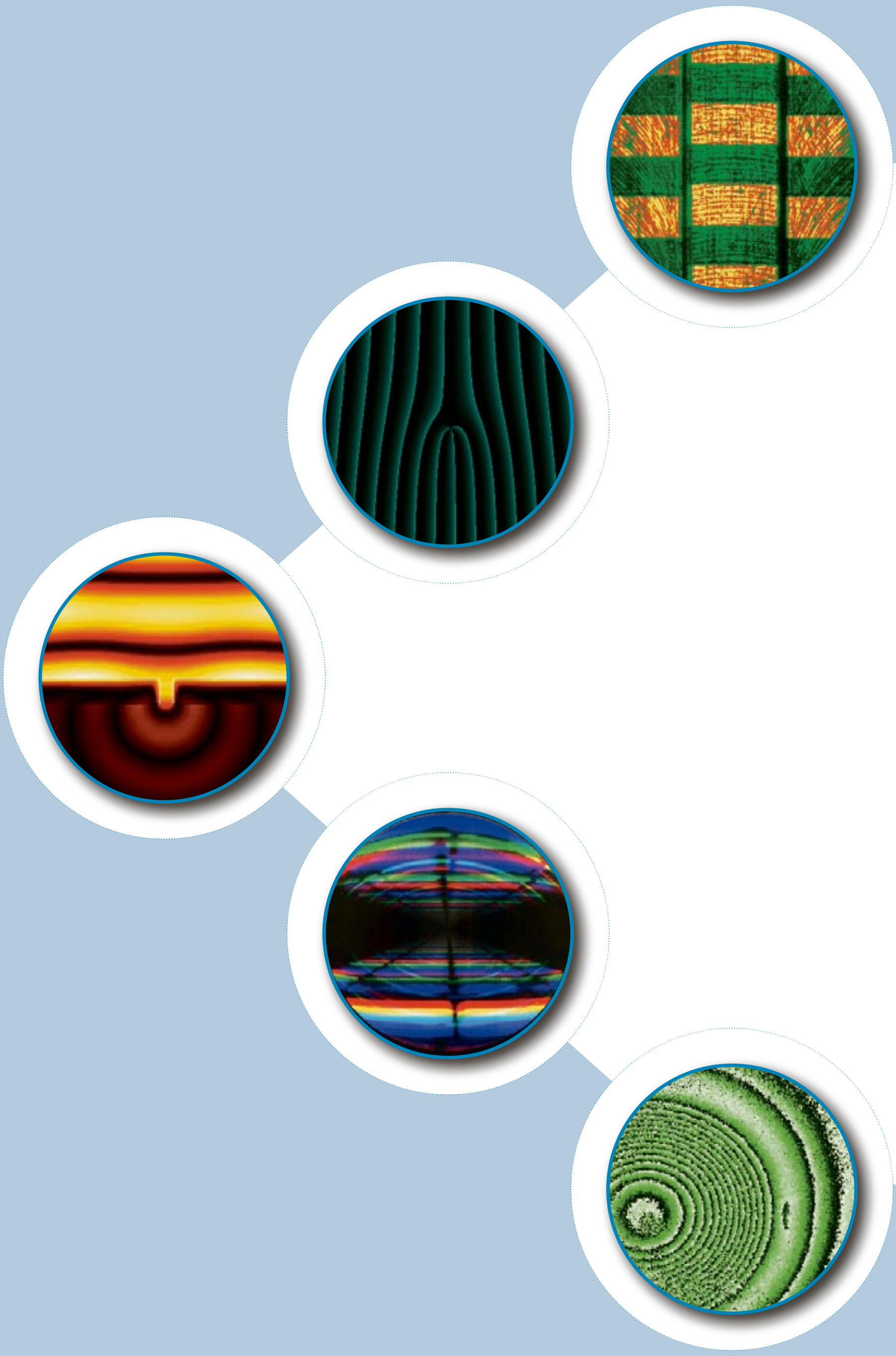
annual report
2007 / 2008

INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART



Universität Stuttgart

Interferometry and Diffractive Optics

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

High resolution cost-efficient optical rotary encoders
Supported by: AiF, project ZN 219

Scanning Interference Lithography (SBIL) for the fabrication of rotationally symmetric diffractive elements
Supported by: Landesstiftung Baden-Württemberg
Project: "Polgit"

Refractive and diffractive micro-optics for the minimal invasive acquisition of combustion parameters
Supported by: BMBF (FKZ 13N9456) and the Landesstiftung Baden-Württemberg
Project: "MIMODIA"

Computer generated diffractive elements on curved substrates for hybrid (diffractive/refractive) objectives
Supported by: BMBF (FKZ 16SV2309)
Project: „Lynkeus"

Optically addressed thermally activated adaptive optics
Supported by: Landesstiftung Baden-Württemberg
Project: „ThermAO"

Active micro optic for spatial polarization control
Supported by: DFG (OS111/26-1)
Project: "AMiPola"

Flexible asphere testing

E. Garbusi, C. Pruss, W. Osten

Aspheric elements are one of the most flexible components in the design of optical systems. Surfaces deviating from a basic spherical shape give optic designers a powerful tool to enhance the performance of optical systems and reduce the number of necessary optical elements (and with it the overall size and weight). However, this comes along with major drawbacks in fabrication and assembling.

