INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

annual report
2009 / 2010

Universität Stuttgart

INSTITUT FÜR TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

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ANNUAL REPORT 2009/2010

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 2009 about their research activities in a comprehensive report. Thus it is again time to inform our partners, sponsors and customers about our recent advances in the field of Applied Optics.

The basic understanding that determines our 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. Our reactive ion etching facility is meanwhile successfully working, although strict environmental requirements delayed the complete start of operation by about 2 years. The installation of the Helios Nanolab 600 focused ion beam (FIB) tool is also on a good way even though the operation of such a high-end facility in a clean room environment imposes some special boundary conditions. Both tools widen our possibilities in the field of nanotechnology considerably and we are optimistic that our planed activities in diffractive optics and high resolution imaging can be realized in the near future. But we have learned, partly very painful, that the step across 3 orders of magnitude from the micro to the real nano world has to be paid by an increased effort of the same magnitude and beyond. Our aim to assure flexible structuring technologies with high resolution and reliability not only for a few crucial experiments but for making dedicated optical components is unbroken.

To make sure that ITO will be able to fulfil its commitment also with changing boundary conditions we have installed a powerful alliance with competent partners in photonics beyond the framework of our faculty: the Stuttgart Research Center of Photonic Engineering[1]. Here experts from 3 different faculties – physics, electrical engineering and mechanical engineering – are working together on topics where the expertise of one faculty is insufficient to meet the grown challenges. Some very first joint results could be already presented: our new but meanwhile approved concepts in resolution enhancement beyond the diffraction limit by a dedicated design of negative index materials and the fabrication of a new class of flexible illumination devices with spatially varying polarisation state. Further projects have been already started and the application for a collaborative research centre under the umbrella of the German Research Association DFG in the scope of future photonic circuits is on the way. Such interdisciplinary cooperation in larger scientific networks, assembled to meet ambitious mid- and long-term targets, is gaining more and more in importance.

As a member of the Faculty of Mechanical Engineering, the Institute represents the University of Stuttgart 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 implementation of a multi-sensor measurement systems where the systematic cooperation of different classes of sensors is controlled by a sophisticated assistance system, the implementation of the prototype of our new tilted wavefront interferometer with the objective to realize a much more effective approach for the testing of aspheres and free-form surfaces, and the further improvement of our model-based reconstruction procedures for the inspection of sub-wavelength structures.

Our overall research approach "Optical Metrology and Systems Design" is structured into eight main research directions:

- Active Metrology
- Model-based Metrology,
- Remote Metrology,
- Resolution Enhancement,
- Computational Imaging,
- Sensor Fusion,
- Hybride Optics and Systems, and
- Sensor Integration.

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.

As already mentioned, high-quality teaching for our students on different levels (bachelor, master, phd) is – besides our wide research activities – an ongoing strong commitment of ITO. Thus we have started in 2010 the new consecutive bachelor-master course in medical technology – a joint and challenging project of the University of Stuttgart and the Eberhard Karls Universität Tübingen. Both universities complement each other with their strong commitment in engineering and medicine, respectively, in an ideal way. The response of the students was very motivating and ITO is one of the drivers of that course. In 2011 we will start a new master course with the dedication "Micro-, Precision- and Photonics Engineering".

To cope with our ambitious and extensive approach to Applied Optics, a deep understanding of physics needs to be combined with practical engineering implementation. This is 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 are a good basis to meet these and future challenges.

Wolfgang Osten

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[1] *http://www.scope.uni-stuttgart.de/*

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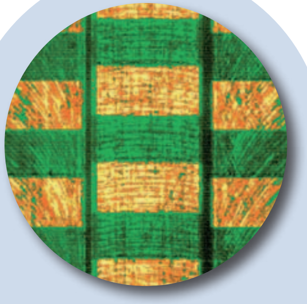
INSTITUTE STRUCTURE

Team and structure

Teaching
E. Steinbeißer

Chair
Prof.Dr. W. Osten

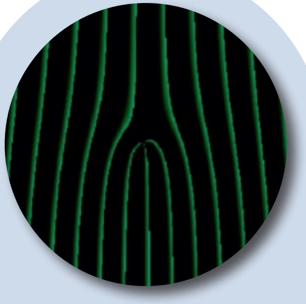
Deputy
Dr. T. Haist



3D-Surface Metrology

W. Lyda

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



Active Optical Systems and Computational Imaging

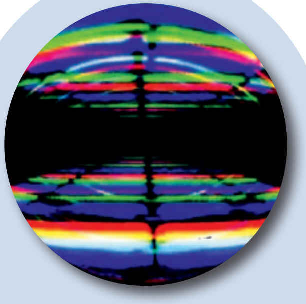
Dr. T. Haist

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

High Resolution Metrology and Simulation

Dr. K. Frenner

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



Interferometry and Diffractive Optics

C. Pruß

- Testing of Aspheres and Freeform Surfaces
- Design, Fabrication and Testing of Hybrid Refractive/ Diffractive Systems
- Microoptical Systems
- Tailored Optics for Metrology Applications
- Interferometry and Wavefront Sensors

Coherent Metrology

Dr. G. Pedrini

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

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Staff of the Institute

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Guest Scientists

Prof. Dr. Bahram Javidi**	Univ. of Connecticut (USA)	
Dr. QuanYing Wu	Soochow Univ., Suzhou (China)	9/2009 – 6/2010
Dr. Guohai Situ*	Chin. Academic of Sciences, Bejing (China)	3/2008 – 9/2010
Yizhuo Zhang	Beijing Univ. of Technology (China)	9/2009 – 9/2010
Jun Ma	Nanjing Univ. (China)	9/2009 – 12/2010
Giorgio Pariani	Politecnico di Milano (Italy)	10/2010 – 3/2011
Dr. Caojin Yuan*	Hunan Univ. (China)	12/2009 – 6/2011
Prof. Ventseslav Sainov	Bulg. Academy of Sciences (Bulgaria)	11/2010 – 12/2010

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* *Humboldt fellowship*

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

Foreign Guests visiting the Institute: 2009 – 2010

Prof. Dr. Yoshiharu Morimoto	Wakayama Univ. University, Japan	January 2009
Prof. Dr. Motoharu Fujigaki	Wakayama Univ. University, Japan	January 2009
Dr. Florian Bociort	Univ. Delft, Netherlands	February 2009
Prof. Dr. Charles Joenathan	Rose-Hulman-Univ., USA	March 2009
Dr. Marc Georges	Univ. Liege, Belgium	September 2009
Prof. Dr. Pryputniewicz	Worcester Polytechnic Institute, USA	September 2009
Prof. Dr. Charles Vest	President National Academy of Engineering, USA	September 2009
Prof. Dr. Ichirou Yamaguchi	Gunma Univ., Japan	September 2009
Prof. Dr. R. Dändliker	University of Neuchatel, Suisse	September 2009
Dr. Chris Koliopoulos	Zygo, USA	September 2009
Dr. Jan Burke	CSIRO, Australia	September 2009
Prof. Xiang Peng	Shenzhen Univ., China	September 2009
Prof. Dr. Armando Albertazzi Jr.	Univ. Florianopolis, Brazil	September 2009
Dr. Arie den Boef	ASML, Netherlands	September 2009
Dr. Kay Gastinger	SINTEF, Norway	May 2010
Prof. Dr. Kazuyoshi Itoh	Osaka Univ., Japan	June 2010
Dr. Nadya Reingand	CeLight Inc., Silver Spring, USA	June 2010
Dr. Arie den Boef	ASML, Netherlands	June 2010
Prof. Ventseslav Sainov	Bulg. Academy of Sciences, Bulgaria	September 2010
Prof. Yoris Dirckx	Univ. Antwerp, Belgium	September 2010
Dr. Yu Fu	National Univ. Singapore, Singapore	October 2010
Prof. Dr. Kazuyoshi	Itoh, Osaka Univ., Japan	November 2010

New professorship for optical design and simulation

Beginning of February 2011 Prof. Dr. Alois Herkommer occupied the newly established professorship for „optical design and simulation" at the ITO. The position could be instituted due to the introduction of the joint bachelor program "medical engineering" at the universities of Stuttgart and Tübingen and is partly funded by the German optical industry. Participating companies are: Trumpf GmbH & Co. KG, Polytec GmbH, Karl Storz GmbH & Co. KG, Sick AG, Berliner Glas KGaA Herbert Kubatz GmbH & Co and Leica Microsystems GmbH.

Alois Herkommer
new professor for optical design and simulation at the ITO

Alois Herkommer was born in 1967 in Thannhausen (Germany) and studied physics at the University of Ulm. After his diploma he was engaged at the department of quantum physics at the University of Ulm under Prof. Dr. Wolfgang Schleich. His research was focused on the interaction of atoms with light fields and he finished his doctor-thesis in 1995 with the title „Atom optics in quantized light fields". In 1996 he decided for a career in industry and joined the Carl Zeiss AG in Oberkochen. Until 2011 he filled several positions within the company: From 1996 to 2000 he worked as an optical designer and project manager on the development of high performance optical systems for lithographic projection and wafer inspection systems. From 2000 to 2005 he was team leader and senior scientist of the optical design group of the Carl Zeiss Laser Optics GmbH. The work of the group was focused on the development of optical components for Excimer lasers, spectral components, laser material processing systems and X-ray optics. Since 2005 he was heading the optical design group at Carl Zeiss SMT GmbH, which is responsible for the optical design of illumination and projection optical systems for microlithography.

Since February 2011 Prof. Herkommer is with the ITO – now looking forward to merge his broad background in optical design with the optical competencies at the ITO. His goal is to generally extend expertise for the optical design of imaging and illumination optical systems at the University of Stuttgart. Accordingly he will focus on the development of design and simulation methods, with a special focus on the application and integration of complex surfaces, like diffractive and microoptical structures. One research topic is the combination of ray-tracing methods with waveoptical and rigorous simulations.

Moreover Prof. Herkommer is interested in the design and application of optical systems for medical purposes: Optical systems are the basis of many modern medical devices. In consequence innovative optical designs are an important factor in the development of more efficient systems for diagnostics as well as for therapy. Advanced and competitive medical devices will be beneficial for patients as well as for economy, since the medical industry is an important business factor in Germany. In order to fulfill industries growing demand on graduates in the field of medical engineering, the universities of Stuttgart and Tübingen have recently established the new joint bachelor program "medical engineering". One fundamental part of the curriculum is an education in optics. Courses in technical optics, optical design and optical metrology within this bachelor program and also within a consecutive master program will thus represent the focus of Prof. Herkommers teaching activities.

I am proud to be selected for this challenging position. Being part of such an excellent optical institute as the ITO is a great honor for me and I am looking forward to work with the team on innovative optical designs for many applications. Thank you ITO for the very warm welcome!

Alois Herkommer

For more information on medical engineering: www.uni-medtec.de

Project partners

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

ASML Netherlands B.V.	Veldhoven, Netherlands
Audi AG	Ingolstadt
Carl Zeiss AG	Oberkochen
Carl Zeiss SMT AG	Oberkochen
Continental Teeves AG	Hannover
Daimler AG	Untertürkheim
FOS Messtechnik GmbH	Schacht-Audorf
Fraunhofer IPA	Stuttgart
Fraunhofer IPT	Aachen
Fraunhofer IWU	Chemnitz
GSAME, University Stuttgart	Stuttgart
Holoeye AG	Berlin
HSG-IMAT	Stuttgart
Ifm electronic	Meckenbeuren
IMTEK, University Freiburg	Freiburg
Institute of Industrial Manufacturing and Management, University Stuttgart	Stuttgart
Institute of System Dynamics, University Stuttgart	Stuttgart
Instrument Systems	München
LaVision GmbH	Göttingen
Mahr OKM GmbH	Jena
MAN Truck & Bus AG	Nürnberg
PMD Technologies GmbH	Siegen
Polytec GmbH	Waldbronn
Promicron	Kirchheim / Neckar
Robert Bosch GmbH	Gerlingen
Singulus Mastering BV	Eindhoven, Netherlands
U-L-M Photonics	Ulm
University of Wuppertal, Prof. Tibken	Wuppertal
Volkswagen AG	Wolfsburg

Studying optics

Our curriculum is primarily directed towards the students in upper-level courses of **Mechanical Engineering, Cybernetic Engineering, Mechatronics, and Technology Management**. Since the academic year 2009/10 we offer for the first time our courses "Fundamentals of Engineering Optics" and "Optical Measurement" for the bachelor students in the above mentioned degree programmes.

For the next academic year 2011/12 we especially recommend the new master programme "Micro-, Precision- and Photonics 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.

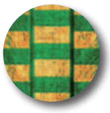
Elective subjects:

- Optical Phenomena in Nature and Everyday Life (Dr. T. Haist)
- Fundamentals of Colorimetry and Digital Photography (Dr. K. Lenhardt)
- Polarization Optics and Nanostructured Films (Dr. K. Frenner)
- Introduction to Optical Design (Dr. Ch. Menke; Zeiss)

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 (macro- and microscopic)
- adaptive techniques using spatial light modulators
- confocal microscopy
- white light interferometry
- spectral interferometry
- sensorfusion and data interpretation strategies

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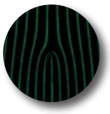

Active Optical Systems and Computational Imaging

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
- computational imaging

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High Resolution Metrology and Simulation

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

Current research areas:

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

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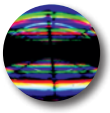

Interferometry and Diffractive Optics

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 for aspheres and freeform surfaces that aim to 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 imaging systems, UV-measurement systems, beam shaping applications and wavefront sensing.

Our research areas include:

- testing of aspheric and freeform surfaces
- design, fabrication and testing of hybrid refractive/diffractive systems
- interferometry and wavefront sensors
- tailored optics for metrology applications
- fabrication of diffractive optics

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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
- remote and virtual laboratories

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RESEARCH PROJECTS

3D-Surface Metrology

Active Exploration:
A Multi-Scale Measurement System for Defect Detection

A. Burla, W. Lyda, 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 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).

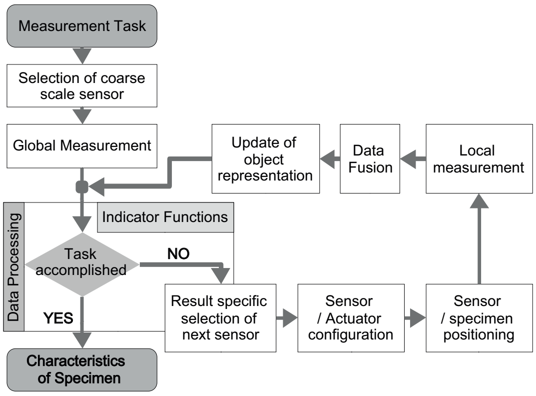

Fig. 1: *AMMS-strategy.*

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 (Fig. 2) for inspection of microlens arrays and micro electromechanical systems (MEMS). A video microscope is used to receive an initial outline of the specimen which is 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 micro-scope down to 0.6 µm with the confocal point sensor. In the middle scale the confocal microscope offers a variable lateral resolution from 10µm 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 from 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 provide 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 microlens arrays and MEMS were used as measurement objects, due to the wide bandwidth of possible defects and defect sizes. On microlens arrays, three distinct defect types were considered: 1) point-like defects, such as minute particles, dust, speckles, etc. 2) one-dimensional defects, including cracks, scratches, fine fibres, etc., 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 also tested for reliability with different surface and shape defects, simulated using synthetic data based on mathematical methods.

The indicator algorithms for the inspection of micro lens arrays include Fourier self-filtering, two-point statistical texture featuring, scratch detection, normalized cross correlation and Fourier descriptors. These algorithms are parameterised according to the type of defect.

For the MEMS-inspection the used indicator algorithms are based on wavelet transformation, correlation and local thresholding. Further indicators include local roughness and the variation in the confocal raw signal.

A crucial point in the AMMS-strategy is the automatic selection of sensors and indicator evaluation algorithms and the task dependent adaption of their parameters. Therefore we introduce two assistant systems (hardware assistant and software assistant), which help in choosing the most suitable components depending on the task considering the properties of the object (e.g. material, surface roughness, etc.) and the defects (e.g. defect types, dimensions, etc.). The hardware assistant system uses general rules of thumb, sensor models/simulations and stored expert knowledge to specify the most suitable sensors along with their parameters and the hierarchy (if necessary) in a multiscale measurement system. The purpose of the software assistant system (SAS) is to automatically generate and optimize image processing algorithms necessary for defect/indicator identification. For this purpose, a stochastic evolutionary method called genetic programming is used. SAS is a learning based system which uses training input and a flexible fitness function to iteratively generate and evaluate the algorithms. Training input contains several measured or simulated measurements along with user generated defect binary masks (indicating defect positions). The Fitness function is weighted combination of specificity, sensitivity and sum of absolute differences. The user will then be able to use the algorithms generated by the SAS based on the training input to identify defects on new measurements. Fig. 3 shows the basic principle of the SAS.

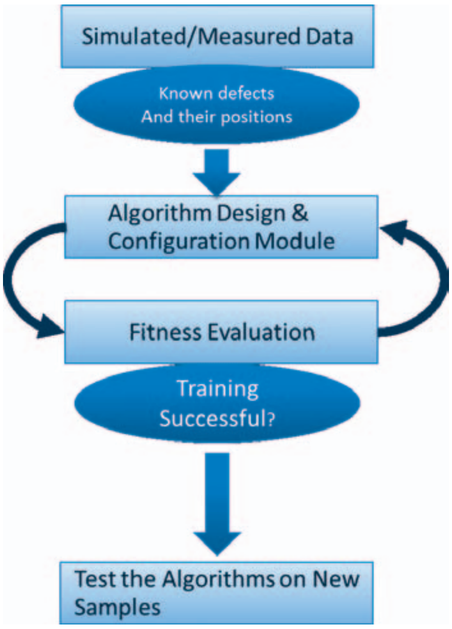

Fig. 3: *Basic working principle of the software assistant system.*

A simple language parser has been implemented to translate the user specifications into machine readable instructions (C++ functions). These instructions are further used for selecting and optimizing the components. The optimization criteria can be freely assembled in the user specifications. Up till now, first assistants for fringe projection, video microscopy, and confocal microscopy have been implemented using C++. It was verified experimentally, that the results from the hardware assistant and from a human expert match for a sample inspection task for detecting surface scratches. For the SAS, it is important to properly choose the training input as well as the optimization parameters like population size, crossover rate, mutation rate, etc. Proper training requires enough measurements/simulations of all possible types of defects. The assistant system is currently implemented using OpenCV in combination with C++.

Fig. 4 shows a measurement of a microlens array measured using a confocal microscope with 20X magnification, here the task was to detect lenses which have form defects. The SAS was able to generate an algorithm to indicate the defects (see Fig 5).

Future work is focused on the transfer of the AMMS-strategy to more complex technical objects. Therefore the field of view planning, data fusion and the sensor registration data have to be improved.

