properties by using simple roughness models while ignoring defects. However, light scattering is usually affected not only by surface properties but also by various other effects. Apart from surface roughness, the scattering distribution of optical components can be influenced by defects, bulk inhomogeneities, internal scatter in coatings, or contaminations. In particular in the infrared spectral range, the light scattering can show completely different characteristics compared to the visible range. Thus, in order to take all of these effects into account, measured light scattering data are required rather than relying solely on predictions.

This means that the measurement systems need to perform in the spectral range of the application, in clean room environment, with a high dynamic range and low noise in combination with a high optical and mechanical resolution. Instruments for light scatter measurements which meet these requirements were developed at Fraunhofer IOF. The instruments are presented together with selected practical measurement examples ranging from super-polished surfaces over coated mirrors and black surfaces to diffraction gratings.

9628-33, Session 2

Process control in optical fabrication *(Invited Paper)*

Oliver W. Fähnle, FISBA OPTIK AG (Switzerland)

Process control in Optical Fabrication

Predictable and stable fabrication processes are essential for reliable cost and quality management in optical fabrication technology. This paper reports on strategies to generate and control optimum sets of process parameters for e.g. sub-aperture polishing of small optics (featuring clear apertures smaller than 2 mm), industrial polishing of medical optics and, finally, superpolishing of laser optics (generating sub-nanometer rms levels of surface roughness). To that aim, various testing techniques are discussed demonstrating that it is possible by in situ measurements of surface quality to minimize polishing time and fabrication cost.

9628-10, Session 3

New challenges in light scattering studies for complex optical components *(Invited Paper)*

Myriam Zerrad, Michel Lequime, Simona Liukaityte, Claude Amra, Institut Fresnel (France)

Theory and experiment in the field of light scattering have been extensively studied and controlled since the nineties. Indeed surface and bulk theories were developed for substrates and optical coatings, and have revealed great agreement with experiment. Furthermore, angle-resolved apparatuses were built with detection limits close to scattering from the air particles. All these tools have allowed to characterize roughnesses lower than 0.1 nm; also, the microstructure of thin film layers was investigated versus the deposition technologies .

Nevertheless, in the last few years, new challenges for light scattering have merged. Actually, modern deposition technologies with their sophisticated monitoring systems today enable the deposition of large numbers of layers, hence providing complex filters which must be characterized at their working wavelengths or in a wide spectral region. Moreover an increasing demand for micro-structured filters has merged and requires new procedures to discriminate scattering from all micro-devices.

In this context, we have developed in our group at Institut FRESNEL new numerical and metrological tools to satisfy these demands. All scattering facilities were rebuilt and upgraded, sometimes with strongly different principles. In this paper, we will present a rapid overview of these developments, with a focus on broad band scattering metrology, topography recovering (rather than roughness spectra), extraction of local defects (not to be confused with intrinsic roughness) and ultra-narrow band filters.

Examples and applications will be given to emphasize all improvements.

9628-11, Session 3

Simultaneous determination of optical constants, local thickness, and local roughness of thin films by imaging spectroscopic reflectometry

Ivan Ohlídal, David Necas, Masaryk Univ. (Czech Republic); Jirí Vodák, Miloslav Ohlídal, Brno Univ. of Technology (Czech Republic); Daniel Franta, Masaryk Univ. (Czech Republic)

In various branches of basic and applied research one can encounter thin films exhibiting miscellaneous defects. Two of important defects are area non-uniformity of the optical parameters and boundary roughness of these films. Some thin films exhibit both the defects simultaneously. Therefore, it is necessary to develop methods of thin film characterization enabling us to determine the optical constants and spatially resolved thickness and parameters of roughness. In this contribution, a new method of the optical characterization is presented that allows the determination of all the parameters describing the thin films exhibiting boundary roughness and non-uniformity in thickness based on imaging spectroscopic reflectometry (ISR). Within this method, the spectral dependencies of local reflectances at normal incidence of light are utilized for this purpose. The local reflectance spectra correspond to small areas (37?37 μm?) on the thin films measured by pixels of a CCD camera serving as the detector of imaging spectrophotometer constructed in our laboratory. To our experience the small areas corresponding to the pixels are sufficiently small so that the majority of the films can be considered uniform in all parameters within these areas. Thus, the local reflectance spectra measured can be processed using the formulas for the reflectance belonging uniform thin films with rough boundaries. Boundary roughness is included into the reflectance formulas by means of the scalar diffraction theory (SDT) as performed in our earlier papers. In these formulas the boundary roughness is represented by the rms value of heights of irregularities ?. This means that the spectral dependencies of the optical constants, map of local thickness and map of local values of ? for the rough boundaries are determined using this method in order to perform the complete characterization of these films. In general, there is a correlation between the searched parameters if the individual local reflectance spectra are fitted separately. It is necessary to use the simultaneous treatment of the local reflectance spectra measured for all the pixels (this is called the multi-pixel method). We found that this multi-pixel method enabled us to remove or reduce this correlation which gives a possibility to determine the values of all the parameters with a sufficient accuracy. We applied this method to the characterization of epitaxial ZnSe thin films prepared by molecular beam epitaxy on GaAs single crystal substrates. Therefore, the lower boundaries could be assumed smooth while the upper ones exhibited considerable roughness because the ZnSe films had a mosaic structure. The local reflectance spectra were measured within spectral range 270–900 nm. The optical constant spectra of the ZnSe films were expressed by the dispersion model based on the parametrization of the joint density of electronic states (PJDOS). The spectral dependencies of the refractive index and extinction coefficient together with maps of local thickness and local ? of the upper boundary of a selected ZnSe film will be presented.

9628-12, Session 3

Automated multi-point analysis with multi-angle photometric spectroscopy

Andreas Kerstan, Marcus Schulz, Agilent Technologies Deutschland GmbH & Co. KG (Germany); Travis Burt, Agilent Technologies Australia (Australia)

Spectral reflection (R) and transmission (T) are fundamental measurements for characterizing the optical properties of materials and optical coatings. Historically the complete characterization of optical materials and coatings for precision optics has been largely accomplished on the basis of normal and near normal incidence measurements due to the experimental simplicity of such an approach. This simplicity, however, is not without compromise. Normal incidence transmission measurements are typically conducted within the sample chamber of a spectrophotometer whilst near normal reflectance measurements require the use of a suitable reflectance accessory. A consequence of this approach is that there is never any guarantee that reflectance and transmission measurements are made from exactly the same patch on the sample due to sample repositioning during the significant changes in instrument configuration between R and T measurements.

Multi-angle Photometric Spectroscopy (MPS) measures the reflectance and/or transmittance of a sample across a range of angles (qi) from near normal to oblique angles of incidence (AOI). A recent development by Agilent Technologies, the Cary 7000 Universal Measurement Spectrophotometer (UMS) combines both reflection and transmission measurements from the same patch of a sample's surface, without sample repositioning, in a single automated platform for angles of incidence in the range 5°≤theta|i|≤85°

The Cary 7000 UMS provides a wide range of functionality for angular measurement of absolute reflectance and transmittance of specular and/or diffuse samples, making it ideally suited for Research and QA/QC. Here the Cary 7000 UMS benefits are extended further to multi-point analysis lowering the cost-per-analysis for high volume optical coating and component testing, and spatial profiling (mapping) of large diameter samples

9628-13, Session 3

Applying a dynamic interferometer to organic thin-film measurement

Yu-Xen Lin, Meng-Chi Li, Kai Wu, Cheng-Chung Lee, National Central Univ. (Taiwan)

This article describes the measurement of the thickness and refractive index of organic thin films. A system based on a polarized interferometer that captures phase values by using a micro-polarizer pixelated mask camera that can capture four polarizers simultaneously was developed. A white light interferometer was employed to obtain the reflection amplitude and phase spectrum by using a piezoelectric transducer and the fast Fourier transformation process discussed in a previous study. This information can be used to determine the thin-film optical constant and thickness. However, this method is vibration sensitive and unsuitable for in-line examination systems. The dynamic interferometer can obtain four phase-shifted interferograms simultaneously without scanning by using a piezoelectric transducer and calculates real-time phase. Therefore, this system can be applied -effectively for vibration isolation measurement. In this study, the thin-film optical constant and thickness were accurately measured using a dynamic interferometer; the technique can be extended to measuring organic materials. After the data acquisition process was completed, a regression method, non-linear fitting algorithm, was adopted to determine the best-matching theoretical reflection amplitude and phase (reflection coefficient). The aim of the fitting process was to determine the organic thin-film optical constant and thickness that minimizes the difference between the measured and theoretically calculated reflection coefficients. The dynamic interferometer can the measure the thin-film thickness and refractive index of single-layer organic films. For the measurements in this study, the organic film thickness and refractive index were within the 1% range of the ellipsometry results.

9628-14, Session 3

Wide spectral range characterization of antireflective coatings and their optimization

Daniel Franta, David Necas, Ivan Ohlídal, Masaryk Univ. (Czech Republic)

Development of antireflective coatings realized by thin film systems requires their characterization and optimization of their properties. Functional properties of such interference devices are determined by optical constants and thicknesses of the individual films and various defects taking place in these systems. In optics industry the characterization of the films is mostly performed in a relatively narrow spectral range using simple dispersion models and, moreover, the defects are not taken into account at all. This manner of characterization fails if applied to real-world non-ideal thin film systems because the measured data do not contain sufficient information about all the parameters describing the system including imperfections. Reliable characterization requires the following changes: extension of spectral range of measurements, combination of spectrophotometry and ellipsometry, utilization of physically correct dispersion models (Kramers-Kronig consistency, sum rules), inclusion of structural defects instrument imperfection into the models and simultaneous processing of all experimental data. This enables us to remove or reduce a correlation among the parameters searched so that correct and sufficiently precise determination of parameter values is achieved. Since the presence and properties of the defects are difficult to control independently by tuning of the deposition conditions, the optimization does not in general involve the elimination of defects. Instead they are taken into account in the design of the film systems. The outlined approach is demonstrated on the characterization and optimization of ultraviolet antireflective coating formed by double layer of Al?O? and MgF? deposited on fused silica.

9628-15, Session 4

Optical surfaces for high power laser coatings *(Invited Paper)*

Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

Optical surface quality plays a significant role when considering laser applications. Specifically, short pulses, high pulse energies and shorter wavelength impose high requirements on surface characteristics. Amongst others, scatter losses, absorption, or the damage threshold place high demands on the specification of an optical part, and each application will define the order in priority of these properties.

We have conducted several experiments to investigate in the impact of surface characteristics of polished substrates on the performance of coated optics, in particular HR mirrors. In this contribution we report on the techniques used to qualify high reflective coatings for excellent power handling capabilities based on the substrate surface finish.

9628-16, Session 4

Characterization and removal of laser damage precursors in fused silica optics *(Invited Paper)*

Jin Huang, China Academy of Engineering Physics (China); Liming Yang, China Academy of Engineering

Physics (China); Yingao Ma, Shanghai United Instrument Component Co. Ltd. (China)

The working life of laser optical elements is extremely directly related with to the quality of manufactured surfaces. To understand the complicated connection between the surface qualities and anti-laser damage performance, the classification of laser damage precursors, relations between laser damage precursors and manufacturing processes and the testing methods during different steps have been investigated. The laser-induced damage threshold of fused silica surfaces was significantly improved by optimizing traditional grinding and polishing processes, introducing advanced fine surface figuring technologies and exploring post-treatment and mitigation methods on defects. This work reports our recent progress on the fused silica surfaces with focus on the manufacturing, testing and laser damage mechanisms.

9628-17, Session 4

Absorption measurement on surfaces and coatings: techniques and applications

Christian Mühlig, Leibniz-Institut für Photonische Technologien e.V. (Germany)

No Abstract Available

9628-18, Session 4

Spectral angle resolved light scattering measurement of optical surfaces and thin films

Sven Schröder, Méabh Garrick, Marcus Trost, Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

The development of high-end optical systems always requires analysis of light scattering effects caused by imperfections of the optical components at some stage in the process. There are numerous potential sources of scattering such as roughness, defects, bulk inhomogeneities, or interference effects from coatings. In particular for interference coatings, substantial variations of the scattering can occur as the wavelength changes within the application band. Characterizing scattering at single wavelengths only can lead (and has led) to a critical underestimation of these effects. Therefore, a new instrument for spectral angle resolved scatter measurements based on a high-power tunable laser source has been developed. The instrument operating at wavelengths from 250 nm to 1750 nm will be presented briefly. Results of investigations of coating systems will be presented which reveal an increase in the scatter losses by more than one order of magnitude when irradiating at wavelengths only slightly off the central wavelength. In addition, a new study to combine spectral laser-induced damage tests with angle resolved scattering measurements will be presented.

9628-19, Session 5

Measuring and quantifying scatter from a variety of sample types *(Invited Paper)*

John C. Stover, The Scatter Works Inc. (United States)

When using the BRDF to learn about surface statistics or to estimate hemispherical scatter from in-plane measurements the assumption is usually made that the surface is isotropic. Unfortunately, this is often not the case; for example a diamond turned mirror is not isotropic. Other common examples are rolled surfaces and situations where scatter is mostly caused by small discrete surface features such as scratches, pits or particles. Another example is scatter from an extended edge that is much longer than the illuminated spot. In these situations the measurements may be made differently and quantified in different units (such as area/sr or 1/deg instead of the common 1/sr associated with BRDF) in order to have a result that can reliably characterize the scatter source. The situation is further complicated by the fact that the popular stray radiation codes accept scatter data only in the standardized BRDF format with units of 1/sr. This paper reviews these situations for both measurement and analysis issues.

9628-20, Session 5

Multi-wavelength light scattering techniques and analysis

Alexander von Finck, Marcus Trost, Sven Schröder, Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Angle resolving light scattering (BSDF) techniques are widely used in the optical industry. Applications benefit in particular from the high sensitivity, the non-contact measurement acquisition, the high robustness versus vibrations, as well as the capability to quickly map entire surfaces. Typical applications range from the evaluation of light scattering specifications, over providing input for ray tracing simulations, up to the quantification of the fundamental imperfections that cause scattered light: interface roughness, defects, subsurface defects, or contamination. Almost all application scenarios benefit from, or even demand for, BSDF measurements at multiple wavelengths. However, usually sequential and elaborated measurement procedures are used.

We propose a novel concept for the measurement of multiple illumination wavelengths at the same time. In contrast to state-of-the-art developments, the concept enables highly sensitive measurements analogously to sequentially operating high-end scatterometers and moreover simultaneous measurement of parameters besides wavelength (e.g. polarization). This is achieved by tailoring a concept from the communication technology known as orthogonal frequency division multiplexing (OFDM) for light scattering measurement techniques. Existing single detector scatterometers can be accordingly upgraded with only minor modifications to the required low inter-channel crosstalk performance.

It is demonstrated how the approach can be used to quickly obtain BSDF measurements at different illumination wavelengths. As the measurement conditions are nearly identical (e.g. same illumination spot geometry and sample position), the individual measurements are highly correlatable. This allows different sources of scattered light to be separated, increases the robustness for inverse scattering problems, and provides additional information content such as color.

9628-21, Session 5

An attempt towards a “direct scatterometer”

Claude Amra, Myriam Zerrad, Michel Lequime, Simona Liukaityte, Institut Fresnel (France)

The increased complexity of light scattering characterization has led to the acquisition of huge data numbers (1 BRDF per CCD pixel, incidence and wavelength...), together with several mechanical movements (source, sensor, sample) and wavelength scans (to cover UV, VIS or NIR ranges). Within this framework, it can be useful to search for new techniques which are less time and memory consuming, with reduced costs. In this paper we propose an original technique* which could answer these specifications. The principles are emphasized, together with the validity and the comparison with other techniques.

9628-22, Session 5

Facility for fast mapping of total scattering and transmission in the spectral range from DUV-NIR

Puja Kadkhoda, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

A system for two dimensional mapping of Total Scattering (TS) and Transmission (T) of optical flat surfaces in the spectral range from deep

UV to NIR will be introduced. The adaptation of the scatter detector concept for the special efforts in the DUV range will be discussed. Also, the specifications of the set-up such as working ambient, background level, and data calibration procedure demonstrate the performance of the system for the analytical tasks in the industrial optics production.

On the basis of the presented measurement facility, the essential properties of bare flat optics in respect of their polishing state, roughness level, state of cleaning and defect distribution can be investigated with the TS system in a nondestructive way. The homogeneity of the whole surface of an optical component can be tested with a defined lateral resolution. The knowledge of the inhomogeneity is an important indication for the quality evaluation of optical components. We present the TS result and the calculated defect density distributions of selected components, which are handled by different cleaning procedures. Also, additional effects in TS and T will be outlined and compared with spectral photometric measurement.

9628-23, Session 6

The absolute radiometric calibration facility ARCF 2.0 at TNO

Bilgehan Gür, Rik Jansen, Gerard C. J. Otter, Jos J. M. Groote-Schaarsberg, Sanneke Brinkers, Niels Dijkhuizen, Mariet Broxterman, TNO Technical Sciences (Netherlands)

Optical components with scattering properties, so-called diffusers, are core elements of calibration units in earth observation instruments. Its performance influences significantly the achievable accuracy of scientific observations. It is of high importance however to characterize the scattering properties of such a diffuser with minimum uncertainty on-ground before launched into orbit and before being utilized in its calibration purpose. In the past decades TNO has operated an “Absolute Radiometric Calibration Facility (ARCF)” to ensure such accurate characterization of space components. In the recent past TNO has put increased efforts in upgrading and modernizing its facility into a modern high class facility (ARCF 2.0) to measure scattering properties of a variety of materials and components to meet the growing demands in accurate measurements for space applications and other. The present paper describes the above mentioned facility ARCF 2.0 with its unique measurement capabilities and outlies several examples on its application on various optical components.

9628-24, Session 6

Scattermeter for measurements of solar cells

Pavel Nádaský, Jakub Klus, Štepán Šustek, Miloslav Ohlídal, Jirí Vodák, Brno Univ. of Technology (Czech Republic)

Knowledge of the electromagnetic radiation (EMR) scattering from surfaces in the structure of a solar cell is important from the viewpoint of enhanced EMR trapping in solar cells. A device for measuring the angular distribution of the scattered EMR intensity from the surface of solids was developed - Scattermeter II (SM II). The device was implemented in cooperation with a solar cell producer, Solartec s.r.o. Measured values can also be used for a comparison with the data calculated using suitable mathematical models (e.g. using Finite Difference in Time Domain method, approaches using geometrical optics etc.).

SM II was primary built for the purpose of measuring the EMR scattered from a surface of a solar cell, therefore the key parameters of the device are possibility of rapid measurements in the hemisphere above the sample surface studied for various incidence angles of EMR beam and the possibility of measurements at different wavelengths (interesting for monocrystalline silicon solar cells).

For transparent samples an angular intensity distribution in the whole sphere around the sample can be measured. The wide spectral range detector (a photodiode) is used. The range from 600 nm - 1600 nm can be measured. Three semiconductor lasers are used as sources of the EMR beam. SM II is computer controlled and is also used for measurement of the “trapped” light inside a solar cell.

The presented contribution deals with not only the description of SM II, but also with visualization of data obtained.

The EMR scattering is studied from alkali etched surface of silicon wafers for the various parameters of their preparation technology. The influence of additional topography modifications performed by plasma etching is studied in the transmission and reflection modes. The experimental results are visually compared with the results of a computer simulation based on geometrical optics.

9628-25, Session 6

A developed method for surface testing based on the scattering interference effect

Zhongqi Tan, Yun Huang, Su-Yong Wu, Xiaobao Zhang, Yibo Zhang, National Univ. of Defense Technology (China)

Light scattering is an important and classical method for optical surface testing. Typical scheme of light scattering measurement often uses a single laser beam incidence, and then evaluates the surface quality via detecting and analyzing the scattering signal. In this work, a developed method for optical surface testing is proposed and demonstrated, and whose measuring principle is based on the scattering interference effect. In this approach, a single longitudinal mode laser beam is divided into two beams, when these beams irradiate the optical surface symmetrically, their respective scattering fields would interfere with each other. If the phase between these incidence lights is scanned periodically, their scattering light interference signal would fluctuate simultaneously. Through analyzing this kind of scattering signal, our method can not only determine the scattering loss of optical surface, but also scale its inhomogeneity performance. A simply set of experimental apparatus is built up and used to demonstrated this method, which uses a single mode He-Ne laser as the light source and an integrating sphere as a signal collector. Furthermore, to modulate the phase difference between two incidence beams, a piezoelectric ceramic is used. Some typical cases are then experimented and discussed, the results show that this method can be used to calibrate the quality of optical surface.

9628-26, Session 6

Possibilities and limitations of imaging spectroscopic reflectometry in optical characterization of thin films

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Imaging spectroscopic reflectometry (ISR) provides methods enabling us to perform an optical characterization of thin films non-uniform in optical parameters (e.g. in thickness). It measures spectral dependencies of a local reflectance at normal incidence of light belonging to small areas on these films (37x37 μm^2 in our case) imaged onto individual pixels of a CCD camera serving as a detector of a spectrophotometer. The local reflectance can mostly be expressed using formulas corresponding to a uniform thin film. There are three methods for treating ISR experimental data in the special case of thickness non-uniformity, i.e. in the case of the same optical constants along the whole area of the film:

i) If optical constants of the non-uniform film are known, spectral dependencies of the local reflectance are used to determine a map of the local film thickness (one pixel method).

ii) If optical constants are unknown, spectral dependencies of these constants are determined using standard spectroscopic ellipsometry and reflectometry under taking into account postulated non-uniformity in

thickness (e.g. wedge-shaped non-uniformity) and a suitable dispersion model for optical constants. Then local reflectances are again utilized for determining the local thickness map (the combined method of the one-pixel ISR method and the standard methods). Note that the spectra of the local reflectance can also be used for the determination of the map of roughness rms values together with the map of the local thickness if the rough non-uniform thin film is characterized by this combined method.

iii) If the situation concerning the optical constants is the same as in ii) one can utilize a simultaneous treatment of the experimental data measured by all the individual CCD pixels without using auxiliary methods. This multi-pixel method enables us to determine simultaneously the spectral dependencies of optical constants and the map of local thickness if a suitable dispersion model of the film is employed.

In this contribution examples of the optical characterization of thin films non-uniform in thickness corresponding to all cases i)-iii) will be presented.

9628-7, Session PTues

Freeform active mirrors experiment: innovative manufacturing process development

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In the frame of freeform mirrors development dedicated to the next-generation of astronomical instruments, innovative manufacturing approaches are mandatory to supply reflective optics coupling non-axisymmetrical form and extreme asphericity (i.e. more than one millimeter of deviation from the best fit sphere). This second parameter opens a new window in optical designs toward compact instrumentation, using less optical components. However, it is also a real issue for the existing manufacturing facilities for VIS/NIR/MIR applications and technological breakthroughs are required.

In this paper, we present the concept and development of an innovative manufacturing process based on plasticity forming. The use of the plastic domain, beyond the elastic limit, will allow imprinting permanent deformations on thin metallic mirrors, following the shape of a pre-defined master mold. The manufacturing process is based on hydroforming of flat and thin metallic substrates, fast and free of high frequency manufacturing errors.

The first part of the paper details the main steps of the process. The result of the process will be a thin freeform mirror that can be integrated on an active array to compensate for residual low frequency manufacturing errors, as well as small misalignments and thermo-elastic effects. A second part of the paper will present the finite element analysis performed to extract all the working parameters and the mold shape, taking into account the springback effect and the microstructure of the material. The last part will discuss about the real tests performed in lab on hydroforming thin mirrors, 140mm in diameter. These results show that the mechanical evolution of the material during work-hardening and the roughness evolution can be controlled to converge toward a recurrent and innovative process. Then, the perspective will be to reach high asphericity.
This work is supported by the FAME (Freeform Active Mirrors Experiment) OPTICON-FP7 program.

9628-67, Session PTues

Dispersion model for optical thin films applicable in wide spectral range

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In the optics industry thin film systems are used to construct various interference devices such as antireflective coatings, high-reflectance mirrors, beam splitters and filters. The optical characterization of complex optical systems can not be performed by measurements only in the short spectral range in which the interference devices will be employed because the measured data do not contain sufficient information about all relevant parameters of these systems. The characterization of film materials requires the extension of the spectral range of the measurements to the IR region containing phonon absorption and to the UV region containing the electronic excitations. However, this leads to necessity of a dispersion model suitable for the description of the dielectric response in the wide spectral range. Such model must respect the physical conditions following from theory of dispersion, particularly Kramers-Kronig relations and integrability imposed by sum rules. This work presents the construction of a dispersion model composed from individual contributions representing both electronic and phonon excitations. The efficiency of presented model is given by the fact that all the contributions are described by analytical expressions. It is shown that the model is suitable for precise modeling of spectral dependencies of optical constants of a broad class of materials used in the optical industry for thin film systems such as SiO?, TiO?, HfO?, Ta?O? Al?O? and MgF? in the spectral range from far IR to vacuum UV.

9628-68, Session PTues

Nanometer-accuracy misalignment aberrations calibration of the point diffraction interferometer for high-numerical-aperture spherical mirror measurement

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Misalignment aberrations in point diffraction interferometric testing system can significantly influence the measurement results in the case of high-numerical-aperture test spherical mirrors, and it is hard to separate the high-order misalignment aberrations from the measured data. The traditional calibration method, which is based on linear-approximation, is applicable in calibrating only the linear misalignment aberration in measurement of high-numerical-aperture spherical mirrors. Based on modified power term for interferometry and 4-overlapping averaging 9-frame algorithm, nanometer accuracy high-order calibration method is proposed to calibrate the linear misalignment aberrations as well as high-order misalignment aberrations. Both the computer simulation and experimental results confirm the feasibility and accuracy of the proposed calibration technique, with the accuracies of (2.2148 nm) RMS achieved. The proposed method can also used in spherical surface measurement by other interferometric setups, such as Fizeau and Twyman-Green interferometer without foreknowledge of numerical aperture of the test surface.

