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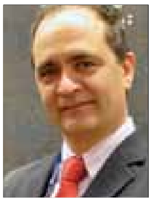

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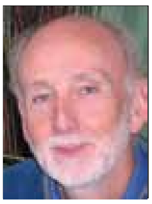

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Conference 8550A: Optical Design and Engineering V

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8550-1, Session 1

Comprehensive modelling and simulation of micro-optical subsystems

Ingo Sieber, Karlsruher Institut für Technologie (Germany)

The target-oriented application of computer-based tools for design and simulation of optical systems shortens the time needed for development and increases the reliability of the systems in operation.

Efficient and reliable optical design requires knowledge of the production chain, the materials used, and the environmental circumstances in the field of operation of the optical system. The fact that most optical systems extend over three dimensions and are realised in modular setups, results in an isolated manufacture and a latter assembly of the individual components to one system. Each individual process step adds its own typical tolerances to the optical component as well as to the mounting structures used for adjusted positioning of the optical components. With knowledge of the fabrication tolerances the designer is able to adjust the functional design to these tolerances in order to compensate them.

Another point the designer has to address is the reliability of the system in operation. Crucial to reliability aspects is the material behaviour in dependence to temperature fluctuations. A change in the environmental temperature may be due to seasonal as well as to operational effects and may cause stress and strain of the components resulting in position errors and deformation of the optical components and therefore in a decrease of the optical performance. Conventional optical design tools do not offer the functionality to model and simulate environmental effects on the optical performance.

To be able to model and simulate the effect of temperature influences on the optical performance a coupling between a mechanical simulator, e.g. a finite element method (FEM) tool and an optical simulator has to be achieved. In this paper the coupling of the commercial FEM tool ANSYS (TM) and the commercial optical simulation tool ZEMAX (TM) is shown and applied to an Alvarez-Humphrey optics, a freeform optics of tuneable refraction power.

8550-2, Session 1

Accuracy of geometric point spread function estimation using the ray-counting method

Javier Portilla, Sergio Barbero Sr., Consejo Superior de Investigaciones Científicas (Spain)

Motivation: The geometric point spread function (PSF) is an appropriate tool to characterize the energy distribution response (irradiance) of an optical system, whenever the effects of diffraction are comparatively small to that of aberrations. The PSF is conventionally estimated by computing the density of ray intersections with the image plane (ray-counting method). Its major advantage, over methods where the irradiance function is directly computed, is that it avoids dealing with singularities (caustics) in the irradiance function. The PSF is particularly useful when modeling image degradation, e.g. for digital compensation, in imaging systems. For such cases, a highly accurate estimation of the PSF is needed. We studied the effect of two factors on the estimation: the number of rays, using an error model, and the influence of the ray pattern. To avoid tracing a large number of rays, we also investigated the benefits of interpolating rays on the ray mapping.

Methods: To obtain a reliable reference for our analysis, we computed the accuracy in the PSFs estimation in three ideal cases where we could derive an analytical expression for the irradiance at the image plane. Two of the cases contain caustics: a pure coma and a spherical wave aberration function. We also used an example of a real optical system: three PSFs generated by a single rear landscape lens. For these PSFs we took as a reference the best result we could achieve given our computational means (using up to 1E7 real traced rays). We tested different uniform ray patterns: square, jittered square, hexapolar and hexagonal. We interpolated the ray mapping data (i.e. ray intersection points at the image plane as a function of pupil coordinates) using cubic splines.

Results: Our model predicts a +4.5 dB improvement in Signal-to-Noise Ratio (SNR), when doubling the number of rays. We have consistently observed this improvement factor in all the studied cases. We also found that the hexagonal pupil sampling outperformed the other considered ray patterns, and that the hexapolar pattern presented a very high variability in its performance. Finally, we demonstrated that, by using interpolated rays, only a tiny proportion of traced rays are necessary to obtain a similar quality in the estimation as when using the same total number of rays without interpolation. For instance, by interpolating only 100 traced rays we may obtain a similar quality as when using 100 million of real traced rays.

Conclusions: The ray-counting method can provide an arbitrarily high accuracy on the estimation of geometric PSFs. However, the method is not very efficient because of the slow improvement ratio as a function of the number of rays. A more efficient alternative, in terms of computational cost, consists of applying interpolation to the ray mapping. Clearly this makes sense only when the ray tracing algorithms are computational more expensive than the interpolation, which is usually the case. Selecting an appropriate ray sampling pattern is also a relevant factor in the estimation performance.

8550-3, Session 1

Super resolution using a modified spherical geodesic waveguide suitable for manufacturing

Hamed Ahmadpanahi, Dejan Grabovickic, Juan Carlos González, Pablo Benítez, Juan Carlos Miñano, Univ. Politécnica de Madrid (Spain)

The previous publications (Miñano et all, 2011) have shown that using a Spherical Geodesic Waveguide (SGW), it can be achieved the super-resolution up to λ /500 close to a set of discrete frequencies. These frequencies are directly connected with the well-known Schumann resonance frequencies of spherical symmetric systems. However, the Spherical Geodesic Waveguide (SGW) has been presented as an ideal system, in which the technological obstacles or manufacturing feasibility and their influence on final results were not taken into account. In order to prove the concept of super-resolution experimentally, the Spherical Geodesic Waveguide is modified according to the manufacturing requirements and technological limitations.

The manufacturing process imposes some parameters such as accuracy or the technological limitation that might change the expected results. We would like to predict the influence of any imposed parameter on super-resolution. Therefore, considering the manufacturing limitations, we modified the SGW according to the most reliable manufacturing process, and then we analyzed the influence of each parameter on the super-resolution properties of the SGW.

We used COMSOL Multi physics to study the influence of different parameters such as spherical tolerance (imperfect Spherical Geodesic Waveguide), the thickness and the material of the conductive wall. The analyzed imperfections did not cause a significant change in the super-resolution properties.

8550-4, Session 1

Integrating optical simulation into CAD/CAM solutions: advantages to designers of optical imaging systems

Jacques Delmau, OPTIS (France)

By integrating optical and photometrical simulation directly into CAD/CAM software, OPTIS presents an innovative solution which answers the global design needs on complex shapes, making optical, thermal, mechanical and cinematic functionalities communicate with each other.

The OptisWorks software, integrated in SolidWorks by Dassault Systèmes, opens up access to a multitude of applications to optical engineers, from analysis of optical performance, stray light analysis, and at the same time putting into a virtual context the final opto-mechanical system under constraint, which now becomes an integral part of the final assembly.

The Optical Design solution inside OptisWorks enables the creation of optical components dedicated to imaging (lenses, mirrors, diaphrams) and their insertion directly in the CAD environment. After having added an optical source and a detection surface plane, the user can analyse the optical performances of his/her imaging system: spot size, wave front default, MTF, etc. The results of these analyses are comparable to what dedicated optical design software can offer. The user can then launch an optimization or a tolerancing of their opto-mechanical system.

CAD integration also offers other physical simulation tools available with SolidWorks : thermal, tolerancing, cinematic, interference detection, etc. For example it is possible, using the thermal simulation model, to take into account dilation of opto-mechanical elements right from the optical design phase, and to determine their influence on optical performances.

This innovation naturally leads onto a change in the methodologies of designing optical imaging systems which are now open to the CAD world. By integrating optics right at the start of the design process, enables designers to arrive quicker at a solution which will fully meet all the criteria and specifications requested, and no longer in isolation to each specification.

This presentation explains and argues the benefits of a shortened and integrated opto-mechanical design process, from creating the optical components, to the optical assembly, to optical performance analysis and optimisation, through the mechanical design and opto-mechanical design phases.

8550-5, Session 2

Tolerancing free form elements considering manufacturing characteristics

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Recent developments in design algorithm enable the design of freeform surfaces, that generate a picture in the target plane using one single optical surface. In contrast to conventional imaging, the light modulation is done by a ray-optical redistribution of the incident light comparable to incoherent beam shaping.

Such picture-generating surfaces normally provide a very complex surface sag, that is manufactured using diamond turning machining. The knowledge of manufacturing tolerances is important to generate the desired intensity distribution with the required accuracy and at the same time reduce manufacturing effort.

However, tolerancing picture-generating free form optical elements is a demanding task, compared to tolerancing conventional optical elements (e.g. spheres). The complexity of their surface shapes and the target intensity distribution lead to a lack of finding tolerance parameters and performance criteria.

Tolerance parameters strongly depend on the manufacturing process. Therefore they can be found by a detailed analysis of their manufacturing process. In this contribution we focused on the manufacturing of picture-generating free form optical elements using diamond turning with slow tool servo support. Typical low-frequent and dominant manufacturing errors with this tool are e.g. astigmatism and spherical aberration. Errors with middle to high spatial frequency have not been investigated so far.

However, conventional software tools for tolerancing, as e.g. implemented in Zemax, provide only tolerance parameters like radius, thickness or tilt, corresponding to conventional manufacturing methods of classical optical elements, as e.g. spheres. Therefore we implemented a software tool based on Matlab using Zemax for raytracing in order to perform sensitivity analysis and Monte Carlo analysis.

Conventional performance criteria to evaluate the tolerance analysis, like spot radius or wavefront error cannot be used for picture-generating free from elements. Consequently, other performance criteria were investigated. In this case, the correlation criterion, that qualifies the match of the intensity distributions generated by erroneous and ideal surface, has been found to be an appropriate performance criterion for the tolerancing analysis.

8550-6, Session 2

Design and modelisation of a strayligth facility for space optical instrument

Emmanuel Mazy, Yvan G. Stockman, Marie-Laure Hellin, Univ. de Liège (Belgium)

In the framework of instrument calibration, straylight issues are a critical aspect that can deteriorate the optical performances of instrument. To cope with this, a new facility is designed dedicated for in-field and far field straylight characterization. Straylight characterizations up to 10E-6 for in-field and up to 10E-10 for far field straylight in the visible to NIR spectral ranges. Moreover, from previous straylight test performed at CSL (i.e. on STEREO heliospheric imager), vacuum conditions are needed for reaching the 10E-10 rejection requirement mainly to avoid air diffusion.

The major constrains are to design a straylight facility either for in-field and out-field straylight measurements. That requires high dynamic range at source level and a high radiance point source allowing small diverging collimated beam (< 25 arcsec for in-field straylight characterization). Moreover, the straylight facility has to be implemented into a limited envelope (i.e. the vacuum chamber) and has to be built with vacuum compatible materials and black coating.

The straylight facility light source is based on a Φ 400 mm off-axis collimator, a set of vanes and a black tent surrounding the instrument. All surfaces are black coated with MAP PU1 paint and locally Velblack® sheets for reaching 10E-10 rejection level. The collimator focal plane is specially designed to provide a collimated beam with straylight rejection better than 10E-10 for $\Phi < 1$ arcdegree for out of field and better than 10E-6 for $\Phi < 100$ arcsec for in-field requirements.

As checking the facility performance requires an instrument better than the facility itself, that is no easy to find, so that the performances have been estimated through a modelisation into a non sequential optical software. This modelisation is based on CAD importation of mechanical design, on BRDF characteristics of black coating and on statistical averaging of ray tracing at instrument entrance. In order to improve the model accuracy, BRDF of black coating are measured at CSL on sample in VNIR and SWIR spectral ranges.

A straylight facility has been designed and built at CSL for testing space instruments with large entrance apertures in VNIR and SWIR spectral ranges. The design drivers are the compatibility for in-field and far-field straylight requirements involving an especially dedicated collimator focal plane and the compatibility with vacuum environment. Straylight facility performances are assessed through a non sequential raytracing model based on measured BRDF characteristics.

8550-7, Session 2

A simulation model for the development of an aspheric lens adjustment system

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The adjustment of aspheric lenses within their mount is a nontrivial task that requires high accuracy whereas on the other hand low effort in handling and time is desired. Alignment turning is a method for the adjustment, i.e. the correction of an erroneous translation, of spherical lenses. Aspheric lenses, however, are much more difficult to adjust because of an additional tilt error. When aspheric lenses are measured by alignment turning the tilt error may disturb the centering error determination. Aspheric lens alignment should minimize simultaneously the translation error and the tilt error.

We present a simulation model for the development of an aspheric lens alignment system that is based on multi-point optical distance measurement. The model is based on distance measurement approximately perpendicular to the lens surface at certain radial positions over 360° rotation of the lens. If the adjustment is erroneous, a sinusoidal distance curve will be obtained. This error curve, however, is influenced by both translation and tilt error. The task is now to separate both influences from this curve. Additionally, it must be noticed that translation error and tilt error may cancel each other. Hence the distance measurement must be performed at several positions.

The simulation model provides a solution of this task based on distance measurement using at least two measurement positions. However, this solution can be only obtained if no disturbances occur. In practice, at least a certain amount of noise is present leading to a remaining error after the determination of translation and tilt by the new method. Consequently, several approaches of error reduction are presented. The simulation model provides the possibility to use arbitrary noise values as input quantity. The individual aspheric lens design data (aspheric lens coefficients), the number of chosen measurement positions, and the specified noise level determine the expected statistical adjustment result. This result gives the (statistical) expected remaining error after the adjustment procedure for given simulated initial translation and tilt errors. These errors are produced randomly. Using the simulation model, the optimal measurement positions for every individual aspheric lens may be found.

Because the requirements of the lens adjustment are high (typically, translation error should be less than 1µm and tilt error less than 3") the distance measurement must be adequately accurate. The simulation model provides the possibility to find out the optimal positioning of the distance sensor and to determine the number of necessary measurement positions and repetitions for every given aspheric lens for the enforcement of the requested measurement accuracy.

A number of simulations were performed using the data of more than twenty aspheric lenses. The results show a very different behavior of the lenses. The remaining error after application using a meaningful expected noise level is considerably different for various lenses. Hence, in order to obtain a certain expected remaining error, for each lens an individual arrangement of measuring positions and a minimum number of measurement repetitions will be the result of the simulation process. In conclusion it can be stated that the newly developed simulation model is a necessary tool for a novel metrology method of adjustment of aspheric lenses.

8550-8, Session 2

Forward tracing technique for diffraction analysis applied to the design of an IR endoscope

Andres F. Cifuentes, ASE Optics Europe (Spain); Josep Arasa, Univ. Politècnica de Catalunya (Spain)

The forward tracing technique for diffraction analysis (FFTD) is a numerical technique for ray-tracing environments inspired by the Boundary Diffraction Wave. The technique was developed specifically considering circular apertures in imaging systems. In previous work the technique was applied to a simple optical system. The value of the method has been geared towards aiding optical design where diffraction effects not produces at the aperture stop are important.

In this work the technique is applied and evaluated as a tool for analyzing a complex system where only circular apertures are present. The chosen system is an IR endoscope on the MWIR region. The system requirements make for circular apertures aside from the stop where diffraction becomes important. FFTD is applied for obtaining irradiance information at the image plane. The key parameters affecting the simulation are described on axis and field.

8550-10, Session 3

Experiences with CodeV® 'Glass Expert'

Mark Jeffs, Qioptiq Ltd. (United Kingdom)

Synopsys OSG (formerly Optical Research Associates) have recently developed a CODE V® feature called 'Glass Expert'. Taking advantage of modern computing power, this program is an extension to the normal optimisation routines, that allows a large number of glass types to be substituted into a lens system in an automatic way.

We decided to find out how to run this software, in detail, by applying it to a small number of suitable test lens systems. We wanted to evaluate aspects such as how quickly it runs, how the user input choice affects the end-result, and at what point of the design process it is most valuable.

The exercise proved to be very interesting. We describe how, in one case of a highly colour-corrected visible system, the macro showed itself to be able to reproduce, within a couple of hours, most of the glass choices I had to discover over a period of a couple of weeks in the original design process.

While this macro is most obviously useful for specially-corrected visible systems, it is also potentially useful for mid-wave IR and the important new short-wave IR (SWIR) band. An example of re-optimisation of a NIR/SWIR -band lens is given.

Glass Expert also offers the interesting possibility of swapping air and glass materials in an automatic way. We tried this option on one example, but ran into some problems that require further thinking.

Some other pitfalls, and some potential future improvements in the software are mentioned. We also note in our paper how Glass Expert and Global Synthesis® can work very effectively in combination.

8550-12, Session 3

Applying optical design methods to the development of application specific photonic crystal fibres

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Photonic Crystal Fibres (PCFs) are well known for their unique waveguiding properties and for allowing the implementation of specific features that cannot be achieved with conventional optical fibres. This results from the design flexibility of the holey structure in the PCF cladding and/or core regions. Today PCFs have found applications for example in supercontinuum generation, optical sensing and fibre lasers. They are now also being combined with fibre Bragg gratings, more specifically in the fields of optical fibre sensing and all-fibre laser applications.

In this contribution we discuss how we applied micro-optical design methods based on commercially available software such as Lumerical MODE Solutions and COMSOL Multiphysics combined with additional optimization methods to develop microstructures fibres for three different purposes, i.e. PCF structures that favour Bragg grating inscription, PCF structures that enable temperature insensitive pressure measurements and bendable PCFs with a very large mode area for high power short pulse fibre lasers. For the three cases we illustrate the fibre design methods and property simulations as well as the tolerance studies that take into account possible variations in material parameters as well as manufacturing imperfections.

A first example deals with PCFs that are equipped with a focusing microstructure in their cladding region that is designed to focus a transversely impinging laser beam in the core region of the PCF core region. This focusing structure is a photonic crystal Mikaelian lens (PCML), which is the implementation of a gradient index lens in a photonic crystal lattice. In a fibre that is equipped with such a PCML, the grating inscription laser optical power densities that reach the core region are one order of magnitude higher compared to a regular optical fibre. This promises to enable the inscription of gratings in the PCF core region using tightly focused high intensity laser pulses and exploiting non-linear multi-photon absorption.

The second topic covers PCF structures for temperature insensitive pressure or transverse load sensing. This fibre uses birefringence as a temperature-insensitive property that can be exploited in conjunction with a fibre Bragg grating as sensor element. The design constraints stem from technological fabrication limits, from the required ability

to connect with standard commercially available fibre and from the required compatibility with conventional Bragg grating inscription techniques. The design of such PCFs has built on extensive thermo-opto-mechanical simulations and has resulted in the highly birefringent "Butterfly" PCF which features unprecedented sensing specifications when compared to state-of-the-art birefringent fibres.

The third type of PCF targets high power short pulse laser applications. Such applications require PCFs with a very large mode area (LMA) to prevent damage to the fibre glass and to mitigate the occurrence of non-linear effects. We designed a PCF cross-section that includes two regions with different air-filling factors at opposite sides of the core region, which allows suppressing higher order modes (HOMs) when the fibre is bent over a 10 cm radius. The fibre then exhibits single-mode (SM) operation within a very large core with a diameter larger than 60 µm. With such PCFs one can consider building compact fibre lasers and amplifiers with a nearly diffraction limited output beam.

8550-77, Session 3

Computer modelling approach to decrease stray light in low light non-imaging optical designs

Selcuk Seyhun, Huseyin Sari, Ankara Üniv. (Turkey)

Opto-mechanical structures (objectives) are employed to transfer photons which are collected from their field of view (FOV) to the detector plane. The sensors used in such systems have high gain which causes them to detect stray light caused by the mechanical body of the objective. This type of stray light is a major problem in low light non-imaging optical systems used in laser seekers which employ four quadrant position sensors to determine laser illumination reflected from a target surface positioned kilometers away. This work, mainly concentrates on unwanted stray light caused by inner mechanical structure of large FOV objectives.

In order to prevent this unwanted stray light a sample laser seeker objective is designed in ZEMAX software environment together with its mechanical mount. Black Delrin is used as the objective material. Its specular and diffused reflective properties are measured with spectrophotometer and defined in the software environment. Ten objectives with different baffle height / pitch ratio (h/p) are designed and used in the same optic design. In order to show that a software model can be used to find the optimum h/p ratio for eliminating stray light, prototype objectives are manufactured and tested with readout electronics. After making measurements with different angles on incidence values best applicable objective with a certain baffle h/p is found. It is verified that the h/p ratio found in software model is in very good agreement with the measurement. This helps us not use more baffles than necessary since increasing baffle h/p astronomically increases production and workmanship costs.

This study shows that, instead of manufacturing expensive prototypes computer simulations can be used to identify and also take necessary precautions to prevent or decrease stray light before production. This prevents loss of significant amount of time, work, and cost.

8550-13, Session 4

Chromatic information coding in optical systems for hyperspectral imaging and chromatic confocal sensing *(Invited Paper)*

Matthias Hillenbrand, Mohamed Bichra, Adrian Grewe, Raoul Kirner, Robert Weiss, Stefan Sinzinger, Technische Univ. Ilmenau (Germany)

Dispersion causes the focal lengths of refractive and diffractive optical elements to vary with wave-length. While most traditional imaging systems are corrected for the resulting chromatic aberrations, dispersion can also be used to encode and decode spectral information. In our contribution we discuss the possibilities of chromatic information coding with respect to the growing fields of hyperspectral imaging and chromatic confocal sensing. In contrast to the human eye and RGB detectors which are only sensitive to three wavelength bands, hyperspectral imaging systems are aimed at recording the full spectral signature of the object under test, i.e. ten to hundreds of wavelength channels. By separating the emitted or scattered wavelengths, unique information about the object can be obtained. Possible applications include agriculture, geology, mineralogy, and surveillance. In chromatic confocal sensing, hyperchromatic lenses with maximized longitudinal chromatic aberration are used for efficient depth to wavelength coding. For this purpose the classical confocal setup is combined with a white light source. The objective lens is replaced by a hyperchromatic lens which focuses each wavelength at a different distance from the sensor. The confocal pinhole attenuates all wavelengths except the one which is focused on the surface under test. The resulting signal is evaluated with a spectrometer and the wavelength of maximum intensity can be directly related to the distance between the hyperchromatic lens and the surface under test. Possible applications of this sensor technology include efficient non-contact profilometry as well as distance and wall thickness measurements.

In our contribution we discuss how the mechanisms of dispersion can be used for chromatic encod-ing and decoding of optical signals. To create the necessary chromatic aberration we use refractive systems as well as hybrid combinations of diffractive and refractive elements. Our design approach enables the tailoring of the sensor properties to the specific measurement problem and assists designers in finding optimized solutions for industrial applications. For example, power balancing between diffractive and refractive elements is used to realize the intended, application-specific chromatic aberration and spectral resolution. High lateral, axial, and spectral resolution requirements are directly related to a large numerical aperture of the optical system. To cope with the resulting monochromatic aberrations we combine paraxial and collinear design concepts with the potential of ray-tracing based optimization. Further application-specific system requirements such as telecentricity and allowed tilt angles of the surface under test can be integrated into the design process. The focus of our study is on parallelized imaging systems that cover an increased field of view. In comparison to point sensors, these systems promise reduced image acquisition times and an increased overall performance. To this end we specifically address the challenges arising from field dependent aberrations as well as image space telecentricity. Concepts for three-dimensional profilometry with chromatic confocal sensor systems as well as spectrally resolved imaging of object scenes are discussed.

8550-14, Session 4

Quantify passive athermalization in infrared imaging lens systems

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Passive athermalization has become a key-technology for automotive and other outdoor applications using modern uncooled 25 and 17 micron bolometer arrays. For high volume applications, passively athermalized optical designs with a minimum of lenses reduce costs and require a careful choice of lens and housing materials. But, up to now, metrics of athermal properties of these lenses are seldom published.

A new thermal drift of focus relation is deducted which is applicable for imaging systems consisting of several groups. This equation becomes for a one-group-design easy to handle which respects thermal coefficients of housing material and of lens material, the focal length and the temperature change. Narrow field lenses with longer focal lengths are most critical for athermalization.

The athermal and achromatic properties of different lens materials are discussed. GASIR? possesses inherent passive athermalization properties. High resolution, two lens designs for different field angles are presented. The lens designs use aspherics and diffractive structures. Resolution values and their variation with temperature are given.

The allowable degradation of MTF (defined as DMTF) in Temperature Range (named DT) depends on the lens application. Different metrics are presented: Through-Focus-MTF-graphs at interesting temperatures, the MTF-versus-field-graph at interesting temperatures offers the complete customer information, the On-Axis-MTF versus temperature shows the typical thermal drift, the Value-Pair DT @ DMTF characterizes every lens design.

Examples are given to demonstrate the relationship between the different metrics.

Several measures to allow passive athermalization to succeed are discussed for demanding narrow field of view examples. These include mechanical methods with different kinds of movement: first lens only, second lens only and both lenses. First order relations help to find the shortest compensation mechanism.

8550-15, Session 4

Development of a real-time optical imaging system for monitoring food quality and assessing human body parts using diffused light

Tsuneaki Genta, Hiromu Tashima, Toyohashi Univ. of Technology (Japan); Ryo Shimokita, Genial Light, Inc. (Japan); Ahinichi Arai, Mitsuo Fukuda, Toyohashi Univ. of Technology (Japan)

Real time imaging techniques are required in diverse fields, such as in food factory production lines for monitoring food quality, and in the medical profession for clinical diagnosis. For these purposes, magnetic resonance imaging and X-ray computed tomography have been developed and are currently used. However, these techniques are complicated and expensive to use and cannot detect organic, wooden or plastic alien substances in food. Optical measurement methods, on the other hand, are simple and cheap, and are suitable for real-time monitoring; however because of scattering and absorption effects, interpreting the measurements can be difficult. To overcome this, optical coherent tomography and photo-acoustic tomography techniques have been developed. These systems need a certain time interval for computing and imaging, and are therefore not classified as real-time imaging techniques. For real-time imaging with light, we previously developed a compact system using near infrared light, which could detect insects and human fair in food, and blood vessels in the human body. In this study, we describe an improved system in which organic foreign substances in food, and the bones in chicken wings, can be imaged in real time using diffused light.

The system consists of an optical source, composed of laser diodes emitting 850-nm light, and a complementary metal-oxide semiconductor (CMOS) sensor covering a wide dynamic range. When the laser beam is incident on the specimen, optical absorption and scattering occur, which deteriorate the image quality. In our system, a high power optical source and a certain optical system compensate for these effects. As the system uses a CMOS sensor, real-time monitoring of the internal structure in food and human body is possible. Various kinds of food and the human hand are examined. Foreign substances, such as human hairs and insects, are detected in images of 8-mm-thick ham. The bone structure in 20-mm-thick chicken wings is also imaged in real-time.

8550-16, Session 4

Multifocus FCS

Vit Dolezal, Lars Kreutzburg, Richard Börner, Christian G. Hübner, Univ. zu Lübeck (Germany)

Fluorescence correlation spectroscopy (FCS) is a well-established method for the study of molecular motions, interactions, and reactions. Already introduced in the 1970s, its development has been boosted in the last 20 years thanks to its combination with confocal optics. Conventionally, a single confocal volume is used, providing only limited information about drift components in the motion of the molecules and complicating the determination of absolute diffusion coefficients. To overcome these limitations, two-focus FCS has been developed, and was shown to outperform conventional FCS in these respects.

We go one step further and introduce a multi-focus FCS scheme, which is also able to provide information on the direction of drift motion. We implement multi-focus-FCS by four separated detection foci, which are shifted relative to each other and with respect to a single, common excitation focus. Thus, four confocal volumes are created, arranged at the vertices of a tetrahedron. The four corresponding fluorescence intensities can be subjected to correlation analysis, resulting in 4 auto- and 12 cross correlation curves (6 times forward/backward cross correlation). These correlation curves allow for determining absolute diffusion coefficients as well as information about the direction of the molecule's movement.

We have first established a computational framework, which allows for simulating the whole experiment, based on random walk diffusion within a defined space, which has the shape of a cylinder. With this simulation, we explore the limits of our approach.

The experiments are performed on a home built scanning confocal microscope with a 488 nm cw laser as the excitation source. The laser is fed through a single-mode fiber for spatial filtering and reflected by a dichroic mirror towards the galvanic scanning mirrors. It is focused by a water immersion microscope objective into the sample cell. Fluorescence, which is collected by the same microscope objective after passing the dichroic mirror, is divided by three 50/50 beam splitter cubes into four beams, each of which is focused by an achromatic lens through a pinhole, which is part of the detection assembly. This assembly is comprised of the pinhole, a biconvex lens, and a photon counting module based on an avalanche photo diode. The whole assembly is pre-aligned and can be moved in x, y, and z in order to place the detection foci at the desired positions. Experiment control and data acquisition is based on a real-time multi-purpose digital/analog IO system controlled by home written software.

