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INSTITUT FÜR
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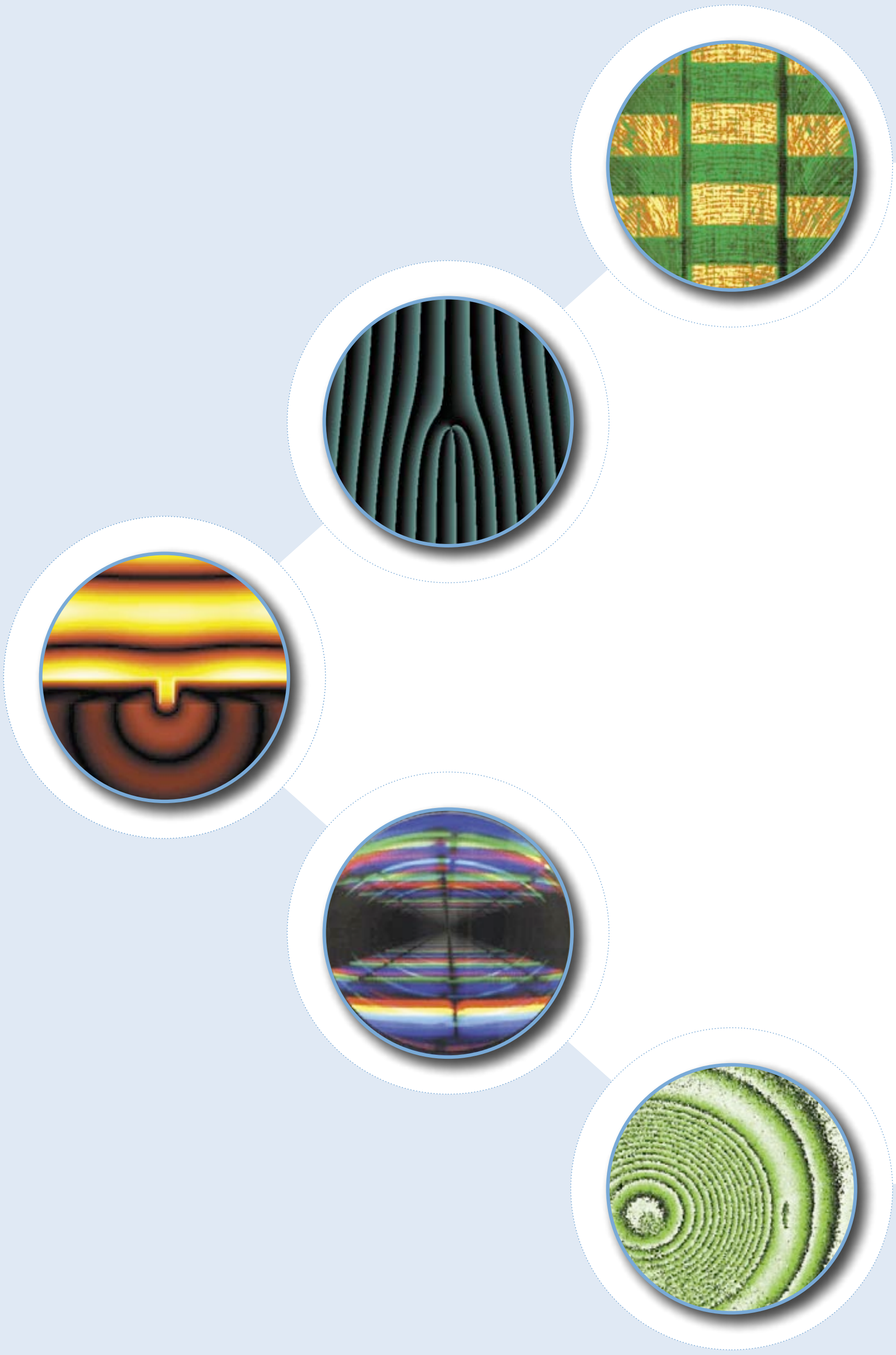
UNIVERSITÄT STUTTGART



Universität Stuttgart

Interferometry and Diffractive Optics

The New Cleanroom:
Fabrication of Diffractive Optical Elements and high precision metrology

Hybrid (diffractive/refractive) objectives for 3D-PMD-measurement cameras
Supported by: BMBF (FKZ 16SV2309)
Project: "Lynkeus: Mikrointegrierte 3D-Echtzeitkamerasysteme für die intelligente Umgebungserfassung"

Refractive and diffractive micro-optics for the
minimal invasive acquisition of combustion parameters
Supported by: Landesstiftung Baden-Würtemberg, Phtotonics BW

Flexible aspheric testing: an interferometer with a dynamic test beam
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Low loss, highly stressable grating waveguide structures for
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Project: "PolGit"

