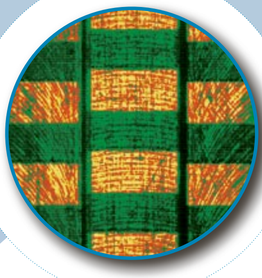
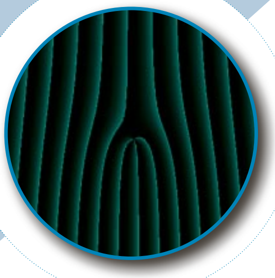
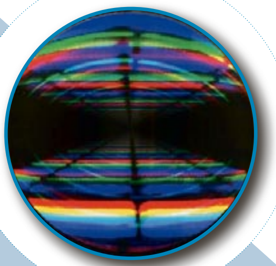
annual report
2007 / 2008

INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

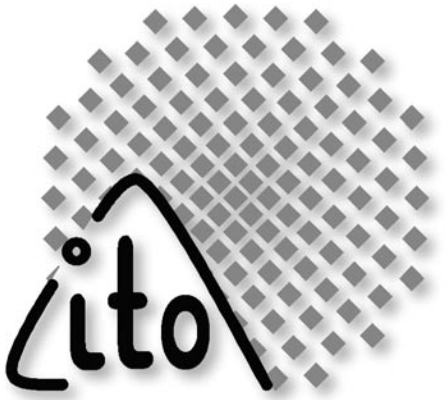






Universität Stuttgart

INSTITUT FÜR TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART
Prof. Dr. W. Osten



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ANNUAL REPORT 2007/2008

Dear Reader,

Another two years filled with many activities in different fields and enriched with fruitful national and world wide cooperation have passed since the ITO staff reported in 2007 in such a comprehensive report about their research activities. 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 work remains unchanged: striving for excellence in research and teaching, together with a good balance of continuity and systematic renewing. Modernization of our environment and equipment is still an ongoing process. For instance, our clean room, the centre of many of our research activities in diffractive optics and high resolution metrology, is now equipped with a new ion etching facility. The installation of a state of the art focused ion beam (FIB) tool is on the way. Both tools widen our possibilities in the field of nanotechnology considerably. However, all of our activities are also accompanied by new initiatives that are embedded in challenging timescales. Two years ago we have reported about our commitment to the Excellence Initiative of the Federation and the States in Germany. Now we can proudly report that ITO is an active member of both successful initiatives of the University Stuttgart, the Cluster of Excellence "Simulation Technology" and the Excellence Graduate School for Advanced Manufacturing Engineering GSaME. Another initiative focuses on the location of Stuttgart as a strong centre of photonic technologies. Eight institutes from the engineering and natural sciences faculties have founded the "Stuttgart Research Centre of Photonic Engineering SCoPE". SCoPE is dedicated to concerted work between engineers and physicists with respect to the next generation of larger joint and ambitious projects in photonic technologies. Several projects are already running and the preparation of a collaborative research centre under the roof of the German Research Association DFG has started recently. Such 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 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 electro-magnetic waves. All these activities are embedded in the five main research directions of ITO

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

that 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 again the success of this approach.

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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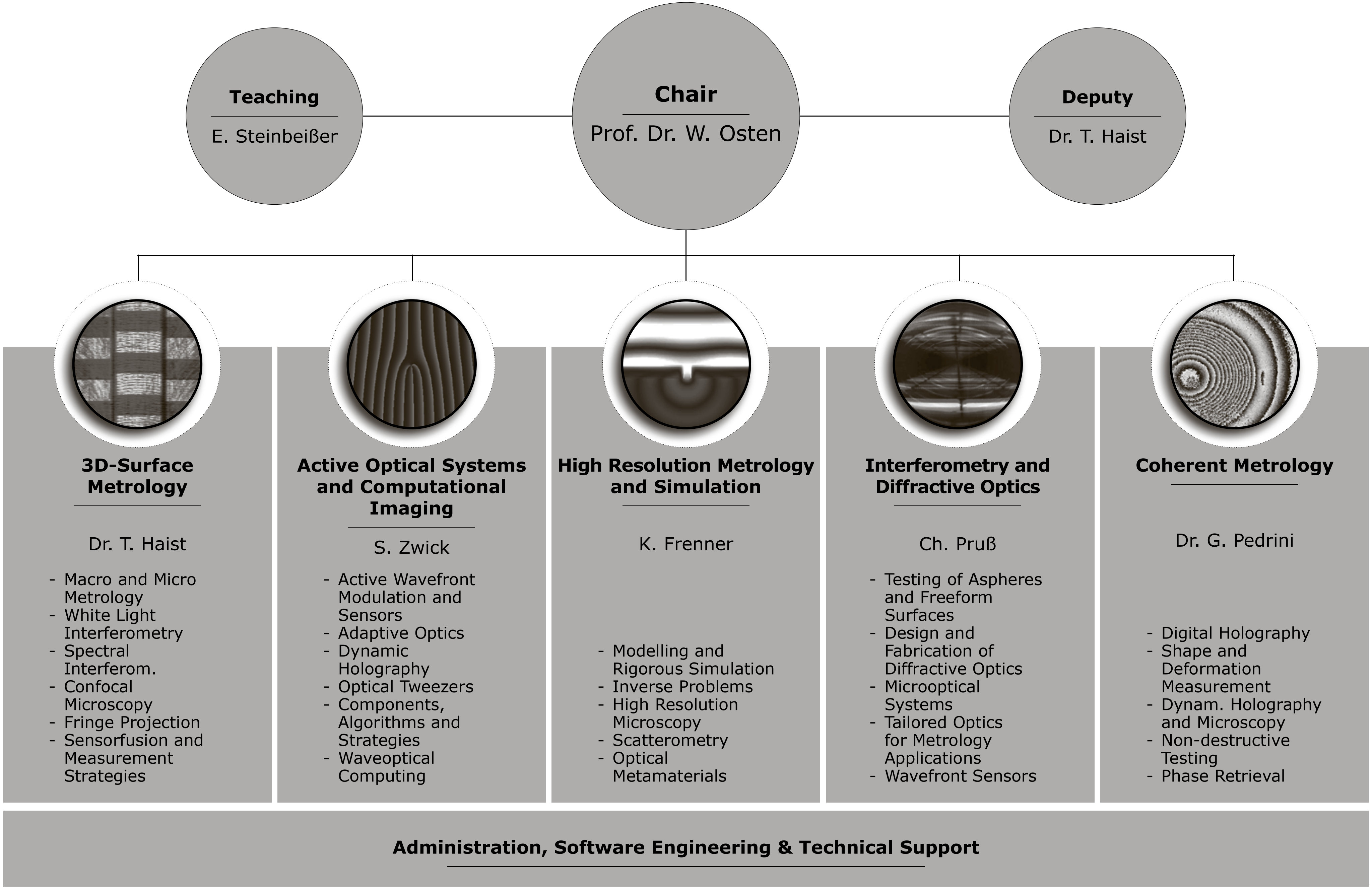
-Structure



Teaching

E. Steinbeißer

Chair

Prof. Dr. W. Osten

Deputy

Dr. T. Haist

3D-Surface Metrology

Dr. T. Haist

- Macro and Micro Metrology
- White Light Interferometry
- Spectral Interferom.
- Confocal Microscopy
- Fringe Projection
- Sensorfusion and Measurement Strategies

Active Optical Systems and Computational Imaging

S. Zwick

- Active Wavefront Modulation and Sensors
- Adaptive Optics
- Dynamic Holography
- Optical Tweezers
- Components, Algorithms and Strategies
- Waveoptical Computing

High Resolution Metrology and Simulation

K. Frenner

- Modelling and Rigorous Simulation
- Inverse Problems
- High Resolution Microscopy
- Scatterometry
- Optical Metamaterials

Interferometry and Diffractive Optics

Ch. Pruß

- Testing of Aspheres and Freeform Surfaces
- Design and Fabrication of Diffractive Optics
- Microoptical Systems
- Tailored Optics for Metrology Applications
- Wavefront Sensors

Coherent Metrology

Dr. G. Pedrini

- Digital Holography
- Shape and Deformation Measurement
- Dynam. Holography and Microscopy
- Non-destructive Testing
- Phase Retrieval

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Status quo: July 2009

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Dr. Roger Groves	left on 31.10.2008	
Xavier Schwab	left on 31.03.2008	
Dr. Quiaofeng Tan	left on 31.12.2007	
Dr. Dayong Wang	left on 30.11.2007	
Dr. Fucai Zhang	left on 30.11.2007	

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Guest Scientists

Dr. Arun Anand	Institute for Plasma Research, Gujarat (India)	5/2006 – 5/2007
Dimitri Denk	Academy of Sciences, Novosibirsk (Russia)	11/2007 – 12/2007
Dr. Yu Fu*	Dep. of Mech. Eng., Nat. University (Singapore)	1/2007 – 12/2007
Dr. Unnikrishnan Gopinathan*	Instrument R & D Establishment, Dehradun (India)	8/2007 – 12/2008
Prof. Dr. Bahram Javidi**	University of Connecticut (USA)	6/2008 – 8/2008
Jun Ma	Nanjing University (China)	since 3/2009
Cristian Israel Mendez	Centro d. Investigationes en Optica, Leon (Mexiko)	7/2007 – 3/2008
Dr. Guohai Situ*	Chinese Academic of Sciences, Bejing (China)	since 3/2008
Dr. Quiaofeng Tan	Tsinghua University, Bejing (China)	3/2007 – 12/2007
Prof. Dayong Wang*	College of Applied Sciences, Bejing (China)	12/2006 – 11/2007
Dr. Yong Yang	Nankai University (China)	1/2008 – 12/2008

Foreign Guests visiting the Institute: 2007 - 2008

Prof. Dr. Xiaoyuan He	Southeast University (China)	Juli 2007
Prof. Dr. Hans-Peter Herzig	Univ. Neuchatel (Suisse)	September 2007
Dr. Vivi Tornari	F.O.R.T.H., Heraklion (Greece)	Oktober 2007
Dr. Vadime Vanine	ASML Veldhoven (Netherlands)	Oktober 2007
Prof. Dr. Gao	Nanjing Univ., Nanjing (China)	Juni 2008

* Humboldt fellowship ** Humboldt prize-winner and stays at the ITO for altogether one year

Project partners

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

ASML Netherlands B.V.	Veldhoven, Netherlands
Carl Zeiss AG	Oberkochen
Carl Zeiss SMT AG	Oberkochen
Daimler AG	Untertürkheim
Diamant-Gesellschaft Tesch GmbH	Ludwigsburg
Fisba Optik AG	Berlin; St. Gallen, Switzerland
FOS Messtechnik GmbH	Schacht-Audorf
Fraunhofer-Institut Produktionstechnologie IPT	Aachen
GEFASOFT Automatisierung und Software GmbH	Regensburg
GFMesstechnik GmbH (GFM)	Teltow bei Berlin
Holoeye Photonics AG	Berlin
IMOS Gubela GmbH	Renchen
Jenoptik LOS	Jena
Johann Fischer Präzisionswerk GmbH & Co. KG	Aschaffenburg

La Vision GmbH	Göttingen
LT Ultra-PrecisionTechnology GmbH	Herdwangen-Schönach
Mahr GmbH	Göttingen
National Gallery_Alexandros Soutzos Museum	Athens, Greece
Optrion s.a.	Liège, Belgium
Polytec GmbH	Waldbronn
Qimonda AG	Dresden
Robert Bosch GmbH	Gerlingen
Schneider Optikmaschinen GmbH	Steffenberg
Singulus Mastering BV	Eindhoven, NL
Tate Gallery	London, England
Till Photonics GmbH	Gräfelfing
Trumpf GmbH+ Co. KG	Ditzingen
UPT-Optik Wodak GmbH	Nürnberg
VW AG	Wolfsburg

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 “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 subjects:

- **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 / Dr. Körner)

  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 moiré-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 subjects:

- Optical Phenomena in Nature and Everyday Life (Dr. T. Haist)
- Opto-Electronical Image-Sensor and Digital Photography (Dr. K. Lenhardt; Schneider, Kreuznach)
- Coherence and Polarisation in Optics / Optics of Thin Films, Surfaces and Crystals (Dr. K. Leonhardt)
- Measuring Techniques for Micro-Structures (Dr. M. Totzeck; Zeiss)
- Design and Calculation of Optical Systems (Dr. Ch. Menke; Zeiss)
- Optoelectronic Devices and Fibre Sensors (Dr. R. Groves)

Additional studies:

- project work and thesis within our fields of research
- practical course “Optic-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 measurement 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

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Active Optical Systems and Computational Imaging

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 and sensors
- adaptive optics
- active wavefront sensors
- dynamic holography
- components, algorithms, and strategies
- waveoptical computing

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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 subwavelength information about the structure.

Current research areas:

- modelling and rigorous simulation
- inverse problems
- high resolution microscopy
- scatterometry
- optical metamaterials

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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 and freeform surfaces
- fabrication of diffractive optics
- interferometry
- dynamic wavefront coding
- wavefront sensors
- tailored optics for metrology applications

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Coherent Metrology

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
- THz technique for non-destructive testing

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3D-Surface Metrology

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

Influence of the object shape in white-light interferometry
Supported by: BMBF (FKZ 16SV1945)
Project: "µgeoMess"

Optical measurement techniques on a six-axis manufactoring machine for freeform Diamond tools
Supported by: BMWi (FKZ 16IN0519)
Project: "iTool"

Improved micro topography measurement by LCoS based fringe projection and z-stitching
Supported by: AIF, PRO INNO II (FKZ 0372001RK6)

Characterization of LCoS displays and hologram reconstruction with regard to polarization effects
Supported by: DFG (OS 111-23/1)

In process measurement of micrometer scaled tools
Supported by: VDI/VDE-IT Berlin (16IN0373)
Project: "WMELF"

Application of phase retrieval for the characterization of LCoS displays
Supported by: DFG (OS 111/23-1)

Optical Simulations of a Biomolecular and Medical Diagnostic Sensor
Supported by: BMBF (FKZ 16SV2328)
Project: "MoDekt"

Chromatic confocal spectral interferometry (CCSI)

W. Lyda, E. Papastathopoulos, K. Körner, W. Osten

Chromatic confocal spectral interferometry (CCSI) is a hybrid measurement method for fast topography measurement without mechanical axial scan. The CCSI-method combines the advantages of the interferometric gain and accuracy with the robustness of confocal microscopy. A one shot measurement is achieved by using chromatically separated foci in the object space and a spectral detection of the white light signal.

In common used spectral interferometers (SI) the measurement range is given by the depth of focus leading to a restriction of the numerical aperture. The combination of chromatic separation and confocal filtering decouples the measurement range from the depth of focus, which yields to higher numerical apertures and improved lateral resolution in comparison to common SI-sensors. The advantage of this method is the single shot retrieval of depth positions by either confocal signal analysis or optical path evaluation. Therefore CCSI is qualified for high resolution topography measurements of reflecting and scattering objects.

The discrepancy of the limited axial-range in previously reported SI-schemes can be visualized as follows. The reference field contains a planar wave front, while the detection wave front acquires a rigorous curvature, when the object lies beyond the depth-of-focus, if aberration effects are neglected. 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 (25µm axial range with 0.95 NA were reported [3]) by means of a diffractive optical element – DOE (Fig. 1).

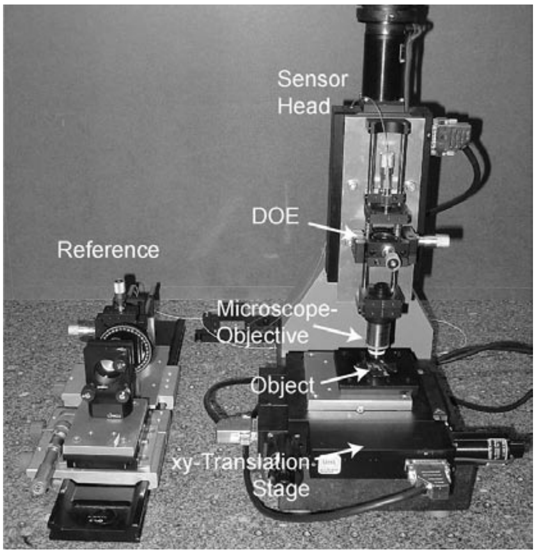


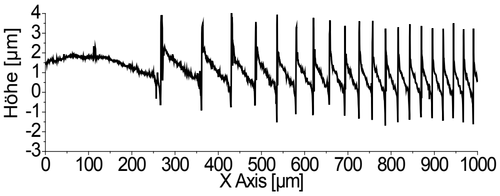
Fig. 1: CCSI sensor in fibre-based interferometer design.

If the object lies within the dispersed focus spectrum, a sharply focused spectral-component 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.

In this project, the CCSI-method was both experimentally and theoretically investigated. The CCSI principle has been implemented in two prototype setups: a Linnik-type interferometer (0.8 NA) and a fibre based interferometer (0.95 NA).

On the basis of topography measurements performed on technical objects, the error budget of the fibre-based interferometer was analysed. A reduction of measurement errors in comparison to the known chromatic-confocal principle was achieved. These first results demonstrate the applicability of this method for the optical detection of objects with rough surfaces and limited reflectivity.

a) Chromatic-confocal measurement (reference arm blocked)



b) CCSI-measurement

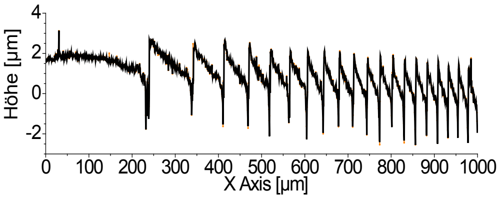


Fig. 2: Measurement of a diffractive optical element (DOE) with chromatic confocal microscopy **(a)** and CCSI **(b)** showing reduced overshooting in the CCSI-measurement.

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

References:

[1] Papastathopoulos, E. et al., Optics Letters 31, 589, 2006.

[2] Papastathopoulos, E. et al., Applied Optics 45, 8244, 2006.

[3] Lyda, W. et al., 109. DGAO-Conference, P15, 2008.

Influence of the object shape in white-light interferometry

R. Berger, K. Körner, W. Osten

A main section of the BMBF-project µgeoMess was the investigation of the measurement uncertainty in white-light interferometry. Especially, the influence of mirrorlike, tilted or curved objects to the measurement result was analyzed. Under ideal measuring conditions, the signals in white-light interferometry – the so called correlograms – are symmetrical. Each signal contains an envelope maximum position along the scanning axis and a phase value at this position. Ideally, this total phase of the signal is zero, independently of the height of the object point. Therefore the zero position of the phase can be used to find a more accurate position of the centre of the correlogram. The two possible algorithms to determine the height values of the correlograms are often called envelope and phase evaluation. The difference between these two evaluation methods is the measured total phase in length units. However, the correlogram can be distorted in the presence of dispersion in the interferometer. If then the phase is used to evaluate the white-light interferometry signal, the height value is different from the result of the envelope evaluation. Since our optical setup uses a Mirau-objective, the rays of both interferometric arms pass the same imaging optic of the white-light interferometer.

In our investigation of mirrorlike, tilted or curved objects, we yield a difference between the envelope and phase evaluation - a function, which correlates with the shape of the object under test. Figure 1 shows the phase along a section of an object with a mirrorlike, sinusoidal surface (period 100 µm, amplitude 0.5 µm).

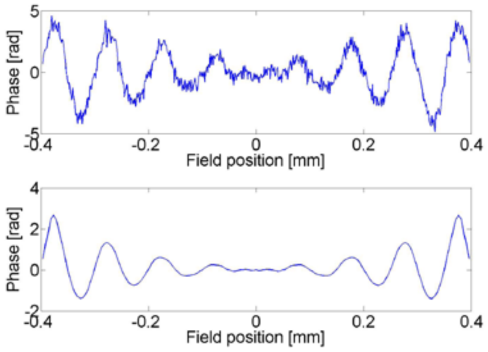


Fig. 1: Total phase at a mirrorlike, sinusoidal object.
Top: measurement,
bottom: simulation.