9628-69, Session PTues

Highly sensitive displacement measurement utilizing the wavelength interrogation

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Spectral interferomeric methods utilizing the interference of two beams in a Michelson interferometer to measure the displacement are analysed theoretically and experimentally. First we consider an experimental setup [1] comprising a white-light source, a dispersion balanced Michelson interferometer and a spectrometer. The position of one of the interferometer mirrors is controlled via a piezo positioning system and the displacement measurement is based on the wavelength interrogation, i.e., the position of a chosen spectral interference fringe in the resultant channeled spectrum is measured as a function of the displacement of the mirror. Employing the setup, we measured the displacement in a sufficiently wide spectral range with a moderate sensitivity. Second we consider a setup with another interferometer (represented by a polarizer, a birefringent quartz crystal of a suitable thickness and an analyzer) to increase the sensitivity of the displacement measurement. In this setup, two channeled spectra are superposed and the resultant spectrum is with envelope which shifts with the position of the interferometer mirror.

We analyze the new measurement method theoretically and show that the displacement measurement is once again possible by using the wavelength interrogation and the sensitivity is substantially increased. We also realized the new measurement setup in which the position of the interferometer mirror is controlled via a closed-loop piezo positioning system and confirmed the theoretical results.

[1] P. Hlubina: Dispersive white-light spectral interferometry to measure distances and displacements. Opt. Commun., vol. 212 (2002), 65-70.

9628-70, Session PTues

Precision optical device of freeform defects inspection

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The automation, speed and precision in the quality control of surface shape require the development of control methods suitable for this purpose. The technique proposed in this paper provides a quality control of surface shape components by non-destructive and contactless way, with high resolution and increased sensitivity. The control is done in real time and instantaneously on all inspected surface. The accuracy of components geometry is the one of parameters which influences precision of the function. Moiré topography is full-field optical technique in which the shape of object surfaces is measured by means of geometric interference between two identical line gratings. The technique has found various applications in diverse fields, from biomedical to industrial and scientific applications. In many industrial metrology applications, contactless and non-destructive shape measurement is a desirable tool for, quality control and contour mapping. This method of optical scanning presented in this paper is used for precision measurement deformation in shape or absolute forms in comparison with a reference component form, of optical or mechanical components, on reduced surfaces area that are of the order of some mm2 and more. The principle of the method is to project the image of the source grating to palpate optically surface to be inspected, after reflection; the image of the source grating is printed by the object topography and is then projected onto the plane of reference grating for generate moiré fringe for defects detection. The optical device used allows a significant dimensional surface magnification of up to 1000 times the area inspected for micro-surfaces, which allows easy processing and reaches an exceptional nanometric imprecision of measurements. According to the measurement principle, the sensitivity for displacement measurement using moiré technique depends on the frequency grating, for increase the detection resolution. This measurement technique can be used advantageously to measure the deformations generated by the production process or constraints on functional parts and the influence of these variations on the function. The optical device and optical principle, on which it is based, can be used for automated inspection of industrially produced goods. It can also be used for dimensional control when, for example, to quantify the error as to whether a piece is good or rubbish. It then suffices to compare a figure of moiré fringes with another previously recorded from a piece considered standard; which saves time, money and accuracy. This optical method of control has advantageous features allows non-destructive and contactless testing, real time speed inspection and measurement; possibility of image tracking in motion analysis and surface deformation, high spatial resolution and high sensitivity may vary depending of the importance of defects to be measured.

9628-71, Session PTues

Establishment of an optical workshop in the ELI-ALPS, the novel laser research facility

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The major mission of the Extreme Light Infrastructure Attosecond Light Pulse Source (ELI-ALPS) is to provide the international scientific community with broad range of ultrafast light sources, especially with coherent XUV and X-ray radiation including single attosecond pulses. ELI-ALPS will be operated as a user facility and hence will serve basic and applied research goals in physical, chemical, material and biomedical science as well as, through spill-over effects, industrial applications. The unique laser systems offer the opportunity of generation of high harmonics and particles with unprecedented specifications. These together challenges the in house optical preparation capabilities of ELI-ALPS, which will have an essential role in the successful long term operation of the facility. In this paper we present the design considerations of the optical fabrication, thin film coatings, and metrology labs linked to the novel research activities of the facility.

The optical workshop will supply the source developments as well as the experiments with special, custom-made optical elements. We expect to reach ultra-high performance regarding surface quality, we need to be prepared for exotic materials with difficult processing needs and partially or fully unknown optical properties. This facility will consist of a polishing, grinding, lapping and cutting workshop, and a thin film coatings laboratory for metal and dielectric thin films and multilayers. A material diagnostics laboratory with profilometer, AFM, and further devices will be assisting the manufacturing. The individual optical elements installed or replaced will have to be tested appropriately for flatness, optical aberrations, spatial phase distortion, and spectral reflection / transmission. The laser pulses with octave wide spectral bandwidth and high temporal contrast demand the optics to be tested against scatter, spectral phase distortions, and also laser induced damages. The lasers with kW class average power require the optics be cleaned appropriately in a clean environment.

9628-72, Session PTues

Analysis of factors important for measurements of focal length of optical systems

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A focal length is a basic optical characteristic of an optical system. Thus, it is important to be able to measure this value for a given optical system very accurately in practice. At present there exist various physical principles of the focal length measurement which can achieve different measurement accuracy. In our work we analyze several methods of measurement of the focal length with respect to factors, which are important for a measurement accuracy. The analysis is performed on examples.

9628-73, Session PTues

The effect of temperature in continuous polishing

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Continuous Polishing is the indispensable method of processing of Nd-doped glass,because of its domination in Full spectrum control.It has been studied on processing of Continuous Polishing in depth and we all know a lot about the influence factors of the processing.But there is little papers on the effect of temperature and ways to control the uncertainty caused by temperature.We had studied something on the production of heat between the conditioner and the worker,the effect of the heat and the solution of control the uncertainty caused by temperature.the heat comes from the friction between the lap and the conditioner except the chemical reaction on here which the friction is the major influence. There is two aspect in relationship of the temperature,the woker and the lap. the temperature difference between the top and the button of the worker contribute the deformation,which make the processing complex.It is a big matter on the creep which happens in processing between lap and worker and it is affected by temperature difference.Moreover,the thermal expansion happens in lap when the temperature is changed.Above all,these is negative factors in the processing. These some works which we do to understand the property of the lap such as pitch penetration test,BBR and DMA.Meanwhile We search some solution to control the uncertainty,such as open slot,circulation fluid injection, modified asphalt. These method will take effect in the processing.

9628-74, Session PTues

Research on absolute testing of the optical flats

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Higher and higher level of optical testing is required with the rapid development of society, especially in the lithographic objective lens system. It requires the surface figure to nanometer RMS even sub-nanometer RMS, which is a great challenge for optical metrology. The relative test precision is limited by the reference surface accuracy, who already cannot meet the requirements of the high precision measurement. Absolute test method eliminates the errors of reference flats and interferometer system, so that the figure of optical surface can be measured with nanometer accuracy .Gradually, the method becomes the key technology of optical metrology. Absolute testing methods for plane surfaces are mainly focused on three-flat method and its extensions. In the Three-flat testing, three flats are combined in pairs in different positions to obtain the surface shape of three tested flats respectively. Traditional Three-flat testing and ZYGO Three-flats program can only a vertical profile of data and a horizontal data profile along the diameter of the reference flat. Extension Methods of Three-flat test based on Zernike polynomial fitting could obtain full aperture surface shape but lose the mid and high spatial frequency errors of component surface. In order to solve the problems above, this paper proposes a method based on rotational average on N positions. This approach increases a set of measurement data with rotating a flat N times on the basis of the traditional four measurements. Then we use odd-even function theory, dividing the surface function into four components, and get the whole plane absolute surface shape distribution by solving each component. Compared with the traditional absolute inspection method, this method is to restore the whole wave without polynomial fitting. And the algorithm is simple and retains full spatial frequency information of the plane. Besides, to verify the accuracy of the rotating average method, we would compare the horizontal and vertical profiles of experimental data with the results of ZYGO interferometer. Finally, this paper would conduct a contrast experiment with even-odd function method and Zernike fitting method to validate the veracity of the results and apply this method to the absolute test of large optical flats.

9628-75, Session PTues

Flow-cytometric identification of vinegars using a multi-parameter analysis optical detection module

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We show a proof-of-concept demonstration of a multi-parameter analysis low-cost optical detection module for the flow-cytometric identification of vinegars. Vinegars can be identified by the amount of absorbance, scattering and fluorescence that is observed. The flow cytometric analysis of such samples aids in the assurance of their quality or the detection of fraudulous imitations. This multi-parameter analysis polymer-based detection module can simultaneously measure laser induced fluorescence, absorption and scattering. To our knowledge no other miniaturized optofluidic chip based system offers these simultaneous measurements.

In classic optofluidic systems, the presence of viscous fingering, air bubbles, and emulsified samples can divert the excitation laser, significantly influencing the base value of every measurement. These phenomena are hard to predict and to simulate. The module we show is built around a novel optofluidic chip concept that counters these effects . Its channel design introduces an amount of periodicity to the signal responses of its photodetectors. This is achieved by the layout of the fluidic channels on the chip. The channels look like a snake that has folded back on itself five times. Every foldback provides an additional location at which the excitation light and the sample can interact over a length of 1 mm. Between each of these five locations there is a small time delay depending on the flow speed. This time delay is what introduces the periodicity to the signal responses of the photodetectors and allows unpredictable variations in viscosity and refractive index of the channel content to be turned into a source of information. The optofluidic chip is built to be robust and easy to handle and is mass-reproducible at low-cost using hot embossing.

The sample is excited by two laser diodes (405 nm and 450 nm) that are driven by custom made low-cost laser drivers. We show a custom optomechanical holder for the optofluidic chip that ensures correct alignment, automatic connection to the external fluidic system and seals the chip, eliminating the need for bonding procedures. As a consequence the chip can be reopened after use and is easy to clean. The amount of scattering and fluorescence are detected by two PMT's, the amount of non-absorbed excitation light is detected by an amplified silicon photodiode. The external fluidics system is completely automated by a Labview program running on a desktop PC that also collects the data of the measurements.

We show an experiment in which 92 samples of vinegar are measured. The obtained signal responses are processed by a Fast Fourier Transform, analysing the interaction of the sample with the periodicity that is introduced by the channel. The Fourier transforms of each photodetector signal response are concatenated into a single individual dataset associated to each respective sample. These datasets are then fed into a principal component analysis. The loadings for the principal components show evidence of weight given to non-zero frequencies in the Fourier transforms. When plotting the measurements in the principal space of the first two components a clear segmentation is proven to be feasible.

When compared to spectroscopic techniques the obtained amount of optical data from an optofluidic system with dual laser excitation and four photodetectors is limited. However, we show that by introduction of the periodic channel and spectral multivariate data analysis the amount of data is significantly increased and we are able to identify 9 different kinds of vinegar. Thus we show an alternative approach to the classic optical spectroscopy solution at a lowered cost and improved expandability compared to previous optofluidic based detection systems.

9628-27, Session 7

Manufacturing and testing large SiC mirrors in an efficient way *(Invited Paper)*

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SiC mirrors are of excellent mechanical and thermal properties compared to their glass opponents; Efficient fabrication and testing of SiC mirrors, particularly the large freeform surfaces are very challenging; In this paper, direct CNC generation, deterministic polishing techniques including CCOS, MRF, and IBF Polishing were addressed in detail. Since testing is critical to make high accuracy freeform surfaces, the paper focused on Computer Generated Hologram (CGH) design and implement to measure large freeform mirrors. In particular, detector to mirror mapping distortion was discussed in detail. Finally, some results for SiC space telescopes were presented.

9628-28, Session 7

Results of a polishing study for SCHOTT XLD glasses

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Extremely low dispersion glasses (e.g. SCHOTT XLD glasses) play an essential role in the color correction of optical systems. Together with short flint glasses (KZFS Types) they can be used for apochromatic color correction in the visible spectrum or even for broadband color correction in combination with lanthanum crown glasses (LAK Types).

Unfortunately the chemical composition of those glasses leads to a high coefficient of thermal expansion, low hardness and low resistance against chemical attacks. As a consequence these glasses tend to be difficulty in processing. Therefore the glass engineer's task is to improve processability while keeping their special optical properties. N-FK58 XLD is an example of a new generation of XLD glasses from SCHOTT with improved processability. In 2014 a processing study has been conducted to optimize the polishing of XLD glasses. This presentation will show the results of this study for N-FK58 and the application to other fluorophosphates glasses.

9628-29, Session 7

Mechanical design implementation and mathematical considerations for ultra precise diamond turning of multiple freeform metal mirrors on a common substrate

Johannes Hartung, Matthias Beier, Thomas Peschel, Andreas Gebhardt, Stefan Risse, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

For optical systems consisting of metal mirrors there exist several diamond turning fabrication approaches which result in different alignment and mounting efforts for the later system. The most degrees of freedom have to considered if every mirror of the system is fabricated as a single optical component.

There are three parts contained in the announced talk. First of all an overview of optical and mechanical design constraints is presented and it is shown which information from the optical design is important for the fabrication depending on the mentioned approaches. In the second part of the talk the alignment efforts and data analysis issues of the fabrication approaches are discussed and compared in the light of current state of the art techniques. Also the role of mechanical references and their interaction with the necessary error correction are discussed. The last part of the talk concludes with some mathematical details and machining results for an anamorphotic four mirror system where the "snap-together" approach was used to reduce the usual mounting and alignment effort substantially in contrast to a single mirror fabrication.

9628-30, Session 7

Light scattering sensors for in-line roughness and defect assessment of optical components

Tobias Herffurth, Sven Schröder, Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Among existing techniques for the characterization of surface imperfections like roughness and defects, light scattering techniques have the advantages of being flexible, robust, non-contact, and highly sensitive. The highest degree of information about imperfections is obtained by angle resolve ng light scattering techniques. This usually requires highly sensitive and elaborated goniometer based measurement systems.

Recently, a new detector matrix based measurement approach has been developed at the Fraunhofer IOF which combines the advantages of light scattering measurements with in-line capabilities. The corresponding compact light scattering sensors can be integrated in manufacturing and inspection processes and are even capable for real-time data acquisition. In addition, the sensors are also suited for the characterization of large surface areas (full aperture characterization) within reasonable measurement times.

The sensor concept and its implementation into manufacturing machines as well as a new robotic system will be presented briefly. We also report on analysis techniques, specifically developed for this new approach, which provide links between the obtained angle resolved scattering (BRDF) results and the structural properties of optical components. Therefore, application examples for the characterization of surface roughness and nano-structures as well as for the classification of defects are presented. It will be demonstrated that the obtained results are comparable to those of white light interferometry, but additionally provide instantaneous information on isotropy or scattering losses. In addition, methods for the quality assessment of multilayer coatings as well as technically rough surfaces are introduced as well.

9628-31, Session 7

Use of a NOM optical profilometer to measure large aspheric surfaces

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We report the use of an autocollimator-based non-contact Nanometre Optical measuring Machine (NOM) profilometer for the in-situ measurement of the base radius of curvature (ROC) and conic constant for E-ELT primary mirror segments during fabrication. The use of profilometers of the NOM design for the evaluation of X-ray optics has been widely reported in the literature where the measurements are taken under tightly controlled environmental conditions to ensure that the temperature variations and mechanical distortions are minimised. The aim of our work is to design and implement a NOM that is deployable onto a CNC polishing machine and in general to make the process of non-contact profilometry more portable and adaptable for use in an industrial optical fabrication environment. This has presented challenges such as temperature variation, electromagntic interference and in-situ alignment and calibration procedures.

The NOM optical system is comprised of an autocollimator (with an alignment laser facility) and a scanning precision pentaprism which is used to deflect the collimated beam by 270 degrees onto the surface of the optic under test. An iris is used to reduce the measurement pupil size to bring the measured surface within the wavelength/8 RMS flatness requirements of the autocollimator and is situated approximately 5 mm from the artefact's surface. The pentaprism and iris aperture are supported from an air-bearing carriage on a granite beam. The position of this carriage along the granite beam is recorded using a linear encoder. The probe beam can scan the surface of the object either continuously or at intervals along the granite beam. The yaw and pitch angle components of the reflected beam together with the carriage encoder position along the beam are recorded using bespoke control software. The height profile of the surface is obtained by integration of the autocollimator pitch data. The natural mode of measurement of a surface by NOM is a linear scan and so an areal measurement pattern scan approach is adopted for the measurement of surfaces. The translational and rotational modes of the CNC polishing machine are used to position the artefact appropriately for the multiple scans.

The areal height measurements are analysed using either curve fitting or surface fitting software. In particular we report on circle fitting to scans taken on spherical surfaces and conic fitting to scans taken on aspheric surfaces. The conic fitting software uses a nonlinear least-squares optimisation technique to obtain the radius of curvature and conic constant of the nearest conic surface. Whilst the measurement of the radius of curvature of spherical surfaces has been reported previously, here we report also on the use of this instrument to measure E-ELT primary mirror segments during fabrication which have typical aspheric departures of 180 micrometres. The repeatability of the measurement has been found to be approximately 1 mm in a measured ROC of approximately 90 m. The absolute accuracy is limited by the accuracy of the calibration of the autocollimator and the in-situ calibration of the instrument during operation.

9628-32, Session 7

Reducing the cycle time of cementing processes for high quality doublets

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For the manufacturing of high performance optical systems, in addition to surface form accuracy, the centered alignment of the optical surfaces within the assembly is becoming increasingly important. In the case of cemented doublets (or triplets), precise centering has to be taken care of before the assembly process as it is a characteristic of the doublet itself. At the same time, high-volume production requires a fast and robust alignment and cementing process.

The standard method for cementing of doublets etc. uses the outer barrel of one element as reference axis. The optical surface of the second element is aligned to this axis. The main limitation of this procedure is the assumption of perfect collinearity of the barrel axis and the optical axis. Any centering error of this element will degrade the optical performance of the assembly. By contrast, the alignment of all optical surfaces to a common axis opens up perspectives for the production of highest quality optics.

In this contribution, we will present a system for the automated collinear alignment of the optical surfaces. In a first step, the center of curvature positions of each optical surface are measured by means of electronic autocollimation and the well-established TRIOPTICS MultiLens principle. The top surface is then aligned using a PC-controlled piezoelectric actuator. Here, instead of aligning with respect to a machine axis (e.g. rotation axis), the optical axis of the bottom element represents the target axis.

In order to increase the throughput of this procedure, the system is equipped with a novel measurement head concept. The single focusing autocollimator is replaced by a head that produces autocollimation images of all 3 surfaces of a doublet at the same time. Thus, the positions of all surfaces are measured simultaneously during just one rotation so that both additional rotations and focus movements are avoided. Cross-talk between the single measurements that may affect the robust application of this procedure is eliminated by synchronized stroboscopic illumination and data acquisition of the single surfaces.

Using this approach, cycle times can significantly be reduced from an average of 1 min to less than 10 seconds (w/o curing time). The system is reconfigurable in order to support a wide range of sample designs, and enables cementing of high quality optics with centering errors below 2 µm.

9628-34, Session 8

Surface assessment and mitigation of DUV optics *(Invited Paper)*

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CaF2 is one of the foremost optical materials used in ArF excimer laser optics. Surface quality of optically finished CaF2 plays an important role in the component's lifetime. Several techniques were employed to assess surface quality of optically finished CaF2 in terms of top surface and subsurface damage, resulting in subsurface-damage-free CaF2. UV light and plasma interaction with CaF2 surfaces were investigated. The results were discussed in terms of surface roughness and cleanness associated with surface finishing and optical coatings.

9628-35, Session 8

Roughness analysis of optical surfaces and functional nanostructures

Nadja Felde, Marcus Trost, Sven Schröder, Angela Duparré, Fraunhofer IOF (Germany)

Surface roughness can be a critical factor for optical applications. This is mainly because even small amounts of surface roughness give rise to light scattering causing image degradation (near-angle scatter) and scatter losses. The range of scatter angles critical for the given application defines the lateral spatial frequency range relevant for that specific application. The thorough characterization of optical surfaces requires the determination of roughness within the entire range of these relevant surface spatial frequencies with high sensitivity as well as over large surface areas. This can be achieved by combining different metrology approaches such as atomic force microscopy, white light interferometry, and light scattering.

9628-36, Session 8

Polishing performances of different optical glasses with different pH value slurries and different size powder during CMP polishing

Jun Cao, Chaoyang Wei, Shijie Liu, Aihuan Dun, Minghong Yang, Xueke Xu, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

Different pH value ceria slurries and different size polishing powder were used to polish fused silica glass?K9 glass and Nd-doped glass on pitch plate. Material removal rates (MRR) of glass polished with various pH value slurries and different size powder, and textures of each sample were characterized. The results show that scratches is most on the surface of Nd-doped glass of all three kinds of glasses, and the scratch densities increase with the increase of polishing powder size. The MRR of fused silica glass were lowest under any situation. On the other hand Nd-doped glass had the largest MRR. The removal rates of all three kinds of glass would rise under alkaline condition. The texture of fused silica glass is very small due to silicon oxygen tetrahedron structure; it can realize ultra smooth surface process when the powder size is smaller than 1.8 ?m. Rough structures were shown on the surface of K9 glass under both alkaline condition and powder size larger than 1.1?m. For Nd-doped glass with loose phosphorus oxygen structure, near neutral polishing environment and smaller size powder were useful for the surface polishing process. The results further reveal polishing mechanism and provide the possible for ultra smooth surface.

9628-37, Session 8

Optical glass: tolerances and accuracy of Abbe number

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High performance optical systems, as for example in professional digital cameras or for microscopes, correct both monochromatic and chromatic aberrations. The Abbe number ?_d is a measure of the dispersion of an optical glass and a first indication for a glass selection for chromatic correction, defined by

?_d=(n_d-1)/(n_F-n_C) (1)

where n_d (n_F, n_C) is the refractive index at the Fraunhofer d-line at 587.6 nm (F: 486.1 nm, C-line: 656.3 nm). Highly chromatic corrected optical systems need a precise and reliable dispersion of the optical glass. Therefore the Abbe number must be precisely measured and controlled.

Recently SCHOTT introduced the tightest refractive index and Abbe number tolerances available in the market with the steps 0.5 / 0.5 meaning a refractive index tolerance of +/- 0.0001 and an Abbe number tolerance of +/- 0.1%.

Estimating the Abbe number uncertainty just by simple methods results in an over-estimation which might lead to false conclusions on tolerance violations. This holds especially since the refractive index is measured at a set of different wavelength and fitted by a Sellmeier series:

n(?)=√(1+(B_1 ?^2)/(?^2-C_1)+(B_2 ?^2)/(?^2-C_2)+(B_3 ?^2)/(?^2-C_3)) , (2)

where n(?) is the refractive index, ? the wavelength, and B_i, C_i the Sellmeier coefficients. With the Sellmeier series the Abbe number can be calculated with much higher precision. The refractive index at different wavelength for the Sellmeier series is measured with a self-developed measurement setup employing the V-Block method. With this method a standard measurement accuracy for the absolute refractive index value is ±3•10^(-5) over a spectral range from the g- (436 nm) to the r-line (707 nm). Using special measures it is possible to increase the measurement accuracy to ±2•10^(-5) for a spectral range from the i- (365 nm) to the t-line (1014 nm). The Abbe number as a relative quantity can be determined with considerably better uncertainty. The V-block method as operated by SCHOTT uses a stack of samples, which can be measured in one single procedure thus allowing inter-sample comparison with even lower uncertainty.

Based on precise V-Block measurement methods we examine the Abbe number uncertainty for different optical glasses such as SF57, F5, FK5 and the recently introduced extreme low dispersion glass N-FK58 covering a wide range of the Abbe number. The evaluation is done using error propagation analysis and statistical evaluation of a large amount of reproduction refractive index measurement results. Simple propagation of the uncertainty in each refraction index would overestimate the Abbe number uncertainty by neglecting the correlation of the measured refractive indices and the broader data set of at least six spectral lines. Especially the newly introduced very narrow Abbe number grade 0.5 requires a suitable measurement uncertainty. We demonstrate that an automated V-Block refractometer fulfills these requirements. The analysis of a high number and long term reproducibility measurements shows that the standard deviations after several hundreds of measurements taken over almost ten years is better than 1•10^(?5) in refraction and 0.02% in dispersion.

9628-38, Session 9

Current developments in optical asphere and freeform metrology

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High end performance optical devices are a key technology for modern production industry. Applications reach from automotive detectors, cameras, cell phones, astronomy up to semiconductor production, to name just the most promising examples. Aspheres and freeform surfaces provide a promising way to improve and further develop these applications. Recently, they become core elements of many optical systems for different reasons. First, it is possible to reduce the number of optical components by using aspheres and freeform optical surfaces lowering production costs and reducing the weight and volume of the optical device. Second, it is possible to minimize the optical aberrations that an optical system exhibits by using aspheres and freeform surfaces. Thus, the overall performance of the entire system can be hugely enhanced.

In principle, optical surfaces can be measured by tactile or optical probe systems. The advantage of an optical measurement is the contactless acquisition of measuring points. Thus, even soft or coated surfaces can be characterized. Interferometric setups such as Fizeau or Twyman Green interferometers are common techniques for contactless measurement of spherical surfaces. Therefore, the surface under test (SUT) is brought to a Nulltest configuration. Regarding aspherical or freeform surfaces the situation gets more complex. The usual Nulltest configuration leads to a high line density of the interferogram that cannot be evaluated. Using computer generated holograms (CGH) or applying stitching techniques are one possible solution to measure aspheres and freeforms with an interferometer.