High resolution optical rotary encoders
Supported by: AIF (219 ZN)
Project: "Drehgeber"

Wavefront scaling for interferometry
Supported by: Landesstiftung Baden-Württemberg
Project: "Metamo"

The New Cleanroom:

Fabrication of Diffractive Optical Elements and high precision metrology

Christof Pruß, Thomas Schoder, Markus Freudenreich

On July 7th 2006 the rebuilt laboratories of ITO were presented to the public. To meet future challenges in both the fabrication of diffractive optical elements and high precision metrology, the Institute cleanroom has expanded to about 100 m^2. The cleanroom is located in the basement of the building, providing free standing, vibration isolated foundations for the most delicate equipment, such as the two laser direct writing systems (CLWS 300) and interferometry equipment. The temperature is stabilized to better than 0.2 K in areas where it is needed and the cleanroom is specified as class 100 in relevant areas. A flexible filter fan unit concept allows us to integrate all the required functionality into the existing building.

The clean room labs are equipped with central purified air, cooling water, vacuum and process gases.

The fabrication of diffractive optical elements is performed in the rooms on the left hand side (see Fig. 2). The main equipment are two CLWS 300 laser direct writing systems working in polar coordinates, a RIE dry etching system, the wet bench, and a mask aligner (MA).

The wet bench contains an automated integrated spin coater modified for the usage of large and bulky substrates, a high temperature hot plate, 2 sinks with ultrasonic agitation and a quick dump rinser.

The processes are specified for the large substrates which are typical for optical applications. Diameters up to 200 mm and substrate thicknesses of up to 20 mm can be handled and some processes even allow diameters of up to 300 mm.

The right hand side of the cleanroom contains high precision metrology (HPM) equipment such as a 6” interferometer (ALI), a UV-microscope (UV), an inspection microscope (MIC), a spectroscopic ellipsometer (WLE) and a white light microscope (ZNV). This forms the experimental basis e.g. for new concepts in optical CD metrology or interferometric testing methods for aspheric surfaces.

We would like to express our thanks to Krebs Ingenieure GmbH who did an excellent job in planning and supervising the construction of the clean room.

Fig. 1: Wet bench for the processing of substrates of up to 200 mm diameter and 20 mm thickness

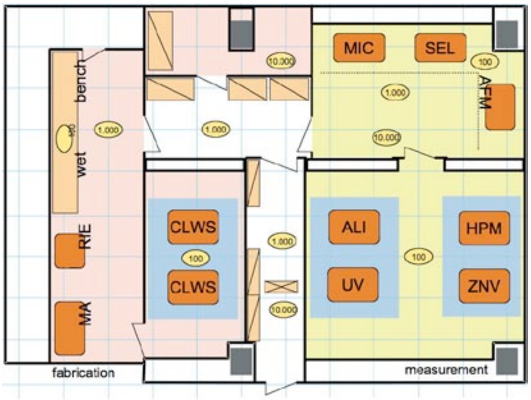


Fig. 2: Layout of the new cleanroom. For abbreviations see text.

Hybrid (diffractive/refractive) objectives for 3D-PMD-measurement cameras

R. Reichle, C. Pruß, W. Osten

The field of application for a robust and cheap sensing device, that allows the acquisition of 3D-information at video rate, is very large. Within the scope of a current collaborative project new sensors based on pmd-technology (photonic mixing device) are developed. The expertise of the project members includes all steps from the design and fabrication of basic hardware like pmd-chips and optics, the camera and software development up to application specialists like companies producing industrial robots. ITO is engaged in the development of modular hardware, which includes the optics for the sensor. The development goals are defined by several robotic applications like a driverless car or robotic arms.

MEASUREMENT PRINCIPLE

The fundamental parts of a pmd-sensor are an intensity modulated illumination in the near IR (Fig. 1) and a camera module with a 2d-array of special pixels. Both of these are designed for the comparison of the phase of the detected intensity variation with that of the illumination, and thereby acquire depth information. The integration of this function on the chip is very advantageous, since it allows an analysis at video rate without supplementary mixing hardware. So the way to a compact and cheap sensor is paved.

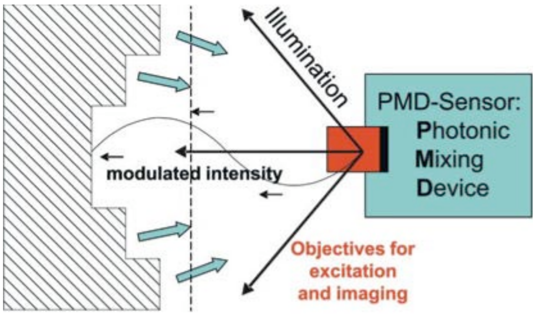


Fig. 1: Principle setup for a 3D-measurement with a PMD-Sensor (illumination + pmd-chip).