Since the phase function is not constant for all measured points, we assumed an asymmetry in our white-light interferometer. A systematic difference between the results of the two evaluation methods could also be found for other shapes of mirrorlike, tilted or curved objects. In [1] we presented a function for the phase against the local tilt on the object surface and the position in the field of view.

In the project, we realized numerical simulations of our white-light interferometer system. The investigations showed that our setup has chromatic aberrations – mainly lateral colour. Further, the mirrorlike, tilted or curved objects influence the reflected rays in a different way than the rays reflected by the reference mirror. This results in an asymmetric use of our white-light interferometer caused by the object. Figure 1 shows also the result of the phase simulation in the case of the sinusoidal object. In figure 2, we also calculated the height deviation of the simulated measurement results of the sinusoidal profile from an ideal sinus for both evaluation methods.

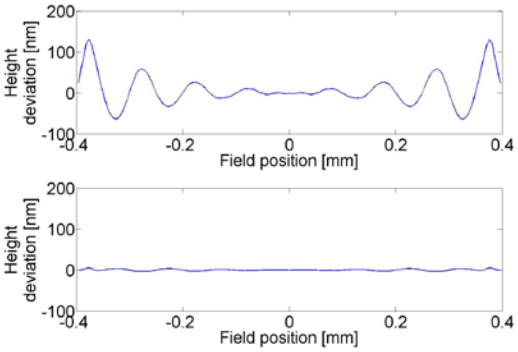


Fig. 2: Height deviation of the simulated sinusoidal profile.
Top: result after envelope evaluation,
bottom: result after phase evaluation.

In this project, we could demonstrate with further simulations as well as with a modified optical setup that the measurement uncertainty of mirrorlike, tilted or curved objects in white-light interferometry can be decreased by reduction of the chromatic aberrations in the optical system [2].

Supported by: BMBF (FKZ 16SV1945)
Project: "µgeoMess"

References:

[1] Berger, R.; Sure, T.; Osten, W. "Measurement errors of mirrorlike, tilted objects in white-light interferometry", Proc. SPIE, Vol. 66162E, pp. 1-9, 2007.

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Optical measurement techniques on a six-axis manufactoring machine for freeform Diamond tools

R. Berger, K. Körner, W. Osten

Diamond tools can produce sophisticated optical surfaces on plane and curved substrates. The production techniques are for example fly-cutting or ultra-precision turning and planing. At these techniques the shape of the Diamond tools are often directly transferred onto the substrates. For example, such objects are needed for the production of micro lens arrays, displays or intraocular lenses.

Therefore, the development of new innovative optical surfaces on such substrates is limited by the supply with commercial Diamond tools, by the supply with the machines, which produce such Diamond tools, and last but not least by the supply with the measurement technique for these manufacturing machines. To give the Diamond tools a predefined shape, they get grinded and polished.

In the BMWi InnoNet-project iTool, eight project partners from industry and research institutes work together to develop a six-axis machine with an integrated optical measurement system for the manufacturing of freeform Diamond tools. The manufacturing process will be intermitted by several measurement cycles. The results of the measurements will be compared with the required geometrical design form of the Diamond tool to be produced. Then a dataset with new control parameters will be transferred to the six-axis manufacturing machine.

Figure 1 shows a view of a Diamond tool with the parameters to be measured in the project. Typical values for the radius of the Diamond tools are between 0.03 and 0.5 mm.

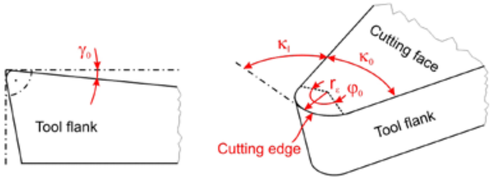

Fig. 1: View of a Diamond tool with the parameters to be measured.

The concept for an optical measurement of the Diamond tools on the production machine consists of the selection of an appropriate measurement principle and the development of a measurement procedure. Our choice is a combined system, which uses digital image processing and white-light interferometry. The basis for this system is a MarSurf WS1 white-light interferometer from the Mahr GmbH. A separate LED-illumination is mounted in front of the optical measurement system to have a transmitted light device for the digital image processing. Figure 2 shows the setup of the optical measurement system, where a Mirau objective is used for the white-light interferometry and the digital image processing as well.

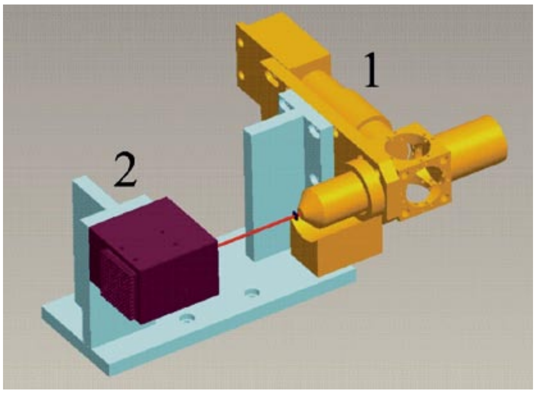

Fig. 2: Optical measurement system consists of a white-light interferometer **(1)** with a transmitted light device **(2)** for digital image processing.

The digital image processing with the transmitted light device is used for the measurement of Diamond tools with a small radius, since their tool flank does not reflect enough light back to the objective, when this part of the Diamond tool is illuminated through the objective. At Diamond tools with a bigger radius and with sections of plane tool flanks, the white-light interferometer can be used to get measurement results with a resolution in the nanometer range. For example, the shape of the cutting edge can be extracted from the topography measurement, since this parameter is an intersection of the 3D-shape of the measured Diamond tool. To acquire all data points along the tool flank, it may be necessary to stitch the point clouds of several topography measurements, achieved by the white-light interferometer.

The next steps in the project are the integration of the optical measurement system on the production machine and the execution of test runs.

Supported by: BMWi (FKZ 16IN0519)
Project: "iTool"

Improved micro topography measurement by LCoS based fringe projection and z-stitching

C. Kohler, X. Schwab, K. Körner, W. Osten

Fringe projection is a widely used method for the measurement of three-dimensional object shapes. Anyway the progress in opto-mechanical devices and computer hardware offer new advantages and consequently new system performances can be achieved. Based on a formerly presented stereo-microscope with integrated fringe projection a new setup with largely improved performance was built.

The basis of the setup is a Leica MZ 12.5 stereo-microscope. It offers a great variability with its exchangeable front lens and its 12.5x zoom. As a light source a high power Osram OSTAR LED was used. With the optic design program Zemax an optimized illumination optics was developed to achieve an as uniform as possible illumination for the different measurement fields of the microscope. As a consequence of the white light illumination a broadband polarizing beam splitter with a high polarization degree was implemented. The generation of the fringe patterns is performed with a recent WUXGA LCoS display, which yields due to its high resolution and its excellent fill factor of about 93% a big advantage to the system used before. Another main issue especially in microscopic fringe projection is the very often occurring high reflectance changes of the objects to be measured. Consequently the dynamic range of the camera is often a limiting factor. For the system presented here a 12 bit PCO Pixelfly camera is utilized. The camera is very sensitive because of its high quantum efficiency as well as it has a high dynamic range.

In cooperation with Leica an adapter for the front lens was developed with the aim of improving the illumination and to better maintain the telecentricity of the optical system. As a result we are now capable of measuring fields from below 1 mm² up to 4.5 cm² with the microscope by simply varying the zoom factor and exchanging the front lens. The image in Fig. 1 shows the topography of a welding point measured with the microscope. The measurement became possible with the increased dynamic range of the setup.

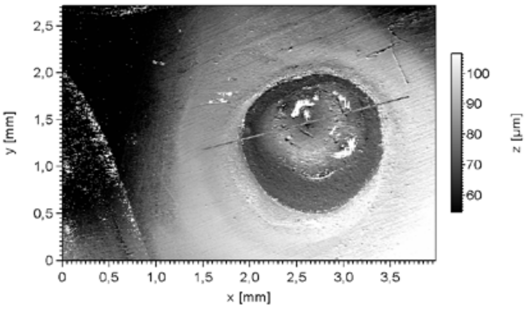

Fig. 1: Topography of a welding point measured with the new stereo-microscope-setup.

Another limitation of microscopic systems is their limited depth of focus. Often one has to choose a lower lateral and depth resolution in favour of a larger depth of focus – as the measurement objects have a too high aspect ratio. We present a solution to this problem based on the microscopic setup described above. Employing the z-stage of the microscope and the calibration data it is possible to incorporate the measurements in different distances to the object into a final topography, i.e. to do a so-called z-stitching. The figure Fig. 2 shows the topography of an air screw measured with the z-stitching technique. In this case an overall number of seven measurements were needed to cover the whole height of the object.

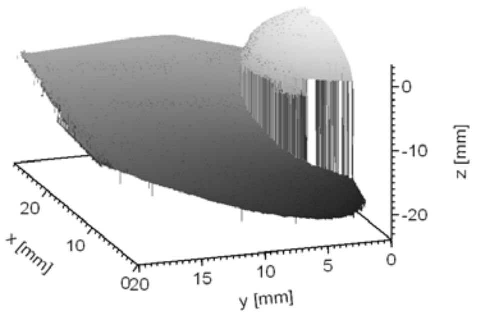

Fig. 2: Topography of an air screw – the topography is stitched out of seven measurements in different heights.

Supported by: AIF, PRO INNO II (FKZ 0372001RK6)

References:

[1] Schwab, X.; Kohler, C.; Körner, K.; Eichhorn, N.; Osten, W. “Improved micro topography measurement by LCoS based fringe projection and z-stitching”, Proc. SPIE 6995-26, 2008.

Characterization of LCoS displays and hologram reconstruction with regard to polarization effects

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

LCoS displays are widely used in optical measurement systems. The two main purposes they are applied for are amplitude modulation and phase modulation. Most modulators are designed as amplitude modulators, e.g. for projection devices, hence using them in their previewed manner yields few problems. The same is the case when special planar nematic displays, which were developed for a phase only modulation, are used in their phase only mode. But as these modulators are quite expensive and one has not a big freedom to choose between models, it can be necessary to use twisted nematic modulators, which are primarily designed for amplitude modulation. In the latter case a characterization of the modulator is needed which delivers at least its phase and amplitude characteristic curves. For an optimized use of these modulators an even more sophisticated characterization has to be carried out, to gain access to the modulator's Jones matrix. Normally this is done using a physical model of the modulator's LC-layer. We introduced a method where no model data are required. It is based on an ellipsometric measurement to obtain a phase reduced Jones matrix and an interferometric measurement for the missing phase information.

When the Jones matrix of a modulator is available it is possible to calculate special characteristic curves, e.g. a phase only or an amplitude only characteristic curve. This is done using simulation software and additional retarder plates.

When using LCDs as phase modulators the reconstruction of holograms is one of the most popular applications. Consequently, beneath this straightforward application of the Jones matrix we developed a technique to directly incorporate the Jones matrix into the hologram optimization. The advantage of including the polarization properties of the LCD used into the optimization process is a gain of light efficiency. This can be achieved by omitting the linear polarizer behind the modulator. But it requires an adaptation of the hologram optimization algorithms used. Therefore we adapted the well known Iterative Fourier Transformations Algorithm (IFTA) and the Direct Binary Search (DBS) algorithm. The illumination, the light modulator and the analyzer behind the display are modeled by their Jones matrices. The both fields for x- and y-polarized light are then propagated separately to the reconstruction plane.

The achieved relative diffraction efficiencies, comparing the zeroth order of diffraction and the first order of diffraction are little lower than for the same modulator used in a phase-only mode. But the overall light efficiency is increased.

In Figure 1 two reconstructed holograms of the institute logo are shown, (a) is the reconstruction using setup #1 and (b) is the reconstruction with setup #2. The achieved diffraction efficiencies and transmission are given in table 1.

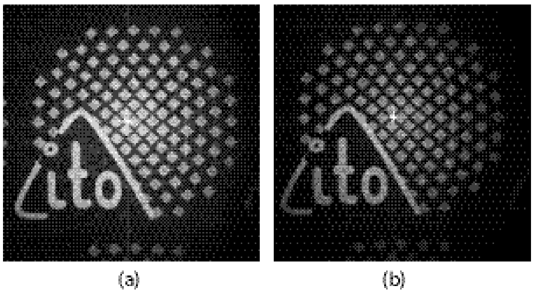

Fig. 1: Reconstructions of the institute's logo. (a) was reconstructed with setup #1, using a linear 2π characteristic curve, (b) was reconstructed without an analyzer behind the display.

Supported by: DFG (OS 111-23/1)

References:

[1] Kohler, C.; Haist, T.; Schwab, X.; Osten, W. „Hologram optimization for SLM-based reconstruction with regard to polarization effects", Opt. Exp.16, pp. 14853-14861, 2008.

#	polarizer	λ/4-plate #1	λ/4-plate #2	analyzer	contrast	maximum phase shift	diffraction efficiency	Transmission
1	129°	55°	44°	39°	1:1.2	2π	79%	59%
2	129°	-	-	-	-	-	72%	100%

Table 1: Diffraction efficiencies and transmissions measured for two setups used for hologram reconstruction. With setup #1 the LCD has a 2π linear phase mostly characteristic curve, as in setup #2 no analyzer is used the geometric phase has to be considered.

In process measurement of micrometer scaled tools

C. Kohler, T. Wiesendanger

The growing amount of highly integrated microsystems and their increased miniaturization demands new high precision manufacturing processes. Especially the newly developed manufacturing method called “Electrochemical micromachining” has the capability to fulfil some of the needs. It offers the possibility of producing stainless steel micro scaled structures with high aspect ratios in only one process step. In order to reach the achievable manufacturing limits adequate measurement instrumentation is necessary.

One of the big advantages of this method is that the tools used are also made with the same manufacturing process as a first step. This greatly reduces the needed precision of the tools blanks. But their precise position relative to the machine coordinate system and their exact shape has to be measured just before the start of process. In addition an in process control of the tool is wanted to observe and correct the 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. In this project stage only cylindrical tools are used so the position to the machine mounted holder, the shape of the cylinder (e.g. small damages) and the concentricity must be measured. But as a future step more arbitrarily shaped tools are planed e.g. to create undercuts and notches. So a versatile in process measurement setup 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,
- a measurement resolution of 0.1 µm.

Due to the large measurement field of the sensor, tools between 10µm and 500µm diameter can be measured with the same setup. No objective change is needed. One important task beneath a ensured resolution of 0.1 µm was the machine integration of the sensor and the protection against environmental influences. Therefore a housing was constructed that could be easily integrated into the machine tool. The image Fig. 1 shows the housed measurement system integrated into the machine tool.

With a series of measurements using a calibration object the wanted resolution of 0.1 µm could be achieved. The image Fig. 2 shows a line cut through a image of a 50 µm tungsten tool.

Supported by: VDI/VDE-IT Berlin (16IN0373)
Project: “WMELF”
Cooperation with: Institut für Zeitmesstechnik, Fein- und Mikrotechnik, Universität Stuttgart

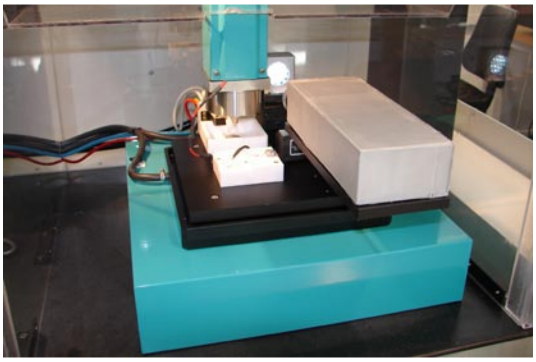

Fig. 1: Machine tool with integrated measurement setup on the right side.

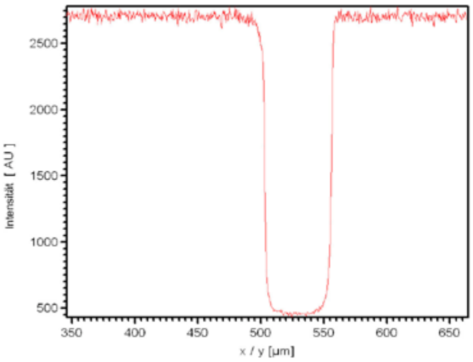

Fig. 2: Line cut through the image of a tungsten tool with a diameter of 50µm.

Application of phase retrieval for the characterization of LCoS displays

C. Kohler, F. Zhang, W. Osten

Recently, we presented a new phase retrieval method [1]. In contrast to the commonly used phase retrieval setups based on through focus series of images, multiple wavelengths or change of curvature, a spatial phase modulator is used. The modulator consists of a binary phase grating with a phase difference of π written into a substrate. A minimum number of three images are recorded for the phase retrieval process. Between the recordings the phase modulator is shifted lateral. Due to the random phase distribution of the modulator the incident wave front is spread deliberately in the frequency domain. Therefore, it shows improved convergence and robustness against environmental influences.

The presented phase retrieval method was applied for the characterization of a Liquid Crystal on Silicon display and the obtained results were compared with previously measured results using a well tested double slit like method. The modulator was setup to operate in a phase only mode with a linear phase shift with incident gray values written into the display. The results achieved with the phase retrieval method (Fig. 1) correspond very well the previously measured results (Fig. 2).

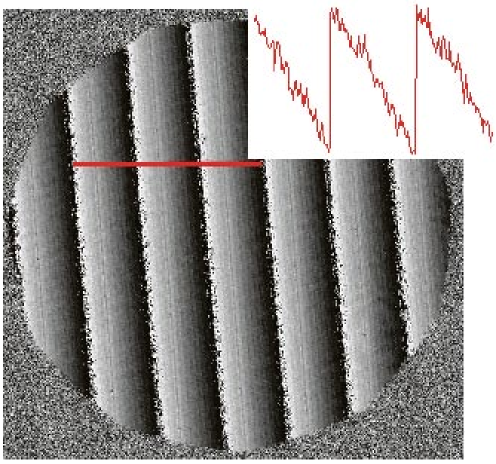

Fig. 1: Blazed phase grating written into the LCoS display measured with the phase retrieval method.

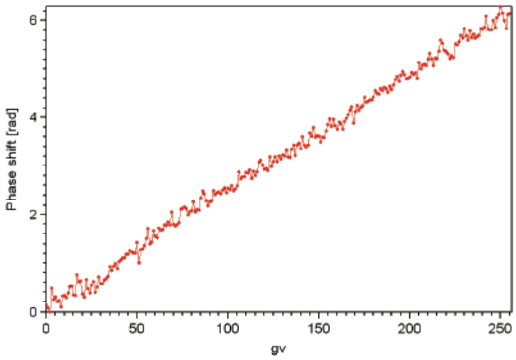

Fig. 2: Phase shift over the gray level written into the display, measured with a double slit like method.

After the successful application of the movable random phase modulator for the characterization of a liquid crystal display the display itself was used as a modulator for the phase retrieval method. The use of the display would facilitate the optical setup even further as no more movable parts remain in the setup and the measurement speed is only limited by the switching time of the modulator. The achieved preliminary results still suffered from a reduced convergence and a strong overlayed grid (Fig. 3).

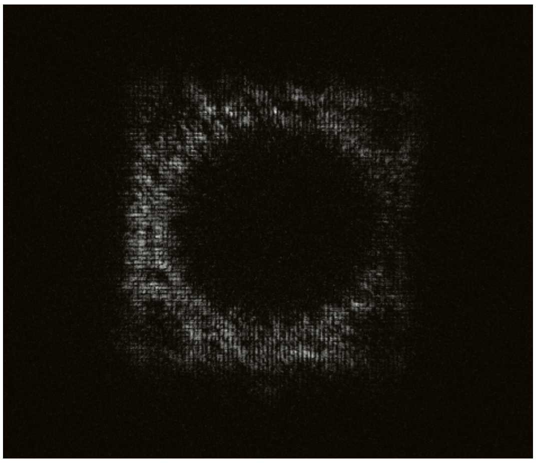

Fig. 3: With the LCoS display as a modulator retrieved intensity distribution of a mounting plate.