In this contribution two different concepts are discussed to measure asphere and freeform surfaces. The first one is the so-called tilted wave interferometer (TWI). It is based on a modified Twyman Green interferometer. Instead of a single monochromatic light source illuminating the object a huge number of different monochromatic light sources are applied. Each of these additional light sources produces a defined tilt of the wavefront illuminating the SUT. This tilt allows to locally compensating the gradient deviation of the SUT from a best fit sphere. Thus, the resulting interferogram exhibits a suitable low line density that can be detected and evaluated. Even aspheres and freeforms with a gradient deviation up to 10 degree from the best fit sphere can be measured without using a CGH or stitching techniques. Measurements of different aspheres and freeforms applying the TWI are presented and compared to state of the art interferometric asphere measurement systems in order to estimate the actual measurement uncertainty.

The second concept for aspheres and freeforms measurements of this contribution is based on an optical point sensor. Based on white light interferometry the point sensor detects the absolute distance to the SUT. A performed scanning along the SUT allows characterizing the form deviation of the asphere or freeform from the nominal design. Again measurements of different asphere and freeform surfaces are presented and compared to actual state of the art point sensor solutions.

Finally, advantages and challenges of both measuring concepts are discussed. Furthermore, the further development of both concepts is outlined focusing on the reduction of the measurement uncertainty.

9628-39, Session 9

Clarifying conversion of radius of curvature to power (and power to radius of curvature) for general surfaces and freeforms in standards

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Manufacturing optical components relies on good measurements and specifications. One of the most precise measurements routinely required is the form accuracy. In practice, form deviation from the ideal surface is effectively low frequency errors, where the form error most often accounts for no more than a few undulations across a surface. Usually surface form error (or deviation) is measured with interferometric methods such as a Fizeau interferometer. However, there are also various tactile methods that are in common use for aspheric surface measurement of low frequency errors. Regardless of the method of measurement, it is routine for optical engineers and opticians to convert measurement between radius of curvature and power (and vice versa).

In the international review and discussion of a new revision of ISO10110-5, the part of the standard covering drawing notation on surface form tolerances, astute review indicated that the current approximation used for this conversion is not entirely consistent for all standardized definitions of sagitta deviation. Historically, the notation for 3/A(B/C) had the term A denoted as “sagitta deviation” in the German DIN 3140 standard. In transforming this part of the German DIN standard to ISO10110-5, the A term was changed to a spherical surface approximation (no longer addressing the total surface form deviation); nonetheless, it is still called “sagitta deviation”. In another part of the ISO standard, ISO10110-12 defines sagitta for describing aspheric surfaces with the letter “Z” in terms of a sag table. Based on this more general ISO10110-12 definition, a revision draft of ISO10110-5 has been modified that the surface form deviation for such an aspheric surface should be called “sagitta deviation” and is measured along Z. This definition is consistent with the general surface standard that can be used for freeform surfaces, ISO10110-19. Discussions on what to call the A term in ISO10110-5 to disambiguate the standard with regard to sagitta for all surfaces is identified and will be updated properly in the final draft.

Consequently, modifications to put standards into a position where they are useful for spheres, aspheres, freeform surfaces, and general surfaces being measured by tactile methods as well as interferometers has effectively re-introduced an age-old geometric problem in optical metrology. The problem relates to the difference in measuring error normal to an ideal surface (or best-fit sphere) versus measuring error with a cosine length difference that is at a datum plane tangent to some point on the optical surface. For a standard rotationally symmetric surface, this tangent plane usually contains the vertex of the surface and the sag is measured along a z-axis parallel to the part’s ideal optical axis.

The overall goal of this paper is to provide a basis for a correct description of power and radius of curvature tolerances, including best practices and calculating the power value with respect to the radius deviation (and vice versa) of the surface form. Moreover, consistent definition of the sagitta is presented, along with different cases in manufacturing that are of interest to fabricators and designers. The results make clear how the definitions and results should be documented, for all measurement setups. Relationships between power and radius of curvature are shown that allow specifying the preferred metric based on final accuracy and measurement method. Results shown include all necessary equations for conversion to give optical designers and manufacturers a consistent and robust basis for decision-making. The paper also gives guidance on preferred methods for different scenarios for surface types, accuracy required, and metrology methods employed.

9628-40, Session 9

The measurement of an aspherical mirror by three-dimensional nanoprofiler

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The demand of aspherical optical elements is raising in various fields. In research field, third-generation synchrotron radiation generators such as Super Photon ring-8 (SPring-8) require ultraprecise optical elements with aspherical shape. In industrial field, the extreme ultraviolet lithography (EUVL) is composed largely of high-accuracy asymmetric mirrors, which realizes the miniaturization and cost reduction of large scale integrated circuit. Moreover, aspherical optics with small radius of curvature are employed for consumer products such as digital cameras and projectors.

At present profile measurement of these optical elements is conducted by phase-shifting interferometers or coordinate measuring machines (CMMs). Phase shift interferometers can measure flat and spherical mirror with high accuracy. However they require reference surface, whose accuracy effects measurement results, so they are not absolute measurement method and have trouble measuring aspherical or free-form figure. CMMs are capable for measuring free-form surfaces. Although disadvantages of CMMs include long measurement time, low measurement accuracy for large inclination angles, and damage to the sample surface. Briefly a measurement method for aspherical or free-form surface with high accuracy don't exist now.

Therefore our purpose is to develop a non-contact profiler to measure free-form surfaces directly with repeatability of figure error of less than 1 nm PV. To achieve this purpose we have developed three-dimensional Nanoprofiler which traces normal vectors of sample surface. The measurement principle is based on the straightness of LASER light and the accuracy of a rotational goniometer. This machine consists of the optical unit and sample unit. The optical unit comprises two goniometers as rotational axes, one translational stage as the horizontal axis and the optical head which has the quadrant photodiode (QPD) and LASER head at optically equal position. The sample unit is composed of sample and two goniometers as rotational axes.

This system is controlled according to following conditions. The incident light path coincide with the reflected light path by controlling each motion axes when LASER is aimed at a sample surface. During measurement the optical path length is made constant by a translational stage motion. In consequence, the reflected beam returns to the center of QPD. If sample has figure error, the reflected beam shifts from the center of QPD. Then we get the angle of rotation of the goniometer, the travel distance of the translational stage and the signal of QPD. The normal vectors and coordinates of sample surface are calculated from obtained date. Also we can acquire the surface profile of sample by applying the reconstructed algorithm to normal vectors and coordinates.

To evaluate performance of this machine we measure a concave aspherical mirror. The measurement area is a circular region with 100 mm in diameter, and measurement is repeated ten times. From ten results we calculate measurement repeatability, and we evaluate measurement uncertainty to compare the result with that measured by an interferometer. In consequence, the repeatability of measurement was 2.90 nm (?) and the difference between the two profiles was ±20 nm. We conclude that the two profiles was correspondent considering systematic errors of each machine.

9628-41, Session 9

Effective method for extracting aspheric parameters inherent in unknown aspheric surfaces

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In this paper, we propose an effective method for extracting the important parameters like radius of curvature, conic constant, and deformation coefficients indwelling unknown aspheric surfaces. These parameters can be inversely found from measured data by using the method that is based on aspheric equations and conic surfaces. To demonstrate the precision of the method, it is compared with a higher-order polynomial curve fit, employing two different examples. In a theoretical case, each largest fitting error (or shape error) resulted from the two methods appears a significant difference in precision. Lastly, we apply the proposed method to a real example and show the results.

9628-42, Session 10

Sensitivity of null testing for a local deformation

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There are a variety of techniques to determine the quality of optical surfaces, which provide quantitative information of the deformation of the shape of the surface under test. This work proposes to use the deflectometry technique using a Hartmann screen to test a spherical surface of the diameter and radius of curvature known, which has a local deformation. In order to make the theoretical analysis, a model of experimental setup in which its input parameters: the position of the Hartmann type screen and the location for each of its holes, the distance of the observation plane and the positions of the reflected rays, are known . With this model, based on the diameter of the deformation and deviation of the incident and reflected rays in the observation plane, we determine the theoretical sensitivity of the technique proposed.

9628-43, Session 10

Two-dimension lateral shearing interferometry with dual-mode

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Lateral shearing interferometry is an attractive technique to measure the wavefront aberration of high numerical aperture optical systems. The lateral shearing interferometry using two-dimensional grating can divide and shear the wavefront in two-dimension simultaneously, without replacing or rotating the grating in the measurements. A two-dimension lateral shearing interferometer based on chessboard grating is designed. It consists of a pinhole, a tested objective, a chessboard grating, and a CCD. A pinhole is placed on the object plane of the tested objective. The chessboard grating is positioned at the Talbot distance of the objective image plane. Then the two-dimensional shearing interferogram, which is also called the Fourier image of chessboard grating, is captured with the CCD. In this condition, The interferometer can work with dual-mode: the phase shifting mode and the Fourier transform mode.

In the phase shifting mode, the phase shifting is realized by moving chessboard grating along the shearing direction in the image plane. After performing phase shifting in two orthogonal directions, a series of interferograms in two orthogonal directions are obtained respectively. In the process of phase shifting, the phase modulation frequencies of different diffraction orders are in proportion to its order numbers. To extract the first order diffraction information and obtain the wavefront derivative in the shearing direction, we select the 8-buckets least-squares algorithm, which is insensitive to the even diffraction orders and the odd diffraction orders below seven. By using the phase shifting algorithm, the wavefront derivatives in two orthogonal directions are solved. After phase unwrapping and differential Zernike polynomial fitting, the wavefront is reconstructed.

In the Fourier transform mode, the spatial carrier frequency is realized by positioning the chessboard grating at the Talbot distance of the objective image plane. By performing two-dimensional Fourier transform of a single frame interferogram, the spatial frequency spectra of the interferogram is obtained. And then by setting a spectral band-pass filter at the +1 order part in the x direction and y direction respectively, shifting the carrier-frequency spectra to the zero, executing inverse Fourier transform, the wavefront derivatives in two orthogonal directions are solved. After phase unwrapping and differential Zernike polynomial fitting, the wavefront is reconstructed.

An experimental setup is designed to measure a 10?, NA0.25 microscope objective at 632.8nm wavelength. The period of the chessboard grating adopted in this experiment is 30 micron, the equivalent period along the shearing direction is 21.213 micron, the shearing ratio is about 0.06. The objective is measured by the experimental setup in two modes, the results show that the wavefront of the objective is 0.176? RMS, in the phase shifting mode, the repeatability (3?) of RMS is 1.1m?, the repeatabilities (3?) of Z5 to Z36 are better than 8m?; in the Fourier transform mode, the repeatability (3?) of RMS is 2.7m?, the repeatabilities (3?) of Z5 to Z36 are better than 17m?; after correcting the coordinates of the wavefront and averaging the results of Fourier transform mode, the differences of Z5 to Z36 between phase shifting mode and the Fourier transform mode are better than 8m?.

9628-44, Session 10

Compact, low-cost lensless digital holographic microscope for topographic measurements of microstructures in reflection geometry

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Digital holography is capable of providing surface profiles of samples with axial resolution in the nanometer range. The spatial resolution of digital cameras, commonly used in digital holography, is low in contrast to conventional analogue holography due to the limited pixel size. This is the main resolution restriction for digital holography. Therefore digital holographic imaging of microstructures requires a certain magnification, which is usually achieved by the use of microscope objectives. However, this lens-based magnification suffers from aberrations, which have to be compensated. Lensless digital holography is a well-established microscopic method providing the diffraction limited resolution of the order of the wavelength of the used light source. It is based on inline holography and usually allows imaging only in transmission geometry. V.R. Singh et al. have proposed a lensless digital holographic microscope setup capable of measuring in reflection geometry [1], [2]. The characterization of microstructures such as MEMS during their fabrication is crucial for their functionality. Profilometer and white light interferometer based measurement techniques are time consuming as the sample has to be scanned line-wise. Digital holography in contrast provide a full-field profile with only one acquisition.

In this contribution we propose a compact low cost lensless digital holographic microscope capable of performing measurements on reflective microstructures. It based on an off-axis digital holography setup. This Michelson Interferometer based setup consists of a laser diode, a beam splitter, a mirror and the CMOS-sensor as main components. The divergent beam is provided by a laser diode which is placed directly in front of the beam splitter without any need of fiber or pinhole. This simplifies the microscope setup significantly. The laser diode can be battery powered. The divergence angle of a laser diode which is typically between 20-40° in vertical direction and 5-10° in horizontal direction provides sufficient magnification to measure microstructures. Theoretical spatial resolution in order of the wavelength of the used light source can be achieved in vertical direction with this divergence. This resolution is in practice pixel size limited and depends on the distance between the light source and the sample. The shorter this distance, the better the resolution. We record holograms of samples with a 2,2 µm pixel size CMOS sensor chip. Amplitude and phase images of the recorded holograms with spatial resolution in order of the pixel size of our used CMOS camera are obtained by using the angular spectrum reconstruction method and the phase unwrapping algorithm. The phase image can be converted into a surface profile of the measured sample. We evaluate our setup by imaging reflective microstructures and confirm the possibility of measuring their topography.

In conclusion, we demonstrate a low cost possibility of realizing a device suitable for fault detection, roughness and shape measurement of microstructures.

[1] V.R. Singh et al. Proc. of SPIE Vol. 7522 75224L, 2010

[2] V.R. Singh et al. Proc. of SPIE Vol. 6995 69950F, 2008

9628-45, Session 10

A common path Mach-Zehnder interferometer

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On the basis of the lateral shearing interferometer, we have developed a common-path Mach-Zehnder interferometer. The interferometer is mainly consists of a ring cavity and an objective lens. The incident wavefront is divided into disturbed part and undisturbed part by the object. The disturbed part and undisturbed part correspond to the sample wavefront and the reference wavefront in a traditional Mach-Zehnder interferometer. The two parts travel along the same path in the ring cavity with opposite directions, and then they combined together and interfere with each other. The spatial frequency of the carrier fringes is determined by the objective lens and the distance between the disturbed wavefront and the undisturbed wavefront. The common-path Mach-Zehnder interferometer combined the advantages of common-path interferometer and double-path interferometers. It is more resilient to environmental vibrations than a double-path interferometer and more sensitive than a usual common-path interferometer. Moreover, because the common-path Mach-Zehnder interferometer doesn't need individual reference beam but a single incident beam, the object to be measured can be shift out of interferometer cavity. Thus the interferometer greatly simplifies the experiment layout.

The common-path Mach-Zehnder interferometer has been applied to laser-driven jet experiment conducted on SG-II. The field of view is about 1 mm in diameter; the incident beam is at least twice size of the field of view. The interferogram and the shadowgram were recorded simultaneously to enhance the image. The recorded spatial frequency of the fringes exceeds 200/mm in objective plane, so a wide range of phase change can be measured. 2-D phase distribution of the jet was obtained from the interferogram, and relative volume density of the jet along axis was inverted calculated.

9628-46, Session 10

Absolute testing of flats in sub-stitching interferometer by rotation-shift method

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Large-aperture optical elements are widely employed in high-power laser system, astronomy, and outer-space technology. Sub-aperture stitching is an effective way to extend the lateral and vertical dynamic range of a conventional interferometer. Most of the commercial available sub-aperture stitching interferometers measure the surface with a standard lens that produces a reference wavefront, and the precision of the interferometer is generally limited by the standard lens. The test accuracy can be achieved by removing the error of reference surface by the absolute testing method. When the testing accuracy(repeatability and reproducibility) is close to 1nm, in addition to the reference surface, other factors will also affect the measuring accuracy such as environment, zoom magnification, stitching precision, tooling and fixture, the characteristics of optical materials and so on. In the thousand level clean room, we establish good environment system. Long time stability, temperature controlled at 22°±0.02°.The humidity and noise control in a certain range. We establish a stitching system in the clean room. Interferometer we use the Zygo company, has established the motion system with Bilz active isolation system at level VC-F. In our paper we use the different sub-apertures as the different flats to get the profile of the reference lens. We review traditional absolute testing of flats methods and emphasize the method of rotation-shift functions. In the past paper, the Dove prism can be inserted in the cavity which will introduce more reproducibility error. The Dove prism is treated here as a device with perfect wavefront, whereas, in practice, inserting it in the measurement cavity is equivalent to adding an unknown surface to the problem that is not accounted for by the original three-flat analysis or that given here (there are indeed not enough measurements now to constrain the problem). We use the rotation-shift method to solve the problem. In our paper we use the different sub-apertures as the different flats to get the profile of the reference lens. According to the rotation-shear method we get the profile of the reference lens and the testing lens. Only two lens in the testing process which is fewer than the traditional 3-flat method. The arithmetic is present in this paper which uses the absolute testing method to improve the testing accuracy of the sub-aperture stitching interferometers by removing the errors caused by reference surface. The problem of the rotation-shear method is the tilt error. In the motion system , we control the tilt error no more than 4 second to reduce the error. In order to obtain higher testing accuracy, we analyze the influence surface shape measurement accuracy by recording the environment error with the fluke testing equipment. We hope to communicate with other people in the meeting to get more ideas about the high accuracy optical shop testing.

9628-47, Session 10

Calibration method to improve the accuracy of lateral shearing interferometer

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A systematic error calibration method is presented to improve the measurement accuracy of lateral shearing interferometer (LSI). This method is used to remove the most significant errors: geometric optical path difference (OPD) and detector tilt error (Fig. 1). The difference fronts of 0th and 1th order diffracted waves in the x and y directions are used to reconstruct wavefront using difference Zernike polynomial fitting, respectively. The difference fronts of 1th order diffracted waves in the x and y directions are also used to reconstruct wavefront. The coefficient differences between reconstructed wavefront are generated from geometric OPD and detector tilt error. The relationship between Zernike coefficient differences and systematic parameters are presented based on shear matrix. Thus, the distance of diffracted light converging point (d) and detector tilt angle can be calculated from the coefficient difference. Based on the calculated d and detector tilt angle, the geometric OPD and detector-tilt induced systematic errors are removed and the accuracy of LSI is improved.

9628-48, Session 11

Advances in corneal topography measurements with conical null-screens

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In this work we report the design of a null-screen for corneal topography. To avoid the difficulties in the alignment of the test system due to the face contour (eyebrows, nose, or eyelids), we design a conical null-screen with a novel radial points distribution drawn on it in such a way that its image, which is formed by reflection on the test surface, becomes an exact array of circular spots if the surface is perfect. Additionally, an algorithm to compute the sagittal and meridional radii of curvature for the corneal surface is presented. The sagittal radius is obtained from the surface normal, and the meridional radius is calculated from a function fitted to the derivative of the sagittal curvature by using the surface-normals raw data. Experimental results for the testing a calibration spherical surface are shown. Also, we perform some corneal topography measurements.

9628-49, Session 11

The instrument transfer function of an interferometer

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As the intense laser and aerospace projects processing,they need many large aperature interferometries to test the optical elements quality. In intense laser system,we always analyse the quality of the optical elements in frequency domain.For example,we used GRMS parameter to evaluate the errors in low frequency.Meanwhile,we used PSD to evaluate the errors in middle frequency.These Parameters are calculated from wave front tested by interferometry. So, the ITF must be good enough.

Elaborate concept and testing principle of the interferometer system transfer function,develop experimental program, and test system transfer function for different interferometer to obtain the transfer function of each interferometer. Finally analyze in the system error influence of the step plate measurement interferometer transfer function, the influence of the actual height of the step plate, the step surface inclination and the distance of the interference cavity.Using magnetorheological processing cycle for 1mm glass plate,measured by atomic force microscope the outline,then do a contrast experiment with interferometer income,suggesting that the study meaning of transfer function.Simulate the steps of 600mm board?examine the feasibility of the manufacturing. Then use it to measure the transfer function of 800mm interferometer.

9628-50, Session 11

Sinusoidal frequency modulation on laser diode for frequency stabilization and displacement measuring interferometry

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A displacement measurement with an uncertainty of less than nanometer and a range of larger than meter is a significant role in modern technologies such as nanotechnology, precision engineering, optical metrology, semiconductor manufacturing, etc. Laser interferometers are widely utilized for the displacement measurement, because the method can keep the traceability to the definition of the meter, if the laser frequency is calibrated.

Recently, a laser diode (LD) is selected as a light source because of its high efficiency, low cost, compact size and longer lifetime by comparing with gas lasers (e. g. HeNe laser). Moreover, the LD offers a direct frequency modulation through an injection current modulation and a large frequency tuning range. However, the typical frequency instability of the LD is approximately 10-6 order. This instability may cause a measurement uncertainty of micrormeter order, if the measurement range is meter order. Therefore, the frequency instability must be improved to less than 10-9 order, if the LD is used for high accurate displacement measurements with the uncertainty of nanometer and the range of meter.

A sinusoidal frequency (phase) modulation is effective for the displacement measuring interferometer. Recently, M. Madden et al. have reported the availability of the sinusoidal frequency modulation on an LD to a Michelson interferometer [Measurement Science and Technology, 25, 094005, (2014).]. They have used the Lissajous diagram to obtain the displacement using 2nd and 3rd harmonic modulated signals. To draw the exact Lissajous diagram with the sinusoidal frequency modulation, it is needed to know the value of the modulation index. In the sinusoidal frequency modulation for the Michelson interferometer, the value of the modulation index is the function of the frequency modulation amplitude and the optical path difference between the two arms in the interferometer.

In the paper, we propose the sinusoidal frequency modulation on a LD to achieve both the frequency stabilization of the LD and a displacement measuring interferometer with an uncertainty of nanometer. The central frequency of the LD is locked to one of absorption lines of iodine (I2) molecule near the wavelength of 633 nm. The frequency of the LD is modulated across the Doppler- broadened or the saturated transitions of I2 molecule and the synchronous detection utilized to observe absorption

signal. The synchronous detection signal is used for the LD frequency control through the null method. The I2 stabilized LD is compared with an I2 stabilized HeNe laser using the beat note between the two lasers. The I2 stabilized LD is then utilized for the light source of the displacement measuring interferometer. In the paper, we also propose the real time determination of the modulation index to draw the exact Lissajous diagram. The developed interferometer is evaluated with another displacement measuring means. The accurate displacement measuring interferometer can be constructed without high cost and complexity, and it can attain an uncertainty of nanometer or less in displacement measurement with a range of larger than meter.

9628-51, Session 11

Analysis of defects on the slopes on a parabolic trough solar collector with null-screens

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The null-screen method has been used to test aspheric surfaces, among them the surface of a parabolic trough solar collector (PTSC). This geometrical method measures the slope of the test surface and by a numerical integration procedure the shape of the test surface can be obtained. In this work, through some numerical simulations sinusoidal deformations with different amplitudes and spatial periods are introduced on PTSC surfaces. Then, an analysis of the deformations of the reflected images of a null-screen by the PTSC surface due to defects on the surface is performed. This procedure allows to validate the kind and magnitude of the surface deformations that can be measured with the proposed method. Also, an analysis of the advantages and limitations of the null-screen testing method will be discussed.

9628-52, Session 11

Terahertz computed tomography

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Over the past years, Terahertz (THz) radiation (frequency: 0.1 – 10 THz, wavelength: 30 – 3000 μm) has proven to be a powerful tool for nondestructive imaging and for spectroscopy in a large variety of fields of application, such as quality control, security technologies, biosensors or medical imaging. Wood, clothes, plastics, paper, ceramics, and semiconductor materials are transparent for THz radiation. Furthermore, different substances show typical spectral signatures in the THz frequency band, and thus, the spectral features can be used to analyze and identify explosives, drugs, or organic molecules.

A powerful and promising application of THz technologies is computed tomography (CT) with time-domain spectroscopy (TDS) systems. Compared to X-rays much more information can be acquired with the THz CT. In addition, radiation protection is not necessary because of its low energy. The amount of absorption can be used to localize inner structures of the samples for creating three-dimensional images. The time information permits the characterization of density distributions and, moreover, the spectral information helps to identify the substances contained in the samples.

We are going to present the horizons and hurdles of computed tomography with THz radiation. The time resolved measurement principle of TDS systems and the reconstruction techniques for different types of measurements will be introduced. We want to show examples of three-dimensional reconstructions, and also discuss the special properties of optical effects for such long wavelengths.

9628-53, Session 12

An automatically calibrated system that combines fringe projection and 2D digital image correlation

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An optical non-contact and full-field system that allows large displacement measurements in x-, y- and z-direction is presented. The system combines 2-dimensional digital image correlation (for in-plane measurements) and fringe projection (for out-of-plane displacements) and uses only one camera. The in- and out-of-plane displacements are obtained at the same instant allowing real-time measurements thanks to a color encoding procedure where fringes are projected in blue and white light strips on the sample surface that has been painted with red speckle on a white background [1]. The out-of-plane measurements allows the correction of the in-plane measurements [2] and the system has to be precisely aligned by following an established alignment procedure. The system is aligned when the optical axis of the camera is placed perpendicular to a reference plane from which the out-of-plane displacements are measured [3]. Furthermore, a calibration has to be done to obtain the fringe constant (K) necessary to perform fringe projection since it relates the out-of-plane displacements with the shifted phase (p) of the projected fringes, z=Kp. The novelty of the presented system is that ‘K’ is obtained automatically for each pixel (i,j) and it varies with ‘p’, due to the divergence and non-normal incidence of the fringe beam onto the sample surface (incidence angle different from zero). The knowledge of the dependence of ‘K’ for each pixel and for the shifted phase is of special importance when high precision or resolution of the out-of-plane displacements is required [4].