NEW DIFFRACTIVE / REFRACTIVE HYBRID OBJECTIVES

The signal-to-noise ratio and thus the measurement resolution depends significantly on the measurement signal. To improve its power and quality, we design, simulate and realize new wide angle objectives (e.g. 100°) with very high light collection efficiency (f-number <1). For small and cheap sensors also small and cheap objectives are required. Therefore in our design the number of optical elements must be reduced to a minimum. Since at the same time high performance is necessary, diffractive elements with aspheric phase function and negative dispersion are integrated for a very effective aberration correction.

A new and effective design freedom is given when these structures can be applied directly onto curved lens surfaces (Fig. 2). Our existing precision direct laser writing technology is therefore developed into the third dimension.

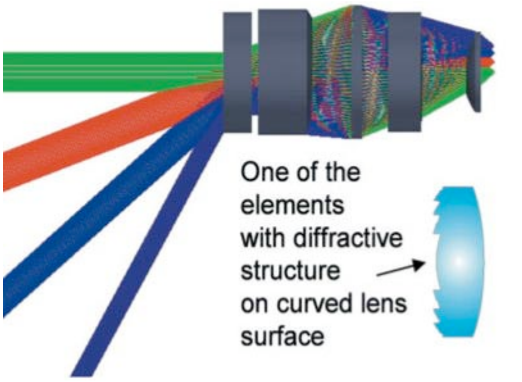
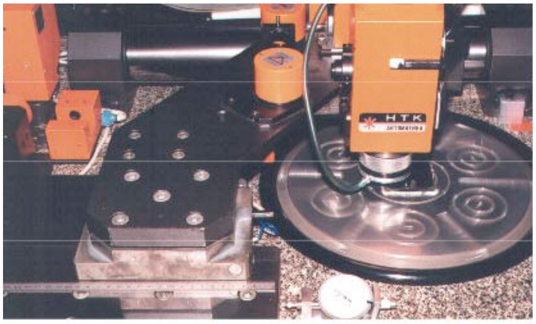


Fig. 2: Hybrid wide-angle design with diffractive structures on a curved lens surface.

The basis for the newly developed fabrication device is an existing polar coordinate writer (CLWS 300, Fig. 3). We are targeting rotationally symmetric curved substrates with tilt angles of up to 15°, while maintaining sub-micron resolution.



Wavelength:	405, 488 nm
Substrate:	
max. diameter	300 mm
max. thickness	25 mm
Resolution:	
radial coordinate	0,6 µm
angular coordiante	1" @ 600 rpm
Writing speed:	typical:
	on-axis: 150 µm/min
	off-axis: 60 µm/min

Fig. 3: Actual direct laser writing at ITO.

Supported by: BMBF FKZ 16SV2309. Project: "Lynkeus: Mikrointegrierte 3D-Echtzeitkamerasysteme für die intelligente Umgebungserfassung", www.lynkeus-3d.de

Refractive and diffractive micro-optics for the minimal invasive acquisition of combustion parameters

R. Reichle, C. Pruß, W. Osten, H.J. Tiziani

For the optimization of the combustion in engines, the time-resolved acquisition of information about the injected fuel/air mixture is very important. To enable non-contact measurements in close-to-production engines, new minimally invasive optical systems have been introduced in cooperation with the PCI (Physikalisch Chemisches Institut, University of Heidelberg). The optics are designed for modern analysis concepts, using the specific UV fluorescence properties of different fuel tracers (Fig. 1) upon laser excitation, to determine parameters like fuel concentration, equivalence ratio or temperature.

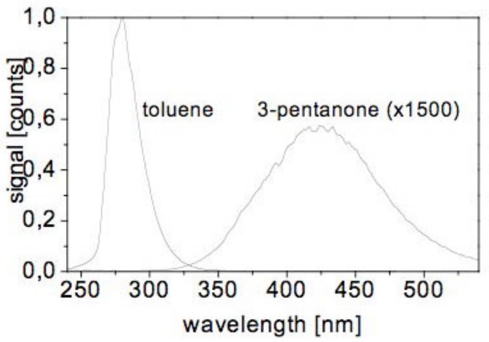


Fig. 1: Separable fluorescence spectra of toluene and 3-pentanone for a common 266 nm excitation.

1D-information via fiber optic sensor spark:

A new sensor spark plug with ignition function and additional micro optics allows measurements in unmodified engines, since both the spatially defined excitation of the tracers and the collection of the resulting fluorescence light is performed via this sensor. For easy handling, the interfaces to the optical supply and analysis units are realized using all-silica-fibers. The sensor head is optimized for this approach and provides a definition of a measuring volume close to the ignition spark by spatial overlap of the optical beam characteristics (Fig. 2). To minimize the number of necessary optical elements, curved front windows serve as lenses, which in principle image the tilted fiber ends onto the measuring volume. This quite simple but robust design enables a subsequent change of size and position of the measuring volume or even an adaptation to further measurement tasks like spark emission spectroscopy.