First experiments on standard fluorophores demonstrate the feasibility of our method. In first approach, we mimic drift by slow motion of the scanning mirrors. The analysis of the correlation functions reproduces the drift component with reasonable accuracy.

Future applications of our method range from detailed studies of flow fields in micro capillary devices to the study of directed motion in living cells.

8550-17, Session 4

Calculation of frontal components for microobjectives

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Abstract: In this publication we present the analysis and geometrical calculation of construction parameters of frontal lenses high-aperture objectives for microscopes.

Generally, those objectives are working with immersion (in explain, cedar oil), which can increase resolution of the objective. For simple achromatic lenses are used single lens made of optical glass, whose refractive index is close to the refractive index of cedar oil. However, the adjustable parameters of such single lens are often not enough to build a flat-field lens in the image space. In this case, use double component. The refractive index of the first lens close to the refractive index of the immersion fluid, and the second lens is made of high-refraction crown. The difference in refractive indices allows us to correct the lens aberrations such as curvature of the image and the secondary spectrum.

However, this design solution is not efficient enough for high-aperture microscope objectives with aberrational correction planapochromatic type. This is due to the fact that its front lens element assumes a maximum value of the input numerical aperture. For oil immersion lens numerical aperture value reaches a value of 1.4. On how the component is able to reduce the front entrance numerical aperture at the highest possible degree of correction of aberrations such as curvature of the image and the secondary spectrum, depends on the possibility of correcting aberrations in the lens as a whole.

In the immersion microscope objective high-aperture there is also a problem in mechanical fastening the front frame component. This is especially difficult to do for the lens numerical aperture of more than 1.3-1.35 oil immersion. The form of the lens, which has contact with the immersion close to a hemisphere, securing it in a frame is not possible. Often used in a thin plane-parallel plate, which is attached to this lens. But this solution is not optimal. Double front lens design has some advantages. But it is also very difficult to secure such a component in a frame. We did an analysis of several optical calculations oil immersion lens, numerical aperture of which should be 1.4. We concluded that the technology of manufacturing of optical and mechanical components of frames can't achieve such a value in a numeric aperture made lenses.

We propose to use triple lens component as the front element high-aperture immersion lens microscope. In this case, it is possible to achieve the maximum numerical aperture, properly secured in a front-end component of a mechanical frame, high-quality correction of aberrations and curvature of the secondary spectrum in the frontal component and the lens as a whole.

8550-18, Session 5

Improving laser material processing objective lenses towards better utilization of high brilliance light sources *(Invited Paper)*

Lutz Reichmann, Hans-Jürgen Feige, Jürgen Finster, Matthias Bening, Jörg Wunderlich, Peter Triebel, Helmut Bernitzki, Uwe Schuhmann, JENOPTIK Optical Systems GmbH (Germany)

Abstract

Today's high brilliance Laser sources cause huge thermal effects on optical components, affecting process stability.

The development of high power cw-laser sources @ 1030 to 1070nm make sources of multi Kilo Watt available. These lasers allow high-speed processes which are very sensitive to changes like focus shift and beam quality.

In fact thermal lensing is limiting the use of high brilliance Laser sources in various processes. To overcome this issue, the public funded project "Brilliant Lasers in Production" (BriPro) was started in 2010 to overcome this challenge.

1 Simulation of thermal lensing

Jenoptik has developed a simulation method which allows simulation of the thermal lensing effect starting with a description of the incident laser beam, generating transient temperature profile and surface deformation using FEM method, uploading the FEM results to optics design software, generating three-dimensional refraction index distribution and calculate the propagation with respect to discrete time steps.

Using this method Jenoptik is able to characterize the thermal behavior of entire objective lenses as F-Theta lenses for example.

Simulation shows three critical effects with different time constants: surface absorption, bulk absorption and temperature drift of the adjacent mechanical structure. There are various approaches to optimize objective lenses with respect to these effects.

2 Optics material selection

The BriPro project contains an extensive test program to characterize and identify feasible optical materials. They should have lowest absorption coefficients @1030- 1070nm. The test program contained fused silica and various sorts of optical glass.

To characterize the test set components, various absorption measurement methods were used and compared.

Fused silica with absorption coefficients of 0,1ppm/cm or 15ppm/cm are used for optimized designs. Jenoptik already successfully tested focus shift of optimized F-theta lenses made of Fused silica up to 4kW Laser power with focus shift less than 0,05 tines the Rayleigh range.

3 Optimization of optical surface finish and coating

Optimized finish of optical surfaces and optical coatings allow absorption coefficients less than 5ppm per surface.

4 Objective lens design optimization

Thermal FEM Analysis of the Objective lens is not only used to simulate thermal lens effect but also allows dimensioning of further optimization like temperature control which is used to stabilize the temperature of the objective lens mechanical structure.

5 Public funding

The BriPro Project is a network project, funded by the Federal Ministry of Education and Research.

Members of the BriPro consortium are TRUMPF, SIEMENS, Schott, Layertec, IFSW Stuttgart and Jenoptik.

8550-19, Session 5

Optical design of a low-loss demultiplexer for optical communication systems in the visible range

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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. In fiber optics BPM software is usually used to research the guidance of light in the inner fiber. This is suitable for fibers with small core diameters such as single mode or multi mode glass fibers. For short distance communications polymer optical fibers (POFs) are gradually gaining in importance. This kind of fiber offers a larger core diameter, e.g. the step index POF features a core diameter of 980 µm. Consequently, POFs have a large number of modes (>3 million modes) and BPM is not suitable anymore. Instead, ray tracing could be used. This simulation method is not only applicable for the fiber itself but also for the key components of a complete POF network, e.g. couplers or other key-elements of the transmission line. In this paper a demultiplexer designed and developed by means of ray tracing is presented. Compared to the classical optical design, requirements for optimal design differ particularly with regard to minimize the insertion loss. In other words, the complete light has to be transmitted to guarantee a good transmission. The basis of the presented key element is a wavelength division multiplex device using a Rowland spectrometer set-up. In this approach the input fiber carries multiple wavelengths, which will be divided into multiple output fibers that transmit only one wavelength. To adapt the basic set-up to POF, the guidance of light in this element has to be changed fundamentally. Here, a monolithic approach is presented with a blazed grating using an aspheric mirror to minimize most of the aberrations. In the simulations the POF is represented by an area light source, while the grating is analyzed for different orders and the highest possible efficiency. In general, the element should be designed in a way that it can be produced with a mass production technology like injection molding and hot embossing in order to offer a reasonable price less than 10 EUR. The paper will give an introduction to POF, its application arrays, and will step by step describe the development of the demultiplexer by means of ray tracing simulations.

8550-20, Session 5

Recent development in light-sheet fluorescence microscopy-ultramicroscopy using aspherical optical elements

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Light sheet fluorescence microscopy (Ultramicroscopy) is a powerful tool for imaging even cm-sized specimen with micrometer resolution. It becomes an increasingly common technique in Neurosciences with high potential towards medical diagnostics. Ultramicroscopy uses light sheet illumination for optical sectioning and the image quality depends on the shape and quality of the light sheet. Using single cylindrical lens to produce a light sheet from a truncated magnified Gaussian beam is the standard method. A combination of a Plano-concave lens and three cylindrical lenses has been suggested as an alternative optical system. In this paper, a new design for generating a thin laser light sheet for ultramicroscopy is presented. The laser beam is divided into two halves by 50% beam splitter and guided toward two identical optical units containing several optical elements with aspheric surface structure. These two units are placed at two sides of a chamber containing the sample for two side illumination. The first part of each unit includes two identical achromatic aspheric Plano-convex lenses of focal length f (facing each other) that are placed at distance d. They are separated by a particular aspheric element called Powell lens that is placed between them at a computed distance. This element reshapes the beam into a beam with semi uniform intensity distribution. This combination produces a semi-uniform elliptical beam that is incident on the second part of unit containing two achromatic-cylindrical lenses of identical focal length. The optical characteristics of the light sheet (i.e. the length and diameter of the line of focus, spatial intensity

distribution along the light sheet) have been improved and the laser energy is used more efficiently as there is no truncation of the beam. A chemically transparent biological specimen (to reduce scattering) is placed in the chamber at the focus of last lens and the length. Using a microscope with infinitive objectives that are optically corrected for refractive index mismatch and a CCD camera a large stack of images is recorded. Amira software is employed for 3D reconstruction of the raw-data obtained in the last step. Using this new design, we achieved a marked improvement in presenting fine details in reconstructions of representative biological specimens such as entire embryo, whole mouse brain as well spinal cords and Hippocampus.

8550-21, Session 5

Accurate and efficient fiber optical shape sensor for MRI compatible minimally invasive instruments

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Background:

Minimally invasive instruments are becoming smaller and smaller. The mechanical properties of these small instruments are limited and thus must be treated as flexible instruments. More frequently, these instruments are positioned by computer control. Proper functional behavior of these instruments can be significantly enhanced when the instrument is equipped with a shape sensor to track the path of the flexible instrument. MRI compatible instruments, and thus the corresponding paths, are long in particular. Therefore, the accuracy of the tip position is stringent.

Approach:

We have developed a Fiber Bragg Grating (FBG) based fiber optical shape sensor. The main advantages of this fiber optical sensor are its minimum dimensions, the intrinsic MRI compatibility, and the ability of sensing deformation with submicro-strain accuracy. Different concepts, each equipped with multiple FBG's, have been evaluated. With these concepts, critical component analysis and numerical error analysis were performed. Based on the outcome of these analyses, we have developed design rules and an accurate calibration procedure for shape sensors in flexible instruments.

Two promising shape sensors are realized and validated, each containing three FBG fibers. The first shape sensor (Type A) consists of three separate fibers positioned at the outer surface of the instrument. For the second shape sensor (Type B), the three fibers are integrated physically by gluing and is positioned inside an instrument. The outer diameter of the shape sensors are respectively 1.4 mm and 300 um, the length of 20 and 10 cm and the minimum bending radius of 500 and 25 mm. After calibration, the instruments were bended by applying a point force at the tip and were imposed to simple shapes to determine the accuracy of shape reconstruction on the basis of the FBG output.

Results and Conclusion:

With current state of the art interrogators it is possible to measure a local deformation with a triplet of FBG sensors very accurately. From multiple deformations, the shape can be reconstructed and thus the position of the tip of the instrument. For proper shape reconstruction, only a limited number of FBG sensors is required, which makes the instrument cost effective.

With the comprehensive design rules we are able to interchange form-factors, usability, robustness and accuracy to support system design optimization.

Special care needs to be taken to ensure that the attachment of the fibers does not inflict inhomogeneities in the mechanical properties in all directions. Especially for the glued version (Type B), the mechanical properties of the glue will strongly influence the performance of the shape sensor. However, this sensor concept has the major advantages of being insensitive to axial pressure and axial temperature gradients and enables a large curvature.

The results show that the tip position could be measured with an accuracy (3 sigma) of less than 1 mm for Type A and 200 um for the Type B shape sensor, which both are less than the diameter of the instrument.

We conclude that FBG based sensors offer the opportunity to accurately reconstruct the shape of MRI compatible flexible instruments.

8550-22, Session 5

Study of aberrational performance and manufacturing tolerances of Klevtsov family of sub-aperture catadioptric telescopes and field correctors for them

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Study of aberrational performance and manufacturing tolerances of Klevtsov family of optical telescopes is presented, with focus on determination of practical boundaries in design space of two-glass solution, which provides correction of spherochromatic aberration comparable with complex full-aperture catadioptric designs at expense of using dense and ultra-dense crowns for sub-aperture meniscus elements with careful mating of Mangin mirror glass. This allows radical improvement of spherochromatic correction in comparison to basic Klevtsov design with corrector lenses of same glass, with increase of both primary mirror's and whole system's speed. This family of designs is subject of late Klevtsov's patents from middle of 90's and allows building of very compact systems with moderate overall focal ratio, like presented analyzed examples with 0.5 m aperture with f/1.5 primary mirror and f/5 equivalent focal ration, with diffraction-limited on-axis performance within whole visible range. This level of spherochromatic correction is far superior to popular single-plate Schmidt-Cassegrain and Maksutov-Cassegrain with small departure from spherical meniscus, the only known viable counterpart in the family of single-lens full-aperture catadioptric telescopes is hybrid system combining Maksutov meniscus with strong Schmidt-type polynomial aspheric on one side, separating spherical aberration correction between them with partial mutual compensation of spherochromatism, which is of opposite sign for meniscus and for Schmidt aspheric. This solution is clearly hard to manufacture and rare. Two-glass Klevtsov solution, contrarily, is very interesting for mass-production due to all-spherical optics and absence of full-aperture refractive elements. It is limited by tradeoff between glass availability and corrective potential of particular glass pair which restricts large-aperture solutions to less extreme glasses leading to use of slower primary mirrors for same spectral ranges and requirements for spherochromatic corrections. High-order spherochromatic correction poses tight requirements for real glass melts fitting of design, modelling results for practically interesting designs are provided. Comparison of practical Klevtsov designs with pure reflective designs such as Cassegrain, Ritchey-Chretien, Dall-Kirkham and full-aperture catadioptric designs such as Schmidt-Cassegrain, Maksutov-Cassegrain and Volosov-Houghton designs is taken for both axial and field aberrations for both basic designs and combinations with field correctors, including variants with reoptimized basic system hard-mated with particular corrector. Basic Klevtsov design doesn't possesses enough degrees of freedom for achievement of good field correction; astigmatism, field curvature and lateral color dominate over field of view, but level of overall aberrational performance in visible range in terms of RMS polychromatic spot size lies between Ritchey-Chretien and Dall-Kirkham without field correctors and with same focal ratio and secondary magnification ratio. Anyway, none of these systems has reasonable FOV for CCD imaging, given consideration of compact telescopes with fast primary mirrors and high magnification ratios, so some type of field corrector is required for all of them. A number of field correctors for Klevtsov telescope is presented, with near-neutral and focal-converting designs. Overall combination of investigated basic variants and correctors forms perspective multi-focal all-spherical optical telescope, highly suitable for large-volume production, combining low cost, short optical tubes, moderate secondary mirror obscuration and decent field for both high-quality visual observations and CCD imaging.

8550-23, Session 6

Dynamic aberration correction for an optical see-through head-mounted display

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This paper deals with a dynamic aberration correction that can be applied in devices where a virtual image is displayed. As an example, we have considered an optical see-through head-mounted display, composed of one static diffractive optical element (DOE) and one dynamic DOE. These DOEs are used to construct a nine points virtual image in a sequential way over a 10°x15° field of view. A nematic liquid crystal display SLM (Spatial Light Modulator) has been used to perform the dynamic setup. A monochromatic light wave with $\lambda 0 = 514.5$nm is considered for the recording of the static element as well as for its reconstruction. The incidence angle of the recording reference plane is 50°. The source point S of the recording object wave is one meter in front of the static hologram with an incidence angle of 25°. The angle between the normal of the static element and the normal of the dynamic element is 50°. Their centers are separated by a distance of 50 mm. The image used for simulation is a 3x3 matrix centered in point S. The eight other points are located at peripheral positions of the 10°x15° field of view. The corrective phase transfer functions of the dynamic DOE for the nine points of the image have been calculated using ray tracing; their analytical forms have been obtained by applying a 3rd order polynomial interpolation. Modulation transfer functions (MTF) with and without aberration compensation have been calculated using CodeV® software. Then an experimental setup using a phase hologram recorded in dichromated gelatin as static DOE, a Holoeye LC2002 SLM as dynamic DOE and an Image-Optic HASO3 as Shack-Hartmann wavefront sensor has been realized. The experimental results for the peripheral image points are presented and show the performed correction on the point spread function and the MTFs. These results are closed to the limit of diffraction whatever the position of the image points into the whole 10°x15° field of view.

8550-24, Session 6

Blue glass lens elements used as IR cut filter in a camera design and the impact of inner quality onto lens performance

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Every digital camera has an IR cut filter to ensure good color rendition and image quality. The trend to backside illuminated CMOS chips enable higher “light gathering” especially under higher angles (field of view). Thanks to virtually angle-independent filter characteristics of blue glass onto absorption, these filter glasses are more and more used. Pure interference filters have a high angle dependency of transmittance and, in addition, reflect the IR light which can cause ghost images. Therefore an IR cut filter made out of blue glass will be analyzed, in a standard plano-plano configuration in front of the image sensor, and as a blue glass lens where the lens takes over the IR cut filter function and a imaging (refractive) function.

A typical design of a smart phone camera will be presented which is based on patent literature. This lens design will be used to analyze the quality of a blue glass absorption filter. The used blue glass is SCHOTT’s BG60 which has high climatic resistance and is produced in highest quality. BG60 blue glass will be examined with respect to inner quality as plano-plano filter plate in front of the image sensor. In a further step the plano-plano filter will be substituted by a BG60 lens. The blue glass lens will be designed and analyzed. It turns out, the blue glass lens can take over the function of a crown glass in an achromate of the design. Typically the Abbe number of BG60 is vd = 62 which clearly shows its crown glass characteristics. The required filter curve (transmittance curve) of the lens will be elaborated and needs to be adapted to take over the correct IR cut filter function. Surprisingly this is very easy to achieve. Such a blue glass lens can shrink down the size of a digital camera.

The BG60 lens needs to have a certain inner glass quality, e.g. high homogeneity combined with low striae contents. Striae inside a glass cause a wavefront distortion and thus the effects of wavefront distortion due to inner glass quality will be investigated. As a result striae of blue glass used as a lens and as a plano-plano filter plate in front of the image sensor needs to be at a certain level. The blue glass lens as an imaging optical component has tighter restrictions on striae than the plano-plano filter in front of the image sensor. For both cases a recommendation of inner glass quality level in terms of wavefront distortion for a blue glass like SCHOTT’s BG60 will be given.

8550-25, Session 6

Development of a nano-profiler using the follow-up normal vector of the surface for next-generation ultraprecise mirrors

Koji Usuki, Osaka Univ. (Japan)

Ultraprecise aspherical mirrors which offer nano-focusing and high coherence are indispensable for developing third-generation synchrotron radiation and X-ray free electron laser (XFEL) sources. In industry, the extreme ultraviolet (wavelength: 13.5 nm) lithography used for high-accuracy asymmetric mirrors is a promising technology for fabricating semiconductor devices. In addition, ultraprecise mirrors with a radius of curvature of less than 10 mm are needed in many digital video instruments. We have developed a new type of nano-profiler by tracing the normal vector of the mirror surface. The principle of our measuring method is that the normal vector at each point on the surface is determined by making the incident light beam on the mirror surface and the reflected beam at that point coincident, using two sets of two pairs of goniometers and one straight stage. From the acquired normal vectors and their coordinates, the three-dimensional shape is calculated by a reconstruction algorithm. The characteristics of the measuring method are as follows. The profiler is based on the straightness of laser light without using a reference surface. Any shape of surface can be measured, and there is no limit on aperture size. We calibrated this nano-profiler by considering the system error resulting from assembly error, and evaluated the performance of the nanometer. We suppressed the influence of the random error by keeping the temperature in a constant temperature room within ±0.01ºC. We measured a concave spherical mirror with a radius of curvature of 400 mm, a flat mirror and aspherical mirror, and compared the results for the concave spherical mirror and flat mirror with those using a ZYGO interferometer. The profiles of both mirrors were consistent within the range of error.

8550-26, Session 6

High numerical aperture silicon collimating lens for mid-infrared quantum cascade lasers manufactured using wafer-level techniques

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We present the design, the fabrication, and the performance of an aspheric collimating lens for mid-infrared (4-14 µm) quantum cascade lasers. The lenses were etched into silicon wafer by an inductively coupled plasma reactive ion etching (ICP-RIE) system on wafer level. Quantum cascade lasers are the light sources of choice for mid-infrared sensing applications. Future developments will require cost effective systems including collimating lenses. Silicon is a well suited material for the realisation of mid-infrared optical elements. Its optomechanical properties being well known and its high refractive index of 3.4 enabling simple elements with high numerical aperture.

A typical quantum cascade laser emits a beam with a semi-angle divergence of up to 60°, corresponding to a numerical aperture of 0.86 in air. The collimating lens is limited by our current fabrication processes to a maximum diameter of 2.0 mm and a maximum apex height of 0.2 mm. We aimed at a beam divergence of 3 mrad for

wavelengths between 4 and 8 µm. For longer wavelengths, the beam divergence is limited by diffraction.

The designed lens is a plano-convex asphere. The high refractive index of silicon helps limiting the surface apex height. While spherical aberration is minimised using both a thick substrate and an aspheric surface profile. The designed lens has a thickness of 3.0 mm, a radius of curvature of 2.45 mm, and a conical constant of -1.74. Its maximum apex height is 0.198 mm and its working distance is 0.15 mm. The optical aberrations are well controlled up to an angle of about 55° or a numerical aperture of 0.82.

1050 lenses were fabricated in parallel on a 200 mm wafer. The curved surface was obtained by ICP-RIE and the substrate thickness was obtained by wafer bonding. An anti-reflection layer made of ZnSe was evaporated on the lenses. Each lens is carried on a chip of 2.2x3.2 mm2. The measured surface roughness is below 50 nm RMS and the surface profile is within 2% of the designed profile. The profile of a collimated beam with a wavelength of 4.64 µm was measured at a distance of 90 cm. From which, the beam semi-angle divergence measured at 13.5% of the maximum intensity was obtained. It is of 3 mrad for the slow axis and of 4.5 mrad for the fast axis.

In conclusion, we present a collimating lens design for mid-infrared lasers suited for mass production. For a laser, beam divergences of 3 mrad and 4.5 mrad were measured. These values are close to the design target. To date, this is the smallest and the most cost effective collimating lens for the mid-infrared range owing to its material properties and to the wafer-level fabrication processes.

8550-27, Session 6

Alignment of phase-shifting interferograms in the two-beam point diffraction interferometer

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Extending technical possibilities of optical fabrication and testing is incredible for efficient design of advanced optical systems. Requirements to the accuracy of optical elements fabrication now approach physical limits being increasingly difficult to fulfill. For interferometric testing of polished surfaces and wavefronts with the best physically accessible accuracy it is good to use a perfect wavefront reference originating from light diffraction by a pinhole aperture in a point-diffraction interferometer (PDI). However the accuracy of the PDI being nominally defined by its inherent reference might fall down due to errors of phase-shifting mode (PSM) which is a basic procedure of wavefront retrieval.

It is evident that phase shifts in the PDI should be fulfilled adequately to perfectness of the reference wavefront unless the PDI will not justify its expected performance.

The goal of the research presented in this paper is to provide a very high stability and accuracy of phase shifts of the reference beam of the two-beam PDI so that PSM measurements would keep the highest possible level of repeatability and accuracy.

The two-beam scheme of the PDI allows handling of phase shifts of both wavefronts - working and reference ones - independently. However this great advantage may be reduced to zero by the influence of phase-shifting mechanism errors rather than instability of the surroundings. It is difficult but principally feasible to diminish the influence of vibrations, temperature gradients etc. to an admissible level, but providing phase shifts accuracy 0.00003 of testing wavelength or about 0.02 nm may look unreal. However such accuracy of PSM is achieved during this research.

The influence of all errors of phase shifts on testing surface or wavefront profiles is being excluded by a two staged alignment procedure being performed on-line when PSM fringe patterns (frames) are being saved. The results of wavefront retrieving from the saved set of PSM frames using any N bucket algorithm by the Durango software in both cases - not aligned PSM and aligned PSM - are analyzed and compared.

The repeatability of PSM measurements by the two-beam PDI is evaluated by the wavefront pixel-by-pixel root mean square (RMS) error without smoothing and fitting procedures.

This research helps keep the PDI accuracy at a level of perfectness of wavefront diffraction reference. Also this research may help in organizing convenient and confident certification procedures for transmission spheres of traditional interferometers and certification of compensators used in convex and aspheric optics testing.

8550-53, Poster Session

Co/Mo2C mirror as studied by x-ray fluorescence and photoelectron spectroscopies induced by x-ray standing wave

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We study a periodic Co/Mo2C multilayer prepared by magnetron sputtering. The period is of the order of 4nm and the sample is designed to work around 778eV, i.e. close to the Co 2p3/2 threshold, at a glancing angle of 11°. In this condition, strong x-ray standing waves develop in the sample. In order to probe different places within the stack, particularly the interfaces, the glancing angle is moving along the first Bragg peak. Meanwhile, the B 1s, C 1s, Mo 3d or O 1s photoelectron spectra, the Co Lα x-ray spectrum as well as the drain current of the sample are measured. Boron is present in the 3.5nm B4C capping layer and oxygen is from surface contamination. The photoelectrons bring information from the superficial zone, i.e. the 5 first nm, while the characteristic x-rays probe the whole stack. Clear modulations of the intensity of the studied signals as well as core level shifts are observed when going through the Bragg peak. In order to understand what happens in the multilayer calculations of depth distributions of the electric field and the energy loss by the radiation are made with the IMD and OPAL codes, respectively. Further calculations based on the density of modes allow us interpreting the experimental results. The combination of experimental results and theoretical simulations enable us to determine from which place originate the various signals and to know if some interaction exists between the Co and Mo2C layers.

8550-54, Poster Session

XRC-PhOBOS: software for optimization of the multi-blade MARS-XRD collimator, an update

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Mars-XRD is an X-ray diffractometer developed for the in situ mineralogical analysis of the Martian soil. The main components of the Mars-XRD experiment are: a 55 Fe radioactive source, a collimator and a CCD-based detector system. XRC-PhOBOS is a software conceived to optimize the collimating system in order to increase spectral resolution and reduce the signal to noise ratio. The choice of the system has been driven out by the following parameters: robustness, versatility, simpleness, efficiency and not less important, costs. After a preliminary study,2 the Mars-XRD team decided to examine in detail a collimating system based on absorbing multi-leaf apparatus. Complementary software based on Montecarlo algorithm have been developed3, 4 from colleagues involved in the project. Those programs analyse the performances of the complete diffractometer system but only one apparatus at time. In fact this useful and sophisticate tools are devoted to analyse one single configuration at time or if more configuration are under evaluation, specific macros should be written in order to run several simulation. The advantage to use a ray-tracing software is the high quality output; a big disadvantage is that a comparison of billion of configuration will probably require months. On the contrary, the author wrote a software able to find a solution instead to simulate it. The optimized collimating system is obtained analysing

all the possible configurations that gives the strongest beam flux that meet the scientific and mechanical requirement of the Mars-XRD project.

To accomplish this task a geometrical computational method instead of a Montecarlo ray tracing algorithm has been implemented. The software compares billion of configurations giving the position of the blades of a converging Soller slits with an expected flux twice higher compared with a commercial converging multiblade system.

8550-55, Poster Session

Design of an optical position detection unit for fast 2D-MOEMS scanners

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Resonantly driven oscillating MOEMS (micro-opto-elctro-mechanical systems) have many applications in the fields of optics, telecom¬munications and spectroscopy. Such scanner mirrors are developed at the Fraunhofer IPMS and they are driven electrostatically with a pulsed driving voltage close to the double of their eigenfrequency.

One of the important challenges in this context is to find a way for providing position feedback in order to assure stable resonant oscillation with well controlled amplitude under varying environmental conditions. Recently, we have developed compact modules comprising optical position sensing, and driver electronics, with closed loop control, which can measure the trajectory of resonantly driven 2D-micro-scanner mirrors. In this contribution we present in much detail the optical design of the position sensing unit and highlight various critical aspects.

Basically position encoding is obtained using trigger signals generated when a fast photodiode is hit by a laser beam reflected from the backside of the mirror. This approach was successfully implemented for 1D scanner mirrors in the past and, for fast scanner mirrors can provide higher accuracies compared to other approaches. We demonstrate that this approach can be extended to the case of 2D-mirrors, which adds significant complexity. In our device the backside of the mirror is hit by two crossed orthogonal laser beams, whose reflections pass cylindrical mirrors in order to suppress the orthogonal dimension. Mirror deflection around one axis is compensated at the plane of the detection diodes while deflection around the other axis leads to a horizontal displacement of the beam. This reduces the problem to the control of a single 1D-oscillation and allows accurate position sensing and closed loop control for this axis.

The optical design of the unit has to provide the optimal compromise between the requirements for small size and simplicity on the one hand and optical accuracy on the other. Also straight light suppression in this compact unit is a critical issue, which had to be dealt with. In our optical simulations we could show, that simple cylindrical mirrors can be sufficient for the deflection angles under consideration (up to 15° mechanical amplitude) even though mirrors with an elliptical cross section could provide better deflection compensation and more accurate results.

