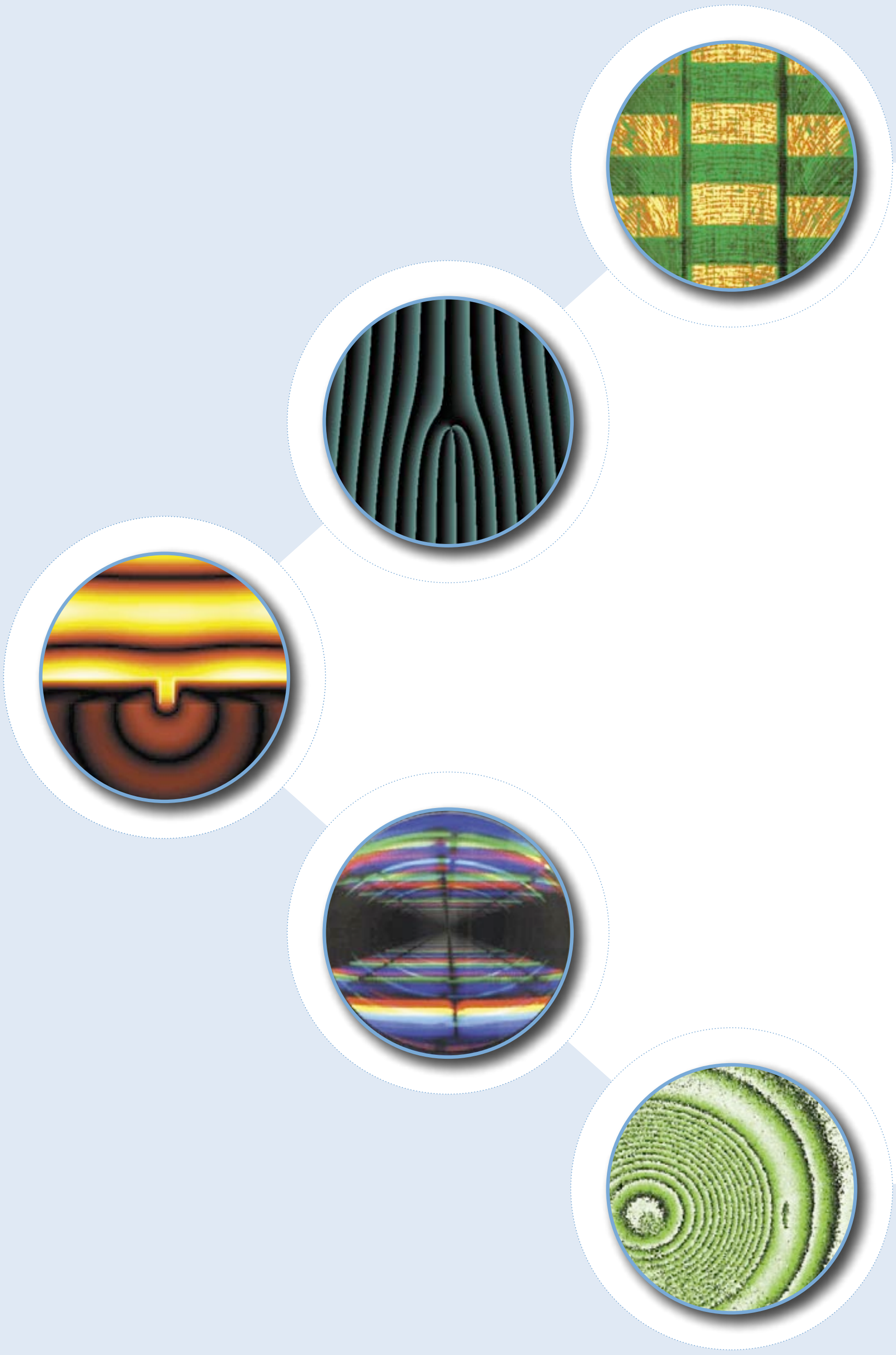
annual report
2005 / 2006

INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART



Universität Stuttgart

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ANNUAL REPORT 2005/2006

Dear Reader,

Two years filled with many activities in different fields and enriched with fruitful world wide cooperations have passed since the ITO staff reported about their previous research activities in the form of such a comprehensive report. Thus it is again time to inform our partners, sponsors and customers about our recent advances in the field of Applied Optics.

The basic understanding that determines our behaviour remains unchanged: striving for excellence in research and teaching, together with continuity and the systematic renewing and modernization of our environment. However, the growing number of ambitious research projects and the fortunately increasing world wide cooperation with key players in the field of optical technologies are accompanied by new initiatives and challenging timescales. In comparison with the past we are faced with stronger competition and faster changing boundary conditions.

The last two rounds in the *Excellence Initiative of the Federation and the States* convinced us that personal and institutional expertise are only necessary preconditions in an intensified competition for recognition and substantial funding. Interdisciplinary cooperation in larger scientific networks assembled to meet ambitious mid- and long-term targets is gaining more and more in importance. ITO is here on a good path. As the partner in pending applications for a Cluster of Excellence and for a Graduate School we are still in the game. Further initiatives for the installation of Collaborative Research Centres and Priority Programs are part of our future strategy.

As member of the Faculty of Mechanical Engineering, the Institute represents Stuttgart University in the field of Engineering Optics in research and education. Together with our national and international partners, our research work focuses on the exploration of new measurement and design principles and their implementation in new optical components, sensors and sensor systems. One of our central goals is the extension of existing limits by combining modelling, simulation and experimental data acquisition in the context of actively driven measurement processes. Several ambitious objectives are on our agenda such as the enhancement of the robustness and resolution of optical sensors, the miniaturization of components and systems, the in-line integration of optical sensors in production processes and machine tools, and the improved exploitation of all information channels of electromagnetic waves. The five main research directions of ITO

- 3D-Surface Metrology
- Active Optical Systems,
- High-Resolution Metrology and Simulation,
- Interferometry and Diffractive Optics, and
- Coherent Metrology

are driven by the five research groups which make up the Institute. Together with strong interactions between these groups, this gives the Institute a strength in depth over a broad range of optics activities. The considerable number of research projects that are referred to in this report reflects the success of this approach.

Along with the fulfilment of these research projects the Institute has been undergoing a considerable modernisation of the equipment and infrastructure over the past 3 years to maintain and to improve its efficiency. The most important activity - the installation of a new class 100 cleanroom, where the fabrication of diffractive optical elements and the high resolution optical metrology find an adequate technological basis and environment, was completed in early summer 2006. The still ongoing installation of some sophisticated infrastructure will complete that process in the near future.

To cope with our ambitious and extensive approach to Applied Optics a deep understanding of the physics of optics needs to be combined with practical engineering implementation. The fulfilment of this boundary condition means a daily challenge for all members of the staff. However, a good mixture of graduates in physics and engineering, a vital and innovative scientific climate, that considers the interdisciplinary cooperation with numerous national and international institutes, and a continuous observation of the technological and scientific progress – the traditional features of the ITO - are a good basis to meet these and future challenges. May this report once again convince our sponsors, customers and partners of this and may this report be received with deep thanks for the good cooperation and the substantial support over the past two years.

Wolfgang Osten

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ito-Structure

Teaching

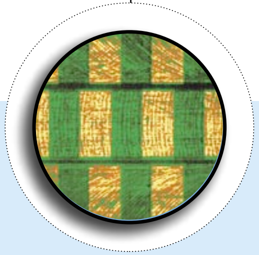
E. Steinbeißer

Chair

Prof. Dr. W. Osten

Deputy

Dr. T. Haist



3D-Surface Metrology

Dr. K. Körner

3D-Macro- and Micro-Topometry

- White-Light Interferometry
- Spectral Interferom.
- Confocal Microscopy
- Fringe Projection
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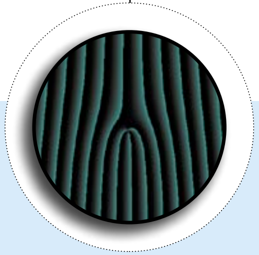

Active Optical Systems

Dr. T. Haist

Modulation of Light

- Adaptive Optics
- Dynamic Holography
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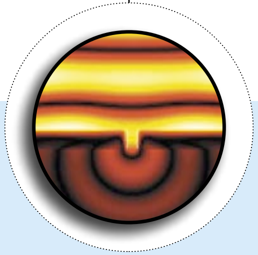

High Resolution Metrology and Simulation

K. Frenner

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- Microscopy
- Super-Resolution
- Scatterometry/ Diffractometry
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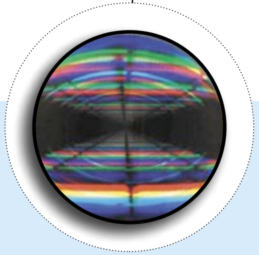

Interferometry and Diffractive Optics

Ch. Pruß

Technology & Components

- Testing of Aspheres
- Microoptics
- Design and Production of DOE
- Wavefront Sensors

Coherent Measurement Techniques

Dr. G. Pedrini

Shape- & Deformation Measurement

- Speckle-Interferom.
- Digital Holography
- Dynam. Processes
- HNDT
- Hologr. Endoscopy
- Hologr. Microscopy

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Dr. Tonatiuh Saucedo	Centro de Investigationes en Optica (Mexico)	1/2005 – 7/2005
Prof. Mikhail Gusev	Kaliningrad State University (Russia)	3/2005 – 5/2005
Dr. Cristina Trillo	University of Vigo (Spain)	4/2005 – 6/2005
Prof. Wenge Wang	Hunan University; PR China	10/2005 - 9/2006
Prof. Percival Almoro	University of the Philippines (Philippines)	10/2005 – 9/2006
Dr. Lingfeng Yu *	Beckman Laser Institute (USA)	12/2005 – 7/2006
Dr. Yoko Miyamoto	University of Electro-Communications (JAPAN)	3/2006 - 5/2006
Prof. Leonid Yaroslavsky	Tel Aviv University (Israel)	4/2006 – 5/2006
Prof. Chittur Narayanamurthy	University of Baroda (India)	4/2006 – 6/2006
Dr. Arun Anand	Institute of Plasma Research (India)	5/2006 – 5/2007
Prof. Dayong Wang	Bejing University of Technology (China)	12/2006 – 11/2007

* Humboldt fellowship

Foreign Guests visiting the Institute: 2005 - 2006

Dr. Peter de Groot	ZYGO Corp., Middlefield, USA	April 2005
Dr. Victor Korolkov	Academy of Sciences, Novosibirsk, Russia	Mai 2005
Prof. Charles Joenathan	Rose-Hulman-Univ., USA	Juni 2005
Prof. Mitsuo Takeda	Univ. of Electro-Comm.Tokyo, Japan	September 2005
Prof. Ichirou Yamaguchi	Gunma Univ. Kiryu, Japan	September 2005
Prof. Toyohiko Yatagai	Univ. of Tsukuba, Japan	September 2005
Prof. Malgorzata Kujawinska	Warzaw Univ., Poland	September 2005
Dr. Peter de Groot	ZYGO Corp., Middlefield, USA	December 2005
Dr. Carl Zanoni	ZYGO Corp., Middlefield, USA	December 2005
Dr. Wei Wang	Univ. of Electro-Comm.Tokyo, Japan	March 2006
Dr. Yoko Miyamoto	Univ. of Electro-Comm.Tokyo, Japan	March-May 2006
Prof. Leonid Yaroslavski	Tel Aviv Univ., Israel	April 2006
Prof. Colin Sheppard	National Univ. of Singapore, Singapore	May 2006
Dr. Fernando Mendoza Sanzoyo	CIOP Leon, Mexico	June 2006
Prof. Alexander Poleshchuk	IAE, Novosibirsk, Russia	June 2006
Prof. Malgorzata Kujawinska	Warzaw Univ., Poland	July 2006
Dr. Arie den Boef	ASML Veldhoven, Netherlands	November 2006
Dr. Vadim Banine	ASML Veldhoven, Netherlands	November 2006
Prof. Ventseslav Sainov	CLOSPI, Sofia, Bulgaria	Dezember 2006

Project partners

Project collaboration with the following companies and organisations (and many others):

Automotive Lighting GmbH	Reutlingen
Carl Zeiss AG	Oberkochen
Carl Zeiss SMT AG	Oberkochen
DaimlerChrysler AG	Germany
Dantec-Dynamic GmbH	Ulm
Diehl GmbH	Germany
Fisba Optik AG	St. Gallen, Switzerland
Heidelberger Druckmaschinen AG	Heidelberg
Holoeye Photonics AG	Berlin
Innovatis AG	Bielefeld
Jenoptik LOS	Jena
Leica Microsystems GmbH	Wetzlar
Mahr GmbH	Göttingen
National Gallery-Alexandros Soutzos Museum	Athens, Greece
Optrion s.a	Liège, Belgium
Qimonda Dresden GmbH & Co. OHG	Dresden
Polytec GmbH	Waldbronn
Robert BOSCH GmbH	Gerlingen, Schwieberdingen
Sirona Dental Systems GmbH	Bensheim
Tate	London, England
Zygo Corporation	Middlefield, USA

Studying optics

Our curriculum is primarily directed towards the students in upper-level courses (“Hauptdiplom”) of Mechanical Engineering, Cybernetic Engineering, Mechatronics, and Technology Management. We especially recommend the course option “Microsystems and precision engineering”. We also welcome students from other courses, such as “Physics” and “Electrical Engineering and Information Technology”.

Concerning the main subject “Engineering Optics” we offer the following

Core lectures:

- **fundamentals of engineering optics** (Prof. Dr. W. Osten)

  basic laws and components: optical imaging with lenses, mirrors, and prism; basic optical set-ups; optical systems and devices (the human eye, magnifying glass, microscope, and telescope); physical optics, physical limits of optical images, resolution of optical devices; geometrical and chromatic aberrations and their influence on picture quality, basic laws of photometry.

- **optical measurement techniques and procedures** (Prof. Dr. W. Osten)

  basics in geometrical optics and physical optics; holography; speckle; components and systems: light sources, lenses, mirrors, prism, stops, light modulators, the human eye and other detectors; measuring errors; measuring techniques based on geometrical optics: measuring microscopes and telescopes, structured illumination, application of moire-phenomenon; measuring techniques based on physical optics: interferometrical measurement techniques, holografic interferometry, speckle measurement techniques.

- **optical information processing** (Prof. Dr. W. Osten)

  fourier theory of optical imaging; basics of the wave theory, coherence, frequency analysis of optical systems, holography and speckle, spectrum-analysis and optical filtering; digital image processing: basics as far as methods and applications.

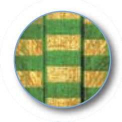
Elective lectures

- optical phenomena in nature and everyday life (Dr. T. Haist)
- opto-electronical image-sensor and digital photography (Dr. K. Lenhardt)
- coherence and polarisation in optics / optics of thin films, surfaces and crystals (Dr. K. Leonhardt)
- optical lithography / measuring techniques for micro-structures (Dr. M. Totzeck)
- design and calculation of optical systems (Dr. H. Zügge / Dr. Ch. Menke)
- optoelectronic devices and fibre sensors (Dr. R. Groves)

Additional studies

- project work and theses within our field of research
- practical course “optics-laboratory”
  - speckle measurement
  - digital image processing
  - computer aided design of optical systems
  - measurement of the spectral power distribution
- practical course “optical measurement techniques”
  - 3D surface measurements applying fringe projection
  - digital holography
  - 2D-interferometry and measurement
  - quality inspection of photo-objectives with the MTF measuring system
- common lab for mechanical engineering (APMB)

The research groups



3D-Surface Metrology

The objective of the group is the analysis and the implementation of new principles for the acquisition of optical 3D-surface data of engineering and biological objects over a wide scale. Our main focus is on the enhancement of the metering capacity by a combination of physical models and optimized system design.

Current research activities are:
- 3D-measurement applying fringe projection and deflectometry (macroscopic and microscopic)
- adaptive techniques using spatial light modulators
- confocal microscopy
- white light interferometry
- spectral interferometry
- sensorfusion and data interpretation strategies
- deflectometry

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Active Optical Systems

The objective of our work is the development of flexible optical systems in order to enable new applications, especially within the field of scientific and industrial metrology. To achieve this goal, we make use of different modern light modulation technologies and computer-based methods.
One focus of our work lies in the application of holographic methods based on liquid crystal displays and micromechanical systems for various applications ranging from optical tweezers to aberration control and testing of aspherical surfaces.

Main research areas:
- active wavefront modulation
- adaptive optics
- active wavefront sensors
- dynamic holography
- components, algorithms, and strategies

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High Resolution Metrology and Simulation

The goal of this research group is the investigation of the interaction of light with 3d object structures in the micro and nano domain. Along with experimental research, one major aspect is the rigorous modelling and simulation as an integral part of the active metrology process. The analysis of all information channels of the electromagnetic field (intensity, phase, polarisation state of light) allows us to obtain sub-wavelength information about the structure.

ITO has developed a modularised program package called MicroSim for:
- the rigorous computing of the light-object interaction using RCWA
- the visualisation of the near and farfield in 2D and 3D
- the simulation of the microscopic imaging process

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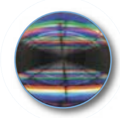

Interferometry and Diffractive Optics

The goal of our research activity is to explore new measurement concepts using diffractive optics. One important application is the testing of optical surfaces, in particular, aspheric lenses. For this purpose we design and produce computer generated holograms (CGH). At the same time, we develop flexible measurement techniques that enhance or even replace static null correctors. In addition to CGH for interferometry, our in house production facilities allow us to produce diffractive elements and micro-optics for a wide variety of applications such as UV-measurement systems, beam shaping applications and wavefront sensing.

Our research areas include:
- design, fabrication and testing of hybrid refractive/diffractive systems
- testing of aspheric surfaces
- interferometry
- fabrication of diffractive optics
- dynamic wavefront coding

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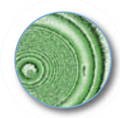

Coherent Measurement Techniques

Our research objective is the analysis and application of methods based on coherent optics for the measurement of 3D-shape and deformation and to determine the material properties of technical objects and biological tissues. Aside from the quantitative measurements of form and deformation, methods for non-destructive material testing are also analysed and applied.

Research areas include:
- digital holography
- pulsed holographic interferometry
- dynamic strain measurements on biological samples
- shape measurement
- wavefront reconstruction
- holographic non-destructive testing
- endoscopy

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3D-Surface Metrology

Chromatic confocal spectral interferometry (CCSI)
Supported by: DFG (OS 111/21-1)

Atraumatic functions preserving precision surgery of the human temporal bone (COCHLEA)
Supported by: BMBF (01 EZ 0405)

Combined optical-tactile metrology for Microsystems
Supported by: BMBF (FKZ 16SV1945)

Hybrid micro-optic sensor which uses the chromatic-confocal focus detection principle
Supported by: BMBF (FZK: 02P D2551)

Multiscale Measurement Strategies: Indicators for the detection of microscopic defects
Supported by: DFG (OS 111/18-2)

In-process measurement of micrometer scale tools
Supported by: VDI/VDE-IT Berlin (16IN0373)

Application of Liquid-Crystal-Displays for digital holography

Chromatic confocal spectral interferometry (CCSI)

E. Papastathopoulos, K. Körner, W. Osten

Chromatic confocal spectral interferometry (CCSI) is a novel technique for topography measurements which combines the techniques of spectral-interferometry and chromatic-confocal microscopy. This hybrid method allows a white-light interferometric detection with high numerical aperture (NA) in a single-shot manner. To our knowledge, CCSI is the first interferometric method which simultaneously uses a confocally filtered and chromatically dispersed focus for detection, and allows the retrieval of the depth position of reflecting or scattering objects from the phase (modulation frequency) of the interferometric signals acquired. For the chromatically dispersed focus, the depth range of the sensor is decoupled from the NA of the microscope objective.