As well as characterization experiments in the laboratory (Fig. 3), first applications of UV-LIF-measurements on fired standard engines have been performed. The sensor design is patent pending.

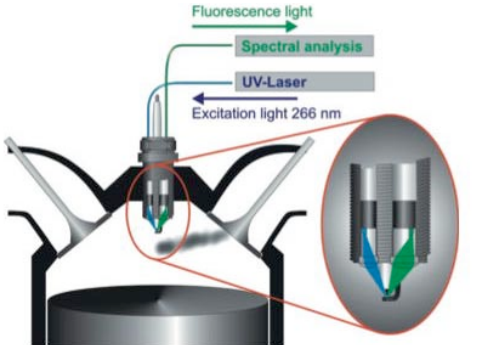


Fig. 2: Design of the sensor spark plug.

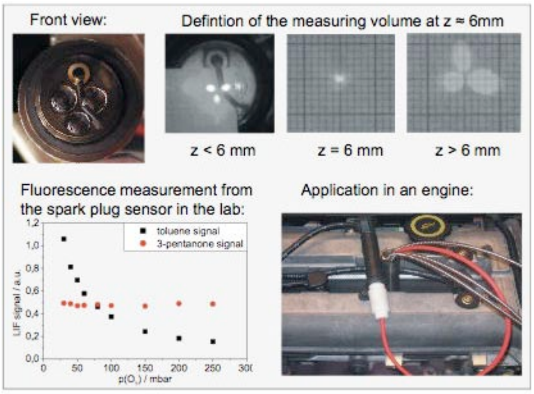


Fig. 3: Experimental results of the spark plug.

2D-information via endoscopic high performance optics with refractive and diffractive elements:

For the 2D-measurement diffractive/refractive (hybrid) excitation and imaging optics with small entry diameters (10 mm) and high performance were realized. The principal application setup is shown in figure 5.

The excitation optics transforms an incoming Gaussian beam into:

- a divergent light-sheet with optimized top-hat-profile (refractive design with aspheric micro-optics) (Fig. 4).
- a fan of 5 single beams with equal power realized by 5 diffractive focusing lenses in sub-apertures and a plano-concave lens for the divergence (Fig. 4).

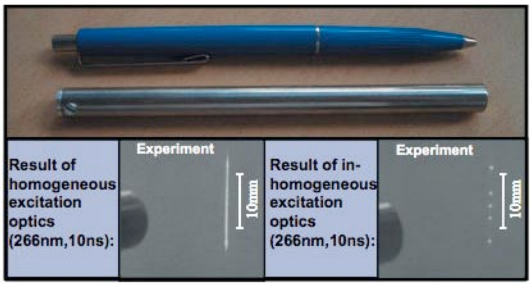


Fig. 4: Excitation optics and beam profiles.

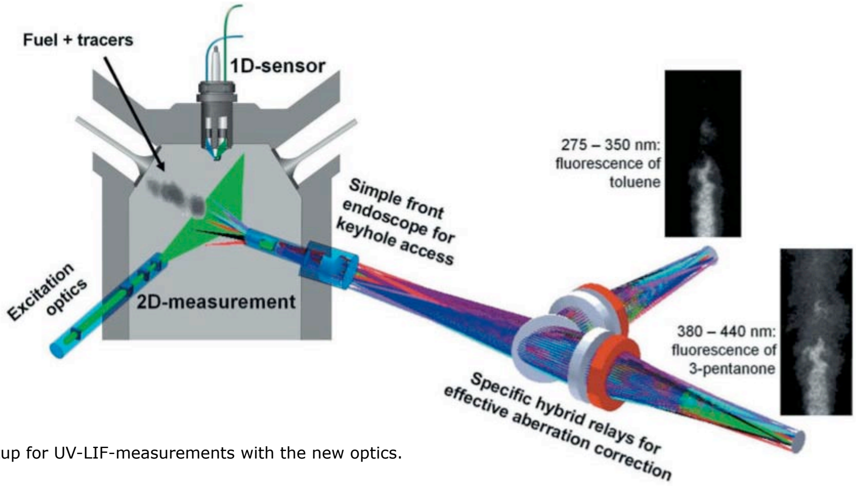


Fig. 5: Setup for UV-LIF-measurements with the new optics.