Supported by: DFG (OS 111/23-1)

References:

[1] Zhang, F.; Pedrini, G.; Osten, W. "Phase retrieval of arbitrary complex-valued fields through aperture-plane modulation" Phys. Rev. A 75, 043805, 2007.

[2] Kohler, C.; Zhang, F.; Osten, W. "Characterization of a spatial light modulator and its application in phase retrieval" submitted to Applied Optics.

Optical Simulations of a Biomolecular and Medical Diagnostic Sensor

S. Maisch, O. Zvyagolskaya, E. Papastathopoulos, K. Körner

The *MoDekt* project was established for the multidisciplinary development of an universally applicable low-cost biomedical sensor based on the principle of reflectometric interference spectra (RIfS).[1]

An optical multilayer structure illuminated by an LED is covalently covered on its top surface with antibodies or antigens which are highly selective for the detection of pathogens or interesting biomolecules, e. g. proteins providing markers for diseases. Absorption of analyte molecules from an aqueous solution, into which the top of the sensor is submerged, leads to a small change in the refractive index of the surface layer which is detected by the evaluation of the RIfS seen by an a-SiC / a-Si piin heterojunction photo diode showing a voltage-dependent spectral characteristic.[2] The system is designed for the parallel detection of 8 – 10 different substances by use of a 2 x 5 array of 10 photo diodes. A microcontroller with A/D converters is used to control the system, process the photo diode readout and send the measurement data to a computer.

Fig. 1 shows the principle of the *MoDekt* detection system. In fig. 2, the shift of the RIfS, when the analyte molecules attach to the surface, is displayed. The wavelength shift of the minimum is easiest evaluated.

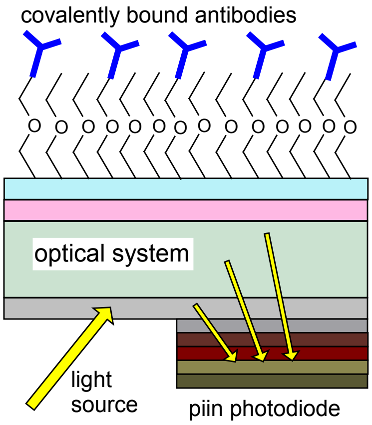

Fig. 1: The MoDekt sensor.

As these shifts are small, it is of particular importance to optimize the optical system for maximum sensitivity. We have therefore implemented a model in Matlab using special compiled MEX functions for the fast computation of wave propagation. This model allows for the variation of the refractive index and thickness of the various layers as parameters, as well as the simulation of the optical properties of the bioorganic surface. Furthermore, it is freely programmable to evaluate the effect of completely different illumination setups and the optical properties of the semiconductor material in the photo diodes itself.

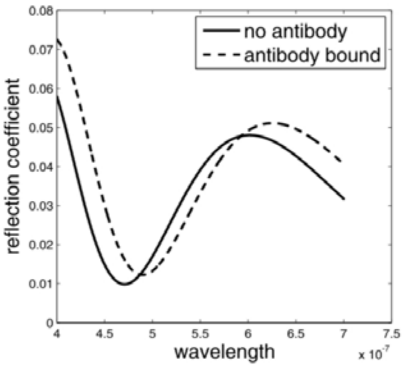

Fig. 2: The shift of the RIfS signal as seen when an antibody or an antigen binds to the detector surface.

In the first step, we have optimized the geometric properties of the detection system and the angle of incidence of the light beam. It was therefore necessary to measure some of the layers involved by ellipsometry, and add their dispersion to the model. Then, we examined the influence of different illuminators and the effect of using polarized light, simulating both commercially available high power LEDs with *Lambertian* radiation characteristics, and a 5 x 2 array of small LED chips. It is of paramount importance to get a simple disposable system which simultaneously is very robust for practical medical applications in various environments.[3]

Supported by: BMBF (FKZ 16SV2328)
Project: "MoDekt"

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[2] Sämann, M.; Steinle, L.; Schubert, M. B. Journal of Non-Crystalline Solids, 354 (19-25) (2008), 2575.

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Active Optical Systems and Computational Imaging

High-resolution phase modulators for micromanipulation – new trapping approaches
Supported by: BMBF (FKZ 13N8809)
Project: "AZTEK"

High-resolution phase modulators for microscopic imaging
Supported by: BMBF (FKZ 13N8809)
Project: "AZTEK"

Image based wavefront correction for wide field microscopy
Supported by: BMBF (FKZ 13N8809)
Project: "AZTEK"

A Multi-Scale and Multi-Sensor Measurement System for Defect Detection:
a systematic approach for sensor fusion in optical metrology
Supported by: DFG (OS 111/18-2)
Project: "STRAMNANO"

High-resolution tomographic microinterferometry
Supported by: DFG (OS 111/20-1)
Project: "TOMI"

Optical computing using white light interferometry

High-resolution phase modulators for micromanipulation – new trapping approaches

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

A major aim of the BMBF project AZTEK is the integration of a micromanipulation system, realized by a spatial light modulator (SLM) in a microscope built by Till Photonics.

The micromanipulation is based on optical tweezers, which operate on the basis of momentum transfer, when photons pass an object like a cell. Under appropriate circumstances (i.e. high numerical aperture, NIR trapping laser) microscopic objects like living cells can be trapped and moved in three dimensions. By applying a phase-only SLM (Holoeye Pluto-NIR) in the Fourier plane of the object plane and displaying a Fourier hologram, one can generate arbitrary light fields in the object plane, which opens a wide range of flexibility. Trap position and shape can be changed independently without any additional mechanics.

Within the project, an add-on module for a Zeiss Axiovert 200 was developed. New trapping methods have been tested, which take advantage of the flexibility of the holographic realization.

Figure 1 shows a yeast cell, which has been trapped by two independent spots. If one moves only one of the traps, the cell could be rotated in three dimensions. Although this is only shown laterally in this picture, three-dimensional manipulation is easily possible with holographic optical tweezers.

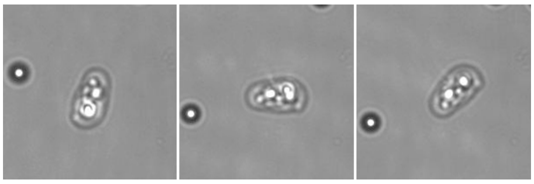

Fig. 1: Yeast cell trapped by two independent traps. By moving one of the traps, one can rotate the cell in three dimensions.

As mentioned before, conventional optical tweezers require high numerical aperture in order to realize stable three-dimensional trapping, as a high axial intensity gradient is needed. This leads to low-working distance and high intensity concentration, which may cause cell damage.

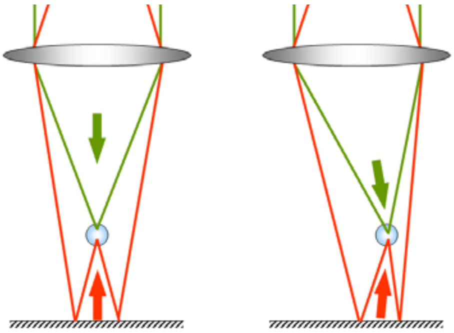

Fig. 2: Holographic twin traps are generated by creating two axially displaced traps via hologram and reflecting one at a dichroic object slide. The counter propagating scattering forces even out each other and stable axial trapping is possible even with low NA.

Holographic optical tweezers enable to realize holographic twin traps (see figure 2). Holographic twin traps are generated by creating two axially displaced traps via hologram and reflecting one at a dichroic object slide. The opposing scattering forces even out each other and stable axial trapping is possible even with low numerical aperture. To move the particle, both spots have to be moved in a synchronized way. Twin traps have been investigated theoretically. Also the principle has been demonstrated experimentally. They open the possibility of using low-NA microscope objectives, therefore increasing the working distance and reducing potential harm on living cells.

Supported by: BMBF (FKZ 13N8809)
Project: "AZTEK"
Acknowledgment: We would like to thank our project partners Holoeye Photonics AG and Till Photonics GmbH for the good cooperation.

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High-resolution phase modulators for microscopic imaging

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

A further objective of the BMBF project AZTEK is the implementation of adaptive phase contrast imaging, realized with a spatial light modulator (SLM), in a microscope built by Till Photonics.

A lot of biological objects are phase objects and require phase contrast imaging methods. Most of these techniques (e.g., Zernike phase contrast) are based on optical filtering in the Fourier plane. Due to their static elements, these methods represent a trade-off, as ideal phase contrast imaging depends strongly on the object.

Therefore, we use a spatial phase–only modulator in the pupil plane for phase contrast filtering (figure 1). By changing the filter via software, we can easily adapt the filter to the object. Furthermore, it is possible to vary the different methods and their parameters in real time. As there are no mechanical changes, it is easily possible to combine those pictures digitally to benefit from the advantages of different methods and to improve the image quality.

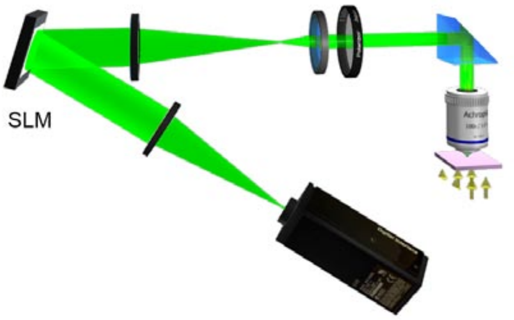

Fig. 1: Setup for adaptive phase contrast. The SLM, which is positioned in the Fourier plane of the object plane, displays a phase contrast filter depending on the applied phase contrast method.

Different phase contrast methods like Zernike phase contrast, dark field, spiral phase contrast, and differential interference contrast (DIC) have been implemented. Figure 2 shows cells of human oral mucosa in bright field (a) without any filter applied, in positive (b) and negative (c) phase contrast, where the filter shifts the zeroth order by $\pi/2$ or $-\pi/2$ respectively by means of the SLM.

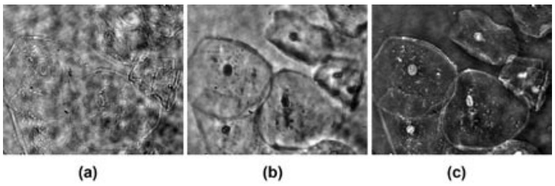

Fig. 2: Human oral mucosa cell imaged in bright field **(a)** without any filter applied, in positive **(b)** and negative **(c)** phase contrast, realized by displaying a Zernike filter by the SLM.

In addition, one can perform quantitative phase measurements by shifting the phase. Several experiments have been performed and good results were achieved for low-frequency objects. As the phase-shift of the phase-modulator strongly depends on the wavelength, the illumination is required to have a narrow bandwidth.

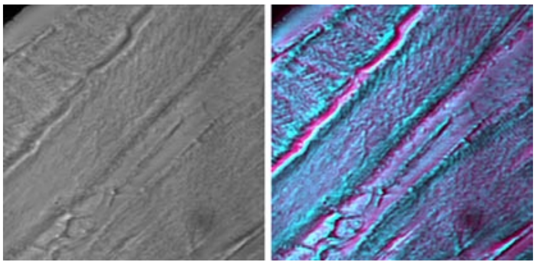

Fig. 3: Rabbit taste bud imaged by phase-shift DIC **(left)** and a superposition of phase-shift DIC and Zernike phase contrast displayed in different colour channels in addition with some image processing.

Figure 3 (left picture) shows a phase object imaged with phase-shift DIC, realized by SLM. Figure 3 (right picture) shows the same object imaged with Zernike phase contrast combined with subsequent image processing, where detail imaging could be improved.

Supported by: BMBF (FKZ 13N8809)
Project: "AZTEK"
Acknowledgment: We would like to thank our project partners Holoeye Photonics AG and Till Photonics GmbH for the good cooperation.

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[1] Warber, M.; Zwick, S.; Götz, J.; Gorski, W.; Haist, T.; Osten, W. "SLM-based phase-contrast filtering for single and multiple image acquisition", Proc. SPIE, 2009, to be published.

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Image based wavefront correction for wide field microscopy

M. Warber, S. Maier, J. Hafner, S. Zwick, T. Haist, W. Osten

We demonstrate a new method to measure and to correct the aberration of an optical system with a spatial light modulator (SLM). The advantage of that system is that we can implement it in our existing system for the BMBF project AZTEK without any additional parts. The Method of the System is related to the Shack-Hartmann principle but without microlenses. We measure the displacement but not of a small spot but of a picture.

In the setup we use the SLM, which is positioned in the Fourier plane of the object plane from the microscope objective lens see Figure 1.

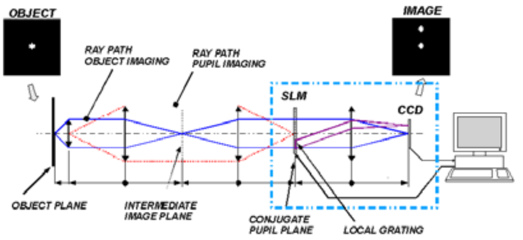

Fig. 1: A local grating written into the SLM leads to a shifted and bandpass-filtered copy of the spatially limited object.

Instead of micro lenses to get the local gradient of the aberrations we use a combination of small apertures with a grating written in the SLM and the tube lens, see Figure 1. As a result we achieve a shifted copy of the image on the CCD. Therefore we did not need additional optics or other parts. The amount of shift is proportional to the gradient of the aberrated wavefront. To accelerate the measurement, simultaneously eight apertures with different gratings were written in the SLM. To avoid the Nyquist problem the pupil is scanned randomly.

After the measurement we get a gradient map over the whole pupil, which is integrated using SVD (singular value deposition) to obtain the wavefront (expressed by Zernike polynomials). It was solved with singular-value decomposition with the first 36 Zernike polynomials. To correct the aberrated image the calculated wavefront has to be inverted and written in the SLM.

Together with a carrier frequency we implemented the measurement and the correction system in LabView. With the Software we could optimize the measurement parameters like aperture size, number of measuring points, etc. With the optimized parameters we have a fully automated system to measure and correct the aberrations. The results are demonstrated in Figure 2.

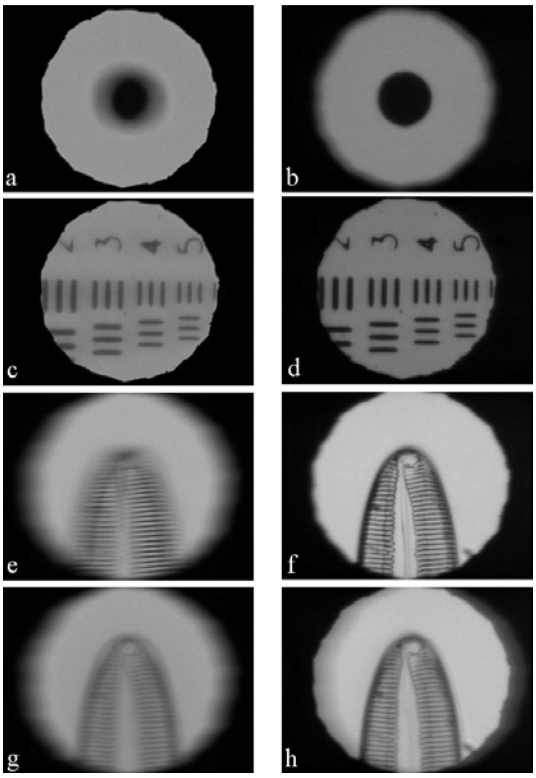

Fig. 2: Correction of different aberrations, (a, b) 10µm dot with defocus and correction, (c, d) USAF-Target with spherical aberration, (e, f) diatom with astigmatism, (g, h) diatom with combination of defocus, spherical aberration and astigmatism.

Because of contrast ratio and the diffraction limited resolution of the SLM it is not possible to use very small apertures. Therefore the measured gradient is an averaging over an area that is to large to detect small local aberrations. But the results show that for the most common (low order) aberrations in microscopy it is sufficient. The main advantage of the System is that one can measure and correct the system without additional parts and without a calibration object.

Supported by: BMBF (FKZ 13N8809)
Project: "AZTEK"

References:

[1] Haist, T.; Hafner, J.; Warber, M.; Osten, W. "Scene-based wavefront correction with spatial light modulators", Proc. SPIE 7064, 70640M, 2008.

A Multi-Scale and Multi-Sensor Measurement System for Defect Detection: a systematic approach for sensor fusion in optical metrology

W. Lyda, A. Burla, T. Haist, W. Osten

Inspection of modern high quality components often requires measurement technologies with sub-micron resolution for surface characterization at wafer scale level. The limited space-bandwidth-product of optical sensors however enforces a conflict between large measurement field, high measurement resolution, and short measurement time. To balance this conflict an intelligent measurement strategy with multiple sensors fused in one system is utilized to characterise the surface at different scales.

The strategy pursues a multi-scale active exploration strategy, where coarse scale sampling provides an initial outline, followed by more detailed samples at higher resolution scales. Sensory and positioning data are processed step-by-step as they are acquired and merged using intelligent data fusion methods in order to find defects on the measured object and also to gradually improve the accuracy as more data becomes available. Task specific, coarse-scale indicator functions are used to select fine-scale features for further investigation (Fig. 1).

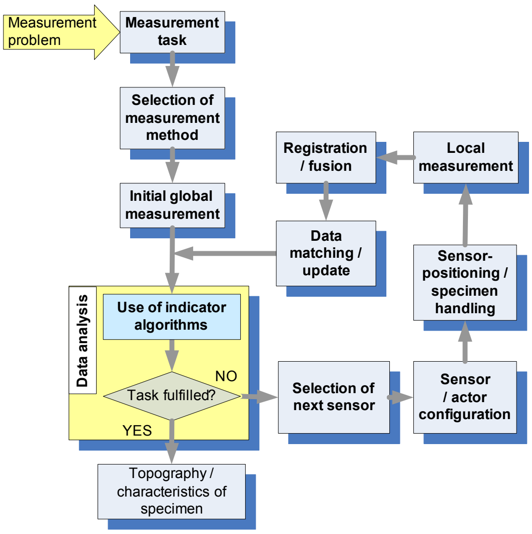

Fig. 1: Multi-scale measurement strategy.

This general design of an Automated Multi-Scale Measuring System (AMMS) was elaborated and realised in a prototype based on a modified Mahr MFU 100 armed with three different sensors for inspection of microlens arrays (Fig. 2). In the first scale, a video microscope is used to receive an initial outline of the sample followed by high resolution measurements with a confocal scanning microscope and a confocal point sensor. The lateral resolution of the sensor systems ranges from 13 µm over a filed of 18 x 12 mm^2 with the video microscope down to 0.6 µm with the confocal point sensor. In the middle scale the confocal microscope offers a variable lateral resolution from 10 µm down to 2 µm depending on the used front lens. This demonstrator was realised in cooperation with the Institute for System Dynamics (ISYS).

Fig. 2: Automated multi-scale measurement system based on a modified Mahr MFU 100.

For the communication between different scales, indicators are used. These Indicators are deviations form the expected measurement results, giving a hint for an unresolved defect on the specimen in the actual sensor scale. For an exact classification of the possible defect, further measurements in finer scales are needed. Hence, in a step by step process the indicator functions pro-vide the locations of the indicators for finer scale measurements. This effective method uses fine-scale sensors only when they are needed, balancing the conflict between measurement time, resolution and measurement field.

With three different sensors measuring a specimen for defects, different indicator detection functions are required to process the data at every sensor scale.