The discrepancy of the limited axial-range in previously reported spectral interferometry (SI) schemes can be visualized as follows. The reference field contains a planar wavefront, while the detection-wavefront acquires a rigorous curvature, when the object lies beyond the depth-of-focus, if aberration effects are neglected. This curved wavefront can be mathematically described by the axially symmetric Zernike polynomial of the second order. Optical interference between those two fields leads to a reduced contrast of the modulated spectral signal. In the CCSI scheme presented here, the axial-range of the detector is expanded due to the chromatically-dispersed foci (40µm axial range with 0.8 NA reported) by means of a diffractive optical element – DOE (Fig. 1). If the object lies within the dispersed focus spectrum, a sharply focused spectral-component λ_o gets reflected and this induces a high-contrast wavelet in the spectral domain. The amplitude of this modulation remains constant within the entire range of the optical spectrum employed and the axial-range of the detector is decoupled from the limited depth-of-focus. The signals acquired from CCSI comprise interference wavelets in the optical spectrum domain. The modulation frequency is then used to detect the longitudinal position of a reflecting or scattering object.

In the current project, the principles of this new spectral interferometry method were both experimentally and theoretically addressed. The CCSI principle has been implemented in two prototype setups: a Linnik-type interferometer (0.8 NA) and a fiber based interferometer (0.95 NA). Finally, on the basis of topography measurements performed on technical objects, the applicability of this method for the optical detection of objects with rough surfaces and limited reflectivity was demonstrated.

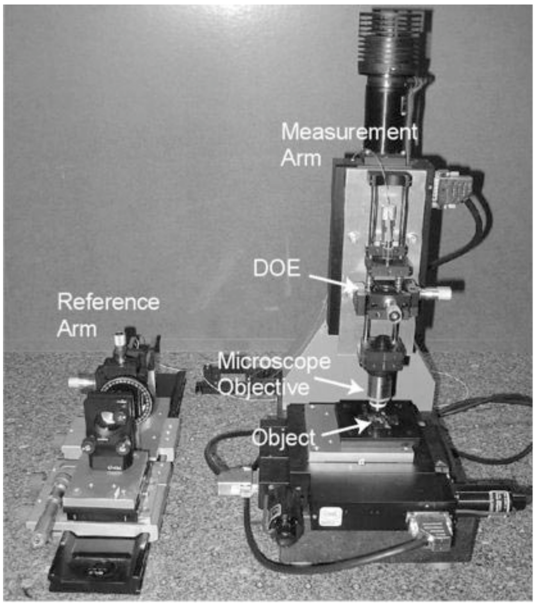


Fig. 1: Fiber-based interferometer with a chromatically dispersed focus, an achromatic reference and detection in the optical frequency domain, utilizing a grating spectrometer.

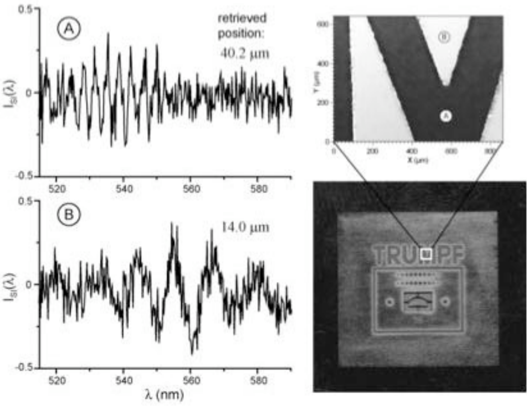


Fig. 2: An experimentally acquired interference wavelet involving a laser-processed Wolfram plate. This object is courtesy of TRUMPF. It exhibits a step structure which was measured by monitoring the modulation frequency of the interference signals from the sampled areas A and B

Supported by: DFG (OS 111/21-1)

References:

[1] Papastathopoulos, E.; Koerner, K.; Osten, W.

[2] Optics Letters 31, 589 (2006)

[3] Applied Optics 45, 8244 (2006)

[4] Proc. SPIE 6292-43 (2006)

[5] Proc. SPIE 6189-39 (2006)

Atraumatic functions preserving precision surgery of the human temporal bone (COCHLEA)

E. Papastathopoulos, K. Körner, W. Osten

In modern surgery, the implementation of navigation systems and robots has become very popular and successful. Current machine vision and navigation systems are proving inadequate techniques to provide the sub-millimetre precision required for surgery on the skull base and on the temporal bone, the bone on which the inner ear organ is located. A typical example of the concept of atraumatic operation is the implantation of a Cochlear electrode in the inner ear, in the area of the temporal bone. When manual methods are used often part of the remaining hearing ability can be destroyed. Within this scope a high-precision position system with a Hexapod-Kinematik system and a miniaturised confocal optical sensor are implemented to provide solution to this a problem.

A schematic of the sensor developed for this purpose is depicted in Fig.2. As a light source, a pigtailed laser diode was employed, which emits quasi-monochromatic light, at a wavelength of 658nm and with a 12mW optical intensity output from a single mode fiber. Due to the limited spatial dimensions in the surgically enfranchised temporal bone area, a compact sensor head was conceived on the basis of graded index optics (GRIN). It is composed of one gradient index rod lens with a focal length of 4.5 mm and a diameter of 1.8 mm, glued together using a glass rod spacer (BK7) with UV-cured adhesive. On the other side of the glass spacer the end of a single mode optical fiber was centred and fixed by adhesive. This serves both as a point-like light source and as a pinhole for the confocal detection. The overall diameter of the sensor head is 2mm. In order to avoid contamination or damage of the operated on outer shell of the Cochlea, a moderate working distance of several millimetres, here more than 4mm, is required. Following an optimised optical design the lateral resolution of the sensor is 10µm. Test measurements performed on human temporal bone tissues showed repeatability of less than 500µm for the longitudinal confocal detection.

The COCHLEA project presented here is performed in cooperation with the Institute for Process Control and Robotics at the University of Karlsruhe, with the Department (IPR) of ORL & HNS at the University Clinic in Freiburg and with the companies Richard Wolf GmbH (Knittlingen) and Cochlear GmbH (Hannover).

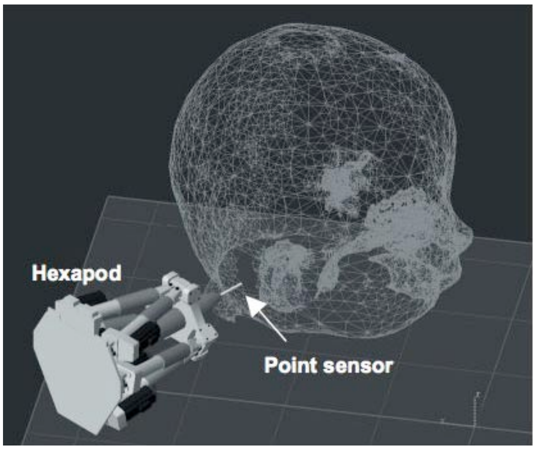


Fig. 1: Schematic representation of the optical measurement of the temporal bone region by implementing a Hexapod and a confocal point-sensor.

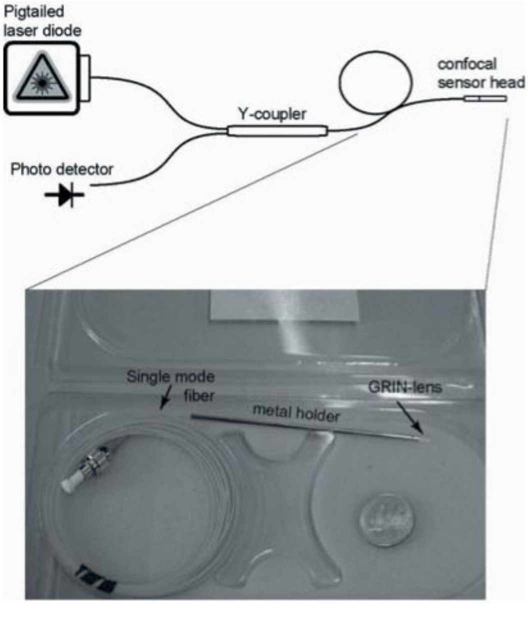


Fig. 2: Schematic representation of the confocal optical sensor (upper) and a photograph of the miniature sensor head (lower frame).

Supported by: BMBF (01 EZ 0405)

References:

[1] Ngan, C. C.; Raczkowsky, J.; Knapp, F.; Klenzner, T.; Papastathopoulos, E. ; Koerner, K.; Schipper, J.; Woern, H. "Micro scaling of robot treatment for skull base operations", Invited paper by IJCARS (in press)

Combined optical-tactile metrology for Microsystems

R. Berger, K. Körner, W. Osten

Microsystems Technology has high potential in research and industry. MEMS [1] and MOEMS [2] devices are in the micrometre to millimetre range. As the structures get smaller, the tolerances become also smaller and even reach the nanometre scale. The structures themselves are often small holes, gratings or other geometrical elements with high aspect ratios in silicon, plastic or metal. For quality inspection the distances, radii, depths and angles of these structures are of interest.

In the BMBF-project µgeoMess measurement systems are developed, which are suitable for a wide range of the above measurement tasks. As we know that there will be no single measurement principle, which can perform these measurements, we investigate a modular combination of three different measurement techniques. On the one hand, there are two optical measurement techniques, which give the 2D- and 3D-profile of the object respectively. Because a field for example as large as 0.6 mm x 0.8 mm can be measured, it is a fast technique to inspect MEMS and MOEMS. For the 2D-investigation there is a light optical microscope, which can record a digital image and perform the digital image processing. To get the 3D-profile, there is a white-light-interferometer, which can achieve nanometre resolution in the vertical dimension. The two optical measurement systems are combined in a compact measurement tool. This is possible by using a special microscope objective, similar to a Mirau objective, which was designed by one of the project partners. We separate the optical wavelength spectrum into two parts to operate the system. In the blue spectral region the beam splitter in front of the last lens surface is transparent and the objective can be used for 2D-measurements as a usual microscope objective. When using light above the blue spectral range, the light will be reflected at the beam splitter and the objective works as a Mirau interferometer. To change between the 2D- and 3D-measurement modes, it is only necessary to switch on another LED in the illumination device. There is no need to move mechanical parts or to modify the optical system. With these two measurement techniques it should be possible to investigate most of the geometrical characteristics of MEMS and MOEMS. But small holes and undercuts can not be detected by these usual optical measurement devices. For this reason, there is also a novel tactile micro probe, which can also be positioned in the micro holes. The probe is a piezo resistive silicon cantilver with an integrated measurement tip. This combination of the two optical techniques with the tactile measurement technique will result in a compact and complete solution for most of the measurement tasks in Microsystems Technology.

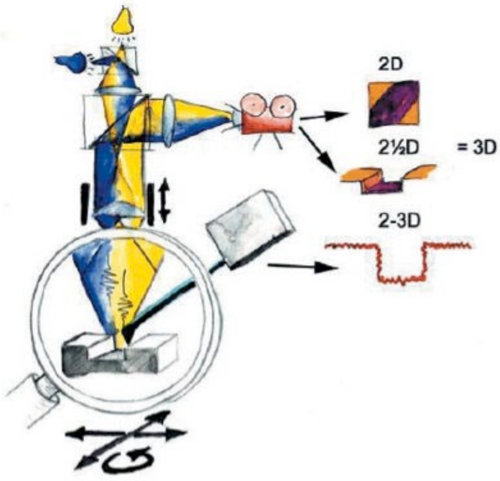


Fig. 1: Schematic of the interaction between the three different measurement principles: the optical microscope with digital image processing; white-light interferometry and the tactile probe.

At the Institute, we focus on the analysis of different measurement errors in white light interferometry. When measuring mirrorlike, tilted objects and performing a phase measurement, we found a correlation between the slope of the object and the phase information in the interference data, at each pixel of the camera. This can result in phase step errors in the topography map of the object under test. The aim is to get a detailed understanding and to provide solutions to the effects that introduce measurement errors [3].

Supported by: BMBF (FKZ 16SV1945)

Footnote and reference:

[1] MEMS: Micro-Electro-Mechanical-System

[2] MOEMS: Micro-Electro-Optical-Mechanical-System

[3] Berger, R.; Sure, T.; Osten, W. "Measurement errors of mirrorlike, tilted objects in white-light interferometry" to be presented at SPIE Optical Metrology, June 2007.

Hybrid micro-optic sensor which uses the chromatic-confocal focus detection principle

A. Ruprecht, C. Pruss, H. J. Tiziani, W. Osten

An increasing demand for the checking of small mechanical and optical precision component tolerances requires improved measurement techniques. In particular, components with a complex geometry are difficult to assess using state-of-the-art tactile measurement systems. Optical measurement systems are non-contact and therefore have the advantage that no mechanical forces occur during the measurement which could distort or displace a miniaturized sensor head and alter the result.

Mahr GmbH, a measurement system manufacturer, the Institut für Mikrostrukturtechnik (IMT) at the Forschungszentrum Karlsruhe, Boehringer Ingelheim microParts GmbH and the Institut für Technische Optik were partners in the research project HymoSens (hybrid micro-optical sensors). The main focus of the project is to develop a miniaturized micro-optical sensor. The sensor makes use of the chromatic-confocal measurement principle and as this technique does not use a mechanical depth scan the sensor was designed without any moving parts. A diffractive element is included to achieve the necessary chromatic axial splitting of the light. The diffractive micro optic was produced by ITO using a photolithographic processes and reactive ion etching to form the structure in thin substrates of fused silica.

A disadvantage of previously designed micro optic sensors [3] is the open beam arrangement. Therefore a part of the light used is reflected at the end of the fibre and by the lens surfaces. This leads to a background intensity in the signal that can disturb the signal evaluation. Here a monolithic layout of the sensor is the best solution, with only very small refractive index changes, in order to minimize reflections. The resulting design is represented in Fig. 1. Here, the numerical aperture is 0.5 and the working distance is 1 mm.

A diffractive lens (DOE) is the last optical element in the ray path, with the diffractive structure is located at the inner side of the DOE. Because of this the final surface of the sensor is a plane surface which can be easily cleaned. For this sensor, a super luminescent diode was used, which emits light in the near infrared region between 790 nm and 850 nm. Such a sensor can be optimized to have focus spots close to the diffraction limit. Calculated focus plots are shown in Fig. 2. The diameters of the circles in the plot are equal to the diameter of the Airy disc of an equivalent diffraction limited focus spots.

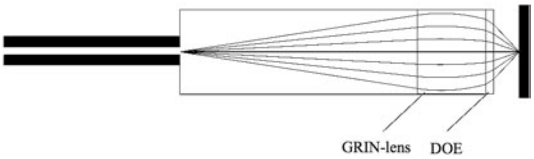


Fig. 1: Principle of the optical setup for the miniaturized point sensor. The elements are an optical fibre, a GRIN lens and a diffractive lens (DOE).

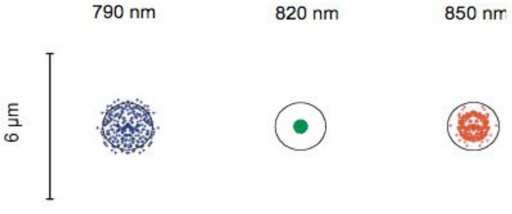


Fig. 2: Focus plots of the raytracing simulation of the setup in Fig. 1.

Supported by: BMBF (FZK: 02P D2551)

References:

[1] Ruprecht, A. K.; Wiesendanger, T. F.; Tiziani, H. J. "Chromatic confocal microscopy with finite pinhole size", Optics Letters 29 (18), 2130-2132, 2004.

[2] Lücke, P.; Last, A.; Mohr, J.; Ruprecht, A.; Osten, W.; Tiziani, H. J.; Lehmann, P. "Confocal microoptical distance-sensor for precision metrology", Optical Sensing, Proc. SPIE Vol. 5459-22, Strasbourg, 27-30 April 2004.

[3] Ruprecht, A. K.; Pruss, C.; Tiziani, H.J.; Osten, W.; Lücke, P.; Last, A.; Mohr, J.; Lehmann, P. "Confocal micro-optical distance sensor: principle and design", Optical Metrology, Proc. SPIE Vol. 5856-15, Munich, 13-17 June 2005.

Multiscale Measurement Strategies:

Indicators for the detection of microscopic defects

T. Wiesendanger, W. Osten

The increasing importance of technical components in the micro- and nanoscale raises the need for fast and economical characterisation techniques.

The limited space-bandwidth-product of optical sensors however enforces a compromise between a large measurement field, a high measurement resolution and a short measurement time. The aim of the research project funded by the DFG is to provide such measurement strategies.

A measurement strategy deploying a smart combination of sensors is the proposed solution to this problem (cf. Fig. 1). Based upon an initial global assessment of remaining areas of measurement uncertainty, local measurement techniques with different configurations are explored. All the measurement data is registered and merged into one consistent data set. The process of data acquisition is repeated until the measurement uncertainty is sufficient to decide whether the object under study is inside or outside of specifications.

The scheduling of the measurement process, especially the decision about where to place the higher resolved measurements, is performed by the application of defect indicators on the global measurement results.

In the context of this project several indicators are being studied: One example is the laterally resolved fractal dimension or the confocal axial response.

These strategies are being applied to the detection of topographic defects and a fast characterization of microlens-arrays (cf. Fig. 2, Fig. 3).

Future work will focus on a new measurement setup to incorporate the strategies in the field of wafer scale testing.

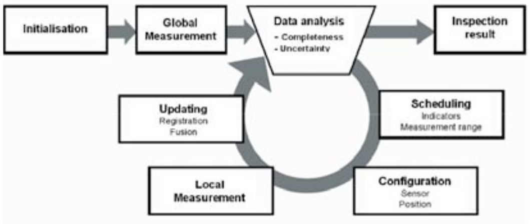


Fig. 1: Schematic illustration of the applied measurement strategy

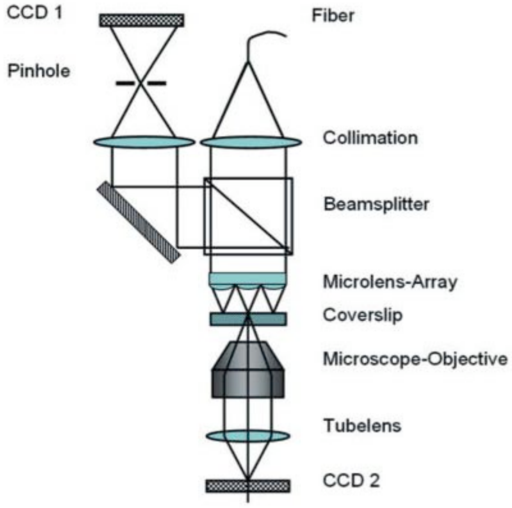


Fig. 2: Example: Measurement of defects on a Si-Wafer

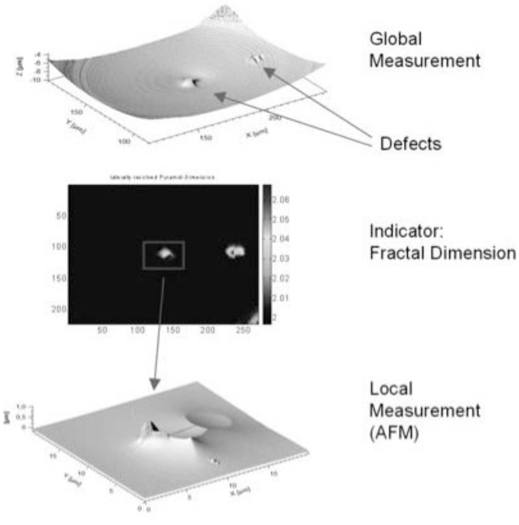


Fig. 3: Set-up for the fast characterization of microlens arrays

Supported by: DFG (OS 111/18-2)

References:

[1] Wiesendanger, T. ; Osten, W.; Pannekamp, J.; Regin, J.; Westkämper, E. "Neue multiskalige Mess- und Prüfstrategien für die Produktion von Mikrosystemen" In: Mikrosystemtechnik Kongress 2005. GMM, VDE, VDI, (eds.), VDE Verlag Berlin, Germany; pp 677-680.