The wide angle keyhole optics to image the UV-fluorescence is divided into two main parts. A simple front endoscope with an entry diameter of 1 cm and fused silica lenses produces a chromatically uncorrected intermediate image, which is then relayed onto the camera by stationary hybrid optics. Here the chromatic correction of the complete system is realized by the strong negative dispersion of a diffractive element. So if different relays are placed behind a beam splitter, each imaging channel can be optimized to a different wavelength band using the same entrance endoscope (Fig. 6). The aspheric phase function of the diffractive element also helps in the correction of further aberrations. To suppress unwanted diffraction orders the etching depth of the diffractive elements are adapted to the individual spectral bands and the position in the relay further helps to minimize the related problems.

Fig. 6: Small front endoscope and hybrid relay.

In characterization experiments the hybrid imaging system proved to have the desired resolution and chromatic correction. In comparison with a commercially available UV-endoscope, a ten times higher brightness was found. Using the same magnification, the lens speed is even comparable to that of the non-endoscopic UV Nikkor objective, f = 105 mm.

To measure equivalence ratio in a lab experiment with 2 tracers, the hybrid endoscope was combined with the homogeneous excitation optics (Fig. 7, 8). In combination with inhomogeneous excitation flow-tagging was demonstrated.

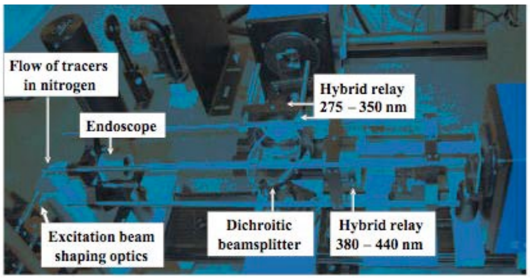


Fig. 7: Setup for lab experiment with 2 tracers.

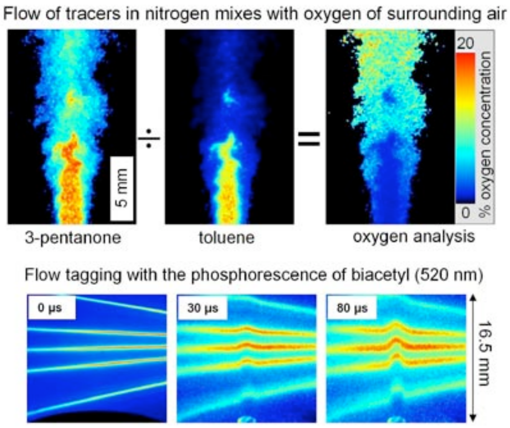


Fig. 8: 2D-measurement of oxygen concentrations with toluene and 3-pentanone and results of flow-tagging with biacetyl.

Supported by: Landesstiftung Baden-Württemberg, Phtotonics BW. The authors especially acknowledge the cooperation with the PCI Heidelberg (Prof. Schulz and Frank Zimmermann).

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Flexible aspheric testing:
an interferometer with a dynamic test beam

E. Garbusi, C. Pruß, J. Liesener, W. Osten

The advantages of aspheric elements have been known for decades. They allow the construction of smaller, lighter and simpler optical systems. Also well known are the difficulties involved in the manufacture and measurement of these elements.

The goal of the project Asphero5 is the economic and rapid fabrication of high precision aspheric elements. In order to fulfil these requirements a precision measurement unit must be integrated in the production chain to accurately qualify the element being produced. Therefore there are several limiting factors for the measurement task, among them in particular is the short measurement time.

Due to these conditions a new interferometric concept for the measurement of the polished surfaces was developed. Our solution is an interferometer with a variable test beam (1-3). Using an array of point sources (monolithic microlens and a pinhole array), the asphere is illuminated from different angles to allow the measurement of zones where the local gradient of the test part is to be compensated.

One of the main advantages of this system is that the measurement process is performed in parallel for many sources, allowing an extremely short measurement time of a few seconds. This is in comparison with the other available techniques, based on stitching procedures, that require several minutes or more. Another important aspect is that the asphere stays in the same position during the whole measurement process; there are no mechanical movements of the test part involved.

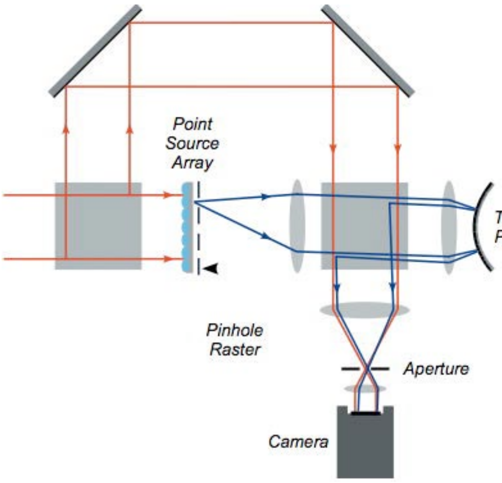

Fig. 1: Interferometer with a dynamic test beam.

The interferometer is based on a Twyman Green configuration where an array of sources (Point Source Array) is placed in the object beam of the interferometer. With this configuration, the reference beam stays fixed (red) while the test beam (blue) is varied through the selection of different sources from the array.