In the presented system ‘K’ is obtained by displacing both camera and projector simultaneously along the optical axis of the camera in incremental steps (z_n=nDz, n=1,2,3,...N). At every step an image is acquired from the fringe pattern and the unwrapped shifted fringe (Dp_n) is computed. In this way the shifted phase for the known z-increments allows to obtain the corresponding fringe constant for each pixel and phase increment: K(i,j,n)= nDz/Dp_n. Finally, for each pixel, a polynomial adjustment is performed for the K(i,j,n) as a function of the shifted phase, so that not all ‘N’ values but just a few polynomial coefficients are stored from which the K(i,j,p) can be obtained for any value of ‘p’.

Although the calibration may be complicate and time consuming, it is performed automatically and only has to be done once for each configuration of the system. The system is portable and can be easily adapted to measure large displacements and wide areas (using small incidence angle) or smaller distances but with higher resolutions (when increasing the incidence angle). Also the in-plane displacements can be adjusted to the requirements of the sample, since the resolution and the coverage of the area to be measured depends on the lens magnification and the field of view.

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9628-54, Session 12

Contribution to the standardization of 3D measurements using a high-resolution PMD camera

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PMD cameras are an emerging technology, which measures object distance using the principle of time of flight (TOF). They produce simultaneously two types of images of the scene - a distance image (or range image) and a gray level image (amplitude image). Typical currently available off-the-shelf PMD cameras offer resolutions of up to 100 k-pixels and a distance measurement precision of less than 10 mm. The characteristics of a camera can vary greatly, depending on their area of application. For indoor applications, higher resolutions can be achieved than for outdoor applications. Because pixel dimensions reaches a maximum, as they have to distinguish the inherent IR signal from the solar spectrum. The specifications seem poor for metrology applications, but significant improvements can be made with temporal and spatial averaging. Our current research project investigates in improving spatial resolution using super-resolution algorithms [Lietz].

Unfortunately, there is currently no standardized method available to measure the real spatial resolution of such PMD cameras. Because of these missing standards, the manufacturers of these cameras define resolution as the number of pixels in the image, avoiding the term spatial resolution.

In this context, we propose a new method to measure spatial resolution of PMD cameras and 3D cameras in general. We understand spatial resolution as the capability of an imaging image sensor to measure small objects clearly with distinct boundaries and extend this concept to PMD cameras. Although the number of pixels correlates to the amount of information within the image, it does not describe the resolving power of the camera system itself. We propose a new 3D measurement standard analogous to the classical MTF measurements for 2D imaging, which measures the spatial resolution of PMD cameras using both, the range image and the amplitude image. In addition, we introduce a newly designed test object for the measurement setup and analyze the influence of ambient light and disturbing light reflections on the measurements themselves.

With this work, we want to contribute to the standardization of 3D measurements. The paper includes the description of a general measurement procedure for the real spatial resolving power of PMD cameras. The measurement method takes into account the different requirements for indoor or outdoor use. Moreover, the standardization should be equally applicable to many imaging 3D measurement methods.

[Lietz] HIRES3D, Superresolution Camera, Innovative Projects 2014, third-party funded project in the country Baden-Württemberg, Germany. In this ongoing research project, the use of interpolation methods is investigated for use with 3D cameras. Cooperative doctorate with TU Illmenau.

9628-55, Session 12

Design and development of a profilometer for the fast and accurate characterization of optical surfaces

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With the advent of techniques devised for the mass production of optical components made with surfaces of arbitrary form (also known as free form surfaces) in the last years, a parallel development of measuring systems adapted for these new kind of surfaces constitutes a real necessity for the industry. Profilometry is one of the preferred methods for the assessment of the quality of a surface, and is widely employed in the optical fabrication industry for the quality control of its products. In this work, we present the design, development and assembly of a new profilometer with five axis of movement, specifically suited to the measurement of medium size (up to 150 mm of diameter) “free-form” optical surfaces with sub-micrometer accuracy and low measuring times. The apparatus is formed by three X, Y, Z linear motorized positioners plus and additional angular and a tilt positioner employed to locate accurately the surface to be measured and the probe which can be a mechanical or an optical one, being optical one a confocal sensor based on chromatic aberration. Both optical and mechanical probes guarantee an accuracy lower than the micrometer in the determination of the surface height, thus ensuring an accuracy in the surface curvatures of the order of 0.01 D or better. An original calibration procedure based on the measurement of a precision sphere has been developed in order to correct the perpendicularity error between the axes of the linear positioners. To reduce the measuring time of the profilometer, a custom electronics, based on an Arduino(R) controller, have been designed and produced in order to synchronize the five motorized positioners and the optical and mechanical probes so that a medium size surface (around 10 cm of diameter) with a dynamic range in curvatures of around 10 D, can be measured in less than 300 seconds (using three axes) keeping the resolution in height and curvature in the figures mentioned above.

9628-56, Session 12

3D printed freeform optical sensors for metrology application

Philippe Maillard, Andreas Heinrich, Hochschule Aalen (Germany)

In any mass production process of industrial manufactured parts, e.g. in automotive or aerospace industry, it is necessary to verify the quality of the products on demand. For that, different optical metrology techniques can be used - just in dependence on the object properties. Standardized tools are, e.g. laser triangulation, deflectometry, fringe projection or light section techniques.

Those optical metrology systems are composed mostly by a projection system which projects an optical signal (e.g. in the case of the light section method a laser line over a sample) and a detection system, which reads the information provided by the projected signal over the sample. From this information, properties like the shape of the object can be deduced.

Today the shape of the produced parts become more and more complex, which in turn makes it harder for the measurement using standards optical techniques. E.g. the projected line for measuring the profile of a part may not reach the whole surface structure due to some shadowing effects. Some areas might not be reached, leading to a lack of data or a higher effort in the measurement procedure.

A solution to solve this shadowing problem is to develop an optical component which is capable to project e.g. a continuous laser line over the sample without any shadowing effect. Therefore certainly a complex shaped optical component (e.g. a complex shaped light pipe) is needed. At this point the technique of additive manufacturing comes it. Using this technique, cost efficient complex shaped optical components can be produced.

Even though 3D printers offer almost unlimited possibilities for CAD designs, it is important to consider the geometrical boundaries and the resolution limits of each machine. They define the limits of the smallest structures in a design and they influence directly the roughness of the printed element´s surfaces, affecting the optical qualities of the sensor.

In this paper we present and discuss our work on the design and the functionality of optical elements, fabricated using additive manufacturing. Additionally we will show an optical sensor which can be used for shape metrology based on such optical components.

9628-57, Session 12

Two-dimensional thickness measurement using acousto-optically tuned external-cavity laser diode

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Optical interferometry is commonly used to perform various types of fine measurements. However, conventional interferometer cannot be adapted to thickness or step height greater than half of the optical wavelength.

Recently, optical coherence tomography (OCT) that uses low-coherence or wavelength -scanning light source has been attracted massive attention on medical and biological measurements. This technology is very useful also for industrial inspections.

Currently, many types of wavelength-scanning light sources use a laser diode (LD) because this diode is susceptible to an external cavity. The Littman configuration that uses a rotating mirror driven by a piezoelectric transducer (PZT) was demonstrated with the LD. The tuning range was commonly greater than 20 nm. An intracavity wedge plate or glass plate can be applied to the Littrow configuration for the wavelength tuning. However, these configurations require a mechanical scanning system that restricts the repetition rate, tuning speed, and reliability. Also, the hysteresis characteristics of the PZT deteriorated the repeatability. On the other hand, other types of external-cavity LDs (ECLDs) that use no mechanical elements have been proposed. The Littrow configurations equipped with an intracavity liquid crystal (LC) array allow wavelength scanning without the use of any mechanical elements. However, the tuning range and rate were restricted by the amount of phase shift and response time at the LC.

In this paper, we propose a swept source (SS-) OCT that uses an original ECLD and demonstrate two-dimensional thickness-distribution measurement. We first demonstrate high-speed, wide-range wavelength scanning with the ECLD that is equipped with a special AR-coated LD working at 770 nm. The wavelength tuning was implemented by changing the incident angle on the diffractive grating. In this process, an acousto-optic deflector (AOD) controlled the incident angle statically. The tuning range and rate of 22 nm and 20 kHz, respectively, were confirmed. Because no mechanical elements are required in our optical source, a fast and stable wavelength scanning can be realized in the measurement.

Next, we have applied this SS system to an OCT and conducted some measurements on thickness-distribution of a thin glass plate. The experimental results confirm that the two-dimensional thickness-distribution was measured accurately without mode-hop phenomenon.

9628-58, Session 13

Laser illumination for diffractive mask-aligner lithography: a special illumination system

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Mask aligner lithography is originally based on shadow printing in order to transfer a photomask pattern into photoresist coated wafers. Mask and wafer can either be in direct contact or in case of proximity lithography separated by an air gap of some 20 to 200 ?m. Contact lithography offers a resolution in a range of 0.5 to 1 ?m but suffers from contamination and yield problems, as well as a possible damage of the photomask. Residual resist on the mask requires a frequent mask cleaning and shortens its lifetime. Using proximity lithography these problems can be overcome, since it profits from a contact-free exposure process. Furthermore, industrial applications are demanding a high yield, thus proximity lithography is a promising and cost effective alternative to projection lithography, having a comparable high throughput.

The illumination system of the Mask Aligner had been further developed during the last years. The introduction of a new illumination system called “MO Exposure Optics” has significantly improved light uniformity and ensures a good telecentric photomask exposure. Additionally, the possibility of free shaped illumination by choosing a specific angular spectrum for exposure is now given. This integrated technology is based on microlens-integrators and illumination filter plates, which define the different angles of exposure. This opens up new possibilities in the field of Advanced Mask Aligner Lithography (AMALITH) for example with optical proximity correction (OPC), Talbot-lithography or phase shifting photomasks as well as for double-sided photomasks.

We now further improved the illumination system and especially the telecentricity of photomask illumination by replacing the spherical lenses by customized aspheric lenses. Many applications benefit from exposures of wafers with sizes up to 300 mm. Therefore a homogenous illumination of the whole photomask and hence the wafer underneath is indispensable.

With the new MO Exposure Optics, a specific angular spectrum of the exposure light can be choosen. But complete collimated light can not be provided. By integrating a laser operating at 355 nm the resolution of printable structures can be further enhanced. Therefor different optical elements like a rotating diffuser and a cylindrical asphere need to be added to the system. The customized cylindrical asphere ensures high collimated light behind the galvanometer scanner that is then illuminating the photomask.

Within this paper we will present an illumination system based on aspheric lenses improving the telecentricity of the photomask exposure. Furthermore the integration of a laser for full-field mask aligner lithography will be discussed. The new high-collimated illumination system will be used to exposure a double-sided photomask for advanced resolution enhancement of non-periodic structures.

In a former work we already presented the fabrication of a double-sided structured photomask which now will be combined with the resolution enhancement technique of a phase-shifting photomasks for arbitrary pattern transfer.

9628-59, Session 13

Microstructuring of glassy carbon molds for precision glass molding

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Replication Technics offer a cost efficient fabrication for high volume diffractive optical elements (DOEs). For plastic materials this is state of the art in industry due to the available Ni molds in combination with e.g. plastic injection molding.

For precision glass molding in high Tg materials, molds with higher thermal strength, low chemical reactivity and high mechanical strength are needed. Glassy Carbon can be operated up to 2000°C making it possible to mold Fused Silica, for which temperatures higher than 1200°C are necessary.

For the structuring of the Glassy Carbon wafers, a hard mask layer in combination with photolithography and a RIE process is used. We use either 250nm of Ti or 70nm of Si as a hard mask material. If the gas flow rates for O2 and SF6 are set to 40 and 10 sccm in the RIE process, the selectivity for GC:Ti is 5:1 and for GC:Si 6:1. The selectivity could be further improved to GC:Si 19:1 by using a gas flow rates of 45 sccm for O2 and 4sccm for SF6. AFM measurements showed that the surface roughness Ra is below 3nm.

We used the process to fabricate multilevel GC molds with 8 levels. The molds were used for precision glass molding of a low Tg glass L-BAL 42 at 555°C and Fused Silica at 1395°C. No anti-adhesion layer is needed. The molds could be separated from the glass after molding. An additional layer would decrease the resolution of the microstructures and would effect the lifetime of the mold.

The optical performance was tested for beamsplitters acting as 6x6 array generators. We will compare the results to the design specifications. The influence of fabrication errors introduced during the mold fabrication and replication are summarized.

Errors during the mold fabrication are etch depth errors, misalignment and the wall shape. This errors are e.g. also present in direct etching of fused silica wafers. During the precision glass molding the glass material has to flow into the microstructures. If not filled completely, the glass DOE will have an additional rounding of the walls. The mold and glass have different coefficients of thermal expansion. If the molding parameters such as temperatures, pressure and times are not adjusted carefully, the stress between mold an glass can cause rupture of GC and/or glass parts. We will discuss the change of the optical performance due to the molding process.

9628-60, Session 13

Optical design and laser ablation of surface textures: demonstrating total internal reflection

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For lighting there exist three key drivers for optical design of surface textures. [1] Integration of optical elements and functionalities into a single surface texture: single emitter components for multiple emitter systems integrated into a single surface texture is no longer size limited from a replication point of view. Moreover, optical functions such as beam collimation, color homogenization, glare reduction and diffusion, may allow for combining as well. [2] Disentanglement of the optical functionality and the visual appearance of the surface texture: facet units of size 50 um cannot be individually identified by the end user. [3] Late stage configuration in lighting systems: mechanical positioning and fixation of the optical component can be decided independently of its optical function as it is defined at its surface and not by its bulk shape.

We have investigated excimer laser ablation as a mastering technology for micro textured surfaces, where we have targeted an increase in correspondence between surface design and ablated surface for high aspect ratio structures. This is mostly achieved by design improvements of the photo mask that is imaged onto the polycarbonate surface. These improvements address several effects, most notably the angular dependence of the ablation process and secondly the loss of image resolution of the photo mask projection system at large ablation depths: as the numerical aperture is 0.13, this yields a depth of field approximately equal to 15 um. Both phenomena lead to a delocalized ablation during processing. For this reason heuristic image processing has been developed to analyze the target structure map on a larger scale than pixel level and incorporate the extracted information into the photo mask design. Using this approach we have been able to demonstrate close correspondence between designed and ablated facet structures up to 75° inclination at 75 um depth.

This extended facet parameter range now allows for the design of surface textures that perform total internal reflection (TIR) as a means of beam deflection. This is confirmed in BSDF analysis for a range of mono shaped cone arrays in hexagonal tessellation, where ray deflection angles down to 28° apex have been measured that match the design. Here, the full width at half max of the deflected beams was determined to be as small as 6°. As the hexagonal tessellation yields an optimal fill factor, we attribute the beam broadening to the geometric tolerances of the surface texture. Here, light collection was performed via the cones' base at normal incidence to the optical plate.

Secondly, a single surface TIR-Fresnel lens has been designed for a focal distance 5 mm using draft angles at 75° inclination. Here, light collection is performed at the textured side. For this design beam collimation up to 12° beam angle and 32° field angle is demonstrated.

These outcomes demonstrate that excimer laser ablation using the optimized photo mask design routines intrinsically yields sufficient small dispersion in structure and fillet radii to be useful for lighting applications.

9628-61, Session 13

Replication and subdivision of chromium nano-grating in atom lithography

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Atom lithography is a novel technique for nanofabrication that can be used to grow periodic arrays of highly uniform nanoscale structures. The pitch standard of chromium is 213.0±0.1 nm?which coincides with ?/2 of the standing wave, in correspondence with the 52Cr atomic resonance transition: 7S3 ? 7P40 ??= 425.5 nm. With the utilization of the material removal ability in AFM scratching, the Cr nanostructures have been transferred to an InP substrate for replication and subdivision. And the uncertainty is better than 1% at 2 ?m area. The AFM lithography method expands the application of atom lithography in metrology to a smaller scale with high precision.

9628-62, Session 13

Enhancement of RIE-etched diffractive optical elements surfaces through ion beam etching

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To achieve high diffraction efficiencies the fabrication of multilevel Diffractive Optical Elements (DOE) with lateral feature sizes in the range of a few microns calls for smooth surfaces and vertical sidewalls. This, in principle, is be provided by Ion Beam Etching (IBE). However, due to the poor selectivity of the process, mask layers with some microns thickness are needed. Structuring of thick metal layers is laborious and thick photoresist layers reduce the resolution. Compared to Reactive Ion Etching (RIE) the etching rates of IBE are small, which leads to long process times.

Tests show that IBE photoresist layers require a long hard bake time at high temperatures to endure the etching process. This leads to a deformation of the photoresist structures. The original rectangular shape of the sidewalls is changed into a trapezoid one. The transfer of this shape into the substrate significantly decreases the diffraction efficiency of the fabricated DOEs.

On the other hand Reactive Ion Etching provides short process times. The high selectivity of the process allows thin mask layers. Vertical sidewalls can be achieved through an anisotropic etching process. The main disadvantage of RIE is the comparatively rough DOE surface that arises during the process.

The surface roughness of fused silica caused by variation of RIE process pressure and power and different mixtures of SF6 and Ar is investigated. Irrespective of the process parameters the surfaces are bumpy and not as smooth as the IBE surfaces. A comparison of simulated diffraction efficiencies to measured values shows an average difference of about 10%.

Neither the IBE nor the RIE process alone provides satisfying results for the diffraction efficiency. To increase the surface quality of the diffractive structures they are treated with Ion Beam Etching after the Reactive Ion Etching. The etching rate of the IBE process changes with the incident angle of the ion beam. With increasing incident angle the etching rate increases. The maximum of this effect is reached at approximately 65° depending on the etched material. If the substrate's surface is adjusted perpendicular to the ion beam, the surface roughness leads to a local variation of the etching rate. Because the etching rate increases with high angles, tips are ablated faster than flat areas and the surface roughness is smoothed.

This is demonstrated both by simulation and experiment. The experiments show the smoothing of the DOE surface during Ion Beam Etching from some 15nm roughness to less than 5nm. The measured efficiencies approach the simulated values after the IBE. The average difference in diffraction efficiency reduces from some 10% to about 1.5%, which is in the range of the measurement error.

The faster ablation of rough areas leads to a change of the overall etching depth. The etching depth also affects the diffraction efficiency of the DOEs and has to be taken into account when planning the process times of the RIE and IBE processing steps. The correlation between the overall etching depth and the single RIE and IBE process times is determined experimentally.

9628-63, Session 13

In-line metrology setup for periodic nanostructures based on sub-wavelength diffraction

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We have developed a methodology based on sub-wavelength diffraction to assess the fidelity of nanoimprinting lithography. Using a diffraction grating with periodic structures on the micrometre scale, changes in the nanometre scale can be traced.

Light diffracted by a grating is determined by the critical dimensions (CD) of the repeated cell in the nanometer scale. We establish a unique relation between the diffraction pattern of a grating, i.e. intensity versus collected angle of measurement, and the CD of the repeated cell. Using this concept, dimensional sub-wavelength features can be detected in periodic structures from the diffraction pattern since a sufficient number of orders of diffraction are measured and the accuracy of the measurement distinguishes deviations from a reference. Volume nanofabrication processes, like nanoimprinting lithography, reproduce a cell with nanometer scale features at least hundreds of times in a repetitive continuous way. The results of such approaches are periodic arrays of cells with well-defined nanometer-scale CD. The periodicity is normally in the micrometer range, and because of that, the periodic arrays constitute themselves good diffraction gratings for optical frequencies light.

Diffractograms are usually collected by positioning the light source and the detector in a sequential way. The data acquisition is slow by nature and allows monitoring only one order of diffraction at a time. To improve on this we have developed and built a diffractometer to implement in-line SWD as a metrology tool for in-line nano fabrication. The optical design allows measuring at once the diffraction pattern of an optical diffraction grating in milliseconds with sub 100 nm sensitivity. The illuminated zone can be made as small as few 10s of micrometres, improving the contrast for local defectivity, or arbitrarily large. Thus, defects of sub-100 nm sizes in structures with a ?m periodicity can be detected during nanofabrication inline, in real time and non-invasively.

9628-64, Session 13

Improved cavity ring-down system for high precision measurement of the specific modes' loss in ring cavity

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In this article, procedure and technique capable of measuring the specific modes' total loss in high quality ring cavity were described. High reflectivity mirrors have been widely used in various areas. However, the precise and reliable measurement of a high reflectivity (>99.9%) is difficult for the conventional method. Since the first exponential decay ring-down signal was obtained by abruptly switching off a continuous-wave (CW) laser when the intra-cavity intensity exceeded a predefined threshold. Cavity ring-down (CRD) technique was the most suitable method for high reflectivity measurement. However, the common CRD technique can not distinguish different modes in a high quality ring cavity with aperture.

In this article, an improved CRD system, consisting of a CW laser, a high speed acoustic optical modulator, high precision optical stages and image acquisition and processing module, was designed to measure the specific mode's total loss in high quality ring cavity. It is possible to control a selection level of every transverse mode's loss such as TEM00, TEM01, TEM10 and TEM11 of a ring cavity with specific size of aperture. As a typical example, the improved CRD system was applied in assembling the ring cavity of high precision ring laser gyro. Current apparatus provides a cavity loss resolution of 1ppm. It is very useful to control the whole series cavity characteristics in assembly process of ring cavity such as quality of cavity alignment and total cavity loss. Moreover it is also very useful to measure the reflectivity of highly reflecting mirror coatings.

9628-65, Session 13

Inkjet printed single mode waveguides on hot-embossed foils

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Inkjet printing is a flexible printing technique and has already been used for different applications such as the fabrication of electronic circuits. It also can be used to apply the core and cladding materials of waveguides as part of an integrated optical circuit. Several parameters determine the shape of the droplets and thus the profile, width and height of the resulting waveguide.

Our work aims for mass-producible all-polymer waveguides as part of Mach-Zehnder interferometers (MZIs) for sensing applications. Flexible foils made of PMMA serve as substrate. To ensure an acceptable performance of the all-polymer sensors both single-mode behavior and high sensor sensitivity are required. To increase the sensitivity the core layer thickness of the waveguides has to be reduced. It is well known that for a good performance of MZIs with core thicknesses of a few ten or hundred nanometers a large index contrast between core and cladding is required. This large index step cannot be reached using polymer materials. But, if a mass fabrication in a non-cleanroom environment is carried out homogeneous layers are more likely in the range of 1 or 2 μm. We showed recently that in this case the refractive index of the core for best sensitivity decreases dramatically to values in the range between 1.58 and 1.52 using PMMA as under cladding. These values can be covered by polymer materials.

Inkjet printed drops can have heights in the lower μm range but then the diameter and the resulting width of the printed line is much bigger resulting in multimode waveguides. Aspect ratios between height and width of 1:1 normally cause waveguide dimensions of several ten microns leading again to a multimode behavior. In order to fabricate single-mode waveguides by inkjet printing we propose the pretreatment of the polymer foil by hot-embossing. In this step grooves are formed to ensure the lateral confinement. Then a homogeneous core layer can be applied to form an inverted rib waveguide. This type of waveguide can be single-mode even if the width is in the range of some μm due to the fact that the higher order modes leak into the residual layer and are therefore not guided.

We show the fabrication of single-mode inverted rib waveguides. To this end, a silicon stamp is fabricated by standard UV-lithography and a subsequent dry-etching step. The replication of the structures into PDMS and then into a flexible PMMA-foil of 175 μm thickness is carried out by hot-embossing. The core layer is both applied by spin-coating and inkjet printing and consists of a custom-made acrylate composite. The refractive index is tunable in the range between 1.514 and 1.569 and the viscosities range between 10-2 and 10 Pas at 25°C. We present single-mode waveguides with different dimensions and optical parameters and discuss their optical performance with respect to their propagation losses and guided modes.

9628-66, Session 13

Additive manufacturing of optics: the new digital way from design to on-demand manufacturing

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Additive Manufacturing for functional optics has arrived and will enable mass customization of optics per project, application or even per single products. The company LUXeXceL – Prism Award Winner 2015 - has identified and effectively eliminated the massive inefficiencies that are present in the lens development processes!

What will such innovation change for you on the way of the old analogue industry to the forefront of the digitization?

SPIE. OPTICAL SYSTEMS DESIGN

9629-1, Session 1

Optical design of static and dynamic laser beam shaping systems *(Invited Paper)*

Fabian Duerr, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

Many commercial, medical and scientific applications of the laser have been developed since its invention. Materials processing applications, like cutting or welding; and medical applications, like corneal surgery are just a few examples. Many of these applications require a specific beam irradiance distribution to ensure optimal performance. There are a number of optical technologies that can be used for laser beam shaping, including simple apertures, diffractive optical elements, lenses and mirrors. The right choice depends on the optical design problem.

Often, it is possible to apply geometrical methods to shape a laser beam profile. This common design approach is based on the ray mapping between the input plane and the output beam which takes into account conservation of energy, a constant optical path length of the geometric wave-front between the input and output planes, and the ray trace equations. Geometric ray mapping designs of laser beam shaping systems with two plano-aspheric lenses have been thoroughly studied in the past. Even though analytic expressions for various ray mapping functions do exist, the surfaces of the lenses are still calculated by numerical integration.

In this work, we present an alternative approach that is based on the analytic description of the optical design problem by means of functional differential equations. This design approach is related to an analytic design method for optimal imaging that enables the coupling of three ray-bundles with only two free-form lens profiles [Opt. Express 20, 5576-5585 (2012)]. However, the key difference in this work is the necessity to incorporate the ray mapping relationship in the design approach. An example of a simple beam expander system is used to explain how the equations can be derived from Fermat's principle. This formalism allows accurate calculation of the lens profiles, which are described by Taylor series coefficients up to very high orders. For obvious reasons, it is only possible to calculate a finite (but high) number of initial terms of the Taylor series. Such a function is called a Taylor polynomial and will be the only approximation made. To demonstrate the versatility of this new approach, further examples of a Gaussian to flat-top irradiance distribution and Gaussian to dark hollow Gaussian (doughnut-like) irradiance distribution beam shaping system are solved.