[2] Westkämper, E.; Osten, W.; Regin, J.; Wiesendanger, T. "Multiskalige Mess- und Prüfstrategien in der Mikro- und Nanomesstechnik" VDI/VDE-Gesellschaft Meß- und Automatisierungstechnik -GMA-, Düsseldorf: Messtechnik für Mikro- und Nano-Engineering : Tagung Erlangen, 29. und 30. November 2006 Düsseldorf: VDI-Verlag, 2006 (VDI-Berichte 1950), ISBN: 3-18-091950-7

In-process measurement of micrometer scale tools

T. Wiesendanger, C. Kohler, W. Osten

The growing amount of highly integrated Microsystems, with an associated increased miniaturization, demands new high precision manufacturing processes. The newly developed manufacturing method called "Electrochemical micromachining", in particular, has the capability to fulfil some of these needs. It offers the possibility of producing stainless steel micro scaled structures with high aspect ratios in a single process step. To reach the achievable manufacturing limits adequate measurement instrumentation is necessary.

One of the big advantages of electrochemical micromachining is that the tools used are also made with the same manufacturing process as a first step. This greatly reduces the required precision of the tool blanks. However their precise position in the coordinate system of the machine and their exact shape has to be measured just before the start of process. In addition, an in process control of the tool is required to observe and correct for tool wear.

The tools are made out of tungsten wire with a diameter of 500µm and a length of several millimetres. The wire is welded in a previous step onto a machine holder. At this project stage only cylindrical tools are used, so the position relative to the machine mounted holder, the shape of the cylinder (e.g. small shape defects) and the concentricity must be measured. As a future step more arbitrarily shaped tools are planed, e.g. to create undercuts and notches. So a versatile in process measurement set-up at moderate costs is needed.

We therefore developed an image processing based machine integrated optical sensor out of standard components. The key features are:

- 10x magnification,
- object space NA 0.1,
- 0.8 x 0.6 mm field,
- 12 Bit CCD camera,
- 45 mm working distance,
- measurement resolution of 0.1 µm.

Due to the large measurement field of the sensor, tools between 10µm and 500µm in diameter can be measured with the same set-up. No change of objective is needed. One important task to guarantee a resolution of 0.1 µm was the machine integration of the sensor. This task was achieved by three design features: splitting the sensor into independent illumination and an observation parts; long working distances; and a folded optical path of the observation optics. The image in Fig. 1 shows a first test set-up of the measurement system with a test object.

Then initial measurements were performed (cf. Fig. 2, Fig. 3) to approve the image quality.

Fig. 1: Prototype of the measurement setup.

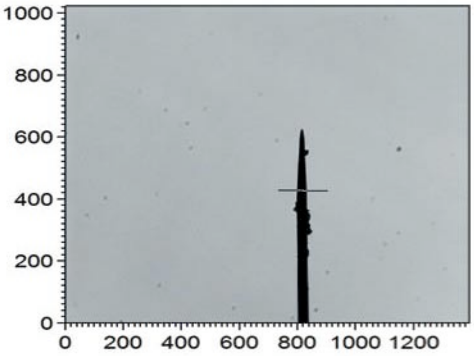


Fig. 2: Measurement of 20µm tool.

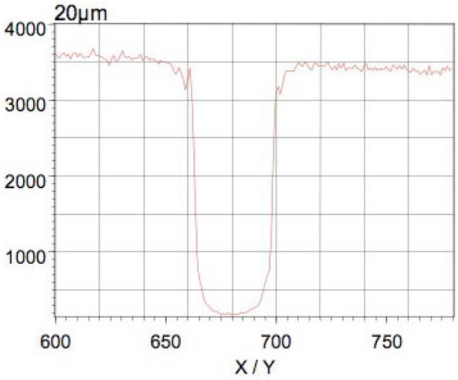


Fig. 3: Profile through the captured image of the 20µm tool (Fig. 2).

Supported by: VDI/VDE-IT Berlin (16IN0373).
Cooperation with: Institut für Zeitmesstechnik, Fein- und Mikrotechnik, Stuttgart.

Application of Liquid-Crystal-Displays for digital holography

C. Kohler, X. Schwab, T. Haist, W. Osten

The advances of liquid crystal displays offer new applications of these devices in digital holography and comparative digital holography. The increasing lateral resolution and the newly offered phase-only devices are enabling elements for new measurement setups in digital holography and micromanipulation devices like optical tweezers. [1]

Though the demands for these applications are very different, both have in common the need for a good knowledge of the modulator used for the optical reconstruction of the digital holograms [2, 3]. So as a first step of a modulator characterization the modulators complex transmission is measured i.e. the amplitude and phase transmission. But these measurements are only the first step in a complex characterization. As for example the modulator characteristic is determined by the modulator, the polarizers and the wave plates used. So the overall efficiency should be considered e.g. a phase only characteristic could be achieved but due to the settings of the wave plates an optical efficiency of 5% could occur as the polarizer and analyzer are working almost in extinction [2]. Other important factors are the surface geometry of the modulator which adds at least a defocus term and of course the modulator's fill factor which is the dominant factor for the achievable diffraction efficiency. E.g. with the LCOS modulator used almost half the incident light is scattered to higher diffraction orders. In consequence the maximum overall diffraction efficiency will be obviously lower than 50%.

As a consequence we did a first investigation of the achievable diffraction efficiencies based on the measurement of the intensities of reconstructed holograms. A hologram of a knight chess piece was recorded (s. Fig. 1) and then reconstructed in different modes:

- As a phase hologram with the modulator in phase-mostly mode (s. Fig. 2)
- As a phase hologram with the modulator in amplitude-mostly mode
- As an amplitude hologram with the modulator in phase-mostly mode
- As an amplitude hologram with the modulator in amplitude-mostly mode

The achieved diffraction efficiency of the different holograms with the distinct operation modes of the display was measured. The results of the measurements are shown in table1. As expected the phase hologram reconstructed in phase-mostly mode offers the highest diffraction efficiency.

Further steps in the SLM characterization will be the measurement of the Jones-Matrix and an optimization of digitally generated holograms based on Jones-Calculus which will lead to an even better understanding of the modulator's properties.

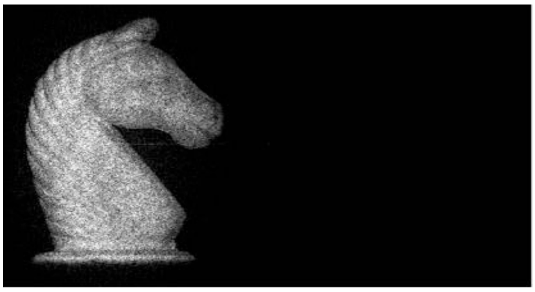


Fig. 1: Digital reconstruction of the recorded hologram of a knight chess piece.

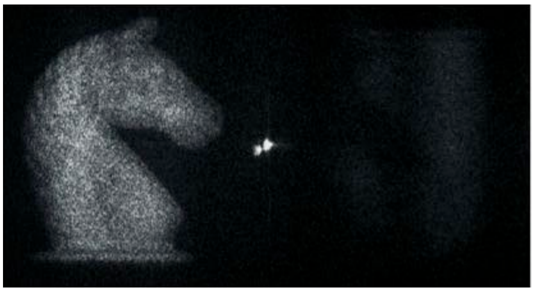


Fig. 2: Optical reconstruction of the recorded phase hologram with the display operated in phase-mostly mode.

References:

[1] Haist, T.; Schönleber, M.; Tiziani, H. J. "Computer generated holograms from 3D-objects written on twistednematic liquid crystal displays", Opt. Commun. 140, 299–308 (1997).

[2] Osten, W.; Kohler, C.; Liesner, J. "Evaluation and application of spatial light modulators for optical metrology" presented at 4a Reunión Espanola de Optoelectronica OPTOEL '05 (2005).

[3] Kohler, C.; Schwab, X.; Osten, W. "Optimally tuned spatial light modulators for digital holography" Appl. Opt., 45, 960-967 (2006).

Display-mode	Hologram transferred to the SLM	0. order [%]	+1. order [%]	-1. order [%]	Diffraction efficency [%]
AM	Amplitude hologram	0.28	0.03	0.01	10
AM	Filtered phase hologram	0.37	0.71	0.05	63
PM	Phase hologram	4.38	2.92	2.92	29
PM	Filtered phase hologram	1.25	7.69	0.81	79
PM	Filtered and shifted phase hologram	1.16	7.96	0.54	82

Table 1: Measurements from phase and amplitude holograms in AM and PM mode of the percentage of intensity in the 0., +1. and -1. orders of the reconstructed hologram relative to the laser intensity (with an error of ± 8% of the value) and the diffraction efficiency.
AM: amplitude mostly; PM: phase mostly

Active Optical Systems

High - resolution tomographic micro-interferometry
Supported by: DFG (OS 111/20-1)

Using consumer graphics boards in optics: hologram computation and ray tracing
Supported by: BMBF (FKZ 13N8809)

Active Micromanipulation using holographic optical tweezers and laser scissors
Supported by: Photonics BW

Active holographic cell sorting
Supported by: BMBF (FKZ 13N8809)

Low Cost Shack-Hartmann Sensor: Wavefront sensing with an aperiodic microlens array

High - resolution tomographic micro-interferometry

W.Gorski, W.Osten

Tomographic interferometer delivers as a result three-dimensional distribution of refractive index. The method is a combination of multidirectional transmission interferometry and tomographic reconstruction algorithms.

In the first stage of the project the research was focused on resolution improvement in the tomographic reconstruction of optical phase microelements. Previous work in this field proved that there are two main factors, which affect the final resolution of the 3D measurement. The first is diffraction, which appears at the border of materials with different refractive indices. An additional difficulty in this respect, may come from the structure of the object, the structure may itself be diffractive. The second factor limiting the resolution is mechanical imperfection of the rotation, resulting in the radial run-out phenomenon.

A tomographic micro-interferometer for the measurement of micro-optical elements has been built (Fig.1). The system is based on a transmission multidirectional interferometer, combined with tomographic reconstruction. The implemented tomographic algorithms were filtered backprojection, diffraction tomography and algebraic reconstruction technique. The system was designed for the measurement of optical fibers and fiber devices, e.g. splices.

As a test object, a photonic crystal fiber was chosen because it has high spatial resolution, and additionally includes a diffractive structure. The fiber, as well as its internal channels, were immersed in an immersion liquid which has the same refractive index as the fiber (fused silica). The matching of the refractive index was aimed at minimizing the diffraction effects at the border between materials with different refractive indices. The results of the tomographic reconstruction using three different algorithms showed that diffraction tomography is best suited to objects such as photonic crystal fibers. The radial run out error was at first reduced numerically, however the results were still not satisfying. Therefore also a manual correction was applied, which required the interaction of the operator and was time consuming. However it delivered acceptable results (Fig.2).

Another investigated aspect of the extension of the resolution was the application of the synthetic aperture technique. It was realized in the setup a tilt of the imaging system, to a certain angle (e.g. α in Fig.1) could be used. By using a synthetic aperture in tomography, one can extend the depth of focus, increase the field of view and reduce aberrations and diffraction effects. The disadvantage is that one has to record and process at least 2 phase maps, corresponding to the single angular position of the object, while when a synthetic aperture is not used only one phase map is needed. The measurement was performed with a use low numerical aperture (NA=0.1) microscopic objective. The results confirm an increase of the resolution and the suppression of measurement errors when this synthetic aperture technique is applied.

In the next stage of the project, a compact measurement setup with LCD modulators, dedicated to high - resolution tomographic interferometry will be built.

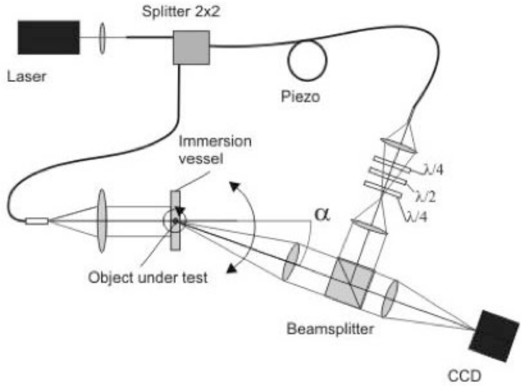


Fig. 1: Tomographic microinterferometer for optical microelements testing, with an optional extension to the synthetic aperture technique.

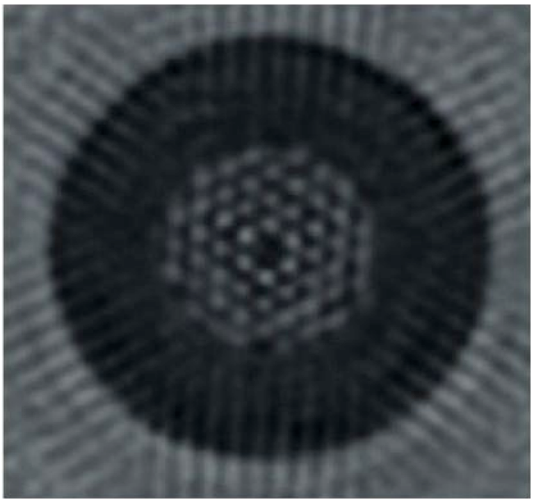


Fig. 2: The tomographic reconstruction of photonic crystal fiber, large mode diameter type (single layer tomogram).

Supported by: DFG (OS 111/20-1)

References:

[1] Gorski, W.; Osten, W. "Tomographic imaging of high-resolution phase structures", submitted to Opt. Letters.

Using consumer graphics boards in optics: hologram computation and ray tracing

T. Haist, A. Burla, F. Soyka, W. Osten

Many people think that the most powerful integrated circuit on their PC is the CPU. Chances are good that they are wrong. Today's consumer graphics boards incorporate highly parallel working processing units that outperform conventional CPUs for computational tasks with strong parallelism.

Within the BMBF project AZTEK real-time hologram computation is necessary to achieve the goal of a fully automated micromanipulation system based on holographic tweezers. Normal CPU based optimization of the holograms was found to be too slow for real-time operation. Therefore different hologram optimization methods were implemented on standard consumer graphics boards using a combination of Cg ("C for graphics"), OpenGL and C++. The most challenging part when writing such applications is to efficiently map the problem at hand to the hardware of the graphics board.

In fig. 1 the program flow for a iterative Fourier transform algorithm is shown. In order to fully exploit the available hardware it turned out that two holograms need to be computed at the same time. With a Nvidia 8800 GTX based graphics board it is possible to generate optimized (10 IFTA iterations) holograms for the holographic tweezers at a rate of 16 Hz. The main computational cost for this Fourier transform hologram optimization is associated with two-dimensional Fourier transforms. The 8800 GTX based board delivers for our application a performance of more than 360 complex (32 bit float) two-dimensional FFTs with 512 x 512 pixel per second and therefore strongly outperforms conventional CPUs. Other applications apart from hologram optimization (e.g. correlation, image processing) are of course possible.

As a technical demonstration, a program that captures part of the screen and computes holograms for the graphics found in the captured part in real-time has been implemented.

For many applications in optical design and simulation the available processing speed still limits optimization. One example is the simulation of the interferometric testing of aspheres. Another example is the design of illumination systems. We performed first experiments using the graphics board for optical raytracing. Benchmarks for tracing rays through systems with spheres and (polynomial) aspheres have been conducted after implementing a simple raytracing scheme.

On a 7800 GTX based card we achieved 200 million rays per surface per second for spherical surfaces and 50 million rays per surface per second for polynomial aspheres. The accuracy at the moment is 32 bit floating point precision.

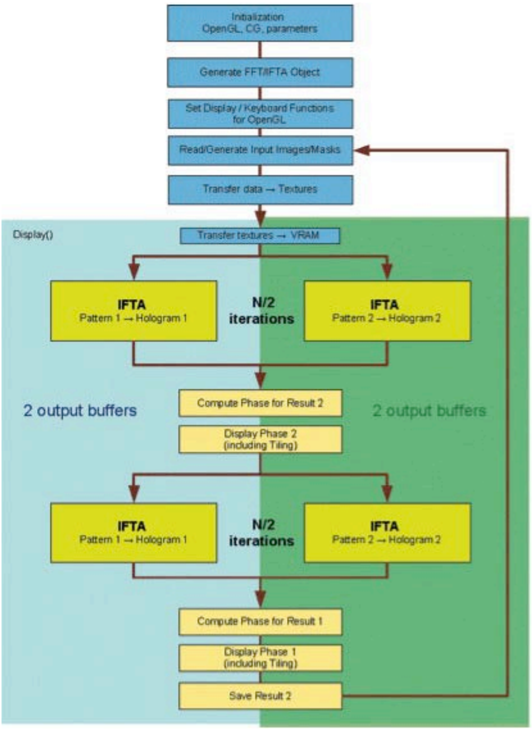


Fig. 1: flow diagram for the implementation of an iterative Fourier transform based hologram optimization on a graphics board. All boxes shown in yellow are completely processed on the graphics board.

Supported by: BMBF (FKZ 13N8809)

References:

[1] Reicherter, M.; Zwick, S.; Haist, T.; Kohler, C.; Osten, W. "Fast digital hologram generation and adaptive force measurement in LCD based holographic tweezers", Applied Optics 45(5), pp. 888-896 (2006).

Active Micromanipulation using holographic optical tweezers and laser scissors

S. Zwick, M. Warber, T. Haist, W. Osten

The aim of the Photonics-BW funded project AMIMA (Aktive MikroManipulation) was to build up a flexible tool, composed of holographic optical tweezers and holographically steered scissors. Such a tool enables the simultaneously movement and processing of micro-scaled objects with very high precision. It is much less expensive than mechanical systems for this application and it opens up a range of new applications in biology and micromechanics using automation.

Optical tweezers enable the trapping and movement of micro-scaled objects within the focus of a laser beam (1064nm) by transferring the momentum. Steering is carried out by a hologram, which is displayed on a liquid crystal display (LCD, LC-R 2500, Holoeye) which works as a spatial light modulator (SLM) and is situated in the Fourier plane of the object plane. By changing the hologram, it is possible to arbitrarily and independently move the tweezers in three dimensions. Thus high-precision-steering with a high repetition rate is possible without the movement of any mechanical parts.

Holographically steered optical scissors work a similiar way. As they work in the ultraviolet (λ=355 nm) a digital micromirror device (DMD; Texas Instruments) is required, since liquid crystals may be damaged by the UV-light. Optical Scissors enable the cutting, welding or destruction of biological or non-biological objects in the micro-scale.

We have combined these two tools in one versatile system, which is shown in figure 1.