Within each test beam, the interferometer aperture selects those ranges which lead to an evaluable Interferogram pattern (no subsampling). Thus each source (test beam) generates a group of zones covering different parts of the asphere. An example of those zones can bee seen in Fig. 2.

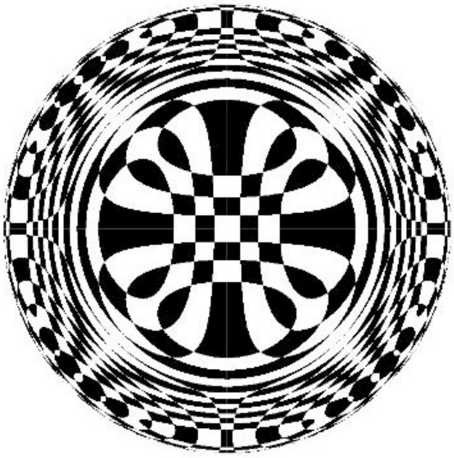

Fig. 2: Zone arrangement due to the different sources in the array.

Due to this fact, it is possible to use simultaneously sources (test beams) which do not lead to overlapping areas on the camera.

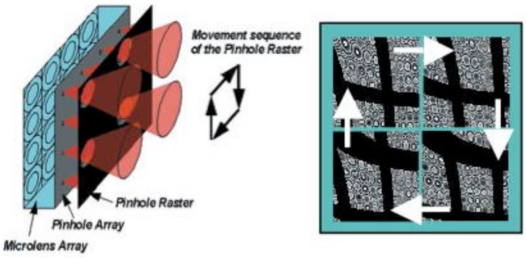

Fig. 3: Every second row and every second column of the source array is activated in order to cover the whole test part.

An example of such an arrangement is given in Fig 3. Every second row and column of the source array is activated by shifting a mask over the array. It is clear that in only four steps the whole surface of the asphere is covered, so the measurement requires an extremely short time.

Calibration and measurement strategies have been developed to evaluate the influence of retrace errors since the configuration is based on a non-null test of the asphere. The technique allows the measurement of strong aspheric elements with departures from the best fit sphere of up to 10°. The method was developed to obtain accuracies of up to λ/30 and better.

Supported by: BMBF (FKZ 13N8742)
Project: "Asphero5"

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[1] Patent applied for: 100 2006 057 606

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Low loss, highly stressable grating waveguide structures for polarization shaping in high power solid state lasers

M. Häfner, C. Pruß, T. Schoder, T. Schuster, S. Rafler, W. Osten

The generation of laser light with radial or azimuthal polarization states is very attractive for many applications, such as laser cutting or drilling, where the process speed can be increased by up to 100 % compared with using unpolarized light.

In the past computer generated diffractive structures proved the feasibility of generating these inhomogeneous polarization states outside the cavity for a wavelength of 10.6 µm. However the most efficient approach to provide special polarization distributions is intracavity selection. Common polarization shaping components, like Brewster angle windows that are suitable for linear polarized light, cannot simply be adapted to inhomogeneous polarization states. Therefore polarization selecting cavity mirrors are preferred for that purpose.

Intra cavity components, especially in low gain lasers like the Yb:YAG disk laser, must have very low losses. This is where mirrors with sub wavelength gratings come into play. They provide the desired polarization selectivity combined with low losses. At the Institut für Strahlwerkzeuge (IFSW) new rotationally symmetric sub wavelength structures are simulated and designed for the applications in laser cavities. These designs are double checked using the rigorous simulation tools available at the ITO i.e. the RCWA-based package MICROSIM, FEMLAB.

The fabrication of sub wavelength structures is still a challenge. Thus a polar coordinate lithography system available at the ITO will be upgraded to scanning beam interference lithography (SBIL). Hence the disadvantages of e-beam lithography i.e. high cost and, in most cases, limitation to Cartesian coordinates, as well as those of conventional optical lithography system i.e. the diffraction limitation for the spot size as well as the relatively small writing speed can be overcome.

The basic principle is to use interference lithography as illustrated in figure 1. Two coherent laser beams overlap under a certain angle 2α creating an interference pattern of equally spaced regions of high and low intensity respectively. The periodicity of the pattern $p=\lambda/2\sin(\alpha)$ can be as small as half the wavelength.

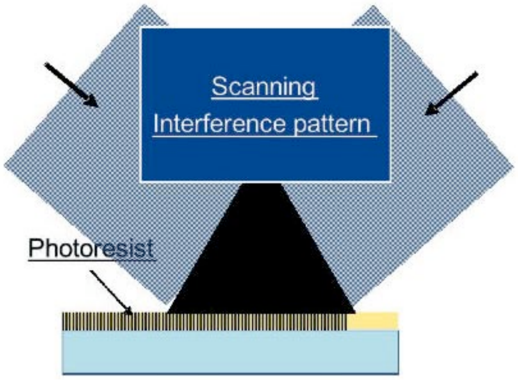

Fig. 1: Principle of interference lithography. Two coherent beams with different angles of incidence overlap at the substrate surface.