So far discussed passive beam shaping elements are only capable of creating a single static intensity distribution. Dynamic beam shaping systems can enable the system to achieve varying shapes; important for some applications in laser material processing. For example, zoom laser beam expanders offer variable magnification levels by translating the axial positions of the lenses. It will be shown that this analytic design method can be also used to solve such dynamic optical systems consisting of four or more optical surfaces.

All presented ray tracing results confirm the high calculation accuracy of both static and dynamic optical systems and underline the potential of this design approach for refractive beam shaping applications.

9629-2, Session 1

Optical design of precision approach path indicators in a portable runway lighting system

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Portable runway lighting systems pose an interesting illumination challenge. They are typically used in harsh environments where generators or batteries are the source of electricity. As a result, not only do the systems have to satisfy the regulatory requirements which determine the light intensity profile but they also need to be highly efficient and within a compact design. The advent of LEDs as a viable lighting source offers the opportunity to significantly improve the wallplug efficiency of these lighting systems. However as they have different characteristics to traditional light sources it is also necessary to redesign the illumination optics to take the maximum advantage of the efficiency benefits that can be obtained using LEDs. One system that has been redesigned to take advantage of LEDs is the Precision Approach Path Indicator (PAPI).

A PAPI has the following characteristics. There are two output regions of light – one is red and the other is white. The light intensity within the respective colours is defined within the specifications from the regulatory bodies (FAA in the USA). Overall the output angular field is 20x8o but is divided into two equal regions of 20x4o and the transition between the two regions must occur within 3 arcminutes.

The main criteria for the optical design were to achieve the required light distribution and high efficiency. Additional requirements included ensuring that the end design is easily manufacturable and compact. The design of the optical system was separated into two parts. In the first section, the light from the LEDs is collected and coupled into a waveguide to create the required illumination pattern at the output of the waveguide. A projection lens is then used to image the output of the waveguides into the far field. The field of view of the projection lens on the input side matches the angle into which the light from the LEDs is collected.

In this paper, the details of the design will be discussed and how design decisions in one part of the system determine key characteristics in another area. Particular areas of discussion will include the preservation of etendu through the system, the design of the collection optics and the projection lens which images the output faces of the waveguide into the far field. One of the key elements is the waveguide which offers a number of advantages: homogenisation of the light distribution from the LEDs; separation of the red and white fields until the back focal plane of the projection lens system and therefore enables the use of one projection lens for the entire system; coplanar positioning of the LEDs which means that only one PCB is required, simplifying the assembly of the unit. The system has now been built and is working in the field and experimental data will also be provided.

9629-3, Session 1

A cross-polarized freeform illumination design for glare reduction in fruit quality inspection

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Common illumination systems in short wave infrared (SWIR) hyperspectral imaging (HSI) in the field of the agro-food industry, include direct or indirect tungsten halogen lights. While direct lights provide more radiation onto the samples than dome setups thus being more energy efficient, the acquired images often suffer from specular reflections and gloss. Glare artifacts in images increase variability in the data limiting the accuracy of machine vision detection algorithms for determination of food quality, or even providing false positives. Although domes are known to provide a near Lambertian illumination and glare free images, in practice glossy regions and heterogeneities may remain in the data. More particularly in the field of fruit and vegetable quality inspection, due to their waxy surface, it remains challenging to design an efficient realistic lighting system. This paper presents inclusion of the shape, bidirectional reflectance distribution function (BRDF) and Stokes parameters of fruit, such as apples, into ray-tracing software for realistic illumination engineering in order to determine the most suitable illumination scheme. The BRDF, polarization and shape are measured using a scatterometer, polarimeter and laser scanner, respectively. A cross polarizer (CP) with freeform optics (FO) optical configuration is proposed, which allows the FO to be optimized to maximize angular uniformity onto the apples observed by the imager. The uniformity of experimental and simulated CP illuminated apples is compared. The resulting design is baselined to an ideal dome configuration. Tolerencing of the apple wax layer, shape and light positioning are investigated.

9629-4, Session 1

Freeform Etendue-preserving optics for light and color mixing

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Today's SSL illumination market shows a clear trend to high flux packages with higher efficiency and higher CRI, realized by means of multiple color chips and phosphors. Such light sources require the optics to provide both near- and far-field color mixing. This design problem is particularly challenging for collimated luminaries, since traditional diffusers cannot be employed without enlarging the exit aperture and reducing brightness (so increasing etendue). Furthermore, diffusers compromise the light output ratio (efficiency) of the lamps to which they are applied.

A solution denominated "Shell-Mixer", based on Köhler integration and consisting of a spherical cap comprising spherical microlenses on both its interior and exterior sides was presented in 2012 (J. Chaves et al., Proc. SPIE 8550, p. 85502X, 2012. DOI: 10.1117/12.981004). When placed on top of an inhomogeneous multichip Lambertian LED, this optics creates a homogeneous (both spatially and angularly) virtual source, also Lambertian, where the images of the chips merge. This virtual source is located in the same position with essentially the same size of the original LED array, so etendue is not increased and the same size secondary optics used to control the bare LED emission can still be employed to control the Shell-Mixer emission.

In this work we present a new version of the Shell-Mixer that overcomes size constraints of the first model. In order to achieve good color mixing the previous Shell-Mixer needed a diameter 3 times bigger than that of the chip-array footprint, which made it not fully compatible with luminaries with tight geometrical/mechanical constraints.

The new Shell-Mixer is based on Köhler integration and Nonimaging Optics principles, and neither the outer shape of the cap nor the surfaces of the lenses are restricted to spheres or 2D Cartesian ovals. Implementing the Edge Ray Principle and loosening the constraints on the cap and microlenses shapes allowed significant size reduction (30 percent smaller diameter): for a source with a diameter of 10mm, the new shell has an equatorial diameter of 20mm. The optical performances are evaluated by means of a perfect imaging system which analyzes the virtual source created as well as by coupling the shell to typical secondary reflector luminaries. As a result, the new Shell-Mixer is free-form, keeps the light mixing capabilities of the previous model (tested in A. Teupner et al. Optics Express, Vol. 23, Issue 3, pp. A118-A123 (2015),http://dx.doi.org/10.1364/OE.23.00A118), meets injection molding manufacturing limitations and is only twice as large as the original chip-array.

9629-5, Session 2

TIR collimator designs based on point source and extended source methods

Taimoor S. Talpur, Alois M. Herkommer, Univ. Stuttgart (Germany)

Most light sources used in our everyday life employ one or the other form of collimation optics. With ever-increasing efficiency and output flux of LED light sources, the collimator design is vitally significant to completely utilize and shape the output. Collimators not only improve the efficiency but can also increase the quality of lighting in terms of color temperature, color rendering and homogeneity.

Total internal reflection (TIR) collimators are most widely used due to their high efficiency and low losses. Various design methods exist to design such collimators, including point source design, design via optimization, iterative functional method, and simultaneous multiple surface (SMS) method. In this paper, different methods are compared in terms of performance along with their benefits and drawbacks for the design of TIR collimators.

Main criteria for collimator design include efficiency and collimator dimensions. In addition to these criteria, there are secondary criteria such as light output homogeneity, beam shaping, etendue requirements, light mixing, source imaging, and so on. The different design methods allow improved control of one or the other parameter, therefore, selection of the design method is crucial in achieving the desired performance.

Optimization in non-sequential systems is subject to various problems, due the large number of free parameters and the statistical nature of the non-sequential ray tracing. Therefore, the design requires more accurate methods requiring less or no optimization. The point source design method allows designing the collimator quickly along with a good control of the output field pattern. The performance, however, drops as extended sources are implemented. The performance for extended sources can be re-gained with either optimization algorithms or routines for multiple iterative design with feedback. The simultaneous multiple surface (SMS) method incorporates the design of multiple surfaces iteratively, giving control on more than one source points. Typically either edge rays or a number of points are used, resulting in high-performance extended-source designs. The final SMS designs require no or minimum optimization.

However the SMS method allows little control on the individual curves making it hard to control the surface shape. Despite lower performance, the point source design allows better control of the surface curves, which is very useful in determining the validity of a preliminary idea or approach.

In this paper, various designs via the point source method are presented. These designs perform well with the point source, but the performance drops with the use of the extended sources. The deviation in performance for the extended source is determined and is compared with the point source. The designs are then optimized for the extended source and the results are compared with various simultaneous multiple surface (SMS) designs. In addition to comparing the efficiency, also other characteristics of the designs, like the achieved beam shape are compared.

9629-6, Session 2

Practical optical design of an LED collimator

Henning Rehn, OSRAM AG (Germany)

We present a detailed investigation of an optical system which couples the light of a Lambertian Source (for example, a high power LED array) to an equal etendue target. Such a system can be applied for gobo illumination or for illuminating a lightguide.

Though the efficiency of such a system may by ideal in theory, real-world constraints make it imperfect. The actual light collection angle by the target may play a role, and requirements such as the clearance between the optics and source or target and the maximum system diameter will have an influence on imaging and non-imaging designs.

As for some applications an uniform illumination of the target may be required, we finally analyze the ability of various designs to deliver homogeneity.

9629-7, Session 2

Design of reflector focusing light flux from LED into arbitrary 3D curve

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The problem of focusing light flux into arbitrary curve in 3D space arises in the design of different laser or illumination systems. Using of diaphragm with a curved hole is not efficient and does not work for any

3D pattern. In this study, we propose a numerical-analytical approach for designing reflective surface, which efficiently produces the prescribed intensity distribution on the arbitrary 3D curve in the space. The method consists of two steps: computation of the eikonal function on the curve and reconstruction of the reflective surface using precomputed eikonal function. At the first step, we use the iterative technique for obtaining eikonal function in the set of points on the curve. After that, we compute the continuous eikonal function by interpolation of the obtained values of the eikonal in points and reconstruct the reflective surface using continuous eikonal distribution. As examples, the reflectors generating spiral line on the inclined plane and polyline on the cube surface are computed and simulated. Simulation data shows the high quality of the produced intensity distributions.

9629-8, Session 2

Freeform array projection

Dirk Michaelis, Peter Schreiber, Chen Li, Andreas Bräuer, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Herbert Gross, Friedrich-Schiller-Univ. Jena (Germany)

Compact, ultraslim illumination systems with high lumen output can be built up by means of the concept of multichannel array projection [1]. In this contribution we generalize this concept by replacing the condenser micro-lens array by an array of two micro-optical freeform surfaces in order to increase the system transmission considerably. Thus, the highly efficient freeform light shaping is combined with high resolution projection imaging and source light homogenization as well as system compactness due to the micro array arrangement.

For conventional array projection systems source light (commonly from LEDs) is collimated using TIR or standard lens elements. A single channel of the subsequent array element consists of a condenser micro-lens close to slide object structure and a projection micro-lens. The condenser lens images the light source into the aperture of the corresponding projection lens enabling large system transmission by Köhler illumination. Each slide object structure is imaged by the corresponding projection lens to the target. In order to superimpose all individual spatial images of all array channels at a common, composite target image, the optical axis of the channels are individually tilted by introducing certain pitch differences between the slides and the projection lenses. Similar to a fly's eye condenser the array projection optics mixes the illumination distribution of each channel leading to homogenization of the source distribution. Depending on the actual illumination task, the overall system transmission could be quite small. Firstly, light is wasted due to the none-perfect array fill-factor. Secondly, nontrivial light distributions at the target (target boundaries, intensity distribution) are usually generated by slide absorption. Those losses can be strongly reduced by freeform light shaping. To this end the condenser lens array is replaced by an array of two micro-optical freeform surfaces. The first surface generates a desired intensity distribution at the slide plane, i.e. the light is concentrated at the location where it is needed. The second surface redirects the light towards the projection lens of the corresponding array channel. Preferably, the freeform projector consists of two stacked wafers, where the freeform arrays are located at the exit face of the first wafer and the entrance face of the second wafer, respectively. The freeform surfaces are obtained by a generalized approach of Cartesian Oval representation. In the frame of the contribution we will discuss different designs for different illumination tasks (smooth illumination distributions, sharp features). Special attention is paid on the possibility of manufacturing of the arrays by means of laser lithography. Most of the stray light of such illumination scheme results from crosstalk of neighboring channels for strongly divergent illumination or due to imperfections at the channel rims. Especially, for very asymmetric light distributions, i.e. with a strong intensity gradient across the target, pronounced discontinuities may ideally appear at the boundary of the freeform arrays. Ways of reducing those discontinuities are discussed and suppression of unwanted straylight is examined.

[1] M. Sieler, et al. „Ultraslim fixed pattern projectors with inherent homogenization of illumination," Applied Optics 51, 64,(2011).

9629-9, Session 3

Freeform surface shape tradeoffs in illumination design *(Invited Paper)*

William Cassarly, Synopsys, Inc. (United States)

Freeform illumination optics couple light from a source to a target using freeform surfaces. The designer has to balance performance criteria like collection efficiency and achieving an ideal target distribution with the way that the freeform surface(s) must change. Although the increasing power of freeform illumination design tools allows freeform surface to be computed automatically, the designer must still contend with how freeform surfaces change to achieve the desired performance. This paper examines some of the common tradeoffs with special emphasis on how the shape of the freeform surfaces changes.

9629-10, Session 3

Color mixing using a freeform lightpipe

Michael Rommel, Univ. Stuttgart (Germany); R. John Koshel, College of Optical Sciences, The Univ. of Arizona (United States); Alois M. Herkommer, Univ. Stuttgart (Germany)

A freeform total internal reflection (TIR) geometry is designed to enhance color mixing for a spectral tunable light source such as a multi-colored light-emitting diode (LED) or an array of discrete LEDs. In order to quantify color mixing in the spatial and angular domain a merit function is proposed. This metric is based on a merit function from literature and is used on current color mixing methods to provide a baseline for novel designs. One novel design type enforces light entering the lightpipe to interact with its geometric boundaries. This lightpipe has a central hollow area ensuring that there are no ballistic ray paths through the lightpipe. Due to the central void, bending occurs in all planes around the optical axis, thus effective color mixing in the angular domain can be added to spatial mixing. Combining the proposed freeform optical component with a mixing rod compared to a solely mixing rod can increase the spatial and angular color uniformity. Excellent color uniformity can be reached with high efficiency. The effectiveness of current and new color mixing methods are presented and compared in detail, showing the parameterization that is important to obtain good color mixing.

9629-11, Session 3

Freeform aplanatic systems

Bharathwaj A. Narasimhan, Pablo Benitez, Dejan Grabovickic, Juan C. Miñano, Milena I. Nikolic, Jose M. Infante Herrero, Univ. Politécnica de Madrid (Spain)

Axisymmetric aplanatic concentrators have been used in the past for condensers and concentrators (Gordon et. al, 2005). It is well know that such a system must be stigmatic and satisfy the Abbe sine condition. This problem is well known (Schwarzchild, 1906) to be solvable with two aspherics when the system has rotational symmetry.

However, some of those axisymmetric solutions have intrinsic shading losses when using mirrors, which can be prevented if freeform optical surfaces are used. (Benitez, 2007)

In this paper, we explore the design of freeform surfaces to obtain full aplanatic systems. Here we prove that a rigorous solution to the general non-symmetric problem needs at least three free form surfaces, which are solutions of a system of partial differential equations (PDE). We present here that the solutions of the said system of PDE can be found using optimization. The merit function for such an optimization includes the spatial and angular deviation of the rays from the target rays according to the aplanatic condition. Therefore, the value of the merit function at the solution will be ideally zero. The examples considered have one plane of symmetry, where a consistent 2D solution is used as boundary condition for the 3D problem. We have used the x-y polynomial representations for all the surfaces, and the optimization has shown very fast convergence.

9629-12, Session 3

Recent advances in tailoring freeform Illumination optics: beyond point sources

Harald Ries, OEC AG (Germany)

Tailoring freeform optical surfaces for illumination was restricted to small (point) sources for which the direction of incoming rays is unique and can easily be determined as a function of location in space. We were able to extend the tailoring method to radiation distorted by a predefined arbitrary freeform reflecting or refracting surface. While the direction of the distorted radiation can be determined on the given freeform surface, it cannot be determined at other locations in an adequate manner. Therefore this requires a radically different approach in tailoring. Applications include tailoring TIR reflectors with user-defines entry surfaces, or the exit surface of a lens with given entry surface or a second reflector which corrects the reflection of a given first reflector. In this contribution a selection of examples shall be shown.

At this point we are still limited to sources of radiation with étendue significantly smaller than the area of the tailored freeform surface. However, the extension to non – point sources is a first step towards tailored freeform surfaces for extended sources.

9629-13, Session 3

Mapping algorithm for freeform construction using non-ideal light sources

Chen Li, Dirk Michaelis, Peter Schreiber, Andreas Bräuer, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Using conventional mapping algorithms for the construction of illumination freeform optics' arbitrary target pattern can be obtained for idealized sources, e.g. collimated light or point sources. Each freeform surface element generates an image point at the target and the light intensity of an image point is corresponding to the area of the freeform surface element who generates the image point.

For sources with a pronounced extension and ray divergence, e.g. an LED with a small source-freeform-distance, the image points are blurred and the blurred patterns might be different between different points. Besides, due to Fresnel losses and vignetting, the relationship between light intensity of image points and area of freeform surface elements becomes complicated. These individual light distributions of each freeform element are taken into account in a mapping algorithm. To this end the method of steepest decent procedures are used to adapt the mapping goal. A structured target pattern for a optics system with an ideal source is computed applying corresponding linear optimization matrices. Special weighting factor and smoothing factor are included in the procedures to achieve certain edge conditions and to ensure the manufacturability of the freefrom surface. The corresponding linear optimization matrices, which are the lighting distribution patterns of each of the freeform surface elements, are gained by conventional raytracing with a realistic source. Nontrivial source geometries, like LED-irregularities due to bonding or source fine structures, and a complex ray divergence behavior can be easily considered. Additionally, Fresnel losses, vignetting and even stray light are taken into account. After optimization iterations, with a realistic source, the initial mapping goal can be achieved by the optics system providing a structured target pattern with an ideal source.

The algorithm is applied to several design examples. A few simple tasks are presented to discussed the ability and limitation of the this mothed. It is also presented that a homogeneous LED-illumination system design, in where, with a strongly tilted incident direction, a homogeneous distribution is achieved with a rather compact optics system and short working distance applying a relatively large LED source. It is shown that the lighting distribution patterns from the freeform surface elements can be significantly different from the others. The generation of a structured target pattern, applying weighting factor and smoothing factor, are discussed. Finally, freeform designs for much more complex sources like clusters of LED-sources are presented.

9629-14, Session 4

Current trends in automotive front lighting lamps: an optics designer's view *(Invited Paper)*

Andreas L. Timinger, Benno Spinger, Philips Technologie GmbH (Germany)

LASER-headlights and LED front lighting in mass-market cars bring automotive lighting to the news pages. But also beyond the spectacular installations, halogen lamps, Xenon-discharge lamps and standardized LED-lamps bring interesting new products to our choice.

This paper aims to figure out how the photometric properties of these light sources can be translated into systems answering the market's needs for styling, cost efficiency and energy efficiency.

9629-15, Session 4

Matrix light and pixel light: optical system architecture and requirements to the light source

Benno Spinger, Andreas L. Timinger, Philips Technologie GmbH (Germany)

Modern Automotive headlamps enable improved functionality, for more driving comfort and safety. Matrix or Pixel light headlamps are not restricted to either a pure low beam functionality or a pure high beam. Light in direction of oncoming traffic can be selectively switched of, potential hazard can be marked via an isolated beam and the illumination on the road can even follow a bend.

The optical architecture that enables this advanced functionalities is divers. Electromechanical shutters and lens units moved by electro motors were the first ways to realize these systems. Switching multiple LED light sources is a more elegant and mechanically robust solution. While many basic functionalities can already be realized with a limited number of LEDs, an increasing number of pixels will lead to more driving comfort and better visibility.

The required optical system needs not only to generate a desired beam distribution with a high angular dynamic, but also needs to guarantee minimal stray light and cross talk between the different pixels. The direct projection of the LED array via a lens is a simple but not very efficient optical system. We discuss different optical elements for pre-collimating the light with minimal cross talk and improved contrast between neighboring pixels. Depending on the selected optical system we derive the basic light source requirements: luminance, surface area, contrast, flux and color homogeneity.

9629-16, Session 4

Optical design of a laser based headlight

Stefan Hadrath, OSRAM GmbH (Germany)

High luminance and thereby large headlight ranges are one of the main targets of current developments in car headlamp designs. An innovative approach is a laser headlight based on the LARP technology (Laser Activated Remote Phosphor). Blue laser diodes are used to pump a phosphor converter to emit bright white light from an extremely small area. Thereby, very compact headlight designs are possible to revolutionize automotive forward lighting.

In this paper an optical design of a laser headlight is presented. The use and functionality of multiple single laser diodes and the phosphor conversion and color mixing are discussed.

Blue light of 450 nm is emitted by a couple of laser diodes from almost a point source within a much smaller beam angle than typically emitted from LEDs, leading to a very small etendue. A few refractive and reflective optical elements are used to combine the single laser beams which are subsequently homogenized in a mixing rod. The exit side of the rod is imaged to the phosphor converter which partly transmits and partly converts blue laser radiation into yellow light, resulting in a mixed white

light with a CCT of about 5000 to 6000 K. The spot size is in the region of a few hundred micrometers resulting in a white, high luminance light source.

9629-17, Session 4

Design method for automotive high-beam LED optics

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In recent years, LED light sources are becoming more and more popular in the automotive industry. LED lighting devices are usually used in premium vehicles, particularly, due to the high complexity of the design of the secondary LED optics redirecting luminous flux and generating the required light distribution. The problem of calculating the optical element generating the prescribed light distribution is extremely difficult. Even in the case of a point light source and a single optical (refractive or reflective) surface, this problem can be reduced to the solving of the nonlinear differential equation of the second order with partial derivatives.

We propose to consider LED high-beam lighting system including a few identical illumination modules. Each module should generate light distribution meeting the requirements of the UNECE Regulations. To generate intensity distribution of this kind we use TIR optical element (collimator working on the total internal reflection principle) with array of microlenses (optical corrector) on the upper surface. TIR part of the optical element enables reflection of the side rays to the front direction and provides a collimated beam which incidents on the microrelief. Microrelief, in its turn, dissipates the light flux in horizontal direction to meet the requirements of the Regulations 112, 113 and to provide well-illuminated area across the road in the far field.

As an example, we computed and simulated the optical element with the diameter of 33 millimeters and the height of 22 millimeters. Simulation data shows that three illuminating modules including Cree XP-G2 LED and lens allow generating an appropriate intensity distribution for the class D of UNECE Regulations.

9629-18, Session 4

Automotive pixel headlamp using DMD and free-form optics

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Today‘s upper class vehicles are often equipped with matrix beam front lighting systems in order to generate highly adaptive light distributions. A next step in this development is the use of DMD modules as beam shaping technology. This increases not only the number of individually controlled pixels, but also reduces the system’s complexity by far.

Classical headlamp systems either contain a Halogen light source with a free-form reflector or a Xenon (HID) lamp and a parabolic reflector. With the ongoing development in automotive lighting, various types of light distributions have been developed and are still being developed to increase road safety and further enhance the driver’s vision. Latest headlamp modules consist of many LED light sources forming a matrix beam array to realize an adaptive front lighting system. These modules require a highly sophisticated mechatronic setup and optical system. At the same time, demands regarding the reliability of an automotive system are high, which increases the costs for such a system. This has the consequence that these highly complex systems can only be integrated into expensive cars with a small series production.

A possibly cheaper and more reliable option to produce a variable light distribution is the use of a DMD module. The advantage of DMD-based light modules is that they do not require mechanical actuators. The light is directed by many micro-mirrors onto the areas on the road where it is needed. This way the amount of light for each pixel can be controlled. The disadvantage of a DMD is that due to its working principle, parts of the light are always dumped and thus a higher luminous flux of the light source is necessary to achieve a comparable light output. To compensate for this disadvantage, at the Institute of Product Development a free-form lens is used to reach an optimum illuminance on important parts of the road without losing to much light. For this purpose, a prototype is built, consisting of a high-performance DMD projection unit, a specifically developed lens with a free-form optical surface as well as an adaption algorithm. The DMD projection unit used has a powerful HID light source in order to meet the requirements arising from the regulations regarding the quality of light distribution.

The image projected by a standard DMD module is in 16:9 format and more or less homogenously distributed. On the other hand the luminous intensity of an automotive light distribution shows high gradients. This would lead to significant losses of light and a very inefficient system. Therefore the optical system typically used for multimedia projection is replaced by the previously mentioned free-form lens.

In this paper we discuss the concept and realization of a demonstrator to generate a fully adaptive light distribution using a DMD module and a specifically designed free-form lens. The variable light distribution is partially achieved by optically shaping the light output from the DMD using the free-form lens and also by a special control algorithm for the DMD.

9629-19, Session 5

Analysis of planar luminescent layers in white LEDS with the extended adding doubling method

Jana Ryckaert, Sven Leyre, Peter Hanselaer, Youri Meuret, KU Leuven (Belgium)

LED technology is increasingly used in different applications such as lighting and display backlights. The most common method to create white light with LEDs is the use of a luminescent material (e.g. phosphor) in combination with one or more blue LEDs. Different configuration can be used (intimate, chip-on-board, remote-phosphor configuration). To design high quality LED sources it is important that these systems can be correctly simulated such that the performance can be predicted and the desired parameters can be optimized. The Monte Carlo method is the traditional algorithm to simulate these systems. A disadvantage of the Monte Carlo method however is the large computation time which makes it less suitable for optimization.