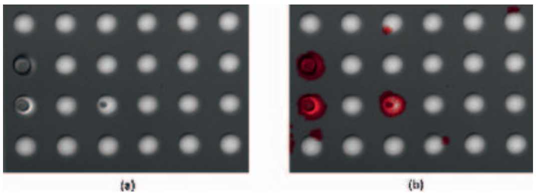

Fig. 4: *(a) A real measurement of a microlens array measured using a confocal microscope with 20X magnification, (b) successfully indicated lens defects (algorithm shown in Fig. 5).*

Supported by: DFG (OS 111/18-3)
Project: "Neue multiskalige Mess-, Steuer- und Prüfstrategien für die Prüfung von Mikro- und Nanosystemen in der Produktion"

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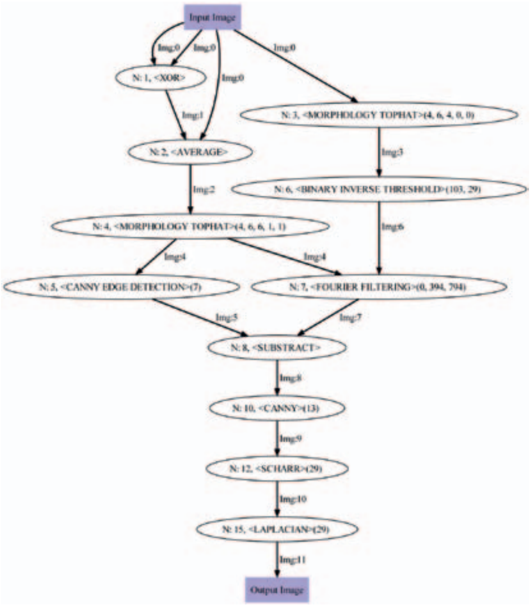


Fig. 5: *Automatically generated algorithm for lens defect detection on microlens arrays measured using a confocal microscope with 20X magnification (see Fig. 4).*

Chromatic confocal spectral interferometry (CCSI)

W. Lyda, M. Gronle, D. Fleischle, 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.

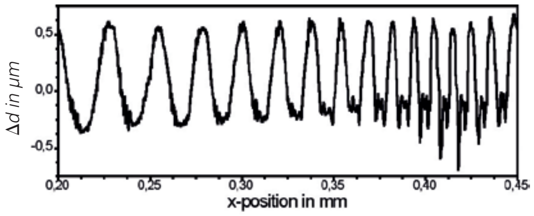
In common used spectral interferometers (SI) the measurement range is given by the depth of focus leading to a restriction of the numerical aperture. The combination of chromatic separation and confocal filtering decouples the measurement range from the depth of focus, which yields to higher numerical 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 (20 µm axial range with 0.6 NA were reported) by means of a diffractive optical element – DOE. 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 employed optical spectrum 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 addressed. The CCSI principle has been implemented in two prototype setups: a Mirau-type interferometer (0.6 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 results demonstrate the applicability of this method for the optical detection of objects with rough surfaces and limited reflectivity as well as strongly curved optical surfaces.

***(a)** Chromatic-confocal measurement*



***(b)** CCSI-measurement*

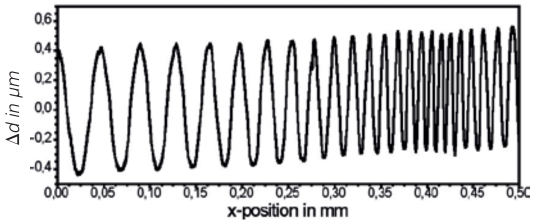


***Fig. 1:** Measurement of a chirp comparison standard (by PTB-Braunschweig) with chromatic confocal microscopy (a) and CCSI phase evaluation (b) showing reduced overshooting in the CCSI-measurement.*

Supported by: DFG (OS 111/21-2)
Project: "Chromatisch-konfokale Spektral-Interferometrie zur dynamischen Profilerfassung"

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Combination of rigorous coupled wave analysis and high speed non sequential raytracing for high accuracy modelling of array spectrometers

F. Mauch, W. Lyda, W. Osten

In the course of the BMBi project "Präzisions-Charakterisierung von weißen LEDs und LED-Beleuchtungen", a simulation scheme for simulating a linear grating spectrometer with high precision and high speed was developed.

The performance of high end spectrometers is typically limited by stray light in the optical system. Figure 1 shows the optical setup of a typical array spectrometer in Czerny-Turner configuration. Figure 1 also shows the ray paths for monochromatic illumination of seven diffraction orders of the grating. All the rays hitting the spectrometer housing will be scattered diffusely and may ultimately still reach the detector.

In order to model this behaviour of the spectrometer with high accuracy, a RCWA simulation using an AFM scan of the grating surface was used to rigorously calculate the efficiencies of the diffraction orders in dependence of the wavelength of the illumination. Furthermore stray light measurements were conducted to phenomenologically account for the diffuse scattering of the grating and the spectrometer housing.

This data was used to create special reflectance functions for the grating and the housing parts for a non sequential ray tracing model of the spectrometer system. However in order to simulate intensity distributions with a SNR of 104, that are typical in spectrometers, at least 108 rays are required to reach the detector.

Tracing times for raysets of that size manifest a serious bottleneck in the systematic optimization of spectrometers. Therefore a non sequential ray tracing tool was developed that is highly specialized for simulating intensity images. The tool can be executed using either a single CPU, multiple CPUs in parallel or modern graphics processing units (GPU). Figure 2 shows the computation times of this tool in comparison to the commercial software ASAP. At a raynumber of 108 the developed tool running on GPU is about 400 times faster than the commercial tool. E.g. the simulation of monochromatic illumination that took a little more than 3h with ASAP on an Intel i7 machine with 3.2 GHz could be done in about 30 s using a GTX460 graphics card.

Future work will elaborate on possibilities to use this kind of high speed simulation for automated stray light optimization of general optical systems.

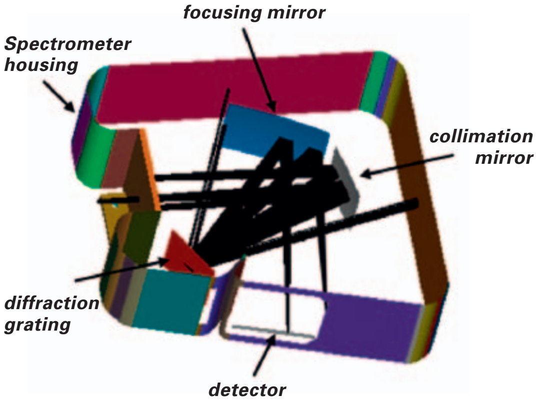

Fig. 1: *3D plot of the Simulation model of the spectrometer in ASAP.*

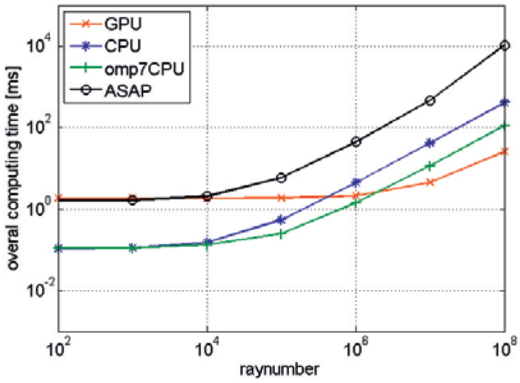

Fig. 2: *Comparing overall computation times. GPU, CPU, omp7CPU and ASAP indicate simulation running on GPU, a single CPU core, 7 hyperthreading cores on 4 physi-cal CPU cores and the commercial software ASAP running on single CPU core respectively.*

Supported by: BMBi (FKZ 13N7861)
Project: "PräziLED"

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Concepts for the integration of optical sensors into machining processes

D. Fleischle, W. Lyda, W. Osten

In manufacturing monitoring and inspection an essential task is to maintain a high product quality. Therefore a variety of systems (e.g. tactile systems, acoustic systems, optical systems) is used. However there is still a lack in controlling the product quality near the production machine. For the selection and the design of an appropriate monitoring strategy the specification of the applied sensors is of crucial importance.

Optical sensors are in general suitable to measure quality relevant features. But they are often not robust enough, to use them in harsh environments such as the workshop floor. However to detect as early as possible if quality runs out of specification, the high resolution of optical measurement systems is often not needed. In these cases optical sensors can be implemented successfully even if their measurement uncertainty is increasing due to the harsh environment. To verify this hypothesis an evaluation of environmental influences has to be made and a comparison between the acceptable and still achievable measurement uncertainty has to be made.

A classification of sensor systems used for monitoring of manufacturing processes can be obtained regarding their degree of integration (fig.1):

- separated measurement (off-line), where the measurement device is separated from the production
- machine integrated measurement (in-situ), where the monitoring system is implemented into the production process, but it is still separated from the machining process.
- tool integrated measurement (in-process), where the sensor is implemented as near as possible to the machining process or even in the machining tool.

The case of in-process monitoring implements the shortest feedback loop and even a process control during machining can be established.

But the measurement system has to deal with the environmental influences. To know what precision and measurement uncertain-

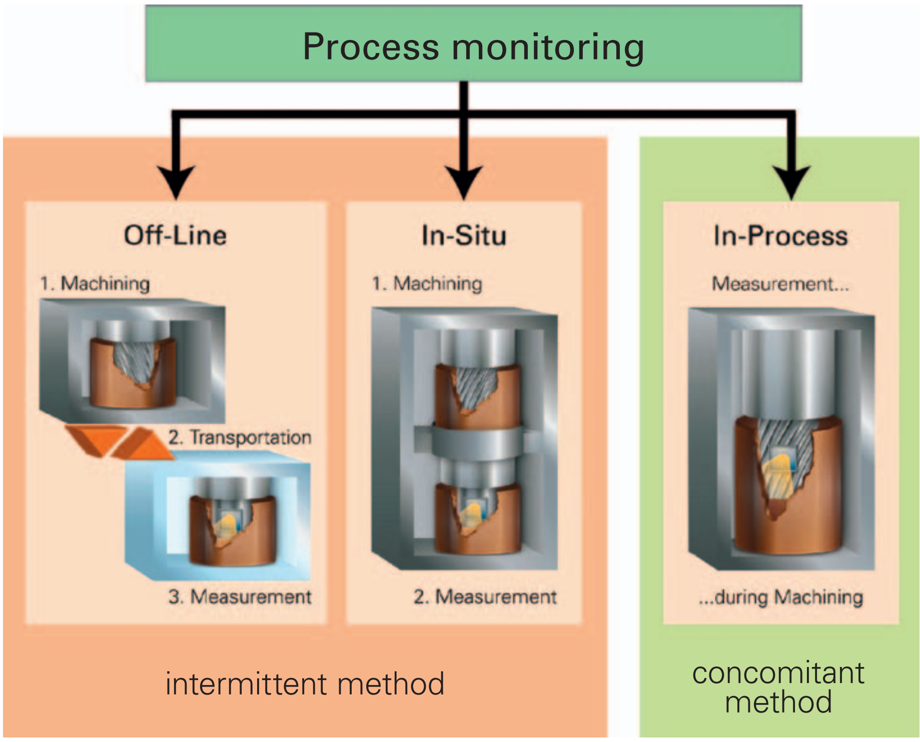

Fig. 1: *Different degrees for the integration of optical sensors into production processes.*

ties are reachable an accurate consideration of the impact of the environmental influences has to be obtained. To come to a schematic consideration of all relevant error sources, the problem should be simplified into different parts of the process to obtain the topography description. In Fig. 2 this process is displayed. The sensor signal is given by the interaction of the specific answer of the sensor system, the response of the reflected light by the object and the influences of the environment. Is the measurement obtained in the production machine the fusion of sensor data and machine data has to be considered. With the investigation of the influence of these parameters the estimation of the achievable measurement uncertainty in the production process is possible.

To investigate into the behaviour of the measurement a simulation tool was developed. With this ray-based simulation it is possible to analyse the resulting signal of optical sensors. For example in Fig. 3 the signal of a chromatic confocal sensor for the measurement of rough surfaces is shown. In the figure the simulation of a rough surface is compared with a measurement of a randomly rough surface.

Furthermore an investigation into the influence of environmental impact is possible. For vibrations the resulting standard deviation for different measurement times for a superposition of sinusodial vibrations with a frequency of 50 Hz to 5 kHz is shown in Fig. 4. It is obvious that with an increasing integration time the standard deviation is decreasing due to averaging of the vibration.

Supported by: Graduate School of Excellence advanced Manufacturing Engineering GSaME

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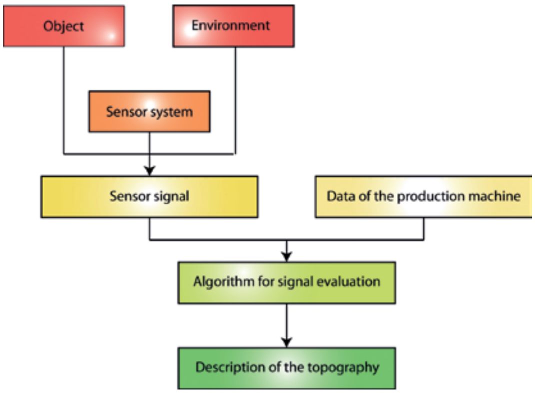

Fig. 2: *Schematic signal formation process to obtain the description of object topography.*

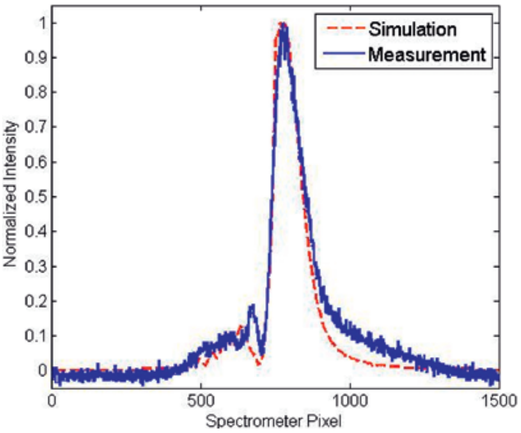

Fig. 3: *Simulation and measurement with a chromatic confocal sensor of a rough surface.*

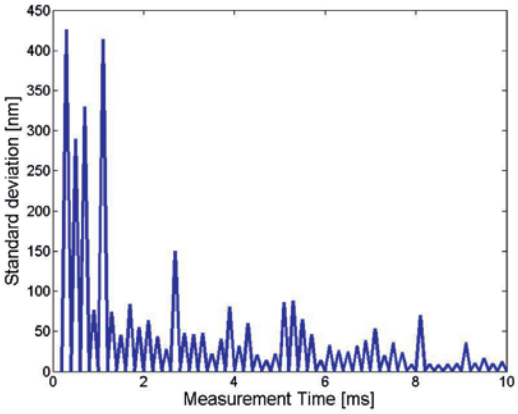

Fig. 4: *Simulated standard deviation of a chromatic confocal sensor for a superposition of sinusodial vibrations with frequencies of 50 Hz to 5 kHz.*

Hybrid simulation for model based characterization of optical measurement systems

F. Mauch, D. Fleischle, M. Gronle, W. Lyda, W. Osten

Within the BMBF project "Anwenderorientiertes Assistenzsystem zum sicheren Einsatz optischer Abstandssensoren", an assistance system for optical surface measurements will be developed. It will assist the user to optimally configure a confocal microscope or a white light interferometer for a specific measurement task. Furthermore, this assistance system will give a traceable estimate of the uncertainty connected to a given measurement. This is of special interest to car manufacturers that want to characterize functional surfaces with optical sensors. While the collaboration partners including several industry partners as well as the Institut für Messtechnik und Sensorik and the Fraunhofer IPT are jointly working on the complete process from desired surface features to a measurement of these features (see figure 1). ITO is focusing on the signal chain from the real surface towards the measured surface with a confocal microscope.

As a prerequisite for this, a simulation scheme has to be developed that is able to correctly predict the behaviour of the various sensor configurations in realistic measurement situations. In particular, this simulation scheme has to be able to reproduce effects related to rough surfaces, surface edges, aberrations in the optical system and diffraction at apertures of the optical system. These specifications manifest a dilemma for choosing an appropriate simulation method. While rigorous methods such as finite difference techniques are able to describe the interaction of a light field with a microstructured surface correctly, their application to simulating optical systems covering a volume exceeding a few cubic micrometers is hopeless. Ray tracing methods on the other hand are widely applied in designing and analyzing optical systems, but offer no obvious mechanism to describe diffraction effects. Unfortunately, combining both simulation methods is far from trivial.

As first steps the measurement of a perfect mirror with a confocal microscope was successfully simulated using conventional ray tracing (see figure 2). However, as the imaging properties of the micro lenses in the micrsoscope are highly diffraction limited, the detection pinhole had to be chosen an order of magnitude smaller than in reality. Furthermore a tool was developed that uses standard graphics cards (GPU) to trace rays depending on the application up to 100 times faster than on CPU based tools (see figure 3).

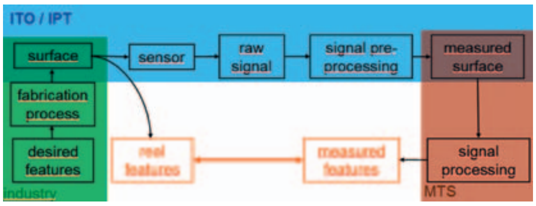

Fig. 1: *Project structure showing the competence fields of the project partners*

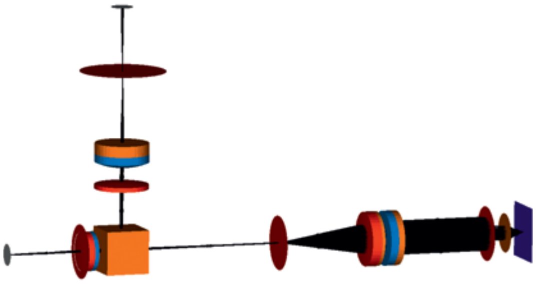

Fig. 2: *3D plot of the Simulation model of a confocal microscope with rotating microlens array showing the ray paths for one microlense in ASAP.*

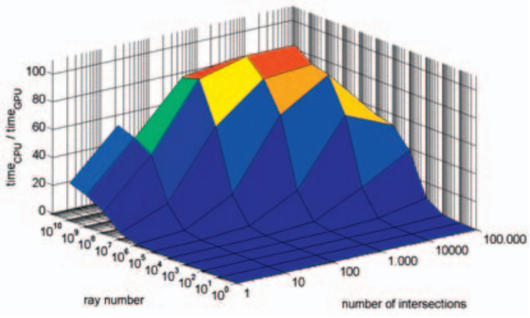

Fig. 3: *Comparing computation times for nonsequential raytracing on GPU and CPU depending on the number of rays and the number of calculated intersections.*

Supported by: BMBF (FKZ 13N10386)
Project: "OptAssyst"

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InSitu surface metrology: Integration of a white light interferometer into a high precision grinding machine for diamond tools

R. Berger, D. Fleischle, W. Lyda, W. Osten

Diamond tools can produce sophisticated optical surfaces on plane and curved substrates. The production techniques are for example fly-cutting for ultra-precision turning and grinding. 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 worked together to develop a six-axis machine with an integrated optical measurement system for the manufacturing of freeform Diamond tools (see fig. 1). The manufacturing process is intermitted by several measurement cycles. The results of the measurements have to 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.

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 (see fig. 2). 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 transmission light device for the digital image processing.

The digital image processing with the transmission 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, the point clouds of several topography measurements, achieved by the white-light interferometer, are automatically stitched together.

Fig. 1: *Six-axis machine wit an integrated optical measurement system (source: IPT, Aachen).*

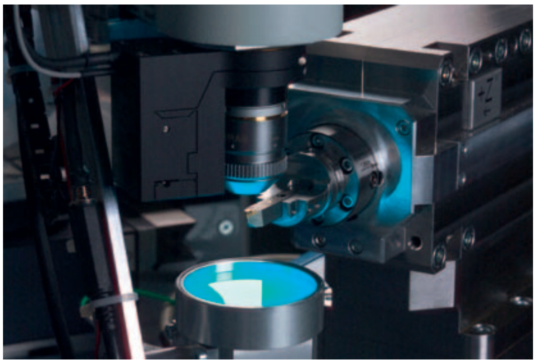

Fig. 2: *Optical measurement system consists of a white-light interferometer with a transmitted light device for digital image processing (source: IPT, Aachen).*

In Fig. 3 a measurement of a diamond tool is shown. This measurement was obtained with digital image processing by edge detection. To sample the whole object it was necessary to obtain a stitching of several measurements. To estimate the vertex radius of this tool a fitting of a circle was obtained. Thus a value of 1,023 mm was determined for that radius.

However the measurement is obtained by the use of the axis of the production machine. This axis has a certain error. But if a precise measurement has to be obtained, the implied error due to axis uncertainty has to known. There for a simulation investigation into the resulting standard deviation in the measurement depending on the uncertainty of the machine axis has been implemented. In Fig. 4 the results of a simulation are shown.

Future work will investigate the reliability of the complete measurement system and its actuators in respect to the environment. Furthermore a complete automatisation of the measurement procedure is desirable.