Finally exact compensation of the deflection of one axis is only provided at zero deflection of the other, because of the projection of the beam onto a planar surface. This results in a small variation of the timing of the photodiode as a function of the deflection around the orthogonal axis. It could be compensated by placing the diodes on a curved surface, which, however, was not realizable in our small module, where we have to keep complexity at an acceptable level.

Our device, has a size of only two cm3 and phase stability better than 1/10.000 has been achieved, based on our optical system design.

8550-56, Poster Session

Optimizing an active extreme asphere based optical system

Tibor Agocs, ASTRON (Netherlands)

We present methods that can be used to design and operate optical systems with actively controlled components. We investigate a system based on an extreme asphere; the surface shape of the mirror can be controlled via actuators. Based on singular value decomposition (SVD) and regularization of the sensitivity matrix, the degrees of freedom (DOF) of the active surface can be analysed. We use phase diversity (PD) as a wavefront retrieval process, to measure the performance metric and determine the sensitivity matrix. We intend to find the correlation between the performance metric of the system and the DOF of the active component. We study different optimization methods to control the surface of the active component, simulate random wavefronts and model the control process in the presence of noise. We explore the parameter space and acquire knowledge on convergence.

8550-57, Poster Session

MarcoPolo-R narrow angle camera: three-mirror anastigmat design proposal with a smart finite conjugates refocusing optical system

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MarcoPolo-R is a medium-class space mission proposed for the 2015-2025 ESA Cosmic Vision Program with primary goal to return to Earth an unaltered sample from a primitive near-Earth asteroid (NEA). Among the proposed instruments on board, its narrow-angle camera (NAC) should be able to image the candidate object with spatial resolution of 3 mm per pixel at 200 m from its surface. Here we present a three-mirror-anastigmat (TMA) common-axis optical design providing high-quality imaging performances by selecting as entrance pupil the system aperture stop and exploiting the motion of a single mirror inside the instrument to allow the wide image refocusing requested, from infinity up to 200 m above the NEA surface. Such proposal matches with the NAC technical specifications and can be easily implemented with present day technology.

8550-58, Poster Session

Effective speckle noise reduction of laser projection displays by high frequency driving current superposition for blue, red and direct green emission laser diodes

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The laser scanning projectors by micro-electro-mechanical-systems (MEMS) using laser diodes (LD's) havebeen developed in recent years owing to reduction in size and weight as well as high power efficiency. However, when generating 2D images by scanning the laser beams with their coherence as it is, granular image defect called speckle noise is caused by the coherent light beam interferences. For the purpose of applications to scanning projector, some approaches of speckle noise reduction for blue and red LD sources, such as expanding their spectrum width by superposing high frequency driving current have been proposed. As for green laser sources, typically LD-pumped solid-state lasers, since the high frequency current superposition is not valid, to degrade the coherence of 500nm band LD-pumped solid-state green laser by some different means has been considered significant so far. Meanwhile, direct green laser emission devices without light conversion appeared commercially available in the last couple of years. In this work, we have achieved for the first time an effective speckle noise reduction simply by means of just high frequency LD driving current superposition for an ultla compact MEMS based high resolution scanning beam RGB-laser projectors including the direct green emission LD. In the experiments, we have carried out quantitative evaluations of the speckle noise by overlaying the projected images using a CCD camera with histogram based estimation of speckle noise intensities. Moreover, we have examined

the reduction of granular images seen by humane eyes in higher ratios in color stereo image pairs using double-stimulus continuous-quality scale (DSCQS) method. As a consequence, the noise reduction rate of 53.5% for the red laser diode, 80.1% for the green laser diode, and 50.3% for the blue laser diode was attained with histogram based estimation, and the image quality was also enhanced by speckle noise reduction with all RGB LD's using DSCQS method. Moreover, we have also investigated the noise reduction mechanisms in these RGB LD's in relation with the relaxation oscillation frequencies from viewpoint of chaotic multi-mode oscillations with existence of optical feedback.

8550-59, Poster Session

Optical relay design for an IR imaging diagnostic system in TJ-II fusion reactor

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The surroundings of a nuclear fusion reactor experiments the presence of magnetic fields, which affects the performance of any electronic device located nearby. Specifically, the TJ-II fusion reactor, located in CIEMAT (Madrid), is a stellerator type which confines the plasma by the generation of magnetic fields with both toroidal and poloidal components. The amount of these magnetic fields and the exact location of the magnetic poloidal and toroidal lines affect the performance of the optical diagnostics, being necessary to determine with precision the optimum location and to design robust optical imaging systems.

Regarding the first task, an experiment has being carried out by measuring the temperature error on the IR sensor. In this case, the system was imaging a constant temperature point in different locations, predicted by the magnetic field vs axial distance calculations. The different positions gave temperature differences between 10ºC and 1ºC, therefore, the position chosen was the one to give lower temperature error. This place is not directly aligned with the sight of the viewport, therefore it was necessary to design an optical relay system to transport the image from inside the vacuum chamber to the IR sensor.

The purpose of this optical diagnostic is to measure the temperature dispersion in the vicinity of the NBI (neutral beam injectors) that heat the confined plasma inside the reactor. The measure is made by processing the information contained in the images of the objects inside the chamber in the 7 to 16 um far infrared wavelength range, through a F2Ba vacuum viewport window. Our main concern is to design the optical relay from this viewport to the IR sensor, a FPA uncooled microbolometer 320x240px, for different axial distances, with a field of view of 24ºx18º and 1.3 mrad of IFOV spatial resolution.

The proposed optical relay system includes the use of a reflexive relay (aspheric concave off axis and plane mirrors) and one refractive and imaging relay, all working in the 7-16um wavelength range. The system has being corrected for primary aberrations and optimized to allow a future second optical system working in visible range after the mirrors, by including a dichroic beamsplitter.

8550-60, Poster Session

Design of computer-generated holograms used for testing aspheric mirrors

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Aspheric mirrors are often tested by using computer generated holograms (CGHs). In addition to fabrication errors of CGH, adjustment errors of testing system can seriously affect the precision of aspheric surfaces testing. In order to eliminate adjustment errors of CGH and the tested aspheric, a CGH is designed including three sections: main section for compensating wavefront in null test, alignment section for adjusting the relative position between CGH and interferometer, fiducial section for adjusting the relative position between CGH and the tested aspheric surface. What is more, this paper compares the accuracy of the common alignment method and the alignment method by using CGH patterns. Then an example designed for measurement of aspheric mirror is presented. At last simulation results of all kinds of errors in the aspheric testing system are analyzed, which shows that the designed CGH meets the requirements of high precision aspheric surfaces testing.

8550-61, Poster Session

The wavefront aberrations in off-axis spherical mirror with object point or image point

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In the current retinal imaging systems, laser cavities or astronomical spectroscopes, there is the need to employ off-axis reflective systems. These systems often used different configuration where the object or image could be at finite distances or at infinity with respect to the spherical mirrors. In this work, expressions for the wavefront aberrations in an off-axis spherical mirror with image point or object point from different cases are presented, analyzed and evaluated. Assuming a relatively small pupil and a small angle of incidence, these formulas are derived from the optical path difference between a reference surface (paraboloid, ellipsoid or hyperboloid), and a sphere. They can be used to design and analyze some off-axis reflective systems.

8550-62, Poster Session

Optical device for precision Moiré topography of micro surfaces

Saïd Meguellati, Smaïl Djabi, Univ. Ferhat Abbas de Sétif (Algeria)

The reduction of systems size, for a specific use, has become a necessity to the economy of matter, energy and volume, and consequently, the miniaturization of components is required. Quality control of these micro components requires adapted and increasingly powerful techniques of control. The accuracy of components geometry is the parameter which influences the 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, contact less 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 or absolute forms in comparison with a reference component form, of optical or mechanical components, on surfaces that are of the order of mm2 and more. The principle of the method is to project the image of the source grating on the 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 the reference grating to detect defects.

The optical device used allows the magnification dimensional surface up to 1000 times the surface inspected, 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 constraints on functional parts and the influence of these variations on the function. 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 method of control and measurement allows real time control; speed control and the detection resolution may vary depending on the importance of defects to be measured.

8550-63, Poster Session

Flux optimization and construction of a multi-blade collimator

Carlo Pelliciari, International Research School of Planetary Sciences (Italy)

Soller slit or equivalent collimating systems are devices usually used in preliminary experiments or application that require robust instrumentation.

They have accessible prices and are easy to use.

Soller slit are composed of several tens of blades parallel or tilted each other.

The distances between the blades is kept by appropriates space bars or gluing the blades to the container.

Thickness and glue can be not really indicated for special application as vacuum or space in which purity, weight and occupied volume are important.

Also, the blades alignment acts directly on the spot image and for this reason, it should be necessary to find a simple and economic method to build the collimator.

In this paper we describe XRC-PhOBOS, a software that for a given source and setup gives number, position and tilt of the blades in the soller like system.

Moreover we illustrate the design of the blades holder and the prototype built with classical lathe without making use of glue or space bar.

8550-64, Poster Session

Simulation of cylindrical interferometric testing with position error of engine cylinder

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The surface microstructure of engine cylinders is critical to engine performance. To reduce wear and generated noise, a sub-micron and even nanometer smooth surface is required, this set more requirements for traditional measurement. While interferometric optical profilers are often used for the testing of surface microstructure and this technique is both noncontract and nondestructive, we set up a cylindrical interferometric measurement system to get the surface shape of engine cylinder wall. This system includes the interferometer; the cylindrical wave converter (cylinder lens) and the five-dimensional precision adjust the platform. Considering the real experiment condition, the location of the converter and the measured object are not possible just in the optical axis, the aberration of cylindrical lens is their inability to measure the surface profile of the tested object with departure from a best-fit reference cylinder. In this paper we set up a model to simulate the interferogram when the axis of measured object is departure off the cylindrical focus line. As the actual experiment environment, there are five situations about the position error of measured object. To derive the exit pupil wave surface formula by the physical optics for each case. Under the condition of measurement center is tiny departure from the measured object, the function of the wave surface can be simplified. Then we can get interferogram. Compared with the simulation result of this system by Zemax, the built model is consistent the simulation result by Zemax software.

8550-66, Poster Session

Realization of low-losses mirrors with sub-nanometer flatness for future gravitational wave detectors

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The second generation of gravitational wave detectors aims at improving by an order of magnitude their sensitivity with respect to the present ones (LIGO and VIRGO). These detectors are based on long-baseline Michelson interferometers with high finesse Fabry-Perot cavity in the arms and have strong requirements on the optics. These large low-losses mirrors (340 mm in diameter, 200 mm thick) must have a near perfect flatness. The coating process shall not change the substrate sagitta by more than 8 nm and not add surface figure Zernike terms higher than second order with amplitude >0.5 nm over the central 160 mm diameter. The limits for absorption and scattering losses are respectively 0.5 and 5 ppm. For each optic the maximum loss budget due to the surface figure error should be smaller than 20 ppm. Moreover the transmission matching between the two inputs mirrors must be better than 99%.

We describe the different configurations that were explored in order to respect all these requirements. Coatings are done using IBS.

In a first test two mirrors were coated in the same batch. They were positioned on a diameter around the axis of rotation. By means of masks optimized for each materials (Silica and Titanium doped Tantalum pentoxide) a coating thickness uniformity of 0.2% rms for both materials was achieved. The measured absorption (0.3 ppm) and scattering (5 ppm) were both in the specifications. This configuration allows obtaining the reflectivity matching and the sagitta specifications but not the surface figure (Z > 2.1 nm). The simulated losses due to the surface figure are 105 ppm.

In a second test just a single mirror is coated. In this configuration without mask the center of the substrate corresponds with the axis of rotation. By optimization of the geometry of the chamber we have obtained uniformity around 0.2% on 160 mm diameter for both materials. Two inputs optics (T=1.4 %) have been coated in successive batches. As for the absorption and scattering losses the transmission matching and the wavefront figure are in the specifications. The surface figure losses are simulated to be around 20 ppm.

However for the Fabry-Perot end mirrors (T=5 ppm) which have thicker coatings (5 µm) the uniformity is not sufficient regarding the surface figure constraints.

A planetary motion completed by masking technique has been studied. The simulated wavefront for the input optics predicts 1.13 nm for the PV and 0.178 nm rms and the Zernike terms are below 0.5 nm.

The values for the end optics are respectively 2.5 nm PV and 0.3 nm rms. With these simulated values the loss budget is below 20 ppm, better than the requirements.

The planetary system is actually under implementation in the coating chamber.

8550-67, Poster Session

X-ray focusing lens obtained by coupling flat FCC crystals in transmission configuration

Carlo Pelliciari, International Research School of Planetary Sciences (Italy)

Usually, X-ray beams generated with low cost and small equipments (i.e. classical X-ray tube) have a quite large angular divergence. In order to reduce this divergence collimator systems, monochromating crystals and X-ray lenses are used, depending on the available budget and the scientific or commercial application.

In this paper we propose a X-ray lens for low and intermediate energy range (from few kev up to 150 keV) making use of flat crystal properly tilted.

A single FCC crystal can focus in one direction thanks to the internal planes that diffract all different beam energies in the same points.

Every crystal is used in Laue configuration, i.e. the beam passes hit the crystal on one face and come out from the opposite side. The minimal system is given by a couple of crystals tilted each other as like two cylindrical optical lenses.

The lens is assembled with tens of pair of crystals.

The efficiency of the system is half of the system based on the single crystal, and the mechanical alignment is complex, but the advantage is that it is possible to use a crystal as it is (they are cut in small pieces of about 10 mm per side) without applying any mechanical deformation, temperature gradient on it or doping inclusion.

8550-68, Poster Session

New adaptive optics concepts for future ELT instrumentation

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The developement of new instrumentations for the future E-ELT (European Extremely Large Telescope) will require new developments in adaptive optics in terms of simulation (end-to-end simulator for an ELT), optimisation of command laws (traditional Kalman filter methods will show limitations because of the power of necessary calculation, multi-stages correction) and experimental validation of new Wavefront concepts.

In order to address these key aspects, a new multi-purpose experimental AO bench is developed at LAM. It is based on the use of a Shack-Hartmann WFS in front of a 140 actuators micro-deformable mirror (Boston), dedicated to "low orders" modes, while a Pyramid wavefront sensor (PWFS) will be combined to a Liquid Crystal Spatial Light Modulator for "high orders" correction. Both systems could be merged in a two stages AO concept allowing us to study the coupling of a telescope pre-correction with a dedicated large M4 deformable mirror and a post focal high order AO system. Analysis and optimisation of the spatial and temporal split of the AO correction between the two systems is therefore essential.

Finally, we will use the world's fastest and most sensitive camera system OCAM2 (developed at LAM) with the pyramid concept (proposed by R. Ragazzoni), to demonstrate a homemade fast and hyper-sensitive PWFS (up to 100x100 sub-apertures) dedicated to the first generation instruments for ELTs.

All these studies are led in collaboration with ONERA and L2TI.

8550-69, Poster Session

The detection of the interaction of protein and cell by a laser scanning confocal imaging-surface plasmon resonance system

Hongyan Zhang, Technical Institute of Physics and Chemistry (China)

Monitoring the dynamics of protein-protein interactions in their natural environment is a challenge but a precondition for further cellomics research. Especially the interactions of protein and living cell happening at the local sits of the surface of the cell is still a sharp challenge for the biological research, as a living cell is fundamentally different from an in vitro solution which is a traditional and widely used biochemical study vector. There are many electrical and optical methods that provide measurement of protein-living cell interaction, such as electrical impedance, scanning electrochemistry, and fluorescence resonance energy transfer (FRET). But it is still an urgent need for stable, real-time and label-free tools which can provide more information both qualitatively and quantitatively. Benefiting from the high sensitivity to small changes in refractive index occurring on the surface of metal film, SPR becomes one of the most promising candidates among optical detection methods for living cell sensing for real-time quality detection, and they are widely used in molecular interaction analysis. However, the results of the SPR are the average effect of the testing region. Distinguishing the non- specific and specific interaction processes localized in situ related to the SPR signals is still a lack of study in experiments. A laser scanning confocal imaging-surface plasmon resonance (LSCI-SPR) system has been developed by integrating a LSCM with a SPR by combining the virtues of the two techniques to monitor the process of antibody-antigen interaction in real-time and in situ successfully.

In present study, the interactions of mouse IgG and living L5178Y murine lymphoblastic cell labeled with FITC (fluorescein isothiocyanate, FITC) are investigated by LSCI-SPR. When the living L5178Y murine lymphoblastic cell flows over the SPR chip surface modified by mouse IgG, a significant difference in the binding amount could be observed from the confocal fluorescence images. Quantitative results were obtained by following SPR cure with different concentration cells and mouse IgG, respectively. The non- specific interaction between L5178Y cell and Mouse anti-Staphyloccocus aureus Monoclonal Antibody is obviously described by the fluorescence imagine and the SPR signal in real-time. The results demonstrate LSCI-SPR is capable of real-time detection of molecular interactions and cellular responses on living cells, and suggest that further studies on the mechanism and the technique may allow LSCI-SPR become a powerful tool not only for the basic research of cell biology, but also for medical diagnosis and drug development.

8550-70, Poster Session

EchMod: a MATLAB toolbox for modeling astronomical echelle spectrographs

Stuart I. Barnes, Stuart Barnes Optical Design (New Zealand)

EchMod is a MATLAB toolbox for the simulation and modeling of astronomical echelle spectrographs. It is designed to allow the rapid calculation of the properties of the most common forms of echelle spectrographs. Construction of synthetic 2D images and output as FITS is possible. User input spectra may be combined with end-to-end efficiency models and signal-to-noise assumptions to create realistic synthetic spectra. EchMod also allows for an interface to and from Zemax which makes the toolbox for the optical design of echelle spectrographs. However, the Zemax image quality information can also be used to improve the realism of the 2D synthetic images. Such images could be used, for example, during the design and construction of the instrument, or while testing reduction software.

8550-71, Poster Session

Investigation of the x-ray reflectivity of the Co/Mo2C system upon thermal treatment

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The multilayer systems are used as optical components in the x-ray and extreme UV spectral ranges for applications such as spatial telescopes, X-rays microscopes, EUV photolithography or synchrotron beamlines. Among them, the Co-based multilayers have been shown promising. Indeed, Co is a valuable material since it can shape up clear interface with a number of common materials. Moreover, its promising optical performance has been confirmed with the Co/Mg system whose reflectivity is more than 50% at 25 nm under 45° grazing angle. Most multilayer systems cannot attain the reflectivity and resolution requirements assumed by theory because of interdiffusion and roughness. Therefore, it is necessary to find out the excellent material possessing optical application in the EUV and soft x-ray range and propose solution to eliminate the interface imperfections or find out new efficient combinations. Here we propose a new system, namely the periodic Co/Mo2C multilayer. The multilayer system are prepared by the magnetron sputtering and characterized by x-ray reflectivity at 8048 eV (Cu Kα emission) and with synchrotron radiation in the soft x-ray range at 778 eV. The measurements are used in order to determine the structural parameters (thickness, roughness and density) of the layers The simulated reflectivity at 11° grazing angle with s-polarized is calculated to be 45% at 778 eV, if there is no interaction between the layers and no interfacial roughness, while experimentally reflectivity is limited to 25%. The relationship between the reflectivity and annealing up to a temperature of 600°C is also investigated. This shows that the Co/Mo2C multilayer is stable up to 600°C. First the reflectivity increases to 27% at 300°C. After the reflectivity slightly decreases to 25% at 500°C and then we observe a reflectivity drop to 20% at 600°C. Relationship between the structural parameters and the reflectivity values is deduced from the fit of the experimental curves.

8550-72, Poster Session

Preliminary optical design of a polychromator for a Raman LIDAR for atmospheric calibration of the Cherenkov Telescope Array

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The preliminary design of a polychromator for a Raman LIDAR (Light Detection and Ranging) for atmospheric calibration to be used in the framework of the Cherenkov Telescope Array (CTA) observatory is presented. CTA is a project in the preparatory phase for a future generation of Cherenkov telescopes, that will observe cosmic gamma rays of very high energy. For obtaining high quality data from CTA, the atmosphere should be monitored continuously and precisely. In current Cherenkov telescopes, the most important portion of the systematic uncertainty, both for energy and flux reconstruction of the gamma-rays, results from the determination of the atmospheric transmittance. Remote-sensing instruments, like elastic/Raman LIDARs, have already been proven as a powerful tool in environmental studies since the light emitted by the LIDAR laser directly interacts with the atmospheric constituents and thus provides the footprint of atmospheric species at each height in return. Therefore, a LIDAR installed and operated at the CTA site can be used for correction of the systematic biases in reconstructed energy and flux. This LIDAR system consists of a laser that emits light to the atmosphere, a telescope which collects the backscattered light and a polychromator unit where the collected light is analyzed, i.e. the different wavelengths are split and directed to different sensors. The laser is a pulsed Nd:YAG with the first two harmonics available at 532 and 355 nm. The laser backscattered light from the atmosphere is collected by a mirror of 1.8 m diameter and then fed - through a liquid light-guide - to the polychromator module. The polychromator currently foresees 4 read-out channels: two to analyze the elastic-backscatter at 355 and 532 nm and two for the Raman back-scattered light on Nitrogen, at 387 and 607 nm, respectively. The polychromator module has to be able to avoid light losses from the exit of the lightguide, separate the different wavelengths and focalize the beam onto photon detectors. The collimation and focalization of the light is done by means of lens-couples and the separation through custom dichroic mirrors and narrow-band filters. The performance of the conceived optical design, the adopted design choice for the glass, surface figure, size of the lenses and detectors, and the expected throughput of the different channels will be described in detail. Attention has to be given to prevent unwanted light leakage from the elastic channels into the Raman ones, since the elastic lines' intensity is intrinsically two tothree order of magnitude higher than the one of the Raman lines.

8550-73, Poster Session

High speed surface slope measuring profiler for an aspheric shape

Yasuo Higashi, High Energy Accelerator Research Organization (Japan)

A New high speed slope measuring instrument has been developing for a small aperture of an aspheric lens and mirrors. In the present study, the normal vectors at each points on the surface are determined by the reflected light beam goes back exactly on the same path as the incident beam. The capability of the developed instrument to achieve sub-microradian surface slope metrology of a small radius lens and aspheric lens is verified. The design principle, data acquisition system, initial alignment and calibration procedure, the developed shape determination procedure from the measured slope metrology as well as high speed slope measuring technique are also described in detail.

8550-74, Poster Session

Design of hybrid optical tweezers system for automated 3D micro manipulation

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Introduction:

Laser trapping, well-known as optical tweezers, was first demonstrated by Arthur Ashkin in 1970 [1]. This technique has been further extended to multi-beam optical tweezers in last two decades, and has been widely used for micro/nano manipulation without physical contacts in various scientific fields, particularly in biomedical fields such as Lab-on-a-Chip, bio-MEMS/NEMS, microfluidic systems, and so forth. The multi-beam techniques of optical tweezers, such as holography, time-shared scanning, and generalized phase contrast (GPC), allow us to trap and manipulate many micro-objects simultaneously, in contrast to mechanical micro-hands manipulate single object at one time. In our previous paper [2], for the dynamic handling of massive micro-bead arrays, we have developed a hybrid optical tweezers system consisting of two multi-beam techniques: the GPC method using a spatial light modulator (SLM), and the time-shared scanning method using galvano mirrors (GMs). This system provided greater versatility while the GPC method created the trap fields for immobilizing massive arrays, where the beads could be manipulated smoothly and very quickly by the GM scanning method. However, in the previous system, arrays formed by the GM scanning tweezers based on the Time-Shared Synchronized Scanning (T3S) technique could be handled only in two-and-half dimensional (2.5D) working space. This limitation arose from the lower bandwidth of Z-axis manipulation due to the lens translation using the linear stage. Therefore, for true 3D manipulation of multiple beads, an alternative Z-axis manipulation method with higher bandwidth must be required. In this paper, using an electrically focus tunable lens with higher bandwidth, we present a hybrid optical tweezers system for true 3D controlled manipulation of multiple micro-beads.

Developed System and Results:

We re-design the GM scanning part of the previous hybrid system, keeping its design concept and its system features. The optical structure is linked to the commercial available microscope via its epi-fluorescence port. The single laser source is a continuous wave (cw) Nd:YAG laser (1064nm, 700mW), and its laser beam passing through a half-wave plate is split into two beams (p- and s- polarized beams) by a polarized beam splitter (PBS). One set of optical tweezers, based on the GPC method, is composed of a SLM, a phase contrast filter (PCF) and lenses, and uses the p-polarized beam. The other set of optical tweezers based on the GM scanning method, is composed of GMs, a focus tunable lens and two relay lenses, and uses the s-polarized beam. The laser power can be distributed between the two methods in varying proportions with the half-wave plate. The geometric shape of the optical trap fields formed by these tweezers can be controlled independently, since the p- and s-polarized beams do not interfere with each other.

In the results of 3D manipulation experiment, the controlled rotation of five beads forming a pentagon and that of four beads forming a tetrahedron about their arbitrary axis of rotation are demonstrated by 3D-T3S technique, only using the GM scanning part of the hybrid system. In another demonstration, 28 beads are full-automatically assembled to specified 2D pattern (two squares), and then one square is translated along the Z-axis.

Conclusion:

For true 3D micro-manipulation, we have designed and developed the hybrid optical tweezers system consisting of the GPC tweezers and the 3D-T3S tweezers using GMs and a focus tunable lens.

References:

[1] A. Ashikin, Phys. Rev. Lett. 24(4), pp.156-159 (1970).

[2] Y. Tanaka, S. Tsutsui, et al. Opt. Express, 19(16), pp.15445-15451 (2011).

8550-76, Poster Session

A space-based Far Infrared Interferometer (FIRI) instrument simulator and test-bed implementation

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FIRI (Far Infrared Interferometer) is a spatial and spectral interferometer with an operating wavelength range 25-300 µm and a sub-arcsecond angular resolution, and is based in the combination of two well-known techniques, Stellar Interferometry and Fourier Transform Spectroscopy to achieve high spectral and spatial resolution in the Far Infrared. The resulting technique is called Double Fourier Spatio-Spectral Interferometry (Mariotti and Ridgway 1988). With increased spatial and spectral resolution a number of interesting science cases such as the formation and evolution of AGN and the characterization of gas, ice and dust in disks undergoing planetary formation, among others, can be investigated. Here the current status of the design of the FIRI system via an instrument simulator is presented, as well as the results of a test-bed implementation.

8550-28, Session 7

Optical design of power adjustable sphero-cylindrical ophthalmic systems

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Purpose: The need for affordable and sustainable ophthalmic systems for measurement and correction of refraction is well-recognized. Power-adjustable spectacles based on the Alvarez principle have emerged as an innovative technology for this purpose. Our first goal was to design spectacles based on this principle that provide good spherical correction over a wide view field. Our second goal was to design a new sphero-cylindrical refractor. This system comprises two lenses. The sphere and cross cylinders power measurement are realized through three independent lateral movements. Additionally, we present a comprehensive methodology for the optical design of this type of systems.

Methods: Our optical design methodology comprises several stages. In ophthalmic lens design, the major aberrations to consider are oblique astigmatism and mean power errors. We set a merit function where these aberrations were evaluated for different configurations. A system configuration is determined by means of the relative position between the two lenses, setting a desired sphero-cylindrical output.

The lenses have a planar and a third degree polynomial surface. The lenses 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 are described by nine terms. The merit function was optimized following a cascade approach where different surface parameters where optimized at successive steps.

The sphero-cylindrical system is designed to be used as portable refractor. Therefore we only considered the central viewing direction in an extended optical range. The sphere power is adjusted with the lateral movement of one of the lenses, whereas the cross cylinders are changed with two orthogonal lateral movements of the second lens.

We also present a design for spherical refraction correction not only for the central viewing direction but also for many different eccentric gaze directions.

Results: We have designed two systems for sphero-cylindrical refraction measurement. A spherical-cylindrical refractor, capable of measuring sphere powers ranging from -5.00 D to +5.00 D and cross-cylinders from -2.00 D to 2.00 D; and, for comparison purposes, a pure spherical refractor with a ±8.00 D power range.

In both designs the astigmatism and power errors are mostly below 0.1 D in absolute value for all the configurations.

We also demonstrate a design for hypermetropia and presbyopia correction with a power variation from +0.5 D to +5 D.” In this design power error and astigmatism is under 0.2 D for ±20 degrees of range in eye rotations.