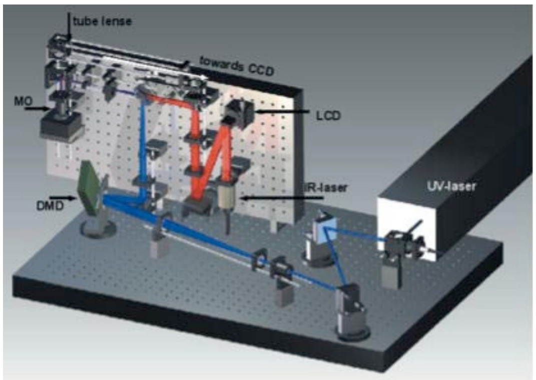


Fig. 1: Complete setup with optical tweezers (red ray path) and laser scissors (blue ray path)

As there are many sources that introduce aberrations into the optical setup, it is important to correct for them. Several different methods of aberration correction were developed and tested and two of them turned out to be practicable:

Optical tweezers are very sensitive to beam spot quality. To correct for specimen-introduced aberrations an automated iterative algorithm was developed, which calculates a new hologram by correcting a random aberration. Depending on the resulting spot intensity, another hologram would be calculated, until no improvement can be achieved.

The most deformed element in the laser scissors setup is the DMD itself. To correct for these aberrations, the wavefront deformation introduced by the DMD was measured with a Twyman Green Interferometer. Based on this measurement, a correction hologram was calculated, which was superimposed onto the holograms used for steering. Fig. 2 shows a holographically written circle on a photo resist. By correcting for aberrations, we could make the redundant -1 diffraction order less intense and thus giving no effect on the resist.

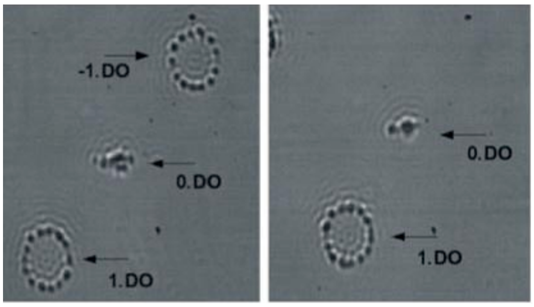


Fig: 2: Holographically written circles in photoresist. Left: without aberration. Right: with aberration control.

We have built the first completely holographically steered processing tool in the microscopic range. Figure 3 shows a human erythrocyte, being moved and destroyed by this tool.

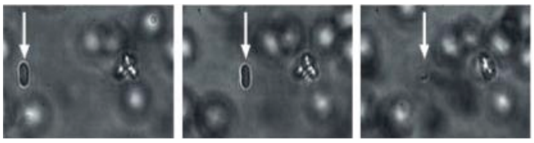


Fig. 3: Human erythrocyte, which first was moved and than destroyed by the laser scalpel.

Supported by: Photonics BW

Active holographic cell sorting

M. Warber, S. Zwick, T. Haist, W. Osten

Drug development is a statistical process. The aim is to filter out genetically modified cells that produce a desired protein. Up till now, to isolate these cells, cells have to be repeatedly diluted and bred, which is a long process when dealing with a high number of cells. To shorten this process, we can separate non-relevant from relevant cells.

In drug development, where there is a need to sort a smaller number of cells but with high accuracy, optical tweezers are an appropriate tool. Optical tweezers enable us to trap and move micro-scaled objects in the focus of a laser beam (λ=1064 nm) by transfer of momentum.

Holographic optical tweezers are an important extension of this tool. The setup includes a spatial light modulator (SLM) in the fourier plane of the object plane. There, a hologram is displayed to steer the object into position and to generate the desired number of traps. By changing the hologram, it is possible to move the tweezers arbitrarily and independently in three dimensions. Thus, high-precision-steering with high repetition rate is possible without moving any mechanical parts.

In the BMBF-founded project AZTEK (Aktive Zellsortierung Transfizierter EuKaryonten), in cooperation with two German companies (Innovatis and Holoeye), there are two aims. One is the realisation of a flexible two-step cell sorting system. The other is to build a holographic tweezers add-on module for a standard research microscope.

For the cell sorting, first a passive pre-sorting by a static light field, which separates cells by attributes like size or refractive index is employed (s. Fig. 1). Second an active sorting by attributes defined by the operator and which are identified by image processing is used. The identification of the relevant cells is done by our partner Innovatis, a specialist in cell analysis by image processing.

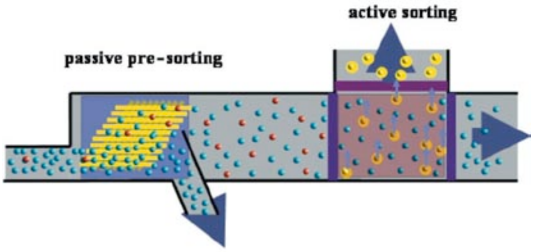


Fig 1: Schematic of a passive pre-sorting and active cell sorting combined with a micro fluidic system. The identification of relevant cells in the active sorting is done by image processing, whereas passive pre-sorting reacts on cell attributes like size.

The add-on module is designed for a Zeiss Axiovert 200M and includes a new phase-only LCOS modulator developed by Holoeye.

Since the parallel ray path is not accessible with a Zeiss Axiovert, the diffraction limited design of the system is not trivial. A detailed simulation had to be performed, in order to achieve an easy-adjustable and compact setup, which produces diffraction limited tweezers. For this purpose, a telescope to enlarge the laser beam diameter was designed in order to illuminate the SLM. Imaging of the hologram into the microscope is done by a 3-lens-system, which can be easily adjusted to the non-parallel ray path.

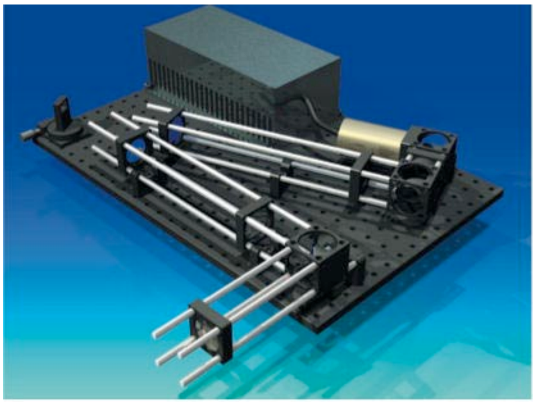


Fig. 2: Compact add-on module for holographic optical tweezers for a Zeiss Axiovert 200M.

Fig. 2 shows the complete and compact add-on module, which enables us to move and sort cells in combination with a microscope and a micro fluidic system. The micro fluidic system enables cells to travel through the device allowing separation. As this system has to be adapted to a sorting process, a special channel alignment is required. Development of such a system is in process.

Supported by: BMBF (FKZ 13N8809)

References:

[1] Haist, T.; Zwick, S.; Warber, M.; Osten, W. "Spatial Light Modulators – Verstile Tools for Holography", Holography and Speckle 2006, Vol. 3, No. 2, pp. 125-136.

Low Cost Shack-Hartmann Sensor:

Wavefront sensing with an aperiodic microlens array

T. Ruppel, L. Seifert, T. Haist, T. Schoder, W. Osten

Shack-Hartmann sensors are commonly used as wavefront sensors in a wide field of applications, such as adaptive optics, beam characterization and non-contact measurements. They are popular because of the ease of use and the robustness of the sensor. We introduce here a new way to improve the performance of these miniaturized and mass-producible optical wavefront sensors for industrial inspection applications.

A commonly used SHS consists of a microlens array and a detector with the same size. The measurement aperture is usually limited by the detector size. Because large detectors are expensive, the measurement diameter is normally in the range of 5-15 mm.

By using an aperiodic diffractive element, it is possible to design a sensor with different microlens array and detector sizes. This is interesting because CCD cameras with smaller detectors are much cheaper and therefore a SHS can be build at a lower price. To demonstrate this, we have built a SHS with a low cost webcam as the detector.

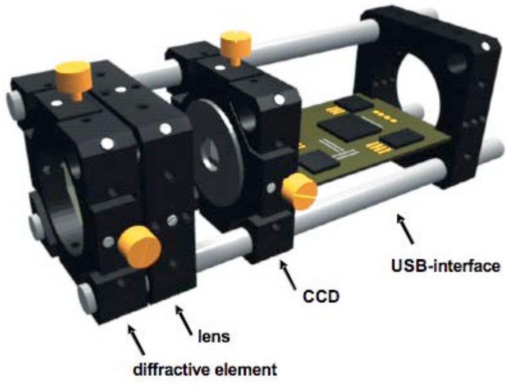


Fig. 1: Our low-cost Shack-Hartman Sensor can measure a 20 mm diameter wavefront using a 4.6x4.0 mm CCD chip from a webcam.

The basic component of this Shack-Hartmann sensor is the microlens array. The number of microlenses is identical to the number of slope measurements made over the aperture. Common SHS often use about 400 microlenses. Due to the low resolution of the chosen camera, in this case the number of microlenses is limited to about 200 lenses.

The measurement aperture of the sensor is circular but the detector area is rectangular. All pixels of the detector should be used. Therefore the assignment from microlens to spot position can not be uniform. Because all microlenses should have the same dynamic range, the path length for all microlenses should also be the same. We choose a remapping scheme in which the path length variation over all microlenses is minimised. Because of the small CCD chip, the phase function of the microlenses contains an additional phase tilt, so that the spots are focused on the detector. This can be seen in Figure 2.

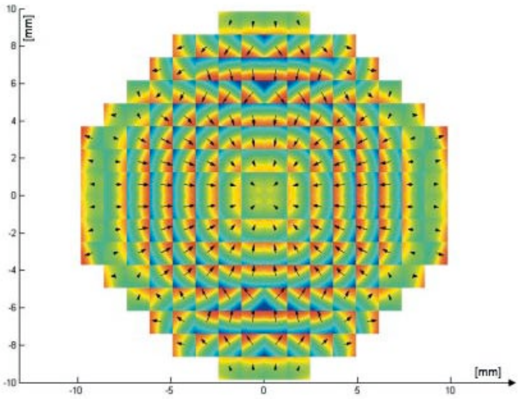


Fig. 2: Phase front picture of the microlens array. The arrows show the direction and amplitude of the tilt.

To enlarge the minimal size of the diffractive structure for simpler and cheaper fabrication, we added a biconvex lens (f=30.3 mm) between the microlens array and the detector.

A known reference wave is needed for the determination of the sensor accuracy. The simplest wavefront for this task is a spherical wave. We compared the measured wavefront of spherical waves with a radius between 4600 mm and 5300 mm. According to these results the average phase error of our low cost Shack-Hartman sensor is below 0.1λ.

References:

[1] Seifert, T. Ruppel, T. Haist, and W. Osten, "Wavefront sensing by an aperiodic microlens array", Proc. SPIE 6293, 2006

High Resolution Metrology and Simulation

Simulation of diffraction at large structures using the fieldstitching method

Scatterometry from arbitrarily shaped 3-D structures:
Comparison between experiment and simulation
Supported by: BMBF FKZ 01M3154D and 01M3131540
Project: "Abbild Part 1 / 2"

Tensor-tomography: Reconstructing a cube of fused silica using projections from three directions

MICROSIM – ITO's Rigorous 3D-Maxwell Solver

New developments in our simulation tool MicroSim:
Convergence improvement for RCWA for crossed grating structures using normal vector fields

Simulation of diffraction at large structures using the fieldstitching method

S. Rafler, T. Schuster, N. Kerwien, W. Osten

A part of the Landesstiftung project “Rigorose numerische Simulation in Optik-Design und hochauflösender Messtechnik (RISOM)” was the investigation of simulation methods for large structures such as diffractive optical elements. As this is not possible in a single rigorous computation when using a method such as the RCWA, due to the size of the simulation area, we have implemented the field-stitching method of Layet and Taghizadeh. This method allows the simulation area to be split in sections that can be computed separately on a desktop PC.

A large aperture, such as the DOE depicted in Fig. 1, is divided into equally spaced sub-apertures. These sub-apertures overlap on the left and right edge. They are treated as local gratings in the following rigorous calculation. The overlap is necessary to minimize the error coming from the "wrong" continuation at the edges of the local grating periods. The bigger the overlap, the smaller the error. We have verified a 10λ distance to yield converged results in all cases. We have computed the nearfields of the sub-apertures (with overlap) with our tool MicroSim to show that they do not deviate significantly from the nearfields of the whole structure computed without field-stitching.

The obtained diffraction orders of the local calculations are taken as Rayleigh coefficients at the top (or the bottom) of the local structure. The field expressed in these Fourier-coefficients is equated with the field at top of the whole structure. Then the Rayleigh coefficients and subsequently the diffraction orders of the whole DOE can be obtained.

For the test structure depicted in Fig. 1, which consists of randomly spaced areas of random refractive indices, the amplitude and phase errors have been investigated. The results can be seen in Figs. 2 and 3.

The field-stitching method offers the possibility of combining faster (e.g. scalar) methods to simulate areas of a structure showing feature sizes well above the considered wavelength with rigorous calculations of areas of the structure showing subwavelength features. It is, however, only useful if the overlap of 10λ can be taken into account. So the aperture size should be 100λ or greater.

Also, 2-D Fieldstitching has been investigated. Unfortunately the 10λ overlap zone rules this approach out for practical use at the moment.

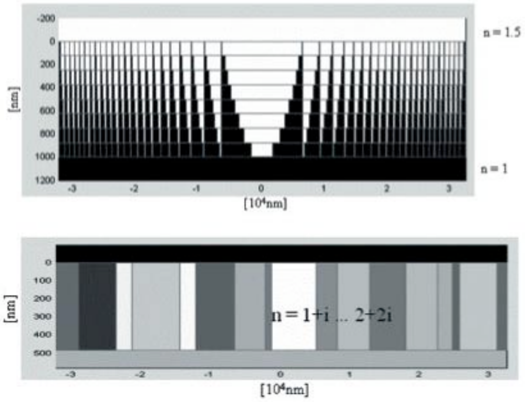


Fig. 1: Structures used for test purposes (modeled with MicroSim)

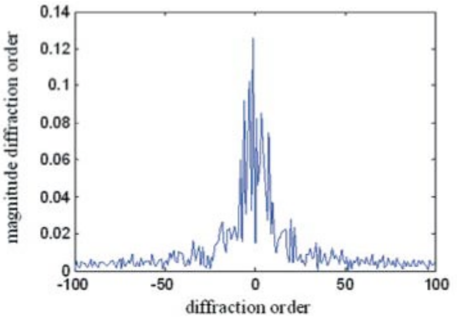


Fig. 2: Diffraction amplitudes for random test structure (computed with MicroSim)

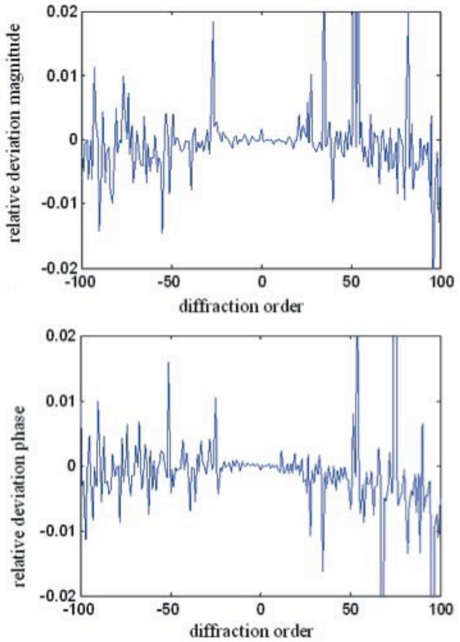


Fig. 3: Errors in the amplitude and phase of the field-stitching calculation compared with the full aperture calculation

Scatterometry from arbitrarily shaped 3-D structures: Comparison between experiment and simulation

T. Schuster, S. Rafler, N. Kerwien, W. Osten

In two consecutive BMBF projects Abbild 1 and Abbild 2 ITO has been a partner and subcontractor of Qimonda, formerly Infineon Technologies. The subject of the work at ITO is the investigation of scatterometry for CD metrology in simulation and experiment.

As was reported in the annual report 2003 / 2004, in the beginning of the project the main focus was on simulation. ITO's simulation tool MicroSim, which comprises an RCWA module, was extended for scatterometry for this project. The accuracy of the simulation results depends on the various input parameters was investigated. A study of sidewall roughness and linewidth fluctuations was carried out and presented on CLEO Europe in Munich [1].

More recently, the RCWA routines have been extended to arbitrary 3-D structures with the aim of matching simulated scatterometric signals with measured ones. Both tasks, the implementation as well as the comparison between simulation and experiment, will be reported below.

As scatterometry is already well established for 2-D structures (line gratings), it was desirable to extend MicroSim to arbitrarily shaped 3-D structures. Fig. 1 depicts the new structure types using a top down view onto an elementary cell. The cell is continued periodically in both directions of the drawing plane. Three structure types can be processed using analytical Fourier series expansion: a rectangle, an ellipse and even a polygon. For totally arbitrary structures, the grating type 'cavity' was introduced, which makes use of the Fast Fourier Transform. The aspect ratio of the elementary cell is arbitrary as well as the number of Fourier modes accepted in the two directions of periodic continuation. Layer stacks of such structures open up virtually endless possibilities for defining structures.

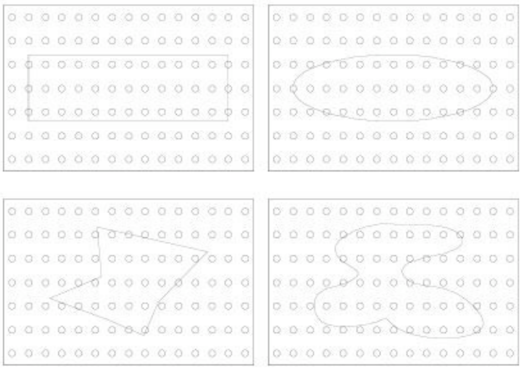


Fig. 1: New structure types in MicroSim.

The new possibilities in MicroSim have been applied to asymmetric nanostructures from Qimonda. A good qualitative agreement between simulation and measurement could be observed, c.f. Fig. 2. The results were presented on the DGaO Jahrestagung 2006 in Weingarten [2]. For a quantitative matching of the spectra an improved modelling is required. One main subject of the present work consists in improving the modelling of structures for RCWA simulations on the basis of SEM images. Apart from that, novel measurement configurations like a ϕ-scan are investigated. This means, that a sample with asymmetric structures is rotated during ellipsometric measurements around its axis. First results will be presented on the "Optical Metrology" SPIE conference in Munich in June [3].

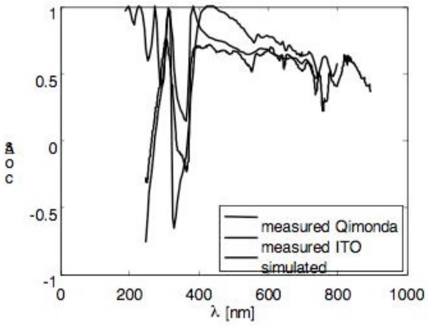


Fig. 2: Comparison simulation and measurement

Supported by: BMBF FKZ 01M3154D and 01M3131540
Project:"Abbild Part 1 / 2"

References:

[1] Schuster, T.; Kerwien, N.; Osten, W.; Reinig, P.; Moert, M.; Hingst, T.; Mantz, U. "Effect of linewidth fluctuations and sidewall roughness in scatterometry", Talk on "Conference on Lasers and Electro-Optics" (CLEO Europe), Munich June 12-17 2005.

[2] Schuster, T.; Kauffmann, J.; Kerwien, N.; Tiziani, H.J.; Osten, W.; Reinig, P. "Scatterometrie an Kreuzgitterstrukturen", Proc. DGaO 2006, Weingarten.

[3] Schuster, T.; Rafler, S.; Osten, W.; Reinig, P.; Hingst, T. "Scatterometry from crossed grating structures in different configurations", Proc. SPIE 6617, 2007.