We present a new method to predict the performance of various white LED packages with a planar phosphor layer using the extended adding doubling method. This method takes luminescence and volume scattering of the phosphor material into account, but demands for a rotational symmetric illumination and assumes an infinite planar luminescent layer.

In a phosphor-converted white LED a large part of both the incident and converted light are backscattered from the phosphor layer towards the LED package. This light will partly be reflected back into the phosphor layer by the LED package. The behavior of the LED package can be approximated by a reflection matrix. This matrix includes the direction in which the light will be scattered, as well as the efficiencies with which the light will be reflected. This reflection matrix is assigned to a boundary layer in the adding doubling model.

We found that, by using the extended adding doubling method with a boundary layer, it is possible to predict the total flux and the spectral angular intensity distribution of the light emitted from the white LED, provided that the right reflection matrix is assigned to the boundary layer. With this method we present a fast technique to predict and optimize the performance of phosphor-converted white LEDs. This method is applied to calculate the optimal scattering properties of a luminescent layer in a remote phosphor configuration.

9629-20, Session 5

Optical modeling of LEDs by combining ray and wave-optical approaches

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Extensive research has been conducted to improve the design of light-emitting diodes (LEDs) so as to enhance the light extraction efficiency, and improve beam shaping, through techniques such as the use of photonic crystal gratings, patterned substrates, surface textures and back reflectors. Increasingly complex designs have necessitated the use of computational simulations which have provided numerous insights for improving LED performance. Ray optics based techniques such as Monte Carlo ray-tracing or rigorous electromagnetic (EM) wave optics based techniques such as finite-difference time-domain (FDTD) and rigorous coupled wave analysis (RCWA) are commonly applied for optical modeling. Whether ray-optic or wave-optic techniques are used for the numerical simulation is usually based on the focus of the design and the geometric scale of the structures involved in the problem. This paper compares the optical responses of prototypical periodically-patterned substrate examples with varying lateral periods and dimensions computed with both methods. It is shown that these results may differ even when the grating periods are much larger than the wavelength, especially when the considered surface is in a realistic LED chip environment. Such results indicate that to accurately model LEDs involving periodically-patterned features a standalone ray-optics approach may be insufficient even at large structure sizes. We have recently proposed a mixed-level simulation approach combining rigorous EM wave based tools (RCWA and/or FDTD) and ray-optic tools. Here, we demonstrate cases where this approach is necessary to comprehensively model the light extraction in modern LED designs

9629-21, Session 5

From BRDF to roughness: defining the link between two key parameters for optical design

Quentin Kuperman-Le Bihan, Light Tec (France)

Link between roughness and Bidirectional Scatter Distribution Function (BSDF) is a challenging issue but a necessary step for designers. Indeed optical designers often speak about scattering where manufacturers speak about roughness. This link would enable an easier understanding between both parts, ending up with better designs. Besides, optical design software deal very well with BSDF, but ray tracing time can be strongly impacted when you have a lot of them in your design. Therefore, replacing BSDF by a real geometrical shape such as the roughness could be of a big benefit.

How can we link BSDF to roughness?

We worked on two ways of finding a link between BSDF and roughness. From measured BSDF with Reflet Bench, we tried to find the equivalent roughness using He-Torrance model. Still using He-Torrance model we also tried to compute the BSDF knowing a roughness profile from a sample.

The study showed great results with specular samples. When roughness is at least ten times bigger than the wavelength, roughness could be estimated within 5% precision. Above this limit, roughness can still be computed but with a 50% precision, which gives us at least an order of magnitude estimation. We also found with our method that, the more scattering the sample is, the more difficult it is to estimate roughness.

Thanks to such a link between roughness and BSDF, it becomes much easier to understand how to go from one to the other. This can be very useful for optical designers, but also for manufacturer who wants to perform roughness measurement. Designers who need a certain scattering for their optical designs, can therefore easily speak with manufacturers by giving them a roughness value to perform the BSDF they are looking for.

9629-22, Session 5

LED luminance beyond 100Mnits and its application in optical system design

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Given the diversity of potential applications, quite distinct LED parameters can be emphasized. Since neither space constraints nor angular admittance can be relaxed for optical systems positioned at the etendue limit, the only way to realize high brightness systems is by employing high luminance LEDs and chips.

In particular, for automotive exterior applications ever increasing luminance has facilitated LED-based low-beam, high-beam and auxiliary functions, culminating in full-LED headlamps.

A significant milestone was the implementation of LEDs with luminance of 100Mnits [1, 2]. However, the progress in high luminance LEDs has continued [3].

In this presentation, we emphasize a few examples that leverage the high LED luminance available today.

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9629-23, Session 5

Design of diffractive optical surfaces within the nonimaging SMS design method

João Mendes-Lopes, Pablo Benítez, Juan C. Miñano, Univ. Politécnica de Madrid (Spain)

The Simultaneous Multiple Surfaces (SMS) was developed as a design method in Nonimaging Optics during the 90s. Later, the method was extended for designing Imaging Optics. The SMS method involves the simultaneous calculation of N optical surfaces (refractive or reflective) using N one-parameter wavefronts for which specific conditions are imposed. The relationship between degrees of freedom (N optical surfaces) and constrains (N wavefronts) is not exactly one to one. For simplicity in our explanation we will consider that it is so. When designing an nonimaging optical system, these conditions comprise coupling of every one of these N wavefronts to other wavefronts with prescribed conditions. [1].

This paper shows an extension of the SMS method to diffractive surfaces. Using this method, diffractive kinoform surfaces are calculated simultaneously and through a direct method, i. e. it is not based in multi-parametric optimization techniques. Using the phase-shift properties of diffractive surfaces as an extra degree of freedom, only N/2 surfaces are needed to perfectly image N one parameter wavefronts. Wavefronts of different wavelengths can also be coupled, hence chromatic aberration can be corrected in SMS-based systems. This method can be used by combining and calculating simultaneously both reflective, refractive and diffractive surfaces, through direct calculation of phase and refractive/reflective profiles.

Raytracing can be used on a diffractive surface with phase using the local grating concept and applying the grating equation. The general vector form of the grating equation is

n_i (n ??(r_i) ?)=n_d (n ??(r_d) ?)+m?/2ϖ (n ??? ??) (1)

Where ri and rd are the incident and diffractive ray, respectively, ni and nd are the refractive index of the incident and diffractive side, respectively, n is the normal vector to the surface in the incidence point, m and ? is the diffractive order and wavelength of interest, and ? ?? is the gradient of the phase function.[2],[3] If a kinoform diffracts a wavefront WF1 into a wavefront WF2 in the diffraction order m = 1, it can be demonstrated that, for two consecutive transition points d1 and d2 of a Fresnel zone, that the phase difference is

Δ?=2ϖ/? [(?OPL?_(WF,d_1)+?OPL?_(d_1,WF2))-(?OPL?_(WF1,d_2)+?OPL?_(d_2,?WF?_2))]=2ϖ (2)

Where ?OPL?_(WF,d_) is the Optical Path Length between the wavefront WF and the transition point d. This equation can be used to calculate N/2 diffractive surface point-by-point, to couple N wavefronts, combined with the SMS, by combining and calculating simultaneously both reflective, refractive and diffractive surfaces, through direct calculation of phase and refractive/reflective profiles.

In the paper several examples will be presented of diffractive SMS optical systems. In particular, a systems with two wavefront and three wavefront coupling based on one and two surfaces, respectively. It will be shown how chromatic aberration can be corrected by applying this method to SMS based-systems.

4. References

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9629-24, Session 5

Fluorescence and multilayer structure of the scorpion cuticle

Yu-Jen Chen, Pei-Ju Chiu, Cheng-Chung Lee, National Central Univ. (Taiwan)

We collect the scorpions, Isometrus maculates, in different instars to analyze the photoluminescence (PL), micro-structure of cuticles and their correlation. The photoluminescence is excited by 405 nm solid laser in room temperature and detected by BWtek BRC 112E spectrometer. The result shows that the intensity of photoluminescence positively correlate to instars of scorpion. The images of micro-structures of cuticles captured by scanning electron microscope (SEM) present the multilayer structure in detail. The samples are prepared in small piece to ensure that the PL and SEM data are caught from the same area. The correlation between instars and intensity of photoluminescence is explained according to micro-structures via the thin-film optics theory.

9629-25, Session 5

Steerable patterned OLED backlight for autostereoscopic display application

Uwe Vogel, Philipp Wartenberg, Bernd Richter, Karsten Fehse, Olaf Hild, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

OLED can be applied as highly efficient and high-resolution patternable illumination source for controllable and steerable backlights, e.g., for use in autostereoscopic displays. To evaluate technology and approach a 3.5” 3D QVGA display prototype has been developed and combines several achievements: large-area OLED backlight, highly-efficient and fast-response OLED top-emitter, striped patterned backlight, individual electronic driving for adaptive backlight control and 3D mobile display application.

9630-1, Session Key

Computation in lithography: perspectives, history, and directions *(Keynote Presentation)*

Donis G. Flagello, Nikon Research Corp. of America (United States)

Optical lithography has been extended to resolution well below the Rayleigh limit, and is currently being used to print features at 1/20th of the optical wavelength. Much of this achievement has been accomplished by extensive computational techniques that have integrated with various hardware components and sub-systems. These techniques have a history that has been developed over a 40 year time period and were created from a wide range of disciplines including physics, chemistry, optics, electrical engineering, computer science, mathematics, materials science and mechanical engineering.

This talk will look at the history of computation in lithography starting from the original basic simulations with photoresist. We explore how and why this evolved into more elaborate optical models, subsequent advanced materials models, and various so-called optical proximity correction schemes. The talk will give attention to why and how this morphed into what we call today as Computational Lithography.

Finally, we will give our perspectives looking at the current computational lithography techniques and where they might evolve. We will also draw some relevant associations with computational techniques used in other industries such as microscopy and digital photography.

9630-2, Session Key

Modeling and measurement of partially coherent light *(Keynote Presentation)*

Henri S. Partanen, Univ. of Eastern Finland (Finland)

We have to treat many modern light sources as partially coherent, one example of this are high power multimode laser diodes. In the coherent case it is enough to know the amplitude, phase and polarization of the light in certain coordinates, but for partially coherent light we have to also know the correlation between all possible coordinate pairs, which greatly increases the complexity of the measurement and modeling. We present our theoretical and measured result on modeling and measuring several partially coherent light sources.

A convenient way to model the partially coherent light is to represent it as an incoherent sum of uncorrelated coherent modes. If we know the coherence or cross spectral density function (CSD), we can find the modes by numerically solving the eigenvalues and eigenfunctions. We could measure the CSD by scanning the pinholes in Young's interferometer over the all possible coordinate combinations, and measure the visibility of the interference fringes. The problem is how to move the pinholes mechanically. We have used a digital micromirror device from a modified video projector to draw them.

Because of the long measurement time the efficient sampling of the coherence function is an important issue. Sometimes we do not have to measure the full four-dimensional coherence function to get full knowledge of the light. Many sources obey Schell model, which means the coherence properties do not depend on the absolute position of the measurement points, but just the distance between them. In this case it is enough to measure the intensity profile of the beam and the degree of coherence as a function of just coordinate separation. A well-known example are Gaussian Schell-model (GSM) beams, where both the intensity and the coherence profile have Gaussian shape.

In many cases the coherence properties separate in x and y direction, and it is enough to measure the coherence just in these directions, and not for the all combinations. This is possible for most lasers with rectangular resonator. We measured a broad area laser diode (BALD) witch resonator is narrow in y direction and therefore essentially single mode and fully coherent. In x direction there are several modes with very irregular shape because of the imperfections in the resonator.

The coherent modes are not unique. For example GSM beams are usually modelled with Hermite-Gaussian modes, but an alternative way is to use Gaussian modes with identical shape, which are shifted in space and weighted with a suitable function, in this case with Gaussian. This shifted-elementary-mode representation works with all Schell model sources. If the source is quasi-homogeneous, and the phase can be assumed constant, it is enough to measure far field intensity of the light to find the elementary mode shape, and source plane intensity for the weight function. This method gives very accurate results for low coherence sources such as LEDs, and often accurate enough approximations for example BALDs.

In the final and most demanding case it might be necessary measure the full four dimensional CSD, with lowest sufficient sampling for a feasible measurement.

9630-3, Session 1

3D imaging and ranging in a snapshot *(Invited Paper)*

Paul Zammit, Guillem Carles, Andrew R. Harvey, Univ. of Glasgow (United Kingdom)

To date, imaging deep samples that exceed the depth of field (DOF) of the objective poses a serious challenge in microscopy. Scanning techniques such as focus-stacking accomplish the task. However, besides requiring complicated optical and mechanical arrangements, such techniques entail the acquisition of several images in order to render the final 3D image; hence, their acquisition time is long. As a result, these techniques are unsuitable for applications involving the imaging of dynamic scenes such as live samples in the study of cell morphogenesis (Development 136, 2403 (2009)) or zebrafish hearts and circulation.

We describe a novel 3D imaging technique based on hybrid imaging (HI) (Appl. Opt. 34, 1859 (1995)) and the recently published Complementary Kernel Matching (CKM) (Optica 4, 209 (2014)) which permits the acquisition of 3D images in a single snapshot with an image quality comparable to that achievable by a focus-stack (which can require up to a few hundred snapshots). HI has been proposed as a simple means of extended the DOF of an optical system, however, no depth information is obtained. More importantly, conventional HI is known to yield poor image quality mainly owing to the formation of post-recovery artefacts (Opt. Express 18, 8207 (2010)).

CKM solves both of these problems by exploiting another phenomenon in HI. Assuming a cubic phase mask (CPM), the captured image will experience a shift proportional to the amount of defocus in the scene. By acquiring simultaneously two images of the scene with the CPM and its complex conjugate (that is the CPM rotated by 1800), this shift can be detected at each location in the scene giving rise to a depth map. The recovery can then be performed using the matching kernel at each point thus yielding a high quality, artefact-free final image. CKM therefore combines the extended DOF provided by conventional HI together with depth information to give a complete 3D image of a significantly superior quality than what is possible with conventional HI, in a single snapshot.

The method proposed here operates on the same principle as CKM; however, it does not require the duplication of the pupil or any moving parts whatsoever. As a result, the implementation is greatly simplified. Furthermore, the operational DOF is effectively doubled by enabling discrimination of the sign of the defocus. The accuracy in the depth measurements is also increased and the technique is rendered insensitive to the coding strength of the utilised CPM.

Experimental verification of the proposed method has been done by mounting a spatial light modulator (SLM) in the pupil plane of a microscope using a 20?, 0.50NA objective (DOF ~ 3μm). Using a CPM with a peak-to-peak modulation of 8 waves, the DOF was increased to ±30μm and images free of the artefacts that often afflict images recovered using HI were obtained. Rigorous measurements of the accuracy with which depth can be determined using this technique are in progress however, from previous measurements, a resolution of about 50nm for an NA of 0.65 is expected.

9630-4, Session 1

Efficient MTF optimization based on linear expansion and quadrature

Jim Schwiegerling, College of Optical Sciences, The Univ. of Arizona (United States)

The Optical Transfer Function (OTF) and its modulus the Modulation Transfer Function (MTF) are metrics of optical system performance. The OTF can be calculated as the autocorrelation of the complex pupil function. However, numerical integration techniques for calculating the autocorrelation integral are computationally slow. The faster route to calculating the OTF is with first calculating the Point Spread Function (PSF) through the squared-modulus of the Fourier transform of the complex pupil function. The OTF is then related to the Fourier transform of the PSF. Fast Fourier Transform (FFT) algorithms are extremely efficient and offer a substantial improvement over the autocorrelation evaluation. However, even with the benefits of the FFT routines, MTF optimization is typically inefficient due to the repetitive need to calculate the MTF targets for each step in the optimization process. We have developed techniques for improving calculation times in MTF optimization. We recently demonstrated that the OTF can be represented as a linear combination of analytical functions. The key to the OTF expansion is to first expand the electric field amplitude in the image plane in terms of an orthogonal set of functions. The expansion coefficients for the electric filed amplitude, or more correctly their squared modulus and complex cross terms, are then directly related to the expansion coefficients of the OTF. The analytic functions used to represent the OTF are variations on the diffraction limited OTF expression modulated by higher order polynomials. By using these techniques, the OTF can be directly related to the wavefront error coefficients and apodization of the complex pupil function. To enable rapid and stable calculation, the expansion coefficients can be calculated using quadrature techniques which converts numerical integration into a series of sums based on raytracing through various pupil locations. Here, we outline the theory behind performing the OTF expansion, as well as demonstrate the quadrature technique. An example of applying this technique to optimizing a traditional optical system at target spatial frequencies is demonstrated. In addition, extended depth of focus systems are analyzed to illustrate optimization of the through-focus MTF. The expansion technique offers a potential for accelerating OTF optimization in lens design, as well as insight into the interaction of aberrations with components of the OTF.

9630-5, Session 1

Computational optics in gamma, infrared, and THz imaging systems

Zeev Zalevsky, Alex Zlotnik, Yuval Kapellner, Amir Shemer, Ariel Schwarz, Bar-Ilan Univ. (Israel)

In this presentation two novel concepts of computational imaging applicable for infrared and THz systems will be discussed and demonstrated. In both cases a controllable array of digital micro mirrors (DMD) will be used. In the first concept a lensless imaging will be demonstrated. In the second an incorporation of one or two DMDs in the aperture plane of an imaging lens will show possible enhancement in the field of view and geometric resolution of the integrated imager.

Imaging systems generally involve tradeoffs between spatial resolution and signal to noise ratio. In a single pinhole based imaging system, the size of the aperture determines the spatial resolution. Up to a certain point, the smaller the aperture, the sharper the image, however, with a small pinhole the number of photons passing through decreases and the uncertainty of the measurements is increased. On the other hand, a larger pinhole allows more photons to pass through, which reduces the relative uncertainty of the measurements, but this comes at the price of degraded spatial resolution. In our first concept we propose a novel method for realizing an imaging system that can enhance the spatial resolution while preserving the energetic efficiency. The imaging system is a lensless configuration in which there is a time varied array of pinholes that is positioned in the aperture plane. The changeable and moving pinholes array is realized using a DMD matrix and the proposed concept can be applied both for infrared as well as for THz imaging.

In the second concept the usage of DMDs allows obtaining geometric resolution improvement and a significant enhancement of the field of view (FOV). The idea behind the above-mentioned imaging features is to use the DMDs to properly encode the spatial frequency domain such that the multiplexed information of the imaged object can later on be separated and reconstructed. The DMD fulfills the task of a fast switching aperture coding agent. The DMD allows generating very controllable point spread functions (PSFs) via the programmable mirror's angle position. The PSFs have replicative features ("train" of impulse functions) due to the ordered grid of mirrors. We change the locations and values of these impulse functions in time in order to create different responses. As a result, the nature of the captured images is replicated and overlapped. Assuming known PSF parameters (obtained via calibration process), we can reconstruct the original imaged object in case of both increasing the geometrical resolution of the imager as well as in extending its FOV. In the case of FOV extension the PSF replicas are introduced into the sensor parts of the object's FOV that, before the replications, were positioned outside the sensor's FOV. We also apply compressed sensing concepts in order to allow capturing in time-less images than the obtainable improvement factor (of resolution or of FOV).

9630-6, Session 1

Large-scale analytical Fourier transform of photomask layouts using graphics processing units

Julia A. Sakamoto, Nikon Research Corp. of America (United States)

Compensation of lens-heating effects during the exposure scan in an optical lithographic system requires knowledge of the heating profile in the pupil of the projection lens. A necessary component in the accurate estimation of this profile is the total integrated distribution of light, relying on the squared modulus of the Fourier transform (FT) of the photomask (reticle) layout for individual process layers. Requiring a layout representation in pixelated image format, the most straightforward approach is to compute the FT numerically via the fast Fourier transform (FFT). However, the file size for a standard 26-mm by 33-mm reticle with 5-nm pixels is an overwhelming 137 TB in single precision; the data importing process alone, prior to FFT computation, can render this method highly impractical. A more feasible solution is to handle layout data in a highly compact format containing vertex locations of pattern features (polygons), which correspond to elements in an integrated circuit, as well as pattern symmetries and repetitions (e.g., GDSII or CIF format). Provided the polygons can decompose into shapes for which analytical FT expressions are possible, the analytical approach dramatically reduces computation time, as well as the burden of importing extensive reticle data. Algorithms have been developed for importing and interpreting hierarchical layout data in CIF format and computing the analytical FT on a graphics processing unit (GPU) for rapid parallel processing. Incoherent imaging is not assumed, so that phase shifts are tracked until the very end, when the squared modulus of the FT is computed. Testing was performed on a 392-um by 297-um "virtual chip" test structure with 43 substructures distributed over six hierarchical levels. Using a state-of-the-art NVIDIA Tesla K20 GPU with 3.5 TFLOPS of single-precision computing power, the factor of improvement in the analytical versus numerical approach for importing layout data, performing CPU-GPU memory transfers, and executing the FT was roughly 1.6e4, 5.0e3, and 3.8e3, respectively. Potential algorithm enhancements will also be discussed.

9630-7, Session 1

Automated simulation and evaluation of autostereoscopic multiview 3D display designs by time-sequential and wavelength-selective filter barrier

Mathias Kuhlmay, Silvio Jurk, Roland Bartmann, Bernd Duckstein, René de la Barré, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

The investigation of new 3D display technologies requires high experimental efforts. Then the solution space can be fully considered using specified criteria. We have designed a semi-automated valuation system that is based on our own simulation software for spatially multiplexed autostereoscopic 3D displays. It can be used for 3D displays with image splitters in the form of lenticular raster or wavelength selective barriers. In conjunction with an imaging display this image splitter act as spatial light modulators and generate stereoscopic views. The underlying simulation models describe the optoelectronic components that interact in multiple levels. The simulation program that imitates the control and operation of the quasi-static arrangement, supply a representations of the beam path and the luminance at the viewing location.

In this paper, we describe the extension of this simulation for a time-sequential multiview 3D displays with wavelength selective filter barriers. We demonstrate an approach that allows design variants to examine and extract workable solutions to the real application. The time-sequential multiplexing allows increasing the resolution of spatially multiplexed 3D displays. Using wavelength selective barriers are then obtained in very complex, difficult manageable contexts. They require a systematic study of the solution space. For this purpose, the existing simulation is extended to a component that cumulates the representation of steps. They should be examined by the step wise image generation under time-sequential operation. Thus, the visible images in both eyes are investigated after each shift of the image splitter. They are summed and evaluated according to the temporal sequence.

To start an automated solving procedure we used a complex algorithm with behavioral which is limiting the multi-dimensional parameter space. That multi-dimensional parameter space comes from variation of different parameters of the based model. It influences the optical permeability of the described display layer and the result on image layer. To describe the image layer it was necessary to expand the current program version. To get the images of self-luminous, simulated 3D-displays a combination of ray-tracing and 3D-rendering was used. Thereto the emitted intensity distribution of each subpixel will evaluated by researching the color, luminance and visible area of it by using different content distribution on subpixel plane. We use that visual illustration to understand the results and to check whether it is accurate. For calculation we use an algorithmic validation by using constrains restrict the problem space.

The control and implementation of display and Image splitter layer can be different. In the following paper we use matrix displays with "vertical aligned RGB stripes" and image splitter with "slanted dot mask" structure by serial control. The automated simulation and evaluation occur by several image sections of the displays, where the parameter will be modified incremental, variation of content assignment changing and the correct landing of subpixel rays to sweet spot area. As a result we get a table with rating values and the corresponding parameter sets to visualize it graphically by different criteria to select possible solutions for research afterwards manually.

9630-8, Session 2

Approximate solution of Maxwell's equations by geometrical optics *(Invited Paper)*

Frank Wyrowski, Huiying Zhong, Site Zhang, Friedrich-Schiller-Univ. Jena (Germany); Christian Hellmann, Wyrowski Photonics UG (Germany)

Geometrical and wave optics are commonly considered as opposite poles in optical modeling. Historically the light representation by rays versus complex amplitudes is closely connected to the use of geometrical optics versus diffraction integrals for light propagation. We like to discuss geometrical optics from a more general point of view, which in fact was already suggested by Born and Wolf in 1959 in Principles of Optics. We follow them and understand geometrical optics as an approximate solution of Maxwell's equations. By this application of geometrical optics to electromagnetic fields instead of rays, it becomes obvious, that geometrical optics can model interference, partial coherence and polarization effects to a large extent, but excludes diffraction effects. Geometrical optics for electromagnetic fields is a fast modeling technique and can be nicely combined with other solutions of Maxwell's equations, rigorous and approximate ones, in order to provide a unified modeling concept for optical systems, to which we refer to as field tracing. We discuss the concept at the example of freeform surface and scattering modeling for coherent and partially coherent light.

9630-9, Session 2

Simulations of general electromagnetic fields propagation through optically anisotropic media

Site Zhang, Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

We develop an angular spectrum of plane waves approach to deal with general electromagnetic fields propagation through arbitrarily oriented anisotropic media. Our approach handles the refraction at a plane interface between isotropic and anisotropic media, as well as the diffraction during propagation inside anisotropic media. By demonstrating conical refractions, which happens when light strikes onto a biaxial crystal along its optical axis, the validity of our approach is testified. Furthermore, we try to find an extended approach which handles light propagation in optically anisotropic and inhomogeneous media, which are typical situations in nonlinear optics. All the simulation techniques fit well in the concept of field tracing, which allows comprehensive simulations of optical systems including anisotropic media.