In a polar coordinate lithography system (figure 2) as it is available at ITO, the substrate rotates underneath a scanning head which moves along the radial coordinate.

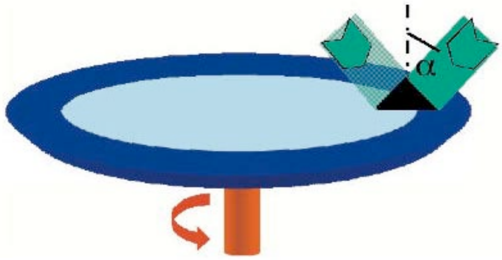

Fig. 2: Polar coordinate lithography system. The substrate rotates underneath the scanning head which moves along the radial coordinate.

Since the pattern is continuously written along the grating lines and not stitched, as it has to be done when working in Cartesian coordinates, smooth rotationally symmetric structures can be achieved.

As a light source we use an Ar+-Ion-Laser operating at a wavelength of 458 nm. This enables us to realize line densities of up to 2000 LP/mm and beyond, which is quite sufficient for the generation of the targeted resonant structures. The system is designed to have a computer control of both the grating period and the writing patch size. This will allow the optimization of the writing speed and the realization of rotationally symmetric gratings with variable line spacing on a single substrate

Supported by: Landesstiftung Baden-Württemberg
Photonics BW
Project: "PolGit"

High resolution optical rotary encoders

D. Hopp, C. Pruß, W. Osten

Rotary encoders are used for angular measurements in numerous applications like rotating machine parts, electrical motors or for example to detect the steering angle in automotive parts. There are different encoding principles available such as potentiometric, capacitive, inductive or optical, with the optical systems reaching the highest angular accuracy. As a disadvantage the resolution enhancement of optical encoder systems is associated with increasing cost.

Considering the need for competitive sensors, the idea of the project is to use a micro-structured plastic disc with a metal coating, as it is used for a common Compact Disc. This encoder disc can be manufactured by a conventional CD compression-mould process. With this well known technique it is possible to create highly precise structures while running a cost effective process for high numbers of parts.

The mechanical and electronic design and the realization of this new kind of optical rotary encoders is performed by our project partner, HSG-IMAT. ITO focuses on the optical design as well as the fabrication of the master disc. The masters are directly written into photo resist on the circular laser writing system CLWS 300M.

The solid scale unit consists of a tangential pattern of diffracting gratings that are situated on a circle on the outer part of the encoder-disc. An incremental code is generated by a periodic arrangement of structured and unstructured fields, which diffract an incident beam into its different diffraction orders. The system is being designed for a conventional VCSEL (Vertical Cavity Surface Emitting Laser) operating at 850 nm.

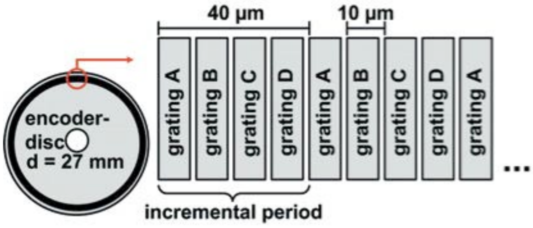

Fig. 1: incremental code cycle on the encoder-disc with diffraction gratings as a solid measure

The first diffraction order is detected by a photo diode. After being illuminated by an appropriately focussed beam, the rotation of the disc results in a sinusoidal intensity signal at the photo diode. This is the desired signal for most applications. In the current concept a disc of 27 mm diameter is chosen to fit into a 30 mm housing. With an incremental tangential period of 40 µm the hardware resolution results in nearly 2000 per revolution, what can be easily interpolated electronically with a standart circuit in order to obtain a higher resolution output if necessary.

To achieve not only an incremental measurement but also a detection of the rotation direction, it is necessary to implement a second incremental track that is 90° phase shifted towards the first. The usage of a different grating leads to a second set of diffraction orders where again the first order is detected by a photo diode. To obtain an offset-compensated output signal this setup is used twice in a nested configuration having four different gratings per period (Fig. 1).

The dimensions of the patterns of the gratings, and therewith the angular resolution of the encoder, depend directly on the illumination spot size and geometry. This in turn defines the fabrication tolerances of the system.