Because aspherical surfaces are almost free in what their design concerns, there is no standard technique to test the quality of the surfaces. Two issues condition the applicability of a measurement technique, namely flexibility and accuracy. The use of null compensators (refractive or diffractive) is nowadays, the most popular measurement procedure. Although the achievable measurement accuracy by means of compensators is more than enough for a broad range of applications, they fail to provide the required flexibility if only a reduced number of asphere types are to be tested.

Flexibility can be achieved in a number of ways but, the straightforward solution is allowing deviations from the null-test configuration. Based on this principle a novel non-null interferometer was developed [1]-[5]. Figure 1 shows the corresponding set-up. A stabilized HeNe laser source ($\lambda = 632.8$ nm) is spatially filtered, collimated and split into the reference (upper path) and test beam (lower path) by the beam-splitter BS_1. A diffractive optical element (*PSA*-Point Source Array) consisting of a microlens array (*MA*) on the front side and a matching pinhole array (*PA*) on the backside of the element is placed in the test path of the interferometer. The function of this element is to generate a two-dimensional array of point sources that after collimation (lens L_2) and focusing by the transmission sphere *O* impinge on the test surface. The outgoing beams are then imaged by lens L_3 and brought to interference with the reference beam at the detector *C*.

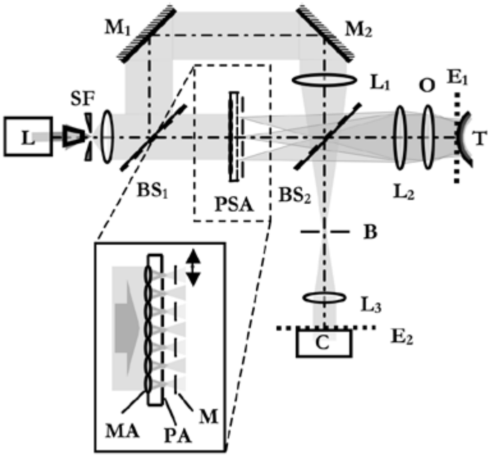


Fig. 1: Interferometer set-up: PSA, point source array; MA, microlens array; PA, pinhole array; M, selection mask; O, transmission sphere; T, test surface.

Each test wavefront is incident onto the test surface with a different amount of tilt, hence partially compensating the local gradients of the aspheric part. Since the compensation is not total, the fringe density on the detector has to be limited. This is accomplished by means of the interferometer aperture *B*. The presence of non-null fringe densities also implies the existence of retrace errors that must be evaluated (calibrated)[4] if high accuracy measurements are expected.

Figure 2(a) shows a typical interferogram when all the sources in the array are active. Spurious interference fringes are also present due to the interference between neighboring sources (see Fig. 2(b)). We can easily avoid this unwanted effect with a partial activation of the source array as shown in Fig. 3 with a blocking mask *M* on top of the array (see Fig. 1).

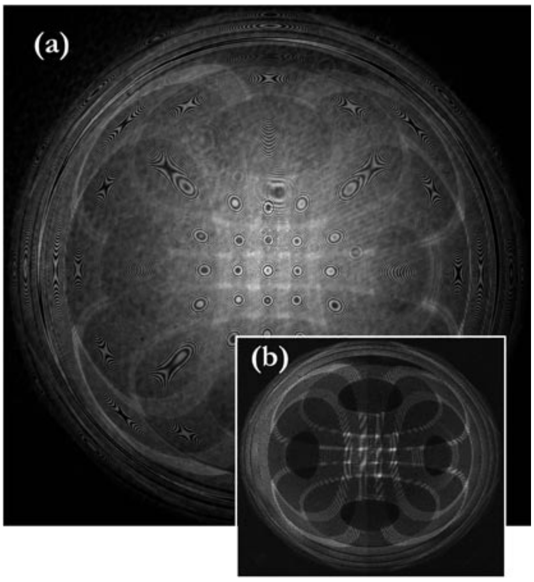


Fig. 2: **(a)** Interferogram with the totality of the array activated. Unwanted interference between contiguous sources of the array can be observed when the reference beam is blocked **(b)**.

Test surfaces with sagitta deviations up to 700 µm and 6° gradient deviations from its best-fit sphere have been characterized with accuracies in the range of λ/10 (PV). The actual accuracy of the method is mainly limited by the mechanical stability of the set-up, which affects the calibration procedure of the interferometer [5].