9630-10, Session 2

A smooth field decomposition applied to modelling of scattering phenomena

Olga Baladron-Zorita, Huiying Zhong, Friedrich-Schiller-Univ. Jena (Germany); Michael Kuhn, LightTrans GmbH (Germany); Frank Wyrowski, Friedrich-Schiller-Univ. Jena (Germany)

In this work, the authors present a 2-dimensional decomposition of electromagnetic fields where the edges of the subfields are softened with a cosine function. The use of the smooth edge, as opposed to a sharp one, is necessary from the sampling point of view, but it has more advantages: a well-behaved Fourier transform and the possibility to mould the extension of the edge depending on the particular requirements of the problem, among others. The potential applications of this decomposition include dealing with non-paraxial light, increasing simulation efficiency for certain set-ups, or improvement in simulation accuracy when the decomposition can help minimise use of geometrical optics. Here we present two scattering modelling problems which benefit from the decomposition: the first includes light interacting with a scattering centre, the second analyses a field propagating through a refractive freeform with scattering effects due to surface roughness. In both cases we argue theoretically the importance of the field decomposition technique, and present simulation results to prove the feasibility and potential of our approach.

9630-11, Session 2

A vectorial ray-based diffraction integral for optical systems

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Simulation of ultra-precision interferometry experiments requires the consideration of diffraction effects. However, the accurate description of diffraction in optical systems is a difficult task. Usually, either the paraxial approximation or simple ray tracing is exploited to achieve computability. For aimed accuracies in the sub-nm range the viability of these approximations is at least questionable. Therefore, the propagation of coherent laser light in optical systems is investigated by a combined method which utilizes vectorial diffraction theory, ray aiming, differential ray tracing and matrix optics. On a global scale the method is not restricted to the paraxial approximation whereas it is properly used for a local representation of the wavefront close to an aimed detection

location. First, the field of a monochromatic continuous wave on an input plane is decomposed into spherical or plane wave components. Then, these components are represented by aimed ray tubes and traced through an optical system. Finally, they are added coherently on a detector plane whose position has to be chosen according to ray-aiming requirements which can be tested by an additional software tool. Provided that the apertures in the optical system are large with respect to the wavelength the results are quite accurate. This has been investigated by comparison to a stepwise propagation method which in turn is based on vectorial diffraction integrals. The theoretical derivation, the algorithm and some application examples as well as rules of thumb for the usability of the shown methods will be presented.

9630-12, Session 2

Experimental method of optical coherence characterization in phase-space measurement

Jie-En Li, Jhih-Syuan Fu, Ming-Shu Hsiao, Chung-Hao Tien, National Chiao Tung Univ. (Taiwan)

A novel approach of phase-space measurement which is able to record the position and angular spectrum of optical field at once is made its debut with the experimental result. By applying the statistical nature of light, the mutual intensity function provide a huge amount of information of partially coherent field. However, the system of measuring the mutual intensity function needs well-calibrated but time-consuming. In order to overcome these issues and measure the information of partially coherent field, it is necessary to develop a new approach to acquire the phase-space. Recently, a brand new method of phase-space measurement is proposed by L. Tian et al. Based on the characteristic of micro-lens array, the angular spectrum of each localized space can be decoded. According to their simulation, the specifications of micro-lens will dominate the influence of 0th-order cross-talk and high-order cross-talk, which exist an optimal region. Unfortunately, previous work only stays in simulating stage. Therefore, in this work, we want to realize their method of phase-space measurement. We first design an optical system which is based on the Young's double-slits interferometer to characterize the spatially coherent property of light source. A positive lens is placed among the conventional optical setup to manipulate the size of coherent area. The double-slits is placed between the focus of the singlet and the screen. As we shift the position of the double-slits along the optical axis, different percentages of coherent area pass. For example, as the double-slits moves toward the focus of the singlet, the fringe visibility is getting lower and lower, and vice versa. By applying the algorithm of regression, we can find the spatially coherent property of our light source. The remaining problem is to make sure that our light source can be regarded as a Gaussian-Schell beam so that we can use the equation proposed by previous work. The result of neural networks approach shows a good agreement with that assumption. Finally, the optimized parameter of the diameter of lenslet of our phase-space measurement system can be determined, which is around 8.27μm to 165.25μm. Among this region, we choose 150μm as the diameter of micro-lens because the spot size of typical light sources are much larger than the pinhole we used in this experiment. The system is still being optimizing. The preliminary result of phase-space measurement do show a good agreement with our expectation. We are going to decode the 2-dimensional image from experiment into 4-dimensional phase-space image. Once we have accomplished that process, we are able to capture the light field image of a "field".

9630-13, Session 3

Exploiting multimode waveguides for in-vivo imaging *(Invited Paper)*

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Small, fibre-based endoscopes have already improved our ability to image deep within the human body. Current fibre-based devices consist of fibre-bundles in which individual fibres represent single pixels of the transmitted image. A novel approach introduced recently1 utilized disordered light within a standard multimode optical fibre for lensless imaging. Importantly, this approach brought very significant reduction of the instrument's footprint to dimensions below 100?m. Such device may be used for imaging of structures deep inside living organisms directly through centimeters of living tissues without bringing about their extended collateral damage. In Neuroscience, this technology may assist to address important unanswered questions related to formation and recall of memories as well as onset and progression of severe neuronal disorders such as Alzheimer's disease.

The two most important limitations of this exciting technology are (i) the lack of bending flexibility (imaging is only possible as long as the fibre remains stationary) and (ii) high demands on computational power, making the performance of such systems slow.

We discuss routes to allow flexibility of such endoscopes by broader understanding of light transport processes within. We show that typical fibers retain highly ordered propagation of light over remarkably large distances, which allows correction operators to be introduced in imaging geometries in order to maintain high-quality performance even in such flexible micro-endoscopes.

Separately, we introduce a GPU toolbox2 to make these technique faster and accessible to researchers. The toolbox optimizes acquisition time of the transformation matrix of the fibre by synchronous operation of CCD and SLM. Further, it uses the acquired transformation matrix retained within the GPU memory to generate any desired holographic mask for on-the-fly modulation of the output light fields. We demonstrate the functionality of the toolbox by displaying an on-demand oriented cube, at the distal end of the fibre with refresh-rate of 20ms.

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9630-14, Session 3

Generalized Monte Carlo model of propagation of coherent polarized light in turbid tissue-like scattering medium

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Modeling the propagation of coherent polarized light through a turbid scattering medium using the Monte Carlo method enables better understanding of the peculiarities of image/signal formation in modern optical diagnostic techniques, such as optical coherence tomography (OCT), coherent/enhanced back-scattering, laser speckle imaging and diffusing-wave spectroscopy (DWS). We present the generalized MC model of coherent polarized light propagation in a turbid tissue-like scattering medium, focusing on the major diagnostic modalities mentioned above. A comparison of modelling results for these diagnostic techniques with the results obtained in experiments is provided. Based on the generalization concept and utilizing modern web applications we generalized MC model and developed an online computational tool suitable for the major applications in Biophotonics and Biomedical Optics.

9630-15, Session 3

Optical properties of textured sheets: an efficient matrix-based modelling approach

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A large variety of optical systems incorporate multiple textured surfaces for reflectance reduction, light redirection or absorptance enhancement. One example for such a system is a textured silicon wafer solar cell. We introduce the OPTOS (Optical Properties of Textured Optical Sheets) formalism [1] for the modelling of optically thick sheets with two arbitrary surface textures at the front and rear side, and demonstrate applications.

Many optical simulation techniques are tailored to specific surface morphologies. They take coherence effects into account or neglect them completely, depending on the feature size and arrangement of the investigated texture and sheet. It is therefore difficult to efficiently model sheets that incorporate textures operating in different optical regimes. The combined calculation in one simulation tool requires an efficient coupling of different techniques. For the modelling of arbitrary surface textures, ray optical approaches can be extended with wave optical methods via reflectance distribution functions [2]. However, each change of parameters, e.g. the sheet thickness, requires a new ray-tracing calculation. Matrix-based methods, which describe the light propagation by matrix multiplications [3], need less computational resources but are restricted to systems with a finite number of diffraction orders, so far.

To overcome these limitations the OPTOS formalism is a matrix-based method that allows for the computationally-efficient simulation of light redistribution and non-coherent propagation inside optically thick sheets incorporating multiple textures that may operate in different optical regimes. By defining a discrete set of channels covering a certain angular range, the angular power distribution within the simulated system can be represented by a vector. This light distribution is modified by interactions with the surfaces of the textured sheets, which are described by redistribution matrices. The matrices can be calculated for each individual surface texture with the most appropriate technique. Optical properties of the complete textured sheet like angle dependent reflectance, transmittance or depth resolved absorptance can be efficiently determined via iterative matrix multiplications. Since the redistribution matrices can be reused, also sheet thickness variations or different angles of the incoming light can be calculated with minimal computational effort.

The application focus of this work is set on silicon wafer solar cells, where surface texturing is used for reflectance reduction and light path length enhancement inside the absorber material. The combined simulation enables us to completely model and investigate different combinations of novel solar cell textures in one simulation tool which was not possible before, and to compare the results to experimental data. This allows an efficient optimization of texture combinations and solar cell thickness in order to increase the overall efficiency. Further possible fields of applications for the OPTOS formalism can be found in the display and lighting technology. Brightness enhanced films offer light management and an increased backlight brightness toward the viewer of liquid crystal displays via multiple light interactions at a prismatic and a diffusive surface. A well-defined distribution of light is also relevant in the field of lighting. Surface textures for an increased outcoupling efficiency in combination with diffusive elements for light homogenization can also be optimized with the presented formalism.

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9630-16, Session 3

Optical tomography by means of regularized MLEM

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To solve the inverse problem involved in fluorescence mediated tomography a regularized maximum likelihood expectation maximization (MLEM) reconstruction strategy is proposed.

This technique has recently been applied to reconstruct galaxy clusters in astronomy and is adopted here.

Given its formulation the framework can potentially easily be augmented to include data from additional modalities (e.g. PET or SPECT) as additional priors.

The MLEM algorithm is implemented as Richardson-Lucy (RL) scheme and includes entropic regularization and a floating default prior.

Hence, the strategy is very robust against measurement noise and also avoids converging into noise patterns.

Normalized Gaussian filtering with fixed standard deviation is applied for the floating default kernel.

The reconstruction strategy is investigated using the XFM-2 homogeneous mouse phantom (Caliper LifeSciences Inc.) with known optical properties.

Initially, X-ray CT tomographic data of the phantom were acquire to provide structural context.

Phantom inclusions were fit with various fluorochrome inclusions (Cy5.5) for which optical data at 60 projections over 360 degree have been acquired, respectively.

Fluorochrome excitation has been accomplished by scanning laser point illumination in transmission mode (laser opposite to camera).

Following data acquisition, a 3D triangulated mesh is derived from the reconstructed CT data which is then matched with the various optical projection images through 2D linear interpolation, correlation and Fourier transformation in order to assess translational and rotational deviations between the optical and CT imaging systems.

Preliminary results indicate that the proposed regularized MLEM algorithm, when driven with a constant initial condition, yields reconstruction data that tend to be smoother in comparison to the classical MLEM without regularization.

Once the floating default prior is included this bias was significantly reduced.

9630-17, Session 4

Flexible analysis of solid-state laser resonators including nonlinear gain saturation, thermal lensing, and stress-induced birefringence effects *(Invited Paper)*

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The computer-aided analysis and optimization of the beam quality of mono-mode, continues-wave solid-state laser sources is of increasing importance to reduced development cycle times and costs of high performance lasers. Especially the increasing number of active media and passive optical components used for the resonator setup and the resulting increase of free parameters requires fast software-based optimization algorithms. As a basis of these optimizations a flexible, fast and accurate model of the laser resonator for the calculation of the transversal dominant mode structure is introduced. It is based the generalization of the scalar Fox and Li algorithm to a fully-vectorial light representation. To provide a unified modelling concept of stable, unstable and ring resonators containing a plenty of different optical elements, rigorous and approximative solutions of Maxwell's equations are combined in different subdomains of the resonator. This flexible approach allows the simulation of passive intracavity components like lenses, mirrors, prisms and diffractive optical elements as well as active media. For the simulation of solid-state active crystals a vectorial beam propagation method (vBPM) is used to analyse the influence of thermal lensing, stress-induced birefringence and nonlinear gain saturation on the polarization state, power and structure of the transversal resonator mode. As an example we simulate the influence of stress-induced birefringence and thermal lensing on the transversal resonator mode and the beam output power in a well-known resonator setup including a Faraday rotator for depolarization loss reduction.

9630-18, Session 4

Simulation of laser radar tooling ball measurements

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The usual Fourier optics methods are applied to the Laser Radar optical system to model and explain some interesting aspects of this unique position measurement scheme.

9630-19, Session 4

Wave optics analysis of corner-cube retro-reflectors in near-to-eye displays based on scanning laser projectors

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Scanning laser projectors can be combined with corner-cube retro-reflectors (CCRs) in various display applications, such as near-to-eye, head-up, and head-mounted-projection (HMP) displays to get unique advantages. In particular, scanning laser projectors provide a high color gamut, always in focus images, and scalability of image resolution; while CCRs provide light efficient screens that maintain image brightness, as well as the ability to multiplex the same screen among different users, etc. In near-to-eye displays, CCRs provide flexibility in optical system design since they can be placed at locations that are near to the eye, rather than the image plane.

A CCR reflects an incoming ray parallel to itself, but with a positional shift rather than along the same line. Moreover, the finite apertures of CCR mirrors introduces diffraction. As a result, especially in a near-to-eye display where the CCR cannot be placed on the image plane but should be placed close to eye or the laser projector, the obtained image suffers some loss in quality and resolution. Although some simplified analysis of diffraction effects are also present for HMP displays, a satisfactory wave optics analysis, especially within the context of a scanning laser projector based near-to-eye display application, is not available.

In this paper, we perform a wave optics simulation to understand the effects of using a CCR as the screen in a scanning laser projector based near-to-eye display. We place a CCR on the path of a beam that converges to a virtual focus spot behind the CCR. We assume that the CCR creates a multitude of real images of the virtual focus spot in front of the CCR. In particular, each CCR cell splits the portion of the incident beam falling on its aperture into six bundles and bends each bundle towards the real image corresponding to that cell. The effective focus spot size (i.e., the pixel spot size apparent to an observer looking into the CCR) is then found by superposing the diverging waves emitted by each real image on the focus plane. Diffraction effects introduced by each CCR cell are accounted for by confining the numerical aperture of the corresponding real image point.

Our analysis indicates that the effective pixel spot size gets larger due to the fact that the waves from each real image point arrive on the focus plane with some phase difference. If this phase difference was removed, possibly by using a curved CCR sheet, it would be possible to obtain the lower bound on spot size, which is equal to that of the incident beam. The results also indicate that if there is random out-of-plane misalignment between CCR cells, the spot size hits the upper bound which is governed by diffraction of each CCR cell. The spot size in the case of a CCR with a planar structure is between the two bounds.

Experiments are performed using various commercially available CCRs and a miniaturized scanning laser pico-projector. The results are in agreement with the simulations in terms of achievable resolution and image quality.

9630-20, Session 4

Comparison of modelling techniques for multimode fibers and its application to VCSEL source coupling

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Both concepts of the ray tracing and the split-step complex amplitude propagation method are widely used in the modelling of multimode fibers. Both techniques work under specific assumptions: (1) Ray tracing allows modeling of non-paraxial situations but ignores diffraction dominated propagation effects as well does not handle light field information like polarization. (2) The split-step technique assumes a paraxial propagation approach and by that ignores polarization crosstalk. We propose a generalization of the ray tracing approach to an efficient geometrical optics field tracing technique, which enables the inclusion of polarization effects including crosstalk within the fiber. We discuss and compare the different techniques theoretically and at the example of the coupling of a VCSEL source into a multimode fiber (OM3, OM4). We calculate the coupling efficiency with respect to adjustment tolerances.

9630-21, Session 5

Systematic investigation of the principal and first secondary maxima of ultrashort optical pulses focused by a high numerical aperture aplanatic lens

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The electromagnetic field in the focus of an optical system with high numerical aperture, which is illuminated by an ultrashort optical pulse, is simulated by taking the vectorial Debye integral and the coherent superposition of a frequency spectrum of monochromatic waves. The behavior of the principal maxima and the first secondary maxima as function of the numerical aperture (NA) and the pulse duration T for the case of an ideal aplanatic lens which is illuminated by a homogeneous linearly polarized plane wave front is investigated systematically. First, one would not expect remarkable deviations from the stationary case. But also this simple system of an ideal aplanatic lens without any chromatic or monochromatic aberrations (of course only simple from the point of theory, but not at all from the point of practical realization) shows some remarkable results.

Concerning the principal maximum one would expect from the scalar theory that the absolute height of the electric field squared |E|^2 for a given incident pulse energy, in our case always normalized to 1 J, increases with the square of the numerical aperture (since the area of the focal spot decreases with 1/NA^2). Concerning the pulse duration, where we only took temporally Gaussian pulse shapes, one would expect a linear increase of |E|^2 with 1/T (pulse duration T) or with nu_e=1.273/T, where nu_e is the full width at 1/e amplitude decrease of the Gaussian frequency spectrum of the pulse. However, it can be seen that this expectation is only the case for small numerical apertures and for small values nu_e, i.e. long pulses. If the NA (in vacuum) tends to the limiting case of 1.0 the maximum value of |E|^2 increases faster than expected from the scalar theory (Airy disc) with a maximum deviation of about 13%. Of course, this is also the case for the stationary case so that it should be well known from the focusing with high NAs. But mostly, there a normalized function is considered so that these effects are also not so well known. The second effect really comes from very short pulses, i.e. large values nu_e. Then, the value of |E|^2 decreases slightly (only less than 2%), but systematically for all NAs.

Even more interesting is the dependence of the height of the first secondary maxima along the x-axis and y-axis on the NA and nu_e. The dependence on the NA for long pulses (small values nu_e), i.e. in the limiting case of the stationary case, is well known from the literature, also for high NAs. Of course, for small values nu_e and a small NA the

secondary maxima converge to a normalized height of 0.0175 along both axes which is well known from the scalar Airy disc. However, it can be seen that along both axes the first secondary maxima nearly vanish for very short pulses, i.e. large values nu_e.

Summarizing, the investigation of the focusing of ultrashort pulses for high numerical apertures (and also for small numerical apertures) shows some unexpected effects.

9630-22, Session 5

Micro-optical freeform elements for beam shaping

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Thin optical elements that produce good quality images and that are operational with different light sources are studied in this work. The influence of the design approach on the smoothness of their surfaces and on the image quality will be evaluated.

Introduction

The headway made in computer numerical control (CNC) tools was crucial for the appearance firstly of aspheric optics and later of freeform surfaces. Simultaneously, the advent of the laser paved the way for diffractive optical elements (DOEs). Both freeform and diffractive optics have been intensively studied for decades.

Whereas light transfer and propagation in the freeform domain, also called refractive, can be explained by geometric optics, in its diffractive counterpart they are necessarily described by wave optics. Refractive elements have macroscopic continuous features and are mostly wavelength independent. In contrast, DOEs are much thinner structures that modulate the phase of incident light by diffraction, hence strongly depending on its wavelength.

Current challenges

The need for mastering light shaping techniques is continuously increasing in industry. In this context, elements combining the advantages of both domains in terms of image quality, light source agnosticism, thus wavelength independence, and feature size, are solid candidates to meet the industrial requirements. CNC methods are not suitable for miniaturization and for mass production and, furthermore, lithographic techniques, cannot easily address the necessary optical surface quality for deep structures. Therefore new strategies have to be explored to devise freeform elements in the depth range of a few tenths of micrometres.

Discussion

The Iterative Fourier Transform Algorithm (IFTA) [1] has been widely used in the design and optimization of DOEs. However, multiple phase shifts in the optimized surfaces make them strongly colour-dependent and extremely sensitive to fabrication errors. The limitations in the image plane distance have determined the use of different propagation methods here: either Fresnel (FR) or Band Limited Angular Spectrum (BLAS) [2]. The optimized phases have been furthermore unwrapped, so that the total number of phase shifts are reduced significantly. Some additional constraints improving the smoothness of the object surface will be studied in the design phase.

Preliminary results show that the unwrapped version of the iteratively generated surfaces have a maximum peak-to-valley (P-V) extension between one and two orders of magnitude lower than their freeform counterpart. Their chromatic behaviour as well as their dependence to the light source coherence need deeper study.

Excimer laser ablation will be used to fabricate the structures on polymer substrate, as it can address ablation depths as low as 50 nm on large and shallow areas. The results will be used as feedback to complete and optimize the modelling of the structures.

Conclusions

It has been shown that micro-optical freeform elements, that bridge refractive and diffractive domains and are suitable for large-scale production, hence fabrication friendly, can produce images with similar quality as thicker refractive elements.

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9630-23, Session 5

Digital holography based image focusing

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In everyday life, we just need to press an ‘auto focusing’ button to let a picture clear. But in the laboratory, usually, there is no ‘auto focusing’ button to press. Nevertheless, focusing becomes a basic step in many modern experiments. Unlike problems of focusing under the condition of incoherent light, the problem can be easy with coherent light, which is frequently used in many laboratories, and digital holography.

Digital holography has been employed in many studies such as biology, environmentology, shock physics, debris cloud, etc. It can easily derive 3D distribution of drops, planktons, fragmentation from an interference pattern. In order to simplify the process of focusing on many experiments, we studied the usability and accuracy of digital holography in ordinary imaging plan.

Image distance and object distance had been fixed separately to study the calculated results of digital holography in these two different conditions. The studied results showed that the calculated depth of digital holography could be linear under the condition of fixed image distance. So, we just need two step to make digital holography useful and accurate in the process of image focusing. First, we must fix the distance between Lens and CCD, in addition, the distance should approximate to the image distance to guarantee the resolution of lens system. Second, the “Lens and CCD” system should catch a page with a distance-known object in the view. By calculating the distance from calibration-used object, the pixel coefficient could be determined. If the object that wanted to be in focus was also in the view, the predicted motion distance could also be calculated to make the object clear. But the digital holography couldn’t find out the motion direction, so we just need one or two times of trying to make an object in focus.

One example was achieved to prove the usability of holography based image focusing. We used the method mentioned above to predict the actual distance between two objects. The calculated interval between two objects was close to the absolute interval measured by vernier calipers. In many laboratories, the high resolution and high definition CCD is common device, but this kind of CCD always needs many seconds to finish the catch and data transmission process. Therefore, tens of minutes may be needed for the image focusing process. For the simplicity and the accuracy of digital holography based image focusing, the function of digital holography could be integrated into camera software to simplify the image focusing process of the laboratory.

9630-24, Session 5

Introducing free-function camera calibration model for central-projection and omni-directional lenses

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To ensure making valid decisions with high accuracy in machine vision systems such as the video-based driver assistant systems, one of the primary key factors is to have accurate data and measurements, which implies that for these systems, we need accurate camera calibration. Since these cameras cover a wide range of optical designs there is a need to be able to model their optical characteristics, estimating accurate camera calibration for various applications, and a very fast approach to analyse the calibration data and correct the image observations in real-time. The correction thereby needs to comply with hardware specification installed in these systems including platforms with low thermal design power.

Conventional and classical camera calibration methods have specific limitations such as limited accuracy, instability by using complex models, difficulties to model the local lens distortions and limitation in real-time calculations that altogether show the necessity to introduce new solutions.

We introduce the techniques for performing the intrinsic camera calibration and modelling the camera lens distortion with high accuracies beyond conventional calibration (distortion) models while yet allowing real-time calculation possibilities to perform image distortion and undistortion. The concept is based on Free-Function modelling in a posterior calibration step using the initial distortion estimation and the corresponding residuals on the observations as input information.

Free-Function modelling is the technique of numerically and locally fitting free functions (using discrete expansion) to the camera distortion field. The idea behind free-function modelling is that instead of finding the best calibration model or (mathematically) the best function to fit to our observation data, we assume unknown functions in our calibration model or in other words the calibration model to be analytically unknown and therefore remove any explicit constraint in the Model which would imply that the functions fit themselves to the observation data no matter what kind of mathematical form they possess. This increases the flexibility of the distortion model to fit itself to different lens distortions and optical designs and furthermore to be able to model the very local lens distortions. The correlation between camera extrinsic and intrinsic parameters is not higher than classical methods as a physically-motivated calibration model (e.g. Brown) is estimated initially.

Using the Free-Function model one can normally observe great enhancements in accuracy (in comparison with classical models) which depends on the complexity of existing distortion and the complexity and order of the free functions (e.g. the number of function series). The quality of local distortion modelling depends on the number and distribution of the observed points and the initial accuracy of point coordinates in object-and-image space (point detection accuracy). Therefore by increasing the number of control points and improving their distribution the quality of lens modelling would be improved; a characteristic which is not present in the classical methods.

9630-37, Session PTue

Design and Implementation of a Cooke triplet based wave-front coded super-resolution imaging system

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Wave-front coding (WFC) is a powerful technique used to extend the depth of focus (DOF) of incoherent imaging system. During the past 20 years, bunches of researches have been carried out, but most of them mainly focus on theoretical studies. Hence in this manuscript, a Cooke Triplet based WFC imaging system is designed and successfully implemented. Besides that, by further exploring the characteristics of WFC, a novel super-resolution reconstruction procedure is designed and experimentally verified.