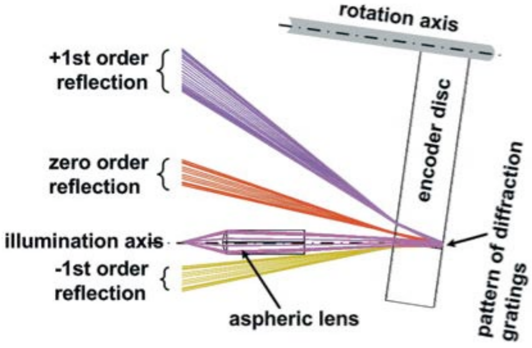

Fig. 2: simulated optical path of the illumination beam and of the first-order diffractions from one grating

By a variation of the gratings the position of the first-order beams relative to each other can be adjusted. As it is shown in Fig. 2, the rotation axis of the encoder-disc is slightly tilted to prevent the VCSEL from being damaged by the zero-order reflection. For the illumination this leads to an angle of incidence on the encoder disc that can be adjusted to also affect the detector positions.

To meet the common request for a reference mark a fifth grating on zero angle position with an additional photo diode can be integrated.

Supported by: AIF (219 ZN)
Project: "Drehgeber"

Wavefront scaling for interferometry

D. Hopp, C. Pruß, H.J. Tiziani, W. Osten

For interferometric measurement of aspheric surfaces the wavefront of the interferometer must be adapted to the particular type of asphere in order to avoid too high fringe density in the interferogram or even vignetting. Computer controlled membrane mirrors can be used to produce aspheric wave fronts. They have some appealing properties such as a high flexibility in terms of the generated wavefront, a smooth surface and quick response time. On the downside there is the relatively small dynamic range of the deflection of only a few tens of micrometers. We propose a novel method to scale the resulting reference wave front by using the membrane in multiple reflection.

The interferometric test assembly used is shown in Fig. 1). Instead of a beam splitter it uses multiple reflections from the membrane mirror . This results in a wavefront with a scaled aspheric deviation that can be used for example as an aspheric reference wave.

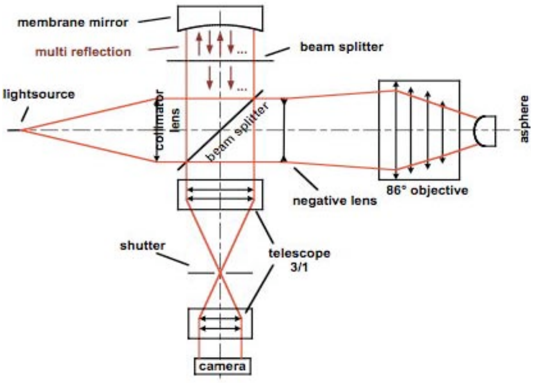

Fig. 1: Interferometric test set-up with an adaptive membrane mirror in the reference path. Using multiple reflection from the membrane mirror, its aspheric deviation is translated into a scaled aspheric wave front.

Naturally, the desired wavefront is accompanied by a large number of additional reflections, which overlap the desired interferogram. To avoid their disturbing interferences we use the coherence properties of a superluminescence laser diode. This light source has a low coherence length of about 200 µm, allowing us to select one specific reflection. The proper adjustment of the optical path lengths of the reference and the test wave is realized in a separate interferometric set-up as shown in Fig. 2).

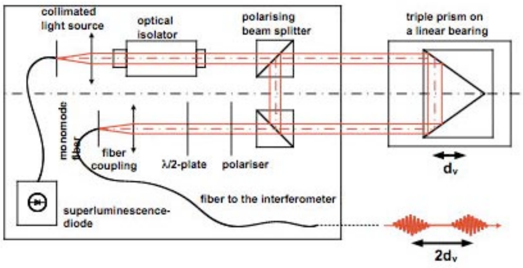

Fig. 2: Cavity with a short-coherence light source. The difference of the two optical path lengths is selected by a triple prism on a linear bearing.

The light in this cavity is coupled into a single-mode polarization maintaining fibre. The distal end of this fibre serves as point source in the interferometer of Fig. 1). By varying the pathlength difference between the two optical paths in the cavity, the designated reflection in the interferometer can be selected. The intensity ratio of the two wavelets, that define the contrast in the interferometer, can be adjusted using a half-wave plate. However, most of the contrast is lost due to incoherence light reaching the detector. Future set-ups will utilize additional polarisation optics to reduce this unwanted light.

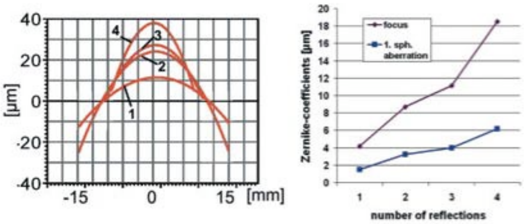

Fig. 3: interferometric measurements of a scaled wavefront; multi-reflections 1 to 4 with increasing focal and spherical aberration coefficients.

Supported by: Landesstiftung Baden-Württemberg
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