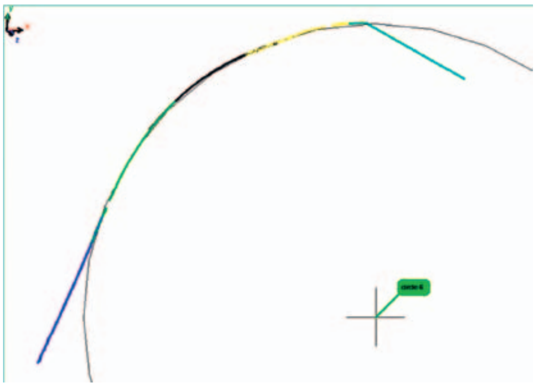

Fig. 3: *Stitched measurement of a diamond tool and fitting of a circle to estimate vertex radius.*

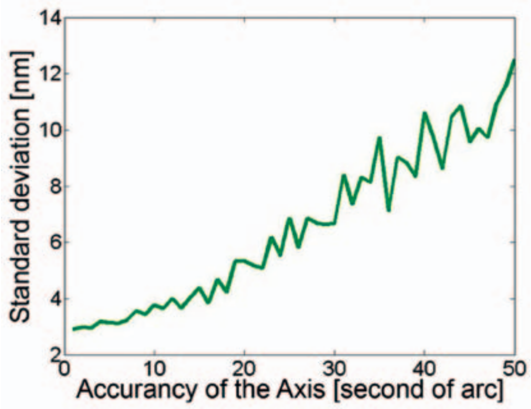

Fig. 4: *Simulation of resulting standard deviation in measurement depending of accuracy of machine axis.*

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

Project partner: Fraunhofer Institut für Produktionstechnologie, Aachen; Mahr GmbH, Göttingen; IMOS Gubela GmbH, Freiburg; UPT-Optik Wodak GmbH, Nürnberg; Diamant-Gesellschaft Tesch GmbH, Ludwigsburg; LT Ultra-Precision Technology GmbH, Herdwangen-Schönach

Optical measurement system for estimation of the position of the piston in a one-way dosing pump

K. Körner, A. Burla, W. Lyda, W. Osten

We investigate approaches for the highly resolved measurement of the position of the piston in an one-way dosing pump, see Fig. 1. The main objective is to ensure a low uncertainty in the rate of delivery from 10 µl/min to 100 ml/min with the pump module. Here, the independence of the measurement from pressure, viscosity, temperature, and colour of the fluid media is of special interest. The planned industrial application requires both, a robust and a low-cost solution that does not allow any modification of the pump construction produced a million times every year.

So we focused our efforts in the project to a VGA-Webcam-based microscopic approach that directly detects the lip of the moving seal of the pump.

In a very first experiment, the whole pump was shifted with a precision stage. A sequence of 200 images was recorded, where in each image, the syringe head is moved 0.5 µm relative to its previous position.

Two methods have been used to detect the motion in the sequence of images.

1. Correlation Based Method:

In this method, the motion of the syringe head is estimated based on the image gradient and cross correlation. The first image in the sequence is considered as the reference image. For every row of the image the edge of the syringe head is estimated using a gradient filter. The resulting gradient row is then correlated with the corresponding gradient row of the reference image. The position of the corresponding correlation peak indicates the shift of the syringe head in that row. This process is performed for every row and on the basis of the mean shift of all the rows, the position of the syringe head in this image is computed.

In order to acquire sub-pixel accuracy the centroid of the correlation peak is used. Measurement images can be cropped based on Region of interest to eliminate errors due to false edges originating from the print on the syringe.

2. Mean Gradient Method:

In this method, the mean shift relative to the reference image is estimated based on just the gradient operation. The average of the centroids computed around the peak positions of every row gradient is considered as the shift of the syringe head in this image.

Fig. 2 shows the calculated position of the moved lip (with the whole syringe) over about 4 pixels of the VGA-Webcam. Every camera pixel is covered by a single micro lens. Therefore, the fine structure of the camera is also detected. These results suggest that interpolation methods can deliver a sub pixel resolution, also for an unsteady shape of a shifting lip under pressure in a medium.

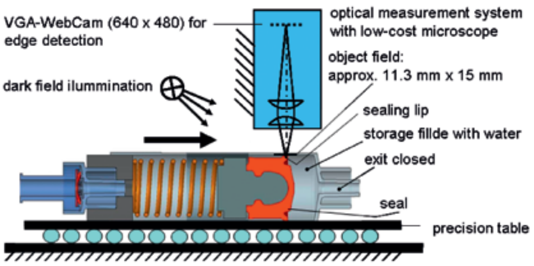

Fig. 1: *One-way pump element (syringe) with optical measurement system (courtesy of HSG-IMAT, University of Stuttgart).*

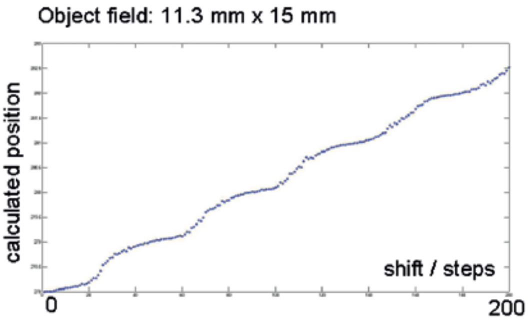

Fig. 2: *Shift of the sealing lip of the one-way pump element (syringe) over about 4 pixels of a VGA-WebCam, signal evaluation was performed by the correlation based method.*

Supported by: AIF, IGF-No.: ZN09560/09, ITO project No.: 16653 N
Project: "Optical measurement system for estimation of the position of the piston in a one-way dosing pump"

Project partner: HSG-IMAT, University of Stuttgart

Active Optical Systems and Computational Imaging

Stable 3D trapping using axially extended intensity distributions

S. Zwick, C. Schaub, T. Haist, W. Osten

Optical tweezers are versatile tools to trap and manipulate microscopic-sized particles by means of light. Using a focused laser beam, particles with the size of nanometers up to several tenths of micrometers can be trapped. In order to achieve stable three-dimensional trapping with optical tweezers, a strong axial intensity gradient has to be generated. This is normally realized using a high numerical aperture microscope objective. A high numerical aperture however leads to strong localization of the trapping region. If an object is not positioned in the trapping plane, it is pushed away by the scattering force. In this case manual trapping in practice is tricky and depends strongly on the experience of the user. Objects are often pushed away during the first try to trap and, therefore, have to be tracked using the defocus of the microscopic stage. This considerably complicates the trapping of several objects at the same time and makes automation difficult.

The main difficulty of trapping is due to the small axial extension of the light field in the object plane. We improve this situation by employing a light field with an axially expanded intensity distribution, which at the same time enables stable axial trapping.

A well-known possibility to do so is the trapping with the so-called Bessel beam. Bessel beams are generated using an axicon which is inserted into a Gaussian beam. The intensity distribution on the optical axis, which is generated by the help of an axicon shows an axial expansion.

Therefore, it provides a focal line of light which is laterally very well localized along the optical axis. For this reason, pushing an object along the optical axis (optical guiding) is easier with a Bessel beam than with a Gaussian beam.

In order to analyse the light field generated by an axicon in the Fourier domain, simulations have been performed using scalar diffraction theory. A homogeneous plane wave illumination of the axicon has been assumed. The simulations as well as the experiments have been performed for/with a water-immersion microscope objective with 63x magnification and a numerical aperture of 1.2 W. The axicon was realized using a spatial light modulator based holographic optical tweez-ers setup. By this approach it is simple to test different axicon parameters and to compare against conventional trapping without the axicon.

It turned out that compared to conventional trapping indeed stable axial trapping is much easier to achieve. The method is especially important for automation of optical trapping.

Additional work has been performed to further improve holographic twin traps (see last annual report).

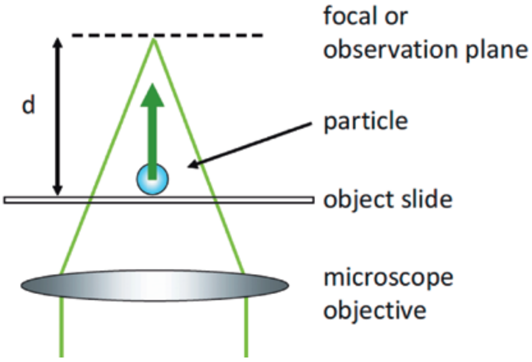

Fig. 1: *The particle is pushed to the focal plane by the forward scattering force. The axicon guides the object along the way.*

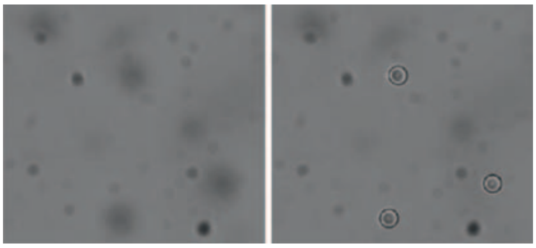

Fig. 2: *Experimental result for polystyrene beads. Left: Objects in the "wrong" plane, not trapped. Right: Switched on holograms (in-cluding axicon term) leads to trapping and movement of the par-ticles into the focal plane.*

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

References:

[1] Zwick, S.; Schaub, C.; Haist, T.; Osten, W. "Light fields with an axially expanded intensity distribution for stable three-dimensional optical trapping" Optics Express 18, 19941-19950 (2010).

[2] Zwick, S.; Haist, T.; Miyamoto, Y.; He, L.; Warber, M.; Hermerschmidt, A.; Osten, W. "Holographic twin traps", J. Opt. A: Pure Appl. Opt. 11, 034011 (2009).

[3] Zwick, S., Haist, T., Warber, M., Osten, W., "Dynamic holography using pixelated light modulators," Appl. Opt. 49, F47-F58 (2010).

Dynamic correction of aberrations using a combination of stochastic optimization and gradient-based measurement

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

Typically, aberrations in high-quality microscopes that degrade the image are due to the specimen to be imaged or from the solution in which the specimen is embedded. Furthermore, aberrations might be introduced by the handling devices (cover slide, microfluidics, multiwell plates, etc.). Therefore, the aberrations are static for one setting, but variation of the specimen or the system will change the aberrations.

We use a combination of a gradient measurement system that is related to Shack-Hartmann sensing and stochastic optimization. The core element is the liquid-crystal display (LCD) that is already present in spatial light modulator-based microscopes. The LCD is located in a plane conjugate to the pupil of the microscope objective and in this plane the aberrations are corrected by writing the phase conjugate of the aberrated wavefront into the (phase-only) LCD. Before this can be achieved, the aberrations are measured. To this end, we first write different localized gratings into the LCD which lead to shifted (low resolution) copies of the object in the camera plane. Local wavefront tilts due to the aberration will lead to additional shifts of the corresponding copies and are detected by digital correlation of the image with reference images taken for the central part of the aperture. This way the local gradients in the pupil are determined and numerical integration (using SV-decomposition) finally leads to an estimate of the wavefront error.

In a second step, this wavefront is further stochastically varied until the image quality is optimum. The optimization criterion is the ratio between the high-pass and low-pass Fourier components.

To obtain impressive corrections, typically some hundred camera frames are necessary. Therefore a setup time in the range of 1 minute for a typical experiment would be necessary but the system can achieve the correction without additional hardware (an external wavefront sensor).

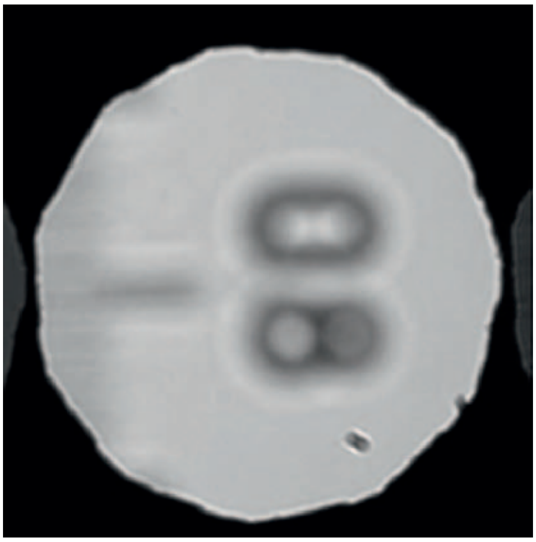
Fig. 1: *Without correction.*

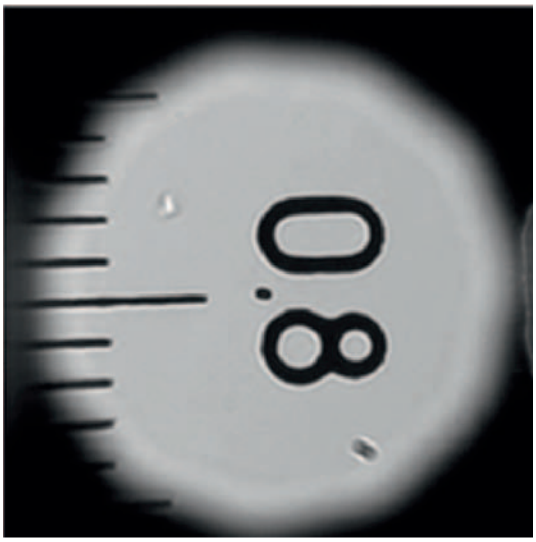

Fig. 2: *With correction.*

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

References:

[1] Haist, T. ; Hafner, J.; Osten, W. "Scene-based wavefront correction with spatial light modulators" Proc. SPIE 7064, 70640M, (2008). [2] Warber, M.; Maier, S.; Haist, T.; Osten, W. "Combination of scene-based and stochastic measurement for wide-field aberration correction in microscopic imaging" Appl. Opt. 49, 5474-5479 (2010).

Dynamic Holography-based Vibrometry

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

The measurement of vibrations is of considerable importance in a lot of engineering as well as scientific applications. Different optical techniques ranging from full-field holography to single-point interferometers are known. Best accuracies for small amplitudes can be achieved using laser Doppler vibrometry (LDV) realized by heterodyne interferometry. Unfortunately, the systems that are commercially available are based on single points or a straight forward parallelization of the heterodyne concept leading to very complex implementations. Single point sensors can measure even complex vibration modes if the vibration is periodic. For transient vibrations multipoint measurements in parallel are mandatory. Programmable dynamic holograms are one interesting possibility to realize such multipoint measurements.

To this end, the beam deviation which is necessary to reach the apropriate object points is achieved holographically. For the implementation a Holoeye Pluto HDTV liquid crystal on silicon (LCoS) modulator is employed. The main problem of the approach is the avoidance of spurious diffraction orders that might reach the detectors. Different approaches to achieve this have been investigated. Currently, the favourite approach is based on a sophisticated hologram optimization where the mapping of the object points to the detectors are used as the main degree of freedom in combination with some fixed stops in the optical system. One half of the HDTV LCoS modulator is used for the illumination hologram and the second half is used for the detection. On the detection side, all object points to be measured are imaged onto a pinhole mask that resides in a plane conjugate to the detectors.

Apart from the advantages for multipoint vibrometry, conventional scanning vibrometry might also profit from the LCoS-based holographic beam deflection. Scanning in this case is achieved without any mechanical moving components (e.g. galvano scanning) that might introduce measurement artefacts (spurious vibrations). Also, compact setups can be easily achieved and it is expected that the long term stability and lifetime of the vibrometer are improved. An additional advantage is the possibility to improve the speckle-contrast by introducing small phase perturbations into the dynamic hologram.

The computation of the holograms is performed directly on the graphics board. A scanning vibrometer prototype has been build in close cooperation with Polytec and first measurement confirm the working principle of the system as well as the speckle optimization.

The work is done in close cooperation with Polytec, Robert Bosch GmbH, Continental Teves, and the University of Wuppertal.

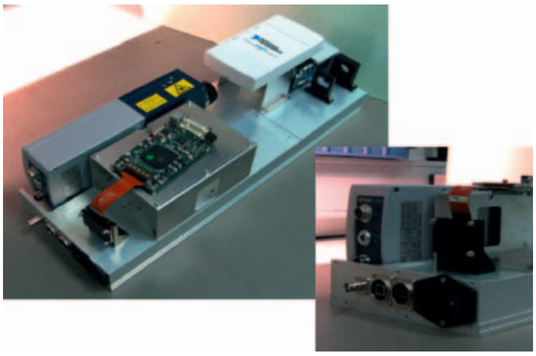

Fig. 1: *Prototype of SLM-based scanning vibrometer.*

Supported by: BMBF (FKZ 13N9339)
Project: "Holovib"

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[1] Schaal, F.; Warber, M.; Rembe, C.; Haist, T.; Osten, W. "Dynamic multipoint vibrometry using spatial light modulators", Proc. Fringe 2009, 529-531 (2009)

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White-light interferometric method for secure data transmission

T. Haist, W. Osten

It is well known that secure data transmission can be achieved if a random key of adequate length can be securely interchanged between the two partners (typically called "Alice" and "Bob"). Once this secure key is distributed, simple encryption/decryption can be achieved, e.g. by the XOR operation.

Unfortunately, for a lot of application this is not feasible (e.g. ordering over the internet). In this case two methods to distribute the key between Alice and Bob are available. Public key cryptography using public known keys and mathematical methods (unfortunately with unproven security) might be employed. One example is the RSA public-key system which is based on the unproven difficulty of factoring large integers. Other methods rely on the similarly unproven difficulty of computing discrete logarithms. Even if the algorithms could be proven secure, this security still would be only given for the transmission of small messages and, even worse, quantum computing can be used to successfully attack them. The second and currently only (hopefully) secure method to generate a secret shared key between two parties that are separated by a certain distance is quantum key distribution (QKD). Different quantum methods have been proposed but the corner stones of these techniques are the no-cloning theorem of quantum physics, the non-commutativity of certain pairs of observables (e.g. different polarizations) and the use of single photon. Practical systems using QKD have been realized but the use of single photons over large distances is still technically challenging and expensive.

We propose to use a white-light interferometric approach as shown in Fig. 1 to achieve the secure key distribution. Alice randomly choses the delay D1 to be a natural number between 1 and N. Bob does the same for D2. Now, Bob sets the delay D3 randomly to 0 or half of the wavelength. Alice then sends a short wavepacket with (on average) M photons (M < N) and coherence length L < 1 to Bob and measures at her interferference detector if interference is present. If yes then she knows that D1 was equal to D2 and then she can find the unknown random bit of Bob, namely D3 by the measurement result. This process is repeated for a large number of Bits. Finally, Alice sends Bob the information which bits have been transmitted with D1 being equal to D2. These bits, which are now known only to Alice and Bob, will be used as a secure key for classical data transmission.

Different possible attacks of an eavesdropper can be analysed and the simple basic protocol described above has to be changed in some minor ways to prevent these attacks [1]. Compared to quantum key distribution the main advantage is that the system achieves the security without the need for single photon operation. Therefore, potentially it should be much simpler to realize such a system. For the operation, "quantized waves" are necessary but no typical quantum features like entanglement or non-locality are necessary. Unfortunately, at the moment we do not have a sound prove of the security of the method.

Fig. 1: *WLI-based method for secure key distribution.*

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

References:

[1] Haist, T. ; Hafner, J.; Osten, W. "Scene-based wavefront correction with spatial light modulators" Proc. SPIE 7064, 70640M, (2008). [2] Warber, M.; Maier, S.; Haist, T.; Osten, W. "Combination of scene-based and stochastic measurement for wide-field aberration correction in microscopic imaging" Appl. Opt. 49, 5474-5479 (2010).

Surface Analysis of Honed Objects

A.Burla, T.Haist, S.Pehnelt, W. Osten

Automatic surface analysis of honed objects (SAHO) is a software module developed to detect, separate, visualize, and analyse thin, medium, and thick grooves on honed objects. For this purpose, measurements of the specimen obtained using a while light interferometer have been used. The process involves taking into consideration several problems and constraints (e.g. poor contrast, complicated structures on the surface, curved or overlapping grooves, grooves in several arbitrary angles, etc). Existing methodologies use Hough transformations and Fourier based filtering to separate the grooves. This method is very sensitive and hence not flexible. Another Fourier based method uses only 2d projections of 3d data.

Using the Abbott Firestone curve (also known as material ratio curve), a preliminary separation of the thin grooves, from the medium and thick grooves of the image can be achieved. The Radon transform is used on the thin grooves image to estimate the thin groove angles. Based on these groove angles a filter mask is generated to separate the thin grooves using Fourier based filtering. (Fig.1b shows the resulting thin grooves) Similarly, the Radon transform is used to estimate the groove angles of the medium and thick grooves.