For the purpose of evaluating the AMMS-concept micro-lens arrays were used as measurement objects, due to the wide bandwidth of possible defects and defect sizes. Currently three distinct defect types are considered: 1) point-like defects, such as minute particles or dust speckle, 2) one-dimensional defects, including cracks, scratches and fine fibres,

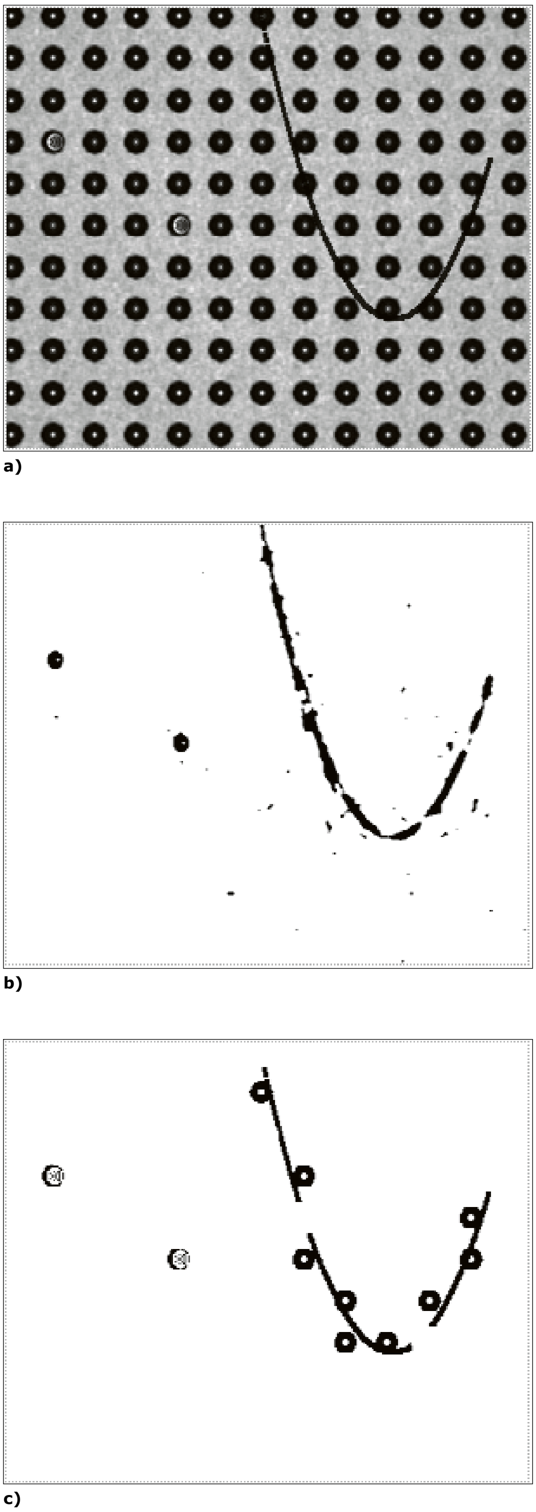

Fig. 3: **a)** shows the source image and **b)** and **c)** show the results of the indicator functions Fourier self filtering and Normalized correlation based filtering.

and 3) irregularities in the shape and size of the microlenses, including missing or partially missing microlenses. Several indicator algorithms were developed to accurately detect flaws and defects on the surface of the micro lens arrays. These algorithms were tested for reliability on microlenses with different surface and shape defects, simulated using synthetic data based on mathematical methods.

The indicator function algorithms include Fourier self-filtering, two-point statistical texture featuring, scratch detection and normalized cross correlation. These algorithms are parameterised according to the type of defect. Figure 3 shows the results of two algorithms, Fourier self filtering and correlation based filtering.

Future work is focused on the design of an expert system and the measurement reliability of the sensor systems. The expert system would suggest suitable sensors and image processing routines to better suit the task, based on the user specifications. Therefore, detailed information of the sensor measurement uncertainty and reliability of measurement data acquired from uncooperative surfaces is necessary.

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

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[1] Regin, J.; Westkämper, E.; Wiesendanger, T.; Zimmermann, J.; Bartscher, M. (Hrsg.), PTB, BAM, DGZfP, VDI Braunschweig, Wirtschaftsverlag NW, Bremerhaven 2007; S. 245-254.

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High-resolution tomographic microinterferometry

W.Gorski, W.Osten

Tomographic interferometry is based on a combination of multidirectional transmission interferometry and tomographic reconstruction algorithms. Usually it involves the multidirectional acquisition using rotation of a sample. The measurement result is the three-dimensional distribution of refractive index.

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 error in the rotation, resulting in the radial run-out phenomenon. The aim of the DFG project "TOMI" was to improve the resolution of reconstruction of optical microobjects, particularly diffractive objects, applying improved algorithms and novel mechanical setup eliminating the rotation.

The successful reconstruction of complex diffractive structures, such as photonic crystal fiber or special structured fibers was achieved [1,2]. Two tomographic reconstruction algorithms were implemented, applied and results were compared (Fig. 1).

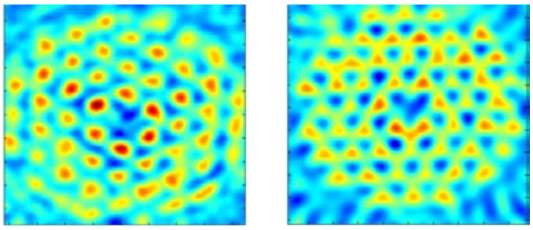

Fig. 1: The tomographic reconstruction of photonic crystal fiber, channels 3.6µm diameter . Reconstruction using diffraction tomography **(left)** and inverse Radon transform **(right)** (single layer tomogram).

The reconstruction of a photonic crystal fiber with channel diameter 3,6µm using the diffraction tomography algorithm delivered significantly better results than the classical inverse Radon Transform. However, when larger (factor two) fiber of the same design is considered the reconstructions obtained with those two methods deliver relatively similar results (Fig. 2).

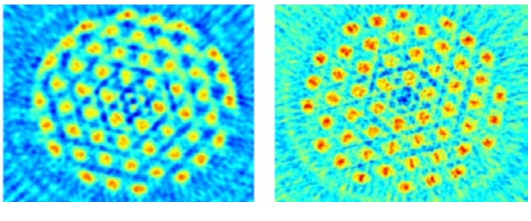

Fig. 2: The tomographic reconstruction of photonic crystal fiber, channels 8.175µm diameter. Reconstruction using diffraction tomography **(left)** and inverse Radon transform **(right)**.

This result is an important contribution to the discussion about the applicability of inverse Radon transform in optical tomography. The measurement of a Bragg fiber was aimed at preliminary quality control of a fiber laser components (Fig. 3).

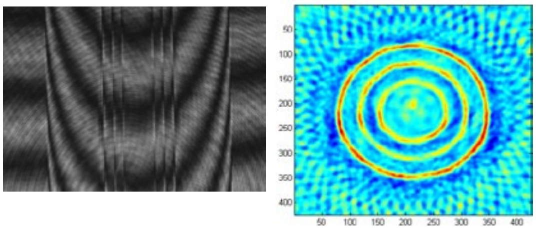

Fig. 3: The tomographic reconstruction of a Bragg fiber. An interferogram **(left)**, a tomogram **(right)**.

In the second stage of the project the specialized tomographic microinterferometer for optical microobjects measurement was designed and patented [3]. The innovative step was that the necessity of the rotation of the specimen was fully eliminated. Instead, small apertures were dynamically switched on using LCD modulators (Fig. 4). The light beams created with these subapertures are redirected using special element in the way, that the specimen is illuminated from many directions. The multidirectional data is registered on a single CCD camera chip. The new compact measurement system was built as a laboratory setup and the proof of principle was achieved.

Fig. 4: The measurement head of a compact tomographic microinterferometer.

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

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[1] Gorski, W.; Osten, W. "Tomographic imaging of photonic crystal fibers", Opt.Let, Vol. 32, No. 14, 1977-1979 (2007).

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[3] Patentanmeldung :"Optisches Abbildungssystem und Verfahren zum Ermitteln dreidimensionaler Amplituden- und/ oder Phasenverteilungen", DE 10 2007 036 309.7.

Optical computing using white light interferometry

T. Haist, W. Osten

White-light interferometry is a very powerful technique for measuring the topography of surfaces or for imaging layers within scattering media. Apart from these well-known approaches it can be also used for solving computational difficult problems. To this end, the problem to be solved is coded by optical path lengths and the superposition of all possible paths that a photon can travel is used for computing the solution. The solution itself is chosen by interference with the reference light. Several gedankenexperiments demonstrate how this method can be used for solving computational hard problems.

The core of the method consists of three steps:

1. Code the problem and its solutions by optical path lengths.
2. Use an optical system to generate a superposition of all possible solutions.
3. Find the correct solution by interference-based detection.

The method is strongly related to quantum computing, but works with purely classical waves. No quantum properties like entanglement are involved. Oltean proposed a pulse-based method for computing that is very similar to this interference-based technique. The main idea is the same as here, namely using superposition of all possible solutions which are coded by optical path lengths. Due to the so-called “coherent gain” that is exploited using interferometric detection, interference-based detection is superior for practical implementations.

The method can be used to solve NP-complete problems in linear time (e.g. the Ricochet Robot Problem). This advantage does not come for free. Due to photon statistics, one has an exponential increase in necessary energy with increasing problem size. For the well known travelling salesman problem we estimate that with 1 W at $\lambda = 1$ μm problems with 16 cities can be solved.

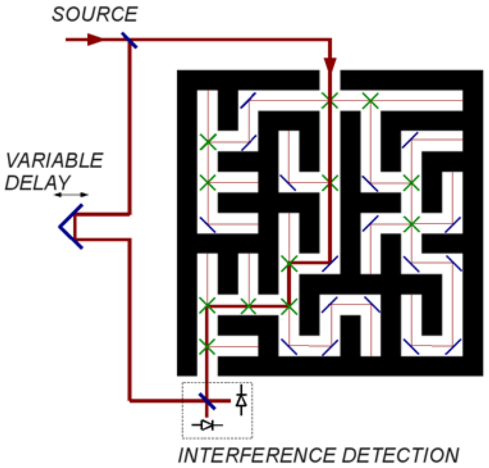

Fig. 1: Simple example for waveoptical computing: Solving th maze by N interferometric measurements if N denotes the number of junctions along the solution path. A photon entering the maze path of the interferometer travels through all possible paths simultaneously.

Apart from the solution of computational hard problems it is also possible to apply the method for the ultra-fast computation of more simple tasks. One important example is the computation of arithmetic expressions. We think that by using the interference it is possible to reduce the computation time and the latency of such computations – even with high precision arithmetic – to a very small delay in the range of some hundred of femtoseconds. The switches are located directly in front of the detectors and therefore the maximum speed that can be achieved by optical means would be reached. To achieve this speed together with high precision, a combination of white light interferometric computing and residue arithmetic is proposed.

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[1] Haist, T.; Osten, W. “An optical solution for the traveling salesman problem,” Opt. Express 15, pp. 10473-10482, 2007 and Opt. Express 15, p. 12627, 2007.

[2] Haist, T. “Ultra-fast waveoptical computing”, Proc. SPIE 7072, 7072M, 2008.

[3] Haist, T.; Osten, W. “Ultra-fast digital optical arithmetic using waveoptical computing”, Lecture Notes on Computer Science 5172, pp. 33-45, 2008.

High Resolution Metrology and Simulation

Simulation based sensitivity analysis of scatterometry measurements for future technology nodes
Supported by: BMBF (FKZ 13N9432)
Project: "Nanoanalytik"

Approximative fieldstitching algorithm for simulating line edge roughness (LER) in scatterometry
Supported by: ASML Netherlands

Recent extension of our simulation tool ITO-Microsim: Automated normal vector field generation

Design of Optical Metamaterials with respect to near-farfield-transformation
Supported by: Landesstiftung Baden-Württemberg
Project: "Optim"

Defect detection on Wafers: Simulation and Measurement
Supported by: BMBF (FKZ 13N9432)
Project: "Nanoanalytik"

Simulation based sensitivity analysis of scatterometry measurements for future technology nodes

V. Ferreras Paz, T. Schuster, K. Frenner, W. Osten

As part of the of the BMBF project "Nano-analytik" we have analyzed the extendability of scatterometry towards small ground rules using a simulation based approach.

Within the last years, scatterometry has evolved into one of the most important methods for CD metrology used actually in semiconductor industry. As the size of semiconductor structures keeps decreasing with up-coming technology nodes, searching for optimized measurement configurations to exploit maximum sensitivity gets more important. These optimized configurations can be accessed with a simulation based approach using our software package MICROSIM [1] to solve the Maxwell equations with help of the RCWA method.

The first task was to verify the agreement of simulation and measurement of a given structure. Therefore we started with simple line-gratings with different pitch periods, produced with e-beam lithography at Qimonda (Dresden). These structures were measured with an industrial scatterometry tool at Qimonda and the same measurement was modelled and simulated with MICROSIM later. As shown in fig. 1 there is a very good agreement of simulation and measurement for these structures.

The next step comprises the analysis of the sensitivity to different structure parameters as structure-height, CD, pitch, sidewall angle and different roundings by varying the measurement configuration as wavelength and incident angle. Fig 2 shows such a sensitivity plot for the CD parameter of a structure. This sensitivity analysis was also performed for different structure sizes correlating with actual and future technology nodes [2]. Performing such sensitivity analysis makes it possible to predict optimized measurement configurations, possibilities and demands on future industrial scatterometry tools. Further investigations on more complex structures and towards smaller structure size are the next tasks in the project and are work in progress.

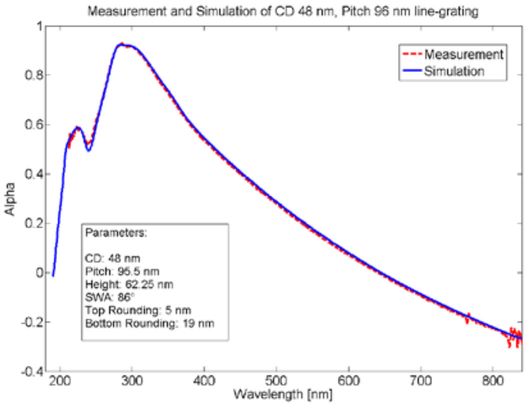

Fig. 1: Comparison of a measurement and the corresponding simulation with MICROSIM of a line grating structure.

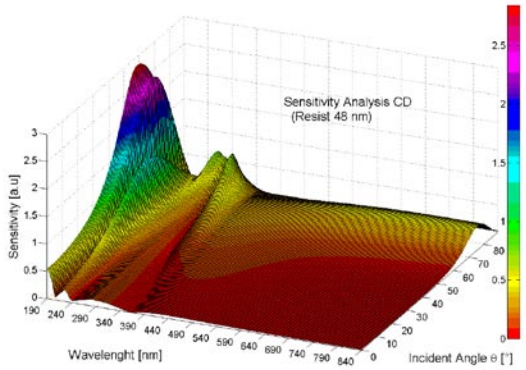

Fig. 2: Sensitivity of resist line-grating (CD 48 nm) to the structure height in dependence of the wavelength and the incident angle.

Supported by: BMBF (FKZ 13N9432)
Project: "Nanoanalytik"

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Approximative fieldstitching algorithm for simulating line edge roughness (LER) in scatterometry

T. Schuster, S. Rafler, V. Ferreras Paz, K. Frenner, W. Osten

Optical scatterometry relies on simulations of light diffraction using rigorous algorithms such as Rigorous Coupled Wave Analysis (RCWA). Up to now, most simulation models neglected any imperfections of the periodic continuation. Since line edge roughness (LER) is presently becoming more crucial in semiconductor technology, one must no longer ignore this perturbation of the periodic continuation. Instead, one has to investigate the influence of light scattering which can arise from LER on the different variants of scatterometry in order to still obtain reliable results.

Recently ITO presented an approach to deal with such imperfections. A well known field stitching algorithm by Layet and Taghizadeh [1] was adopted. Whereas these authors comprised an overlap region in the simulation of single patches to be stitched together in order to be fully rigorous, we skip this overlap and thus introduce Kirchhoff-boundaries, i.e. the fields at these virtual lateral boundaries feature unphysical leaps which is the key point of Kirchhoff's diffraction theory.

The idea of applying Kirchhoff's approximation to present dense line structures with, e.g., 50 nm CD and 100 nm pitch appears incomprehensible at first glance bearing typical interaction lengths of 5..10 wavelengths in mind. However, Kirchhoff's approximation can be applied whenever the influence of the unphysical leaps is small. This is the case when structures are sufficiently large such that the overall portion of the erroneous nearfield is small, but also, if the leaps themselves are small compared to the absolute values of the fields. Considering LER a small perturbation of a perfect periodic structure is hence a good justification for applying Kirchhoff's approximation. Of course, the approximation is better the smaller the LER amplitude and depending on the acceptable error a threshold for its validity can be defined.

The range of validity of the proposed method was investigated. The method proved to be applicable to the problem if the LER amplitudes are sufficiently small. Figure 1 shows an example nearfield for the case of a relatively large LER amplitude of 4 nm peak to peak and a wavelength of 400nm. The illumination is a single plane wave with almost grazing incidence. The leaps in the field amplitude are small but clearly recognizable. Figure 2 shows the field amplitude of the 0th diffraction order of the resulting farfield for the stitched and unstitched case. The peak to peak depth of the LER is gradually increased in order to study the error of the stitched field amplitude as a function of a small perturbation of the periodic continuation. As can be seen the errors keep acceptable for roughness depths of a few nanometers. A more detailed review of these activities is given in [2].

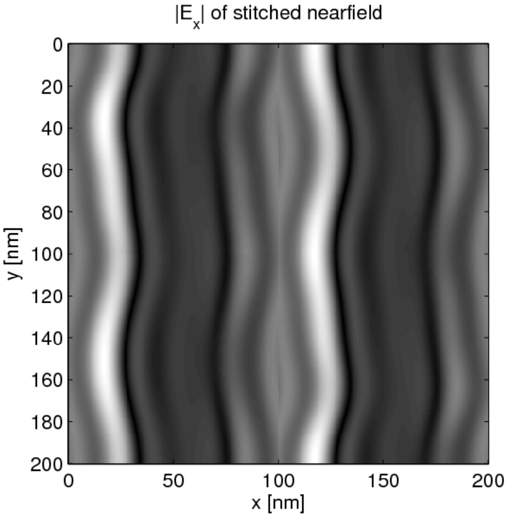

Fig. 1: Stitched nearfield with virtual lateral Kirchhoff boundaries.

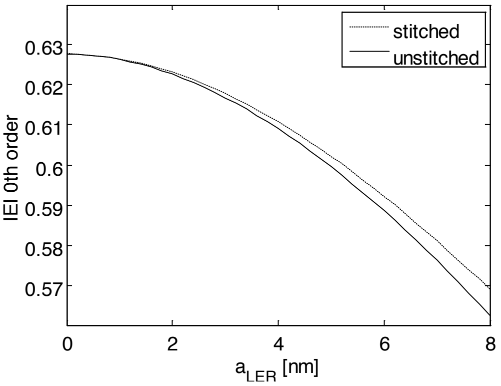

Fig. 2: Field modulus of stitched and unstitched fields as a function of the peak to peak roughness depth.

Supported by: ASML Netherlands

References:

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[2] Schuster, T.; Rafler, S.; Ferreras Paz, V.; Frenner, K.; Osten, W. "Fieldstitching with Kirchhoff-boundaries as a model based description for line edge roughness (LER) in scatterometry", Microelectron. Eng. 86 (2009) 1029-1032, doi:10.1016/j.mee.2008.11.019.

Recent extension of our simulation tool ITO-Microsim: Automated normal vector field generation

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

The rigorous Maxwell solver ITO-Microsim has been under constant development for many years. Recently, the convergence of the diffraction computation using Rigorous Coupled-Wave Analysis (RCWA) has been improved for the case of 2D periodic gratings.

The achieved convergence improvement is based on Popov's and Nevière's reformulation of the differential method [1] which is closely related to RCWA. After a long discussion these authors recognized that prior convergence problems due to an erroneous application of convolution rules in discrete Fourier space can be overcome by decomposing the electric field in real space into a component parallel and perpendicular to each point of a material boundary and taking the information about the local orientation of the boundary over to Fourier space by a Fourier expansion of the normal vector (NV) field.

To that end a continuation of the NV field from the material boundaries toward the homogeneous regions is required. Applying this technique to the RCWA poses the additional restriction that the NV field must point only in lateral directions which inevitably introduces singularities and / or discontinuities, c.f. Fig. 1.

While in a first work [2] semi-automated algorithms with moderate computational efficiency served the purpose to demonstrate the principle of the method, the recent improvements [3] consist of a fully automated NV field generation with optimized performance. The new algorithm can cope with arbitrarily shaped geometries, unit cells with three or more different materials and even multiply connected regions.