Tensor-tomography: Reconstructing a cube of fused silica using projections from three directions

J. Kauffmann, H.J. Tiziani, W. Osten

Transparent bulk components show anisotropic inhomogeneities of their refractive index. These components can be for example glass blanks for high precision optics or polymer melts for rheological studies. Fig. 1 shows a model of such a spatial distribution of the refractive index ellipsoids.

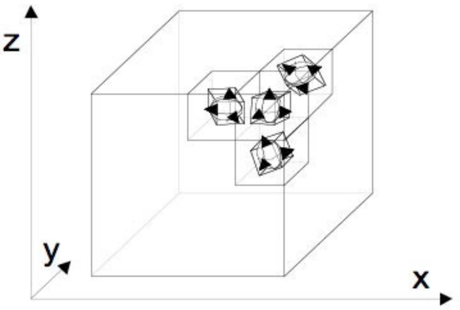


Fig. 1: Model of the spatial distribution of the refractive index ellipsoids.

Optical tensor tomography reconstructs 3D tensor fields of transparent bulk components from Jones matrix measurements taken from different projection directions. The 3D tensor fields are the anisotropic refractive index ellipsoid variation.

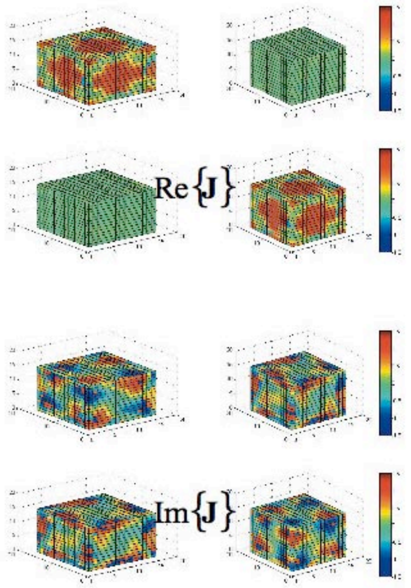


Fig. 2: Jones matrix of a cube measured from three projection directions.

A measurement of a fused silica cube (18cm x 18cm x 18cm) is shown in Fig. 2. Just three projections from the sides of the cube were used, with 15 x 15 measuring points. The Jones transition matrices were measured with a commercial Jones polarimeter at Carl Zeiss SMT AG. Reconstruction using a 17x17x17 cell model is shown in Fig. 3.

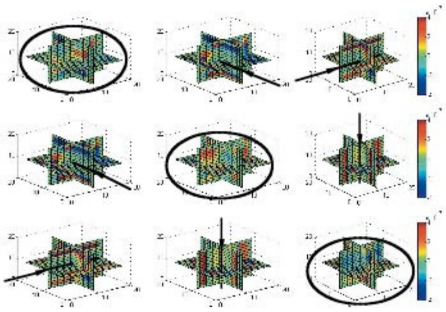


Fig. 3: Reconstruction using a 17x17x17 cell model

The diagonal tensor elements can be resolved in depth. However due to the tensor projection the off diagonal elements cannot be resolved in depth with just three projections. Also on the cubes the effect of corner clamping and gravitation effects on birefringence can be seen. The consistency of the reconstruction was tested by simulating a measurement with the reconstructed anisotropic inhomogeneity. Comparing that to the actually measured values results in a correlation of better then 0.95.

The contributions from Michael Totzeck, Birgit Enkisch, Ralf Müller and Daniel Krähmer and the financial support by the Photonics BW are gratefully acknowledged.

References:

[1] Kauffmann, J.; Kerwien, N.; Tiziani, H.J.; Osten, W. "3D anisotropy reconstruction: an iterative tensorial tomographic algorithm" Proceeding of the ICO, 615-616, 2004 Tokyo

[2] Kauffmann, J.; Kerwien, N.; Tiziani, H.J.; Osten, W. "Tomographic methods to characterize three-dimensional refractive index inhomogeneities" ASPE 2005 Summer Topical Meeting, Middletown, USA

MICROSIM – ITO's Rigorous 3D-Maxwell Solver

K. Frenner, S. Rafler, T. Schuster, W. Osten

MICROSIM is a software package for the full numerical simulation of Maxwell equations, without physical approximation in the diffraction problem domain. In addition to its simulation features, the calculation and visualization of the corresponding near-fields and microscopic far-field images are also possible. The applications of MICROSIM range from rigorous treatment of scatterometry and diffractometry, e.g. for semiconductor industry, to near-field calculations and systematic investigations of microscopic imaging techniques.

MICROSIM is completely implemented in Matlab. This allows us to combine the necessary flexibility required for a research environment with a user-friedly graphical interface. Due to MICROSIM's modular structure, extensions and adoptions of the simulation kernel to different project related demands can be performed quickly and easily.

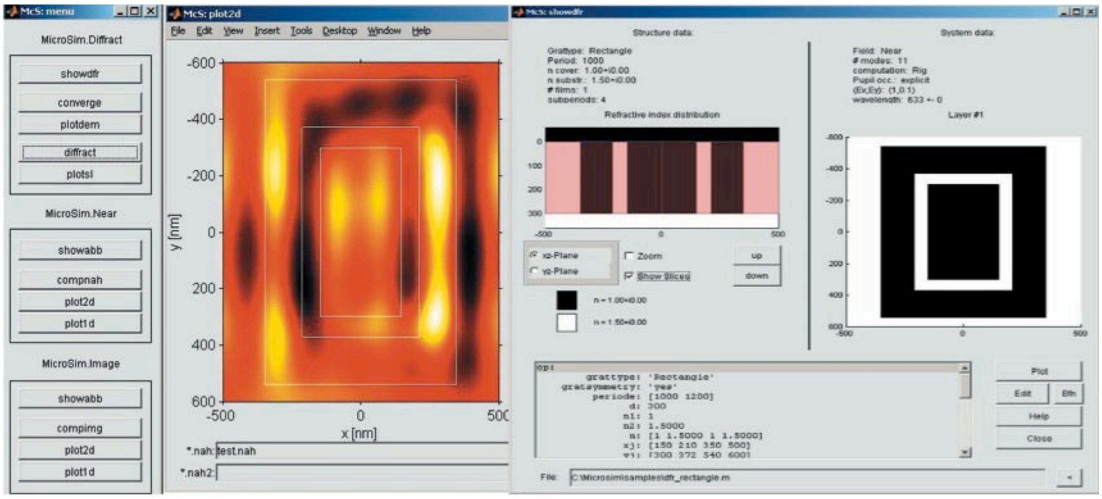
The diffraction spectrum computed with the program module *Diffract* is the basis for the calculation of the corresponding near and far-fields. It provides complete information on the grating in the pupil-plane of an imaging system. *Diffract* is based on rigorous coupled wave analysis (RCWA), in combination with the enhanced-transmittance-matrix approach. This provides the coupling of different grating layers. The parameters for the structure, illumination and computation are defined in a Matlab-file and can be visualized and changed in a GUI. The whole operation of the program can be done via this interface (Fig. 1) or with batch-files for systematic variations of parameters in overnight-computations.

MICROSIM provides different classes of gratings in 2D and 3D. The implemented 2D structure types consist of line-gratings with multiple layers, where in each layer the refraction index is piecewise constant but otherwise arbitrary.

In the 3D case different cross-sections are implemented. These include circles, squares, ellipses and rectangles with different grating-periods in the x- and y-directions, as well as structures within any given user defined boundary in the framework of RCWA.

In order to compute near- or far-fields for arbitrary illumination conditions, the diffraction spectrum has to be calculated for a group of different plane waves which are defined by a set of polarisation-states, wavelengths and angles of incidence. When the complete rigorous diffraction spectrum in the pupil-plane becomes accessible, different microscopic imaging techniques can be simulated by appropriate filtering in the pupil-plane. These include bright field microscopy under full consideration of polarisation dependent aberrations and apodisations, dark-field imaging, Zernike phase contrast, interference microscopy and different types of polarisation microscopy.

The computation of the near-fields in particular offers a deep insight into the interaction of the light with the structure and thus also into the optical image formation by the consideration of evanescent field components. These modes carry the complete high resolution information of the structure. Because of their exponentially short range they don't contribute to the far field, so they don't become directly apparent in the microscopic far-field image.



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*.nah2:

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Period: 1000
n cover: 1.00+i0.00
n substr.: 1.50+i0.00
films: 1
subperiods: 4

Field: Near
modes: 11
computation: Rig
Pupil occ.: explicit
(Ex,Ey): (1,0.1)
wavelength: 633 +- 0

● xz-Plane

☑ Show Slices

■ n = 1.00+i0.00

□ n = 1.50+i0.00

```
op:
          grattype: 'Rectangle'
      gratsymmetry: 'yes'
           periode: [1000 1200]
                 d: 300
                n1: 1
                n2: 1.5000
                 n: [1 1.5000 1 1.5000]
                xj: [150 210 350 500]
                yj: [300 372 540 600]
```

File: C:\Microsim\samples\dfr_rectangle.m

Fig. 1: typical Screenshot of the MICROSIM graphical user interface

New developments in our simulation tool MicroSim:

Convergence improvement for RCWA for crossed grating structures using normal vector fields

T. Schuster, J. Ruoff (Carl Zeiss SMT), N. Kerwien, S. Rafler, W. Osten

MicroSim is a versatile simulation package for computing grating diffraction and high NA microscopic images [1]. The mainly applied method in the diffraction module is rigorous coupled wave analysis (RCWA). MicroSim was developed in the late 1990's at ITO and since then has been under constant development.

Recently an improvement of the convergence of RCWA for crossed grating structures was proposed by ITO and Carl Zeiss [2]. RCWA is based on a Fourier series expansion. In order to save computation time as few Fourier coefficients (modes) as necessary to obtain a sufficiently accurate result are retained. The complexity of RCWA applied to crossed gratings with the truncation order n is $O(n^6)$; thus it is a great benefit to reduce the number of required Fourier modes for crossed grating structures.

The proposed improvement is based on the reformulation of the differential method of Popov and Nevière. The key point in this formulation is to find a normal vector (NV) field which is orthogonal to the material boundary and which contains the local orientation of the material boundary. This information has to be transferred to Fourier space, in order to correctly form the product $D=\varepsilon \cdot E$ as a convolution in Fourier space. To this end the NV has to be continued throughout the complete elementary cell. This continuation, however, is not unique and different continuations can lead to different convergence behavior. The theoretical details of this procedure are omitted here for the sake of brevity, but can be found in [2].

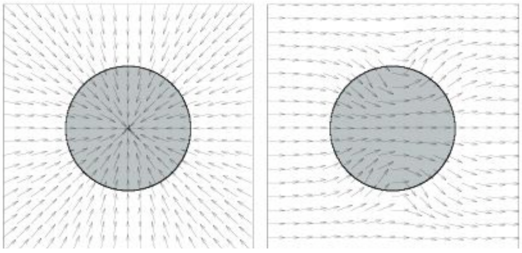


Fig. 1: Possible NV field for a circle

For various example structures we set up different types of NV fields. Fig. 1 shows two possible fields for an array of circles, each of the shown square cells is continued periodically in both directions of the plane to form a grating structure. The NV field on the left hand side (named "radial") shows discontinuities at the cell boundaries, which should be avoided using Fourier series expansion. The field on the right hand side (named "electrostatic"), however, shows two point singularities on the material boundary, i.e. two points where field is not normal to the boundary.

It can be seen that setting up an ideal NV field is impossible. Nevertheless, the convergence of the proposed formulation of the RCWA using either of the two NV fields is better than the formulations known from the literature. The convergence curves are depicted in Fig. 2. The previous formulations are denoted by "Li" and "Moharam". For details please see [2].

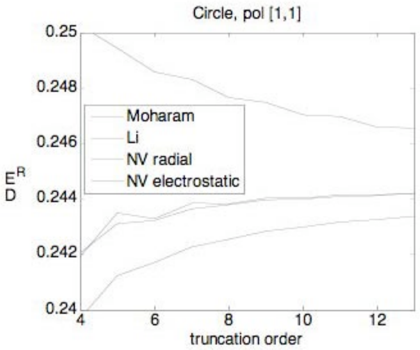


Fig. 2: Convergence curves for an array of circular cavities

References:

[1] Totzeck, M. "Numerical simulation of high-NA quantitative polarization microscopy and corresponding near-fields", Optik 112 No. 9, 399-406, 2001

[2] Schuster, T.; Ruoff, J.; Kerwien, N.; Rafler, S.; Osten, W.; "Normal vector method for convergence improvement using the RCWA for crossed gratings", S. Opt. Soc. Am. A 24 No. 9, 2880 - 2890, 2007.

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

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

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

Supported by: Landesstiftung Baden-Württemberg Photonics BW
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

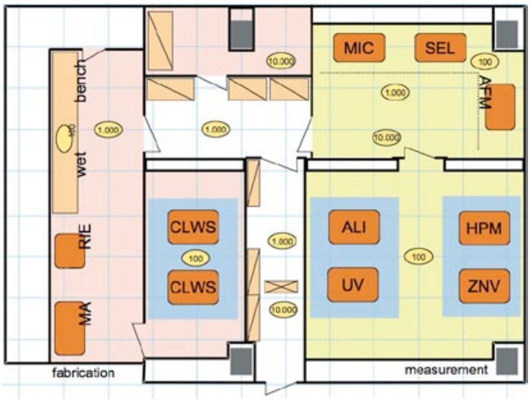


Fig. 2: Layout of the new cleanroom. For abbreviations see text.

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.

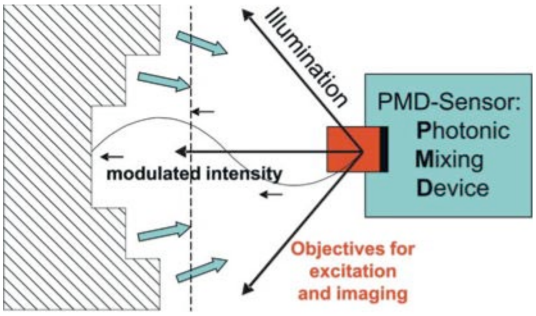


Fig. 1: Principle setup for a 3D-measurement with a PMD-Sensor (illumination + pmd-chip).

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.

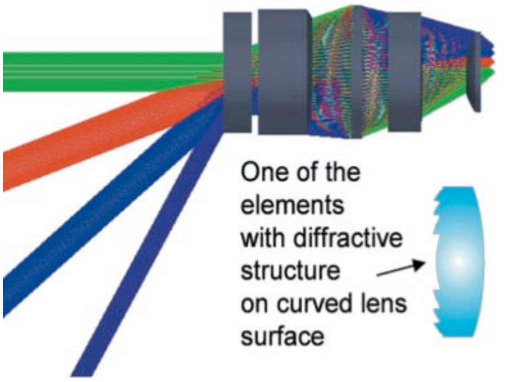
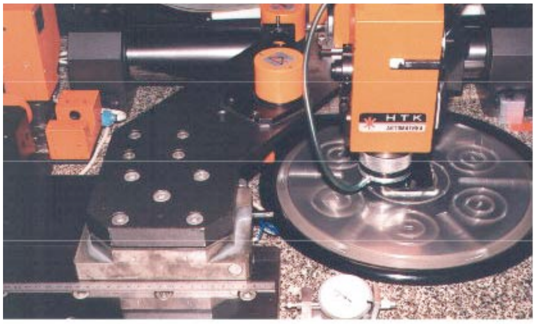


Fig. 2: Hybrid wide-angle design with diffractive structures on a curved lens surface.

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.

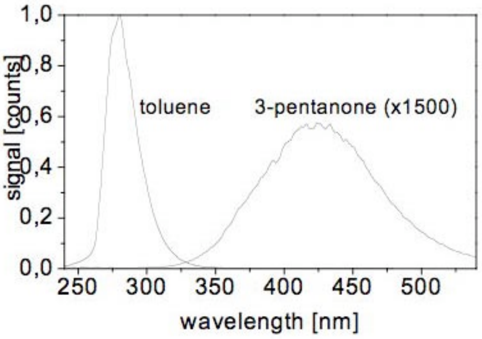


Fig. 1: Separable fluorescence spectra of toluene and 3-pentanone for a common 266 nm excitation.

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.

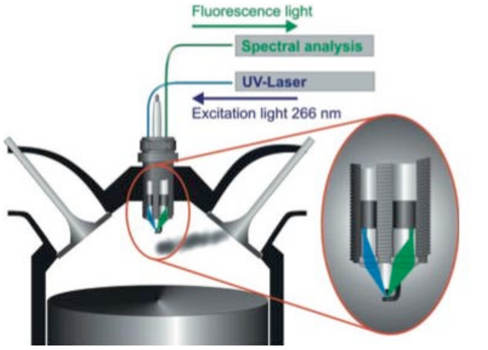


Fig. 2: Design of the sensor spark plug.

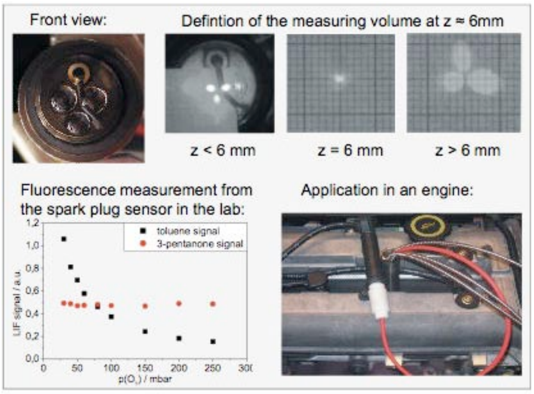


Fig. 3: Experimental results of the spark plug.

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).

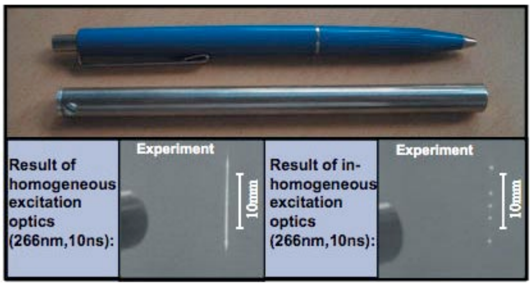


Fig. 4: Excitation optics and beam profiles.

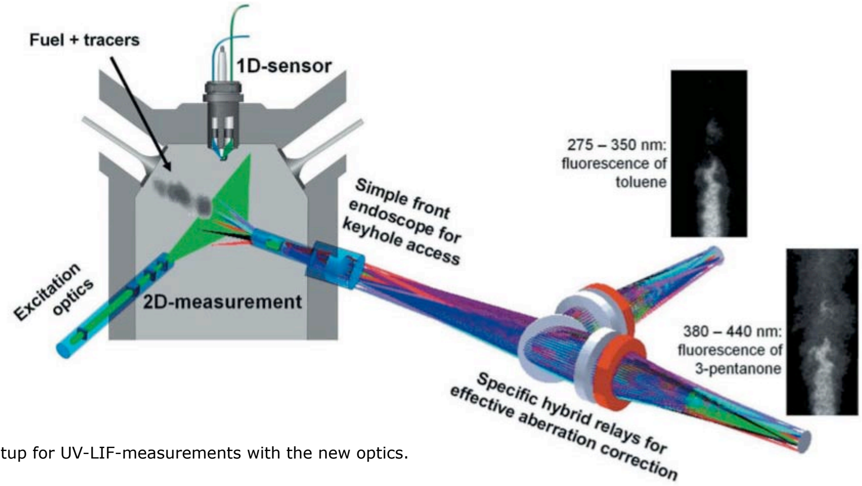


Fig. 5: Setup for UV-LIF-measurements with the new optics.

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.