Unlike thin groove separation, thick and medium grooves are separated using a special groove detection algorithm that takes the groove angles as input. For every angle the image is scanned to find all corresponding grooves within the required constraints (e.g minimum width, depth, groove quality factor etc.). The grooves can later be separated into thick and medium based on their widths. (See Fig.1c).

An average volume of the thin grooves is estimated using mathematical morphology. Also, several groove properties like primary groove angles, length, position, width, average depth, average volume etc are computed for the medium and thick grooves.

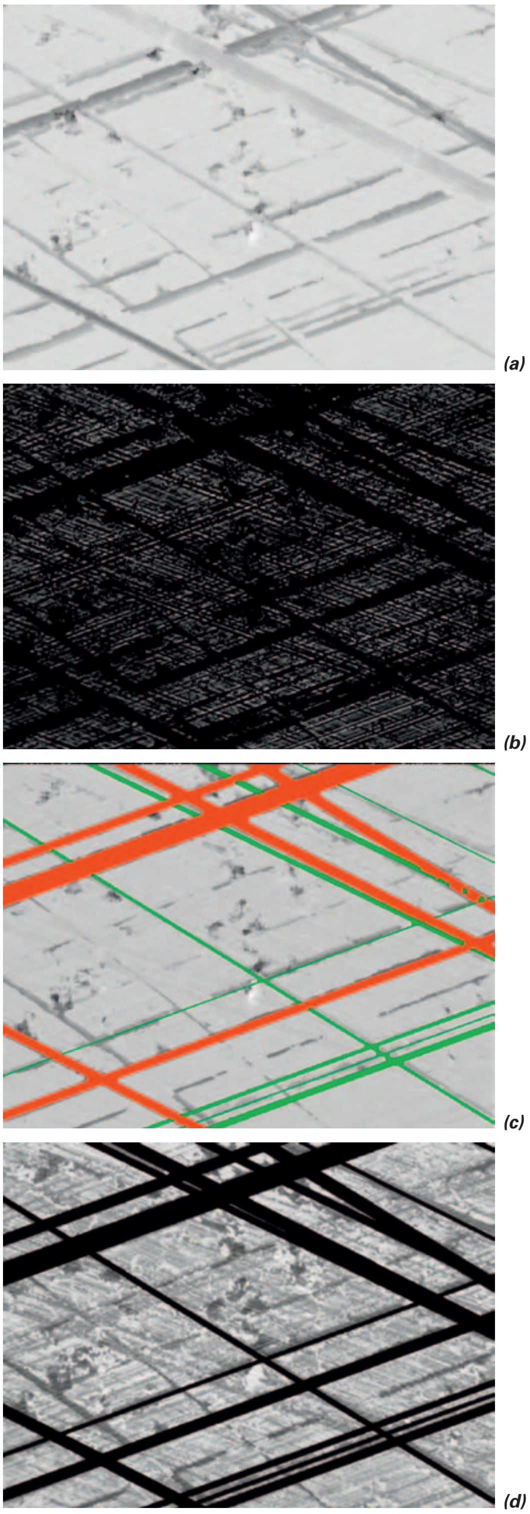

Fig. 1: *(a) Measured surface image, (b, c) visualization of the thin, medium and thick grooves, and (d) visualization of the background after eliminating the grooves.*

Supported by: AUDI
Project: "SAHO"

Wavefront sensing for applications in adaptive optics

S. Dong, T. Haist, W. Osten, T. Ruppel, O. Sawodny

The goal of DFG project "SHAO" is to develop a precise and real-time sensing and control system to increase the spatial and temporal resolution in adaptive optics. A combined optimization of the control strategy and the wavefront sensing is the cornerstone of the joint project of the Institute for Systemdynamics (ISYS) and ITO. One important task is the characterization of the dynamic response of the wavefront corrector (a deformable mirror (DM)). This response is used to create a feedforward control of the membrane allowing for faster settling time and reduced membrane vibrations. Fourier transform (FT) based interferometry is used to meet the measurement requirements of high speed and spatial sampling rate (SSR).

The interferometer is constructed based on a Twyman-Green geometry (λ = 633nm, 1280 × 1024 pixel, CMOS camera), and a Kepler telescope is employed to image the DM onto the CMOS sensor. The reference mirror is tilted to introduce a carrier frequency. The interferogram can be evaluated by the FT based carrier frequency method to extract the object height information. For eliminating the aberration introduced by the interferometer and unmodulated mirror and for removing the carrier frequency, the phase map of a reference surface where no voltage is applied to actuators is subtracted to obtain the final dynamic deformation.

Because the strongly curved DM brings dense fringes, only quarter of the DM can be tested in one shoot with speed of 500 fps in full resolution. Series of interferograms are recorded sequentially and processed afterwards to characterize the dynamic response of the DM. An exemplary result is shown in Fig. 1. The measurement results of four quarters of DM can be stitched at the end. With this technique, the surface of the DM can be measured with a resolution of 100 nm peak-to-valley. The setup is also used for static measurements (static influence function). In this case phase shifting with a piezocontroller is performed. In this case the whole membrane is imaged onto a 2048 × 2048 pixel CCD camera.

Apart from the modal wavefront sensor that is planed for the final control loop a fast Shack-Hartmann wavefront sensor (SHWFS) running at 1000 Hz has been implemented. The system parameters (NA of micro-lens, SSR of SHWFS) are optimized with consideration of the typical wavefront aberrations that are caused by certain strength of atmosphere turbulence as well as the system bandwidth. The CAD model is shown in Fig. 2. The calibration strategy and image processing ensures the wavefront sensing accuracy of $\lambda/50$ RMS. Using a quad-core CPU In C, the bandwidth of the SHWFS reaches 600 HZ with 8x8 subapertures. This sensor is used for testing the control strategy of DM in closed-loop operation.

Future work will focus on the design and implementation of a high speed modal wavefront sensor. Efforts will also be made to improve the speed of SHWFS by performing the wavefront reconstruction on the graphics processing unit (GPU) of the PC.

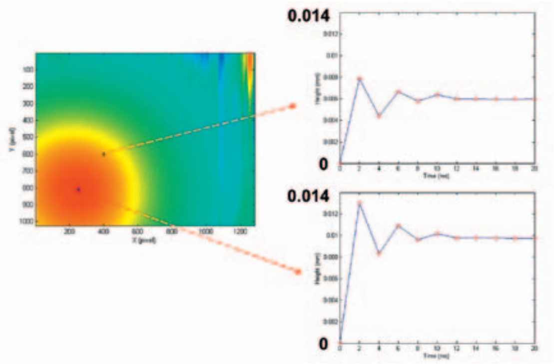

Fig. 1: *Dynamic response of the DM when one actuator is triggered with certain voltage.*

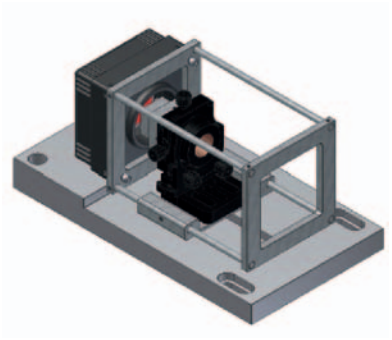

Fig. 2: *The CAD model of SHWFS in use. The micro-lens array is fixed on a Five Axis Lens Positioner from Newport.*

Supported by: DFG (OS 111/29-1)
Project: "SHAO"

Cooperation with: Institute for Systemdynamics, University of Stuttgart

High Resolution Metrology and Simulation

Fourier-Scatterometry for the characterization of sub-lambda periodic structures

V. Ferreras Paz, S. Peterhänsel, K. Frenner, W. Osten

As part of the of the DFG pri-ority programme SPP 1327 "Optisch erzeugte Sub-100-nm-Strukturen für biomedizinische und tech-nische Applikationen"[1] we analyse the applicability of the Fourier-Scatterometry method to characterize periodic sub-100 nm structures produced by two-photon-polymerization technique.

In recent time Fourier-Scatterometry has become of increasing interest for quantitative wafer metrology. But also in other fields the fast and precise optical characterization of periodical gratings of sub-100 nm [1] size is of great interest.

We investigated the application of Fourier-Scatterometry, extended by the use of white light for the characterization of sub-wavelength periodic gratings. First a simulation-based sensitivity comparison of Fourier-Scatterometry at one fixed wave-length, Fourier-Scatterometry using a white light light source and also a reference-branch for white-light-interference has been carried out. The investigated structures include gratings produced by two-photon polymerization of photosensitive material and typical semiconductor test gratings. The simulations were performed using the rigorous-coupled-wave-analysis (RCWA) included in our software package MicroSim [2]. The sample is illuminated with white light through a high-NA microscope objective (NA: 0.95) allowing an incoming illumination with wide incident (0°-72°) and azimuthal angle ranges (0°-360°). Using the full pupil illumination, Fourier-Scatterometry gives access to the complete information for every incident direction in one shot compared to fixed incident angle scatterometry equipment which has to scan over these angle ranges. The full information is contained in the backUsing white light instead of a fixed wavelength illumination gives a new dimension of freedom and finally using scanning white-light-interference allows increasing sensitivity towards structure height and shape.

The results of this sensitivity analysis show increased sensitivity towards the structure height compared with traditional Fourier-Scatterometry at one wave length and without a scanning reference-branch.

For the experimental implementation of the measurement setup we use a white light laser and a modified Leica DMR Microscope (NA 0.95) extended by an attached Linnik-type reference-branch. A scheme of the set-up can be found in Figure 1.

A comparison of measured and simulated pupil images for the combination of Fourier-Scatterometry and white-light interferometry during a scan of the reference mirror for an e-beam written resist linegrating on silicon with a line width (CD) of 200 nm and a period (pitch) of 400 nm can be found in Figures 2 and 3. The pupil images already show quite good agreement, but for actual model based recon-struction by comparing measured and simulated pupil images still some calibration has to be performed.

Supported by: DFG (SPP 1327)
Project: "Optisch erzeugte Sub-100-nm-Strukturen für biomedizinische und technische Applikationen" (http://www.spp1327.de)
Cooperation with: Nanotechnology Department at the Laser Zentrum Hannover e.V.

References:

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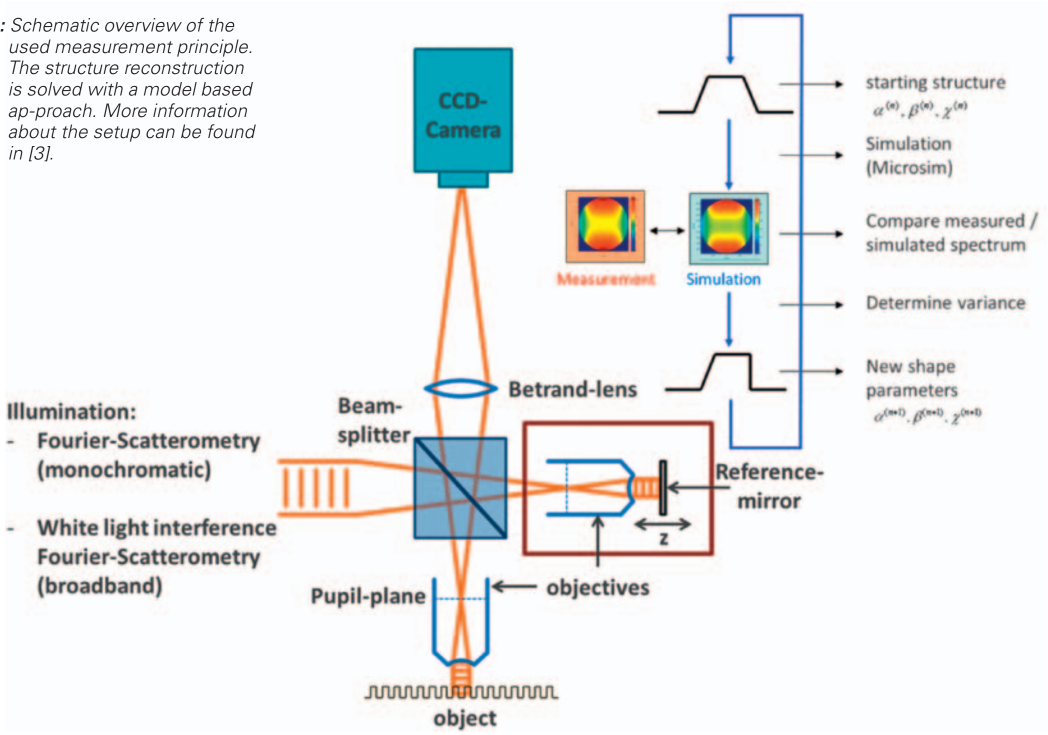
[2] Totzeck, M., "Numerical simulation of high-NA quantita-tive polarization microscopy and corresponding near-fields," Optik – International Journal for Light and Electron Optics 112, 399-406 (2001).

[3] Ferreras Paz, V.; Peterhän-sel, S.; Frenner, K.; Osten, W.; Ovsianikov, A.; Obata, K.; Chich-kov, B. "Depth sensitive Fourier-Scatterometry for the characterization of sub-100 nm periodic structures," Proceedings of SPIE 8083, 80830M-80830M-9 (2011).

Fig. 1: *Schematic overview of the used measurement principle. The structure reconstruction is solved with a model based ap-proach. More information about the setup can be found in [3].*



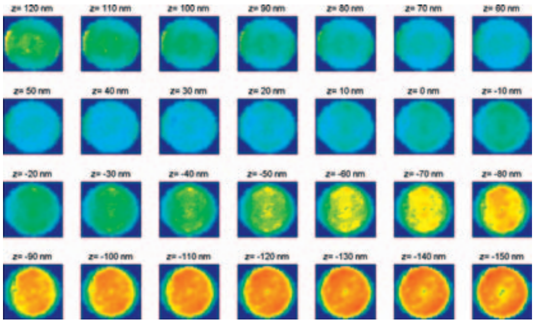


Fig. 2: *Measured white-light interference Fourier-Scatterometry pupil-images (NA: 0.95, λ=400-700 nm) of an e-beam structured photoresist line-grating on silicon (CD=200 nm, Pitch=400 nm).*

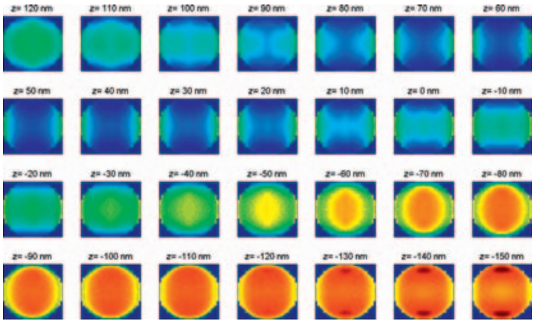


Fig. 3: *Simulated white-light interference Fourier-Scatterometry pupil images (same configuration as in Fig. 2).*

Inverse opto-mechanical simulation

H. Gilbergs, K. Frenner, W. Osten

The SimTech project "Optical simulation for model-based identification and suppression of static and dynamic aberrations in optics", in combination with its counterpart "Mechanical simulation …", conducted by the Institute of Engineering and Computational Mechanics, aims at an understanding of the coupling between mechanical and optical disturbances in high performance optical systems.

A common framework to support the combined simulation of mechanical and optical properties of the system has been deployed. It is based on Matlab, which controls the individual simulation modules and evaluates the results. The optical simulation is based on the commercial raytracing software Zemax, while the mechanical simulation is based on tools for multibody dynamics and finite element analysis developed at the ITM (MatMorembs and Neweul-M²).

The focus of the project lies in the identification of mechanical system disturbances from optical wavefront data. This reconstruction belongs to the group of inverse problems, which generally link an effect to its cause. Inverse problems are ill posed, which means that their solution may be not unique, continuous or even existent.

To solve this inverse problem two approaches have been investigated. The first one is a library search method, which compares the simulated outcome to a library which has been precalculated with known parameters. As the minimum size of the library, and thus the computation time for the precalculation, grows exponentially with more degrees of freedom, this method has only been applied for the tracking of single lenses with 5 degrees of freedom.

The second approach is Tikhonov regularization. Here the ill posed inverse problem is replaced by a neighboring well posed problem that delivers the most probable solution for the original problem. This approach can profit from the additional mechanical simulations as it relies on a certain amount of a-priori information on the system, which can be derived from the analysis of the mechanical properties of the system. Most notably the Eigenmodes of the system can be used as a coordinate system for the reconstruction of dynamical perturbations of the system. A frequency analysis can give a-priori knowledge on the Eigenmodes and their amplitudes for a given excitation of the system.

A reconstruction of one dimensional lateral shifts of single lenses in a lithography objective (Figure 1) from simulated wavefront data has been implemented based on Tikhonov regularization with promising results (Figure 2). The results have been presented at the "111. Jahrestagung der DGaO".

Future work will focus on a regularization based reconstruction using modal system coordinates, as well as building an experimental setup to validate the results of the simulations. Additionally development on an optical tracking method for single lenses based on total internal reflection has already started and will be carried on in the next year.

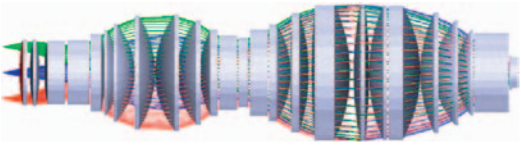


Fig. 1: *Projection lithography objective designed for an operation wavelength of 248 nm. The design is adopted from the US Patent listed in the references.*

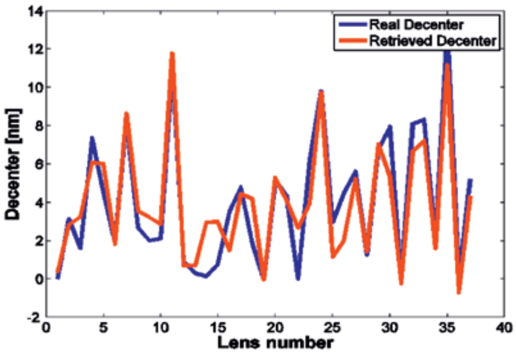


Fig. 2: *Reconstruction of 1D perturbations in the projection lithography objective depicted in Figure 1. The blue curve corresponds to the real decenter values, the red curve to the values retrieved with Tikhonov regularization.*

Supported by: DFG (EXC 310/1) "Cluster of Excellence in Simulation Technology"

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Metamaterials for Optical and Photonic Applications in Space

P. Schau, K. Frenner, L. Fu, H. Schweizer, H. Giessen, W. Osten

Metamaterials (MTMs) are understood as metaldielectric nanostructures for light processing in the nano-scale. A specific physical feature of MTM structures is their ability to sustain coherent electron oscillations known as surface plasmon polaritons (SPPs), which confine electromagnetic energy to much smaller mode volumes than in the case of photon modes. It turns out that the interaction of these SPPs in metamaterial structures represents the basis of all metamaterial functionalities just as the exchange interaction of electrons do in solids. Moreover, the tight confinement of SPPs on metallo-dielectric interfaces is the basis of ultra-high photonic/plasmonic integration. The high energy confinement of SPPs enables the further miniaturization (integration) of optical components (waveguides and devices) to size dimensions comparable to electronic integration. A factor of 100 and better below standard optical integration density appears possible due to the large wave vectors of SPP-excitations.

Devices and networks realized with such plasmonic metamaterials provide in principle the same functionality as conventional electronic and photonic elements and networks have today. In cooperation with the 4th Physics Institute, we identified the main fields metrology, optical data processing devices and coatings, and propose novel structures for each of them.

In the field of metrology for instance, plasmonic metamaterials with magnification properties are particularly interesting. Two promising approaches are metamaterial structures with hyperbolic dispersion (Fig. 1) and metamaterials on the basis of (non-periodic) meander stacks.