Conclusions: Novel ophthalmic systems are presented. One is a sphero-cylindrical refractor based on only two lenses and three independent lateral movements. The refractors designed in this study provide accurate, reliable and portable systems for subjective sphero-cylindrical refraction. The second system is a spectacle providing spherical correction over a wide range of gaze directions and a large range of spherical powers.

8550-29, Session 7

Planar plano-convex microlens in silica using ICP-CVD and DRIE

Eric Markweg, Matthias Hillenbrand, Stefan Sinzinger, Martin Hoffmann, Technische Univ. Ilmenau (Germany)

Introduction: We demonstrate a microlens that can be integrated with photonic elements on the same substrate by utilizing planar technologies such as UV lithography, ICPCVD and Deep reactive ion etching. For reaching an optical 3D functionality with 2 D methods we used a stepwise variation of the refractive index during the layer deposition process for a focus in the vertical direction to the substrate. For the horizontal direction, parallel to the substrate, the shape of perpendiculary etched side walls determines the focus. That procedure allows the independent control of light collimation in the two perpendicular directions with planar technologies.

Technology: The maximum reachable height of the lens structures dependent on the deposition time, but is limited to 30 µm to keep the deposition time acceptable. The smallest featured width of a lens was 2 µm for a Fresnel lens. We used an ICPCVD siliconoxynitride process for the variation in refractive index. To reach the requirements for the device high transmittance especially a low absorption for the used wavelength is needed. That method allows a wide range of possible index progress. In our case a symmetric change of refractive index was deposited in a film of 30 µm by modifying the gas ratio of nitrogen and nitrous oxide, as silicon precursor we used silan. The etch mask was done by UV lithography and electroplated of nickel. A fluorine based ICP RIE deep etching process defined the perpendicular side walls. This technology allows the production of different lens forms. We realized plano-convex, bi convex and Fresnel lenses. The range of refractive index is between n = 1.47-1.85. The function of the refractive index is free selectable.

Design: To demonstrate the potential of the technology we present optical elements for the collimation of fiber-based light sources. The elements are designed using raytracing-based optimization. The refractive index profile perpendicular to the etching direction is modeled using a polynomial series. The refractive surfaces are described by cylindrical, acylindrical and polynomial functions. Diffractive elements can be easily realized as kinoform elements and are characterized by the realized phase function. E.g., we demonstrate a hybrid plano-convex GRIN lens for collimation of a HeNe-beam leaving a NA 0.10 fiber with a core diameter of 4.3µm. With a peak-to-valley wavefront error of 0.03 wavelengths the lens shows diffraction limited performance. The variation of the refractive index was done stepwise with 115 different films with a minimum film thickness of 28 nm per film.

Experimental results: We used a fiber coupled He-Ne laser (& #955; = 633 nm) with a fiber output beam diameter of 4.3 µm. The incident beam was focused and collimated by the produced planar lens system. The focusing pattern was observed with a camera CCD in different distances. The collimated beam shows a symmetric beam profile in both directions. The comparison between simulated beam shape and measured beam at different distances from the surface of the lens demonstrates the possibility of that principle.

8550-30, Session 7

110 years BK7: optical glass type with long tradition and ongoing progress

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The SCHOTT glass catalog of 1902 lists the borosilicate crown glass type BK7 for the first time. Since that time it has grown to a high volume glass with equivalents available from all glass manufacturers

and became so omnipresent, that many people value it as a cheap bulk commodity type not worthwhile to be looked at closer. This might hold for small thin lenses. However, BK7 can be produced from strip glass format over thick blocks up to large disks of more than 1 m diameter and half a meter thickness. Achieving high homogeneity in thicknesses of 50 mm and above is far from trivial and with increasing thickness it is a challenge even for outstanding glass producers. The present state-of-the-art at SCHOTT is represented by a world record refractive index homogeneity of 1•10-6 peak-to-valley in block glass with more than 200 x 200 mm2 and 100 mm thickness measured in all directions top-to-bottom and in lateral directions. The progress in transmittance led to the introduction of a new quality grade N-BK7HT. The transmittance improvement in the blue-violet spectral range leads to noticeably better twilight vision in use with binocular prisms and image stability in cinema digital projection.

8550-31, Session 7

Laser-diode digital holography with frequency-modulated continuous-wave techniques

Yukihiro Ishii, Tokyo Univ. of Science (Japan); Takeshi Takahashi, Ribun Onodera, Polytechnic Univ. (Japan)

Laser-diode (LD) unbalanced interferometry1) has a unique feature that the wavelength shift of an LD introduces temporal carrier beat frequencies, following the frequency-modulated continuous-wave (FMCW) techniques. The beat frequency is proportional to the optical path difference of each pair of interfering beams in an interferometer. Laser-diode digital holography is presented with FMCW techniques. Beat interference signals in holograms are generated by changing widely tuned wavelengths of an external-cavity laser diode (ECLD) without mode hops.

Two 3-D reflecting objects are put in the object arm of an unbalanced interferometer with various OPDs, li, as shown in the figure. The subscript i denoted an index from 1 to N of the total number of 3-D objects. The i-th beat frequencies become b,i=li/(Tc); they are proportional to the OPDs, li of 3-D objects. In the figure, two objects (N-2) with l1 and l2 are used for the experiment. Here the LD is modulated by a sawtooth waveform with a period T, an optical frequency diversity  and a light speed c. The interference signal multiplexed by N objects is not a simple sinusoid that is reduced to a 2-D interference pattern, i.e., a hologram recorded by a CCD. A phase i of an i-th object in a digital hologram can be derived from a Fourier spectrum of a multiplexed hologram, extracted from an i-th beat frequency, b,i/(2). An isolation between two adjacent objects is inversely proportional to a wavelength diversity &# 61508;wide tunability of an ECLD is appropriate for increasing a longitudinal isolation in multiple-object reconstruction. 3-D objects can be reconstructed from numerical Fresnel diffraction calculation of a phase i in a hologram. In the lower right panel of figure, each of two “sheep” objects can be selectively reconstructed from each phase of a twofold multiplexed hologram with no crosstalk. In the experiment, OPDs in two objects are l1=45 mm and l2=135 mm with a wide frequency diversity of & #61481;=6.6 GHz for a wavelength of =634.6 nm in an ECLD light source.

This presentation demonstrates a new heterodyne digital holography with laser-diode frequency-modulated continuous-wave techniques.

Ref. Y. Ishii, “Laser-diode interferometry, in Progress in Optics 46,” ed. E. Wolf, Elsevier, Amsterdam, Chap. 3, pp. 243-309 (2004)

8550-32, Session 8

The design of a multi-point probe for a low-coherence distance measuring interferometer

Christopher T. Cotton, ASE Optics (United States); Damon W. Diehl, Monroe Community College (United States); Christopher J. Ditchman, Nathan Burdick, ASE Optics (United States)

A highly efficient method for splitting the probe beam produced by a scanning low-coherence distance-measuring interferometer (SLCDI) is presented. The SLCDI is used to measure thicknesses of materials with thicknesses in the range of 12 microns-50 mm, with a repeatability of 0.1 microns. The measurements are made optically with a beam with a wavelength of 1.3 microns. The SLCDI is also capable of simultaneous measurement of a stack of multiple films.

Splitting of the beam from the SLCDI probe to create a multi-point probe allows for multiple, simultaneous measurements to be made at a surface. An advantage of this capability is that it provides the ability of measuring the surface normal at each of the surfaces that you are measuring.

The operation of the SLCDI will be described along with how the operation impacts the requirements for the multi-point probe system. The requirements will be discussed from the standpoint of the coherence length of the SLCDI source and the operational usage of the probe. The splitting is achieved through the use of polarization components. The function of the polarization components is described through the use of Jones Matrices. The function and performance of the resulting probe is also discussed.

8550-33, Session 8

MWIR zoom with focal extender

Marta C. de la Fuente, Jose M. Infante Herrero, Luis Rivera, Indra Sistemas, S.A. (Spain)

This paper describes the design of a 3-5microns 26:1 zoom with a focal length extender capability that increases NFOV focal length by 1.75x. Mechanical restrictions for a payload envelope will be considered as well as cold stop efficiency issues.

8550-78, Session 8

Verification of the optical design by simultaneous measurement of centering errors and relative surface distances inside of optical systems

Patrik Langehanenberg, TRIOPTICS GmbH (Germany)

Especially for optical compound systems the precise geometric alignment of every single element according to the optical design is essential to obtain the desired imaging properties. In this contribution we present a technology for the measurement of the complete set of geometric alignment parameters in assembled systems. During the measurement the deviation of each center or curvature with respect to a reference axis is measured. These data are further processed in order to provide the shift and tilt of every single lens or group of lenses with respect to a defined reference axis. The centering errors of up to 40 surfaces within a system under test can be measured with accuracies in the range of an arc second. In addition, the relative distances of the optical surfaces (center thicknesses of lens elements, air spacing in between) are optically determined in the same measurement system by means of low-coherent interferometry.

The measured results can be used for tolerance testing of the sample with respect to the given optical design. In addition, the obtained information can also be applied for the direct compensation of geometrical alignment errors of every single lens in the assembly for the optimized assembly of high-precision optics.

8550-36, Session 9

Skew aberration analysis *(Invited Paper)*

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Skew aberration is an intrinsic rotation of polarization states in optical systems. Skew aberration is a component of polarization aberration but is independent of the incident polarization state or the coatings applied to the optical interface. It arises from purely geometric effects,

due to the parallel transport of vectors. Skew aberration is typically a small effect in optical systems, but it should be of concern in microlithography optics and other polarization-sensitive systems with high numerical aperture and large field of view. Until recently [1], skew aberration had not been diagnosed separately from other polarization aberrations such as diattenuation or retardance in spite of the distinct origin. There is a need to analyze skew aberration in terms of first order optics and conventional image quality metrics such as point spread function (PSF) and optical transfer function (OTF).

Although the computer now makes it easy to trace real rays, the linearity of the paraxial ray trace allows us to provide simple closed form formulas to help understand the first-order properties of radially symmetric optical systems. Using paraxial optics, we demonstrate that the skew aberration is proportional to the Lagrange invariant, and is closely related to the sum of the individual surface powers of the system. The existence of skew aberration in the paraxial regime shows the possibility to further describe skew aberration using a series expansion method, which is one of the directions for the future work.

We demonstrated in ref[1] that for radially symmetric optical systems, skew aberration only occurs for skew rays and has the functional form of a circular retardance tilt, linear variation perpendicular to the meridional plane. At higher numerical apertures and fields, coma-like aberration term occurs next, followed by other higher order forms. The skew aberration and associated variation of polarization state across the exit pupil causes undesired polarization components in the exit pupil. Typically, cross polarized satellites form around the PSF. The PSF and OTF are different from ideal PSF or OTF and thus the image quality can be degraded.

Optical design and ray tracing software calculate the PSF of an optical system to evaluate and analyze wavefront aberration and/or polarization aberration. The PSF calculated from existing software already includes the effects from skew aberration but does not provide analysis on skew aberration alone. In the presence of polarization aberration, the scalar PSF can be generalized to either a two-by-two point spread matrix (PSM) in Jones matrix notation or a four-by-four PSM in Mueller matrix notation. Similarly, an OTF can be generalized to either a two-by-two optical transfer matrix (OTM) or a four-by-four OTM. We demonstrate analysis of skew aberration effects separate from other polarization aberrations by using a four-by-four PSM and OTM of the U.S. patent 2,896,506.

1. G. Yun, K. Crabtree, and R. A. Chipman, “Skew aberration: a form of polarization aberration,” Opt. Lett. 36, 4062-4064 (2011).

8550-37, Session 9

SMS design and aberration theory

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The SMS (Simultaneous Multiple Surfaces) design method was originally born to Non Imaging Optics applications and is now being applied also to Imaging Optics. In an SMS rotational optical system design, isolated point/normal vector couples for several surfaces (up to four) are computed simultaneously imposing the constancy of the optical path length. Starting from this couples point/normal vector a best fit is used to obtain the desired aspherical surfaces. For that purpose, the functional form of the wave aberration function W is obtained thanks to general theoretical considerations. This function W results to depend on two auxiliary functions called A and B, whose arguments will be just by the conventional rotation invariants. Otherwise is proved there are infinite couples of function A and B, and a criterion to choose these functions is given. For a well corrected SMS system, the function A and B are expected to be almost constant, which suggests the possibility to characterize such a well corrected SMS system with a little set of parameters.

With the hypothesis that A and B are analytic and remembering that every analytic function has an unique expansion in Taylor series it is easy to proof that this functional expression is unique and that every other expression could be written in this form.

Moreover, the connection of this model with the “conventional” aberration expansion is presented, and a novel simplification of the usual complex set of restrictions on the summation indexes is introduced. Finally, in order to validate this model, two selected SMS systems have been analyzed and with good results, calculate their associated A and B functions and the corresponding “classical” aberration coefficients.

8550-38, Session 9

Single optical surface imaging designs with unconstrained object to image mapping

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In this work, novel imaging designs with a single optical surface (either refractive or reflective) are presented. In some of these designs, both object and image shapes are given but mapping from object to image is obtained as a result of the design. In other designs, not only the mapping is obtained in the design process, but also the shape of the object is found. In the examples considered, the image is virtual and located at infinity and is seen from known pupil, which can emulate a human eye.

In the first introductory part, 2D designs have been done using three different design methods: an extended SMS design, a compound Cartesian oval surface, and a differential equation method for the limit case of small pupil. At the point-size pupil limit, it is proven that these three methods coincide.

In the second part, previous 2D designs are extended to 3D by rotation and the astigmatism of the image has been studied. As an advanced variation, the differential equation method is used to provide the freedom to control the tangential rays and sagittal rays simultaneously. As a result, designs without astigmatism (at the small pupil limit) on a curved object surface have been obtained. Finally, this anastigmatic differential equation method has been extended to 3D for the general case, in which freeform surfaces are designed.

8550-39, Session 9

Perfect imaging analysis of the spherical geodesic waveguide

Juan Carlos González, Pablo Benítez, Juan Carlos Miñano, Dejan Grabovickic, Univ. Politécnica de Madrid (Spain)

Perfect Imaging (PI) stands for the capacity of an optical system to produce images with details below the classic Abbe diffraction limit. In 2000 Pendry proposed a new device built with material of negative dielectric and magnetic constant (left-handed materials) that reaches the theoretical limit of PI. In the last decade PI has been shown experimentally with devices made of left-handed materials

An alternative device for PI has recently been proposed by Leonhardt: the Maxwell Fish Eye (MFE) lens. Unlike previous PI devices, MFE uses materials with a positive, isotropic refractive index distribution. This device is well known in the framework of Geometrical Optics because it is an Absolute Instrument, so every object point has a stigmatic image point.

Recently, it has been analyzed the PI properties of the Spherical Geodesic Waveguide (SGW) for microwave frequencies. The SGW, a device suggested in is a spherical waveguide filled with a non-magnetic material and isotropic refractive index distribution proportional to 1/r (ε = (r0/r)2 and μ = 1), r being the distance to the center of the spheres. Transformation Optics theory proves that the TE-polarized electric modes of the cylindrical MFE are transformed into radial-polarized modes in the SGW, so both have the same imaging properties. The results show that this device presents up to/500 resolution for a discrete number of frequencies, called notch frequencies, that are close to the well known Schumman Resonance frequencies of spherical systems.

The theoretical result presented by Leonhard and the analysis of the SGW shows a concept of perfect imaging different from the NRL one presented by Pendry:

-In the NRL lens, the radiation emitted by the object plane with tangent electric field E(x,y,z0) (plane x-y in z=z0) is formed by a complete set of plane waves travelling in z direction. The optical system transmits the plane waves to the image surface (the plane xy, z=z1) generating the same field E(x,y,z0)= E(x,y,z1). In particular, if the field in the object plane is for example E(x,y,z0)=d(x,y) (Dirac delta), the field in the image plane is E(x,y,z1)=d(x,y)

-In the theoretical and experimental results for the MFE and SGW, the concept of object and image surface does not exist, since the source and drain are points. The electric field has asymptotic behavior at the point source and drain when they are placed in the focal points. In the case of the SGW, it has been shown that a small displacement of the drain (much smaller than the wavelength) from the focal point has the effect of radical change in the field distribution and a drastic fall in the transmitted power from the source to the drain.

Here, it is presented an analysis of the SGW based on the concept of object and image surface. The object surface is theta=theta0 (equivalent to z=z0 of the NRL) and the image surface is theta1=pi-theta0 (equivalent to z=z1 of the NRL). The analysis shows that the SGW can focus below the Abbe diffraction limit.

8550-41, Session 10

Improved wavefront reconstruction using difference Zernike polynomials for two double-shearing wavefronts

Hai Wang, Yanqiu Li, Ke Liu, Jianfeng Wang, Beijing Institute of Technology (China)

Lateral shearing interferometer (LSI) is an important technique for wavefront sensing. LSI needs no extra reference wavefront because of the wavefront under measurement interferes with its laterally sheared copy. With the advantages of self-referencing interference, good immunity to environmental disturbance and mechanical vibrations, LSI has been developed in many applications. To realize in-line wavefront aberration measurement of high numerical aperture lithography projection optics in deep ultraviolet, we presented a new measuring technology named cross phase grating lateral shearing interferometer (CPGLSI). CPGLSI has the function of continuously adjustable shearing amount. And the cross phase grating (CPG) in CPGLSI with special structure diffracts the incident plane wave into four replicas, which are (+1, +1), (+1,-1), (-1,-1) and (-1, +1) orders diffraction beams. Because of the shearing interference of the above four diffraction beams, then double-shearing wavefronts appear respectively in x and y directions, which are different from the usual single-shearing wavefronts in x and y direction. Wavefront reconstruction is a critical process to obtain measured wavefront in LSI. In the past, many wavefront reconstruction algorithms were investigated and proposed for wavefront reconstruction in LSI. Among these algorithms, Zernike polynomial fitting algorithms with low noise accumulation can be well used in recovering circular-shaped wavefront, in which wavefront reconstruction using difference zernike polynomial algorithms has higher accuracy than the other wavefront reconstruction algorithms using Zernike polynomial fitting. However, studies of the past algorithms were limited in wavefront reconstruction for single-shearing wavefronts in x and y directions, so these algorithms are not suitable for wavefront reconstruction for two double-shearing wavefronts produced by CPGLSI in x and y directions. Consequently, to achieve wavefront reconstruction with high accuracy for the two double-shearing wavefronts in x and y directions, improved wavefront reconstruction using difference zernike polynomials is studied in this paper. Furthermore, when the interferogram produced by the four diffraction beams is processed by Fast Fourier Transform, the actually retrieved x directional whole difference wavefront information is half of the sum of the shearing wavefront of (+1, +1) and (-1, +1) orders diffraction beams and that of (+1, -1) and (-1,-1) orders diffraction beams. Similar case also appears in the y direction. So in the studied algorithm, first, the double-shearing wavefronts in the x direction are represented respectively by the corresponding difference zernike polynomials. Then the whole difference wavefront in x direction is represented by the half value of the sum of the x directional double-shearing wavefronts. Similarly, the whole difference wavefront in y direction is also represented by the half value of the sum of the y directional double-shearing wavefronts. Second, the least square fitting is used to obtain the whole wavefront. Investigations into wavefront reconstruction accuracy and reliability are carried out by numerical experiments, in which influences of different shearing amounts and noises on wavefront reconstruction accuracy are evaluated. The simulation results show that the studied wavefront reconstruction algorithm can reach high accuracy corresponding to different shearing amounts and also validate that our wavefront reconstruction technique is very robust to

noise.

8550-42, Session 10

Double tailoring of freeform surfaces for off-axis aplanatic systems

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Freeform surfaces allow elegant solutions in illumination optics as complex functions of the system can be achieved by a single optical element. As the optical design of freeform surfaces is particularly demanding due to the inherently large number of degrees of freedom, the technique of tailoring optical freeform surfaces (mirrors or lenses) is routinely used in non-imaging optics to efficiently achieve predefined light distributions. This techniques is based on solving the underlying differential equations.

Tailoring can also be employed in for imaging optics: an optical freeform surface can be tailored such that one condition is exactly fulfilled - i.e. spherical aberration at a specific point is corrected. Recently, we extended this method such that two freeform surfaces can be tailored at the same time (double tailoring). This gives the freedom to impose a second condition, which is also exactly fulfilled; thereby, this method allows for instance to simultaneously correct spherical aberration and satisfy additional conditions, i.e. the sine condition.

As an example for a tailored off-axis aplanatic system we show a head-up display (HUD) consisting of two simultaneously tailored freeform mirrors.

8550-43, Session 11

Lightweight stable sandwich mirrors: current achievements in the development

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RUAG Space, together with THALES SESO, initiated the development of light weighted sandwich structures for optical applications, already some years ago. The results of the use of this type of structure applied for optical benches and the first outlook for their use as mirror substrates were published in previous papers. This paper is going to present the results of the polishing activities performed on a 650 mm diameter mirror manufactured with Zerodur face sheets and a high density aluminium core. This substrate showed a mass density of below 16 kg/m2. The excellent optical quality achieved proves the suitability of this technology for several applications, in particular for scanning mirrors for space and possibly for moveable mirror in ground based astronomical telescopes.

With the emerging need for extremely high flatness under thermal loads (radius of curvature > 400km) activities have been initiated to identify materials for the core of the substrate closer matching the extremely low CTE offered by materials like Zerodur. The progresses made in this field are presented and an outlook for future activities is provided.

8550-44, Session 11

Development of a light-weight beryllium cassegrain telescope

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The BepiColombo Laser Altimeter (BELA) is selected to fly on board of the ESA's BepiColombo Mercury Planetary Orbiter (MPO). The instrument will be the first European planetary laser altimeter system. RUAG Space is the industrial prime for the Receiver part of the scientific instrument. The BELA Receiver is a joined effort of Swiss industries under the leading role of RUAG and University of Bern as co-Prime. A core element is the light weighted Receiver Telescope (RTL), to collect the laser pulse reflected from the planet's surface.

An innovative design was required to deal with the very challenging Mercury's environmental conditions and with the very stringent instrument's mass budget. The Opto-thermo-mechanical analyses lead to the design of a 1250mm focal length Cassegrain telescope made of Beryllium. It provides an aperture of 204 mm diameter and a 2 mm thick primary mirror for a total mass of less than 600gr. The manufacturing and the integration needed special developments.

This paper presents the design analyses and the major challenges which had to be solved. Discussing some aspects of the telescope integration and test campaign, the finally achieved performances and lessons learnt will be presented.

8550-45, Session 11

Ultra stable off-axis telescope: lessons learnt from the optical design to the correlation of the test results

Antonio Casciello, Thomas Weigel, Matthias Raunhardt, Andreas P. Herren, Steffen Blum, Nicolas de Roux, Thibault Seure, Ulrich E. Krähenbühl, Martin Herbert, RUAG Space AG (Switzerland)

RUAG developed, manufactured and demonstrated the capability of an afocal Kepler like telescope for space applications. The telescope serves the purpose of an optical communication payload (OCP) for geo-stationary and low-earth orbit satellites, in both transmitting and receiving modes.

The design is made off-axis, such that no central obscuration exists. Optical interfaces are provided by well defined pupil positions towards space (ø = 135 mm) and towards the payload (ø = 12.5 mm). The telescope magnification is $\Gamma = -10.8$, where the negative sign indicates an image inversion. Main characteristics of the optical system are:

- Low WFE (e.g. ≤35nm)
- High transmissivity (>96%)
- High polarisation extinction ratio
- Low stray light (>60dB in the complete FOV)
- Low mass

Stability of optical performances was demonstrated under various environmental conditions including vibrations, shock and thermal-vacuum loads.

These properties enable the use of the telescope in a broad range of applications, not limited to space applications.

The optical layout is composed of four mirrors (Zerodur and Fused Silica) integrated in a nearly zero CTE CFRP structure and it is designed for an operative wavelength of 1064nm.

A detailed characterisation and development of our understanding of the CFRP structure behaviour represented a main achievement. The water absorption of the CFRP in air determines elastic distortions of the telescope structure (until it is saturated). Some optical performances (e.g. defocus) are affected by this phenomenon which has to be taken into account when testing the system in thermal-vacuum environment. These effects were characterised and pre-compensated in the integration phase in order to tune the performances for the in-orbit conditions.

The stability of the performances was also verified for thermal loads (up to +55°C operative temperature) confirming the selection of the CFRP as nearly-zero CTE material for the main structure of the telescope.

Combined effects of moisture release and thermo-elastic distortions under thermal-vacuum loads were detected. The optical performances verification approach was consequently and successfully tailored in order to separate the individual effects and prove the telescope stability e.g. under thermal-vacuum environment.

8550-47, Session 11

Multiespectral optical design of the Dust Sensor for MetNet Space Mission for the measurements of the heat transfer parameters in Martian Boundary Layer: Dust, CO_2 and Surface Temperature

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Martian atmosphere contains a significant and rapidly changing load of suspended dust that never drops to zero. The main component of Martian aerosol is micron-sized dust thought to be a product of soil weathering. Although airborne dust plays a key role in Martian climate, the basic physical properties of these aerosols are still poorly known. The scope of Mars MetNet Mission is to deploy several tens of mini atmospheric stations on the Martian surface. Infrared Laboratory of University Carlos III (LIR-UC3M) is in charge of the design and development of a micro-sensor (accomplishing 45g. of mass and 1W of power) for the characterization of airborne dust. The spectral power density scattered and detected between 1 and 5 m by a certain particle distribution and by a sensor configuration has been calculated through a radiative transfer model. Taking advantage of the strong dependence of MIE scattering on particle size, radiation wavelength, and angle of observation, the data retrieval algorithm will be based on multispectral angular measurements. Alternating deposited interference filters in the MWIR spectral band on each detector element are proposed as the most optimal solution for spectral as well as angular resolution. Furthermore, the dust sensor is also capable of more conventional temperature and gas concentration measurements by means of additional deposited filters and sensors designed specifically for each species and parameters of interest to be detected.

The data correlation about the airborne dust distribution, surface temperature and gas concentration obtained at the same point in the PBL, will be a very useful data to understand the Martian climate. For that purposes, we will add new capacities in the actual DS. This new concept of the DS is based in the addition of a few more of IR PbSe elements, operating in well selected bands, not incrementing too much the mass of the DS but contributing with new parameters of interest.

8550-49, Session 12

Microscope with 3D mapping capabilities for planetary exploration applications

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An innovative microscope system had been developed by MDA and INO for planetary exploration applications funded by the Canadian Space Agency (CSA). The device is designed for the capture of low and high resolution images, providing multispectral and colour images, and for 3-D mapping of soil or rock samples. The system consists of a microscope equipped with a monochromatic CMOS sensor, a pattern projector and active multispectral illumination. The compact and lightweight device is intended to be mounted on the robotic arm of a planetary exploration rover developed by the CSA.

In image capture mode, the microscope operates on a quite large 400-900 nm spectral band. The illumination of the samples is done using LEDs of different colors turned ON and OFF in sequence providing calibrated reflectance images as well as synthesized color images. Fluorescence imaging is supported by UV illumination at 365 nm. The microscope consists only of fixed optical components. Changing the numerical aperture and resolution of the microscope is done by changing the diameter of the system aperture stop and by pixel binning. The 3-D mapping is done with the Moiré phase shift method requiring that periodical light patterns be projected on the sample surface and the patterns deformed by the surface are observed with a camera from another point of view. In the system presented in this paper, the projection of the Moiré patterns on the samples is done with a specially designed video projector equipped with a DLP from Texas

Instrument (TI) while the microscope acts as the camera.

Both the microscope and the projector are based on the reflective Offner configuration. The microscope is an Offner layout with a folding mirror for more compactness. The projection of the Moiré patterns is done at an angle of 30 degrees with respect to the microscope optical axis which is nominally perpendicular to the mean plane of the sample surface. The DLP is also tilted at 30 degrees with respect to projector optical axis according to the Sheimpflug condition to ensure that the projected patterns are in-focus in the nominal sample plane. Many compensation components have to be added in the projector optical train to compensate for the aberrations introduced by the thick window of the tilted DLP. The light source of the illumination system for the DLP projector is a high power LED.

The system allows the generation of superb high resolution color images with very large depth of field (focus stacking) or color textured 3-D maps from a set of images acquired at different heights using the 3-D map for the segmentation of the in-focus pixels in each image.

This paper briefly describes the concept of the instrument and details the optical design of the optical system. An overview of the key performances is also provided.