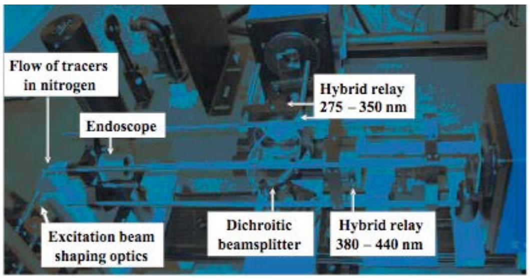


Fig. 7: Setup for lab experiment with 2 tracers.

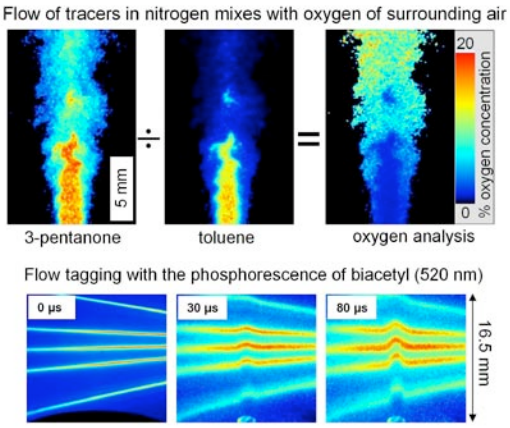


Fig. 8: 2D-measurement of oxygen concentrations with toluene and 3-pentanone and results of flow-tagging with biacetyl.

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

Publications:

[1] R. Reichle, C. Pruss, W. Osten, H. Tiziani, F. Zimmermann, and C. Schulz, "Microoptical sensor for integration in a functional spark plug for combustion analysis by UV-laser induced fluorescence spectroscopy", Proc. VDI 4th Conference on Optical Analysis Technology (2004).

[2] R. Reichle, C. Pruss, W. Osten, H. J. Tiziani, F. Zimmermann, and C. Schulz, "Fiber optic spark plug sensor for UV-LIF measurements close to the ignition spark", Proceedings of SPIE - The International Society for Optical Engineering vol. 5856, 158-168 (2005).

[3] R. Reichle, C. Pruss, W. Osten, H. Tiziani, F. Zimmermann, and C. Schulz, "UV-Endoskop mit diffraktiver Aberrationskorrektur für die Motorenentwicklung", Proc. DGaO 2006.

[4] R. Reichle, C. Pruss, W. Osten, H. Tiziani, F. Zimmermann, and C. Schulz, "Hybrid excitation and imaging optics for minimal invasive multiple-band UV-LIF-measurements in engines", VDI-Berichte 1959 (2006), pages 223-235, VDI Verlag.

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.

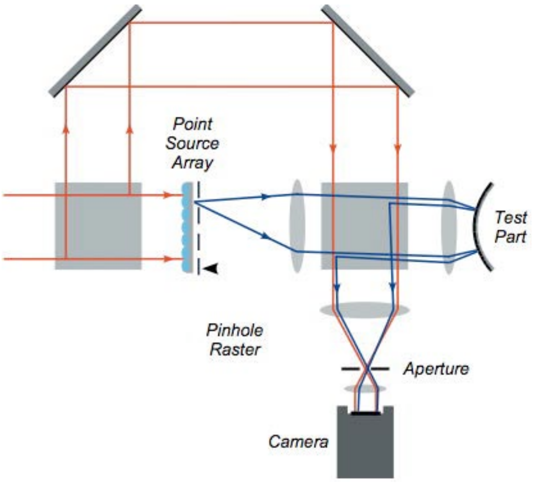


Fig. 1: Interferometer with a dynamic test beam.

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.

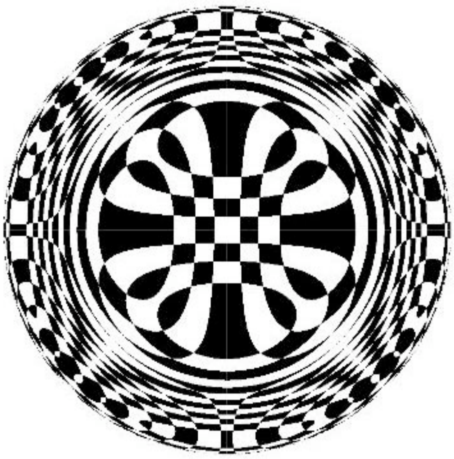


Fig. 2: Zone arrangement due to the different sources in the array.

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

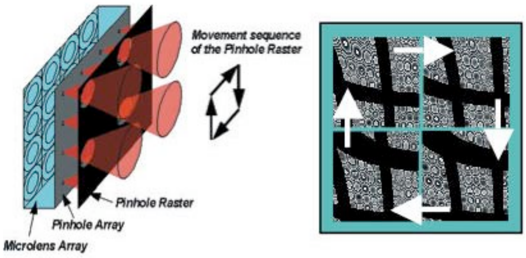


Fig. 3: Every second row and every second column of the source array is activated in order to cover the whole test part.

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 $\lambda/30$ and better.

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

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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.

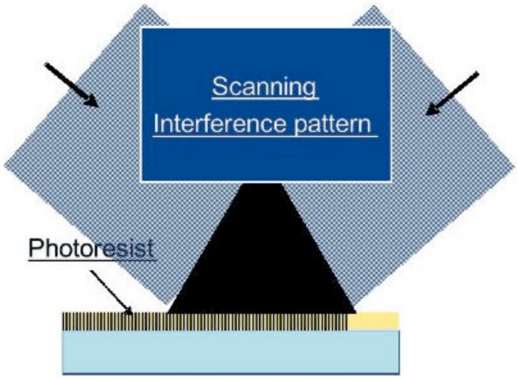

Fig. 1: Principle of interference lithography. Two coherent beams with different angles of incidence overlap at the substrate surface.

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.

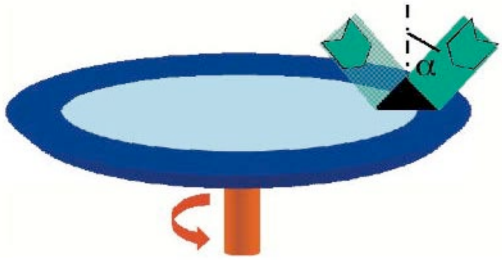

Fig. 2: Polar coordinate lithography system. The substrate rotates underneath the scanning head which moves along the radial coordinate.

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.

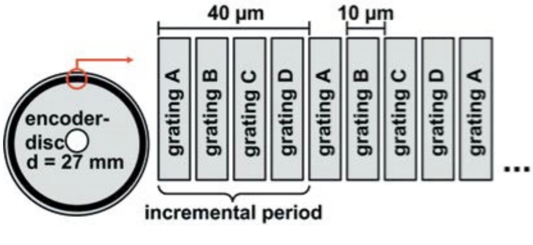

Fig. 1: incremental code cycle on the encoder-disc with diffraction gratings as a solid measure

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.

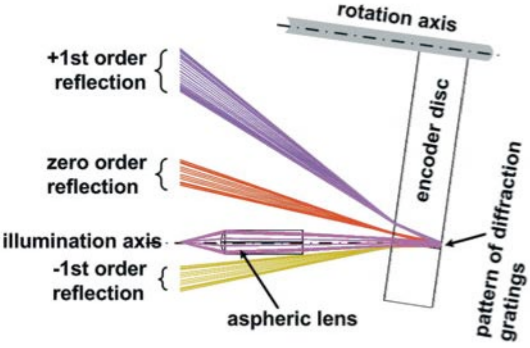

Fig. 2: simulated optical path of the illumination beam and of the first-order diffractions from one grating

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.

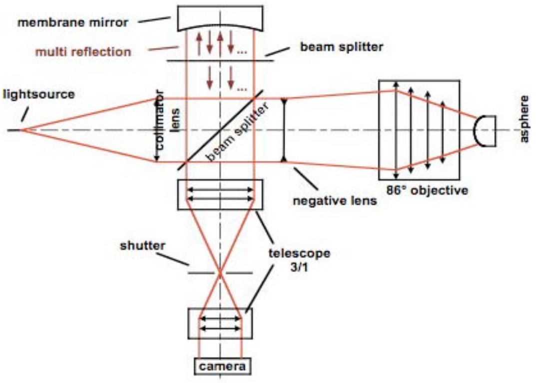

Fig. 1: Interferometric test set-up with an adaptive membrane mirror in the reference path. Using multiple reflection from the membrane mirror, its aspheric deviation is translated into a scaled aspheric wave front.

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).

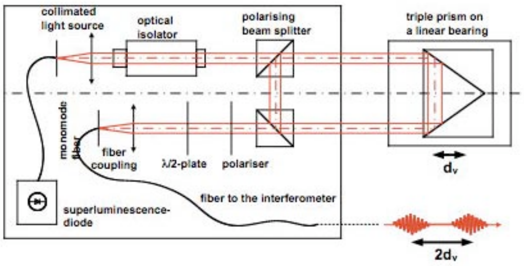

Fig. 2: Cavity with a short-coherence light source. The difference of the two optical path lengths is selected by a triple prism on a linear bearing.

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.

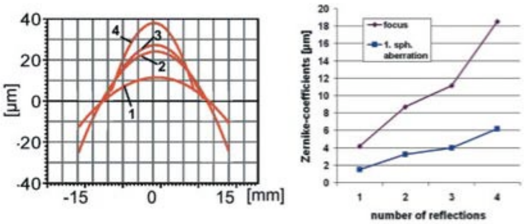

Fig. 3: interferometric measurements of a scaled wavefront; multi-reflections 1 to 4 with increasing focal and spherical aberration coefficients.

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

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Coherent Measurement Techniques

Pulsed digital holographic interferometry for endoscopic investigations (HoEnd)
Supported by: Landesstiftung Baden-Württemberg

Multi-Functional Encoding System for the Assessment of Movable Cultural Heritage (Multi-Encode)
Supported by: European Union (006427 SSPI)
Project: "Multi Encode"

Time resolved digital holographic interferometry for the investigations of dynamic events

Wavefront reconstruction using sequential intensity measurements of a volume speckle field
Supported by: DFG (OS 111/19-1)

Compensation of the misalignment between master and sample in comparative digital holography
Supported by: Landesstiftung Baden-Württemberg (Photonics BW)
Project: "KoMa"

Digital holographic microscopy in the deep UV (DUV)
Supported by: DFG (OS 111/19-1)

Modified convolution reconstruction algorithm for high numerical aperture holograms
Supported by: DFG (OS 111/19-1)

Phase retrieval using a movable phase mask
Supported by: DFG (OS 111/19-1)

Pulsed digital holographic interferometry for endoscopic investigations (HoEnd)

G. Pedrini, W. Osten

Holographic interferometry combined with endoscopy enhances the versatility of standard 2D-endoscopic imaging as it opens up the possibility of measuring additional parameters on hidden surfaces. Combinations of digital holography, with an endoscope to transfer the image, and a pulsed laser as a light source, allows measurements in an industrial environment (e. g. vibration measurements, non destructive testing of technical objects) and in-vivo investigation of biological tissues. It might be useful for the detection of pathology in medicine.

Fig. 1 shows schematic illustrations of rigid and flexible endoscopes combined with a system based on pulsed holographic interferometry. The optical set-up consists of the pulsed laser, the interferometer unit with the CCD-camera and the endoscope unit. Fig. 1.a) shows the arrangement for a rigid endoscope but this endoscope can be replaced with a flexible fibre endoscope, as shown in Fig. 1.b). Rigid and flexible endoscopes have a lot in common. The objective lens forms an image of the subject which in turn is transferred by the relay optics and magnified by a lens system onto the sensor. The difference is in the relay itself.

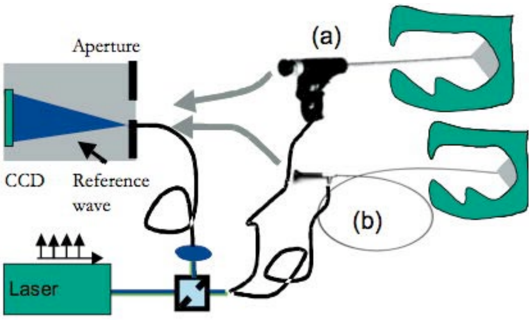

Fig. 1: Set-up with (a) rigid and (b) flexible fiber endoscope for investigations using pulsed digital Holography.

For both arrangements, the recording procedure and the way to process the digital holograms is exactly the same. The pulsed laser emits short (20 ns) Q-switched pulses, which are divided at the beamsplitter into the reference and the object beams. The reference beam is conveyed to the interferometer unit with a single-mode optical fibre. The object beam is coupled into a fibre bundle and conveyed to the object. The light is diffusely reflected back from the surface towards the endoscope, which brings the object image to the interferometer unit. An image-plane hologram is formed on the CCD-detector as a result of the interference between the slightly off-axis reference beam and the object beam. The aperture serves to limit the spatial frequencies of the interference pattern, in such a way that the detector resolves it. Two or more digital holograms, corresponding to different laser pulses, are captured on separate video frames by the CCD-camera.

For one of our investigations the test object was a metallic cylinder with a diameter of 65 mm and a height of 110 mm. The end of a rigid endoscope, which was combined with a system based on digital holography, was inserted into the cylinder through an aperture in order to measure the vibration inside the object. Fig. 2.a) shows an example of a measurement with the object excited at the frequency of 5010 Hz using a shaker. The flat inner surface was examined. There is a discontinuity in the fringes due to a delamination defect of the object surface. A pseudo 3D representation of the deformation can be seen in Fig. 2.b.

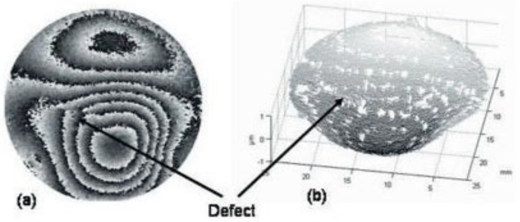

Fig. 2: Measurement of the inside of a cylinder excited at a frequency of 5010 Hz. Phase map (a) and pseudo 3D representation (b) of the vibration.

Recently, with the newer smaller CCD detector arrays, it has become possible to build the complete interferometric system (CCD included) within small dimensions (diameter 6 mm). Fig. 3.a) and b) show a sketch and a picture of the prototype.

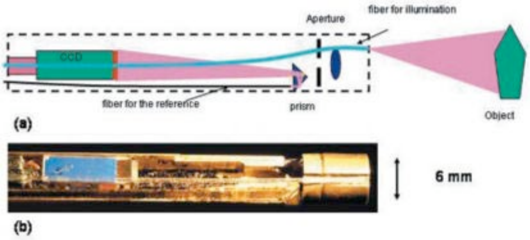

Fig. 3: Sketch (a) and picture (b) of the miniaturised prototype.

The illumination of the object is from a multimode fiber that has a 600 μm diameter. The reference beam is conveyed with a single mode fiber and is directed towards the sensor by a small prism. This prototype has been used to perform measurements inside a cylinder and some results (phase map) are presented in Fig. 4.

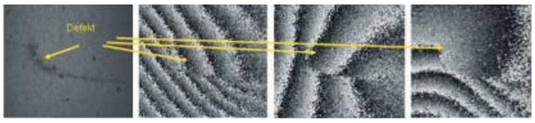

Fig. 4: Measurements inside a cylinder using the prototype shown in Figure 3. Image of the object (a) and phase maps obtained by harmonical excitation of the object with frequencies 950 Hz (b), 4024 Hz (c), and shock (d). Image size: 5x4 mm².

The quality of the phase maps is not as good as that obtained by using a rigid endoscope combined with an external holographic system. This is due to the fact that in the miniaturized prototype a color camera has been used and this is not well suited for the recording of digital holograms. Unfortunately it was not possible to find a B/W miniaturized camera with small dimensions. Furthermore, the acquisition speed of the camera was limited to 50 images/s.

Supported by: Landesstiftung Baden-Württemberg

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Multi-Functional Encoding System for the Assessment of Movable Cultural Heritage (Multi-Encode)

R.M. Groves, G. Pedrini, W. Osten

The protection of cultural heritage using speckle interferometry and holography sensors is the subject of the Multi-Encode Project. This topic is of great interest to museums and galleries. The principle is that interferometric signatures of artwork are collected, that can later be used to identify forged artwork or identify that recent damage has occurred.

ITO have developed a portable compact shearography prototype, see Fig 1, specifically for cultural heritage applications. The sensor is based on the out-of-plane displacement gradient sensitive shearography configuration and has a high degree of automation of peripheral devices and sensor components. For example the object loading is controlled and the experimental conditions are recorded automatically. In operation, for the user to assess the object defect locations, wrapped and unwrapped phase maps are displayed in real-time at 1 Hz, and a comprehensive data set is archived, including experimental conditions.

Fig 1: The photograph of the shearography prototype shows the main components: tripod mounted sensor head, electronics controller, PC and the laser. The object under investigation is a canvas painting sample from the TATE Gallery, London.

One aspect of the collection of interferometric signatures of artwork is the development of standardised loading conditions. Artwork objects have a complex structure. They are often constructed on an unstable base, e.g. a wooden panel or a stretched canvas, upon which a number of layers of dissimilar materials, e.g. gesso, oil paint, gold leaf, are added. The types of defect are many and varied and include cracks and delaminations of different sizes and additionally for panel paintings nail holes and surface scoring. In the standardisation of the measurement procedure, a range of defect types and sizes in a number of artwork samples, prepared by project partners at the National Gallery of Athens and Tate, London, were studied and the optimal loading conditions for defect location and identification for the different artwork types were established as the standard. The measurement sensitivity of the sensor was also determined.

Fig 2 shows an example from the measurement programme. This 19th century British landscape painting has undergone restoration and this included the affixing of a second canvas behind the original. Defects present in the central region can clearly be seen from the phase map.

Fig 2: Location of defects in a 19th century British landscape painting.

Current research is the study of artwork through artificial aging processes and the development of image processing techniques to compare interferometric signatures with those already stored in a database.

The authors would like to thank Dr Vivi Tornari (FORTH, Crete), Dr Marc Georges (CSL, Liège), Dr Stephen Hackney (Tate, London), Eleni Koloumpi (National Gallery of Athens) and Guy-Michel Hustinx (Optrion). Project: "Multi-Encode" Supported by: European Union (006427 SSPI)

References:

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Time resolved digital holographic interferometry for the investigations of dynamic events

G. Pedrini, W. Osten

In order to measure dynamic events, high speed digital holographic interferometry was developed. In this technique the phase of a wavefront recorded at different times is calculated from the recorded intensity by use of a 2D digital Fourier-transform method,. As we obtain the phase from a digital hologram, only one image hologram is needed for the phase to be determined at a given time. No temporal phase-shift methods are used. By unwrapping the phase in the temporal domain it is possible to get the displacement including the direction of motion of an object as a function of time.

Fig. 1 shows a sketch of the measuring system used for our investigations. Light from a laser is divided into a beam for illumination of the object and a reference beam. The object beam illuminates the object along a direction e_i. Some of the light is scattered by the object in the observation direction eo towards the detector, where a positive lens forms an image of the object on a CCD sensor. An image-plane hologram is formed on the CCD as a result of the interference between the reference beam and the object beam. The aperture serves to limit the spatial frequencies of the interference pattern. The reference beam diverges toward the detector system from a point located close to the aperture. The reference wave is carried by an optical fiber, which makes the arrangement more compact, as no additional beamsplitter is needed to recombine the object and reference waves.