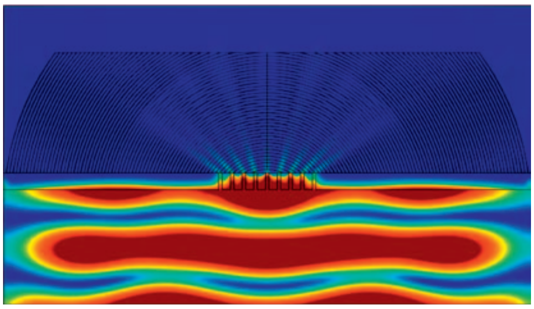

Fig. 1: *Metamaterial consisting of stacked, curved metal-dielectric layers with hyperbolic dispersion.*

The field of optical data processing devices is most promising for ultradense integrated circuits, eventually leading to an all-plasmonic nanoprocessing of light. Furthermore, spectacular properties of plasmonic structures can be demonstrated for filtering and polarization beam splitters, which can consist of only a few meander layer structures (Fig. 2). The use of slow light media can drastically improve the precision of interferometer devices and optical image processing devices.

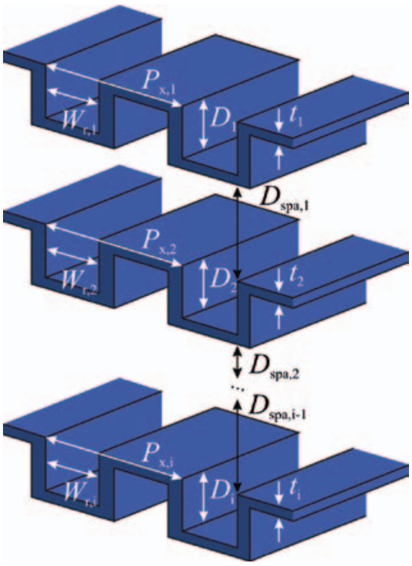

Fig. 2: *Meander stack feasible for various applications in space such as polarization beam splitters, color filters or imaging devices.*

As for coatings, a perfect absorber layer made of a metamaterial can be useful in optical instruments as well as in optical data processing circuits to suppress unwanted crosstalk by scattered light. The realization of this function by plasmonic metamaterials requires only the combination of two layers.

In all these fields, the intrinsic properties of plasmonic metamaterials meet general device and material requirements for applications in space. They are well-known as having low weight, intrinsically high radiation stability, high functionality of devices and ultra-high integration density potential.

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Metallic Meander Structures and their Potential for Sub-Wavelength Imaging

P. Schau, K. Frenner, L. Fu, H. Schweizer, H. Giessen, W. Osten

Especially in the fields of semiconductor manufacturing and nanotechnology, imaging with a very high resolution is crucial for process control and quality control measurements. At this point there exist specialized tools to perform high-resolution imaging or metrology for each process step along the fabrication chain. While demands of the industry have driven technology to the limits, none of the pre-sented solutions is capable to image arbitrary sub-lambda structures directly in a contactless, fast and non-destructive way.

This is where the new field of metamaterials can come into play. Metamaterials consist of periodic structures with dimensions smaller than the wavelength and can be designed to create particular electromagnetic responses that don't exist in nature. Particularly interesting is the Veselago material that exhibits a negative refractive index and can be used for superlensing as investigated by Pendry in 2000. Although a simple slab of silver already creates a perfect image of a sub-wavelength source, the image is still in the near-field and non-magnified. Hence, all sub-wavelength information will still decay exponentially and vanish in the far field. Our research goal is the design of a superlens capable of transforming evanescent waves to propagating modes, which then can be imaged via conventional microscopy (see below).

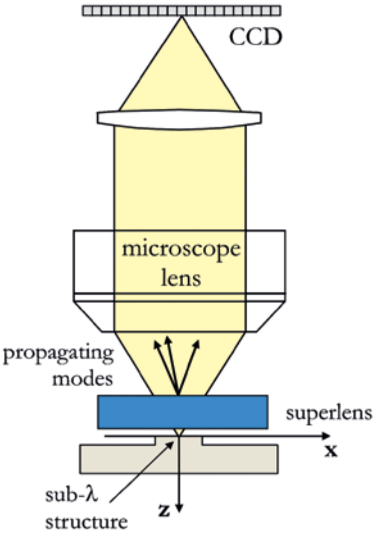

Fig. 1: Basic setup for a superlens attached to a conventional microscope to enable sub-wavelength imaging.

It has been shown that surface plasmon polaritons (SPPs) propagating on the metal/dielectric interfaces of a bulk negative index material (NIM) have a dominant influence on the unique properties of these materials. Consequently, one could replace bulk NIMs by resonantly coupled surfaces that allow the propagation of SPPs.

A metallic meander structure (Fig. 2) is perfectly suited as such a resonant surface due to the tunability of the short range SPP (SRSPP) and long range SPP (LRSPP) frequencies by means of geometrical variation.

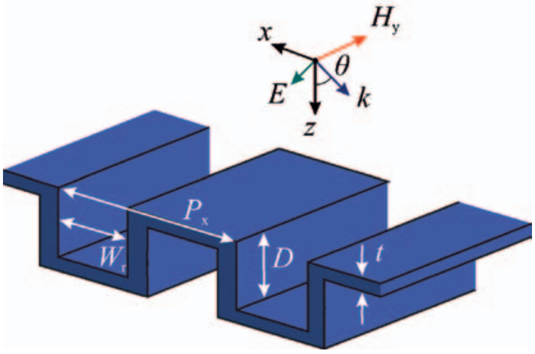

Fig. 2: Meander structure.

We demonstrated numerically how a stack consisting of two meander structures can mimic perfect imaging known from Pendry's lens (Fig. 3).

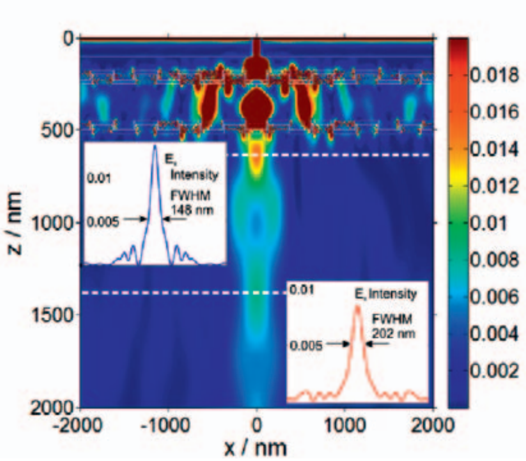

Fig. 3: A stack of two meander structures enabling near-field imaging similar to Pendry's perfect lens.

On the other hand, to observe sub-wavelength features in the far-field more than (perfect) near-field imaging is necessary. We are investigating stacks of meander structures with successively increasing periodicity capable to decrease the lateral wave vector until near-field to far-field transformation is achieved.

Supported by: Baden-Württemberg Stiftung
Project: "OPTIM"

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Interferometry and Diffractive Optics

Testing of aspheric and freeform surfaces

E. Garbusi, G. Baer, C. Pruss, W. Osten

The use of aspheric and freeform surfaces becomes more and more important in the design of modern optical systems. These surfaces offer additional degrees of freedom to the optical design, allowing to improve the optical imaging as well as to reduce the number of surfaces needed for an optical design. However the fabrication and testing of such surfaces is still a difficult task. At the ITO we developed and patented the so called Tilted Wave Interferometer [1][2][3] (TWI) which makes it possible to measure these kinds of surfaces. The main advantage of the TWI as compared with other available systems is the short measurement time. Furthermore, the TWI has the possibility to not only test rotationally symmetric aspheres, but also freeform surfaces, a feature rarely found in commercially available systems. To verify the measurement results of the TWI, we compared them with the results from two different measurement methods. As test surface we used an asphere with a diameter of 40 mm. The deviation of the surface from the spherical form was 600 µm peak to valley, with a maximum slope of 8°. The surface was measured on the TWI (fig. 3), on a Zygo Verifire Asphere which is another interferometric system (fig. 2), as well as on a tactile UA3P measurement machine form Panasonic (fig. 1). It could be shown that the measurement results of the TWI correspond to those of the two commer-cial systems. The advantage of the TWI is, the huge enhancement in the time needed for the measurement. Unlike the UA3P which needed 42 minutes for the measurement or the Zygo interferometer, where the process took 8 minutes, the TWI only needed about 30 seconds to measure the whole surface. The possibility for a fast measurement is of high importance for the introduction of a system into the automated fabrication of optical elements. In a running BMBF project we bring the interferometer from its laboratory state into a demonstrator setup, which will be working under industrial conditions. Further we are working on the extension of the measurement process to freeform surfaces, as well as to stitching, which is necessary for the measurement of larger surfaces.

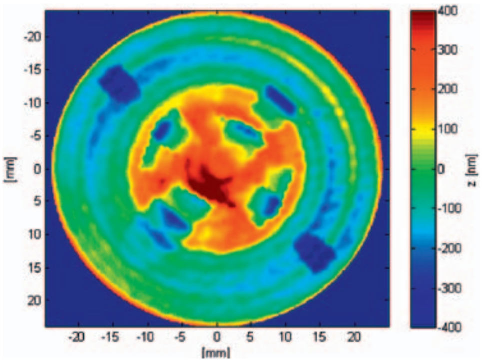

Fig. 1: *Measurement on a UA3P Panasonic*

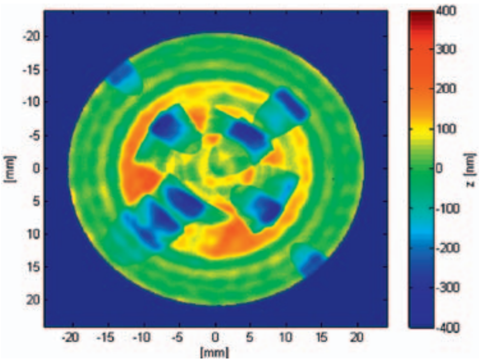

Fig. 2: *Measurement on a Zygo Verifire Asphere*

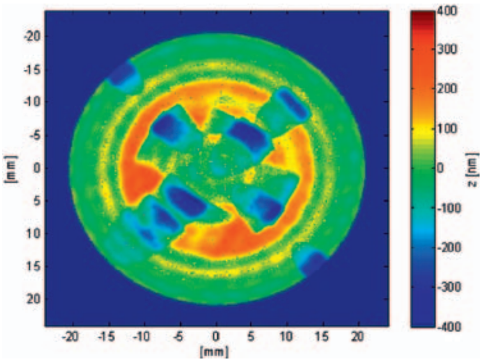

Fig. 3: *Measurement with the Tilted Wave Interferometer*

We thank the Bundesministerium für Bildung und Forschung for the support (project Mesofrei, (FKZN 13N10854).

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Automated alignment of aspheric test surfaces in a non-null interferometer

G. Baer, E. Garbusi, W. Lyda, C. Pruss, W. Osten

In the measurement of aspheric surfaces the positioning of the test surface in relation to the interferometer axis is an important task. When the surface geometry deviates from the classical spherical or planar form, the aberrations, which result from the surface geometry itself and those, which are introduced due to misalignment of the surface cannot be told apart any more. Therefore it is no longer possible to eliminate those errors in the post processing, which makes it important to minimize the alignment error of the surface. To achieve a high quality alignment of the test surface, we developed a fully automated process, which iteratively aligns the object under test. The setup of the interferometer is shown in fig. 1.

The beam from the laser source L is split to an object and a reference wave by the beamsplitter BS1. The object wave is collimated by C1 and then impinges on a microlens array L1 which is followed by a pinhole array. These two parts form a point source array. The light from the point sources propagates through the beam splitter BS2 and is collimated by C2. After the collimator lens we obtain a set of plane wavefronts with different amounts of tip and tilt. The tilt angles of these wavefronts compensate deviations of the test surface from the spherical form which have a similar slope to the tilted waves [1]. A transmission sphere then generates spherical wavefronts from the waves which are reflected by the object under test. The light then propagates back to the beam splitter where it is reflected and overlapped with the reference wave to generate the interference pattern. It follows the imaging lens and the camera C. The positioning of the object under test is accomplished by means of a computer controlled, three axis air bearing stage.

In the beginning of the alignment process a course alignment is performed, where the corrected position is calculated by analyzing binarized images of the test surface with the central point source activated. The test surface is then moved to the corrected position. This process is iterated until interference fringes are resolvable. We obtain an image as it is shown in fig. 2. In the next step, an interferometric process for the alignment is started. The region of interest is the ring we can see in fig. 2. For its measurement, the center and radii of the annular spot are needed, which are gained from image processing. These values are then used to generate the boarders for a measurement of the annular area. After the measurement is done, a Zernike-Annular-Polynomial fit is applied to the measurement. The Zernike coefficients for tip, tilt and defocus are used to calculate the necessary correction of the position [2] and the stage is moved to the new position. This process is iterated until the Zernike coefficients fall below a predefined value. It could be shown, that the process has a high repeatability of less than 1 µm in space. The high accuracy, as well as the fully automated execution, is ideal for the use in an industrial process.

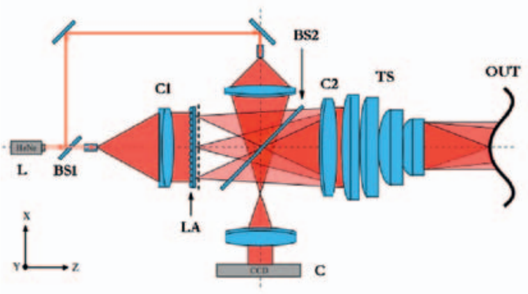

Fig. 1: *Schematic setup of the interferometer.*

Fig. 2: *Interferogram with the central point source activated.*

We thank the Baden-Württemberg Stiftung project Nanoform for the financing.

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High frequency axicon structures and their use in high power radially polarized beam generation and interferometry

M. Häfner, M. Abdou Ahmed, J. Ma, C. Pruss, W. Osten

Axicons are interesting optical elements for a variety of applications. Optical metrology, micro manipulation or laser beam shaping are examples for their wide field of use. Typically these optical elements are realized with refractive conical surfaces. An alternative are circular concentric diffractive structures that have several advantages in terms of fabrication and their application. Compared to refractive axicons the in-plane property of the diffractive variant allows for higher accuracy with regard to the deflection angle. The attainable deflection is directly dependent on the minimum structure size that can be realized. Direct laser lithography is a very convenient and cost effective method for the production of diffractive optics since it is very flexible in terms of substrate geometries that can be used. However, there is a limitation with regard to the smallest critical dimensions that can be manufactured. The limit for conventional laser direct writing system working with visible light sources is typical in the range of 0.5 µm. Thus for a wavelength of 633 nm the maximum first order diffraction angle is approx. 40 degrees. If one wants to increase the angle the structure period has to be reduced. There are several approaches for the realization of sub-micrometer periodical structures that make use of ultraviolet light sources or use advanced highly nonlinear photo resists that allow to shrink the area that interacts with the focused laser beam.

At the ITO a completely different approach that is optimized for the fabrication of rotational symmetric periodic structures has been realized. Instead of reducing the spot size, the substrate is exposed with a tiny interference pattern (figure 1) whose period matches the one of the final structure.

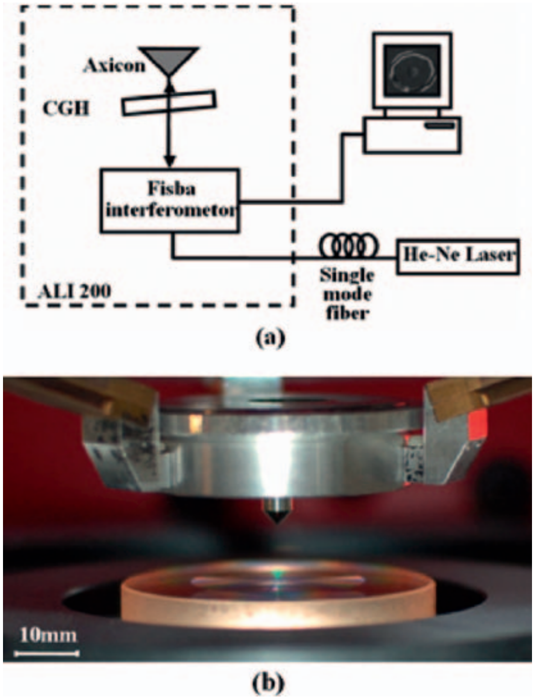

Fig. 1: *Setup for measurement of a precision conical mirror (a). Photograph of the diffractive axicon structure integrated into the setup (b).*

The pattern is scanned ring wise over the substrate. Through careful subsequent stitching of a large number of ring patterns, the substrate is completely exposed. The advantage of this technique is the high writing speed that can be maintained through the comparably large interference pattern and does not drop for smaller periods.

Furthermore, by means of an active fringe locking system one can achieve a high uniformity of the final structure.

The following two examples show applications that benefit from this novel technique:

In material processing, especially in laser cutting and drilling, it is beneficial to use radially polarized laser radiation. It has been shown that the process speed can be increased roughly by a factor of two. In a joint research project together with the "Institut für Strahlwerkzeuge" (IFSW) we implemented this technique with the goal to generate radially polarized laser light with state of the art thin disc lasers.

The working principle of the realized laser is based on intra cavity polarization selection by means of a sub wavelength axicon grating structure. Compared to the refractive solution the diffractive approach benefits from the low losses in the grating structures which is essential for the use in thin disc lasers.

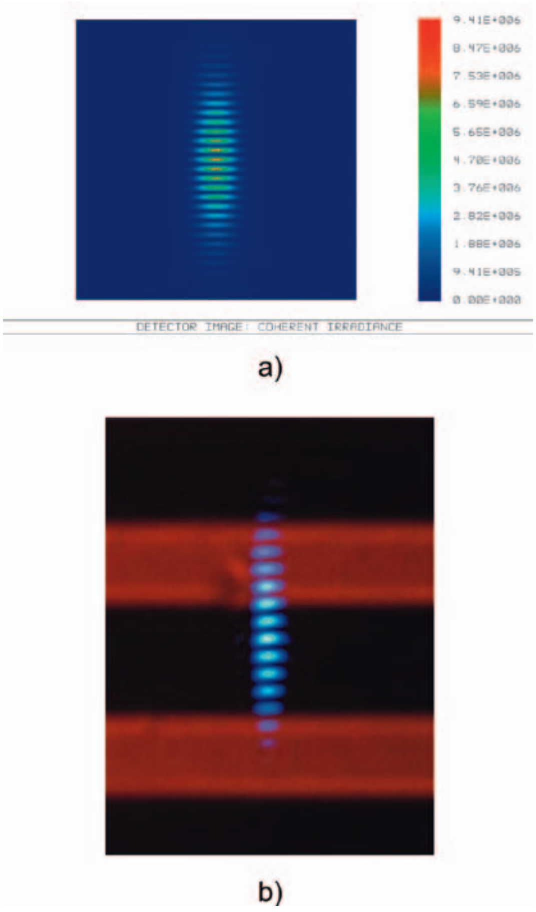

Fig. 2: *Simulation of the expected exposure pattern performed with ZEMAX (a). Picture of the real interference pattern taken with the camera of the writing system (b)*

A schematic of the laser built at the IFSW is shown in figure 2. At the current state it delivers up to 275W of radially polarized light [1].

As a second example we present the application of diffractive axicon structures in optical metrology. Figure 3 shows the setup for the measurement of a precision conical mirror.

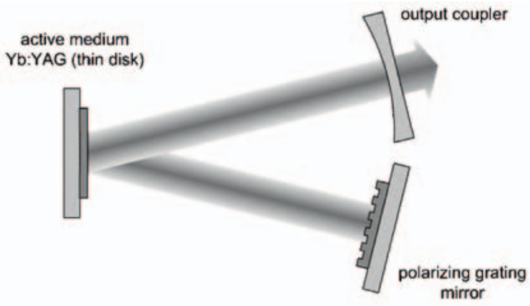

Fig. 3: *Schematic of the radially polarized thin disc laser. The polarizing grating mirror consists of sub wavelength axicon structures.*

Measuring an optical surface with an interferometric null test requires a reference structure with the inverse optical function of the specimen to be tested, typically a computer generated hologram (CGH). Testing steep surfaces such as right angle cones requires a deflection angle of 45°, which leads to extremely fine hologram structures, making the CGH difficult to manufacture in a conventional writing process. Our novel writing technique allows to easily fabricate such structures with high uniformity and high writing speed Thus one can now focus on the optimization of the metrological aspects of this challenging task [2].