8550-50, Session 12

Predict and simulate final optical performances of TMAs: application to the NIRSpec instrument

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The Near-Infrared Spectrograph (NIRSpec) is one the instruments that will be installed on the James Webb Space Telescope. It is composed of three TMAs:

- FOR: fore optics, which give a reduction ratio of JWST's focal plane
- COL: collimator, which gives a parallel beam on the gratings
- CAM: camera, which images the spectra on the detector

NIRSpec is an instrument fully made of SiC (optical bench, TMAs structures and mirrors), so that a global temperature change gives an homothetic shrinkage of the overall optical system. Thus, the performances are kept between ambient (300 K, alignment and testing) and flight (35 K) environments.

Sagem REOSC has been in charge of the following tasks:

- mirror grinding and polishing
- coating
- integration, alignment and interferometric measurement
- cryogenic testing at 20K
- modelization of final performances

The as-built models requested for each TMA have been delivered after the final alignment of the individual TMAs. Since the COL and CAM were aligned and tested separately, an additional COL-CAM model has been made to guarantee the performances after the final assembly.

At first, a tolerancing analysis is necessary to know the acceptable ranges for the geometrical parameters (radius of curvature, conical constant, vertex position, polishing surface error...).

The simulations are based on Monte-Carlo analyses, where the various parameters are randomly perturbed, and the compensating mirrors are virtually displaced to simulate the alignment.

Since the packaging constraints are very tight, this model will allow a reliable evaluation of the potential vignetting that can occur after alignment. A bad positioning of the vertices with respect to the useful aperture will lead to unexpectedly large displacement during alignment, and introduce vignetting.

A second model is built during manufacturing to predict the performances after alignment. Since the tolerancing analysis has given the acceptable deviations on various parameters, the main interest of this model is to check the alignment ranges that will have to be applied after manufacturing, and hence verify that no vignetting will appear.

Once the final alignment is done, the measured performances are used to make the as-built models. Since optical design softwares are not dedicated to make a system converge with a particular performance, a specific tool has been developed.

The idea is to decrease the discrepancy between the model and the measurements. An optical design software is used to compute the compensators sensitivities and the model performances.

The departures from measured data are used as the merit function that has to be decreased. A singular value decomposition algorithm (SVD) is used to compute the mirror displacements (decenters, tilts). Those displacements are virtually applied within the model, and the performances are computed again.

The method developed to predict the performances and make the as-built models has given very satisfactory results. The COL and CAM models allowed to evaluate the performances of the COL-CAM combination. The measurement of the actual COL-CAM instrument have shown a good similarity, and have validated the as-built models.

8550-51, Session 12

Alignment based on 'no adjustment' philosophy for Immersion GRating INfrared Spectrometer (IGRINS)

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Immersion GRating INfrared Spectrometer (IGRINS) is an astronomical instrument that can observe H band (1.49 ~ 1.80 um) and K band (1.96 ~ 2.46 um) simultaneously using immersion grating made of silicon material. The resolution of the instrument is more than R=40,000 across the near infrared atmospheric windows in a single exposure. Currently in its design phase, IGIRNS employs 11 lens elements for input relay optics (IO) and slit-viewing camera (SVC), and 8 lenses and 5 folding mirrors for H and K band camera system. Besides, there is a temperature variation of about 170 K for all containing lenses and mirrors. In order to assemble such a complicated and temperature-dependent optical system, we have decided to input an alignment concept called "no adjustment" philosophy out of the ordinary. The concept calls rigorous tolerance analysis in order to allocate enough budget and precise process control (PPC) of fabrication, assembly, alignment and testing with highly accurate metrology for all optical elements. The geometric spot size in RMS radius for IO and SVC is less than 25.7 um so that a seeing disk is enlarged by no more than 10% of its original size. The FWHM limit of simulated images is that the PSF of a point source across 90% of the area of the H and K echellograms shall be smaller than 1.53 pixels (i.e. 27.4 um). The resulting tolerance budget for lenses of IO from our sensitivity analysis, for example, shows surface wedge of ± 1 arc-minute in degree, the surface decentration of ± 100 um in length, radii of ± 0.1 mm in radius and surface figure of $\lambda/4$ in rms WFE (Wave Front Error). The tolerances of SVC, H and K camera system have practically similar budget ranges and do not require tight tolerance. The laser interferometer named ZYGO DynaFizTM, 4D PhaseCam, and contact profilometer named Coordinate Measurement Machine (CMM) will be used to measure all optical and opto-mechanical components such as lenses, mirrors, lens barrels, dewar boxes and spacers. The integrated IGRINS will be installed on the 2.7 m Harlan J. Smith Telescope (HJST) at McDonald Observatory and will be examined optical quality early 2013. In this paper, we present the tolerance analysis, inspection details of optical and opto-mechanical components, assembly and alignment procedure for the IGRINS.

8550-75, Session 12

MEGARA Optical design: the new integral field unit and multi-object spectrograph for the GTC 10m telescope

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We describe the optical design of MEGARA, the future optical Integral Field Unit (IFU) and Multi-Object Spectrograph (MOS) for the 10.4-m Gran Telescopio CANARIAS (GTC). MEGARA is being built by a Consortium of public research institutions led by the Universidad Complutense de Madrid (UCM, Spain) that also includes INAOE (Mexico), IAA-CSIC (Spain) and UPM (Spain).

MEGARA IFU includes two large central fiber bundles and a grid of 100 robotic positioners with mini-bundles, allows observing up to 100 targets in 3.5?3.5 arcmin2. All these fibers are coupled to microlens arrays at the side of the focal plane, and feed the entrance of a spectrograph placed on one of the Nasmyth platform of the telescope. There are some technological challenges related to Optics like the use of the sliced-pupil grating concept, large high transmission holographic gratings at pupil, and a high performance design that allows to reach different regimens of spectral resolution without changing the overall geometry collimator-camera. MEGARA is in the Final Design Phase and it is expected to be in operation at the end of 2015.

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8550-81, Session 13

Image registration software data correction algorithm for hyperspectral imager

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In this paper we present a technique to accurately build a 3D hyperspectral image cube from a 2D imager overlaid with a wedge filter with 128 spectral bands, providing time-multiplexed data through scanning. The spectral curve of each pixel in the physical scene being the combination of its spectral information captured over different time stamps, its correctness is directly related to the alignment accuracy and scanning sensitivity. To overcome the accumulated alignment errors from scanning inaccuracies, noise, lens distortions, frequency-dependent scaling and blur, spectral band separations and the imager's spectral filter technology limitations, we have designed a new image alignment algorithm based on Random Sample Consensus model fitting. It estimates all mechanical and optical system model parameters from image feature matching over the spectral bands, further finetuned with Levenberg-Marquardt optimization, ensuring a high immunity against the spectral reflectance variations.

One of the biggest challenges for the image alignment algorithm is that of finding the correlation between the image features at different wavelengths, especially in the presence of wavelength dependent luminance variation, scale change, blur, noise, etc. Our feature point matching and system models tackle these error sources robustly, precisely detecting the feature points at their physically correct spatial location, without any drift between spectral bands. This strengthens the feature matching to the high level of accuracy required in reliably aligning up to 128 spectral bands.

To align images, we select the middle wavelength image at 700nm as an anchor image for any hyperspectral image captured in the range of 400nm-1000nm. Images at extreme wavelengths such as 400nm or 1000nm might have a limited number of features matching with the anchor image, in which case our algorithm automatically selects a more appropriate intermediate wavelength image as an intermediate anchor image. Consistency between the sequence of anchor images and their surrounding wavelength images is pursued, allowing a very accurate estimation of the model parameters with minimal fitting error.

Consequently, the average alignment error is reduced to 0.5 pixels, much below the alignment error obtained with state-of-the-art techniques. The image feature correspondences between the images in different bands of the same object are hence consistently produced, resulting in an hardware-software co-designed hyperspectral imager system, conciliating high quality, correct spectral curve responses with low-cost.

8550-82, Session 13

Towards Image Data Processing in Vehicles under Adverse Weather Conditions

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Camera-based advanced driver assistance systems (ADAS) are available in most commercial vehicles for different purposes. With increasing acceptance of such systems comes an increasing expectation of its performances. One topic, which has been covered relatively sparsely over the last few years, is the processing and exploitation of video data in vehicles in bad weather conditions, especially rain. Such circumstances influence the data quality and hence the sensor performance massively.

There exist several image processing algorithms for locating single image drops on the windscreen that are used in order to exclude such regions from further processing steps. But in practice, due to the deep camera focus and the short distance between camera and windscreen, the localization of single drops becomes impossible. A single drop then is rather disturbing large areas of the image than just covering a single spot.

Especially at higher driving speeds like on motorways, new approaches must be considered. A clear sight of the relevant objects is then only given for a couple of frames following the windscreen wiper passage. Both effects are responsible for the fact, that algorithms which were designed for good weather conditions cannot be adapted for bad weather conditions by simply resetting the algorithm parameters. In fact, most algorithms must be completely redesigned to be capable of recognizing and handling these special circumstances.

In this paper we present an approach for detection and tracking of vehicles under extreme rain conditions. Analysis of the respective image regions allows for an estimation of the spray amount produced by the preceding vehicles. This information is used as an input for an ADAS application which regulates the brightness of the backlights in order to adapt it to the environmental conditions.

8550-83, Session 13

Optomechanical device for the sensitive metal ion concentration measurement based on changes in the fluorescence lifetime of GFP

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The need for the analysis and high performance detection of heavy metal ions such as copper, zinc and nickel is important in several different areas of daily life. In the environmental context limits for heavy metal ions exist which should not be exceeded in order to allow an undisturbed development of floral life. In technical and industrial applications threshold values are regimented for instance in the wine regimentation and in the EU and WHO standards for drinking water (32 ?M in water for copper). Measuring the heavy metal concentrations in these liquids is cost intensive and requires the transmittal of samples to specialized laboratories or commercial companies. Hence, there is an increasing need for devices that are fast, easy to handle and provide best value for money making them accessible to a large potential market.

Countless reports on the use of variants of the Green Fluorescent Protein (GFP) as sensors in basic research can be found in literature. In these experiments changes in the fluorescence intensity or in the fluorescence lifetime could be assigned to copper concentrations. Nevertheless, devices exploiting this class of fluorophores are still lacking.

Here we report the development of an automated optomechanical device that exploits lifetime changes from 3 ns to less than 1 ns of GFP in dependence of the copper ion concentration from 0.1 to 200 ?M. Measurements in water and in various liquids from the beverage industry like red wine and soft drinks are performed. Basis characteristics of the system are the fast acquisition time below five minutes, low purchase costs, high sample throughput and the selectivity for copper ions. Transport to the optical chamber is realized by automated pumping of the sample.

8550-84, Session 13

Multichannel serial-parallel analog-to-digital converters based on current mirrors for multi-sensor systems

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The paper considers results of design and modeling of analog-to-digital converters (ADC) based on current mirrors for multi-sensor systems with parallel inputs-outputs. Such multichannel serial-parallel analog-to-digital converters based on current mirrors (M SP ADC CM) have a number of advantages: high speed and reliability, simplicity, small power consumption, high integration level for linear and matrix structures. We show design of the M SP ADC CM for Gray and binary codes. Each channel of the structure consists of several base digit cells (ABC) on 20-30 CMOS FETs and one photodiode. The supply voltage of the ABC is 1-3.3V, the range of an input photocurrent is 0.1 – 10uA, the transformation time is 30ns at 5-8 bit binary or Gray codes, power consumption is about 1mW. Such M SP ADC CM open new prospects for realization of linear and matrix (with picture operands) photo-electronic structures which are necessary for neural networks, digital optoelectronic processors, neural-fuzzy controllers, and so forth.

8550-85, Session 14

Low-light signal detection using a high dynamic range, high-responsivity image sensor with multiple sampling modes

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This paper presents a high dynamic range imaging sensor for detection of low light level signals. The sensor utilizes a 12x12 array of large 150µm x150µm pixels. The readout circuitry allows for multiple readout options including; multiple sampling (which allows for techniques such as Correlated Double Sampling (CDS)) and Time to Digital Conversion (TDC) techniques, operated both independently and under the same integration period. Scope for test patterns is also present in the design.

All samples taken from the pixels before during and after exposure are converted digitally through the use of a single slope ADC utilizing a 10 bit DAC and a comparator. No sample and hold capacitor is present. 4x10 bit SRAMs (Static Random Access Memory) per pixel are utilized to record multiple samples, or act as a counter for the TDC mode of operation.

The large dynamic range of the system is attributable to both the novel timing system implemented within the multiple sampling mode of operation and the TDC mode of operation (operated independently or intermittently within the same integration time), which combines the use of 4x10 bit SRAMs with the 10 bit DAC to produce a counter capable of monitoring the pixel signal over extremely long integration times; in this case up to 30 seconds.

8550-86, Session 14

New generation CMOS 2D imager evaluation and qualification for semiconductor inspection applications

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Semiconductor defect inspection industry is always driven by inspection resolution and through-put. Higher resolution image utilizes more detector pixels to represent same defect compared to lower resolution, therefore smaller optical field of view, which fundamentally limits inspection throughput. With fabrication technology node advances to 2X ~1Xnm range, front-end wafer processing critical macro defect size reduces to a few microns, falling into typical silicon area scan camera pixel size range. Therefore single pixel defect inspection becomes more and more essential, which fundamentally constrained by camera performance.

There are a numerous CMOS detectors available for selection. Unfortunately at the most of time the vendor’s data sheet cannot be easily converted into camera performance description for end user due to different application emphasis. This paper presents a model to describe camera performance for semiconductor machine vision particularly. Most of performance items tested separately in camera industrial general protocol like EMVA1288 are condensed into two complex charts: dynamic range and noise profile, which address all critical factors for low defect contrast high speed semiconductor machine vision applications.

Current mainline cameras and high-end OEM cameras are evaluated with this model. Camera performances are clearly differentiated among CMOS technology generations and primary vendors, which will facilitate application driven camera selection and operation optimization. The new challenges for CMOS detectors are also discussed for semiconductor inspection applications.

8550-87, Session 14

2D simulation for the impact of edge effects on the performance of planar InGaAs/InP SPADs

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InGaAs/InP Single-Photon Avalanche Diodes (SPADs) are solid-state devices able to detect near-infrared single photons up to 1700 nm. One of the main drawbacks is the quite high dark count rate (DCR), due to thermal generation and tunneling effects, because of the high electric fields required for triggering the avalanche process. To lower the DCR, the common InGaAs/InP SPAD structure is the separate absorption-and-multiplication one, where the InGaAs absorption layer has low electric field and the lattice-matched InP multiplication layer experience the high electric field to trigger the avalanche. The pn junction is defined by a Zn diffusion in a lightly n-doped InP layer. If a simple Zn diffusion were employed, it would suffer edge effects, therefore a double diffusion is used in order to smooth the electric field at the active area’s edge. However, since most of the main parameters of the SPAD depend on the electric field profile, it is of the utmost importance to properly evaluate the field both in the active area and closer to its edges. Currently-available programs for 2D simulations require heavy and long computation overheads, thus often 1D simulations are performed for qualitative characteristics evaluation. Moreover, no commercial simulator is able to predict the SPAD detection performances, like dark counting rate, photon detection efficiency, triggering probability, and so on.

We developed two device simulators suitable to perform respectively 1D and 2D simulations of InGaAs/InP SPADs. We investigated the main differences between the two approaches in terms of electric field profile, breakdown voltage, trigger efficiency, dark count rates and afterpulsing. We show how the mono-dimensional simulator overestimates breakdown voltage (few percent), while the bi-dimensional simulator properly foresees the dependence on the geometry of the Zinc diffusions and highlights which are the areas that will show higher electric fields. Trigger efficiency depends on the “local” breakdown value, thus it is not constant through the device but has a peak at the edge of the active area, eventually increasing the local photon detection efficiency. High electric fields at the edge of the active area also contribute to increase the noise due to tunneling, as well as to increase the avalanche current, thus increasing carrier trapping and afterpulsing effect. A quantitative description of these phenomena is made possible thanks to the 2D simulator, able to account at best the real SPAD performances.

In order to understand better which parameters influence the SPAD performances, we report the models we implemented in the simulator to calculate electric fields, trigger efficiency, noise generation and afterpulsing effect. We show how to tailor drift-diffusion equations in order to optimize the SPAD simulation, hence demonstrating how this approach can reduce simulation time. In fact the reported 2D simulator computes breakdown voltage with a faster method than commercial programs, thus reducing the total calculation time by a factor of about 44.

8550-88, Session 14

Diffraction grating-based optical readout for thermal imaging

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Thermal detectors are used for thermal mapping of the environment for numerous defense, security, medical and industrial applications. Uncooled thermo-mechanical detectors incorporating optical readout into MEMS structures promise high performance at low cost. In this work, three different optical readout systems for a MEMS based thermal detector array are analyzed.

Operation principle of the detector is based on the conversion of heat, due to incident infrared radiation, to mechanical bending which is read using a laser-based optical interferometer. A diffraction grating interferometer is formed underneath each detector pixel. Typically the first diffraction order is used to monitor the sub-micron mechanical displacement with sub-nanometer precision.

Detector readout is performed from the backside of a transparent substrate with a light source illumination. The first order diffracted light from the detector pixels is imaged onto a CCD camera to monitor the mechanical displacements of the detectors. An image processing algorithm is developed to characterize the optical readout system and thermal sensor arrays. This post-processing algorithm is applied to the obtained CCD images during direct heating and infrared radiation experiments.

Three different types of optical readout systems have been developed. First setup employs a conventional 4f optical system. In the 4f system, a collimated beam is split into two paths by a beam splitter. The beam reflects from the MEMS chip and propagates through a lens. An aperture is used at the Fourier plane to filter out the 1st order diffracted light and to block the 0th and other diffraction orders. After filtering, the image is formed on a CCD camera by a second Fourier transformation lens.

Second system is more compact to improve image quality and to reduce noise. This is achieved by using an off-axis converging laser beam illumination that forms the Fourier plane near the imaging lens. 1st order diffracted light remains on-axis due to off-axis illumination. It is filtered out and it forms the image of the detector pixels on the CCD. This approach has important advantages such as reducing the number of optical components and minimizing the optical path and offers better image quality due to on-axis imaging optics. The system was optimized considering parameters such as laser convergence angle, laser beam size at the MEMS sensor chip, magnification of the imaging system, the distances from chip to light source, lens and CCD.

Third system is based on CMOS and MEMS integration without the need for imaging optics. A customized CMOS sensor was post-processed to make it thinner and to define through-holes to transmit readout beam. Reflected light from MEMS detectors are captured by the photodiodes around the holes on the CMOS wafer. CMOS ROIC (readout integrated circuit) was characterized experimentally and aligned to MEMS detectors effectively.

8550-89, Session 14

MM-wave hybrid narrow-gap hot-carrier and Schottky diodes detector arrays

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Terahertz (THz) technologies (radiation frequencies from ~0.1 THz to 10 THz) now are emerging ones and promise wide choice for potential applications in vision systems, spectroscopy, medicine, security, etc. Important components of these technologies are detectors and in many applications un-cooled detectors capable for integration into arrays are desirable.

Here un-cooled narrow-gap mercury-cadmium-telluride (MCT) semiconductor thin layers grown on GaAs substrates that are hybridized with antennas on low permittivity dielectric substrates were considered as 128-144 GHz direct detection 6-element bolometer array. To compare the results obtained the measurements of GaAs conventional Schottky barrier diode (SBD) detectors were fulfilled in the same conditions for which the comparable to MCT bolometers noise equivalent power (NEP) was obtained.

6-element antenna array on low permittivity dielectric substrate (quartz, permittivity~4.8) hybridized with MCT bolometers on GaAs substrate (permittivityHgCdTe~permittivityGaAs~13) with intrinsic conductivity was considered. Input of radiation into the detecting elements from antennas on low permittivity substrates is much more effective compared to antennas that are formed directly on substrates with high dielectric permittivity at comparable thicknesses. Hybridizing technology of small area detectors with antennas on substrates with low dielectric permittivity was applied here to increase the antennas efficiency and to decrease the cost of MCT detector array for hot-electron bolometers manufacturing.

To decrease the influence of hot electron bolometer on antenna parameters in hybrid structures the bolometer dimensions should be much less than the antenna ones. Area of antenna optimized for frequency in ~128-144 GHz range was about 1.5 mm2. Total bolometer area (thinned to d~20 microns) was taken 0.6x0.2 mm2 with contact pads to be used for hybridization with antennas on quartz substrates. From the same area as quartz substrate used for array of 6 detectors (10x15 mm substrate) it is possible to obtain at least one hundred sensitive elements. Bolometers were hybridized to antennas by flip-chip technology with galvanically grown indium bumps.

In current bias range Ibias=0-5 mA for sensitive elements the signal voltage changes linearly. The measurements of signals were made by lock-in amplifier (Stanford SR 830) at modulation frequency fmod = 1 kHz. In ~128-144 GHz spectral range the response signal dependences of MCT bolometers and Schottky barrier diodes (SBDs) with the same antennas are rather similar. In spite of notably higher voltage sensitivity SV values of SBD detectors compared to those of SHEBs the NEP observed in SHEBs with antennas on quartz substrates have comparable values because of much lower intrinsic noises and such hybrid structures can be used at least as small number mm-wave FPAs. NEP of such detectors in observed frequency range reaches NEP300K ~ 2.6 10-10 W/Hz1/2 (with calculated gain G~9 dBi). For SBDs NEP300K~2.6 10-10 W/Hz1/2 (G~1.05 dBi).

8550-90, Poster Session

Infrared small target tracking technology under complex background

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Small target tracking in infrared (IR) image sequences has been an important part in many military or civil fields such as video supervision, precision guidance and human-computer interfaces. Nowadays, different algorithms have been proposed for infrared target tracking. However, under complex backgrounds, such as clutter, varying illumination, and occlusion, the traditional tracking method often loses the real infrared small target. To cope with these problems, in this paper we have researched on the traditional infrared small target tracking methods, summarized the advantages and disadvantages of these algorithms. On the basis of the analysis of these methods, according to the characteristics of the small target in infrared images, we propose an improved tracking algorithm to enhance the tracking performance. The experimental results show that, compared with the traditional algorithm, the presented method greatly improves the accuracy and effectiveness of infrared target tracking under complex scenes, and the results are satisfactory.

8550-91, Poster Session

Evaluation of optical radiation detectors in the range from 0.8 to 20 um at the NIST infrared spectral calibration facility

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The analysis of the multiple factors affecting the uncertainty of the measured absolute spectral responsivity of optical radiation detectors is presented. This includes both the validation of the radiometric scale of the infrared reference detectors and the scale transfer process to the unit under test. Reference detectors include a low NEP pyroelectric detector, InSb-, and a sphere-input extended InGaAs detectors. While all three types of reference detectors were calibrated independently, lower than 0.5 % mismatch of spectral responsivities was observed in the spectrally overlapped regions. We provide the performance evaluation of the NIST IR Calibration Facility designed for testing of optical radiation detectors in both radiant power and irradiance measurement modes. This facility utilizes a high throughput monochromator with interchangeable diffraction gratings. Depending on the spectral range, a black-body at 1100 oC or a quartz halogen lamp is used as a radiation source with about a10-4 long-term relative output variation. In order to minimize the uncertainty budget for calibration data, specific attention was given to the profile of the incident beam, precise positioning of detectors, influence of atmospheric absorption. In addition to spectral responsivity calibration of detectors, the facility allows precise mapping of the detector active area for spatial non-uniformity of response. Typical calibration uncertainties that can be achieved are about 1 % and 2.5 % (k=2) in the radiant power and irradiance modes, respectively. Examples for responsivity calibrations of different detectors will be presented.

8550-92, Poster Session

Algorithm for concentration analysis with laser absorption spectroscopy

Alberto Rodrigues, Volker Lange, Dietrich Kühlke, Hochschule Furtwangen Univ. (Germany)

The wavelength of some lasers is usually tunable through current, which also leads to a non-linear change of the output power of the laser. Absorption spectroscopy is basically a modulation of the laser output power whenever the laser wavelength matches the wavelength of an absorption transition of the fluid (gas or liquid) under analysis. Any further and undesired power modulation can disturb the concentration measurements because of the increased complexity to precisely determine how much power was absorbed by the fluid under analysis. The increase on the laser output power is non-linear to the laser current due to saturation processes which increase even further the complexity of the laser output power profile without absorption transitions. Furthermore other effects can modulate the signal measured with the photodetector.

An algorithm for automatic detection of absorption transitions from tunable lasers has been developed. A processed version of the first order derivative of the absorption signal is retrieved assuming that the base signal profile, i.e. the signal profile measured by the photodetector if there were no absorption transitions, can be piecewise approximated to second order polynomials. The algorithm recognises the absorption transitions by searching characteristic profiles on the processed version of the first order derivative of the absorption signal. Those found transitions are then fitted to Lorentzian lineshape profiles using an implementation of the Levenberg-Marquardt optimization algorithm [1] and its parameters are stored in a data structure. The data structure parameters are compared to the parameters found on the HITRAN database [2] and the concentration is calculated from the best approximation among all parameters from the transitions found on the signal.

The developed algorithm was tested with a set of simulated curves with different concentrations of carbon dioxide transitions at the 2.004 µm band. The algorithm could measure concentrations with relative error better than 1% for concentrations down to approx. 200 ppb and it has a comparable performance even with noisy signals up to 30 dB SNR. Even for higher concentrations in which transitions overlap strongly and the information of the base signal profile is completely lost, the algorithm could measure concentrations also with relative error compared to theoretical values better than 1%, as long as the transitions do not overlap so strong that they merge into one wide absorption transition (at high concentrations or high gas pressures).

The algorithm was tested on our prototype sensor for oxygen at 760 nm wavelength [3] at normal air oxygen concentration. Computation time including acquisition time and graphical output display is around 0.5 s for a 6-transitions measurement curve.

8550-93, Poster Session

Spatial-temporal order of the photoresponse of the sensor materials

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Due to natural imperfection and self-organization the series of unique photo-electric proper-ties are inherent to binary and triple AIIBVI and AIBIIICVI (CuIn5X8 (X - S, Se, Te)) semiconductor compounds. Thus non-uniformly scaled disorder in the crystalline structure of sensor materials stipulates the local spatial-temporal features of the photo-electric processes. In most cases it is the reason of ambiguity and contradiction of the received information during exploitation of sensors, especially in extreme conditions. Therefore the search for the tools of analysis of the spatial-temporal order of the photoresponse structure of the sensor materials is the highly actual task.

As a result of transition from time presentation of sensor's photoresponse to its signature in a phase space it is shown that along with noise constituents in the dynamic structure of sensor's photoresponse the both «rough» dynamic and «thin» informative constituents are contained. Its time-frequency distributing was exposed by means of discrete Haar wavelet-decomposition. On this basis the numeral differentiation and integration of kinetics of photoresponse of crystal was carried out with a variable pitch. This allowed to carry out transition from time presentation of ap-proximation and detail wavelet-coefficient subsets to wavelet signature of phase space. The most in-formative decomposition levels were defined by means of the analysis of the Shannon entropy evolution in the wavelet decomposition tree nodes.

For the analysis of spatial-temporal disorder of the photoresponse structure at these de-composition levels the following differential-geometrical, dynamic and entropy parameters and indexes of wavelet-signature were applied:

- length of the i-th arciform segment of the wavelet-signature and its curvature, that repre-sented the constituents of spatial-temporal structure of crystal's photoresponse at certain level of wavelet decomposition;

- wavelet signature forms asymmetry relatively to zero level, as a measure of time-frequency imbalance of the photo-electric processes;

- area of wavelet signature as measure of Boltzmann's entropy and divergence of phase trajectories of wavelet-signatures in a package as a measure of Kolmogorov's entropy and order parameter consequently.

Application of the given parameters and indexes within the framework of time-frequency approach gave possibility to set that dynamic instability of photoresponse of complex semicon-ductor compounds is accompanied by the origin of spatial-temporal structures of phoresponse in different time-frequency domains that are the result of alteration of the multiscale internal field.

It gave possibility to define ranges of external actions in which the local instability of crystal's photoresponse are appeared. It is important for the purposeful selection of sensors for the certain conditions of exploitation and forecasting of its operability in extreme conditions. Also of-fered tools of analysis of the spatial-temporal order of the crystal's photoresponse appeared effec-tive at determination of optimum conditions of postcrystallization treatment for the increase of stability of crystal's parameters.