The NV generation consists of two steps. In a first step the NVs at the material boundaries are computed by a simple gradient operation. In the second step the remaining points of a Cartesian raster are filled by an interpolation relying on inverse distance weighting. This way the discontinuities in the NV field are placed in sufficient distance to the boundaries. The numerical complexity of this interpolation can be reduced from $O(n^3)$ to $O(n^2)$ by a progressive refinement algorithm which ensures that the gain of computational speed is not wasted by additional costs for the NV field generation.

Figure 1 shows the NV field for a structure of intersecting circles obtained with the new algorithm. The corresponding convergence curves labeled "NV method without preferred direction" can be seen in Figure 2. They are compared to an alternative version of the algorithm "… with preferred direction" and previous RCWA formulations which feature poorer convergence. For details please refer to [3].

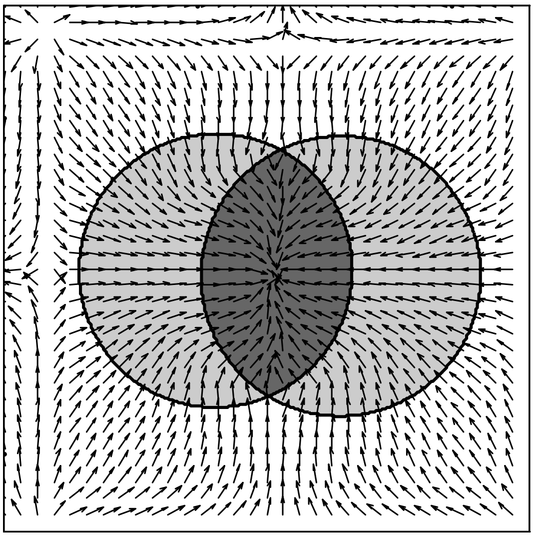

Fig. 1: NV field for a structure of intersecting circles obtained the new algorithm.

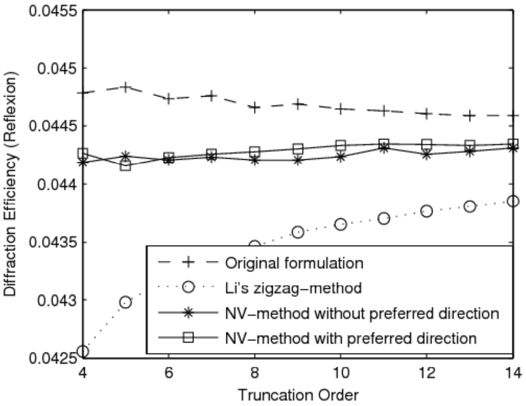

Fig. 2: Convergence curves for the intersecting circle structure comparing different RCWA formulations.

References:

[1] Popov, E.; Nevière,M. "Maxwell equations in Fourier space: fast-converging formulation for diffraction by arbitrary shaped, periodic, anisotropic media", J. Opt. Soc. Am. A 18, 2886–2894 (2001).

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Design of Optical Metamaterials with respect to near-farfield-transformation

S. Maisch, K. Frenner, W. Osten

After the theoretical prediction of V. Veselago[1] in 1976, materials with simultaneous negative magnetic permeability $\mu < 0$ and electric permittivity $\varepsilon < 0$ being able to transmit electromagnetic waves without exponential damping, J. Pendry [2] showed these systems bending light in the "wrong direction", namely showing a negative index of refraction $n < 0$.

These materials gained attention because they can be used for sub-λ resolution imaging and invisibility cloaking.

The main problem was and remains the fact that metamaterials have to consist of internal features smaller than the wavelength used, but for applications in the optical range still larger than typical molecular structures or lattice constants. While being relatively simple to be built for the microwave range by a spatial arrangement of electrical resonators of millimetre size, at optical and infrared frequencies, the resonator size is in the nanometre range requesting the most advanced nano fabrication tools for their construction.

We performed a careful evaluation of layered metamaterials of resonant gold and silver structures in dielectric resin by RCWA (rigorous coupled wave analysis) simulation of their effect on the phase and amplitude of the transmitted light and calculating an effective index of refraction of these materials. These results are used in a closed-loop process to geometrically optimize nano patterned metamaterials.

Fig. 1 shows a four-layered resonant structure (split ring resonator, SRR) used as one example and manufactured by the 4th Physics Institute, among other radically different structures as a starting point for the optimization of the negative magnetic response by variation of the geometric parameters. RCWA is capable of simulating the optical properties of these structures including the effects of mutual coupling of the resonators.

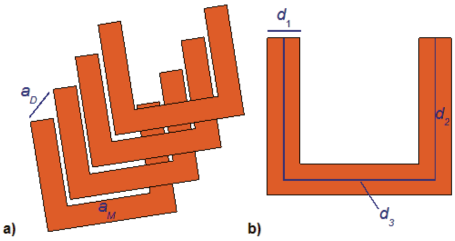

Fig. 1: Four-layered resonant gold nano structure and its geometric parameters.

In fig. 2 the simulated transmission and reflection spectra of the SRR are shown. Fig. 3 shows the retrieved index of refraction for a different meander nanostructure exhibiting a strongly negative resonance.

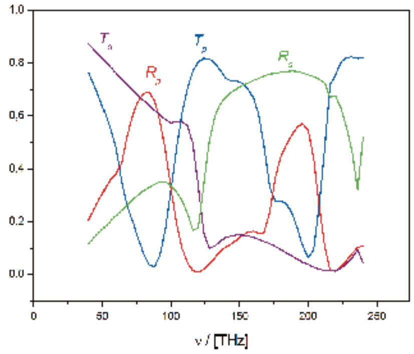

Fig. 2: RCWA-simulated transmission (*T*)- and reflection (*R*) spectra **(left)**, and index of refraction **(right)** of the structure in **fig. 1**, in s- and p-polarization.

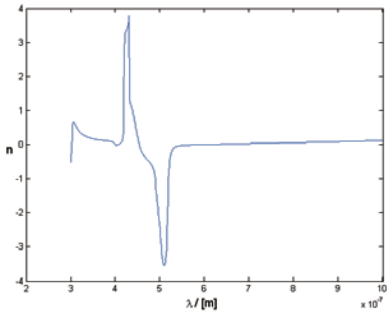

Fig. 3: Retrieved real part n of the refractive index for a meander nanostructure. Just above a wavelength of 500 nm the index of refraction exhibits strongly negative behaviour.

These materials are suited for the design of *Pendry's* superlens, capable of imaging the near-field. Further research is about magnifying super lenses using geometric shape functions and a near-field to far-field transformer. Both RCWA and differential method analysis were performed on magnifying superlens designs.

These investigations showed meander shaped nanostructures being well suited for manufacturing negative index materials. Their optical properties may be tuned similar to the SRRs, while being less demanding in the nano patterning process, allowing metamaterials at visible wavelengths instead of near IR.

Supported by: Landesstiftung Baden-Württemberg
Project: "Optim"
The Authors especially acknowledge the cooperation with 4th Physics Institute (Prof. Giessen and Prof. Schweizer).

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Defect detection on Wafers: Simulation and Measurement

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

In the BMBF project "Nano Analyik" the ITO works on with its industry partner Qimonda within the subtopic „Defectoscopy". The goal in this subtopic is the derivation of methods for the prediction of defect signal strengths for certain configurations of inspection tools.

The inspection system in our case is a microscope with high NA objectives, monochromatic Köhler illumination and pupil filters. The image is generated on a CCD camera. Such a microscope is available in the ITO clean room and we can get samples from the inspection systems at Qimonda.

Since the defects are of nanometer size (Fig. 1) they are not resolved, although UV illumination can be used. Nonetheless one can see dark or light spots where the defect is in the surrounding field without defects (Fig. 2). The contrast of this defect signal to the surrounding pattern noise is the value which is crucial for the successful detection of the defect. One can enhance the contrast, i.e. the signal to noise ratio, by varying optical System parameters.

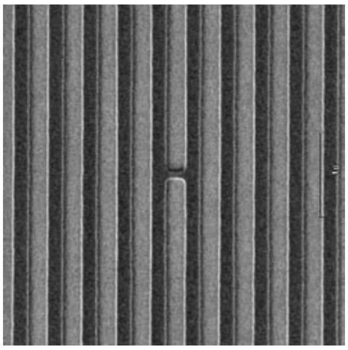

Fig. 1: SEM picture of an "open" type defect.

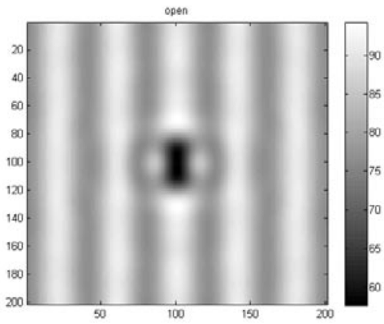

Fig. 2: Simulated defect type "open" as seen in an optical microscope.

To be able to get ahead of the current node in the development of even smaller technologies, one seeks to simulate the defect detection. This is done at the ITO with the program package Microsim which was developed at the institute and is based on the Rigorous Coupled Wave Analysis. The advantage of this method is that once the diffraction orders of the structure of interest have been computed, the far field image can be generated in short time. In the course of this an arbitrary set of diffraction orders can be left out to model different pupil filters.

The defect types of interest require the time consuming simulation of two-dimensionally periodic gratings. In the project several methods to shorten this time have been implemented [1]. Symmetries of structure and illumination are used and for orthogonal polarizations only one computation has to be carried out. Furthermore the computation has been parallelized so it can run on several computers at once.

Littrow angles play a special role in the discretization of the illumination pupil [2]. First they allow the optimal approximation to the theoretically infinite densly sampled pupil (Fig. 3) and second they allow to use information from the normal incidence computation to be used for the oblique incidence angles which saves most of the computation time. In the course of the project we must now bring simulation and measurement together more closely by modelling the structures in a more complex way and by testing a whole range of parameters.

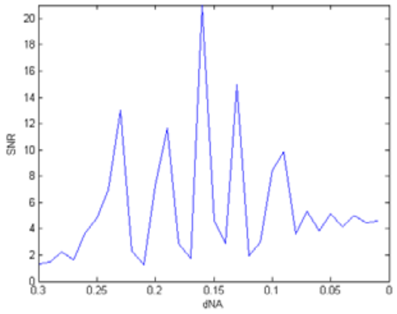

Fig. 3: Convergence of the signal to noise ratio with respect to the pupil discretization step.

Supported by: BMBF (FKZ 13N9432)
Project: "Nanoanalytik"

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Interferometry and Diffractive Optics

Flexible asphere testing

Supported by: BMBF (FKZ 13N8742)

Project: "Asphero5"

High resolution cost-efficient optical rotary encoders

Supported by: AiF, project ZN 219

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

Supported by: Landesstiftung Baden-Württemberg

Project: "Polgit"

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

Supported by: BMBF (FKZ 13N9456) and the Landesstiftung Baden-Württemberg

Project: "MIMODIA"

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

Supported by: BMBF (FKZ 16SV2309)

Project: „Lynkeus“

Optically addressed thermally activated adaptive optics

Supported by: Landesstiftung Baden-Württemberg

Project: „ThermAO“

Active micro optic for spatial polarization control

Supported by: DFG (OS111/26-1)

Project: "AMiPola"

Flexible asphere testing

E. Garbusi, C. Pruss, W. Osten

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

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

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

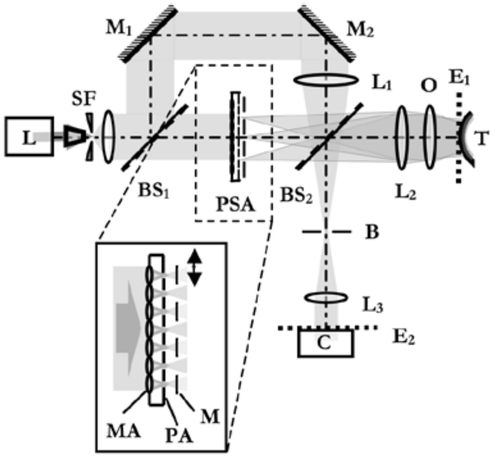

Fig. 1: Interferometer set-up: PSA, point source array; MA, microlens array; PA, pinhole array; M, selection mask; O, transmission sphere; T, test surface.

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

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

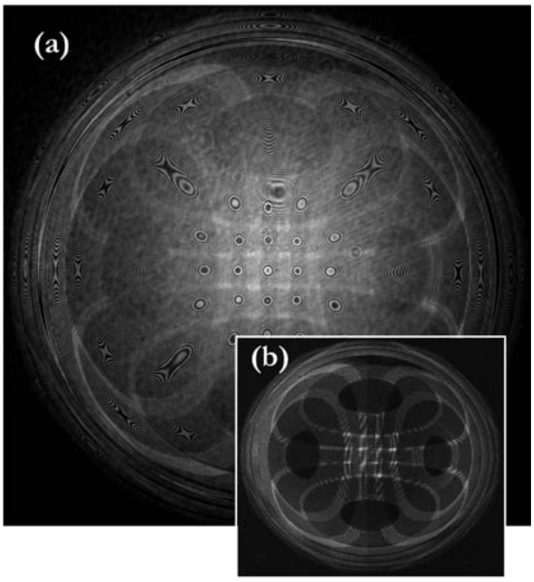

Fig. 2: **(a)** Interferogram with the totality of the array activated. Unwanted interference between contiguous sources of the array can be observed when the reference beam is blocked **(b)**.

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

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

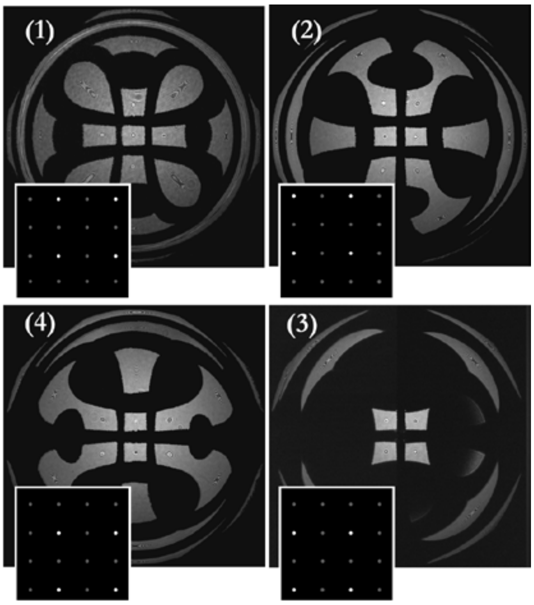

Fig. 3: Partial activation of the source array. Every second row and second column is activated for each one of the four frames. Bottom left of each interferogram: active sources for the current interferogram are shown **(white: active, gray: blocked source)**.

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

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High resolution cost-efficient optical rotary encoders

D. Hopp, C. Pruss

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

To achieve a cost-efficient production process the idea of the project is to use a micro-structured plastic disc with a metal coating, similar to a common DVD, which can be manufactured by a conventional compression-mould process. With this well known technique it is possible to create highly precise structures while running a cost effective process for high numbers of parts.

The mechanic and electronic design and the realization of this new kind of optical rotary encoders were performed by our project partner, HSG-IMAT. ITO focused on the optical design as well as the fabrication of the testmaster discs.

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

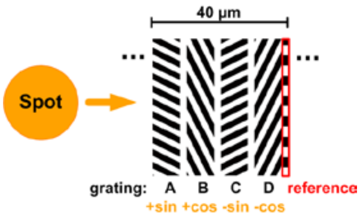

Fig. 1: one period of the diffractive pattern on the encoder disc including the reference mark.

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

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

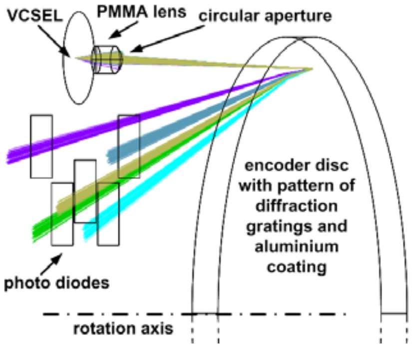

Fig. 2: scheme of the optical path of the illumination and the reflected first order spots.

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

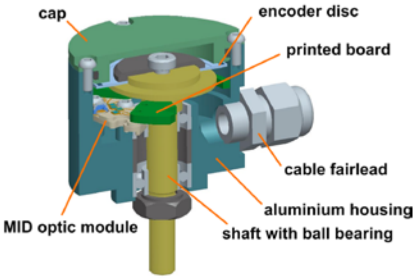

Fig 3: model of the assembled rotary encoder.

Supported by: AiF, project ZN 219

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

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

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

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

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

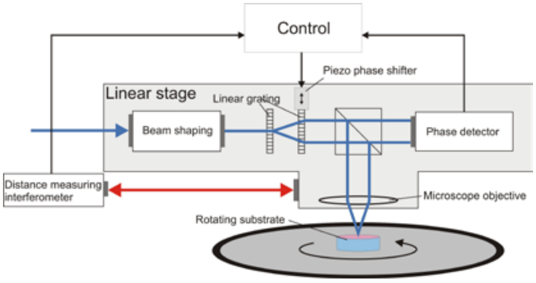

Fig. 1: Scanning beam interference lithography system. A fringe locking system stabilizes the position of the interference fringes by adjusting the phase between the two interfering beams.

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

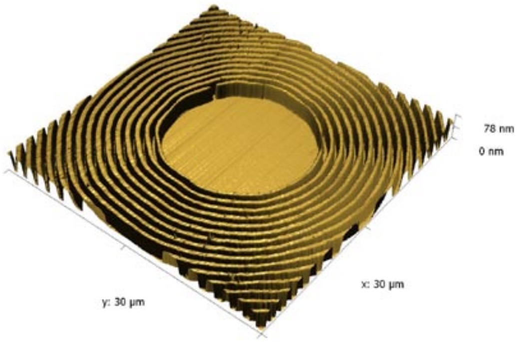

Fig. 2: AFM-Scan of the axicon centre. It is possible to realize concentric structures with a diameter as small as approx. 15 µm.

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

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

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

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

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

R. Reichle, C. Pruss, W. Osten

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

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

The wide angle keyhole optics for 2D-measurements images the UV-fluorescence of a measurement plane onto an image intensifier. The optics is divided into two main parts. A simple front endoscope with an entry diameter of 1 cm and fused silica lenses produces a chromatically uncorrected intermediate image, which is then relayed onto the camera by stationary hybrid optics. Here the chromatic correction of the complete system is realized by the strong negative dispersion of a diffractive component. So if different relays are placed behind a beam splitter, each imaging channel can be optimized to a different wavelength band using the same entrance endoscope. To suppress unwanted diffraction orders the etching depth of each diffractive element is adapted to the individual spectral band. The positions of the diffractive elements in the relays further help to minimize the negative effects of the unwanted diffraction orders regarding the image quality.

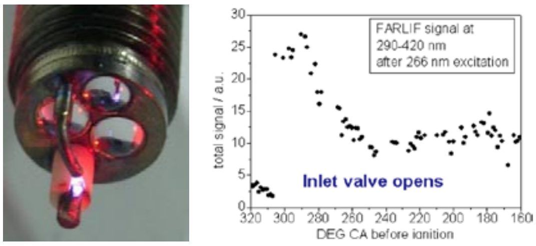

Fig. 2: Spark plug sensor and UV-FARLIF signal measured with the sensor inside a running engine [2,3].