We would like to thank the Baden-Württemberg-Stiftung for financing major parts of this work.

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Diffractive optics in advanced optic design

R. Reichle, C. Pruß, W. Osten

One of the challenges in the design of hybrid diffractive/refractive optical systems is their effective simulation. The mixture of large area and micro- to nanoscaled structures makes modelling of diffractive structures difficult, especially when realistic diffracting structures need to be taken into account. Here, the distribution of unwanted stray light varies with the local periodicity of the diffractive optical element (DOE) and the illumination wavelength. We have developed a model based local grating approximation approach that can be implemented into commercial ray tracing soft-ware [1].

The basic idea is to extend the standard local grating approximation (LGA) approach with a simulation based on a diffraction model that takes into account fabrication limitations and other above-mentioned dependencies. This can be an analytical model, a numerical model or even a model fed from experimental data. The model returns the probability to scatter light into the different diffraction orders, depending from the incoming ray data (angle, wavelength) and the local grating parameters (line density, orientation). This information is then used to decide into which diffraction order an incoming ray is directed. If the system contains several diffractive elements, this allows an automatic and efficient further splitting of the power.

Our implementation in ZEMAX uses the built-in scatter functionality with a self-programmed dynamic link library (DLL) to integrate the more realistic diffractive simulation. This implementation works in sequential mode, which allows us to use the numerous analysis and even some available functions for optimization. The first model we have integrated is simple scalar diffraction on rotational symmetric diffraction gratings with continuously changing periods that were fabricated by gray scale laser writing. Here, the diffraction limited writing spot limits the quality of the obtained structures. Other models might take into account the effects of alignment errors in multistep mask processes. For calculation efficiency purposes the model is saved to the RAM as a look-up table that is linearly interpolated. This approach still permits quite efficient ray tracing with only about two times increased calculation time.

One of the most important benefits of the new simulation capability is that it can be used within an automated optimization process. This allows taking fabrication constraints quantitatively into account during the optimization. Fig. 1 shows a simple system for focussing light onto a detector with finite size. The system consists of a plano-convex lens and a DOE. Free parameters are the radius of the refractive lens and the phase function of the DOE.

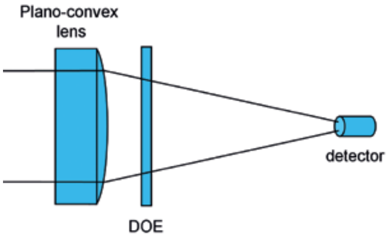

Fig. 1: *Test configuration for automatic optimization taking fabrication effects of the DOE into account.*

With the standard diffractive surface in ZEMAX, the optimizer puts a considerable amount of power into the DOE, reducing the formation of spherical aberration but leading to high line densities, since there is no penalty for the difficulties in fabricating those structures, see fig. 2.

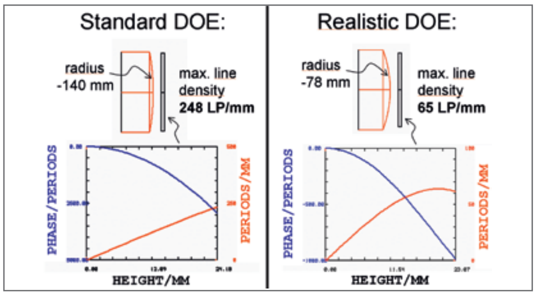

Fig. 2: *Optimizing results. Left: standard simulation that does not take into account fabrication dependent artefacts, right: fabrication artefacts are considered.*

The realistic DOE simulation leads to considerably reduced line densities, here the diffractive surface acts as a correction element for spherical aberration. We simulated the fabrication for both designs and calculated the amount of light that would reach the detector. We obtained 85% for the optimization with the realistic model vs. only 63% for a design with conventional optimization.

Supported by: BMBF (FKZ 13N9456)
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References:

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Minimal invasive combustion analysis: diffractive/refractive hybrid imaging optics on close to production engines

R. Reichle, C. Pruss, W. Osten

The analysis and optimization of modern stratified combustion engines requires information about the spatial and temporal distribution of the fuel-air-mixture inside the combustion chamber of a running engine. To get realistic data, the influence of the applied measurement techniques on these processes must be reduced to a minimum. Contactless optical measurement concepts are of special interest, various optical techniques allow the determination of many different parameters.

Fuel concentration, equivalence ratio or temperature are for example parameters that can be analysed by laser-induced fluorescence (LIF) of the tracer substances toluene and 3-pentanone. This technique can be used for imaging, i.e. 2D-analysis: an excitation light sheet (pulsed laser, e.g. 10 ns, 266 nm) defines a measurement plane, from which the resulting fluorescence bands (for example toluene 280-350 nm or pentanone 380-480 nm) are imaged onto intensified cameras (Figure 1).

To enable this application on production-line engines with only small modifications and thereby measurements on very close to reality situations, we developed a wide angle diffractive/refractive (hybrid) imaging system (Fig. 1) with a small access diameter of 10 mm. It has a high lens speed and a broad band chromatic correction range (about 70 nm) [1].

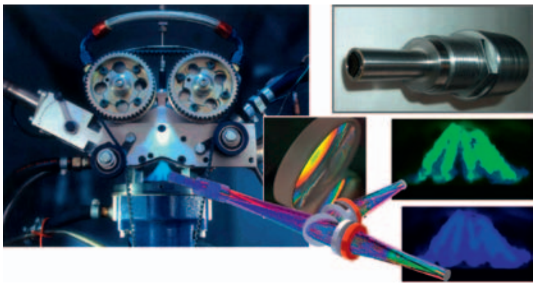

Fig. 1: *Application of the hybrid imaging system with two spectral channels on an optical engine at Robert Bosch GmbH.*

This system was designed to image 10.000 pixels in a field of 30 x 30 mm² out of a working distance of 35 mm onto an image intensifier at about 30 cm distance with a paraxial image magnification of 0.5 only. For this image magnification, the hybrid imaging system with small access optics has shown to be even faster than the widly used UV-Nikkor lens (f=105 mm, F#4.5), which can only be used on heavily modified optical motors. The system is modular, different spectral bands can be imaged using different optimized hybrid relay stages. The system has proven its performance in the lab, at the optical engine at Robert Bosch GmbH (Figure 1) and on modified production-line test engines at IVG, University of Duisburg-Essen (Figure 2, 3) and Volkswagen AG in Wolfsburg.

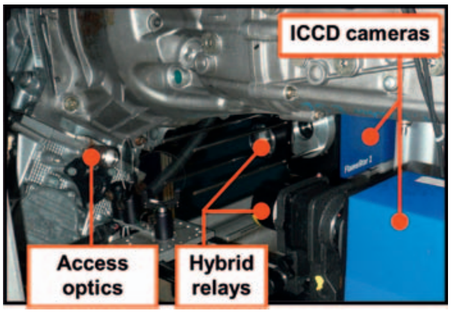

Fig. 2: *Application of the hybrid imaging system on a test engine at IVG [2].*

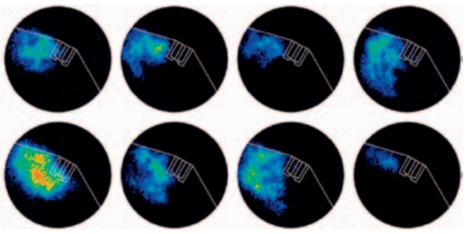

Fig. 3: *Single-shot OH* chemiluminnescence images, detection 312 ± 17.5 nm [2].*

Other wavelength bands have been implemented for further applications like NO-detection at 230-250 nm, soot detection at 500-540 nm and MIE-scattering at multiple wavelengths.

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Project: "MIMODIA"
The authors especially acknowledge the good cooperation with the group of Prof. Schulz (IVG, University of Duisburg-Essen).

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A novel diffractive code for absolute optical rotary encoders

D. Hopp, C. Pruß, W. Osten

Rotary sensors are used in numerous manufacturing and automotive applications, where cost effectiveness is a major criterion. To meet the increasing demand for competitive optical rotary encoders a microstructured plastic disc, manufactured by a conventional and costeffective DVD-moulding Process, can be used to replace the common but costly glass disc.

In a previous AiF-project (219 ZN) a new kind of incremental encoder was presented [1, 2], where the realisation of the mechanical and electronical design were performed by our project partner, HSG-IMAT, while the optical layout and the design of the new diffractive incremental code were performed by ITO.

Consisting of four different binary phase gratings with a periodic sequence and being illuminated with a Gaussian spot, the grating structure generates a sine- and cosine-signal by detecting the first order spot intensities of its diffraction pattern. The four gratings have different orientation angles to separate the diffracted spots. With that principle, on a diameter of 27 mm a resolution of 2048 solid measure increments on the circumference can be achieved. By interpolation of the signals this leads to up to 15 bit of incremental steps.

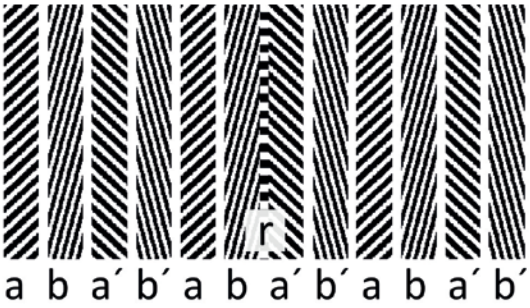

Fig. 1: *Detail of the incremental diffractive solid measure.*

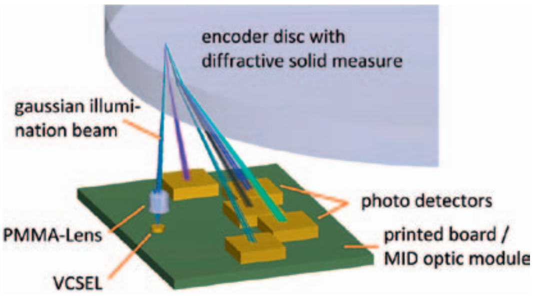

Fig. 2: *Scheme of the diffractive incremental encoder setup.*

For some applications, e.g. robotics, it is essential to also know the absolute angular position. For this purpose, the diffractive code was enhanced by exploiting a residual degree of freedom: By variation of the gratings periods and angles the resulting first order spots on the detector plane can be moved arbitrarily. To obtain an absolute coding, ten different positions of a single first order spot are used to encode ten different states. The spot positions can be determined by detecting the intensitie's centre of gravity on an array of photodiodes or a position-sensitive device.

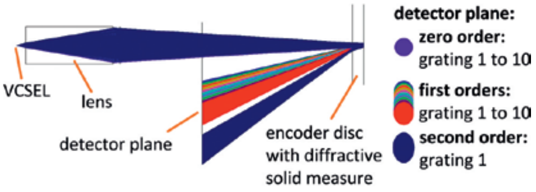

Fig. 3: *By a variation of the grating period the diffraction angle of the first order spot can be controlled to hit ten different positions in the detector plane.*

Again, the solid measure consists of four spatially separated gratings, each of those having ten states which vary periodically from the largest to the smallest grating period and back. A continuous variation is necessary since jumping between the minimum and maximum spot position would lead to an ambivalent state for the associated angular position signal.

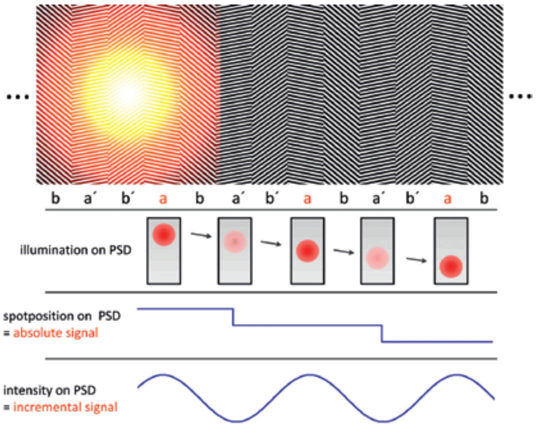

Fig. 4: *Generation of a combined incremental and absolute signal using a variation of the grating period and angle to modify the diffraction angle and therewith the position of the first order spots on the detector plane.*

To build the absolute code, the signal from the first set of gratings, respectively on the first detector, covers the whole circumference with two steps, dividing it into twice 180 degrees. The second set of gratings on the second detector has twenty steps per circumference, dividing each step of the first into ten steps. The angular segmentation now is coded in 20 explicit states.

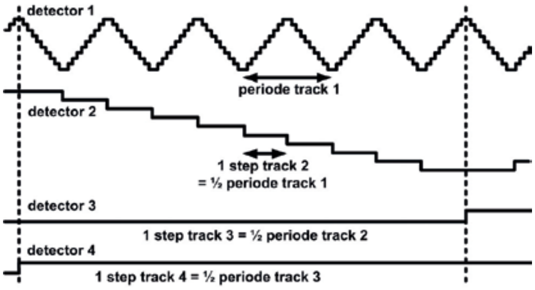

Fig. 5: *Schematic illustration of the absolute coding with four nested tracks. Each track provides ten different states which vary periodically. By cascading the four signals, an absolute Gray code with 2000 explicit states is built.*

Each of those 20 steps generated by the two first signals is subdivided ten times by the third signal, whose period thereby is ten times shorter, which leads to 200 angular segments. The fourth set of gratings again generates a signal with a tenth of the period length of the previous set and therewith contains the highest resolution of the cascaded code. The number of absolute states results in 2000, respectively in 2000 angular segments. which corresponds to 10.8 arcminutes each. The absolute code therewith pro-vides a resolution of 10.9 bit generated in the Gray code principle.

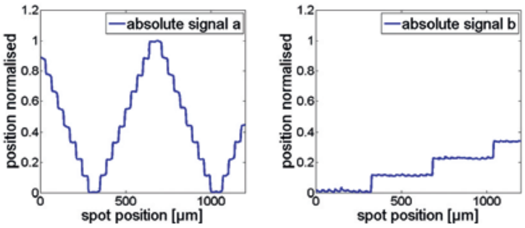

Fig. 6: *Experimental results for the two first of the four absolute signals.*

Compared to a common binary Gray code, with the presented absolute code the challenge of the correct switching point does-n't need to be handled, because the detection of the centre of intensity can be done stepless. Furthermore, the principle only needs a single diffractive track as a solid measure, which makes it very robust to a radial shift of the encoder disc.

While the position of the first order spots is used to generate the absolute signal, the varying intensity of the spots still is used to generate the known incremental signals. With 2000 periods, the incremental code physically corresponds to the absolute code, the two principles do not affect each other. Therewith, each period of the interpolated incremental signal can be explicitly identified by using the absolute code. The absolute resolution of the combined principles results in 15 Bit or even higher, depending on the accuracy of the interpolation.

Supported by: AiF (349 ZN)
Cooperation with: HSG-IMAT

References:

[1] Hopp, D., Pruss, C., Osten, W., Seybold, J., Mayer, V., and Kück, H., "Optical incremental rotary encoder in low cost design", in Sensor &Test Proceed-ings Opto 2009 (2009).

[2] Hopp, D., Pruss, C., Osten, W., Seybold, J., Mayer, V., and Kück, H., "Optischer inkrementaler Drehgeber in Low-Cost-Bauweise", Technisches Messen 77, 358-363 (2010).

Optical excentricity compensation in optical rotary encoders

D. Hopp, C. Pruß, W. Osten

For all rotary encoder principles the accuracy is directly dependent on the lateral mounting tolerance of the encoder disc, i.e. the discrepancy between the axis of the shaft and the axis of the encoder disc. An excentricity between those axes results in a significant cosine-shaped deviation once per revolution between the mechanical angle of the shaft and the measured angular signal.

To increase the accuracy or to simply avoid the cost-intensive alignment of the encoder disc, there are several mechanical or electronic techniques to minimize the measuring error. Mostly, two or more sensor heads or separate solid measures are used to detect the deviation and to then compensate the defective angular signal after its generation.

We present a new approach to use an optical compensation scheme prior to the generation of the angular signal, without an adjustment of the encoder disc and without having any additional sensor heads or electronics [1].

Solid measures with an incremental or absolute code, based e.g. on a reflective plastic disc, are typically robust against a radial movement of the encoder disc. If the encoder disc, by excentricity, is shifted in tangential direction, the solid measure track is illuminated at a wrong position, i.e. it is not showing the correct angle (fig. 1, left). Here, we propose a second diffractive track on the encoder disc for the compensation of a tangential movement. This track is fabricated in a single step together with the solid measure to assure their concentricity, a vital condition for the proposed compensation.

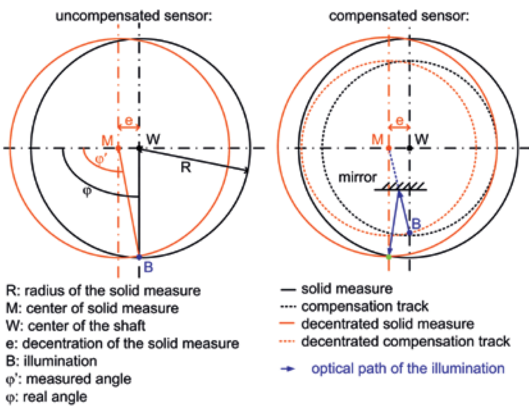

Fig. 1: *Schemes of excentered solid measures of an uncompensated and an optically compensated sensor setup.*

The compensating track consists of an axicon structure, which is illuminated by a stationary light source. The light of the first diffraction order is directed towards the common center of both tracks (fig. 1, right). This is true even if the encoder disc is shifted in tangential direction. This allows to compensate the angular deviation with the help of a stationary mirror or prism that deflects the light onto the actual solid measure where the angular information of the shaft angle is coded. Chosing the optical path length between the compensation track and the solid measure the same length as it would be without a deflection between the compensation track and the common center, the read-out beam illuminates the solid measure at the correct position.

The tangential movement of the encoder disc causes a variation of the deflection angle which enables the optical self-compensation of the system prior to the signal generation. The shaft angle is detected independently of the excentricity of the encoder disc.

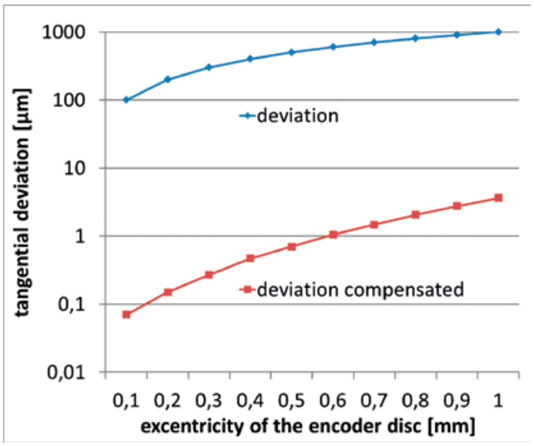

Fig. 2: *Tangential deviation and compensated deviation for a 27 mm diameter solid measure (1 µm = 15.3'').*

Supported by: AiF (349 ZN)
Cooperation with: HSG-IMAT

References:

[1] Hopp, D.; Pruss, C.; Osten, W. „Vorrichtung und Verfahren zur optischen Kompensation der Maßspurdezentrierung bei Drehwinkelsensoren", patent pending, WO 2011/029587 A1.

VCSEL-integrated beam shaping for active spatial polarization control

F. Schaal, C. Pruss, W. Osten

Besides the spatial control of intensity and phase of light fields the spatially resolved polarization control becomes more and more important for applications in beam shaping and measurement.

The scope of this project is the development of a compact micro optical device (Fig. 1) for non-pixelated spatial polarisation control [1].

The device (Fig. 1) is based on a photoaddressable material (PAM) witch transfers the shape of the optical addressing beam into a spatially shaped polarization pattern. The change in polarization depends on the polarization and intensity of the addressing light. The addressing is done with red light (655 nm), the usable wavelengths for polarization manipulation lie in the near infrared (NIR).

The micro optical addressing module (Fig. 3) uses VCSELs as light sources and two diffractive optical elements (DOE) for beam shaping. Due to the small dimensions of the illumination system, several addressing channels can be realised in one device. By controlling the current through the VCSELs, different illumination patterns can be switched or combined.

The first DOE is directly integrated on the VCSEL surface and is used for course beam shaping to optimize the illumination for the second, larger DOE. The DOEs on the VCSEL surface can be realized as phase or amplitude elements, the sample shown in fig. 2 is an amplitude element.