8550-101, Session 15

Optimization of LED primary optics with orthogonal polynomial surface description *(Invited Paper)*

Peter Brick, OSRAM Opto Semiconductors GmbH (Germany); Christopher Wiesmann, OSRAM AG (Germany)

In the frame-work of non-imaging optics several analytical methods for lens optimizations have been developed within recent years. However, most of them relied on point-source approximations. The efficiency of those approaches for extended sources has been analyzed and questioned recently by Kari et al. [1].

An alternative approach is based on Monte-Carlo raytracing. In this context, the parameterization of optical surfaces plays an important role and contributes considerably to optimization success. Historically, a popular parameterization is the “extended polynomial” representation consisting of monomial basis functions.

Basis functions related to orthogonal polynomials have received considerable interest as descriptors of lens shapes for imaging optics starting with a seminal paper by Forbes [1]. However, there is little information on the application of orthogonal polynomials in the field of non-imaging optics.

Here, the benefits of orthogonal polynomial for parameterization of LED primary optics are evaluated in comparison to a surface description by widely used monomials.

[1] T. Kari, J. Gadegaard, T. Søndergaard, T.G. Pedersen, K. Pedersen, “Reliability of point source approximations in compact LED lens designs”, Optics Express 19 (S6), p. A1190, 2012.

[2] G.W. Forbes, “Shape specification for axially symmetric optical surfaces”, Optics Express 15 (8), p. 5218, 2007.

8550-103, Session 15

Optical design and prototyping of a light module for constant climate chambers based on LED technology

Paola Belloni, Hochschule Furtwangen Univ. (Germany); David Rose, Hochschule Furtwangen Univ. (United States)

Climatic chambers play a crucial role in industrial and scientific applications because they allow to perfectly simulate environmental conditions like humidity, temperature or illumination. The light modules used in the constant climatic chambers on the market have been equipped since years with fluorescent lamps. However, the rapid improvements of the LED technology provide now a very interesting alternative to the conventional light sources. In this work we have developed the optical design of a light module for a constant climate chamber based only on LED light sources in visible and UVA- range. Then we have produced a prototype in collaboration with the specialized german company BINDER GmbH to test our results. The optical design has taken into account the following constraints:

1) LED spectrum similar to that defined in the ICH Q1B: Guideline for photostability tests. In particular, the spectrum has significant amount of radiation between 320 nm -400 nm band- with emission peak between 350 - 370 nm - as well as broadband emission in the visible range.

2) Uniform radiation at 12 cm distance from the light module

3) Irradiance and illuminance values greater than 1,4 W/m? and 7500 lux.

We first conducted a market analysis to identify suitable LEDs in the required spectral range and soon discovered the UVA- LED technology is still far to be able to provide standardized and reliable products.

In fact, only two LED--types suitable for this industrial application were identified.

The first LED emits broadband cool white light in the range from 400 nm 780nm and the second is a high-power UV-LED with the radiation emission peak of 365 nm (Seoul Semiconductor).

Both the CAD-redesigned light module and the UVA- and cool-white LED were modeled with the software LightTools®. The geometrical position of the LEDs arrays able to provide uniform illumination at the defined distance was obtained through some optimization procedures.

Finally a scale 1:1 prototype was built and measurements were performed taking also into account the regulation in matter of measuraments of this specific application field.

We found that the measured values were in good agreement with the simulation results.

This means that the irradiance in the UVA-range was about 2,24 W/m? whereas the illuminance values greater than 22000 lux. Through an optimized relative position of both cool-white and UVA-LEDs arrays we could also match the target uniformity of ±10%.

Therefore, the new developed light module with LEDs provides better performances that the standard/old one both in radiation intensity and uniformity. Furthermore it is more than 1,3 kg lighter than the standard one and thus more handable.

Of course, due to the still very expensive UVA-LEDs the new light module is more expensive and the amortisation period for the investments is about 36 months.

As far as we know, this work represents the first attempt to implement LEDs in the constant climatic chambers . We hope that it will contribute both to update the ICH Q1B guidelines for photostability tests and to motivate manufacturers to produce more efficient, reliable and affordable UVA-LEDs.

8550-104, Session 15

VLC oriented energy efficient driver techniques

Guillermo del Campo Jiménez, Francisco José López Hernández, Univ. Politécnica de Madrid (Spain)

LEDs are substituting fluorescent and incandescent bulbs as illumination sources due to their low power consumption and long lifetime. Visible light communications (VLC) make use of the LEDs short switching times to transmit information. The so called smart lamps, capable of illuminate and communicate at the same time blink light at speeds higher than human eye perception. No amplitude modulation schemes (on-off keying, OOK) can be use as illumination continues to be the primary function of these smart lamps. In VLC usually a Pulse Width Modulation (PWM) is used for dimming and a Pulse Position Modulation (PPM) is responsible of the communication. Although LEDs switching speed is around Mb/s range, higher speeds (100Mb/s) can be reached by using modulation techniques as Orthogonal Frequency-division Multiplexing (OFDM) or Discrete Multi-tone Modulation (DMT). However, the use of OFDM or DMT requires a more complex driver which elevates drastically its power consumption. So maintaning low-power consumption of LEDs lamps while reaching high transmission speeds must be one the most important accomplishment for VLC research. In this work an energy efficiency analysis of the different VLC modulation techniques and drivers is presented. Besides, the design of new schemes of VLC drivers and preliminary results using power sources techniques and illumination LEDs drivers is described. Different results for diverse LED lamps (white, RGB) are expected.

8550-105, Session 15

Estimating the performance of remote phosphor SSL devices by simulations

Christopher Wiesmann, Julius A. Muschaweck, Alexander Linkov, OSRAM AG (Germany)

Solid State Lighting (SSL) is widely seen as a promising solution for near-future energy-efficient lighting. In order to achieve white light emission from those devices, typically an almost monochromatic blue LED chip is combined with phosphor particles embedded in a matrix that down-converts a fraction of the primary blue emission. During the design of SSL devices thermal management plays an important role, especially if available space is limited. Besides the LED chip also the

phosphor acts as a heat source due to the limited quantum efficiency of the phosphor and due to the photon energy down-conversion itself, i.e. the Stokes losses. Consequently, the heat conductivity of the matrix together with the light distribution inside the phosphor matrix determine the heating and hence the performance of white light SSL devices.

For the geometrical arrangement of blue light sources and phosphor two general possibilities exist: near chip conversion and remote conversion. In the first arrangement the phosphor is placed in the direct vicinity of the chip like in most LED packages on the market today. The latter is also called remote phosphor configuration with the phosphor in some distance apart from the source. This leads to lower power density/irradiance on the phosphor compared to the near chip solution and consequently to less heat generation per unit area.

For the remote phosphor setup we will present simulation results to show the impact of different matrix materials, like silicone or glass, on the performance of the device taking into account not only the efficiency, but also parameters like color homogeneity of the light output. The latter is of special interest since different matrices introduce different refractive indices and accordingly, the scattering of light by the phosphor particles changes. Hence, the resulting light distribution inside the phosphor matrix alters the heat distribution. Here, the thermal conductivity plays also an important role along with the correlation between temperature and conversion efficiency. Finally, also the maximum temperature has to be taken into account as high temperatures accelerate degradation of components like plastics.

8550-152, Session 15

Development of standardized light sources ray file format

Julius A. Muschaweck, OSRAM AG (Germany)

In today's practice, light source ray files used in the optical design and simulation software tools are formed in different formats, which make the process tedious and error prone. At IESNA, a working group has been formed to create a consistent but flexible, downward compatible standard file format for LED and other light sources. This presentation provides the information of the progress made at the working group.

8550-106,

Illumination optimization using angle to position mapping

William J. Cassarly, Synopsys, Inc. (United States)

No abstract available.

8550-107, Session 16

Analytic free-form lens design for tracking integration in concentrating photovoltaics *(Invited Paper)*

Fabian Duerr, Vrije Univ. Brussel (Belgium); Pablo Benítez, Juan Carlos Miñano, Univ. Politécnica de Madrid (Spain) and Light Prescription Innovators, LLC (United States); Youri Meuret, Hugo Thienpont, Vrije Univ. Brussel (Belgium)

Tracking integration for concentrating photovoltaics (CPV) introduces additional degrees of freedom with respect to traditional concentrators; eliminating the clear separation between stationary units of optics and solar cells, and external solar trackers. The introduction of laterally moving lenses allows to combine both the steering and concentration of the incident sun light. This approach is therefore capable of further increasing the point concentration ratio and makes high concentrating photovoltaics (> 500x) available for single axis tracker installations, reducing the external mechanical solar tracking effort in favor of a cheaper and more compact installation. The concept of tracking integration for external single axis trackers has been introduced and discussed in our paper on "Tracking integration in concentrating photovoltaics using laterally moving optics," Opt. Express 19, A207-A218 (2011).

Given the specific symmetry conditions of the underlying optical design problem, it has been shown that rotational symmetric lenses are not ideal for this application. Free-form lens design based on an extended Simultaneous Multiple Surface algorithm in three dimensions (SMS3D) can be used to address this problem as we have shown in "Integrating tracking in concentrating photovoltaics using non-rotational symmetric laterally moving optics," Proc. SPIE 8124, 81240M (2011). However, the wide field of view and clearly separated optical surfaces make that the chosen initial conditions have a significant impact on the obtained SMS3D design result.

A new free-form optics design method presented in previous papers provides an analytic solution for these initial conditions and enables the coupling of an additional ray set at the same time. The presented design method is derived directly from Fermat's principle, leading to sets of functional differential equations. These equations are transformed into linear systems of equations allowing the successive calculation of the Taylor series coefficients of each implicit surface function up to an arbitrary order. The truncation of the Taylor series is the only approximation made. To demonstrate the potential of this design method, we will show ray tracing results for calculated free-form surfaces, each described by more than 50 Taylor series coefficients. For optical systems designed for wide field of view and with clearly separated optical surfaces, this new analytic design method has potential application in both fields of nonimaging and imaging optics.

8550-108, Session 16

Novel lateral moving tracking optics with the SMS design method

Wang Lin, Pablo Benítez, Univ. Politécnica de Madrid (Spain); Juan Carlos Miñano, Univ. Politécnica de Madrid (United States)

Lateral moving optics with moving lens arrays has recently been designed with an SMS method [2] to systems like solar tracker [1]. This system consists of two planar optical lens arrays that concentrate the sun energy onto a solar cell array located in a third plane. The second lens array and the cells move laterally (i.e. in the direction parallel to planes) with respect to the first array to track parallel incident rays within a certain input angular range.

In this work, a new design concept of SMS moving optics is developed, in which the movement is no longer lateral but follows a curved trajectory, which is calculated in the design process. This makes it possible to broaden the incident angle's range. In this design, we have chosen an afocal system, which aim to direct the parallel rays of large incident angles to parallel output rays, and we have obtained that the rms of the deviation angle of the output rays remains below 1 deg within a input angular range of ±45 output, more than triple of what is obtained with only lateral movement. Potential applications of this beam-steering device are: skylights to provide steerable natural illumination, building integrated CPV systems, and steerable LED illumination.

8550-109, Session 16

Volume scattering characterization for illumination design

Quentin Kuperman-Le Bihan, Light Tec (France)

Optical design tools allow more and more complete physical phenomena simulation and illumination design itself becomes more and more complex. A big part of these designs uses volume scattering materials. However, those are not yet implemented in such tools. For this reason we worked on a way to characterize volume scattering materials.

How can we characterize and implement volume scattering materials in optical design tool for illumination design?

We worked on two ways of characterizing volume scattering materials based on real BSDF measurements made with Reflet bench. LightTools software with its Henyey-Greenstein and Mie scattering model was also used in the process of material characterization.

The study showed that the results with both Henyey and Mie characterization, allow simulation of volume scattering materials within of 5% precision compare to real measurements.

Thanks to such simulations it is now possible to have custom shape illumination design using volume scattering materials from a library. Sony Ericson was the first user to benefit from these study's results.

8550-110, Session 16

Optical design of a laser scanning pico-projector

Ian R. Wallhead, Roberto Ocaña Pérez, AIDO Instituto Tecnológico de Óptica, Color e Imagen (Spain)

The optical design of a laser scanning picoprojector can be separated into discrete tasks. Typically, compact diode lasers are employed which have a highly divergent and asymmetric emission. Each laser first needs to be collimated with a simple, low cost approach, ideally using a moulded single component lens. This task requires some consideration of Gaussian beam propagation to produce an appropriate spot size for the desired image resolution at the chosen projection distance.

The asymmetric divergence leads to an elliptical collimated beam and so some beam shaping is required to produce a circular beam. There are several ways to achieve this such as with cylindrical lenses or anamorphic prisms and the optimum choice is not obvious.

The shaped red green and blue beams then need to be combined to produce a single beam. A suitable electronic driver modulates the power of each individual colour at high speed in order to produce any coordinate of the available colour gamut. As before, there are many ways to achieve the combination of the three laser beams using several optical elements but there are also unconventional aspects that we consider in this study. In this sense, we discuss the possibility to use one single optical element for beam combination

The final step of the process is to direct the combined beam towards a MEMS scan head which may either comprise a single, bi-axis or two, single axis scanning micro-mirrors. In this study two, single axis MEMS mirrors are used. Several orientations of the two scanning mirrors are considered and advantages and disadvantages are discussed. The role of the distortion of the projected scan area as function of the scanning mirror orientation is also analyzed.

Currently, picoprojectors are mainly standalone devices but there is impetus to embed the projector engine (lasers, optics, mechanics etc) into other devices such as mobile telephones, tablets, netbooks, etc. Therefore, there is an incentive to minimise the 3D volume taken up by the collimation, beam combination and MEMS scan head.

So along with conventional optical engineering tasks such as lens design, tolerancing, laser safety and cost etc there is an additional aspect of determining the best optical architecture to achieve the goal.

Here we present a design study of a laser scanning picoprojector where the various optical architecture possibilities are presented. The study takes a system approach to producing the best compromise between real estate, image quality and manufacturing consideration. A novel solution is presented which has been built as a prototype projector and which offers excellent future miniaturisation possibilities.

8550-111, Session 17

Investigation of the design space for low aspect ratio LED collimators *(Invited Paper)*

Oliver Dross, Philips Research (Netherlands)

Collimators for spot LED lamps have to meet stringent requirements like high efficiency and on axis intensity, good beam control, color and position mixing, low cost, and a low aspect ratio to enable compact devices with sufficient space for drive electronics and cooling. To meet such requirements only very few optical architectures are routinely used, namely Fresnel lenses, parabolic or aspheric reflectors, and so-called Photon funnels.

Collimators make use of five different deflection mechanisms, namely refraction, total internal reflection, metallic or metallic like reflection, scattering, and diffraction. Light, when travelling through a given collimator type undergoes a characteristic sequence of deflections but many collimators exhibit different paths where portions of the light undergo different deflection sequences.

In this paper we illustrate the design space for collimators for a single Lambertian LED or LED array source located on the optical axis under the boundary conditions of low aspect ratio, rotational symmetry and little Etendue dilution. All possible optical architectures with up to 4 deflections are mapped out in terms of paths of distinct deflection sequences. Some standard collimators as well as a few unusual and novel collimators are classified into this scheme.

The important characteristics of all deflection sequences are investigated. For a given collimator, the deflection sequence characteristics of all paths involved allow predicting efficiency, on axis intensity, and compactness. Additionally beam shape as well as position and color mixing capabilities are estimated by analyzing the effect of path length, ray assignation and deflection type on pinhole image rotation and distortion. Such results are compared to raytrace results for some designed collimators of standard and novel architectures.

8550-112, Session 17

Design of LED optics with two aspherical surfaces and the highest efficiency

Mikhail A. Moiseev, Image Processing Systems Institute (Russian Federation) and LED Optics Design, LLC (Russian Federation) and Samara State Aerospace Univ. (Russian Federation); Sergey V. Kravchenko, Leonid L. Doskolovich, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation) and LED Optics Design, LLC (Russian Federation); Nikolay L. Kazanskiy, Image Processing Systems Institute (Russian Federation) and Samara State Aerospace Univ. (Russian Federation)

Design of LED optics is one of the most difficult parts of modern lighting device development. LED optics affects on quality of light distribution, characteristical dimensions of lighting device, it's cost and, of course, it's efficiency. All techniques of LED optics computation can be divided into two groups: analytical methods and numerical methods. Analytical methods are fast and reliable but they cover a small subset of lighting problems. Usually the analytical solutions can be used as an initial estimation for future optimization only. The numerical techniques provide good results but the success of design process depends on many variables including experience of man who uses the numerical technique, chosen initial surface for optimization etc.

The presented analytical method for design of axially-symmetrical optical elements with two aspherical surfaces makes possible generation of any circular illumination pattern with efficiency up to 92 % (even in case of collimating or generating uniform circle with angular size of 150°-160°). The both aspherical surfaces are computed simultaneously from condition of generation of prescribed irradiance distribution at highest possible efficiency. The proposed design and the design with inner spherical surface are compared for wide range of illuminated area sizes. The advantage of the presented design method is proofed for all considered angular sizes. Despite the fact that the method of computation is developed for point-source case the computed optical elements work perfectly with extended light sources too.

The presented LED optics design and the method for its computation can be used in three ways. Firstly, the method allows to generate the compact LED optics to produce the prescribed circular illumination pattern. Secondly, the design method makes possible estimation of maximal efficiency that can be reached for axis-symmetrical and similar non-symmetrical problems. Finally, the computed optical elements can be used for future optimization taking into account non-circular shape of the illuminated region, size of the light source etc. The development of such optimization technique using specially adapted quick raytracing method is the next problem on the way to the development of the universal method for LED optics design with free-form surfaces and the highest possible efficiency.

8550-113, Session 17

Design and manufacturing of LED primary optics for road lighting engine

Jae Young Joo, Wan Ho Kim, Korea Photonics Technology Institute (Korea, Republic of); Soon Sub Park, Korea Institute of Industrial Technology (Korea, Republic of); Sang Bin Song, Korea Photonics Technology Institute (Korea, Republic of)

GaN-based blue LED with various types of phosphor become ubiquitous in many application including miniaturized mobile projector, portable personal mobile devices, and LCD backlights. Particularly, in Solid State Lighting (SSL), LEDs in indoor/outdoor application has provided high brightness with the integration of various nonimaging optical components; primary and secondary optics.

Those optics have a significant effect on the light output of Luminaries; reliability, color uniformity and energy efficiency. The primary optic provides refractive index matching to increase extraction efficiency and mechanical protection from ambient environment. Another Important role of primary optics is to deliver a uniform beam, i.e. lambertian, into the secondary optic, and the secondary optic collects and manipulates such a beam pattern for desirable illuminance or luminance into the correct space.

In most of lighting applications, the secondary optic becomes a crucial component because the specific lighting function always requires a specific light distribution such as street lighting. Unfortunately, however, secondary optics inherently loses its light flux about 10% in practical due to Fresnel reflection with additional cost in luminaries. Making primary optics of LED as functional as secondary optics, brightness of LED can be further increased while maintaining its intensity distribution. Such a suggestion is simple to describe, but extremely technically hard to accomplish because it is almost impossible to make an illumination source as real as chip level physically.

In this paper, we presented the primary optics of LED as functional as secondary optics.

In general ,optical engineers assumed LED as extended light source whose information of rays come from quasi- point or extended surface light source, and developed various types of secondary optics for outdoor lighting. These design method, however, cannot be applicable when LED die is as large as the size of optics and showed poor optical performance because of relatively large luminous distribution differences between designed optics and manufactured one.

Design of die configuration in primary LED encapsulant optics is intimately intermingled to produce an optimal LED package. In this reason, optical Modeling of LED chip die is a key function in primary optics design and even more in this study. We regarded InGaN multi quantum wells (MQWs) as a realistic light source which emits ray from its six faces and modeled a LED die with representative epitaxial structures and the measured geometry in LightTools which can trace a ray based on Monte Carlo approach. Such precisely modeled GaN LED chip was verified by measuring near-field light distribution.

With such precisely modeled LED, primary optics for road lighting was designed in LightTools and the most critical design factor is manufacturability of the lens and inherent light loss due to its miniaturization. Mold of the designed lens was machined by UVM-450C (Toshiba co.) and primary optics was manufactured by compression molding equipment (TOWA co.). Peak intensity was about 55 degree with 6% inherent flux loss.

The suggested light engine were able to increase brightness of LED road lighting luminaries and is even sufficient enough to lead the cost-cut of LED Luminaries with no secondary optics.

8550-114, Session 17

Novel LED coupling design for semiconductor inspection applications

Wei Zhou, Rudolph Technologies, Inc. (United States); Todd Rutherford, Greenlight Optics, LLC (United States); Darcy Hart, Rudolph Technologies, Inc. (United States)

High speed strobe based illumination scheme is one of the most critical factors for high throughput semiconductor defect inspection applications. HB LEDs is always the first and best options for such applications due to excellent flash to flash spatial and temporal stability, fast responding time, larger linear intensity range and no heat issue for this extremely low duty cycle applications. For some applications that a large area is required to be illuminated simultaneously, it remains as a great challenge to efficiently packaging large amount of HB-LEDs in a highly confined 3D space, to generate a seamless illuminated area with high luminance efficiency and spatial uniformity.

Traditional circular shaped TIR lens can be optimized for better luminance control, but inherently introduce spatial non-uniformity due to air gaps between lens channels. A novel 3D structured TIR lens is presented in this paper. The non-circular edge shape fundamentally reduces the intensity drop at the channel boundaries, while positive curvatures on the TIR lens's top surface efficiently guide the light into desired angular space. Number of edges and radius of top surface curvature are control parameters for system level performance and manufacture cost trade-off. With the novel advantages, the proposed 3D structured TIR lens also maintains the benefits of traditional TIR lens such as coupling efficiency and mold manufacture capability.

8550-115, Session 17

Optimization of light output efficiency of LED drivers and optics

Omer F. Farsakoglu, Ipek Inal, Kilis 7 Aralik Üniv. (Turkey)

In this case, diffusers and Fresnel lenses were proposed depending on the use. Diffusers can be used indoors combined with the reflector. To this end, also Fresnel lenses were designed. In this study, a practical nonimaging optical design method is used and high illumination quality power LED armatures are designed according to this method.

Note: Our study is Repucl1c of Turkey Government's project 'SODES' and project number is 229

8550-153,Session 18

Tailoring illumination optics for real sources

Harald Ries, OEC AG (Germany)

We have pioneered tailoring as a design tool, particularly well-suited for illumination optics, since more than 10 years. However, because it is based on numerically solving a PDE it requires idealization of the radiation source. More exactly, tailoring requires an ideal mathematical model which yields the direction and the intensity of the radiation as a continuous and differentiable function of location in space. Real sources are not point-like but have a finite extent. Furthermore, most manufacturers do not specify directional distribution of an LED as a differential model, but rather in the form of a ray data set as discussed in several other contributions to this conference. While ray data sets are useful for validation based on ray tracing they cannot be used as such for tailoring. In our contribution we present an approach to both shortcomings.

We model the directional distribution with an appropriate differential model by a maximum likelihood best fit approach. We will describe the model which is designed to exhibit the correct topology and physics, i.e. an intensity which is everywhere strictly positive and differentiable. We will present results obtained with this model and compare these results with ray tracing validation based on the original ray data set.

The finite size of the source is accommodated by a different approach based on an idea of Ari Rabl and – independently – of William Cassarly. The high speed of our numerical algorithm for finding the numerical solution allows it to be integrated inside an optimization loop. The optimization uses the desired irradiance of a point source as a free parameter to be optimized such that the actual distribution obtained with a real source of finite size approaches the targeted result. We will show examples for this approach as well.

8550-116, Session 18

Irradiance tailoring for extended sources using a point-source freeform design algorithm *(Invited Paper)*

Rolf Wester, Fraunhofer-Institut für Lasertechnik (Germany); Adrien Bruneton, RWTH Aachen (Germany); Axel Bäuerle, Jochen Stollenwerk, Peter Loosen, Fraunhofer-Institut für Lasertechnik (Germany) and RWTH Aachen (Germany)

The advent and rapid development of efficient high power LED sources with their unique emission characteristics enables the development of illumination systems that meet very strict requirements concerning light distribution and efficiency. Most of the algorithms used to design the necessary optical freeform surfaces rely on the point source assumption. As long as the optical surfaces and the distance between LED and those surfaces are large, this is a good approximation. One further important design goal is to make the optical components as small as possible, which makes the point source assumption less accurate. The existing design algorithms thus have to be accompanied by methods to treat the finite-sized LED sources. We examine the limits that are set by the finite size of the light sources and present algorithms to optimize optical freeform surfaces up to these limits. Point source results are iteratively improved to get the desired illumination pattern employing finite sized LEDs. At each iteration step the illumination pattern used in the point source computations is adapted so that the real illumination pattern of an LED approximates the originally desired pattern. We propose that the use of ray mapping information derived in a Monge-Kantorovich framework can directly improve the performance of such iterative algorithms.

8550-117, Session 18

Optimizing nonimaging free-form optics using free-form deformation

Simon Wendel, Julian Kurz, Cornelius Neumann, Karlsruher Institut für Technologie (Germany)

The increasing efficiency of high power LEDs has resulted in many new applications in general lighting. To take full advantage of the properties of LEDs, free form surfaces can be utilized to create compact non imaging optical systems with high efficiencies and high degrees of freedom for optical designers.

One of the commonly used methods to do optical design for this kind of system is optimization. Appling this powerful tool allows the enhancement of given optical elements to achieve a desired performance. In this way, freeform surfaces which are usually represented by NURBS, can be optimized and applied even close to an extended LED light source.

However, using optimization for freeform surfaces is far from being straight-forward and requires a lot of experience mostly due to the high amount of possible optimization variables for NURBS. This comes along with high computational effort and difficulties concerning the choice of boundary conditions and merit functions.

This contribution presents a novel non-imaging optical design approach using the concept of Free Form Deformation (FFD) in conjunction with customized optimization algorithms to create efficient optical freeform surfaces for extended LED light sources. Within this framework, specific coordinate system transformations are used to modify the global shape of free form surfaces. In this way, optimization techniques relying on relatively few and easy accessible variables can be applied successfully. All presented concepts are implemented in a flexible and fully automated FFD-Optimization software tool incorporating a commercial raytracer and numerical optimization techniques. Several examples are presented in detail and the scope of FFD based optimization for nonimaging optical design is demonstrated.

8550-118, Session 18

Aplanatic thin TIR lens

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Aplanatic designs present great interest in the optics field since they are free from spherical aberration and linear coma at the axial direction. Nevertheless nowadays it cannot be found on literature any thin aplanatic design based on a lens. This work presents the first aplanatic thin lens (in this case a dome-shaped faceted TIR lens for light collimation), designed for LED illumination applications. We will show its optimum optical properties with computer ray-trace simulated results: low full width half maximum, high efficiency, uniform illumination pattern and good color-mixing properties.

When designing a faceted lens (for illumination or CPV applications), its global shape can be tailored in order to fulfill one out of several conditions. In this way, minimum dispersion, no dilution or no geometrical losses are presented as commonly used conditions in non-imaging for faceted elements. Depending on the condition we take, we can have designs with quite different shapes and properties. However, for an aplanatic design, the Abbe sine condition must be fulfilled, entailing the constant étendue condition (i.e. input and output radiation étendue are identical).

Color-mixing properties are here explained since lenses based on TIR facets are composed of anomalous microstructures. Previous publications on non-imaging optics have demonstrated that this kind of microstructures have the interesting property of producing a rotational symmetric intensity pattern from a non-rotational symmetric source. This is the case of an LED chip placed at a certain distance from the optical axis. Therefore, if several chips are placed at the same distance to the optical axis, their intensities will coincide and they will simply add. When this is applied to LED composed by chips of different colors, we will be providing spatial and angular color mixing.

Beyond the design procedure and raytrace simulations, we will show a novel manufacturing process for this TIR lens as well. Our alternative is based on developing the lens design with spiral symmetry. In this way, optical surfaces are not obtained from the usual revolution symmetry with respect to a central axis (z-axis), but they are calculated as free-form surfaces in such a way that they describe a spiral trajectory around z-axis. The main advantage of this new concept lies in the manufacturing process: a molded piece can be easily separated from its mold just by applying a combination of rotational movement around z-axis and linear movement along z-axis. By applying this "spiral" movement, demolding process renders very easy.

8550-119, Session 18

Strategy to obtain initial configurations for free form reflectors design

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A strategy to obtain sets of initial configurations to design freeform reflector surfaces is presented. This strategy brings the initial configuration of the reflector surface using a collection of elemental facets defined by Bezier surfaces and able to face the optimization process of the illumination system.