Current efforts concentrate on the improvement of the evaluation algorithms as well as the overall stability of the set-up to increase the measurement accuracy. Also several algorithms and configurations for rapid interferogram evaluation are under development [6].

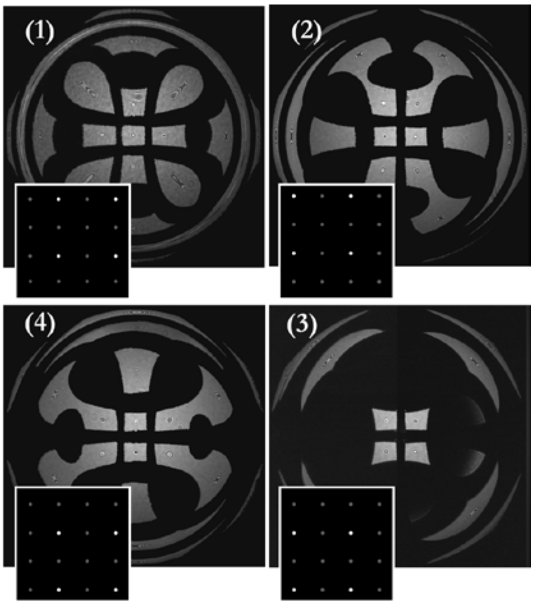


Fig. 3: Partial activation of the source array. Every second row and second column is activated for each one of the four frames. Bottom left of each interferogram: active sources for the current interferogram are shown **(white: active, gray: blocked source)**.

Supported by: BMBF (FKZ 13N8742)
Project: "Asphero5"
The authors especially acknowledge the good cooperation with our industrial partner Jenoptik L.O.S. GmbH.

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High resolution cost-efficient optical rotary encoders

D. Hopp, C. Pruss

Angular measurements can be realised using different encoding principles like potentiometric, capacitive, inductive or optical, with the optical systems reaching the highest angular accuracy. Currently, the aspired resolution enhancement of the optical systems is directly linked to increasing cost. Considering the wide range of applications for high resolution rotary encoders there is a great demand for competitive sensors.

To achieve a cost-efficient production process the idea of the project is to use a micro-structured plastic disc with a metal coating, similar to a common DVD, which can be manufactured by a conventional 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 mechanic and electronic design and the realization of this new kind of optical rotary encoders were performed by our project partner, HSG-IMAT. ITO focused on the optical design as well as the fabrication of the testmaster discs.

The light source of the system is a conventional VCSEL (Vertical Cavity Surface Emitting Laser) operating at 850 nm. A polymer lens and aperture are used as imaging elements to obtain a diffraction limited illumination of the solid measure, which consists of a tangential pattern of diffracting gratings that are situated on a circle on the outer part of an encoder-disc. An incremental code is generated by a periodic arrangement of structured and unstructured fields. The incident coherent beam is split into its different diffraction orders from which the first order intensity is detected by a photo diode. We have optimized the pattern geometry and spot size to obtain a sinusoidal signal when rotating the encoder disc.

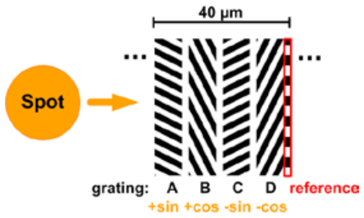

Fig. 1: one period of the diffractive pattern on the encoder disc including the reference mark.

A second incremental track having a 90° phase shift towards the first allows the detection of the rotation direction. The usage of a different grating leads to a second set of diffraction orders. The first order of this set is detected by a second photo diode. To obtain an offset-compensated output signal this setup is used twice in a nested configuration having four different gratings per period.

The spatial separation of the resulting four first diffraction order spots is achieved by using different angles for each set of gratings per signal. To meet the common request for a reference mark a fifth grating is implemented on zero position once on the circumference to generate a reference signal on a fifth photo diode.

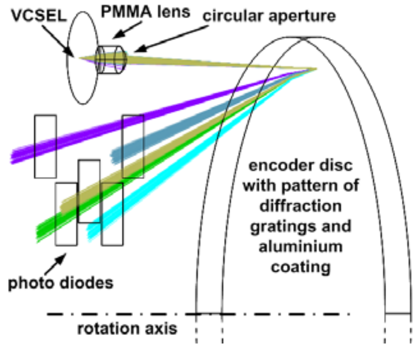

Fig. 2: scheme of the optical path of the illumination and the reflected first order spots.

A first demonstrator with a 30 mm disc fitting in a 36.5 mm housing was built and tested: Having 2048 incremental periods per circumference the solid measure is providing a resolution of 11 bit. The quality, precisely the THD+N (Total Harmonic Distortion + Noise) of the output signals allows a tenfold electronic interpolation with a standard circuit. Thus a total incremental output resolution above 14 bit respectively one arcminute of rotation angle is achieved.