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

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

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

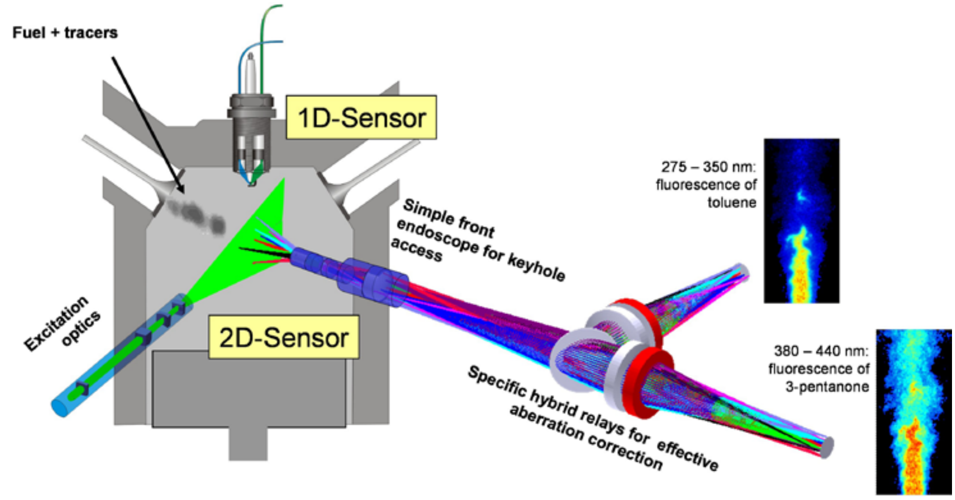

Fig. 1: Setup for minimal invasive UV-LIF-measurements.

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

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

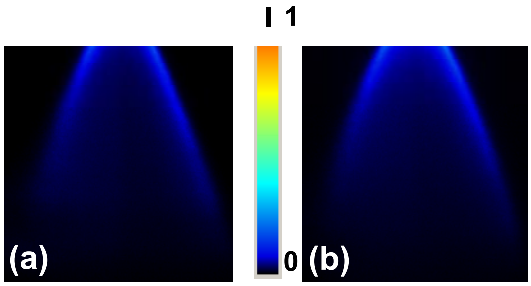

Fig. 3: Comparison of a standard non-endoscopic UV imaging lens (UV Nikkor, **(a)**) with the hybrid endoscopic system **(b)** imaging LIF of toluol at 307 nm, measured at the LaVision GmbH.

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

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

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

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

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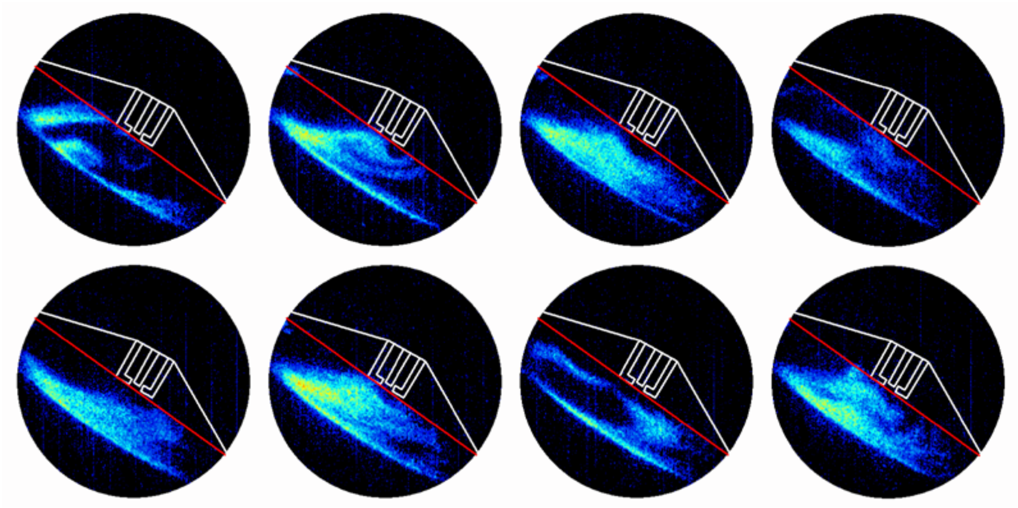

Fig. 4: Single shot images of fuel LIF out of a running engine realized with minimal invasive access optics [4].

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

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

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

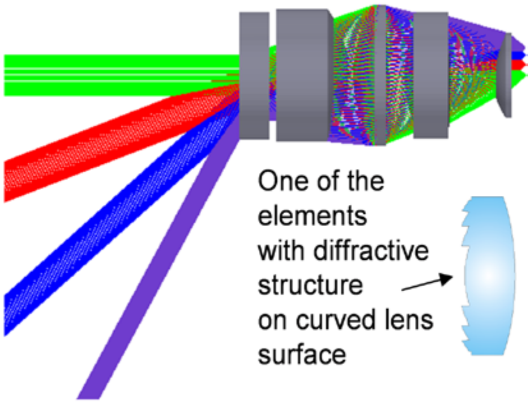

Fig. 1: Optic design for a hybrid wide angle objective.

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

To meet the conditions of a compact objective the number of optical elements is reduced to a minimum. Since at the same time high performance is necessary, diffractive elements with aspheric phase function and negative dispersion are integrated for a very effective aberration correction. The optical design profits from diffractive structures fabricated on curved lens surfaces.

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

Fabrication of diffractive optics on curved substrates

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

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

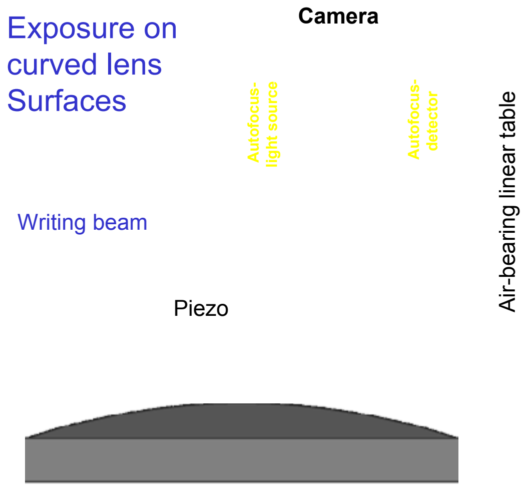

Fig 3: Schematic of the new laser direct writing head for writing on curved substrate.

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

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

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Optically addressed thermally activated adaptive optics

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

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

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

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

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

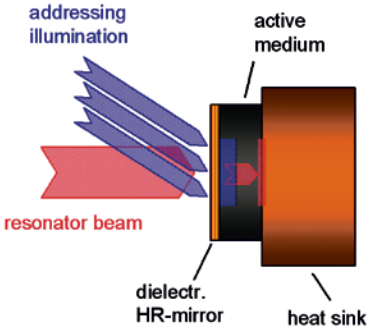


Fig. 1: Principle setup of an optically addressed, thermally activated adaptive mirror for intra-cavity application.

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

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

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

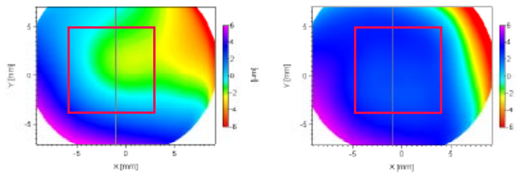


Fig. 2: Asymmetric correction of aberrations. Left: uncorrected wavefront. Right: The wavefront has been corrected in the red square.

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

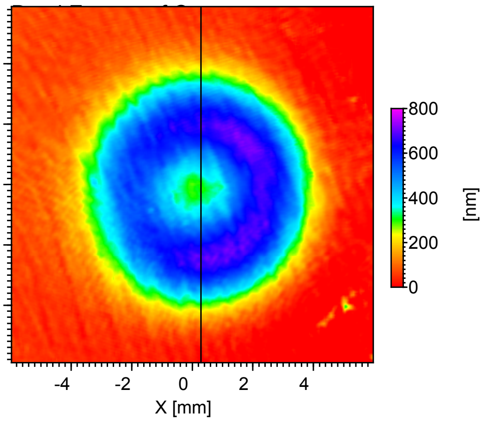


Fig 3: Rotationally symmetric wave front correction.

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

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

Active micro optic for spatial polarization control

F. Schaal, C. Pruss, W. Osten

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

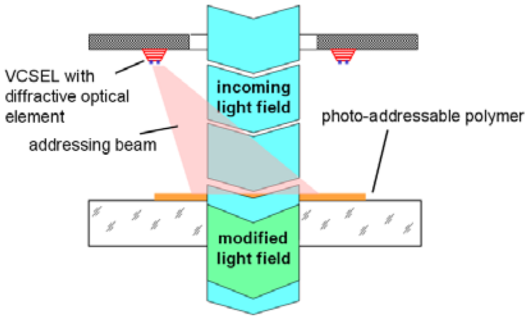


Fig. 1: Schematic diagram of the basic setup.

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

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

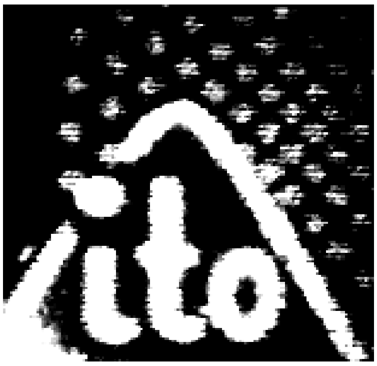


Fig. 2: ITO logo written into photo-addressable polymer.

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

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

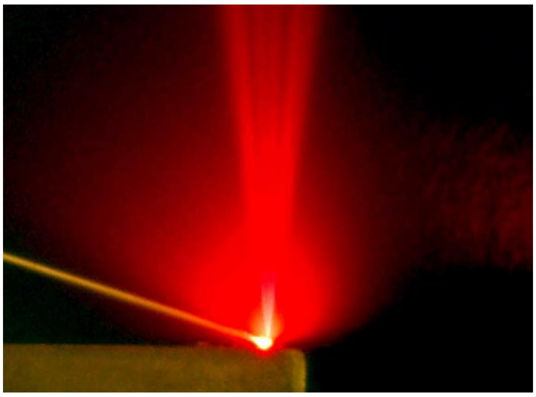


Fig 3: Red Vertical-Cavity Surface-Emitting Laser (VCSEL).

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

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

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

Coherent Metrology

Multi-functional measuring unit for the assessment of cultural heritage

Supported by: European Union Grant No. 006427 SSPI
Project "Multi-Encode"

Microelectromechanical Reference Standards for the Calibration of Optical Systems

Supported by: DFG (OS111/22) and PA792/4

Digital holographic microscopy at 193nm

Supported by: DFG (OS 111/19)

Comparative Digital Holography: z-resolution

Supported by: Landesstiftung Baden-Württemberg

Coherence effects in digital in-line holographic microscopy

Supported by: Alexander von Humboldt Foundation and DFG (OS111/19)

Phase retrieval by tuning illumination wavelengths

Supported by: China Scholarship Council

Collision in double random phase encoding

Supported by: Alexander von Humboldt Foundation

Spiral phase filtering and orientation-selective edge detection/enhancement

Supported by: Alexander von Humboldt Foundation

Multi-functional measuring unit for the assessment of cultural heritage

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

In this project, optical holographic methods were chosen to protect and study cultural heritage. The basic idea of the project is to develop an optical system including shearography, digital holographic interferometry and high resolution holographic interferometry with photorefractive crystal. These methods have a high sensitivity and the precision to measure sub-micron displacements and deformations. The combination of these methods in one prototype enables the measurement of the state of artworks, not in a laboratory environment, but in museums and galleries as well.

ITO's contribution included the development of multifunctional automated control and analysis for the measurement session. The control software has friendly dialog options, realizes measurement control and post processing (comparison algorithm and defect recognition)

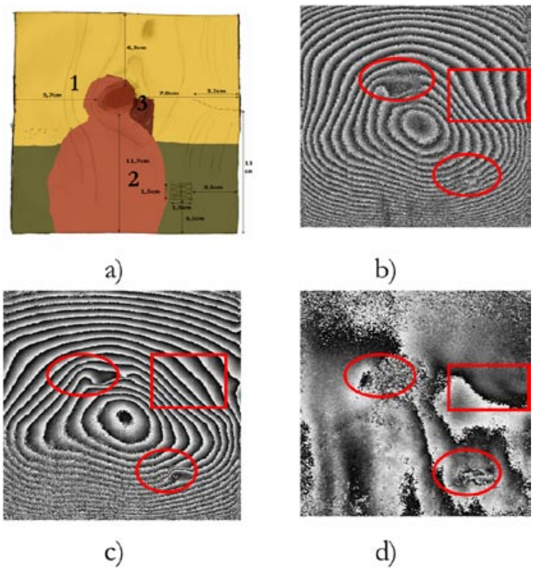
A cooperation with partners from Belgium (OPTRION s.a.) allowed the building of a portable prototype for real experimental investigations in art galleries. Fig. 1 shows the optical head (sensor).

Fig. 1: Portable prototype optical head.

The main application of the sensor is to measure and visualize defects, delaminations and cracks on/in icons and canvas. All measurements can be observed in real-time as well.

The complex and delicate structure of the investigated objects restricts the loading methods used to identify defects. For this case two infrared lamps were used to subject the artworks to a 1-2 °C temperature rise. To avoid damage, the temperature of the object was controlled during the measurement.

Figure 2 shows the result of the three sensor types in the prototype. The investigated object is a wooden panel painting (icon).



a) b)

c) d)

Fig. 2: Test of the wooden panel (icon) by prototype:
a) object,
b) ESPI method's result,
c) DHI (digital high resolution) method's result
d) Shearography method realized.
The red square and circles represent defect locations reference **1**,**2** or **3** on the real object image.

Another important part of the project is to collect the basic information about defects and standardized loading condition and to store them in an online database. This is important to identify the originality of artworks or to determine temporal changes.

Supported by: European Union Grant No. 006427 SSPI Project "Multi-Encode"
The authors would like to thank Jonathan Rochet and Guy-Michel Hustinx (OPTRION s.a., Belgium).

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[1] Groves, R.M.; Pedrini, G.; Osten, W. "Real-time extended dynamic range imaging in shearography", Appl. Opt., 47, pp.5550-5556, 2008.

[2] Groves, R.M.; Osten, W.; Hackney, S.; Kouloumpi, E.; Tornari, V. "Laser shearography as part of a multi-functional sensor for the detection of signature features in movable cultural heritage", Proc. Lacona VII, pp. 427-434, Lasers in the Conservation of Artworks, Madrid, 2007.

Microelectromechanical Reference Standards for the Calibration of Optical Systems

G. Pedrini, W. Osten

The increasing trends towards miniaturization in many different application fields have produced in the past few years a dramatic progress in the development of microelectromechanical systems (MEMS) and microoptomechanical systems (MOEMS). Miniature robots, micro mirrors, micro actuators, optical scanners are some examples. The reliability of such systems is an important issue that still requires advanced research. For the quality inspection, it is necessary to know not only their geometry but also the displacements or deformations due to the mechanical, thermal or electrostatic loads that along with the evaluation of applied forces, allows for obtaining stresses and consequently extraction of material parameters. This information may in turn be used for the validation of FEM models and eventually detect defects in microsystems. Since the structures themselves exhibit typical dimensions of the order of some micrometers, it is necessary to measure the deformation with accuracies in the nanometer range. Techniques for the measurement of deformation and strain have been successfully tested in the laboratory; so far, their use in an industrial micro-manufacturing environment took place only in few cases however. A deficit is that calibration procedures are not available.

The goal of this work is to narrow such gap and develop standards or norms for the measurements of translations and deformations in microsystems. This involve the development of reference test objects, which are measured by using very accurate systems in order to check if they have the wanted characteristics. The references are then used for the calibration of measuring systems and the uncertainty of the measurement is determined according to internationally recognized guidelines (GUM). This procedure has a general character and the developed reference may be used for calibrating different measurement devices. The calibration procedure was at first applied to the in-plane displacements of a micromechanical reference (Fig.1) which consists of an inner movable part connected to an outer fixed frame. The application of a voltage produces displacements of different magnitude of the different elements of the device. The displacement was measured by using a method based on speckle interferometry. We found a very good agreement between expected and measured displacement, (see Fig. 2). It was shown that the in-plane displacements may be performed with an accuracy of ±3.5 nm. More accurate measuring systems are under development.

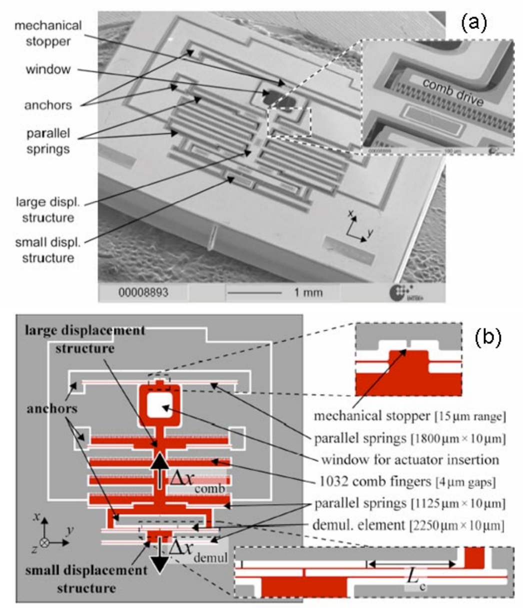

Fig. 1: Scanning electron micrograph **(a)** and schematics **(b)** of the reference object with in-plane movable structures.

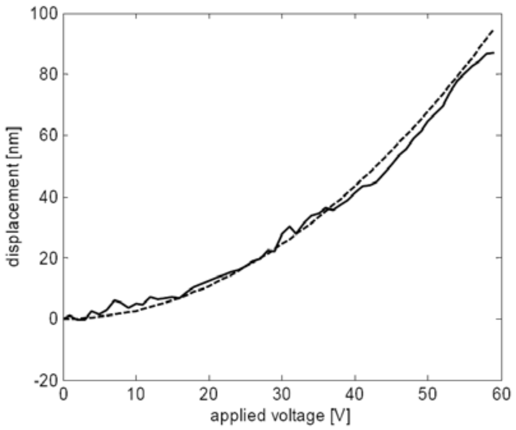

Fig. 2: Deformation of the structure, measured **(solid line)** and theoretical value **(dashed line)**.

Supported by: DFG (OS111/22) and PA792/4
We would like to thank our project partners J. Gaspar and O. Paul (University of Freiburg, Germany) for the good cooperation.

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[1] Pedrini, G.; Gaspar, J.; Wu, T.; Osten, W.; Paul, O. “Calibration of optical systems for the measurement of microcomponents”, Optics and Lasers in Engineering, 47, 203-210, (2009).

[2] Pedrini, G.; Gaspar, J.; Osten, W.; Paul, O. “Development of Reference Standards for the calibration of Optical Systems used in the measurement of microcomponents”, accepted for publication in Strain (2009).

Digital holographic microscopy at 193nm

G. Pedrini, U. Gopinathan, D. Fleischle, D. Hopp, W. Osten

Digital holographic (DH) techniques are capable of reconstructing both the amplitude and phase of the wavefield that passes through or is reflected/ scattered by the object.

The spatial resolution of the method is given by the numerical aperture and the wavelength. In order to increase the resolution we developed microscope systems based on digital holography working at the wavelength of 193 nm. Different approaches were investigated, the most simple is based on a lensless in-line system without a separate reference beam.

As compared to off-axis DH systems, in-line DH makes better use of the available Space-bandwidth product (SW). The twin-image problem is also not very significant while imaging microscopic objects which block only a fraction of the illumination field. The absence of a separate reference beam simplifies the setup reducing the number of components in the optical path and thereby the sources of image degradation. In our experimental set-up light from the UV source is imaged on to a 1 µm pinhole. The spherical wave emanating from the pinhole and the wave scattered from the object interferes to form a hologram recorded by a CCD sensor. Figure 1 shows the reconstructed intensity of latex beads (average size 500nm). The distance between the centres of two beads was 2.2µm as calculated from the reconstructed image. This gives an indication as to the resolution achieved with the configuration used. One of the main factors which limit the resolution achieved is the spatial coherence of the source, better results could be obtained by using a 500 nm diameter pinhole. Figure 2(a) shows the reconstructed amplitude and 2(b) shows the corresponding phase of human blood cells. In all the above cases, the reconstruction was done from a hologram obtained by subtracting the reference beam (recorded without the object) from the object hologram. The beads appear as bright in a dark background. Also in the reconstruction of blood cells, the regions undergoing more absorption appear brighter.