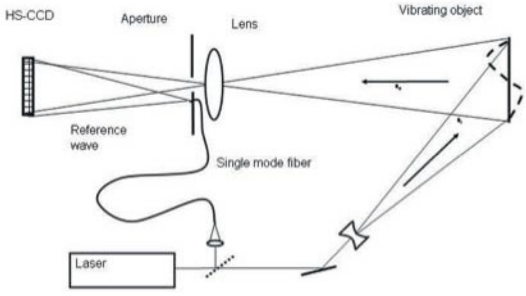

Fig. 1: Optical arrangement for high speed digital holographic interferometry

The intensity is recorded on a two dimensional electronic device composed of an array of sensors and the information about the amplitude and phase of the object wave is obtained by spatial filtering using the Fourier transform method. By using a high power cw-laser and a high speed recording device, we are able to record a sequence of holograms and to determine from the intensity the phase difference between two successive wave fronts recording. In order to avoid a spatial phase unwrapping we require a phase difference that is smaller than π between two holograms. A phase map corresponding to the deformation of the sample between the beginning of the measurement (t=0) and any other point in time can be calculated by summing the phase differences. This phase map can be used to determine the displacement observed along the direction of $s = e_o - e_i$, where e_i and e_o are the unit vectors of illumination and observation respectively. Fig. 2 shows a result obtained by using a metallic brass plate (63 mm x 70 mm x 0.5 mm) located 1400 mm from the imaging lens. The plate was clamped at one edge and excited by a small shaker at a frequency of 943 Hz. A sequence of interferograms has been acquired with an integration time for each interferogram of 30 µs and the vibration as a function of the time is calculated from the phases.

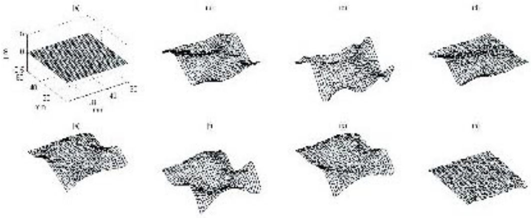

Fig. 2: Plate vibrating at 943 Hz, (60 x 60 x 0.5 mm³). a-h) deformation of the plate as a function of the time.

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Wavefront reconstruction using sequential intensity measurements of a volume speckle field

G. Pedrini, P. Almoro, A. Anand, W. Osten

Phase retrieval methods have been utilized with the purpose of reconstructing amplitude and phase from intensity patterns only (in this case no reference is added to the wave front). We have shown that by recording a sequence of intensity patterns of the object at different planes and by application of iterative algorithms, it is possible to increase the quality of the reconstructed wavefronts. Fig. 1.a) shows the experimental set-up for the recording of a volume speckle field.

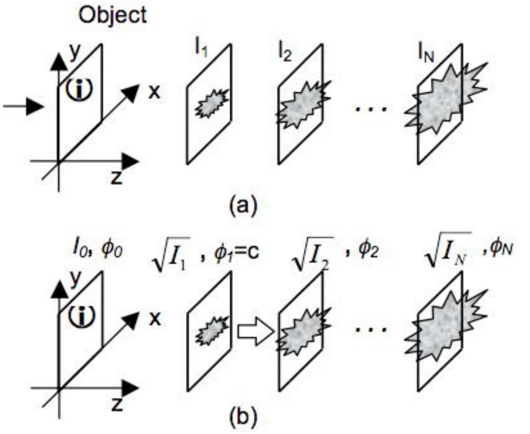

Fig. 1: Schematics of the phase retrieval methods: a) intensity measurements, and b) wave field reconstruction.

When a coherent light source, such as a laser, illuminates the rough surface of an object it generates a volume speckle field. The intensities of the speckle patterns (I_1, I_2,…I_N) at equal-interval planes are sequentially measured using a CCD camera and stored in the computer. Fig. 1.b) shows the diagram for the reconstruction of the test object wave field, represented by intensity I_0 and phase ϕ_0 located at the origin. The measured intensities are utilized to reconstruct the object wave field. The reconstruction process starts with the wave amplitude being obtained from the square root of the first intensity distribution measured at position d_1. This amplitude is multiplied by the phase (initially a constant) and the resulting complex-valued function representing the wave field at that particular plane is propagated to the next plane. The propagation of the wave is done according to the Rayleigh-Sommerfeld equation. The process of multiplying the square root of the measured intensity distribution with the calculated phase at each plane followed by wave propagation is repeated until the quality of reconstructed image at the object plane changes by amounts that are smaller than a threshold. Increasing the number of intensity measurements will result in better approximation of the true phase. The calculated wavefront in the measurement planes should also exhibit numerical focusing when propagated back to the image space. The technique is a very promising wavefront reconstruction method because it offers a very simple setup and a straightforward procedure. Fig. 2 shows the experimental results for a diffusely transmitting object. The test object used is a transmitting mask with a ground glass diffuser attached to it in order to randomize the phase. After calculation of the wavefront (amplitude and phase) in the measurement planes, numerical focusing is obtained when propagated back to the image space.

Fig. 2: Reconstructions of a diffusely transmitting object at 2 mm -interval reconstruction planes using multiple intensity measurements. The width of the whole object is 2 mm.

Supported by: DFG (OS 111/19-1)

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Compensation of the misalignment between master and sample in comparative digital holography

X. Schwab, G. Pedrini, W. Osten

Comparative digital holography (CDH) is a technique suitable for shape and deformation comparisons between master and sample objects with rough surfaces. The innovative aspect of CDH is the illumination of the sample by the conjugated wavefront of the master, as a type of coherent mask, using a liquid crystal display (LCD) (Fig. 1). The resulting interferogram indicates directly the shape or the deformation differences between the master and sample. As it is not necessary that both objects to be compared are located at the same place for this technique, remote shape or deformation comparison is possible. A current research topic is the precise alignment of the sample and the reconstructed master wavefront.

Here we present the experimental result of a shape difference measurement. As master object, we used a cone with a given surface microstructure and for the sample object, the same cone with a modified surface microstructure, but containing one defect at the point. In Fig. 2a, we see the illumination of the misaligned sample object with the reconstructed master wavefront. Due to the misalignment, additive fringes appear in the resulting interferogram (Fig. 2b). These fringes disturb slightly the evaluation of relatively large defects, however small defects are more sensitive to the fringe pattern due to misalignment, with the effect that small defects cannot be precisely located in position or size. In the presence of a misalignment, we lose the main advantage of the null test, the direct difference between master and sample. Therefore we have to compensate for this misalignment.

The compensation can be done by using the phase shifting properties of the LCD. By adding a phase factor to the original hologram, the sample object will be corrected illuminated (Fig. 3a) so that the defects are directly visible and quantifiable without the application of complex image post-processing (Fig. 3b). The phase factor is dependent on the misalignment compensation and this compensation can be done for all six degrees of freedom of the object.

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Project: "KoMa"

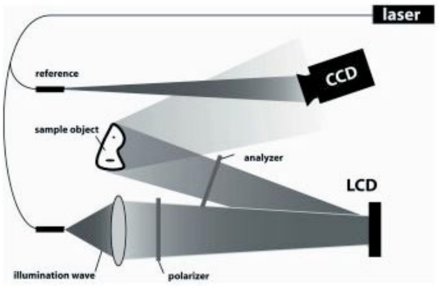

Fig 1: Coherent illumination of the sample with the optical reconstructed wavefront of the master in CDH.

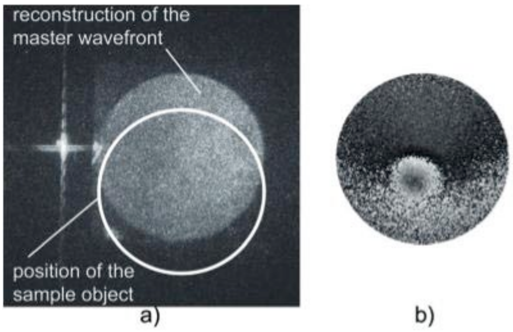

Fig 2: Shape comparison in CDH in the presence of a misalignment. a) Illumination of the misaligned sample object (shown by the circle) with the reconstructed master wavefront, by writing the original master phase hologram in the LCD. b) The corresponding shape difference between the master and sample objects.

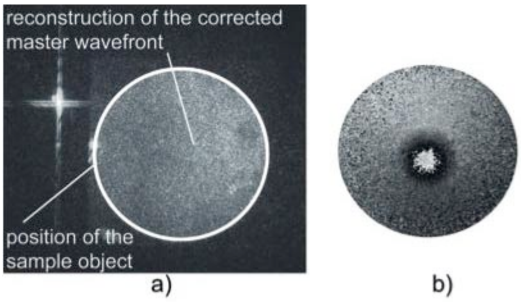

Fig 3: Shape comparison in CDH. a) Correct illumination of the misaligned sample object (shown by the circle) with the reconstructed master wavefront, by writing the corrected master phase hologram to the LCD. b) The corresponding shape difference between the master and sample objects.

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Digital holographic microscopy in the deep UV (DUV)

F. Zhang, G. Pedrini, W. Osten

Digital holography is a well established technique which is frequently used for the investigation of microscopic objects. The method allows for the reconstruction of both the amplitude and the phase of a wavefront from the acquisition of a single hologram recorded by a CCD. Previously digital holographic microscopy was explored for applications in visible and infrared light.

The spatial resolution of the method is given by the numerical aperture and the wavelength. In order to increase the resolution we developed a microscope system based on digital holography working at the wavelength of 193 nm. Fig. 1 shows the optical arrangement. Basically, it is Mach-Zehnder interferometer configuration. Directly after the laser output aperture, a spatial filter is inserted to improve the poor beam quality and to reduce the beam intensity. Then the randomly polarized laser beam is converted to linear by polarizer Pol1, and is split by a polarized beamsplitter PBS1 into two beams. One is used as the reference and the other is for illumination. The illumination beam is further split by the beamsplitter BS and may in turn be used to illuminate the object from two opposite sides, thus allowing the investigation of reflecting and transmitting samples. PBS3 directs the reference beam into a delay line, where the optical path length of the reference arm can be matched to the path length of the object arm. Matching the optical path lengths is necessary because the coherence length of the laser is only of the order of 100 µm. PBS2, placed just in front of the CCD, directs the object beam and the reference beam to the CCD. Their common polarization components, selected by the second polarizer (POL2), interfere on the CCD.

A CCD camera with excellent UV sensitivity (PCO Sensicam em680 with quantum efficiency of 20% at 193 nm) is used to record the interference pattern. The recorded intensity is processed to get the amplitude and the phase of the wavefront at the object plane. It is well known that one may get an aberration free reconstruction only when the reference in reconstruction is exactly the same as the one used in the physical recording. Technically it was not possible to produce an ideal reference wave at 193 nm (e. g. spherical), for this reason we had to deal with a not well-defined wave. Therefore an algorithm was developed to determine the curvature of the reference. By knowing this we were able to get an aberration free reconstruction. Other reconstruction algorithms which are free from aberration and are suitable for high numerical aperture holograms are proposed and described in the references [1-4].

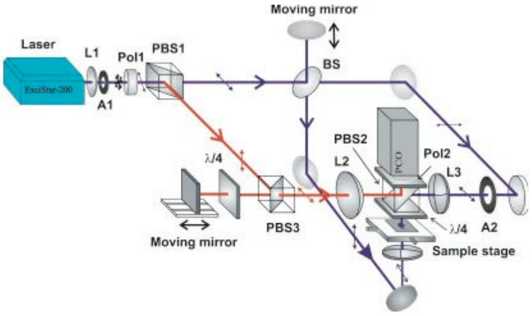

Fig. 1: Experimental setup for hologram recording.

Fig. 2 shows an example of a reconstructed amplitude and phase wavefront. The sample was an electronic circuit (Pentium I processor).

The setup was designed to be able to investigate both reflection and transmission samples [5]. Figure 3 shows the result of the investigation of a lenslet array.

Future work will focus on the combination of information obtained in reflection and transmission of a semi-transparent samples.

Fig. 2: Reconstructed wavefront from a digital hologram of a microcircuit illuminated in reflection. Amplitude (a) and phase (b) are represented. The field of view is 300 x 300 µm².

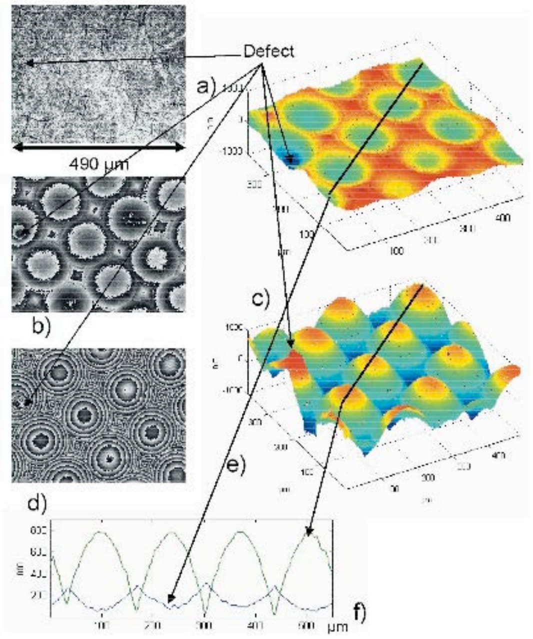

Fig. 3: Investigation of a lenslet array. Object intensity (a); phase map (b) and pseudo 3D representation (c) of the transmitted wave front; phase map (d) and pseudo 3D representation (e) of the reflected wave front; reflected and transmitted wavefront along two lines (f).

Supported by: DFG (OS 111/19-1)

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Modified convolution reconstruction algorithm for high numerical aperture holograms

F. Zhang, G. Pedrini, and W. Osten

In the reconstruction of digital holograms recorded at a very short object to sensor distance, one has to evaluate the Rayleigh-Sommerfeld integral without any approximation. The three commonly used fast algorithms, i.e., Fresnel algorithm, angular spectrum algorithm (AS), and convolution algorithm (CV), have their respective drawbacks and can not be applied directly. The Fresnel algorithm is limited to Fresnel holograms due to its involved approximation. Although the AS and CV algorithms do not make any approximations of the diffraction integral in its analytical form, their conventional implementation gives a samplings only on a computation grid with the same spacing as the sensor pitch. For holograms recorded of high numeral aperture (NA), such a computation grid is too coarse to present the object precisely, i.e., the sampling interval is too larger than the physical resolution.

To overcome this drawback, the CV algorithm is modified by redefining the reconstruction co-ordinate system. Two shift parameters, accounting for the relative displacement of object coordinate and the hologram coordinate, are introduced in the discretized diffraction kernel. Combination of the results for different shift values gives object sampling on any computation grid. Compared with other methods that are mostly based on interpolation, this method is free from artifacts. We also proved that the modified CV algorithm is capable of achieving aberration free reconstruction for various recording numerical apertures if the object extension is finite. Notice that no requirement on the bandwidth of object is imposed and the object can be arbitrarily rough.

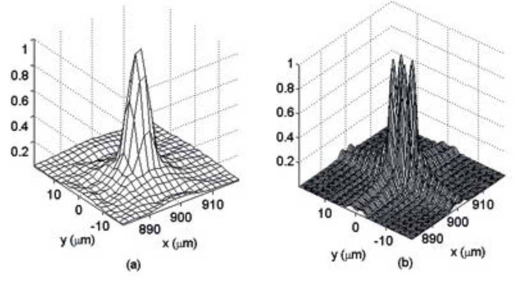

Fig. 1: Reconstruction of a simulated four-point object by (a) Fresnel algorithm and (b) the modified CV algorithm.

Fig. 1 shows reconstructions of a simulated four-point object. The four points are located near the boundary in the object view; therefore the reconstruction by the Fresnel algorithm suffers larger spherical aberrations and the four points merge into one broad peak (a). In the reconstruction by modified CV algorithm (b), they are clearly separated.

Results obtained from experimental data are shown in Fig. 2. The object consists of a set of black spots. The blur caused by spherical aberration in Fresnel algorithm can be easily seen in (a), as indicated by a white box; but it is less noticeable in the reconstruction by the modified CV method (b). The recording numerical aperture for the holograms used is only about 0.2. Further work is to record a hologram with a higher NA and to show the improvement quantitatively.

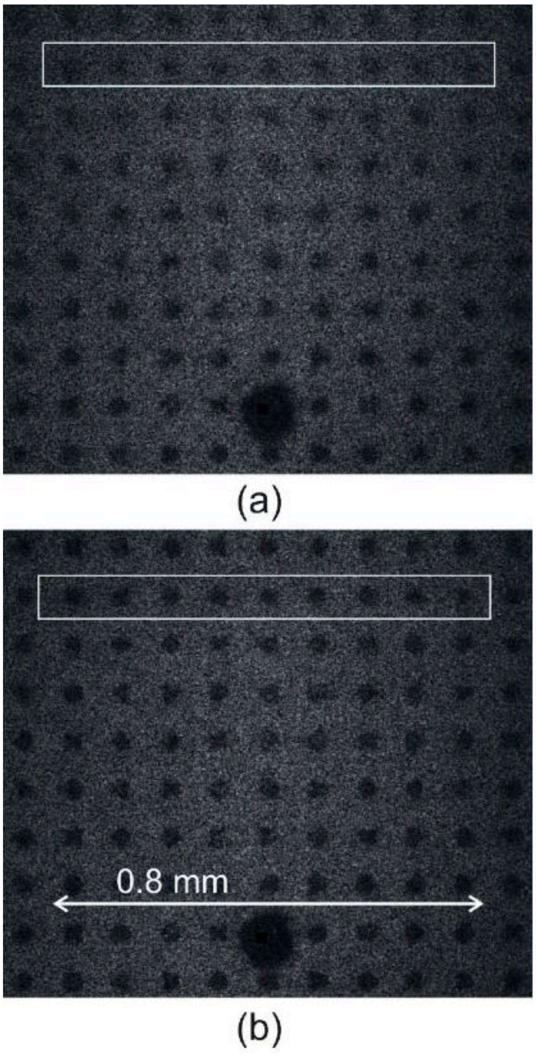

Fig. 2: Comparison of the reconstruction with (a) the Fresnel algorithm (b) the modified convolution algorithm.

Supported by: DFG (OS 111/19-1)

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Opt. Lett. 31, 2848 (2006)

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Phase retrieval using a movable phase mask

F. Zhang, G. Pedrini, and W. Osten

The existing phase retrieval algorithms have been demonstrated successfully in many applications, but mainly for phase only or amplitude only objects. Although the phase retrieval of complex-valued fields is of general interest in many fields, it still remains a difficult problem. In this work, we proposed a new idea to solve the problem by using a mask.

Fig. 1 illustrates the experimental arrangement. An extended object, which can be of transmissive or reflective type, is illuminated by coherent light. A pixellated phase mask, mounted on a linear stage, is positioned in the path between the object and the sensor (CCD: charge coupled device). The phase of the plate distributes uniformly between 0 to 2π and is known. The transmissive area of the mask is limited by an aperture to ensure the resultant diffraction pattern is resolvable by the CCD. Four or more diffraction patterns are collected as the mask shifts by a multiple of its pixel size. The complex amplitude immediately before the mask is retrieved using an iterative algorithm. At each iteration, the modulus of the calculated complex amplitude on the CCD plane is replaced by the square root of recorded intensity, while the modulation introduced by the mask is updated to that of the next mask position. The iteration loop starts from a random guess of the complex amplitude before the mask and ends when the difference in amplitude between two successive retrieved estimates is less than a given value. Further propagation of the retrieved wavefront from the mask to the object gives the original object field. Simulations show that this approach works even for the most difficult object field – random amplitude plus random phase. The convergence is also fast, good reconstruction can be obtained within 30, 50, 110, or 1840 iterations when 6, 5, 4, or 3 recordings are to be used.

Fig. 2 and 3 show the experimental results. The light source was a He-Ne laser with a wavelength of 632.8 nm. The camera, a Teli-CS3910, had 1300 x 1030 pixels with a pixel size of 6.7 μm^2. The bit-depth was 8. In fig. 2(a-b), the object was a resolution target illuminated by a spherical wave. In fig. 3, the mask was simply illuminated with a spherical wave that was modified by a singlet lens. As is shown, the reconstruction quality is comparable to holography. With this technique no aberration compensation is required.