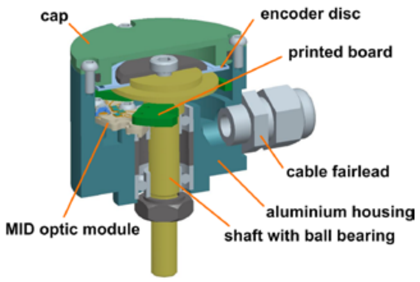

Fig 3: model of the assembled rotary encoder.

Supported by: AiF, project ZN 219

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[1] Hopp, D.; Pruss, C.; Osten, W.; Seybold, J.; Mayer, V.; Kück, H. "Hochauflösender optischer Drehgeber in Low-Cost-Bauweise", DGaO-Proceedings 2008, A35, Esslingen.

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Scanning Interference Lithography (SBIL) for the fabrication of rotationally symmetric diffractive elements

M. Häfner, C. Pruss, T. Schoder, W. Osten

The efficient fabrication of diffractive optics is of growing interest for many applications. Laser direct writing of such structures has proven be a flexible, fast and cost-effective approach.

In spite of all these attractive features, laser direct writing suffers from the disadvantage of diffraction limited writing spots, what limits the smallest feature size to approx. 0.5 µm when visible light sources are used. At the same time the writing time of very fine features is a problem and can be limiting for point-wise writing systems.

Sub wavelength structures with feature sizes of a few hundred nanometres are interesting for applications which benefit from the lack of propagating diffraction orders, e.g. intra cavity polarization control. To generate such structures efficiently, we have developed and implemented a scanning beam interference lithography (SBIL) option on one of our existing polar coordinate direct laser writing systems. This enhancement allows us to fabricate rotational symmetric structures with features sizes of less than 400 nm. Furthermore, since the structures are written by a large interference pattern with outer dimensions of several micrometers, the writing speed could be greatly increased.

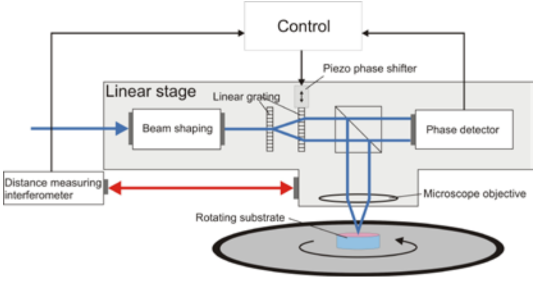

Fig. 1: Scanning beam interference lithography system. A fringe locking system stabilizes the position of the interference fringes by adjusting the phase between the two interfering beams.

During the writing process a large number of ring patterns is stitched with nanometre accuracy to each other, thus forming a large ring structure of theoretically any size. A fringe locking system and a compact design assure stable pattern positioning and a high exposure contrast. There is one limitation of the presented technique. Since the interference pattern consists of straight fringes, the lateral extension of the pattern leads to a decreasing contrast with increasing ring curvature, thus limiting the diameter of the smallest ring. By means of a beam shaping optic that generates an elliptic pattern envelope, we were already able to realize ring structures with a diameter of 15 µm (figure 2).

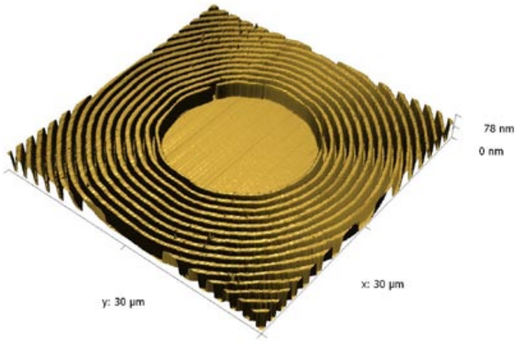

Fig. 2: AFM-Scan of the axicon centre. It is possible to realize concentric structures with a diameter as small as approx. 15 µm.

In the scope of a joint project together with the IFSW, University of Stuttgart, we have produced axicon-structures with a period of 933.5 nm and a diameter of 16 mm (figure. 3). The structures are part of a low loss, highly stressable, polarization shaping grating waveguide structures. It is designed for the use in high power solid state lasers.

The maximal grating area is only limited by the available laser power and dimensions of the writing system. We expect to be able to fabricate such structures with a diameter of 150 mm and beyond.

Fig 3: Photograph of an axicon-structure produced with scanning beam interference lithography.

Supported by: Landesstiftung Baden-Württemberg
Project: "Polgit"

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

R. Reichle, C. Pruss, W. Osten

For the optimization of the combustion in engines, the time-resolved acquisition of locally resolved information about combustion parameters like the injected fuel/air mixture or the temperature is very important. To enable non-contact measurements in close-to-production engines (see fig. 1), new minimal invasive optical systems have been introduced [1-4] and are actually further enhanced in cooperation with Prof. Schulz (IVG, University of Duisburg-Essen). The optics are custom designed for modern analysis concepts such as UV laser induced fluorescence (LIF), using the specific UV fluorescence properties of different fuel tracers upon laser excitation to determine the desired parameters.