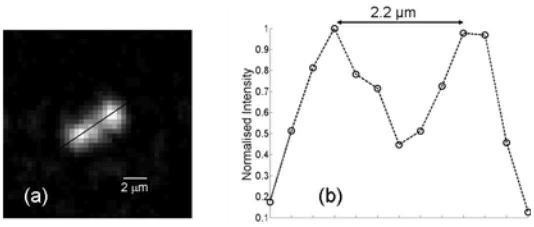

Fig. 1: Reconstructed intensity of latex beads average size 500nm **(a)**. Profile taken along a line **(b)**.

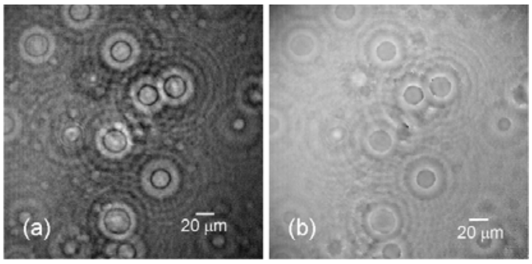

Fig. 2: Reconstructed **(a)** amplitude and **(b)** phase of human blood cells. The cells are located at different planes and in the shown single reconstruction some of them are out of focus.

In another arrangement a separate off-axis reference has been used and a lens has been introduced between the object and the CCD. We have shown that the aberration of the lens can be digitally corrected in order to get a clear reconstruction of the sample (see Fig. 3). This digital compensation open new possibilities allowing to get high resolution images by using low quality and low cost lenses.

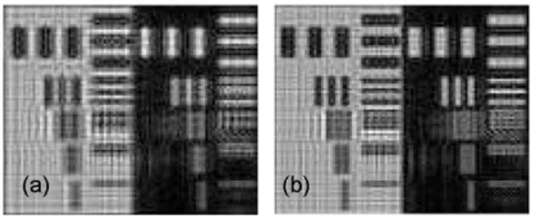

Fig. 3: Digital simulated reconstructions obtained from a hologram. Without **(a)** and with **(b)** aberration correction.

Supported by: DFG (OS 111/19)

References:

[1] Pedrini, G.; Zhang, F.; Osten, W. "Digital holographic microscopy in the deep (193 nm) ultraviolet", Appl. Opt. 46, 7829-7835 (2007).

Comparative Digital Holography: z-resolution

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. A current research topic is the characterisation of the influence of the roughness and roughness difference between master and sample on the resolution of the system [1]. In classical interferometry, a change of microstructure causes decorrelations of the involved speckles fields with the consequence of vanishing macroscopic interference fringes, but in CDH, the effect of the microstructure can be minimized by a double illumination, using two different wavelengths, of both master and sample. The change of wavelength induces decorrelation between the speckle fields reflected by a rough object. The z-resolution is limited by the noise, which can be quantified by calculating the standard deviation σ of the synthetic phase map [2].

The influences of the roughness, the synthetic wavelength, the variation of reflectivity over the surface and the optical reconstruction of the digital master hologram using a LCD, have been investigated theoretically and by experiments [1]. For the experiment, we used three roughness reference standard (Rq: 56 nm, 352 nm, 2170 nm), and tilted each of them from 0° to 40° (angle between the sensitivity vector and the vector normal to the surface of the object). Holograms of a master (standard deviation of the microstructure Rq=352nm) were recorded by using different wavelengths (fig. 1a). The sample was illuminated by the conjugated wavefront of the master, as a type of coherent mask, using a liquid crystal display (LCD) (fig. 1b). Finally, the digital reconstructions of the comparativ holograms give a synthetic phase map which contain only the difference between master and sample object.

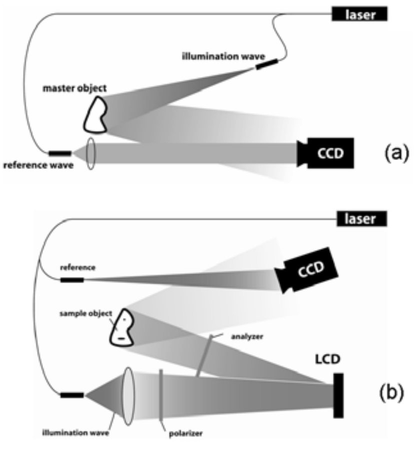

Fig. 1: Schematic representation for the experimental setup for the CDH. a) Recording of the hologram of the master object. b) Coherent illumination of the sample with the conjugated wave front of the master.

The maximum wavelength difference and the z-resolution were calculated for the three roughness reference standards as samples (s. Fig. 2 and 3). A low maximum wavelength difference indicates that the sample induced a high degree of decorrelation. In general, the samples with small roughness give the best results. When the sample is tilted, the noise increases and the consequence are the diminution of both maximum wavelength difference and z-resolution.

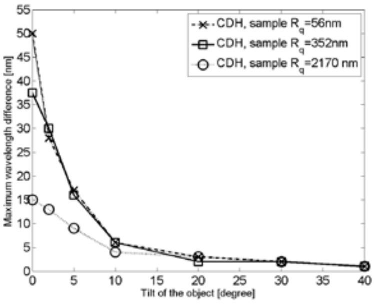

Fig. 2: Maximum allowed wavelength difference in CDH with the roughness reference standard Rq=352nm as master and with different roughness reference standard as sample (see legend).

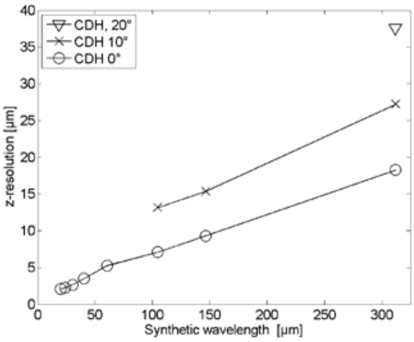

Fig. 2: z-resolution in CDH with the roughness reference standard Rq=352nm as master and sample.

Supported by: Landesstiftung Baden-Württemberg

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[1] Schwab, X. “PhD thesis” ITO, Uni. Stuttgart, to be published.

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

[4] Kohler, C.; Haist, T.; Schwab, X.; Osten, W. „Hologram optimization for SLM-based reconstruction with regard to polarisation effects“; Opt. Express 16, 14853-14861, 2008.

Coherence effects in digital in-line holographic microscopy

U. Gopinathan, G. Pedrini, W. Osten

In many applications using digital in-line holography, it is common to treat the source as completely coherent, both spatially and temporally. This assumption, though valid in many cases, will not hold in all. For instance, X-ray sources are partially coherent. Partially coherent light are also used for many applications in optical microscopy. These applications benefit from a generalised treatment that takes into account the state of coherence of light. We provided a theoretical framework for analysing the partial coherence effects in digital in-line holographic microscopy. The schematic of the setup used to study these effects is shown in Fig. 1. Let σ denote the pupil of a planar source with a coherence state characterised by the cross spectral density function (CSD) $W(\mathbf{p}_1, \mathbf{p}_2, \omega)$ of the fluctuating field $U(\mathbf{p}_1,\omega)e^{-i\omega t}$ and $U(\mathbf{p}_2,\omega)e^{-i\omega t}$ at two points P_1 and P_2 in the source illumination, ω is the light angular frequency. The analysis is valid for primary or secondary sources of any state of coherence characterised by the CSD. We provided an expression for the impulse response of the system in terms of CSD of the source.

The impulse response for the case of a Gaussian shell source is simulated (see Fig. 2). In this case the source has a spectral intensity distribution and degree of coherence given by:

$$S(\mathbf{p},\omega)= A(\omega)\exp\{-|p|^2/(2\sigma_s^2(\omega))\}$$
$$\mu(\mathbf{p}_1, \mathbf{p}_2,\omega)= \exp\{-|p_1-p_2|^2/(2\sigma_\mu^2(\omega))\}$$

The parameter β, defined as the ration of σ_s and σ_μ is the measure of the degree of global coherence.

It is seen that reduction in coherence of the light leads to broadening of the impulse response. This is also validated by results from experiments where digital holography was used to image latex beads using light with different spatial and temporal coherence.

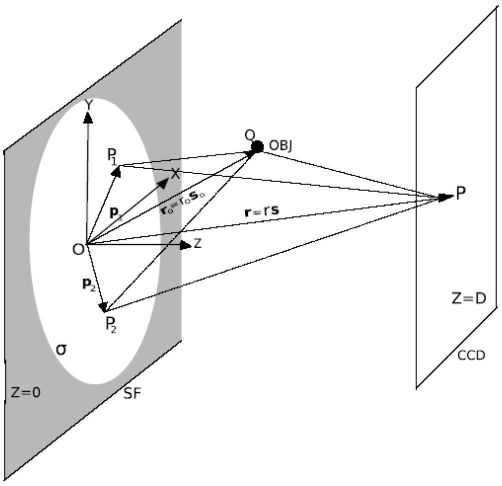

Fig. 1: Schematic of a lensless digital in-line holography setup. The object is illuminated by an extended light source σ. The light scattered by the micro-object (OBJ) and the unscattered light forms an in-line hologram at the CCD plane.

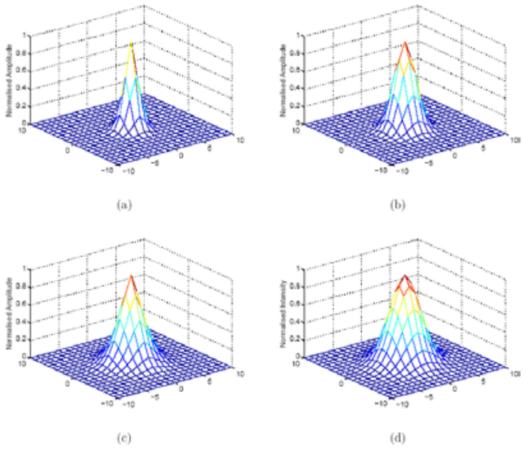

Fig. 2: Impulse response evaluated for a Gaussian Schell source with **(a)** $\beta = 5$, $\beta = 0.2$ and temporal FWHM bandwidth equal to 7nm **(b)** $\beta = 5$, $\beta = 0.2$ and temporal FWHM bandwidth equal to 14nm **(c)** temporal FWHM bandwidth equal to 7nm and 14nm with $\beta = 5$ **(d)** temporal FWHM bandwidth equal to 7nm and 14nm with $\beta = 0.2$. The X and Y axis in all the four plots are indicated in pixels. Each pixel translates to a physical distance 3µm. The Z axis shows normalised amplitude.

Supported by: Alexander von Humboldt Foundation and DFG (OS111/19)

References:

[1] Gopinathan, U.; Pedrini, G.; Osten, W. "Coherence effects in digital in-line holographic microscopy", J. Opt. Soc. Am. A 25, 2459-2466 (2008).

Phase retrieval by tuning illumination wavelengths

P. Bao, F. Zhang, G. Pedrini, W. Osten

We present a phase retrieval method where a sequence of diffraction speckle intensities, recorded by tuning the illumination wavelength, is used. These recordings, combined with an iterative calculation method, allow the reconstruction of the amplitude and the phase of the wavefront. The main advantages of this method are: simple optical setup and high immunity to noise and environmental disturbance, since no reference beam or additional moving parts are needed. Furthermore, this method allows for an extended wrap-free phase measurement range by using synthetic wavelengths. The technique shows great potential in some fields of micro-metrology, such as lensless phase contrast imaging and wavefront sensing.

Only a very simple setup is needed for recording the intensities of the diffraction fields (see Fig.1). For a transparent object, the illumination beam is first expanded, and then collimated as a plane wave illuminating the object. A camera is positioned at the distance Z from the object to record the intensities of the diffraction patterns. By changing the illumination wavelength, a set of M diffraction intensity patterns is collected. For the investigation of reflecting objects, a beam splitter should be used.

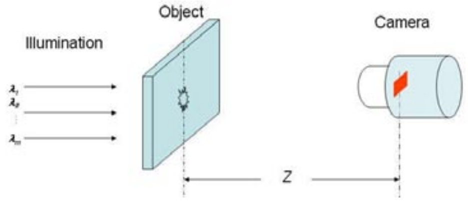

Fig. 1: Experimental setup.

For some objects, such as lenses, the diffraction pattern changes only slightly when the illumination wavelength changes. In this case, the camera cannot resolve the difference diffraction patterns and then the experimental setup should be modified as shown in Fig. 2. A modulator is placed in Z_1 away from the object, and the intensities of the modulated diffraction patterns are recorded by the camera located in Z_2 away from the modulator. The modulator can be a phase or amplitude plate with known random pattern.

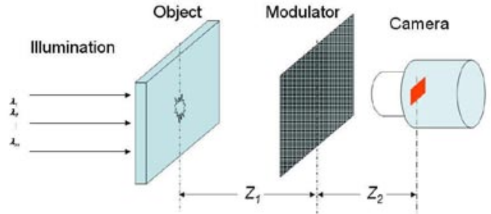

Fig. 2: Modified experimental setup for smooth objects.

In the experimental setup, the light source was a Titanium-Sapphire laser with a wavelength tuning range between 750 nm and 890nm. The test object was a USAF resolution target attached on a random phase plate. Fig. 3 shows the recovered amplitude and phase after 120 iterations. In the iteration process, the amplitude pattern began to be recognizable after 30 iterations, and no obvious improvement was observed after 100 iterations. The high contrast in the retrieved amplitude shows that the retrieved phase must be correct.

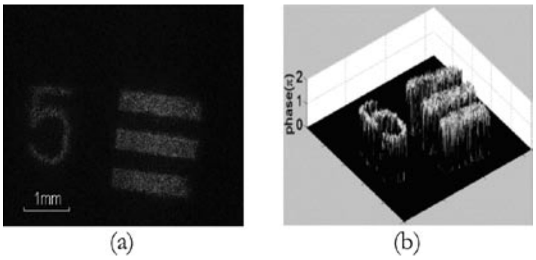

Fig. 1: Experimental result: retrieved amplitude **(a)** and phase **(b)**.

The experimental result with modified setup is shown in Fig. 4. A binary pixelated phase plate (16×16 μm pixel size) was used as a modulator. Nine different illumination wavelengths were used. The test object was a lens (focus length f =200mm) limited by an aperture (diameter $D \approx 2m$). The recovered lens phase after 140 iterations is shown. Since the focus length of the lens is quite long, and the aperture is very small, the profile of the phase does not change much in the acquired portion.

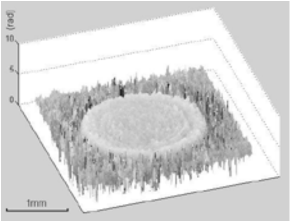

Fig. 1: Experimental result: retrieved lens phase.

Supported by: China Scholarship Council

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[1] Bao, P.; Zhang, F.; Pedrini, G.; Osten, W. “Phase retrieval using multiple illumination wavelengths,” Opt. Lett. 33, 309-311 (2008).

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Collision in double random phase encoding

G. Situ, G. Pedrini, W. Osten

Collision is a situation that occurs when two or more distinct inputs into a security system produce identical outputs, which is undesirable in many security applications such as authentication, message integrity, and password verification

In double random phase encoding (DRPE), an input image or watermark, $f(x, y)$, is encoded into a stationary white noise, $g(x, y)$, using two statistically independent random phase masks $\exp[i\phi(x, y)]$ and $\exp[i\psi(u, v)]$ located at the input and Fourier plane, respectively, in a 4f system as shown in Fig. 1. The purpose of collision is to find another key-set, $[\phi'(x, y), \psi'(u, v)]$, which encrypts a different image, $h(x, y)$, into $g(x, y)$, the cyphertext of $f(x, y)$.

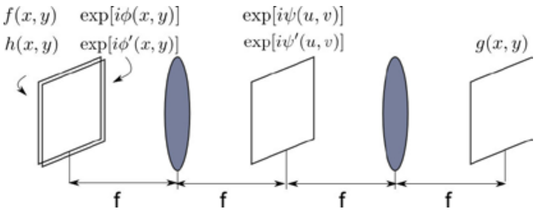

Fig. 1: Schematic illustration of the optical setup for double random phase encoding. The collision property indicates that given any two different image *f* and *h*, it is possible to find two associated sets of phase $[\phi, \psi]$ and $[\phi', \psi']$ that respectively transform *f* and *h* into the same cyphertext *g* in DRPE.

The algorithm we used to find collisions involves iterative Fourier transforms forward and backward between the input and Fourier planes. In these two planes, the magnitudes of the resulting complex amplitudes are respectively replaced with $h(x, y)$ and $|G(u, v)|$, the magnitude of the Fourier transform of $g(x, y)$, while the phases are kept unchanged. The iteration process is repeated until the convergent criteria are satisfied. Then the phase obtained at the input plane is $\phi'(x, y)$, while the subtraction of the phase obtained at the Fourier plane from $\arg\{G(u, v)\}$ is $\psi'(u, v)$.

Numerical calculations show that the algorithm converges within 100 iterations. The converging behaviour in the logarithm scale is in Fig. 2. One can see that the error curves drop very fast in the first few iterations, then become much flatter but keep decreasing. This is a typical converging behaviour of the error-reduction algorithm. Figure 2 also indicates that if the input watermark is a phase-only distribution, the algorithm converges even faster, and to a better solution.

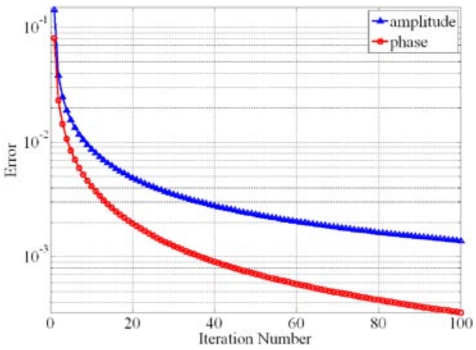

Fig. 2: The converging behaviour of the algorithm in the logarithm scale.

Note that no restriction is imposed on the selection of the collision image, the initialization of the algorithm or the spectrum of the cyphertext. What this means is that an illegal user has a lot of flexibility in choosing the collision image, and he can always retrieve two feasible phase keys that validate the transform.

The collision property represents a weakness that needs to be fixed for DRPE to be used for authentication in this way.

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Spiral phase filtering and orientation-selective edge detection/enhancement

G. Situ, G. Pedrini, W. Osten

Spiral phase plate (SPP) with an azimuthal structure exp[$i\phi$] ($0 \le \phi < 2\pi$) has been used as a filter in a system shown in Fig. 1 to achieve edge enhancement. When the SPP is placed at a position where its singularity is coincident with the zero-order Fourier spectrum component of the input pattern (defined as the origin of the Fourier plane), such edge-enhanced effect is isotropic.

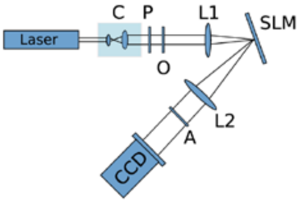

Fig. 1: Setup of the optical experiment. A: Analyzer, P: Polarizer, C: collimator, O: object. The focal lengths of the Fourier lens L1 and L2 are 140 and 250 mm, respectively.

If we shift the singularity of the SPP out of the origin, e.g., to a position (r, θ) in the polar coordinates as shown in Fig. 2, the radial symmetry of the filtering process breaks down. As a result, the output pattern presents a relief-like render along the $\theta + \pi/2$ direction. By changing this value, we can selectively enhance the edge of any orientation. The degree of enhancement, on the other hand, is controlled by the value of r, the distance between the singularity and the origin. Experiment results are shown in Fig. 3. The smaller r is closed to 0 the higher degree the enhancement obtains. If r is large, the edge-enhanced effect becomes insignificant, as shown in Fig. 3(c).

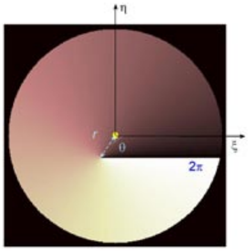

Fig. 2: Schematic illustration of the method by shifting the singularity of the SPP out of the origin, where the zero-order Fourier component is located.