This technique has a very simple set-up and is robust to external disturbance and sensor noise. It is also suitable for various wavelengths. Therefore, we believe that the technique would find many practical applications in phase contrast imaging, wavefront sensing and metrology.

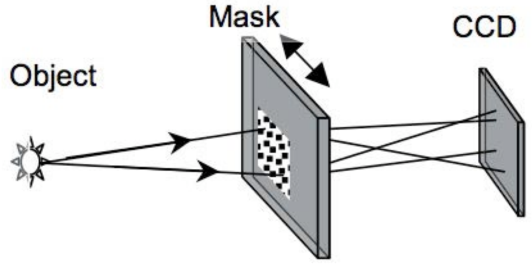

Fig. 1: Experimental arrangement.

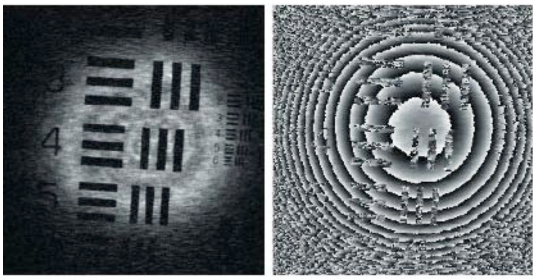

Fig. 2: Experimental results: Retrieved (a) amplitude and (b) phase of a resolution target illuminated with a spherical wave (after 80 iterations and using 5 recordings).

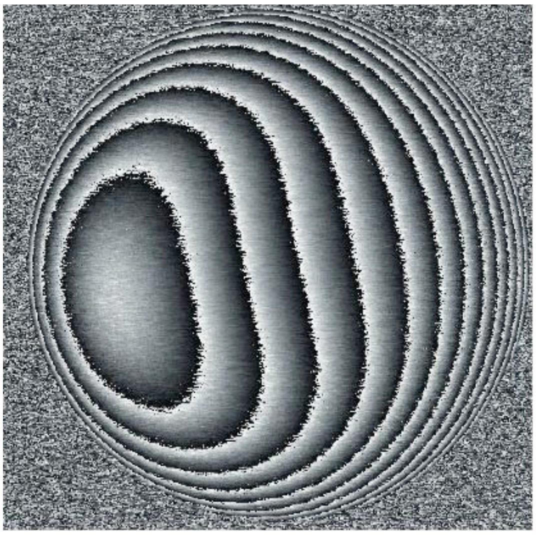

Fig. 3: Retrieved phase on the mask after 140 iterations using 4 recordings.

Supported by: DFG (OS 111/19-1)

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Invited lectures on international conferences

T. Haist:

Dynamic holography in biomedical applications

21. Biomedical photonics symposium, Tokyo (JP), 1-2 Dec 2006

N. Kerwien, M. Totzeck, W. Osten:

Polarization effects of a partially coherent light field: applications in optical metrology

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Freimann, Rolf; Mayer, Maximilian; Reichelt, Stephan:

Method for absolute Calibration of an Interferometer

United States Patent US 6940607 B2 2005.09.06, filed: 2002.05.21 (Assignee: Carl Zeiss SMT, Oberkochen)

Körner, Klaus; Wiesendanger, Tobias; Ruprecht, Aiko; Berger, Reinhard; Droste, Ulrich; Pruß, Christof, Kohler, Christian; Osten, Wolfgang:

Interferometrisches, konfokales Verfahren und interferometrische, konfokale Anordnung für optische Datenspeicher, insbesondere Terabyte-Volumenspeicher

DE 2005 006 723 B3 2006.06.08, priority: 2005.02.03

Körner, Klaus; Papastathopoulos, Evangelos; Berger, Reinhard; Osten, Wolfgang:

Verfahren und Anordnung zur Spektral-Interferometrie mit chromatischer Tiefenaufspaltung, insbesondere auch Mirau-Interferometer

DE 10 2005 042 733 B3 2007.01.25, priority: 2005.09.05

Doctorial Thesis, Diploma Thesis & Student Research Projects

Doctoral Thesis

Liesener, Jan
Zum Einsatz räumlicher Lichtmodulatoren in der interferometrischen Wellenfrontmesstechnik
5/2007 (oral examination 11/2006)

Franz, Stefan
Optische Vermessung von Bohrungen
7/2005

Vetter, Herbert
Verformungsmessung mit gestörten Interferogrammen
7/2005

Diploma Thesis

Merz, Michael (Betreuer : Kohler, Schwab)
Interferometrische Wellenfrontanalyse zur Qualitätsbestimmung von mit einem LCD rekonstruierten Hologrammen
(FH Aalen)
9/2006

Hopp, David
Flexibler Asphärentest mit Membranspiegeln: Wellenfrontskalierung durch Mehrfachreflexion
7/2006

Weiger, Ulrich
Endoskopoptiken mit umschaltbarem Sehfeld
5/2005

Bohr, Roland
Charakterisierung eines Argon-Fluorid Excimerlasers mittels Fouriertransformations-spektroskopie
2/2005

Zwick, Susanne
Grundlegende Untersuchungen zur hochgenauen Positionsbestimmung in holografischen Pinzetten
2/2005

Student Research Projects

Nagel, Cornelia
Untersuchung von Algorithmen zur Kantendetektion
12/2006

Petschow, Matthias
Implementierung der Vektoriell Kirchhoffschen Näherung (VKA) zur Nahfeldberechnung in MicroSim
11/2006

Matic, Mario
Entwicklung einer optisch adressierten, thermisch adaptiven Optik
11/2006

Meister, Eugen
Kompensation der Positionierungsfehler in der Vergleichenden Digitalen Holografie
11/2006

Beutelspacher, Hanna
Der Einfluss von Beleuchtungs- und Strukturparametern auf die Linienbreitenmessung von Photomasken
9/2006

Droemmer, Stephan
Photometrische Kalibrierung eines 3D-Laserprojektors
6/2006

Drust, Manuel
Automatisierte Optimierung von Einfangkräften in der holografischen Pinzette
6/2006

Utz, Annika
Vergleich von Lasersystemen zum Trimmen von Leiterplatten
6/2006

Ruppel, Thomas
Entwicklung und Aufbau eines Low-Cost Shack-Hartmann-Sensors
5/2006

Bader, Johannes
Integration eines 2-PEM-Ellipsometers in ein Diffraktometer
12/2005

Hopp, David
Flexibler Asphärentest mit Membranspiegeln: Simulation und Realisierung eines interferometrischen Vielstreifen-Prüfaufbaus
12/2005

Leroux, Charles
„Membrane mirror for active optics‟ (Institute d´optique, Orsay, France)
2005

Fringe 2005: The 5th International Workshop on Automatic Processing of Fringe Patterns

W. Osten

In 1989 the time was hot to create a workshop series dedicated to the discussion of the latest results in the automatic processing of fringe patterns. This idea was promoted by the insight that automatic and high precision phase measurement techniques will play a key role in all future scientific and industrial applications of optical metrology. However, such a workshop must take place in a dynamic environment. Therefore the main topics of the previous events were always adapted to the most interesting subjects of each period. In 1993 new principles of optical shape measurement, setup calibration, phase unwrapping and non-destructive testing were the focus of discussion, while in 1997 new approaches in multi-sensor metrology, active measurement strategies and hybrid processing technologies played a central role. 2001, the first meeting in the 21st century, was dedicated to optical methods for micromeasurements, hybrid measurement technologies and new sensor solutions for industrial inspection. The fifth workshop took place in Stuttgart and was organized by the staff of ITO. Thus after Berlin 1989, Bremen 1993, 1997 and 2001, Stuttgart was the third Fringe city where international experts met each other to share new ideas and concepts in optical metrology.

The focus of the Stuttgart meeting was in particular directed to resolution enhanced technologies, new approaches in wide scale 4D optical metrology and advanced computer aided measurement techniques. Since optical metrology becomes more and more important for industrial inspection, sophisticated sensor systems and their applications for the solution of challenging measurement problems were chosen again as one of the central topics of the workshop. This extended scope was honored again by a great response on our call for papers. Scientists from all around the world offered more than 110 papers which were summarized under 5 topics:

- New Methods and Tools for Data Processing,
- Resolution Enhanced Technologies,
- Wide Scale 4D Optical Metrology,
- Hybrid Measurement Technologies,
- New Optical Sensors and Measurement Systems.

Each session was introduced by an acknowledged expert who gave an extensive overview of the topic and a report of the state of the art. All papers are published in the proceedings which were printed by Springer [1].

The organizers and the whole audience appreciated the presentations of many internationally recognized scientists such as Malgorzata Kujawinska, Karl Stetson, Rene Dändliker, Walter Schumann, Cesar Sciammarella, Josef Braat, Mitsuo Takeda, Toyohiko Yatagai, Ichirou Yamaguchi, Leonid Yaroslavsky and Jim Trolinger. Since the early beginning of the Fringe series it has been a good tradition to distinguish deserved scientists with honorary lectures. In 2005 Walter Mirande was awarded with the honorary lecture while Rajpal Sirohi was selected to present the key note at the banquet. On occasion of the Stuttgart conference the Hans Steinbichler award was presented for the first time by his son Marcus Steinbichler. The winner of the 2005 price was Johannes Schwider, an internationally acknowledged expert in optical interferometry, for his numerous contributions to the field over many years of active scientific work.

The engagement of many people is necessary to make a conference to a successful event in all aspects. Special thanks goes to the international program committee (see Figure 1) that again was a guarantee for a high class scientific meeting, with the special spirit of a workshop where people find time and space for inspiring discussions about such an exciting topic as modern optical metrology is.

Looking forward to FRINGE 2009.

[1] Osten, W. (Ed.), Fringe 2005. Proc. 5th Int. Workshop on Autom. Processing of Fringe Patterns. Springer Berlin, Heidelberg, New York ´05

Optik-Kolloquium 2005

Innovative optische Systemkomponenten I

am 2. März 2005, Teilnehmer: ca. 250

Begrüßung und Einführung	Prof. Dr. W. Osten ITO, Universität Stuttgart
Stand und Perspektiven plasmabasierter XUV-Quellen	Prof. Dr.-Ing. R. Poprawe Fraunhofer-Institut für Lasertechnik ILT, Aachen
Thermisch beeinflusste Strahlformung in Festkörperlasern	Prof. Dr. Th. Graf Institut für Strahlwerkzeuge IFSW, Universität Stuttgart
Stand und Perspektiven der diffraktiven Optik	Dr. R. Brunner Carl-Zeiss Jena GmbH
Electrowetting: Fundamentale Aspekte und optische Anwendungen Physik komplexer Flüssigkeiten	Prof. Dr. F. Mugele Universität von Twente/NL
Organische Leuchtdioden und Laser	Prof. Dr. W. Kowalsky Institut für Hochfrequenztechnik, Technische Universität Braunschweig
MEMS Mikrospiegel Arrays zur adaptiv optischen Phasenkontrolle	Dr. A. Gehner Fraunhofer Institut für Photonische Mikrosysteme, Dresden
DMD Mikrospiegelsystem – Eigenschaften und Potential für optische Technologien	Dr. R. Höfling VIALUX GmbH, Chemnitz
Mikrodisplays für Anzeigen und optische Anwendungen	Prof. Dr. N. Frühauf Lehrstuhl für Bildschirmtechnik LFB, Universität Stuttgart
Stand und Perspektiven der CMOS-Sensortechnik	Prof. Dr. B. Höfflinger IMS-Chips, Stuttgart
Photoadressierbare Polymere zur holographischen Datenspeicherung in Hochsicherheitsanwendungen	Dr. Stephan Völkening Bayer Innovation GmbH, Düsseldorf
Ein endoskopischer Sensor zur Form- und Verformungsmessung	Dr. C. von Kopylow BIAS GmbH, Bremen
Moderne Modulatoren in der optischen Mikromanipulation	M. Reicherter Institut für Technische Optik ITO, Universität Stuttgart

Optik-Kolloquium 2006

Innovative optische Systemkomponenten II

am 22. Februar 2006, Teilnehmer: ca. 250

Begrüßung und Einführung	Prof. Dr. W. Osten ITO, Universität Stuttgart
Ultrapräzise Asphären: Moderne Fertigungsverfahren und Anforderungen an die Messtechnik	M. Haag-Pichl, G. Schneider Schneider Optikmaschinen, Steffenberg
Hochleistungsobjektive für die Immersionsmikroskopie	Dr. T. Sure, P. Euteneuer, Dr. W. Vollrath Leica Microsystems SG, Wetzlar
Entwurf und Realisierung von Freiform-Mikrooptiken für die Strahlformung	Prof. Dr. K.-H. Brenner Lehrstuhl für Optoelektronik, Universität Mannheim
CCD- und CMOS Kamerasysteme und ihre Eigenschaften im UV-Bereich des Spektrums	Dr. G. Holst PCO AG, Kelheim
Photorefraktive Optik: neue photonische Komponenten durch nichtlineare Brechungsindexänderungen	Prof. Dr. C. Denz Institut für Angewandte Physik Westfälische Wilhelms-Universität Münster
Phase-Retrieval in System-Metrologie und Phasenmikroskopie	Dr. H. Gross Carl Zeiss AG, Oberkochen
Optische Sensorik für Fahrerassistenzsysteme	Dr. H. Winter Aglaia GmbH, Berlin
HoloGraphics: Kombination von optischen Hologrammen und interaktiver Computer Grafik	Prof. Dr. O. Bimber Augmented Reality, Bauhaus Universität Weimar
3D Gesichterkennung mittels ultraschneller Holographie	Prof. Dr. P. Hering Stiftung caesar, Bonn
Anwendungsmöglichkeiten moderner räumlicher Lichtmodulatoren	Dr. T. Haist ITO, Universität Stuttgart
Diffraktive Optik für miniaturisierte Sensorik	C. Pruß ITO, Universität Stuttgart

Fest-Kolloquium Optik 2006

Optische Technologien – Innovation und Produktion am Standort Deutschland

ITO-Festkolloquium aus Anlass des 70. Geburtstages von Herrn Prof. Dr. H. Tiziani und der Eröffnung der neuen Mess- und Reinräume

am 7. Juli 2006, Teilnehmer: ca. 350

Eröffnung	Prof. Dr. W. Osten ITO, Universität Stuttgart
Begrüßung	Prof. Dr.-Ing. Prof. E.h. Dr. h.c. mult. Engelbert Westkämper Dekan der Fakultät Maschinenbau, Universität Stuttgart
Congratulations from the SPIE –the Int. Society for Optical Engineering	Prof. Dr. M. Kujawinska Immediate Past President of SPIE
Strategien zur Sicherung von Produktion und Arbeitsplätzen am Standort Deutschland im Bereich der optischen Technologien	Ministerialrat W. Kraus Referatsleiter im BMBF
Moderne optische Technologien in der Medizintechnik und Augenoptik	Dr. M. Kaschke Mitglied des Vorstandes der Carl Zeiss AG
Die enge Kooperation zwischen Wissenschaft und Industrie auf dem Gebiet der Optik als Innovationstreiber und Wirtschaftskraft	N. Thiel Mitglied des Vorstandes der JENOPTIK AG
Flexibilität durch Innovation und Produktion in Deutschland	Dr. R. Bauer Mitglied des Vorstandes der Sick AG

Optik-Kolloquium 2007

Innovation in der Medizintechnik durch Optische Technologien

am 28. Februar 2007, Teilnehmer: ca. 250

Begrüßung und Einführung	Prof. Dr. W. Osten ITO, Universität Stuttgart
Bildgestützte Femtosekundenlaser-Chirurgie in der Augenheilkunde	Prof. Dr. J. Bille URZ, Universität Heidelberg
Neue Entwicklungen der Kohärenztomografie in der Augenheilkunde	Prof. A. Fercher Institut für Sensor- und Aktuatorsysteme, Universität Wien
Moderne Anwendungen der Optik in der Ophthalmologie	Dr. M. Wiechmann Carl Zeiss Meditec AG, Jena
Spezial-Lichtleiter-Applikationen für medizinische Anwendungen	Prof. Dr. R. Hibst ILM, ULM
3D-Messtechniken für die Zahnmedizin	Dr. J. Pfeiffer SIRONA Dental Systems, Bensheim
Leica TCS 4PI - Funktion und Anwendungen der 4PI Mikroskopie	Dr. T. Szellas, Dr. T. Zapf Leica Microsystems GmbH, Wetzlar
Smart textiles für den Bereich Life-Science	Prof. Dr. H. Planck Institut für Textil- und Verfahrenstechnik, Denkendorf
Bildsensoren für die Medizintechnik	Dr. C. Harendt IMS Chips, Stuttgart
Digitalholografische Mikroskopieverfahren zur markerfreien quantitativen Lebendzellenanalyse	Dr. B. Kemper, Prof. G. v. Bally Labor für Biophysik, Universität Münster
Optische 3D-Sensorik in der Medizintechnik	Dr. E. Papastathopoulos Institut für Technische Optik, Universität Stuttgart
Digitalholografische Endoskopie zur Gewinnung von Gewebeeigenschaften	Dr. G. Pedrini Institut für Technische Optik, Universität Stuttgart

Dr. Stephan Reichelt receives the Frankowski Award

The ITO-Kolloquium of 2007 provided the dignified setting for the bestowal of the Gottfried-Frankowski award for the first time. This newly established prize is awarded for innovative development and research in the field of optical 3D metrology. It was founded by the GFMesstechnik GmbH, Teltow with the aim of promoting young scientists in particular.

This year's winner is Dr. Stephan Reichelt for his dissertation "Interferometrische Optikprüfung mit computergenerierten Hologrammen", which describs absolute interferometric testing procedures for aspheric optics and computer generated holograms. These new measurement methods allow the testing of aspheric surfaces to an accuracy that was achieved previously only for flat or spherical elements.

Dr. Reichelt was studied mechanical engineering at the Universities of Chemnitz and Stuttgart. He wrote his doctoral thesis at the Institut für Technische Optik (ITO) receiving his PhD in 2004.

A postdoctoral research position followed at the Institut für Mikrosystemtechnik (IMTEK), University of Freiburg. He is now with the company SeeReal Technologies GmbH in Dresden.

In his acceptance speech he thanked Gottfried Frankowski and the referees committee and stressed, that this award would be both an appreciation for his past achievements so far as well as a high motivation for his future work. Furthermore he expressed thanks to his teachers in optics, Prof. Tiziani and Prof. Osten, as well as to his former colleagues of the ITO for the excellent "micro-environment" at the Institute which is a prerequisite in pursuing new scientific ideas with the necessary care and endurance. He also highly valued the "macro-environment" around the Institute that is required at the same time to develop new ideas and to identify real research topics. Therefore he thanked project partners, the German Ministry for Research and Education (BMBF) and the optical community in the audience for all the support that was received.

Organized International Conferences: 2005 – 2006

W. Osten:

Optical Measurement Systems for Industrial Inspection IV

SPIE Congress, June 13 – 17, 2005, Munich, Germany

W. Osten:

Optical Sensing and Metrology

CLEO Europe, June 12 – 17, 2005, Munich, Germany

W. Osten:

Fringe 2005

5th International Workshop on Automatic Processing of Fringe patterns, September 9 – 14, 2005, Stuttgart, Germany

W. Osten:

Optical Micro- and Nanometrology in Microsystems Technology

April 5 – 7, 2006, Strasbourg, France

W. Osten:

Interferometry XIII– Applications

SPIE Congress, 16 – 17 August 2006, San Diego, USA

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