Further work will focus on the generation and test of more complex DOEs on the VCSEL surface, the use of optimized PAM (higher induced birefringence and faster response), the extension to larger addressing areas and the application in phase contrast microscopy.

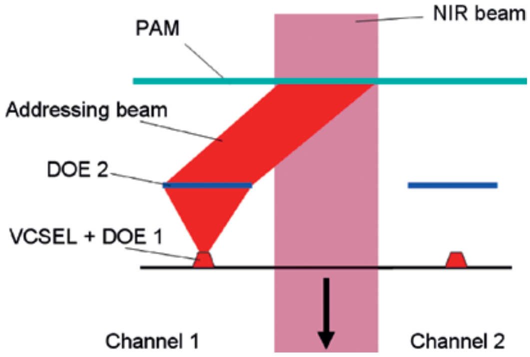

Fig. 1: *Schematic diagram of the basic setup*

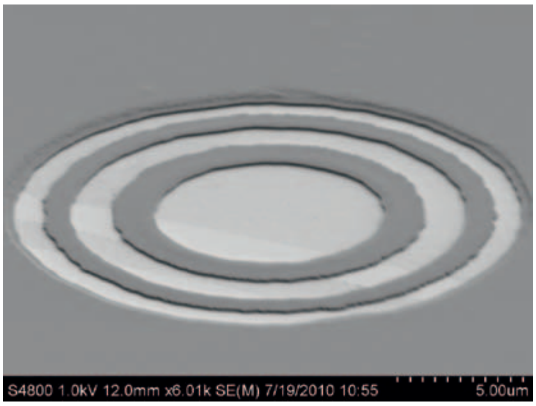

Fig. 2: *Fresnel zone plate directly etched into the VCSEL surface (IHFG, Uni Stuttgart)*

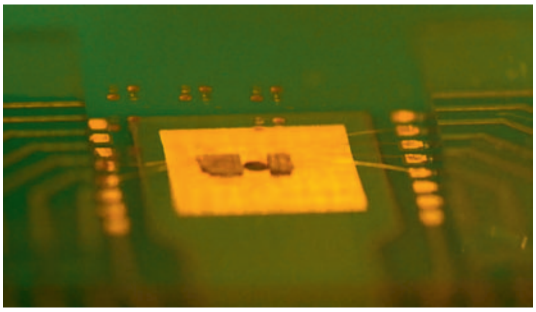

Fig. 3: *Diffractive optical addressing module with 4 different switchable addressing patterns*

Supported by: DFG (OS 111/26-1)
This project is part of the DFG priority programme 1337 "active micro optics" and is done in collaboration with the IHFG (University Stuttgart) and University Potsdam.

References:

[1] Schaal, F.; Pruss, C.; Osten, W. "Active spatial polarization control induced by diffractive optical illumination." In: EOS Topical Meeting on Diffractive Optics 2010, ISBN 978-3-00-024193-2. Koli, Finland; 2010:2455.

Coherent Metrology

Microelectromechanical Reference Standards for the Calibration of Optical Systems

G. Pedrini, I. Alexeenko, W. Osten

The trend towards miniaturization of microelectromechanical systems (MEMS) and micro-opto-electro-mechanical systems (MOEMS) continues to lead to more and more compact devices. Advantages lie in the integration with control electronics, lower power dissipation, higher sensitivity and better performance. Applications cover a wide range of fields, from optical telecommunications to medicine. Part of the functionality and reliability of the devices is based on the displacement and deformation of micromechanical parts under mechanical, thermal, magnetic or electrostatic loads. The measurement of the deformation of such systems is thus of great importance for confirming analytical and finite element models, accessing material and device properties, detecting potential defects and determining performance. Since typical structures exhibit dimensions in the order of some micrometers, it is necessary to measure their deformation with accuracies down to the lower nanometer range. Standardized approaches and calibrated setups are therefore essential for the measurement of displacement and deformation fields in the static and dynamic cases. Our work aims is to develop standards and guidelines for the use of different full-field optical techniques in the measurement of out-of-plane and in-plane displacements of microsystems. This process involves:

- Development of micromechanical reference components designed to deform in a reproducible and precise way when submitted to known loads;
- Calibration of the reference devices by means of optical techniques, performed in laboratory-controlled conditions;
- Determination of the measurement uncertainties according to the guide of expression of uncertainty in measurement (GUM) and certification of the calibration setups allowing for traceability of the observed quantities to the international SI standards.
- After development and calibration, the reference devices may then be used for the general calibration of optical measurement systems used in the MEMS industry.

In the annual report 2007/2008 we reported how the calibration procedure was applied to the in-plane displacements of a micromechanical reference, here in Fig. 1 we show some results obtained with the out of plane MEMS. The application of a voltage produces displacements of different magnitude of central elements of the device. The displacement was measured by using a method based on digital holography. We found a very good agreement between expected and measured displacement. It was shown that the out-of-plane displacements may be performed with an accuracy of 1.0 nm.

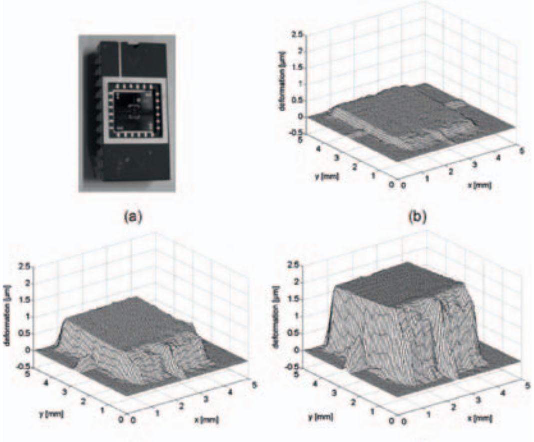

***Fig. 1:** Photo (a) and out-of-plane deformations of the MEMS obtained by applying 15 V (b), 30V (c) and 50 V (d).*

Supported by: DFG (OS 111/22)
Cooperation with: University of Freiburg (Prof. O. Paul and Dr. J. Gaspar)

References:

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

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[4] Pedrini, G.; Gaspar, J.; Schmidt, M. E.; Alekseenko, I.; Paul, O.; Osten, W. "Measurement of nano/micro out-of-plane and in-plane displacements of microme-chanical components by using digital holography and speckle interferometry" Opt. Eng. 50, 101504 (2011).

Nanoscale imaging:
Deep ultraviolet digital holographic microscopy

A. Faridian, D. Hopp, G. Pedrini and W. Osten

A deep ultraviolet off-axis digital holographic microscope (DHM) has been developed. The microscope has been arranged with as least as possible optical elements in the imaging path to avoid aberration due to the non-perfect optical elements. We employed an ArF Excimer Laser, ExiStar 200 (TUI), lasing at deep UV (193 nm). The laser is pulsed and the setup does not need to operate in vacuum, which make it a robust and practical arrangement for industrial applications. Moreover, a digital camera is commercially available for this wavelength with high UV sensitivity, (PCO Sensicam). A custom-designed objective was constructed to meet the demands of the off-axis setup while having a low price for imaging with a deep UV light source. The objective has a numerical aperture of 0.75 and it can image a field with the radius of 10 µm.

To increase the resolution, oblique illumination was performed through an incident angle of ~10° relative to the normal axis of the object plane. To avoid artifacts appearing in the image, we have performed oblique illumination from four symmetric directions. To test the resolution of the setup we have used our designed template, which includes structures, ranging from 500 to 100 nm in width (Fig. 1.a). Figures 1.b-c show a typical recorded hologram and its Fourier transform. The reconstructed amplitude and phase for two selected oblique directions are shown in Fig. 1.d-g. The amplitude image has been separately reconstructed for each of four directions. We have combined the reconstructed amplitude images, obtained from each individual direction, by adding the complex amplitude of the raw images and without implementing any further image processing technique (Fig. 1.h). In this image the "ito" logo is clear and even the line structures with the width of 250 nm are well-resolved (Fig. 2), that confirms a significant enhancement in resolution compared to the result obtained with a conventional optical microscope (Fig. 2.b.), in which the line structures with the size of 500 nm are the smallest resolvable structures.

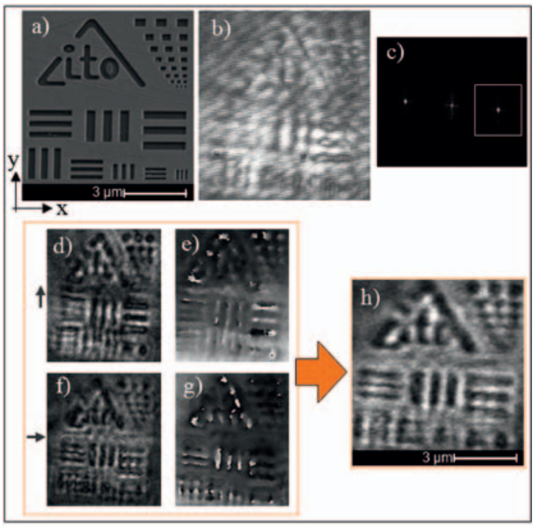

Fig. 1: *(a) The Scanning Electron Microscope (SEM) image of the nano-structured template, (b) a typical recorded digital hologram and (c) its Fourier transform, (d,f) the reconstructed amplitude and (e,g) phase of the object illuminated with oblique illumination along "y" and "x" axes, (h) the final image obtained by combining the reconstructed amplitude images taken from four symmetric oblique directions. The scale bar is 3 µm.*

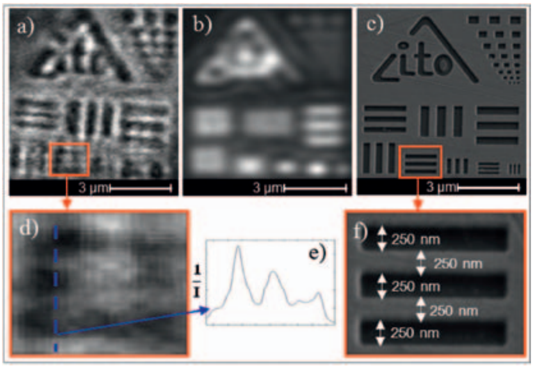

Fig. 2: *A fine comparison of (a) the image obtained using our DHM setup, (b) the image taken using a conventional optical microscope with NA:0.7 and (c) the SEM image of the template. (d-f) the magnified section and the inversed intensity profile of the smallest resolvable structure (250 nm).*

Supported by: DFG (OS111/19)
Project: UV-DigiHolo

References:

[1] Faridian et al. "Nanoscale imaging using deep ultraviolet digital holographic microscopy", Optics Express 18(13), 14159-14164, 2010.

[2] Gopinathan, U.; Pedrini, G.; Javidi, B.; Osten. W. "Lensless 3D Digital Holographic Microscopic Imaging at Vacuum UV Wavelength", Journal of Display Technology, Vol. 6, 479-483, 2010.

Knowledge Management in Virtual Labs and Remote Experiments

M. Wilke, M. Riedel, G. Situ, I. Alekseenko, G. Pedrini, W. Osten

The MWK-funded project BW-eLabs focuses on the development of a collaboration infrastructure for scientist, providing access to remote laboratories, data bases for results (stored as raw data with added meta data) and publication of experimental results. The ITO contributes a remote experiment for holographic microscopic metrology. The experimental setup is shown in Fig. 1.

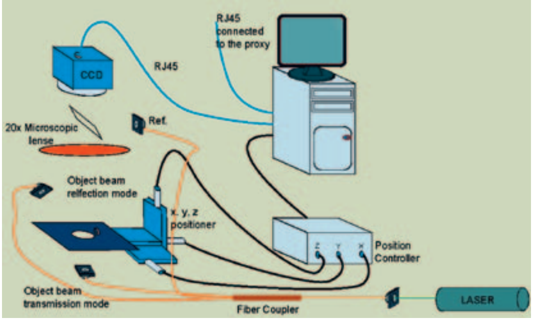

Fig. 1: *Holographic Microscope*

A Nd-YAG Laser is coupled into a fiber, which guides the beam into a coupler that subsequently divides the input laser beam into a reference arm and object arm. The object arm fiber can be switched for different illumination modes, i.e., transmission mode or reflection mode, depending on the property of the object to be investigated. The object is imaged through a 20x/0.5 microscopic objective. The reference fiber is coupled into the system using a beam splitter as shown in Fig. 1, to interfere the reference beam with the object wave. The microscopic table is mounted on an electric-driven 3D positioner, allowing the user to shift the field of view at submicron precision. The object is imaged using a 20x/0.5 microscopic objective and a CCD camera is used to record the hologram. The camera has a large sensing area, and a high numerical aperture can be obtained when it is placed close to the object, even in a lenseless configuration. The hologram is transferred to the computer for subsequent processing, including numeric reconstruction of phase and intensity and the calculation of phase difference compared to previous holograms. The data and control flow of the remote experiment are shown in Fig. 2. Figure 3 shows the frontpanel of the LabView vi used for the control of the experiment. The control is provided by remote desktop system (VNC), connecting through a proxy using an encrypted channel (SSH tunnel), adding standard authentication through the modular authentication system PAM and encryption for security, based on existing software such as Java-Portlets running on the BW-eLabs Portal server and Python modules on the proxy server. The connection to the data base and publication backend eSciDoc is work in progress and will allow automatic storage and access to experimental results, including identification through a unique, persistent digital identifier (DOI). eSciDoc is connected to the OPUS document server at the University of Stuttgart for publication. Sets of actual experimental data can be accessed and referenced through OPUS, using the DOI identifiers. In addition to the generic access using VNC, a 3D virtual environment (Wonderland) is being implemented. This frontend is intended to provide intuitive access to the hardware, as well as support collaboration between users by providing communication channels.

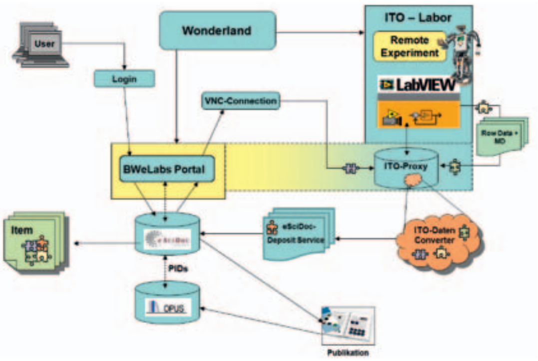

Fig. 2: *Data and Control Flow in BW-eLabs*

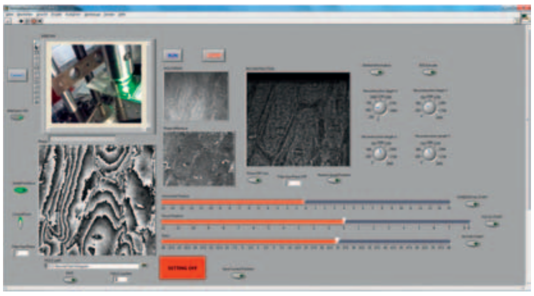

Fig. 3: *Sample view of the remote panel*

Supported by: Ministerium für Wissenschaft, Forschung und Kunst Baden-Wuerttemberg (MWK)
Project: BW-eLAB
Project partners: Rechenzentrum RUS (Uni Stuttgart), Universitätsbibliothek Stuttgart, Hochschule der Medien Stuttgart, FIZ Karlsruhe, FMF (Uni Freiburg), Rechenzentrum (Uni Freiburg).

Full-Field Advanced Non-Destructive Technique for Online Thermo-Mechanical Measurement on Aeronautical Structures

I. Alexeenko, G. Pedrini, W. Osten

Thermography is a method used to measure temperature inhomogeneity's and allows determining defects located at different depths inside composite structures.

Electronic Speckle Pattern Interferometry (ESPI) allows measuring the mechanical displacements of the surface of a structure submitted to loading and to get informations about the elastic parameter and defects of the structure.

A set-up which combines thermography and ESPI was built. The spectral range of the ESPI system was expanded up to the long wave infrared (LWIR) in order to decrease 20 times the sensitivity compared with methods using visible light and allowing the recording of large deformations as they usually occur in aeronautical structures.

Figure 1 shows the sketch of the set-up using a CO_2 laser light source with wavelength 9.3 µm and coherence length 1–1.5 m. The thermographic images and the interferograms are recorded on the same detector which is an uncooled microbolometer infrared camera (VarioCam-hr manufactured by InfraTec). This Focal Plane Array (FPA) detector has 640 x 480 pixels (physical dimension of each pixel is 25 x 25 µm²), its dynamical range is 16 bits and the frame rate is 50 Hz. The imaging system is composed by a Germanium objective with 50 mm focal length. The basic parts of the interferometer have been isolated inside a beam delivery system in order to avoid that unwanted reflections from the surrounding environment hit the detector which is very sensitive and could be destroyed irreversibly by the CO_2 laser radiation. The reference beam was delivered by using a flexible hollow silica fiber with core diameter 300 µm. Attenuators were used to reduce the output intensity for the illumination and reference beams. The system was full automated by using LabView software and NI data acquisition boards (DAQ).

Figure 2 shows a result obtained by using the developed system. The investigated object (part of an aircraft) was a Kevlar 360 x 300 cm² plate with delamination defects located at different depths. The loading system was an infrared lamp located in front of the object that increases the temperature of the sample and produces its deformation. Since we recorded simultaneously holograms and thermal images on the same detector, the separation of these two signals is needed and is done by using a four step algorithm allowing to calculate the phase changes of the coherent wavefront due to the object's displacement and extract the temperature distribution on the sample surface. From Fig. 2 we may see that thermography and LWIR-ESPI are both able to detect defects located inside the Kevlar plate, furthermore the ESPI system allows to monitor the deformation of the object surface.

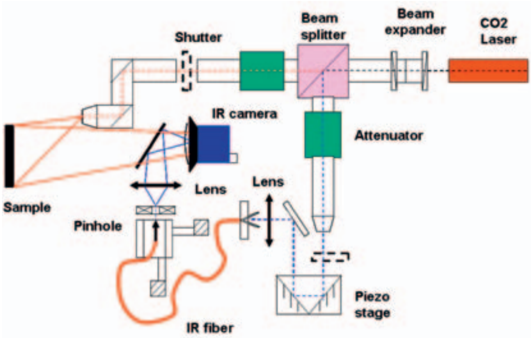

Fig. 1: *Experimental set-up which combines simultaneous acquisition of holographic and thermal images.*

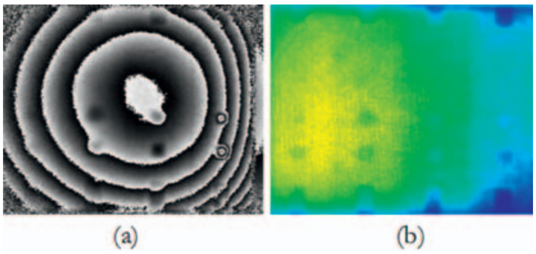

Fig. 2: *Phase difference representation of the deformed object: a), and its temperature distribution: b).*

Supported by: FP 7 European Project (ACP7-GA-2008-213457) "FANTOM"
Cooperation with: CSL Liege (Belgium), OPTRION (Belgium), INFRATEC (Germany), CTA (Spain), INNOVSUP (Belgium).

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Imaging through tissue using short-coherence digital holography

G. Situ, Y. Zhang, G. Pedrini, W. Osten

Image formation through scattering media using visible light is a subject of great interest. One of the practical aspects of the challenging problem concerns the possible application in identifying internal structures of objects embedded within or hidden behind scattering media like translucent biological tissue, which has great potential in assisting the non-invasive diagnosis of a number of clinical problems such as early detection of tumours. Photons migrating through strong scattering media dominantly undergo multiple scattering, thereby preventing the tissue from being transparent.