Orientation-selective edge-enhancement can be achieved by using a fractional SPP, exp[$ip\phi$] (p is a fractional number), whose singularity is located at the origin, as shown in Fig. 4. Since the phase of the filter is asymmetric along any radial line with respect to the origin, the filtering effect then has a relief-like render. The relief-like effect takes the direction of $\beta + \pi/2$, where β is the orientation of the phase discontinuity of the SPP. Figure 5 shows the experiment results. By changing the value of β, i.e., rotating the SPP, one can selectively enhance the edge of any orientation. The degree of enhancement in this case can be specified by the topological charge p. The more the p value is closed to 1, the higher degree the enhancement obtains. An interesting phenomenon is that no edge enhancement can be observed when $p < 0.5$ as shown in Fig. 5(c) because the SPP cannot produce a vortex in this case.

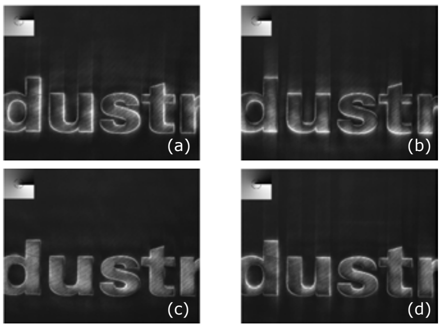

Fig. 3: Experimental results of method 2. The (r, θ) values are **(a)** (3δ, $\pi/2$), **(b)** (6δ, 0), **(c)** (11δ, $3\pi/2$), and **(d)** (10δ, π), where δ=9.5 microns is the pixel dimension of the SLM.

The methods proposed in this work can be applied in anisotropic edge enhancement or detection Further works involve the applications of the two proposed techniques in phase contrast microscopy.

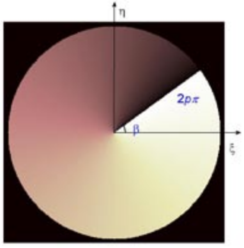

Fig. 4: Schematic illustration of the method by using a fractional.

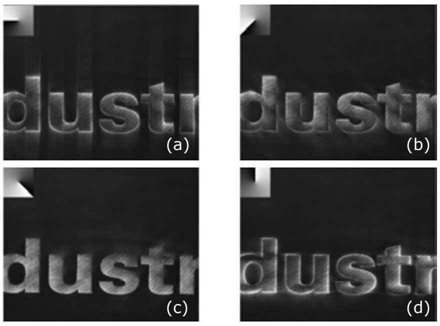

Fig. 5: Experimental results of method 1. The (p, β) values are (a) (0.8, π), (b) (0.6, $5\pi/4$), (c) (0.4, $7\pi/4$) and (d) (0.9, $\pi/2$).

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W. Osten:

Different approaches to overcome existing limits in Micro and Nano

Metrology, Joint Sino-German Symposium on Metrology in Micro- and Nanosystems,
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New Flexibility for Optical Metrology and Optical Trapping by Digital Holography
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Reichle, R.; Yu, K.; Pruss, C.; Osten, W.
Spin-coating of photoresist on convex lens substrates
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Improvements on the simulation of microscopic images for the defect detection of nanostructures
Proc. SPIE, Vol. 6922, 692215 (2008)

Schuster, T.; Rafler, S.; Frenner, K.; Osten, W.
Influence of line edge roughness (LER) on angular resolved and on spectroscopic scatterometry
Proc. SPIE, Vol. 7155, 71550W (2008)

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Improved micro topography measurement by LCoS-based fringe projection and z-stitching
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Schuster, T.; Rafler, S.; Ferreras Paz, V.; Frenner, K.; Osten, W.
Fieldstitching method comprising Kirchhoff's approximation for description of small perturbations of perfectly periodic structures
6th IISB Lithography Simulation Workshop 2008

Schuster, T., Rafler, S. , Ferreras Paz, V.; Frenner, K.; Osten, W.
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Microelectron. Eng. (2008), doi:10.1016/j.mee.2008.11.019

Yu, L.; Pedrini, G.; Osten, W.
Propagation vector analysis of digital holography and its application for three-dimensional angle measurement
Proc. SPIE, Vol. 6912, 69120B (2008)

Zimmermann, J.; Regin, J.; Lyda, W.; Wiesendanger, T.; Sawodny, O.; Westkämper, E.; Osten, W.
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Euspen, Zürich (2008) Vol.2 pp. 430-435

Patents

Patent Applications

Körner, Klaus; Kohler, Christian; Papastathopoulos, Evangelos; Osten, Wolfgang:

Method and Arrangement for a Rapid and Robust Chromatic Confocal 3D Measurement Technique

WO 2007/090865 A1, PCT/EP2007/051212,
date of publication: 2007.08.16
EP 1 984770 A1, date of publication: 2008.10.29
US 2009/0021750 A1, date of publication: 2009.01.22

Priority: Anordnung zur schnellen und robusten chromatisch-konfokalen 3D-Messtechnik

DE 10 2006 007 170 A1 2007.08.16, priority data: 2006.02.08
Assignee: Sirona Dental Systems GmbH

Körner, Klaus; Kohler, Christian; Papastathopoulos, Evangelos; Ruprecht, Aiko; Pruss, Christof; Wiesendanger, Tobias; Osten, Wolfgang:

Verfahren und Anordnung zur schnellen, ortsaufgelösten, flächigen spektroskopischen Analyse, bzw. zum Spectral Imaging oder zur 3D-Erfassung mittels Spektroskopie

DE 10 2006 007 172 A1 2007.08.16, priority data: 2006.02.08

Hering, Marco; Happold Walter; Herrman, Sven; Knoll, Christian; Körner, Klaus; Osten, Wolfgang:

Interferometrische Messvorrichtung

DE 10 2006 015 387 A1 2007.10.04, priority data: 2006.03.31

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

Arrangement and Method for Confocal Transmitted-Light Microscopy, in particular also for Measuring Moving Objects

WO 2007/131602 A1, PCT/EP2007/003644,
date of publication: 2007.04.25

Priority: Anordnung und Verfahren zur konfokalen Durchlicht-Mikroskopie, insbesondere auch zur Vermessung von bewegten Phasenobjekten

DE 10 2006 023 887 B3 2007.08.23, priority data: 2006.05.16

Ruprecht, Aiko:

Optisches Verfahren mittels Vielstrahlinterferenz

DE 10 2007 030 814 A1 2009.01.08, priority data: 2007.07.03

Gorski, Witold; Osten, Wolfgang:

Optisches Abbildungssystem und Verfahren zum Ermitteln dreidimensionaler Amplituden- und/oder Phasenverteilungen

DE 10 2007 036 309 A1 2009.02.05, priority: 2007.07.31

Körner, Klaus; Lyda, Wolfram; Osten, Wolfgang:

Anordnung und Verfahren zur konfokalen, spektralen Zweistrahl-Interferometrie

AKZ: 10 2008 020 902.2, priority data: 2008.04.18

Körner, Klaus; Osten, Wolfgang:

Verfahren und Anordnung zur skalierbaren konfokalen Interferometrie

AKZ: 10 2008 0620879.4, priority data: 2008.12.15

Rembe, Christian; Haist, Tobias:

Interferometer zur optischen Vermessung eines Objekts

AKZ: DE 10 2007 010 387 A1, priority data: 2007.03.03

Granted Patents

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 data: 2005.09.05

Franz, Stefan; Windecker, Robert:

Messeinrichtung zur Erfassung von Dimensionen von Prüflingen sowie Verfahren unter Verwendung der Messeinrichtung

EP 1 018 631 B1 2007.03.07, priority data: 1999.12.07

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

Anordnung und Verfahren zur konfokalen Durchlicht-Mikroskopie, insbesondere auch zur Vermessung von bewegten Phasenobjekten

DE 10 2006 023 887 B3 2007.08.23, priority data: 2006.05.16

Reichle, René; Pruss, Christof; Zimmermann,
Frank; Schulz, Christof:

Optischer Sensor und Zündkerze mit optischem Sensor und Detektionskaskade

DE 10 2005 028 113 B4 2007.08.30, priority data: 2005.06.13

Osten, Wolfgang; Garbusi, Eugenio;
Pruß, Christof; Liesener, Jan:

Verfahren und Messvorrichtung zur Vermessung einer optisch glatten Oberfläche

DE 10 2006 057 606 B4 2008.12.11, priority data: 2006.11.24

Doctorial Thesis, Diploma Thesis & Student Research Projects

Doctoral Thesis
2007-2008

Reicherter, Marcus
Einsatz von Lichtmodulatoren zum
Teilchenfang und zur Aberrationskontrolle
in holografischen Pinzetten
5/2007

Kerwien, Norbert
Zum Einfluss von Polarisationseffekten in
der mikroskopischen Bildentstehung
12/2007

Ruprecht, Aiko
Konfokale Sensorik zur Hochgeschwindigkeits-
Topografiemessung technischer Objekte
4/2008

Kauffmann, Jochen
Rigorose Rekonstruktionsmethoden der
optischen Messtechnik zur tomographischen
und diffraktometrischen Bestimmung
von Struktur-Stoff-Systemen
oral examination 11/2008

Seifert, Lars
Flexible Verfahren zur Vermessung
asphärischer Flächen
oral examination 1/2009

Diploma Thesis
2007-2008

Utz, Annika
Simulation und Aufbau zur phasenmessenden Deflektometrie
3/2007

Ruppel, Thomas
Advanced Control of Adaptive Secondary Mirrors for Astronomical Adaptive Optics
4/2007

Frank, Marc
Aufbau eines 3D Messstandes und Charakterisierung eines schnellen konfokalen monochromatischen Punktsensors
(HTW Aalen)
10/2007

Dilger, Richard
Erstellung und Anwendung eines Simulationstools zur Untersuchung verschiedener Kodierungsverfahren bei Multiplex-CGHs in der interferometrischen Messtechnik
11/2007

Hafner, Jan
Entwicklung eines Verfahrens zur automatisierten Aberrationskorrektur in Mikroskopen
12/2007

Lyda, Wolfram
Analyse des Fehlerbudgets zur Verringerung der Messfehler bei chromatisch-konfokalen Topografiemessungen
12/2007

Schmid, Ulrich
Ultraschnelle grafikkartenbasierte Bildverarbeitung für die Mustererkennung und Hologrammoptimierung
12/2007

Lischke, Mathias
Implementierung eines hochgenauen X-Y-Positioniersystems in ein Laserdirektbelichtungssystem
4/2008

Fleischle, David
Numerische Bildfehlerkorrektur in der digitalen Holografie im tiefen UV-Bereich
5/2008

Götz, Peter
Simulation von Gitterbeugungen mit der Normalenvektormethode
7/2008

Radeschütz, Florian
Neuartige aktive polarisationsoptische Komponenten, basierend auf den photoadressierbaren Polymeren (PAP)
9/2008

Petschow, Matthias
Berechnung anisotroper periodischer Strukturen mittels Differentieller Methode
11/2008

Student Research Project
2007-2008

Fleischle, David
Aufbau und Integration eines optischen Sensors in eine Bearbeitungsmaschine für das elektrochemische Fräsen
4/2007

Lyda, Wolfram
Untersuchung der idealen Objektorientierung in Digitaler Holografie und in Vergleichender Digitaler Holografie
4/2007

Schmid, Ulrich
Low-Cost Spektralsensorik zur schnellen Hand-Holz-Klassifikation
5/2007

He, Lin
Simulation der Einfangkraft holografischer Doppelfallen
8/2007

Lischke, Mathias
Herstellung zweiseitiger Diffraktiver Optischer Elemente
9/2007

Henke, Martin
Erste Untersuchungen zur holografischen 4Pi-Mikroskopie
1/2008

Xu, Chang
Defekterkennung für die multiskalige Mess- und Prüftechnik
1/2008

Graupner, Daniela
Entwicklung und Erprobung eines transportablen adaptiven Optiksystems mit thermischem Aktuatorprinzip
3/2008

Rominger, Volker
Bestimmung und Kompensation von Aberrationen in einer holografischen Pinzette mit einem Low-Cost-Objektiv
3/2008

Schaal, Frederik
Klassifikation von Zellen mit einer holografischen Pinzette
3/2008

Schubert, Moritz
Konstruktion eines Interferenzlithografie-Aufbaus und Herstellung von sub-λ Lineargitterstrukturen
3/2008

Beck, Johannes
Untersuchung der Störordnungsproblematik computergenerierter Hologramme in der Laser-Doppler-Vibrometrie
6/2008

Wu, Tianshu
Entwicklung von optischen Interferometern zur Messung von Verformungen und Verschiebungen in nm-Bereich
6/2008

Dhidah, Nacef
Holografische Pinzette als Add-On Modul mit integriertem Justagekonzept
11/2008

Eger, Pamela
Quantitativer Phasenkontrast mit Hilfe eines SLM
11/2008

Burger, Florian
Methodenvergleich von RCWA und FIT zur Simulation elektromagnetischer Felder
11/2008

Konstantin, Georg
Experimentelle Realisierung des adaptiven Phasenkontrast- und Dunkelfeldverfahrens mit einem SLM
12/2008

Lingel, Christian
Entwicklung eines Matlab-basierten Systems zur Phasenkontrastsimulation
12/2008

Awards 2007 / 2008

The European Optical Society awarded the Best Presentation Prize to
F. Schaal, M. Warber, S. Zwick, H. van der Kuip, T. Haist and W. Osten
for the presentation on
"Cell discrimination by holographic optical tweezers"
at the EOS Topical Meeting on Dynamical Optics (TOM 7)
from 29th September to 2nd October 2008.
(Prof. Roberta Ramponi, President of the EOS & General Chair of EOS AM 2008)

The „Vereinigung von Freunden der Universität Stuttgart e.V." awarded
Dipl.-Ing. Thomas Ruppel
the price of the „Freunde der Universität Stuttgart" for
spezialised scientific achievements for his diploma paper
"Advanced Control of Adaptive Secondary Mirrors for Astronomical Adaptive Optics".
(Stuttgart, July 2008, Dr. rer. pol. Claus Dieter Hoffmann)

The „Gustav-Magenwirth-Stiftung" awarded
Dipl.-Ing David Fleischle
with the price for extraordinary scientific work in the field of
precision engineering in his student research project
„Aufbau und Integration eines optischen Sensors in eine Bearbeitungsmaschine für das elektrochemische Fräsen".
(Bad Urach, February 2007, Gustav-Magenwirth-Stiftung)

The SPIE Europe and Rhenaphotonics Alsace awarded
Dipl.-Phys. René Reichle
with the "2008 Rhenaphotonics Alsace **Best Overall Product** Awards" for the
"Diffractive / refractive endoscopic UV-imaging system"
presented at the "European Photonics Innovation Village" on the international
conference "Photonics Europe 2008". The system has been developed in
cooperation with Prof. Schulz (IVG, University of Duisburg-Essen).
(Strasbourg, April 2008)

Presentation booth at the Innovation Village of Photonics Europe 2008.

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

Optik-Kolloquium 2008

Optik: Grenzen überschreiten (beyond the limits)

am 27. Februar 2008, Teilnehmer: ca. 250

Begrüßung und Einführung	Prof. Dr. W. Osten ITO, Universität Stuttgart
Nanoskopie mit fokussiertem Licht	Prof. Dr. S. Hell Max Planck Institut für Biophysikalische Chemie, Göttingen
Optische Atomuhren	Prof. Dr. F. Riehle Physikalisch-Technische Bundesanstalt, Braunschweig
Ultraschnelle optische Spektroskopie der elastischen Eigenschaften kleinster Metallpartikel	Prof. Dr. M. Lippitz Max Planck Institut für Festkörperforschung, Stuttgart
Metamaterialien für sichtbares Licht	Dr. C. Rockstuhl Institut für Festkörpertheorie und -optik, Friedrich-Schiller Universität Jena
Optische Terabyte Disk – Hologramme am Auflösungslimit	Prof. Dr. S. Orlic Optisches Institut, Technische Universität Berlin
Status EUV Lithography Program at ASML	Dr. V. Banine ASML Netherlands B.V., Veldhoven, Niederlande
Ionen-Multi-Strahl Strukturierung (PMLP – Projection Mask-Less Patterning) für Nanotechnologie-Anwendungen	Dr. W. Rupp IMS Nanofabrication AG, Wien, Österreich
Detektierbarkeit von LER (Line Edge Roughness) mittels Scatterometry an EBDW Teststrukturen	Dr. M. Mört Qimonda Dresden GmbH & Co. OHG, Dresden
Performance-Vorhersage für Lithographie-Optik durch ultra-präzise Komponentenmesstechnik	Dr. B. Dörband, Dr. M. Totzeck Carl Zeiss SMT AG, Oberkochen
Optische Lithographie Simulation: Projection Printing, Proximity Printing und Interferenz-Lithographie	Dr. P. Evanschitzky, Dr. A. Erdmann Fraunhofer Institut für Integrierte Systeme und Bauelementetechnologie, Erlangenr
Scatterometrie an Kreuzgitterstrukturen in verschiedenen Messkonfigurationen	T. Schuster Institut für Technische Optik, Universität Stuttgart
Fertigungsintegrierte Asphärenmesstechnik im Spannungsfeld zwischen Flexibilität und Geschwindigkeit	E. Garbusi Institut für Technische Optik, Universität Stuttgart

Optik-Kolloquium 2009

Photonik im Maschinenbau

am 25. Februar 2009, Teilnehmer: ca. 200

Begrüßung und Einführung	Prof. Dr. W. Osten ITO, Universität Stuttgart
Materialbearbeitung mit High-Brightness-Lasern	Dr. A. Wetzig, Prof. Dr. E. Beyer Fraunhofer IWS, Dresden
Scheibenlaser in der industriellen Materialbearbeitung	Dr. K. Mann TRUMPF Laser GmbH, Schramberg
Innovative Bearbeitungsverfahren und Maschinenkonzepte für reibungsoptimierte Zylinderlaufbahnen	Dr. T. Abeln, G. Flores, T. Birkner Gehring Gmbh, Ostfildern
Zerstörungsfreie Prüfung im Maschinenbau mit photonischen Methoden	Prof. Dr. G. Busse IKT Universität Stuttgart, Stuttgart
New design methods for state-of-the-art lithographic objectives	Dr. F. Bociort Delft University of Technology, Delft, The Netherlands
Interaktion zwischen optischer Verbrennungsdiagnostik und CFD-Simulation in der Daimler Vorentwicklung zur Optimierung verbrauchs- und schadstoffarmer Brennverfahren	Dr. C. Krueger Daimler AG, Stuttgart
Photonik im Verbrennungsmotor: Beobachtung von innermotorischen Detailvorgängen mit Lasermesstechniken	Prof. Dr. T. Dreier, Prof. Dr. C. Schulz IVG Universität Duisburg-Essen, Duisburg
Innovative optische Komponenten für die minimal-invasive Diagnostik in Verbrennungsmotoren	R. Reichle, C. Pruß, Prof. Dr. W. Osten ITO Universität Stuttgart, Stuttgart
Dynamische Formvermessung von rotierenden Objekten mit dem Laser-Doppler-Distanzsensor	Prof. Dr. J. Czarske Universität Dresden, Dresden
Schwingungsmessung mit Licht	Dr. C. Rembe Polytec GmbH, Waldbronn
Vision-basierte Fahrerassistenzsysteme	Prof. Dr. P. Knoll Robert Bosch GmbH, Leonberg
Interferometrische Messung von 3D Innenraumkonturen für den industriellen Einsatz	A. Knüttel ISIS sentronics GmbH, Mannheim

Organized International Conferences: 2007 – 2008

S. Dolev, T. Haist, M. Oltean:

Optical Super Computing

First International Workshop, OSC 2008,
August 26, 2008, Vienna, Austria

W. Osten:

1st Sino-German Symposium on Metrology in Micro- and Nanosystems

March 27 – 29, 2007, Shenzhen, China

W. Osten:

Modeling Aspects in Optical Metrology

SPIE Congress, June 18 – 22, 2007, Munich, Germany

W. Osten:

Optical Measurement Systems for Industrial Inspection V

SPIE Congress, June 18 – 22, 2007, Munich, Germany

W. Osten:

Optical Micro- and Nanometrology in Microsystems Technology

SPIE Congress, April 8 – 10, 2008, Strasbourg, France

W. Osten:

Interferometry XIV: Applications

SPIE Congress, August 13 – 14, 2008, San Diego, USA

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