Point measurements without engine modifications are enabled by our measurement spark plug, which still provides the ignition function and has additionally integrated microoptics to serve as a LIF-sensor. In fired engine experiments the robustness and optical function has been demonstrated (fig. 2), actually the sensor function is further developed towards simultaneous measurements in multiple volumes.

The wide angle keyhole optics for 2D-measurements images the UV-fluorescence of a measurement plane onto an image intensifier. The optics 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 component. 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. To suppress unwanted diffraction orders the etching depth of each diffractive element is adapted to the individual spectral band. The positions of the diffractive elements in the relays further help to minimize the negative effects of the unwanted diffraction orders regarding the image quality.

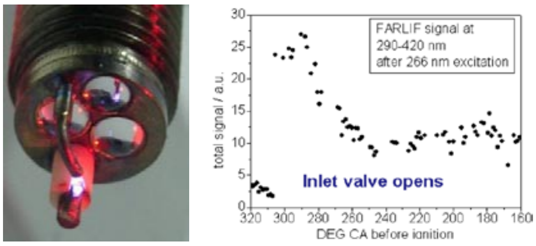

Fig. 2: Spark plug sensor and UV-FARLIF signal measured with the sensor inside a running engine [2,3].

A new simulation tool has been implemented on the basis of the widely used ray tracing tool ZEMAX. It accounts for the behaviour of real diffractive optics in optical systems, including fabrication errors dependent on the local grating constant and broadband illumination effects. The simulation tool integrates seamlessly into ZEMAX and can also be used for optimization. This new capability further improves the design of hybrid diffractive/refractive optical systems.

For the characterization of diffractive elements and hybrid optical systems at wavelength we have set up a test bench that works from the NIR to the UV. It uses a double monochromator with automatically exchangeable gratings and an optional Ulbricht sphere for the defined illumination of test charts.

In our characterization experiments we could show the expected performance in terms of resolution and chromatic correction. Benchmarking our system against a commercially available UV-endoscope, we

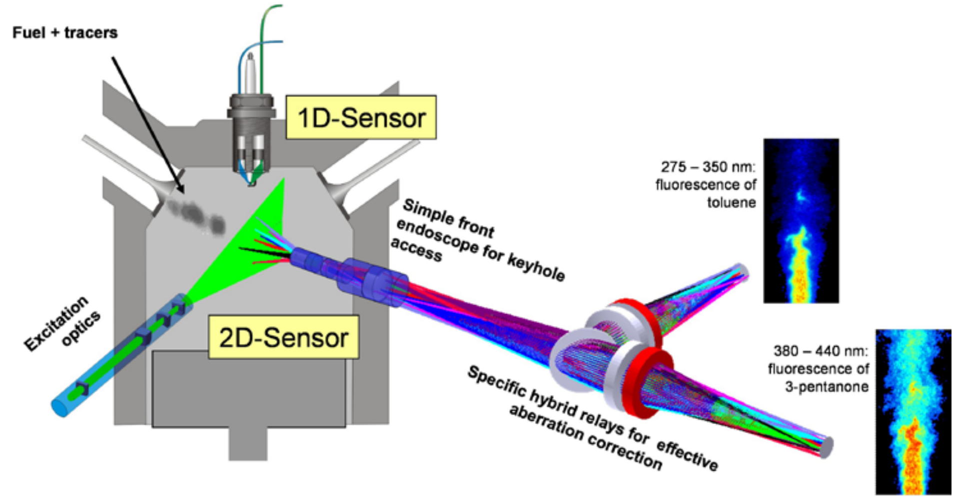

Fig. 1: Setup for minimal invasive UV-LIF-measurements.

could show a dramatically higher brightness and at the same time a broader chromatic correction range. If a broad correction range is required, as is typical for fluorescence observation, our system delivers about 30 times more brightness, for monochromatic applications still about 10 times.

Benchmarking our system against the non-endoscopic UV Nikkor objective (f = 105 mm) at the same image magnification, we found comparable values in terms of brightness, as can be seen in figure 3. The averaged images show LIF of toluol for an excitation at 266 nm imaged with the non-endoscopic UV Nikkor lens and our system with the same camera settings.

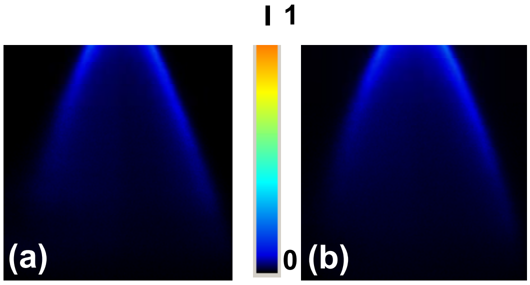

Fig. 3: Comparison of a standard non-endoscopic UV imaging lens (UV Nikkor, **(a)**) with the hybrid endoscopic system **(b)** imaging LIF of toluol at 307 nm, measured at the LaVision GmbH.