The purpose of this communication is to provide initial configurations to obtain a set of parameters defining the freeform facets described by Bezier curves. Those parameters can be modified by a global optimization process of the lighting system [1]. This task can be accomplished using a set of simple geometric elements that are the basis for calculating a first approximation to the surface.

The freeform facets are generated using a set of simple geometric elements, which suffices to calculate the surface in a first approximation. The values of these parameters are obtained by applying a ray tracing algorithm for 2D Bezier curves in a predefined pair of orthogonal axes and searching the set of parameters that minimize the spot diagram in each of those axes. A full 3D description of each elemental facet is obtained through a network of control points of the Bezier surface using the 2D Bezier curves parameters.

Defining the initial surfaces with Bezier parameters instead of defining them as conic surfaces has the advantage that the former can be

modified afterwards with CAD-calculation tools, as they are easily expressible in terms of B-splines or NURBS [2], [3], [4].

The starting point to calculate the parameters of each freeform facet is a quadrangular and flat reflecting surface. The calculation method allows us to describe a new Bezier surface that meets the optical characteristics compatible with the initial conditions. The process starts by defining six points into space, four for the corners of the mirrors ("R1, R2, R3, R4".), one for the source (S), and one for the target (T). The mirror is divided into four horizontal and vertical axes, which set the directions of the sagittal and tangential axes of the mirror. In each of the axes applies an algorithm in 2D and you get a network of control points that uniquely define a Bezier surface. These surfaces are suitable for insertion into any optimization software for luminaries and for obtaining compatible CAD tools expressions.

Conclusions

The proposed strategy provides a simple geometric design method to perform valid initial configurations for lighting systems with reflective surfaces that can be further optimized.

The method is based on ray tracing and uses a merit function to find the parameters defining the Bezier curve that best meets specifications in each elementary facet.

Applying this method to 2D tangential and sagittal axes, a network of control points are obtained for describing a Bezier surface compatible with any standard optical optimization tool and suitable for viewing with CAD tools.

8550-120, Session 18

Quasi-aplanatic free form V-groove collimators for LED color mixing

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The aim of this work is to present the quasi-aplanatic free-form V-groove collimator optical designs (the XX and the RXI design) with the property of color mixing. We want to use free-form quasi-aplanatic design and microstructured optical surfaces in order to obtain spatially and angularly far field color mixing of the light emitted by several LED sources placed off-axis. Structured optical surfaces, such as Fresnel lenses, TIR lenses, or Fresnel mirrors, are often used in nonimaging optical design.

As defined previously [1], in two dimensions microstructures (either reflecting or transmitting) were classified in two groups, the regular type and the anomalous type depending on the actual design of the microstructure and its corresponding deflection law. According to this classification, non-microstructured surfaces (i.e., conventional refractive surfaces and mirrors) are of the regular type. Afterwards, [see 2] the study of those microstructured optical surfaces is extended to three dimensions with rotational symmetry and it is mentioned the concept of a perfect ring-spot type system with an odd number of rotational, anomalous, ideal microstructures that has direct application for mixing the light coming from several sources.

As an example of color mixer described previously we are mentioning the V-groove reflectors with rotational symmetry designed using the SMS method [3]. They are performing color mixing, but the rotational symmetry design is creating far-field pattern that has a ring-like shape not centered at the optical axis for LED sources placed off-axis so color mixing quality is to be improved.

The idea of the free-form quasi-aplanatic design presented here is to improve color mixing property by using anomalous microstructures and V-grooves, as the far field image of any of the off-axis located chip in an anomalous aplanatic system will be a collimated beam with the shape of a ring. By superposition of these rings we are obtaining satisfactory color mixing properties.

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8550-121, Session 19

Inhomogeneous source uniformization using a shell mixer Köhler integrator *(Invited Paper)*

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High flux and high CRI may be achieved by combining different chips and/or phosphors. This, however, results in inhomogeneous sources that, when combined with collimating optics typically produce patterns with undesired artifacts. These may be a combination of spatial, angular or color non-uniformities. In order to avoid these effects, there is a need to mix the light source, both spatially and angularly. Diffusers can achieve this effect, but they also increase the etendue (and reduce the brightness) of the resulting source, leading to optical systems of increased size and wider emission angles.

The shell mixer is an optic comprised of many lenses on a shell covering the source. These lenses perform Kohler integration to mix the emitted light, both spatially and angularly. Placing it on top of a multi-chip lambertian light source result is a highly homogeneous virtual source (i.e, spatially and angularly mixed), also Lambertian, which is located in the same position with essentially the same size (so the average brightness is not increased). This virtual light source can then be collimated using another optic, resulting in a homogeneous pattern without color separation.

Experimental measurements have shown optical efficiency of the shell of 94%, and highly homogeneous angular intensity distribution of collimated beams, in good agreement with the ray-tracing simulations.

8550-122, Session 19

Time-space conversion for short pulse generation with a long lifetime phosphor

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Optical communications are currently achieved in various spectral ranges, e.g., the 1.5-µm band for long-haul communications, the 0.8-µm band for wireless LANs or mobile phone communications, and the visible spectral band for polymer fiber networks. Recent advent of LED illuminators is promoting development of white-light communication systems. Interconnection between these different communication systems requires wavelength conversion of optical signals. Signal delay is also required for time-division multiplexing or bit-rate adjustment between fast and slow communication systems. Such signal processing is usually conducted with electric signals; i.e., a photodetector converts an optical signal to an electric signal, and then the amplified and delayed electric signal drives a light source of another wavelength.

In this study, we designed an all-optical signal processing system for infrared-to-visible conversion. Although the visible-to-infrared conversion is achievable with various dyes, the reverse process is difficult to achieve, since it requires increase in photon energy (upconversion). Rare-earth ions realize the upconversion through an efficient two-photon absorption process; i.e., owing to the long lifetime of the excited states, an electron that is excited by an infrared photon can wait for another photon arrival to be excited to a higher level. A phosphor that contains Er ions, for example, absorbs two 940-nm photons and emits a 530-nm photon. The long lifetime, however, causes a long-lasting phosphorescence, and consequently, a high bit-rate infrared signal turns to a continuous phosphorescence signal that carries no bit-information. To address this problem, we propose a time-space conversion method, in which a phosphorescent disk converts a temporal signal to a spatial signal; i.e., a pulse train that is irradiated

on the rotating disk creates a phosphorescence dot array along the disk periphery. If the phosphorescence is picked up at a downstream position, a quickly-blinking pulse signal is observed regardless of the phosphorescence lifetime. This process is also useful for inducing a signal delay, since a phosphorescent dot has to travel a distance between the irradiation and pickup positions. Further, multiple signals with a varied delay can be generated simultaneously by picking up the signals at several different positions.

On the basis of the above optical system design, we conducted experiments of the signal upconversion and delay. A pulse train with 500-ns duration and 1-MHz repetition rate was generated by modulating a laser beam of 940 nm wavelength. The laser beam was focused on the disk (120 mm diameter) containing upconversion phosphor (YbEr:Gd2O2S), and the phosphorescence was observed at a position 0.1-0.9 mm apart from the irradiation point. The phosphorescence spectrum exhibited peaks at 530 and 660 nm together with a peak at 940 nm that was caused by the scattered laser beam. The output signal was therefore detected through a color filter that cut off the wavelength range beyond 600 nm. The detected optical signal exhibited the same pulse shape as that of the input laser beam. A signal delay of 10-30 μs was also observed depending on the detection point.

8550-123, Session 19

Light output losses of prism light guides

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Cylindrical prismatic hollow light guides are able to transmit daylight properly into the spaces of a building where natural light has a difficult access. Prismatic sheet developments have provided further improvements in sunlight systems, boosting efficiency for specific incidence angles with regard to the aluminum guides. Prismatic lightguide is a prismatic hollow tube with a thin polycarbonate film with right angle prism sections. The prism light guide transmits light by total internal reflection, which gives higher efficiency and homogeneous light distribution through the guide. Transmission through the guide depends on the optical characteristics of the material, the shape of the guide and the fidelity of the geometry in prisms structure. Generally, the associated absorption loss in prismatic film is not evaluated because is rather low; in this study this parameter will be studied in order to quantify the importance in the losses of the design. Furthermore, it is important to analyze the micro-structure prism imperfections of the surfaces like the existence of the curved area on the prism apex which can modify the optical behaviour of the prism film; this imperfections, change the incidence angle and therefore the rays are refracted to other directions instead of undergoing total internal reflections.

In this paper, several cylindrical guides made of transparent dielectric material characterized with an absorption factor have been developed. A numerical simulation has been carried out by software to analyze the flux distribution in the light guidance system comparing the efficiency by optical analysis in different simulations. These simulations include high reproductively related to the light pipe material´s and optical properties including a study of the impact of imperfect geometry which it is necessary to allow rigorous comparison with experimental simulations. The obtained results had been compared with experimental data got by real scale analysis. These experiments indicate the effects of the attenuation due to the absorptance of the material and imperfections in the geometry of the prism film that can play an important role in limiting the transmission of light in high-quality light pipes.

8550-124, Session 19

Method for design of axis-symmetrical TIR-optics with use of special quick raytracing technique

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Most LED lighting devices include LED optics - the refractive optical elements which redirect the light flux from the source and generate the prescribed light distribution. For producing of light patterns with narrow angular size the secondary optics with TIR surfaces is often used. Usually such optics has three surfaces with different roles. The inner surface works on the refraction principle, rays enter the optical element through this surface. The lateral surface works on the total-internal-reflection principle and rotates the side rays from the source. The upper surface works on the refraction principle like inner surface and finishes the beam shaping. Presence of such set of surfaces makes the design process extremely hard. The analytical solutions exist only for point-source approach and they don't work in case of extended light source. And the optimization techniques are very slow because the "real" raytracing procedure takes a lot of time.

Quick raytracing technique adapted for usage with axis-symmetrical surfaces was developed for this problem. The technique is based on splitting of surface of revolution into a big amount of truncated cones and further searching of intersection points for rays and cones. The time of 20 thousand rays raytracing is about 1.5 seconds on computer with Intel® Core™2 Quad processor that allows to use this raytracing method in surface optimization procedures. Few examples of compact TIR lenses designed with use of developed quick raytracing technique are presented. The lenses generate uniformly illuminated circle spots with angular sizes of 10°, 20° and 30° for Cree® XLamp® XP-G LED. The light efficiency of all solutions exceeds 90%.

New raytracing extra-fast technique doesn't use any simplifications that makes possible generation of new high-efficient TIR design in an hour. The only restriction that should be taken into account is axial symmetry of LED lens. Therefore, the set of possible illumination patterns is limited to the various rings and circles. The next step of this work is development of quick raytracing technique for free-form surfaces that enables generation of square, rectangular or even hexagonal illumination patterns with use of TIR optics.

8550-125, Poster Session

Model-based validation and development of LED-systems: MValEnt

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Durability of LEDs is usually specified to 10,000 hours though numerous LED products feature a lesser operation life. This might be caused by faulty constructions or improper physical environments and operating conditions. Since such failure cannot be accepted for cost intensive applications in automotive, medical or illuminating engineering simulation based prediction of LEDs durability is a promising design approach.

Main causes of degradation are manufacturing and operation temperatures or temperature gradients, respectively. These result in an increased diffusion, accelerated chemical reactions and induced material stresses. In a consequence, chemical, physical and mechanical properties of parts are altered.

To investigate conditions of LED operation, LEDs degradation and conditions of failure a test environment considering electrical and thermal loads as well as optical emission has been designed.

Furthermore, the LED test environment has been modeled within the software application MatLAB/Simulink to simulate and predict the durability of complex LED systems.

Test environment, computer-aided simulation and a test design using design of experiments are combined to a design tool named MValEnt (Modellbasierte Validierung und Entwicklung von LED-Systemen). This supports validation and design of complex LED systems for varied conditions of operations and component characteristics. Integrated data interfaces provide an iterative product development.

Load measurements reveal different failure mechanisms due to characteristics of operating current, ambient temperature and pulse-width modulation (pwm) as well as operation interruptions. Electrical and thermal coupling of LED circuits results in additional loads and thus degradation. With increasing power mechanisms of LEDs degradation are comparable to those found in power electronics.

8550-126, Poster Session

Detailed illuminator design for full-field ArF lithography system with a method based on the fly's eye

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Lithography is the key technology to semiconductor manufacture. In the lithography system, with the rapid improvement of projection lens and resolution enhancement technique (RET), the essence of the illuminator can never be overestimated.

Illumination uniformities on both the reticle and the wafer are required, as the variance of the intensity on the wafer makes it hard to control the line width of the pattern. Further, with its direct influence on CD, aspects of the illumination pupil fill become critical. Even though the illuminator does not require as tight a fabrication precision as the projection lens, it does present demanding requirements challenging the designer. Lev Ryzhikov introduced the requirements of the illuminator design, while Paul Michaloski divided the illuminator into three parts: the beam shaping unit, the uniformizers and the relay. Despite this, the peer-reviewed papers or patents on design methods for illuminator are scarce compared with those for the projection lens. Moreover, the commercial design software, like CodeV and Zemax, are especially developed for imaging rather than beam shaping.

In this paper, we designed an illuminator for NA 0.75 lithography system on 90nm node and the exposure field at the reticle plane is 104mm?42mm. The illuminator mainly contains three parts: the beam shaping unit, the uniformizer and the relay lens. In order to construct the matching relationship among the various and complex components in the illuminator, a design method based on the fly's eye, which is the core and starting point, has been proposed. With this method the matching relationship can be determined easily and the illumination NA and size can be guaranteed simultaneously.

At the beginning of the design, the specifications of the fly's eye have been choosen after careful analysis. Also, the diameter of the aperture pupil is obtained, based on which the beam size exiting from the beam shaping unit and the first order of the condenser and relay are determined. Thus, the relationship has been constructed. Meanwhile, we introduced the important design issues of the condenser: the local NA and the angle of the chief ray at each field point across the reticle. Two cylindrical lenses have been inserted into the 1X relay to get the trapezoid intensity distribution in the scan direction. The working principle of the beam shaping unit, which consists of the diffractive optical element (DOE), zoom lens and axicon, has been derived in this article. By switching different DOE, changing the focal length of the zoom lens and the distance between the two prisms, the required shape of source, and can be achieved. The design method for the elements in the beam shaping unit are also shown. The calculated diffractive source in the far field is inserted into LightTools as an apodization source at the entrance face of the fly's eye. A demonstration simulation result is given, and the uniformity of the non-scan and scan direction reached 1.2% and 1.7% respectively under annular illumination. The result showed good performance and the requirements of the lithography tools have been met.

8550-127, Poster Session

Controlling daylight illumination in cultural heritage buildings by using thin-film and thermographic technologies

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The Pórtico de la Gloria (Gate of the Glory) is probably the most relevant masterpiece of the Santiago de Compostela cathedral. It is located at the narthex of the west gate. It is a masterwork of Romanesque sculpture built between 1168 and 1188 by Master Mateo. The naturalism of the figures and the beauty of the composition make this work something unique in the world. During the XVIII century a new Baroque façade was place in front of it replacing the middle ages wall. However, this façade is full of windows to allow daylight lighting of the romanesque work. Although these sculptures are today gray with a color very similar to the granite stone which they are made with, they were painted with a whole palette. In fact the sculptures have been painted in different centuries with many materials and curator must decide how they must work. The spectral reflectance and color characterization have been done in order to evaluate the suitable methodology for cleaning the sculpture. A comparison has been made with the results obtained with chemical, mechanical and laser cleaning tools. This analysis will help to conservator to decide which will be the best solution and how will be the image of this masterpiece after the . . Daylight has been analyzed and Thermal imagers have been used to test the thermal performance of the antireflection treatment used in the windows and how it change the actual temperature of the stone sculptures. Daylight which makes possible to see the masterpiece can produce photochemical deterioration in the pigments but the sun can generate too other serious conservation problems. When the sun hits the sculpture it heats the stone and evaporates the humidity. This water flow moves the mineral salt from back to front and finally they come to the surface and deteriorate the paintings. Thermal imagers have been used to test the thermal performance of the antireflection treatment in the actual temperature of the stone sculptures. Use of multilayer film in order to reduce the direct sun radiation onto the surface sculpture must be designed with these both objectives in mind: minimize the heating of the surface but to maintain the luminance, contrast and color reproduction no far away from the original one. In this work a study about color differences has been developed taking into account all these parameters.

8550-128, Poster Session

Design of blue LEDs arrays with high optical power

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Technical progress in the field of blue light emitting diodes (LEDs) based on III-V compounds has been breathtaking during recent years around the world. With the rapid development of the device, high optical power is expected from blue LEDs in a wide range of applications such as optical-communications, medical optics and Biomedical optics.

In this paper, an array of blue LEDs with high optical power is presented and discussed. Optical of the novel design is completed with the help of running simulation in TracePro to predict the performance of the module.

Cree XP-E LEDs with a square reflector was used in the novel design. In addition, the length and depth of the reflector was 23.7mm and 20mm respectively. To verify the simulation results, Aluminum substrate, Copper substrate and Aluminum reflector have been made, respectively.

Optical characteristics of the samples with different substrates were measured under the HAAS-2000 High Accuracy Array Spectrophotometer at room temperature. The relationship between input current (A) and optical power (mW) of the samples with Aluminum substrate and Copper substrate can be observed that the optical power of sample 2 was higher than that of sample 1 and it can be attributed to the better thermal dispersion performance of Copper. The optical power of sample 1and sample 2 was 8126mW and 9445mW at 2A, respectively. The experiment result of sample 1 is consistent with previous simulation. Due to the better thermal characteristic of Copper substrate, the optical power of sample 2 is even higher than the simulated result.

8550-129, Poster Session

Study of chromatic variations between metameres by varying the lighting in the painting “Boy in a turban holding a nosegay” by Michiel Sweerts

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When artificially lighting a restored painting, it is important to ensure consistency in the visual perception of original and restored areas. The current paper has worked out how chromatic difference varies between restored and original areas when modifying the lighting source. In colorimetry, metamerism is the matching of apparent color of objects with different spectral reflectance. The color of a surface is the value resulting from the product of the spectral reflectance curve of the material and the spectral emittance curve of the lighting source casting light on it. As a result, the color of surfaces depends on the lighting source used to illuminate them. This paper describes the work carried out to study the color difference between original and restored metameric areas of a painting with some chromatic reintegrated areas under different light sources. Firstly, based on an ultraviolet photograph from the painting, the areas with chromatic reintegration were identified. Secondly, using a PR-655 SpectraScan spectroradiometer as well as a calibrated lighting source and measuring geometry 0º/45º, the spectral reflectance was measured at four points of the same apparent color both next to original painting and in chromatic reintegrated areas. Finally, colorimetric calculations for a 2º CIE pattern observer were performed by using spectral measurements. The color difference between the original and the restored areas was estimated under different CIE pattern illuminants by using the CIE L*a*b color space.

8550-149, Poster Session

A ridge waveguide quantum well AlGaAs/GaAs laser design

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An advanced structure of AlGaAs laser diodes has been designed using the simulation software.

Simulation results suggest that the thicknesses of SCH layers, inner cladding and outer cladding layers should be changed in order to give low loss, narrow far-field divergence angle and high confinement factor. The Thickness of the etch stop layer is optimized to give the required effective lateral refractive index. At the end the channel width and ridge width are also optimized to obtain single lateral mode.

The aim of our study was three folds: (1) to provide the comprehensive analysis and calculations to design a ridge waveguide laser. In the simulations, the thicknesses of SCH layers, inner cladding layers and outer cladding layers are varied in order to observe variations of far-field divergence and the total confinement factor as functions of layer thicknesses. Comparison among loss, narrow far-field divergence and high confinement factor are made to optimize layer thicknesses, (2) The thickness of an etch stop layer is optimized to achieve the required lateral effective refractive index difference, and also the far-field divergence of the ridge waveguide laser, (3) the channel width and ridge width are designed to maintain single lateral mode and low loss by using the three layer dielectric slab waveguide calculations. The details of simulation using WAVEGUIDE software are provided in the following figures. Also there is a summary of the designed laser:

Confinement factor (Γ): 0.01297672 , far field Divergence angle (θ) : 26 0

Conclusion:

It is believed that our study might provide an accurate analytical approach to design ridge waveguide lasers. The width of the ridge region is obtained by calculation for single-lateral-mode operation and we have 3.47 micrometers for it which only TE0 mode can propagate which satisfies neff In ridge region: 3.372425, neff in wing regions: 3.37020 the minimum requirement for a perfect laser. The present results are also useful for the design of other equivalent lasers.

8550-150, Poster Session

A digital holography technique for generating beams with arbitrary polarization and shape

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The propagation of polarized light and its interaction with matter have been extensively explored in optical inspection and meteorology, display technologies, data storage, optical communications, material sciences and astronomy, as well as in biological research [1]. While past studies mainly dealt with spatially homogeneous polarization states such as linear, elliptical and circular polarization, in recent years the interest for arbitrary spatially-variant polarized beams has increased significantly due to their special properties compared to homogeneously polarized beams thus enhancing the functionality of optical systems [2].

Recently, we presented an optical setup for the generation of spatially-variant polarization beams using digital holography techniques [3]. Our approach is based on a Mach-Zehnder setup combined with a translucent phase-only modulator in each path of the interferometer. To separate horizontal and vertical component from each other the oscillation direction of beam one is rotated 90º. The transverse x- and y- components of the incident light beam are processed independently, modified by means of specifically designed holograms. Subsequently, the components are recombined and led into the on-axis reconstruction system consisting of a 4f lens arrangement.

In this communication we present a description of the algorithm developed for generating the required holograms. This codification is derived from Arrizon's method to encode complex optical signals using phase-only SLM [4]. Our approach entitles us to encode any polarization state in each point of the wavefront taking into account that the displays used are able to modulate the phase from 0 to 1.4pi and present some amplitude coupling. Additionally, the amplitude of the wavefront may also be modeled so as to obtain a particular shape.

Holograms for different kind of spatially-variant polarized beams are calculated. In particular, we present some results including radial, azimuthal, spiral and other polarization distributions. Regarding the shape of the beam some different cases are considered: Gaussian, Hermite-Gauss, Laguerre-Gauss, etc. The performance of the method and its limitations are be discussed.

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8550-151, Poster Session

Impact of line edge and line width roughness on diffraction intensities in scatterometry

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We investigate the impact of line edge and line width roughness (LER, LWR) on the measured diffraction intensities in angular resolved extreme ultraviolet (EUV) scatterometry for a line-space structure designed for EUV lithography. LER and LWR with amplitudes in the range of a few nanometers can no longer be neglected in the course of the profile reconstruction. The 2D rigorous numerical simulations of the diffraction process for periodic structures are carried out with the finite element method (FEM) providing a numerical solution of the two-dimensional Helmholtz equation. To model roughness, multiple calculations are performed for domains with large periods, containing many pairs of line and space with stochastically chosen line and space widths. The resulting mean efficiencies and their variances in dependence on different degrees of roughness are estimated. The studied structures are composed of TaN-absorber lines with an underlying MoSi-multilayer stack representing a typical EUV mask.

A systematic decrease of the mean efficiencies for higher diffraction orders along with increasing variances is observed and established for different degrees of roughness. In particular, we obtain simple analytical expressions for the bias in the mean efficiencies and the additional uncertainty contribution stemming from the presence of LER and/or LWR. As a consequence this bias has to be included into the reconstruction model to provide accurate values for the evaluated profile parameters. We resolve the sensitivity of the reconstruction in dependence on the revealed bias by using the LER/LWR perturbed efficiency datasets for multiple reconstructions. If the datasets are bias-corrected, significant improvements are found in the reconstructed bottom and top widths toward the nominal values.

8550-154, Poster Session

Precise control of the light-induced deformation of azobenzene polymers: new insight and ideas

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Photoresponsive polymers containing azobenzene moieties in their structure have been extensively explored in the last decade as photo-deformable smart materials which are able to transform light energy into mechanical stress [1, 2]. Presently, there is a great need for theoretical approaches to accurately predict the quantitative response of these materials based on their microscopic structure. We propose a microscopic theory which is able to describe the light-induced deformations of azobenzene polymers of different chemical structures: uncross-linked low-molecular-weight azobenzene polymers [3] and cross-linked azobenzene networks [4, 5]. Our theory provides the values of the light-induced stress comparable and higher than the values of yield stress typical for glassy polymers. Thus, the theory is able to explain the possibility for the inscription of surface relief gratings (SRGs) in glassy azobenzene polymers. We show that depending on the chemical structure, an azobenzene polymer can either elongate or contract along the polarization direction of the light [3]. Using this finding, the direction of light-induced mass transport under SRGs can be exactly predicted and controlled that is important for production of optical elements such as sensors, actuators, data storage, etc. Our theoretical treatment has been extended to describe the light-induced deformation of cross-linked azobenzene networks [4, 5]. Because of the large absorption coefficient of azobenzene chromophores, the laser light is absorbed nonuniformly across the thickness of the film leading to its bending [5]. Depending on chemical structure, a polymer film can demonstrate the bending deformation toward / away the laser source, the direction and magnitude of bending deformation being exactly controlled by the intensity and polarization direction of the light. Theoretical calculations of the magnitude of bending deformation are in a good agreement with experiment [6]. Bending is a three-dimensional movement and is of a special interest for different technical applications, especially for artificial muscles, microrobots, micropumps, etc. Our theoretical findings can be fruitful for further development of photosensitive smart materials with exactly controllable optical response.

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8550-130, Session 20

3D modeling of metamaterials at oblique incidence and effective analysis

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The straightforward modeling of a metamaterial at its characteristic scale is a broad issue. The use of the "material" word implies that one can measure macroscopic quantities from it (such as an effective permittivity or an effective permeability). This approach has yet to be validated for any angle of incidence. The dependence of the refractive index on this angle becomes especially strong when the system is in the grazing incidence configuration, or as it starts guiding light. An effective model thus becomes of great importance if one wants to model the behavior of complex integrated devices based on metamaterials.

The studies presented here have been done as part of the ANR METAPHOTONIQUE project, whose first purpose is to design metamaterials operating on top of SOI guiding structures (Silicon on Insulator) at 1.55 micron. We present results of 3D simulations, done through the FDTD method, of a metamaterial of which the optical response has been computed at normal incidence and oblique incidence. The algorithm used for the computations at oblique incidence is briefly presented, and relies on a modified version of [1].

Those structures are strongly anisotropic, and describing them through an effective index model requires the knowledge of the permittivity and permeability tensors. We show that those tensors can be retrieved numerically thanks to the simulation data at both normal and oblique incidence [2], fitted using [3] coupled to an optimization algorithm. We then study the range of validity of the effective index model, and under which conditions it cannot be applied for the presented structures.

Finally, we compute the optical response of the metamaterial in the guided light configuration, that is when the structures are crafted on top of a silicon waveguide, and study the behavior changes of the structure with respect to the different TE and TM modes in the waveguide. We then compare those results with the expected ones assuming the effective index model is valid.

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8550-131, Session 20

Stochastic physical optics and Bell's theorem

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In theoretical physics the EPR paradox plays a significant role in discussions whether or not quantum mechanics is a statistical theory or not. Recently, the author has demonstrated (Adv. Studies Theor. Phys., Vol. 4(20), 945-949 (2010) and Adv. Studies Theor. Phys., Vol. 5(11), 545 - 549 (2011)) that classical statistics is sufficient to explain quantum paradox. Because most of the time experiments on the Clauser Horne Shimony and Holt (CHSH) contrast were performed with photon sources, this conclusion is relevant to photon measurement theory. In the presentation the previous claim is finalzied using a 'stage gate' conception of the measurement instrument plus a stochastical argument.

8550-132, Session 20

Vector Slepian functions and the inverse problem of high numerical aperture focusing

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Precise control of the focal spot of a high numerical aperture (NA) lens is a central problem in several optical applications such as laser scanning microscopy, optical trapping and laser micromachining. There have been several examples of the design of annular amplitude or phase masks for an input beam with a given amplitude profile and polarization state [1--4]. These calculations usually rely on the Debye--Wolf diffraction integral [5] for determining the focused field.

Instead of the direct numerical evaluation of the Debye--Wolf integral, some methods use analytical series expansions such as the multipole theory of focusing [6], the technique of Kant using Gegenbauer

polynomials and spherical Bessel functions [7], the extended Nijboer--Zernike approach [8] or the scalar eigenfunction expansion of Sherif et al. using Slepian's prolate spheroidal functions [9]. Some of these methods were also used for solving the inverse problem of focusing [10-12]. Recently, a technique using dipole arrays has also been proposed [13, 14].