The system under discussion contains two parts: WFC imaging lens and 1/3in camera having 5.2um pixel. The imaging lens is a combination of a simple Cooke Triplet and cubic phase mask. Except the mask, other three components are spherical. The focal length and the F number of the original Cooke Triplet are 50mm and 4.5. With working wavelength set to 587.5nm, the estimated DOF is only about 24um. This is quite a low DOF that easily brings in mis-focus. Therefore, we aim to extend the DOF more than 10 times. First, a plate with a thickness of 2mm is added to the aperture and auto-optimization engine in CodeV is activated to obtain an initial optimization result. Second, the plate is replaced by the cubic mask with the same thickness and multi-configuration containing six selected imaging distances within the range [5m, infinity] is constructed. After that, one user defined opto-digital joint optimization procedure considering restoration quality is realized through Macro language programming and works with the optimization engine of CodeV to search for the optimum mask parameter value which equals about 0.0123mm here.

With such a design, the complete imaging system is established and tested. Usually, the sampled PSF (point spread function) is used as restoration kernel, but we do not do so here. To WFC, the optical continuous PSF before being sampled by camera has a large supporting region. In this case, the sampled PSF corresponding to different pixel size could be directly computed from the optical PSF provided by CodeV. Using the calculated sampled PSF corresponding to the pixel size of 5.2um here, it is found that the quality of restored image is comparable with the conventional well focused imaging system and the objects ranging from 5m to infinity could be clearly restored, which indicates a more than 20 times DOF extension. Besides that, the probable artifacts pointed out by literatures are not that prominent according to our research and the system works well in versatile environment conditions including sunshine, cloudy sky, low-light and et.al. Based on this characteristic, the restoration could be applied in the level of higher resolution. First, a magnification ratio is selected and the wanted pixel size is computed. Second, the intermediate image is resized according to the magnification ratio and the sampled PSF corresponding to the wanted pixel size is re-calculated. Third, the magnified blurred image is restored using the re-calculated sampled PSF through Richardson-Lucy algorithm. With this procedure, a maximum super-resolution magnification ratio of 4 could be obtained and the quality of restored image is improved as well.

9630-38, Session PTue

Investigation of light propagation methods used to calculate wave-optical PSF

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In this study, we investigated the suitability of various light propagation methods and their usefulness in terms of calculating the wave-optical point spread function (PSF) of an optical imaging system. To analyze an aberration in an optical imaging system in order to obtain its PSF, light propagation methods are widely used to obtain the light intensity distribution on the observation plane. Both the Fresnel–Kirchhoff and Rayleigh–Sommerfeld diffraction formulae are commonly used in light propagation simulations. These formulae are approximated as Fresnel and Fraunhofer diffractions in order to improve the calculation speed of light propagation simulations. The angular spectrum method, which is a technique used to calculate the Rayleigh–Sommerfeld diffraction formula without any approximations, through convolution based Fourier transformation, is also used. In some cases involving low sample numbers, the Rayleigh–Sommerfeld diffraction formula is calculated directly as the integration formula.

Recently, there have been many reports concerning light propagation methods in the field of digital holography. There methods are based on the Rayleigh–Sommerfeld diffraction formula and use discrete Fourier transformation. These methods are referred to as the angular spectrum and Fresnel diffraction methods. For systems containing a long propagation distance, these methods can vary the sampling interval arbitrarily by limiting the bandwidth of the chirp function, and shift the coordination of the source and observation planes.

In this study, these propagation methods are evaluated in terms of the degree of accuracy offered and their associated calculation costs. In order to demonstrate and investigate the features of these propagation methods, we employed a Tessar lens system, which is composed of four lenses. The wavefront aberration of the lens system is obtained by a ray tracing simulation and is used to generate the generalized pupil function. Next, the Rayleigh–Sommerfeld diffraction formula and the light propagation method based on this formula are used to calculate the wave-optical PSF using the pupil function. We applied these simulation methods to various recently proposed propagation methods and discussed the suitability of the various light propagation methods under consideration for calculating the wave-optical PSF.

9630-39, Session PTue

Pixel-based mask optimization using particle swarm optimization algorithm in optical lithography

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A novel pixel-based mask optimization method using particle swarm optimization (PSO) algorithm in optical lithography is proposed. Because of the simplicity of principles, the ease of implementation and the efficiency of convergence, PSO has been widely used in many fields, such as signal processing, image analysis, pattern recognition and so on. In this study, PSO is used to solve the pixel-based inverse problem of mask optimization. The pixel-based masks are encoded into particles, which are evaluated by using the pattern fidelity as the fitness function. The mask optimization method is implemented by updating the velocities and positions of these particles. Simulation results show that the image fidelity is significantly improved after using the proposed mask optimization method.

9630-40, Session PTue

Cylindrical plasmonic microcavity and its excitation

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In the most of known structures the strongly confined SPP resonant modes are circulated in the same plane where SPP's are guided. Cylindrical plasmonic microcavity structure considered in this report gives opportunity to manage SPP in 3 dimensions. The system consists of a cylindrically curved metallic structure placed above the flat metallic surface, supporting SPP propagation, and are separated by dielectric gap. To improve the resonant features of considered system the reflecting wall was placed. Hence the coupling of two Fabry-Pérot structure and cylindrical structure microcavities has been realised.

The active coupling between SPP resonant modes and SPP modes propagating over the flat metallic surface has been demonstrated. The direction of propagating SPP modes and axis of the cylinder are perpendicular, so the lateral excitation of resonant SPP modes has been carried out. The excitation efficiency dependence on structure's geometric and electrodynamics parameters of plasmonic microcavity has been investigated. The possibility of controlling (or modulating) resonant SPP modes by varying different parameters such as minimal distance between cylindrical metallic and flat surfaces, relative permittivity of the dielectric gap, as well as working wavelengths has been demonstrated. The quality factor of metallic (as the metallic surface has been chosen gold: Au) cylindrical plasmonic microcavity has been estimated Q≈90, for fixed values of working wavelength: 690nm, relative permittivity of the dielectric media: ?d=3, and the radius of cylinder R=3?m . Considered structure shows strong dependence on the relative permittivity of the dielectric media, the change of third decimal of dielctric relative permittivity brings to the significant change (up to three times) of microcavity excitation efficiency. Such phenomena can be successfully used for sensors construction based on such relatively simple plasmonic structures.

9630-25, Session 6

Fast integral methods for integrated optical systems simulations: a review
(Invited Paper)

Bernd H. Kleemann, Carl Zeiss AG (Germany)

Boundary integral equation methods (BIM) or simply integral methods (IM) in the context of optical design and simulation are rigorous electromagnetic methods solving Helmholtz or Maxwell equations at the boundary (surface of the structures) for scattering or/and diffraction purposes.

This work is mainly restricted to integral methods for diffracting structures such as gratings, kinoforms, diffractive optical elements (DOEs), micro Fresnel lenses, computer generated holograms (CGHs), holographic or digital phase holograms, periodic lithographic structures, and the like. In most cases all of the mentioned structures have dimensions of thousands of wavelengths in diameter. Therefore, the basic methods necessary for the numerical treatment are locally applied electromagnetic grating diffraction algorithms.

Interestingly, integral methods belong to the first electromagnetic methods investigated for grating diffraction. The development started in the mid 1960ies for gratings with infinite conductivity and it was mainly due to the good convergence of the integral methods especially for TM polarisation. Examples of such methods are the ones by J.Pavageau and J.Bousquet in 1970 and P.M. van den Berg in 1971. The first integral equation methods (IEM) for finite conductivity were the methods developed by D.Maystre at Fresnel Institute in Marseille: in 1972/74 for dielectric, and metallic gratings, and later for multiprofile, and other types of gratings and for photonic crystals. Other methods such as differential and modal methods suffered from unstable behaviour and slow convergence compared to BIMs for metallic gratings in TM polarisation from the beginning to the mid 1990ies.

The first BIM for gratings using a parametrization of the profile was developed at Karl-Weierstrass Institute in Berlin under a contract with Carl Zeiss Jena in 1984-1986 by A.Pomp, J.Creutziger, and the author.

This integral method with trigonometric and spline collocation, iterative solver with $O(N^2)$ complexity, named IESMP, has been significantly improved by an efficient mesh refinement, matrix preconditioning, Ewald summation method, and an exponentially convergent quadrature in 2006 by G.Schmidt and A.Rathsfeld from Weierstrass-Institute (WIAS) Berlin.

The so-called modified integral method (MIM) is a modification of the IEM of D.Maystre and has been introduced by L.Goray in 1995. It has been improved for weak convergence problems in 2001 and it was the only commercial available integral method for a long time, known as PCGRATE.

All referenced integral methods so far are for in-plane diffraction only, no conical diffraction is possible. The first integral method for gratings in real conical mounting and for demanding applications was developed and proven under very weak conditions by G.Schmidt (WIAS) in 2010. This very fast method has then been implemented for parallel processing under Unix and Windows operating systems.

This work gives an overview over the most important BIMs for grating diffraction. It starts by presenting the historical evolution of the methods, highlights their advantages and differences, and gives insight into new approaches and their achievements. It addresses future open challenges at the end.

9630-26, Session 6

A reduced basis finite element method for fast optical simulations of nano-structured devices

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Rigorous optical simulations of 3-dimensional complex nano-structures are an important tool in the analysis of scattering properties of nano-photonic devices. They allow to optimize optical properties (such as light-trapping in solar cells) or to reconstruct parameter values from measurements which is of critical importance in optical critical dimension (OCD) metrology. To construct geometrically accurate models of complex structured nano-photonic devices such as solar cells, the finite element method (FEM) is ideally suited due to its flexibility in the geometrical modeling. High accuracy solutions of the time-harmonic Maxwell's equations in 3D can be obtained for a number of applications areas [1,2,3]. Many applications require the solution of Maxwell's equations for multiple parameters or a single parameter, but in real time. Reduced order models such as the reduced basis method (RBM) allow to construct self-adaptive, error-controlled, low-dimensional approximations for input-output relationships which can be evaluated orders of magnitude faster than the full model. We present an extension of our reduced basis method for 3D Maxwell's equations [4] based on the finite element method which allows variations of geometric as well as material and frequency parameters. We demonstrate accuracy and efficiency of the method for solar cell and scatterometry applications.

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9630-27, Session 6

Efficient electromagnetic field solver based on finite-element methods

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Rigoros, 3D electromagnetic field solvers are required for designing optical components that include structures on a micrometer or nanometer scale.

We discuss how to approach challenging optimization tasks with finite element methods (FEM) and we comment on quantification of numerical discretization errors.

The general framework of FEM allows to employ adaptive numerical resolution and accurate geometry modelling for arbitrary shapes.

Further, advanced methods like domain-decomposition algorithms and reduced-basis methods can be implemented in a rigoros framework.

We also briefly discuss application of these methods to simulation and optimization tasks ranging from industrial applications (optical lithography and metrology, microcavity design [1,2,3])

to academic research (plasmonics, chiral metamaterials [4,5,6]).

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9630-28, Session 6

Combining ray-tracing with FDTD to enable the simulation of complex optical devices in an iterative simulation process

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The development of complex photonic devices with tailor-made optical properties requires often the control and the manipulation of light propagation within structures of different length scales, ranging from sub-wavelength to macroscopic dimensions (multi-scale devices). The highly innovative development of suchlike devices can be very complex and needs optical simulations to obtain a better understanding of the functionality of the different elements of the device as well as to lower the R&D costs and development time. Unfortunately, applications of common optical simulation methods are usually restricted to particular size regimes. For this reason, a complete optical simulation of multi-scale devices can only be conducted by combining different simulation methods. For this purpose, well-defined criteria for switching between different simulation methods are needed, in order to ensure mathematical and physical consistency of the simulation results and to avoid a summation of errors due to the interfacing process.

In our previous work we already introduced an interface method that uses the Poynting vector to bridge between classical Ray-Tracing (RT), a simulation method based on geometrical optics, and the Finite-Difference-Time-Domain (FDTD) method, a simulation method based on a numerical algorithm to solve the Maxwell's equations in space and time. This interface method connects two commercial simulation tools (ASAP, Breault Research and FDTD Solutions, Lumerical) to ensure the suitability of the interface method for a large number of applications. The model of geometrical optics is based on approximations that are neglecting the wave nature of light. Unfortunately, these approximations prevent to adopt all available properties of the electromagnetic fields into the model of geometrical optics. Consequently, the phase information is lost for the transition from the FDTD domain into the RT domain. In another work, we investigated the applicability and accuracy of our interface procedure and derived an error function for the estimation of the error due to the loss of phase information.

In this contribution, we will present and discuss the most recent developments of our interface method. The discussion will be focused on methods and approaches to reduce simulation effort and time consumption of the interface simulation process. Furthermore, multi-scale simulations of complex optical devices containing both diffractive and refractive optical elements will be presented. In these complex optical devices light which passes a diffractive optical element (DOE) can interact with another DOE or the same DOE again. For this reason, the simulation settings require multiple bidirectional interface steps between RT and FDTD simulations, in order to achieve proper simulation results. The exact number of interface steps which is required for the simulation of suchlike devices cannot be predicted in advance; therefore, the interface method will be applied in an iterative simulation process.

9630-34, Session 6

Topology optimized design of carpet cloaks based on a level set approach

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Carpet cloaks have been received much attention as a new strategy to realize invisibility. Topology optimizations are powerful numerical method to design high performance devices and were applied to cavity, waveguide, and optical cloaks. We present topology optimized carpet cloaks rendering a PEC scattering object upon a reflector invisible. We define the electric field when no PEC object exists as a reference field, and the reference field and electric fields scattered by PEC are made to approach congruence by designing carpet cloak structures. An objective functional is defined as the integral of the absolute value of the difference between the reference field and the electric field when PEC object exists and carpet cloak structures are designed and transformed in order to minimizing the objective functional. A level set approach is employed to express dielectric carpet structures in the process of optimizing the topology. A finite element method is used for light scattering analyses, the computation of adjoint fields, and updating level set functions. The designed carpet cloaks indicate good performances and the value of the objective functional becomes less than 1% that when no carpet cloak exists.

9630-29, Session 7

Computational methods in localization microscopy *(Invited Paper)*

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Localization microscopy offers the opportunity for optical imaging on the nano-scale. The diffraction limit is circumvented by the combination of labeling with switchable fluorescent molecules and post-processing of the sequence of sparse single molecule images. This computational imaging approach to super-resolution microscopy necessitates new ways of thinking about resolution, image quantification, and optical design for novel contrast modalities. The buildup of spatial image correlations during data acquisition gives access to image resolution, and to quantification for samples labeled with reversibly switchable fluorophores. 3D and multi-color imaging is aided by the application of diffractive optics. In my lecture I will address these topics with emphasis on the underlying computational methods.

9630-30, Session 7

Analysis for simplified optics coma effection on spectral image inversion of coded aperture spectral imager

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As a novel spectrum imaging technology was developed recent years, push-broom coded aperture spectral imaging(PCASI) has the advantages of high throughput, high SNR, high stability etc. This coded aperture spectral imaging utilizes fixed code templates and push-broom mode, which can realize the high-precision reconstruction of spatial and spectral information. But during optical lens designing, manufacturing and debugging, it is inevitably exist some minor coma errors. Even minor coma errors can reduce image quality. In this paper, we simulated the system optical coma error's influence to the quality of reconstructed image, analyzed the variant of the coded aperture in different optical coma effection, then proposed an accurate curve of image quality and optical coma quality in code template, which provide important references for the design and development of push-broom coded aperture spectrometer.

9630-31, Session 7

High-resolution microscopy with low-resolution objectives: correcting phase aberrations in Fourier ptychography

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The spatial resolution of a microscope is inversely proportionate to the sum of the objective numerical aperture (NA) and the illumination NA. Fourier Ptychography microscopy achieves high-resolution, wide-field imaging by use of a low-NA, wide-field objective combined with time-sequential synthesis of high NA illumination using an array of LEDs. We describe reconstruction algorithms based on Fresnel propagation, rather than the traditional Fraunhofer propagation, which enables more accurate representation of LED illumination and hence reduced aberration in image construction.

Each illumination of the sample by a LED from the array interrogates a distinct range of spatial frequencies. A band-limited image for each LED illumination is obtained and these are stitched in Fourier space using Fourier-ptychography algorithms to obtain the complex field of the high-resolution image. The maximum achievable NA is limited by the maximum angle of the illumination and partial coherence of the light source. We describe the implementation of Fourier ptychography system with algorithms that are able to yield high-performance imaging even when used with a low-cost microscope objective with high levels of aberrations.

Starting from an initial low-resolution image, our algorithm progressively estimates higher-resolution images based on iterative Fresnel propagation of the light fields between the detector array, the sample and each LED within the illuminating LED array. At the end of this process a high-resolution image is obtained, which is artefact-free since aberrations in illumination and optical setup are incorporated into the Fresnel propagation. The aberrations for illumination are corrected by applying the corrected illumination light field in the first step and aberrations in lens are corrected by using the appropriate lens transfer function.

Since Fresnel propagations are used in the reconstruction procedure instead of Fourier propagation any aberrations or deviations in the experimental setup can be corrected accurately, improving the final image. Also propagating the field back to the object plane allows correction for spatially variant aberrations in illuminations. Correcting aberrations in the object plane is not limited to the illumination aberrations; it can also be used in cases where there are strong phase variations present in the object for e.g. refractive index mismatch. We have evaluated this algorithm on synthetic data that, compared to conventional Fourier ptychography, the use of Fresnel propagation enables removal of illumination phase aberrations and consequently higher image quality. Also it can be noted that using Fourier transforms instead of Fresnel propagations is a special case where the lens plane is the Fourier plane of the system, for e.g. in a 4F system. Hence this algorithm can also be extended to the Fourier Ptychography reconstruction algorithm to correct aberrations in illumination.

9630-32, Session 7

Application of principal component analysis in EUV multilayer defect analysis

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Due to the high absorption of EUV radiation in all materials, optical system of EUV lithography employ multilayer mirrors to reflect the light, i.e. a reflective mask and mirror. The dark areas of masks are defined by an absorber pattern on the top of the multilayer. Deposition of particles below or inside the multilayer or pits on the mask substrates creates a deformation of the reflective multilayer, called multilayer defects. The fabrication of EUV masks cannot avoid such small defects, which destroy the reflectivity in that location and must be removed.

Several methods and various types of equipment for multilayer defect detection and characterization are presently under development. One of the key challenges is the extraction of relevant defect parameters from measured optical, EUV, SEM or AFM images and to use them to characterize the printing behavior of the defect and to derive appropriate repair parameters.

In general, a multilayer defect causes an intensity loss and phase shift of the reflected light in the defect area. The defects are mixed amplitude and phase objects with an asymmetric printing behavior versus the normal image plane. The image intensity of the defect in a single image plane does not provide information on the phase. In a previous publication [1], the Transport of Intensity Equation (TIE) was employed to retrieve the phase information of multilayer defects from measured or simulated images at different focus positions.

Figure 1 shows a cross section cut of a mask with a typical multilayer defect, the corresponding aerial image and the recovered phase in the nominal focal plane. To quantify the image and phase distributions as shown in Figure 1, several optical defect properties (i.e. intensity at the center, minima and width of the intensity and the phase) were extracted in reference [1]. However, they are not sufficient for the complete characterization of the defect. An accurate retrieval of the defect geometry or required parameters is not possible. So, an alternative representation of defect image and phase distributions is highly desired.

In this paper, the Principal Component Analysis (PCA) [2] is employed. The central idea of PCA method is to reduce the dimensionality of a data set by transforming the old set to a new set of variables, the Principal Components (PCs), which are mutually orthogonal. The first few PCs retain most of the variation present in all of the original variables. Here, the PCA decomposes the aerial images of the defects to a set of PCs, which provides a new orthogonal basis in the image space. All the images of the defects can be represented in this basis by the PC Coefficients (PCCs).

All used Gaussian shape defects produce a similar rotational symmetric drop of the aerial image intensity (as shown in Figure 1). Therefore we employ spherical Zernike polynomials in the projection lens to construct the base functions of the PCA. The image of an unknown defect is obtained as a superposition of images of a known reference defect with different spherical aberrations. Figure 2 presents the original image distribution of an unknown defect and the fitting result by the first few PCs in the focal plane. The result demonstrates that the method can perfectly fit the image of an unknown defect. The method can be also applied to the recovered phase base.

Finally, the correlation between the PCCs and the defect geometry parameters or required repair parameters is investigated. All simulations are done with the lithography and imaging simulator Dr.LiTHO.

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9630-33, Session 8

A Wigner-based ray tracing method for imaging simulations

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The Wigner distribution function (WDF) was introduced into optics in 1968 by Walther. It offers an alternative representation of the optical field and has proven to be a valuable tool for understanding and classifying optical systems and fields. Ten years after the paper by Walther, Bastiaans published a paper which lay the foundation for the simulation of optical systems using the WDF. Bastiaans studied the evolution of the WDF as it passes through an optical system and noted that for paraxial systems, the WDF remains constant along the paths of geometrical optical rays.

In this study this property is used by incorporating the WDF into a geometrical ray tracing simulation. Thereby wave optical effects, like diffraction at an aperture, are incorporated into a geometrical simulation. By using ray tracing we investigate the potential of the WDF to overcome some of the challenges of wave based methods and extend the use of the WDF beyond the paraxial domain.

Using this Wigner based ray tracing method (WBRT) we simulate diffraction effects at apertures in free space and in imaging systems. Both paraxial and non-paraxial systems are simulated and the results are compared to numerical implementations of the Rayleigh-Sommerfeld, Debye-Wolf, and Fresnel diffraction integral.

The intensities predicted by WBRT for diffraction at apertures in free space, are in good agreement with results using a numerical Fresnel diffraction integral. For the calculations of point spread functions (PSFs) of imaging systems, the Rayleigh-Sommerfeld and Debye-Wolf diffraction integrals and WBRT are used. The results are in good agreement for aberration free systems, even at numerical apertures that are usually considered to be non-paraxial. For imaging systems with aberrations the PSFs produced by WBRT diverge from the results using diffraction integrals. For large aberrations WBRT gives negative intensities, suggesting this model is unable to deal with aberrations.

Although WBRT has been used in the past to calculate diffraction effects of paraxial systems, this is, to the knowledge of the authors, the first time the results have been systematically compared to those of other methods and the first time results for non-paraxial systems have been published.

9630-35, Session 8

Computer holography as an application of computational optics

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This paper provides a different point of view to computational optics. Traditional holography was introduced as the technique for three-dimensional imaging into popular sciences. The technique of computer-generated hologram (CGH) is, however, commonly applied to producing optical devices for conversion of wavefronts. To create 3D images similar to that of traditional holography by CGHs, we must handle tremendous space-bandwidth product of wave field of light.

We have partially got over the problem. Some extremely high-definition CGHs have been created to reconstruct holographic spatial 3D images [1-4]. These high-definition CGHs are commonly composed of more than billion pixels and sometimes more than ten billion pixels, where the pixel pitch is less than 1 micron. The CGH fringe pattern is printed on photo-masks by using a laser writer available in the market. The 3D images reconstructed by these high-definition CGHs give very impressive sensation of depth to the viewers, because the 3D images show not only binocular parallax but also smooth natural motion parallax as well as accommodation. The perfect depth cues have never been achieved by any other current 3D technologies. Thus, one of our high-definition CGHs were on display at Massachusetts Institute Technology (MIT) museum in Boston USA [5].

To create this kind of large-scale CGHs, we need techniques to handle gigantic number of sampling points of complex amplitude distribution, i.e. wave fields of light. Therefore, we developed some new techniques for field propagation, such as band-limited angular spectrum method [6], rotational transform of wave fields [7,8], and shifted angular spectrum method [9].

In this paper, we propose additional new technique to handle large-scale wave fields for creating high-definition CGHs. Numerical field propagation based on discrete convolution using FFT commonly requires extension of sampling array in order to avoid sampling problems caused by circular convolution. This strongly increases the computational effort of field propagation. In fact, increase of memory usage caused by the sampling extension commonly limits the maximum field size in numerical propagation. We propose frequency filtering to avoid the sampling extension in this paper. The sampling extension is required in cases where the field spreads over the sampling window and invades neighbor region in the periodic structure caused by discrete Fourier transform. In the proposed technique, the field bandwidth is limited so that the field does not invade the neighbor region. The memory usage is significantly cut down by this technique.

Several high-definition CGHs created by the proposed technique will be exhibited in the presentation room if approved.

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9630-36, Session 8

Fast and end-to-end x-ray differential phase contrast imaging simulator

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A grating-based Talbot-Lau interferometer enables differential phase contrast imaging employing a low brilliance X-ray source. The modality has been actively researched in medical imaging community to image fine structure of bio samples. Recently Such an X-ray phase imaging for aviation security becomes of interest because it measures index of refraction, along with absorption, that enables discriminating hazardous materials inside a luggage. For such applications, object of interest is surrounded by various kinds of and randomly oriented clutter which alters amplitude, spectra and phase of X-ray image. Such effects have to be taken into account during the design phase of the X-ray DPC imaging modalities. Thus, we developed fast, integrated and end-to-end simulation environment to systematically optimize and predict imaging performances of X-ray DPC imaging system. The simulation environment consists of two off-the-shelf modules, 3D CAD and Optical ray-trace code, as well as a custom physical optics simulation code to simulate polychromatic fractional Talbot fringe formation. Each module are interfaced to pipeline data. The 3D CAD data of the object under inspection with clutter is exported to Ray-trace Code. The Ray-trace Code calculates shift of monochromatic fringes as well as attenuation by non-sequential ray-tracing though objects and clutter. Finally the ray-trace data is interfaced to the physical optics module to obtain signal from detector. The simulator enables optimizing the system parameters, design energy, X-ray tube voltage and beam hardening while taking into account practical objects and clutter. We also present comparison of simulation with experimental results for objects surrounded by clutter.

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