In combination with our beamshaping optics with 9 mm outer diameter, the high performance of the optical imaging system allowed first minimal invasive 2D-UV-LIF-measurements out of a running engine at IVG (fig. 4). Figure 5 shows the front piece that is attached to the test engine.

The diffractive/refractive imaging optics is commercialized by the LaVision GmbH.

Fig. 5: Front piece of the hybrid endoscopic system attached to a test engine.

Supported by: BMBF (FKZ 13N9456) and the Landesstiftung Baden-Württemberg
Project: "MIMODIA"
The authors especially acknowledge the good cooperation with the group of Prof. Schulz (IVG, University of Duisburg-Essen).

References:

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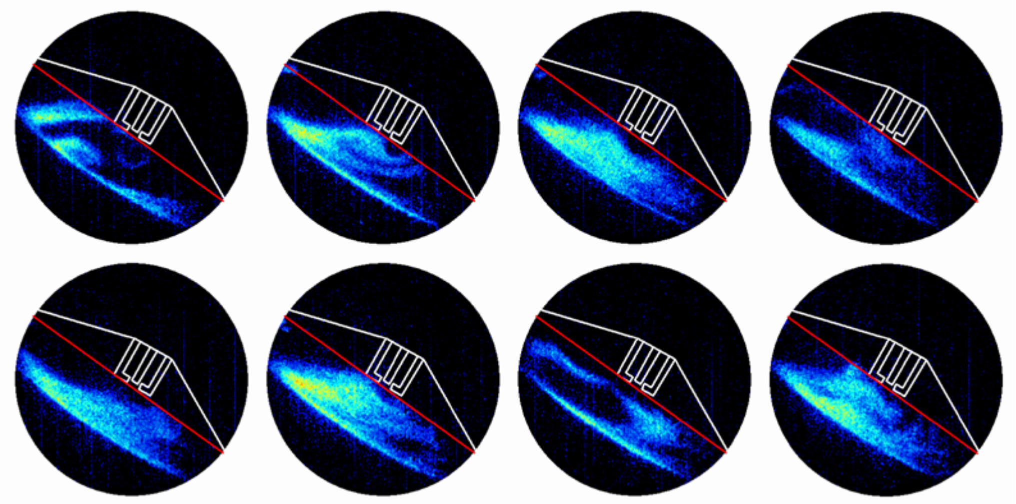

Fig. 4: Single shot images of fuel LIF out of a running engine realized with minimal invasive access optics [4].

Computer generated diffractive elements on curved substrates for hybrid (diffractive/refractive) objectives

R. Reichle, M. Häfner, C. Pruss, W. Osten

The light collection power or lens speed is the prominent property of a lens for some applications. Especially active systems such as 3D-Sensors based on PMD-Technology (photonic mixing device) benefit from high lens speeds. In the scope of the cooperation project "Lynkeus" we therefore design and realize high performance optical systems, optimized for the application. One example, a compact wide angle objective, is shown in figure 1 and figure 2.

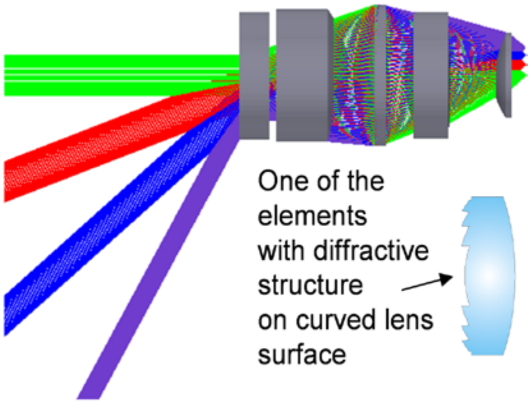

Fig. 1: Optic design for a hybrid wide angle objective.

The targeted light collection efficiency should be as high as an F# of about 1 in spite of a field-of-view of 140°. This increases the signal-to-noise-ratio and supports distance measurements with acceptable accuracy.

To meet the conditions of a compact objective the number of optical elements is 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. The optical design profits from diffractive structures fabricated on curved lens surfaces.

Fig. 2: Hybrid wide angle objective for 3D-PMD cameras.

Fabrication of diffractive optics on curved substrates

The corresponding production technology is actually developed at ITO based on our existing precision direct laser writing system. We are targeting rotationally symmetric curved substrates with surface gradients of up to 15° while maintaining sub-micron precision. The principal setup is shown in fig. 3. A key component is the newly developed autofocus system that works both on flat as well as on tilted surfaces. Its dynamic behaviour is improved using predictive algorithms that can be applied well to circular scanning systems.