Based on the multipole theory of focusing [6], we recently proposed the orthonormal basis of vector Slepian harmonics (VSLHs) by investigating Slepian's concetration problem for tangential vector fields on the sphere [15]. The VSLH basis is naturally suitable for approximating the illumination in a high NA system. Its main advantage is that a subset exhibits excellent directionality, i.e. its angular energy distribution is confined to the solid angle of illumination. Each VSLH basis function represents the angular spectrum of a focused field described by a corresponding vector Slepian multipole field (VSLMF). The directionality of the VSLHs allows us to approximate common illumination angular spectra using a smaller number of coefficients than a representation using the vector spherical harmonics [15]. Besides being advantageous for inverse focusing problems where the number of parameters is desired to be kept as small as possible, no additional constraints are needed to ensure the directionality of the illumination.

We demonstrate the applicability of these novel vector bases for inverse problems in high NA focusing by prescribing a three-dimensional intensity distribution in some reasonably chosen volume around the focus and finding the corresponding illumination. As illustrations, three examples are considered: the optical needle [13], tube [14] and bubble [4] focal spots. The focused field is approximated by a finite linear combination of VSLMFs and numerical optimization is used to determine the coefficients with the integrated squared difference between approximate and the prescribed intensity used as a cost function. With the help of the coefficients obtained, the corresponding illumination can be calculated in a straightforward way.

The examples presented involve a cylindrical vector beam illumination, however, our method can easily be applied to construct illuminations exhibiting other inhomogeneous polarization patterns, as well as the conventional linearly and circularly polarized ones. In these three illustrative cases, our general method produces comparable results to those previously published using special techniques, or even surpasses them in some aspects.

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8550-133, Session 20

Optical characterisation of polymeric nanocomposites using tomographic, spectroscopic and Fraunhofer wavefront assessment

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Polymeric nanocomposites (PNCs) provide the potential to realise enhanced material properties such as stiffness, strength and electrical conductivity for small amounts of nanofillers; the level of particle loading within the material affects the scaling of the properties that needs to be enhanced. Uniform dispersion is a key to success, however there is currently a very limited number of characterization techniques (X-ray diffraction and transmission electron microscopy) to study dispersion profiles. The main drawbacks associated with these techniques that need to be overcome is the capability of analysing dispersion profiles at higher levels, the analysis of larger areas, in addition to the reduction of time and cost associated during their assessment.

This work presented has concentrated on the non-destructive characterisation of larger sample areas facilitated by optical coherence tomography (OCT), oscillatory photon correlation spectroscopy (Osc-PCS) and Fraunhofer wavefront correlation (FWC).

OCT uses four beams focusing at different depths of the material, with each beam operating in a frequency swept mode. By inverse Fourier transforming the resulting back-scattered radiation, it is possible to acquire two dimensional (2-D) information resulting from refractive index boundaries within the material. In order to numerically quantify the visual representation resulting from the measurement data, it is necessary to post-process the images by performing image analysis and study the greyscale standard deviation between different segments at different depths for each sample. Each layer is also analysed in terms of particle count and total area covered. By repeating the process throughout the material, an accurate picture of the level of dispersion can be provided.

In Os-PCS, two laser beams intersect to create an ellipsoid volume of interference fringes; the material under investigation is placed at the measurement volume and mechanically oscillated. During this process, photons are scattered and analysed by means of their auto-correlation function (ACF). The ACF is directly affected by a number of parameters of the optical configuration, in addition to the quality of the medium, which is the PNC in this case. By analysing the dynamic range of the ACF it is possible to differentiate between various dispersion profiles.

FWC uses a generated 2-D optical waveform; materials under test are placed in the optical propagation path of the pattern such that the emerging wavefront becomes spatially modulated by the material itself, with the camera capturing each emerging wavefront. Each wavefront resulting from PNC samples is cross-correlated with the one resulting from a neat polymer and the analysis of the cross-correlation plane, in terms of the resulting signal-to-noise energy, allows the discrimination between levels of loading and dispersions.

A number of different transparent, semi-transparent and opaque materials have been analysed, with various levels of particle loadings and dispersion profiles. The nanofillers used for the preparation of PNCs have included clay, ZnO, $LiAlO_2$ and multi-walled carbon nanotubes. The three optical techniques investigated have presented the capability to characterise PNCs in a non-destructive manner, also enabling the study of much larger material areas with shorter measurement times compared to existing techniques.

8550-134, Session 21

Scalar wave solution for the scattering of a partially coherent beam from a statistically rough metallic surface

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The scattering of a spatially partially coherent wave from a one-dimensional statistically rough metallic surface is investigated. Assuming a Gaussian Schell-model form for the incident field autocorrelation function, a closed-form expression for the scattered field autocorrelation function is derived using the physical optics approximation (Kirchhoff approximation). Two forms of the solution are derived-one applicable to very rough surfaces and the other applicable to moderately rough surfaces. It is shown that for very rough surfaces, the solution, under certain circumstances, remains Gaussian Schell-model as has been previously reported. As such, closed-form expressions for the angular coherence radius and angular scattering radius are derived. These expressions are, in general, complicated functions of both the source (size and coherence properties) and surface parameters (surface height standard deviation and correlation length). It is demonstrated that for many scenarios of interest, the angular coherence radius can be safely approximated as a function of just the source parameters and the angular scattering radius can be simplified to a function of just the surface parameters. For the moderately rough surface solution, the scattered field autocorrelation function is in general not Gaussian Schell-model and it is therefore not possible to derive analytical forms for the angular coherence radius or angular scattering radius. Nonetheless, the form of the autocorrelation function is physically intuitive and is discussed in this work. To verify the presented theoretical analysis, wave optics simulation results are presented and compared to the predictions of the analytical models. This analysis is concluded with a discussion of future work.

8550-135, Session 21

Optical vortex scanning microscopy with new scanning technique

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The idea of microscopic imaging with phase singularities is more than forty years old. A few concepts have been proposed so far. One of them is based on using optical vortex as a phase marker seeded inside the scanning beam. For this purpose we need to introduce an optical vortex into a scanning beam. The most popular method is to put into a laser beam special element which can be called “vortex generator”. The most popular vortex generators are holograms (also obtained with spatial light modulators) or spiral phase plate (vortex lens). The vortex generator opens one more possibility. Instead of moving the sample (or the whole beam) we can move the vortex generator. What we expect is that vortex point (i.e. point where the phase is undetermined) follows the vortex generator move at the reduce range (inside a focused beam). We derived formulas describing the vortex point’s trajectory in a system consisting of: laser beam (Gaussian beam), vortex lens (as vortex generator), and microscopic objective. The conclusions are surprising. We assume here that vortex lens moves along x-axis. In such a case a vortex trajectory is also a line, but the angle  between vortex trajectory and x-axis depends on the position of the observation plane. This angle changes very rapidly when being closed to the waist plane of the focused Gaussian beam. At the specific position (critical position), the vortex trajectory becomes perpendicular to the vortex generator shift. Our theoretical results were confirmed by experiment. We have also investigated the influence of various system imperfections on the vortex trajectory. The conclusion is that standard errors in optical element manufacturing and system adjusting are not harmful for the effect described above. When inserting the phase micro-step at the critical position the vortex point (inside the diffracted beam) behaves in a characteristic way. The reason is that on the both sides of the phase step the critical position differs a bit. This small difference is strong enough to change the optical vortex behavior. Observing this behavior we can find the position of the phase step which resolution exceeding classical limit. In our presentation we show the results concerning the vortex dynamics caused by vortex generator shift. We discuss also the possible methods for high precision measurements with our new scanning technique.

8550-136, Session 21

Diffraction efficiency considerations and experimental realization for adaptive phase gratings with liquid crystal panels

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We report on diffraction efficiency considerations and experimental implementation of diffraction gratings by means of a phase-only spatial light modulator, parallel aligned (PAL) liquid crystal on silicon (LCoS) display. We present results of the implementation of continuous phase profiles with optimal efficiency, and their application for blazed gratings, diffractive lenses and digital holograms.

8550-137, Session 21

Application of extraordinary transmission effects for contrast enhancement in optical lithography

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Lithographic techniques are being challenged by the constant technological demands for smaller feature sizes. Lithographic masks with thin absorber layers are preferred because of their better imaging properties and fabrication considerations. On the other hand, the residual transmission through thin absorber layers decreases the intensity contrast between the nominally transparent and intransparent areas of the patterned mask. In this context, we investigate the extraordinarily low transmission effect in structured ultrathin metal films in the visible spectral range. The “posts” structure consists of squared metal islands with the same width and periodicity in both lateral dimensions. A commercially available Rigorous Coupled Wave Analysis Tool - “Dr.LiTHO” - developed by our coworkers was used for initial simulations [1]. The theoretical results indicate a resonant effect. The resonance wavelength mainly depends on the width of the remaining metal islands. For our experimental studies, a 30 nm thick metal film is fabricated on a BK7 glass substrate via magnetron sputtering and structured by Focused Ion Beam (FIB) milling. The sample is probed in a self-built far field scanning setup (similar to [2]) whereby transmission and reflection can be measured simultaneously. In the confocal setup the incoming light is focused onto the sample with a microscope objective which is also used to collect the backscattered light while a second high numerical aperture objective is collecting the forward scattered light. The sample can be scanned through the beam via a 3D piezo stage that enables high resolution positioning in the nanometer range. Results gained by probing the geometrical parameter space and measuring the resonance curves support the theoretical predictions. In order to further investigate the plasmonic excitation responsible for the suppressed transmission effect, the angular dispersion of the resonance is measured. Simulations and experimental results [3], especially those proving an almost vanishing angular dispersion, indicate that a localized plasmonic excitation inside the single building blocks of the metamaterial structure is responsible for the resonantly suppressed transmission in these ultrathin films. Obviously the single posts act as individual antennas. This simple antenna model is also in agreement with the accompanying enhanced reflection. These results suggest that only a few post structures are required to suppress the transmission in the close vicinity of larger openings. Therefore a possible application in thin metal masks for optical lithography is investigated theoretically and tested experimentally. For that purpose, mask structures consisting of squared openings with an increasing number of surrounding posts structures are fabricated. The measured

contrast enhancement could be useful for performance enhancement for example in the field of mask aligner lithography [4].

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8550-138, Session 21

Intensity fluctuations of scattered light caused by acoustic phonons in H-bonded liquids

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1/f fluctuations are widely observed in various physical, chemical and biomedical systems. T.Musha [1] have explained one manifestation of this phenomenon as energy partition fluctuations among phonon modes in homogeneous (quartz) and inhomogeneous (water, electrolyte solutions) media by means of light scattering experiment. The experimental result for liquids shows that the scatterers are not propagating ones such as phonons, but localized ones.

It was shown [2,3] that H-bonded liquids have structural heterogeneities of nanometer size (supramolecular ones) which can act as localized scatterers of a light beam.

In this study the 1/f fluctuations of light scattering in H-bonded liquids has been investigated. Relationship between statistical parameters of fluctuations and structural properties of media is discussed. Experimental method is used the fact of specific angular distribution for different types of scattering. Useful signal is formed as a differential intensity of two beams which are scattered at angles 90±phi. According to T.Musha this fraction of intensity of light caused by scattering on acoustic phonons.

The experimental setup consist of semiconductor laser (405 nm, 60 mW), a specimen which was provided in a PMMA cuvette, two-beam optical scheme, synchronous detection and PC. It is observed dependence of the parameter alpha on the molar ratio water/glycerol. We explain the distinction of the parameter alpha as a difference in molecular packing in liquids and the existence of different-scale inhomogeneities where acoustic phonons may be localized.

By examining the percullation model in H-bonded liquids distribution of inhomogeneities by size depends on the average number of active bonds. Particularly, by changing molar ratio in water/glycerol solution accompanied restructuring and change the effective inhomogeneities size[3].

This work provides new experimental evidences for existence of supramolecular inhomogeneities in H-bonded liquids.

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8550-139, Session 22

Parabasal field decomposition and its application to non-paraxial field propagation

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We propose a parabasal field decomposition of non-paraxial fields, which enables various operations on such fields which are otherwise not feasible because of too high numerical effort. It is useful to distinguish between two basic cases of non-paraxial fields: 1) The field can be sampled without problems in the space domain but it is very divergent because of small features. A Gaussian beam with large divergence is an example. In this case the propagation of the field typically causes too high numerical effort and is not feasible. 2) The field possesses a smooth but strong phase function, which does not allow its sampling in space domain. Spherical, cylindrical and astigmatic waves with small radius of curvature are examples. In this case all operations which require a field sampling cannot be applied. For both cases a parabasal field decomposition is suggested which overcomes the problems. By separating linear phase factors from the parabasal fields the sampling effort is reduced drastically. This technique is applied to propagate non-paraxial fields.

8550-140, Session 22

Gaussian beam Z-scan analysis for nonlinear optical materials possessing simultaneous third- and fifth-order nonlinear refraction with saturable absorption: an application to semiconductor CdSe quantum dot-polymer nanocomposites

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A Z-scan technique presented by M. Sheik-Bahae et al. in 1989 has been widely used for characterizing the nonlinear optical properties of various photonic materials.

The original Z-scan theory treats nonlinear optical materials possessing either the third-order nonlinear refraction with two-photon absorption (TPA) or the fifth-order nonlinear refraction without TPA. Later, the theory was extended to nonlinear optical materials possessing either multiphoton absorption or saturable absorption (SA). Also, the extension of the theory to more general case was done for nonlinear optical materials possessing the third- and fifth-order nonlinear refraction without nonlinear absorption. These extensions also include the open-aperture Z-scan for simultaneous TPA and three-photon absorption and the closed-aperture Z-scan for simultaneous third- and fifth-order nonlinear refraction with TPA. Such generalization is useful for materials characterization and design of photonic devices such as optical limiters and all-optical photonic switches/logic gates using third- and higher-order nonlinear optical effects. However, no Z-scan theory has been reported so far for the closed-aperture Z-scan that takes both SA and simultaneous third- and higher-order nonlinear refraction into account. Such a high-order nonlinear effect was indeed observed in our recently developed novel nonlinear inorganic-organic nanocomposites, the so-called photopolymerizable semiconductor CdSe quantum dot-polymer nanocomposite (QDPN) capable of constructing nonlinear photonic crystal structures by holographic patterning.

In this work we present a theoretical analysis of the closed-aperture Gaussian beam Z-scan for nonlinear optical materials with both SA and simultaneous third- and fifth-order nonlinear refraction. We show that a theoretical expression for the closed-aperture Z-scan transmittance can be found by means of the Adomian's decomposition method and the thin film approximation. It is found that the shape and symmetry of the closed-aperture Z-scan transmittance are strongly influenced by the relative sign and magnitude of the fifth-order optical nonlinearity with respect to the third-order one. Because the light-induced transparency takes place due to SA, the peak and valley transmittances increase in the closed-aperture Z-scan setup. The theoretical model is applied to the experimental characterization of the nonlinear optical properties of QDPN films by using a single-shot picosecond laser operating at a wavelength of 532 nm. Our measured results of the open- and closed-aperture Z-scan transmittances of QDPN films are well explained by the theoretical analysis. It is shown that QDPN films exhibit SA of a homogeneously broadened type as well as the negative third-order and the positive fifth-order nonlinear refraction. Such coexistence of the third- and fifth-order optical nonlinearities was also confirmed by our degenerate multi-wave mixing measurement. The intrinsic and cascaded contributions to the effective fifth-order optical nonlinearity are also discussed. Finally, it should be stressed that the Z-scan model presented in this work has been proved to be useful for characterizing the nonlinear optical properties of novel QDPN materials capable of constructing nonlinear photonic crystal structures by holographic patterning.

8550-141, Session 22

Numerical simulation of a tunable ultrashort laser pulses generation using a distributed feed-back LiF:F2- laser

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Preliminary results obtained in numerical simulation of the generation of single ultra-short and tunable wavelength (1140 -1280nm) laser pulses using lithium fluoride crystals with F2- color centers (LiF:F2-) as active media mounted into a Distributed Feed Back (DFB) setup are presented. For pumping the LiF:F2- active medium is used a dynamic interference pattern generated by a high energy laser pulses with 5-10 ns FWHM duration emitted by an Nd:YAG laser oscillator at 1064 nm. An analysis of the pumping Nd:YAG laser resonator is performed regarding its output spatial and temporal coherence. The use of variable reflectivity mirrors for design of the pumping Nd:YAG laser resonator is numerically simulated. Two numerical simulation procedures are considered for the LiF:F2- DFB setup analysis: one based on solving a rate equation system and the other relaying on equations developed on the structure of pumping.

8550-142, Session 22

Tilt operator for harmonic fields and its application to propagation through plane interfaces

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The propagation of harmonic fields between non-parallel planes is a challenging task in optical modeling. Many well-known methods are restricted to parallel planes. However, in various situations a tilt of the field is demanded, for instance in case of folded setups with mirrors and tolerancing with tilted components. We propose a rigorous method to calculate vectorial harmonic fields on tilted planes. The theory applies a non-equidistant sampling in the k-space of the field before rotation in order to obtain an equidistant sampling of the rotated field. That drastically simplifies the interpolation challenge of the tilt operation. The method also benefits from an analytical processing of linear phase factors in combination with parabasal field decomposition. That allows a numerically efficient rotation of any type of harmonic fields. We apply this technique to the rigorous propagation of general harmonic fields through plane interfaces. If the field is known on the interface a fast algorithm results from a plane wave decomposition of the field. However in general, the field is not known on the interface. Then a rotation operator must be applied first.

8550-143, Session 22

Investigation the effect of shapes, size, and orientation of dielectric rods on the photonic band gap for various lattices in 2D anisotropic photonic crystals

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The photonic band structures of two-dimensional anisotropic photonic crystals have studied by solving Maxwell's equations with use of the plane-wave expansion method.

Three distinct theoretical approaches are pursued: the calculation of photonic bands and density of states, and of modes in the gap associated with line and point defects; the calculation of optical properties like reflection, transmission and diffraction; numerical simulation of the propagation of electromagnetic waves in photonic crystals, including the effects of disorder.

We have calculated the photonic band structure for electromagnetic waves in a structure consisting of a periodic array of parallel dielectric rods of various cross sections, whose intersections with a perpendicular plane form a different shape of lattice.

We reveal that a maximum absolute band gap for these structures is achieved for an intermediate rotation angle of the rods. This angle depends on the radius of the rods and the refractive index of the background material.

It has recently been reported that the symmetry reduction of atom configuration by introducing two-point basis set in simple 2D lattices can remarkably increase absolute band gaps. Owning to different refractive indices for electromagnetic waves with E and H polarization, the band gaps for the two polarization modes can be freely adjusted and matched to overlap optimally. The anisotropy in atom dielectricity can break the degeneracy of photonic bands and remarkably increase absolute band gaps. We prefer to choose the extraordinary axis of uniaxial crystal parallel to the extension direction of rods with a positive anisotropy.

We considered three type of lattice (triangular, square and Hexagonal) with anisotropic tellurium rods in air background with different geometric shapes (oval, circle, square, hexagon and rectangle).

The numerical results show that the overlap photonic band gap (PBG) between the TM and TE gaps (polarization-independent PBG) is the largest for a triangular lattice of oval rods with 0^°orientation. The overlap PBG for a square lattice of rectangular rod with (150)^° orientation is the next largest.

An important result is that compared to isotropic photonic crystals, which maximum photonic band gap is achieved by selecting a rod of the same symmetry with lattice; this inference is not true in the case of anisotropic crystals.

8550-144, Session 23

Imaging characteristics of binary and phase shift masks for EUV projection lithography

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Projection lithography at a wavelength of 13.5nm (EUV-lithography) employs reflective masks. These masks consist of a multilayer stack to reflect the incident light and absorber features with a typical thickness in the order of 4-6 wavelengths to block the reflection in the nominally dark areas of the mask. Local removal or vertical shift of parts of the multilayer and thinner absorber features can be used to devise phase shift masks for EUV-lithography. To separate the reflected from the incident light, the masks are obliquely illuminated. The light diffraction from relatively thick absorber patterns and the angular dependency of the multilayer reflectivity result in several imaging artifacts like feature- and focus-dependent feature size and telecentricity errors.

We apply rigorous electromagnetic field (EMF) simulation in combination with vectorial projection image modeling to explore the impact of mask geometry and material parameters on the characteristics of lithographic image projection. To obtain correct results, the light diffraction from the mask is rigorously computed for several representative incidence angles of the respective illumination source. The resulting images are evaluated in terms of obtained feature size and placement versus the focus position of the projection system. The obtained results demonstrate the sensitivity of EUV-typical imaging artifacts versus mask parameters. Different types of masks including standard binary masks and various types of phase shift mask are evaluated and compared. An optimization strategy to minimize the imaging artifacts is outlined.

8550-145, Session 23

Wafer thin film effects in lithographic focus detection

Daniel G. Smith, Nikon Research Corp. of America (United States)

No Abstract Available

8550-146, Session 23

In situ aberration measurement technique based on aerial image with optimized source

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An in-situ aberration measurement technique based on aerial image with optimized source is proposed. A linear relationship between aerial image and Zernike coefficients is established by principle component analysis and regression analysis. The linear relationship is used to extract aberrations. The impacts of the source on regression matrix character and the Zernike aberrations measurement accuracy are analyzed. An evaluation function for the aberrations measurement accuracy is introduced to optimize the source. Parameters of the source are optimized by the evaluation function using the simulators Dr.LiTHO and Prolith. Then the optimized source parameters are adopted in our method. Compared with the previous aberration measurement technique based on principal component analysis of aerial image (AMAI-PCA) [1], the number terms of Zernike coefficients that can be measured are increased from 7 to 27, and the Zernike aberrations measurement accuracy is improved by more than 20%.

Reference:

[1] Lifeng Duan, Xiangzhao Wang, Anatoly Y. Bourov, et al., “In situ aberration measurement technique based on principal component analysis of aerial image,” Opt. Express 19(19) , 18080-18090 (2011)

8550-147, Session 23

High numerical aperture Hartmann wavefront sensor with pinhole array extended source

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With the development of low k1 lithography, the requirements on aberration of projection objective (PO) are increasingly stringent. Rapid and accurate in situ lens aberration measurement is essential to ensure output and yield. In recent years, a variety of pupil phase measurement techniques for in situ lens aberration measurement have been reported, including ILIAS (integrated lens interferometer at scanner), iPot (integrated projection optics tester) and iPMI (in situ phase measurement interferometer). In these measurement systems, instead of point source smaller than resolution limit of test optics, extended source is used to provide sufficient light intensity on detector when using light provided by illumination system of exposure tool. For example, iPot uses diffuser on a pinhole reticle to form extended source. Instead of point diffraction, iPMI use line diffraction to increase light transmittance. In this paper, a novel high numerical aperture (NA) Hartmann wavefront sensor with pinhole array extended source is proposed. The sensor can be integrated on lithography tool to conduct in situ aberration measurement. The sensor uses source mask with pinhole array on the object plane of PO to filter the aberration of illumination optics as well as provide sufficient power required by Hartmann sensor. When illuminated by the uniform light with coherence factor of 1, the pinhole array produces an array of spatially incoherent point sources. The extended source propagates through PO under test. A coupling objective (CO) is installed at confocal position of PO. The CO transforms high NA spherical waves produced by PO to plain waves, which can be measured by Hartmann sensor. The measurement result consists of not only aberration of PO, but also but also aberration of CO and other some systematic errors. A null mask, which has similar structure with source mask, can be inserted at the image plane of PO. With the null mask installed and source mask uninstalled, test result consists of only aberration of CO and some systematic errors, which can be calibrated by a relative measurement process. In this paper, some design considerations of source mask are presented. Pinhole spacing of source mask must be carefully determined to obtain an array of spatially incoherent point sources. Van Cittert-Zernike theorem is used to determine pinhole spacing values which make complex degree of coherence for adjacent pinholes on object plane of PO to be zero. Fourier optics theory is used to determine the maximum allowable pinhole array area. Finally, measurement accuracy of the sensor is evaluated using three-dimensional electromagnetic simulation of high NA converging beam propagation through pinhole with different pinhole parameters. Simulation results show that, measurement accuracy of the sensor is better than 0.5 nm rms in theory after systematic errors calibration.

8550-148, Session 23

In situ aberration measurement technique based on quadratic Zernike model

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A novel technique (AMAI-Quad) for aberration extraction of lithographic projection based on quadratic relationship model between Zernike coefficients and aerial images is proposed. Zernike coefficients in this case represent the imaging quality of lithographic projection lens in a semiconductor wafer exposure scanner. The proposed method uses principal component analysis and multivariate linear regression for model generation. This quadratic model is then used to extract Zernike coefficients by nonlinear least-squares. Compared with earlier techniques, based on a linear relationship between Zernike coefficients and aerial images, proposed by Duan[1], the new method can extend the types of aberrations measured. The application of AMAI-Quad to computed images of lithography simulators Dr.LiTHO and PROLITH for randomly varied wavefront aberrations within a range of 10nm demonstrated an accuracy improvement of 20%.

References

1.L. Duan, X. Wang, A. Y. Bourov, B. Peng, and P. Bu, “In situ aberration measurement technique based on principal component analysis of aerial image,” Opt. Express 19(19), 18080- 18090(2011).

Plenary Sessions

Plenary Session

Photon Absorption in Intermediate Band Solar Cells

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The Intermediate Band (IB) solar cell is a device that delivers to the external circuit photons with energy below the bandgap at a voltage limited by the bandgap, using a band of energy located within the bandgap a stepping stone (two photons are needed for generate an electron hole pair). A very high efficiency limit has been calculated for this device. They are manufactured either using as IB the confined levels of quantum dots (QDs) with IBs formed by certain impurities.

The QD way is probably closer to current cell technology. A major problem of current IB solar cells is the below-bandgap photons. Simplified quantum calculations are presented to explain the QD energy spectrum and why QDs absorb photons poorly. More desirable QDs are presented taking also into account the preservation of the voltage. Furthermore, photon management techniques to enhance the absorption based on far and near field photon absorption are presented.

Plenary Session

Manufacturing of Freeform Optical Components

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Optical freeform surfaces find wide applications in the fields of optics, photonics, telecommunication, and commercial products. Due to the geometrical complexity and optical particularity, machining of optical freeform surfaces is more difficult comparing to conventional machining. The freeform feature points are designed according to the application requirements. These points are fitted to the NURBS formula with the calculation of linear equation. Therefore, the designed points of freeform become math formula, and the attributions of freeform surface can be calculated. At the same time, the given points have the mapping coordinates in the NURBS variable space, where other points in the freeform surface also have their NURBS coordinates due to interpolation technique. The tool path of machining can be generated by the formula derivation of fitting surface considering the mechanism of three-axis lathe.

Another important thing for the machining is to get the cutting tool path with the radius compensation. The cutting interrelation is the main problem in freeform machining because the surface is undefined. The interrelation would impact the machining accuracy, and even destroy the machine, cutting tool and workpiece. The solution for this problem is to determine the right parameters of cutting tool before cutting. The range values of cutting tool parameters, including the rake angle, cutting edge radius and clearance angle are calculated in advance according to the surface feature. The feature of freeform surface is analyzed using the proposed sectional curve method.

Plenary Session

Transformation Optics

Ulf Leonhardt, Univ. of St Andrews, United Kingdom

The field of transformation optics and metamaterials has been named by Science as one of the top ten research insights of the last decade (in fact, it was the only one in physics and engineering that made it into the top ten). What is it? In transformation optics manmade dielectric materials, called metamaterials, are used to implement a coordinate transformation of space (or in some cases of space and time). What can it do? For example, such transformation devices can make things invisible or create perfect images with a resolution no longer limited by the wave nature of light. These and other applications will be discussed in the lecture.

Plenary Session

Recent Developments in Optics for Solid State Lighting

Rubén Mohedano, Managing Director, LPI-Europe, Spain

LED performance features have experienced a spectacular evolution in the recent years. The possibility of getting high quality white light, along with the increase in luminance, make LEDs a worthwhile alternative in almost all illumination applications. This not-new-anymore type of light source has its own challenges, tough, which make lamp retrofitting a quite inefficient choice in most cases. Customized optical designs, adapted to LED characteristics and to the specific illumination goals can make LED-based concepts a real alternative even in high flux applications. This work will show examples of advanced optical designs adapted to particular illumination problems and overcoming the specific LED challenges in such contexts.

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