Spin-Coating proved to be a suitable technique to uniformly coat convex lenses up to 28° inclination angle [1]. We could realize photoresist coatings with surface homogeneities with peak-to-valley of only 86 nm at a thickness of about 4 µm.

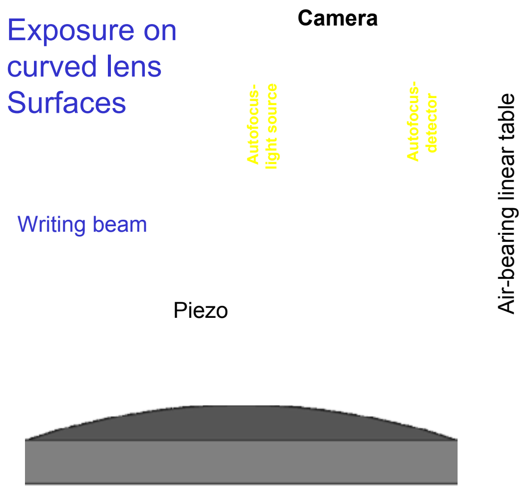

Fig 3: Schematic of the new laser direct writing head for writing on curved substrate.

The new fabrication capabilities allow the realization of advanced hybrid optic designs that further increase the performance of optical systems.

Supported by: BMBF (FKZ 16SV2309)
Project: „Lynkeus"

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Optically addressed thermally activated adaptive optics

C. Pruss, M. Matic, D. Graupner, W. Osten

Adaptive optics (AO) for high power applications requires a robust addressing mechanism. One of these applications is intra-cavity aberration correction for high power lasers. Here, thermal effects typically limit the scalability of laser systems such as the thin disk laser. The goal of intra cavity AO therefore is to correct output-power dependent aberrations to maintain a high beam quality. Different solutions exist for the correction of the power term, but when it comes to higher order aberration correction, still no satisfying solution has been presented.

In the joint project THERMAO we have developed together with our partners IFSW (University Stuttgart) as well as the HSG-IMAT (Stuttgart) new AO solutions based on thermal activation.

The basic principle of activation is the thermal expansion of bulk material. If the bulk material is heated locally we can produce a temperature distribution that translates into a topography change on the surface of the material. The required topography deviation is in the rage of 100 to a few hundred nanometers. This can be achieved with moderate temperature changes and material thicknesses.

At ITO, the focus was on the realization of an optically addressed, thermally activated AO. Figure 1 shows a schematic of the developed AO. The local heating in this scheme is realized with structured illumination. This addressing light is absorbed in the active mirror, resulting in the required temperature distribution.

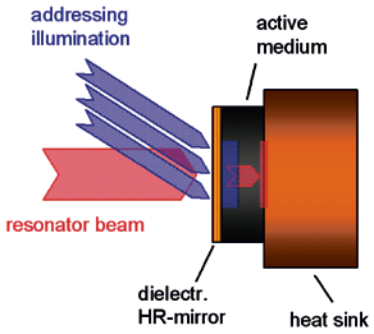

Fig. 1: Principle setup of an optically addressed, thermally activated adaptive mirror for intra-cavity application.

The setup of the active mirror itself is very simple: It consists of a highly reflective coating on top of the active medium which is glued to a heat sink. The HR coating is transparent for the addressing light, but highly reflective for the laser resonator light. The active medium on the other hand is highly absorbing for the addressing light but highly transparent for the resonator laser light in order not to absorb it. This reduces the influence of spurious resonator light that gets transmitted through the HR coating. One of our actual implementations uses the long pass filter glass RG 830 (Schott) in combination with a standard HR coating.

The addressing illumination module uses a DMD micro mirror array as flexible amplitude modulation mask in combination with a 35 W peak power laser diode bar at 808 nm (DILAS M1B H112). The laser diode bar is collimated in both axes.

We have tested the new optically addressed AO in an interferometric setup. Fig. 2 shows some of the results we have obtained with our systems.

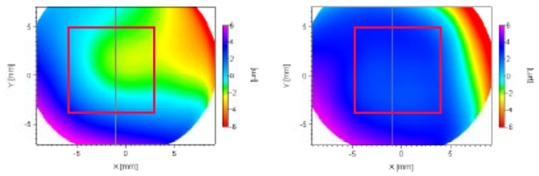

Fig. 2: Asymmetric correction of aberrations. Left: uncorrected wavefront. Right: The wavefront has been corrected in the red square.

In other implementations we used dyed plastic layers as active medium, fig. 3 shows the response for an epoxy-based element.

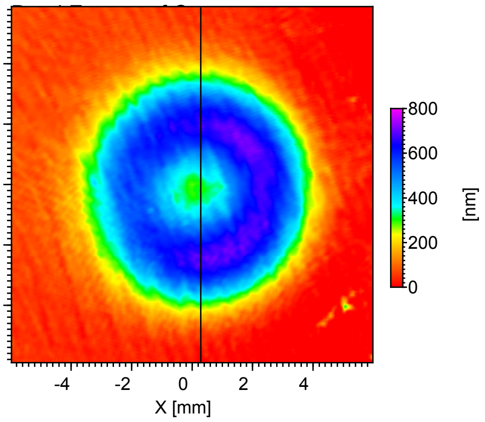

Fig 3: Rotationally symmetric wave front correction.

Future work will focus on the optimization of the choice of materials to obtain high deflections with smaller layer thicknesses, to further reduce the response time of now several hundred milliseconds.

Supported by: Landesstiftung Baden-Württemberg
Project: „ThermAO“

Active micro optic for spatial polarization control

F. Schaal, C. Pruss, W. Osten

The intention of this project is the development of a compact micro optical device (Fig. 1) for non-pixelated spatial polarisation control of an incoming light field (300 µm diameter).

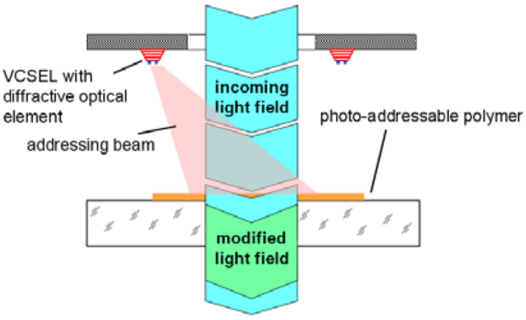

Fig. 1: Schematic diagram of the basic setup.

Spatial micro optical polarisation control enables new applications in the field of beam shaping, measurement techniques and stray light modelling.

The principle of operation is based on a photo-addressable material (e.g. PAP). Birefringent properties of the material are changed by illumination with red light. The spatial shaping of the light field is achieved by structured illumination of the thin polymer layer (Fig 2).

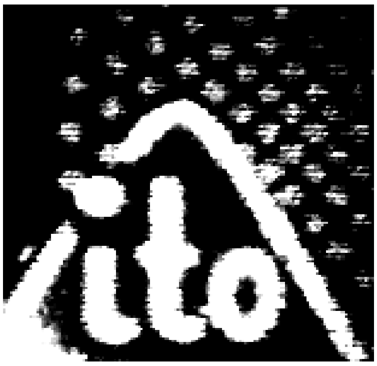

Fig. 2: ITO logo written into photo-addressable polymer.

Red Vertical-Cavity Surface-Emitting Lasers (VCSEL, Fig.3) are used as a light source of the illumination system. The shaping of the laser beam into the desired illumination pattern is done by diffractive optical elements (DOE). The first transmissive DOE will be monolithically integrated into the exit aperture of the VCSEL. Due to the small dimensions of the VCSEL exit aperture, it is necessary to use additional DOEs to achieve complex high resolution illumination patterns on the polymer layer.

The system will consist of several VCSELs with separate beam shaping optics. The dynamic superpositioning of the individual illumination patterns allows the active control of the polarisation shaping.

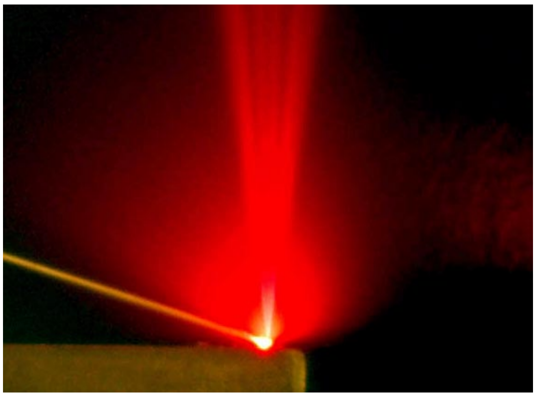

Fig 3: Red Vertical-Cavity Surface-Emitting Laser (VCSEL).

This project is part of the DFG priority programme 1337 “active micro optics” and is done in collaboration with the IHFG (University of Stuttgart) and University of Potsdam.

Further work will focus on the detailed simulation and design of the device and the diffractive optical elements, the development and test of new photo-addressable materials with high induced birefringence and fast response and finally the production and characterisation of device prototypes.

Supported by: DFG (OS111/26-1)
Project: “AMiPola”

Impressum:

Publisher: Institut für Technische Optik (ITO)
Universität Stuttgart
Pfaffenwaldring 9
D – 70569 Stuttgart
www.uni-stuttgart.de/ito

Editor: Dipl.-Ing. (FH) Erich Steinbeißer................................steinbeisser@ito.uni-stuttgart.de
Dipl.-Des. Matthias Staufer, mamadesign.net (Graphic & Layout)......mail@mamadesign.net

Printing: Breitschuh & Kock GmbH, Kiel

Print run: 400

ISBN 978-3-923560-62-2

ISBN 978-3-923560-62-2