We propose an imaging method based on short-coherence lensless digital holography (see Fig. 1). By using a beam splitter, the laser beam is divided into two, one of which is used to illuminate the object behind a scattering medium, and the other as a reference. The two beams are then recombined at the CCD plane. Note that in short-coherence holography interference occurs only when the object and reference photons are from the same coherence volume. Photons take random walks in strong scattering media. The less-scattered photons leave the media first while the multiple-scattered all behind. Careful adjustment of the pathlength difference between the two arms enables us to select the early-arriving photons, and reject the diffusive. The recording time is much longer than the coherence time and the diffusive photons are still recorded by the camera and produce a strong noisy background. To reduce the noise and obtain clearer imaging we inserted a ground glass in front of the object to produce speckle illumination. The beam then passes through the object, and the scattering medium. During the record-ing, we shifted the ground glass stepwise in a transversal direction by using a translation stage, and recorded a hologram at each step. Illumination in this way not only allows the reduction of speckle noise, but also plays a central role in the reduction of the multiple-scattering noise.

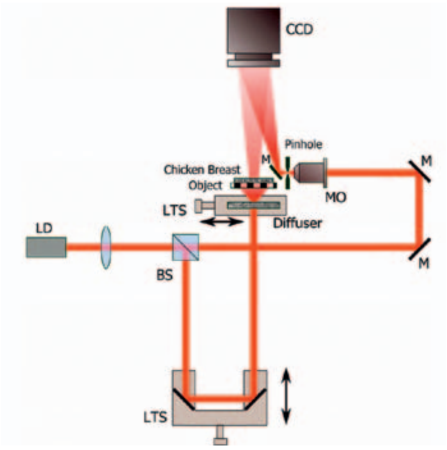

Fig. 1: Experimental setup of the proposed digital Fourier holography for imaging in tissue. LD: Laser diode, BS: beam splitter, LTS: linear translation stage, M: mirror, MO: microscope objective.

We carried out prove-of-principle experiments to demonstrate our technique. The light source was a 3 mW diode laser with the central wavelength 634 nm and coherence length of 40 µm. The object beam sequentially passed through a ground glass, an object printed on a transparent slide [Fig. 2(a)] and a fresh chicken breast slide of 3:1 ± 0:1 mm thickness. The chicken tissue slide was cut in fresh and laid on a microscope slide. The tissue presents very strong scattering as the direct reconstruction is barely recognizable [Fig. 2(b)]. However by using the proposed method, significant improvement can be observed by averaging 60 holograms as evidenced in Fig. 2(c). The signal-to-noise ratio (SNR) is improved from 1.9 to 4.7. The reconstruction is far better if the tissue thickness is reduced to 2:2 ± 0:1 mm [Fig. 2(d)].

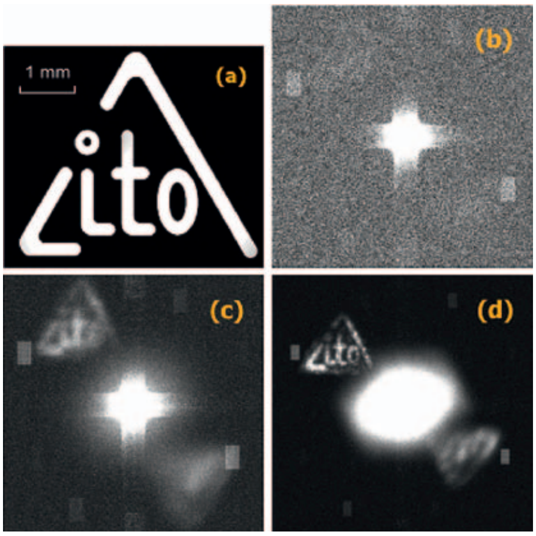

***Fig. 2:** Experimental results. (a) the original image printed on the transparent slide. (b) Reconstruction from one hologram. (c) Image formed by averaging 60 holograms. (d) Same as (c) except that the thickness of the chicken breast is reduced from 3:1±0:1 mm to 2:2±0:1 mm and that z = 21 cm.*

Supported by: Humboldt Foundation for G. Situ.

Resolution enhancement in digital holography

C. Yuan, G. Pedrini and W. Osten

Digital holography is a useful tool for three dimensional imaging, vibration and deformation measurement and particle analysis. The resolution of digital holography is determined by the numerical aperture (NA) of the recording system. To increase the NA, we proposed a method where several holograms are recorded in one CCD frame by using spatial multiplexing techniques and structured illumination.

The recording system is depicted in fig. 1. In the object beam arm, an imaging system composed by lens L1 and L2 is used to project a demagnified image of a grating onto the object. The object illuminated by the structured light is magnified by a microscope objective and imaged in front of the recording plane. In the reference beam arm, a lens L3 is inserted to compensate the curvature introduced by the objective in the object beam. A He-Ne laser (λ=633 nm) is used as a light source and a CCD (2452×2054 pixels) records the interference pattern (hologram) produced by the interference between the reference and the object beam. The spatial frequencies of the sinusoid grating are 25.2 lp/mm and 21.0 lp/mm along the x and y directions, respectively. A 3.2× microscope objective with NA=0.12 is used to image the object. A USAF1951 test target has been used to demonstrate the resolution improvement by this system.

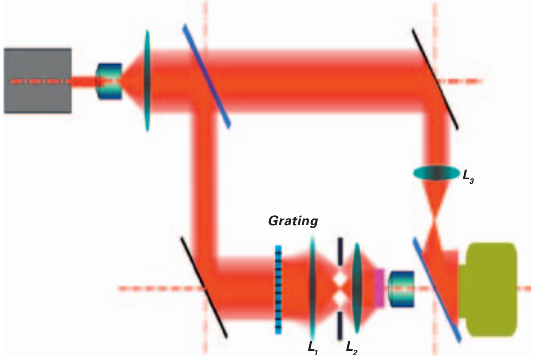

Fig. 1: *Experimental setup.*

Five light beams diffracted from the two dimensional grating illuminate the object from different directions. The zero order diffraction beam carries the low frequency information of the object to the CCD and the other beams shift the high spatial frequencies and allow them to enter into the imaging pupil. Introducing additional spatial frequencies to the imaging system is equivalent to increase the NA and thus enhance the resolution. The low and high frequency components are recorded in one frame and separated in the frequency domain. The resolution is improved by adding the reconstructed five complex amplitudes covering low and high frequency bandwidths. From the experimental results given in Fig. 2 we may see that under on-axis illumination we may resolve the 6th element of the 6th group and by using structured illumination the 6th element of the 7th group is resolved. Therefore, the resolution of the system has been improved from 114.0 Lp/mm (under on-axis illumination) to 228.0 Lp/mm (under structured illumination) in both vertical and horizontal directions.

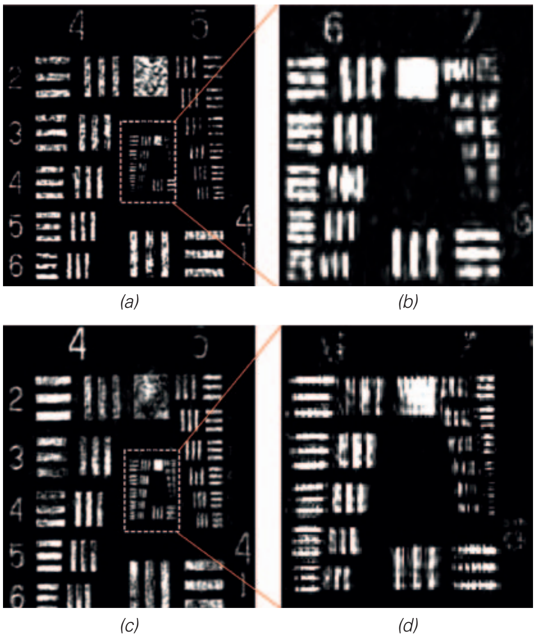

Fig. 2: *(a) Intensity distribution under on-axis illumination; (b) magnified area (dashed) of (a); (c) intensity distribution under structured illumination; (d) magnified area (dashed) of (c).*

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Phase retrieval by pin-hole scanning

G. Pedrini, F. Zhang, W. Osten

Holography allows to get the complex amplitude of a wave front by overlapping to it a reference wave. Nowadays, thanks to CCD and CMOS sensors and to modern computer resources, digital holography permits a straightforward and almost instantaneous evaluation of the amplitude and phase. Configuring a separate reference from a single light source, however, entails additional problems and for sources having reduced spatial coherence a filtering is necessary to get a homogeneous beam (e.g. spherical). Furthermore, when the source has low temporal coherence a tedious and sometimes cumbersome process of optimizing the path length between object and reference beams is necessary. Investigations have been made with the purpose to reconstruct amplitude and phase without using a reference beam and thus avoiding the disadvantages described above. We propose a simple non-iterative (deterministic) method to retrieve the phase by using the set-up shown in Figure 1.a). A transmitting or reflecting object is illuminated by coherent or partially coherent light. If we insert an opaque screen in the x-y plane with two pin-holes at A and B then two spherical waves are produced and their interference is described by a system of hyperbolic Young fringes which can be detected in a plane located at the distance zb from the screen. By performing a Fourier transform (FT), (see Figure 1.b), applying a filter in order to keep only one lobe (see Fig. 1.c) and then performing an inverse Fourier transform (iFT) we may get a complex distribution (see Fig. 1.d) and from this be taking into account the geometry of the arrangement we are able calculate the phase difference of the wavefront between the points A and B. The phase differences between the points A and B_{jk} may be determined by keeping fix the pin-hole located at A (this will be our reference) and shifting the other one along a grid to different positions B_{jk}. In this way we get the complex amplitude at each grid point (see Fig. 1.e) and by using the law of propagation we are able to reconstruct the object wave front at a given distance from that plane. The recording of the interference pattern at $\xi-\eta$ is done by a pixelated detector. The proposed method was at first tested by using simulated pattern (binary ITO logo shown upper left in Fig. 1.a) with random phase added). We simulated

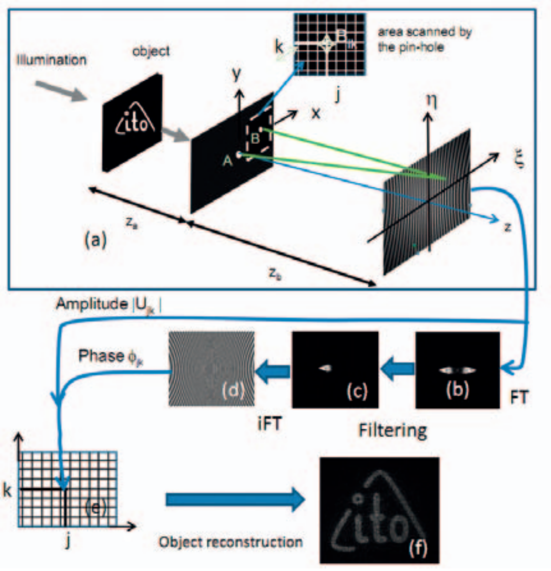

Fig. 1: *Recording arrangement (a) and procedure for determining the phase difference of the wavefront between the points A and B_{jk}. Fourier Transform of the recorded intensity (b), filtering (c) and inverse Fourier Transform (d). The complex amplitude on a grid (e) allows the reconstruction of the object (f).*

the recording of interferograms obtained by interfering the spherical wave coming from the reference pin-hole (located at point A) and the waves coming from the other pin-hole which is shifted along a 512x512 grid. From the interferograms, we get the phases, and amplitudes allowing the reconstruction of the object (see Fig. 1.f).

An experiment has been carried out where a 2.5x2.5 mm² transmission mask (see Fig. 2.a) was illuminated by light produced by a Nd:YAG laser. One pinhole was mounted on a computer controlled 2D translation stage and was translated along a 128x128 grid. The interference pattern were recorded by a CCD camera. The retrieved phase at the plane x-y is shown in Fig. 2.b) and the object reconstruction in Fig. 2.c). The quality of the reconstruction is not very good due to the small number of scanned points (128x128).

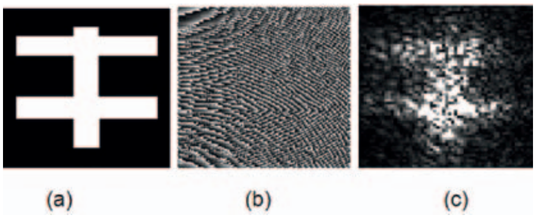

Fig. 2: *(a) Original mask used for the experiment (2.5x2.5 mm²). (b) Retrieved phase of the wave front at the scanning pin-hole plane (128x128 points) (c) Reconstructions of the object from the complex amplitude.*

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Proceedings of SPIE 7736 (2010) pp. 77363Y

Schau, P.; Frenner, K.; Fu, L.; Schweizer, H.; Osten, W.

Coupling between surface plasmons and Fabry-Pérot modes in metallic double meander structures

Proceedings of SPIE 7711 (2010) pp. 77111F

Patents

Patent Applications

Ruprecht, Aiko:

Optisches Detektionsverfahren mittels Vielstrahlinterferenz

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

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

Method and arrangement for a rapid and robust chromatic confocal 3d measurement technique

US 2009/0021750 A1 2009.01.22, priority data: 2006.02.08
JP 2009 526 216 (T) 2009.07.16, priority data: 2006.02.08

Verfahren und Anordnung zur schnellen und robusten chromatisch-konfokalen 3D-Messtechnik

AT 442 604 (T) 2009.09.15, priority data: 2006.02.08
(all from family list for DE 10 2006 007 170 B4)
Assignee: Sirona Dental Systems GmbH

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

Anordnung und Verfahren zur konfokalen, spektralen Zweistrahl-Interferometrie

DE 10 2008 020 902 A1 2009.10.29, priority data: 2008.04.18

Körner, Klaus; Osten, Wolfgang:

Verfahren und Anordnung zur skalierbaren Interferometrie

DE 10 2008 062 879 A1 2010.05.12, priority data: 2008.10.10, 2008.10.14, 2008.12.15

Verfahren und Anordnung zur Interferometrie

PCT/EP 2009/007327, WO 2010/040570 A1 2010.04.15

Hopp, David; Pruß, Christof; Osten, Wolfgang:

Verfahren zur optischen Kompensation der Maßspurdezentrierung bei Drehwinkelsensoren

DPMA-AZ: 10 2009 040 790, priority data: 2009.09.09
PCT/EP2010/005514

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

Verfahren und Anordnung zur robusten Interferometrie

DPMA-AZ: 10 2010 006 239, priority data: 2010.01.22

Additional patent application
Körner, Klaus; Osten, Wolfgang:

Verfahren zur robusten, insbesondere weitskaligen Interferometrie

DPMA-AZ: 10 2010 056 122, priority data: 2010.12.20

Wibbing, Daniel; Hopp, David:

Positionsmesssystem und Verfahren zur Ermittlung einer Absolutposition

DPMA-AZ: 10 2010 045 355, priority data: 2010.09.14
Assignee: Festo AG & Co. KG

Körner, Klaus; Osten, Wolfgang:

Robustes One-Shot-Interferometer und Verfahren, insbesondere auch als Scout-Sensor zur multisensoriellen Materialmessung oder Tumorzellen-Erkennung

DPMA-AZ: 10 2010 046 907, priority data: 2010.09.24

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Lehmann, Peter; Lücke, Peter; Mohr, Jürgen; Morgan-Iglesias, Javier Carlos; Osten, Wolfgang; Ruprecht, Aiko; Schönfelder, Sven:

Optical Measuring Head

US 7,486,394 B2 2009.02.03, priority data: 2006.09.02
Assignee: Carl-Mahr Holding GmbH

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

Interferometrisches Verfahren und Anordnung

EP 1 805 477 B1 2009.04.08, priority data: 2004.10.20, 2005.02.03, 2005.09.05

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

Verfahren und Anordnung zur konfokalen, chromatischen, interferometrischen, spektroskopischen Abtastung für optische Mehrlagendatenspeicher

EP 1 846 923 B1 2009.04.08, priority data: 2005.02.03

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

Verfahren und Anordnung zur schnellen und robusten chromatisch-konfokalen 3D-Messtechnik

DE 10 2006 007 170 B4 2009.06.10, priority data: 2005.02.08
EP 1 984 770 B1 2009.09.09

Method and arrangement for a rapid and robust chromatic confocal 3d measurement technique

US 7,787,132 B2 2010.08.31
Assignee: Sirona Dental Systems GmbH

Górski, Witold, Marek; Osten, Wolfgang:

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

DE 10 2007 036 309 B4 2009.09.03, priority data: 2007.07.31

Ruprecht, Aiko:

Optisches Detektionsverfahren mittels Vielstrahlinterferenz

DE 10 2007 030 814 B4 2010.02.11, priority data: 2007.07.03

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

Anordnung und Verfahren zur konfokalen, spektralen Zweistrahl-Interferometrie

DE 10 2008 020 902 B4 2010.07.29, priority data: 2008.04.18

Körner, Klaus; Osten, Wolfgang:

Sensor zur Erfassung der Topografie mit einem Zweistrahl-Interferometer

DE 103 21 895 B4 2010.09.16, priority data: 2003.05.07

Körner, Klaus; Osten, Wolfgang:

Verfahren und Anordnung zur skalierbaren Interferometrie

DE 10 2008 062 879 B4 2010.10.28, priority data: 2008.10.10, 2008.10.14, 2008.12.15

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Doctoral Thesis 2009–2010

Seifert, Lars

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2/2009

Kauffmann, Jochen

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5/2009

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7/2009

Schuster, Thomas

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1/2010

Jackisch, Sebastian Maximilian

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10/2010

Zwick, Susanne

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11/2010

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Schaal, Frederik

Grundlegende Untersuchungen zur Punktgenerierung für die Laser-Doppler-Vibrometrie

3/2009

Xu, Chang

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Halser, Malte

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Lingel, Christian

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2/2010

He, Lin

Untersuchungen zur Kalibrierung der Hologrammkoeffizienten in holografisch optischen Pinzetten

3/2010

Maier, Selim

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7/2010

Götz, Johannes

Weiterentwicklung der optischen Messanlage zur Vermessung von Fahrdrahtposition und Fahrdrahtstärke

7/2010

Student Research Project 2009–2010

Yu, Kejian

Photoresist-Beschichtung auf gekrümmten Oberflächen für die Fertigung diffraktiver Elemente

1/2009

Maier, Selim

LabVIEW basierte Implementierung zur Korrektur mikroskopischer Abbildungen

5/2009

Rappold, Jörg

Numerische Simulationen zur Untersuchung von Asymmetrien im Strahlengang eins Weißlichtinterferometers

7/2009

Körner, Markus

Realisierung einer Strahlformungsoptik für die Substratvorbelichtung

12/2009

Neumayer, Axel

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12/2009

Xu, Xiaodong

Die Untersuchung der Zeitmittelscherografie und der Vibrationserregung zur zerstörungsfreien Prüfung von Kunstobjekten

1/2010

Gronle, Marc

Referenzierung von Sensoren in einem Multi-Sensor-Aufbau am Beispiel des konfokalen Mikroskops

2/2010

Schaub, Christian

Entwicklung einer Anwendungssoftware zur Untersuchung der Automatisierung des Einfangs in holografischen Laserpinzetten

5/2010

Wagner, Mario

Optisches Design und Aufbau eines SLM-basierten scannenden Vibrometers

7/2010

Müller, Mathias

Entwurf und Realisierung einer kurzkohärenten Lichtquelle für nicht abgeglichene Interferometer

10/2010

Götz, Johannes

LabVIEW-basierte, automatisierte Phasenkontrastanalyse und -optimierung

7/2010

Baer, Goran

Verfahren zur automatisierten Justage asphärischer Oberflächen

10/2010

FRINGE 2009

The 6th International Workshop on Advanced Optical Metrology

In 1989 the time was hot to create a workshop series dedicated to the discussion of the latest results in the automatic processing of fringe patterns. This idea was promoted by the insight that automatic and high precision phase measurement techniques will play a key role in all future scientific and industrial applications of optical metrology. However, such a workshop must take place in a dynamic environment. Therefore the main topics of the previous events were always adapted to the most interesting subjects of each period. In 1993 new principles of optical shape measurement, setup calibration, phase unwrapping and non-destructive testing were the focus of discussion, while in 1997 new approaches in multi-sensor metrology, active measurement strategies and hybrid processing technologies played a central role. 2001, the first meeting in the 21st century, was dedicated to optical methods for micro-measurements, hybrid measurement technologies and new sensor solutions for industrial inspection. The fifth workshop took place already in Stuttgart and was organized by the staff of ITO. Here the focus was directed to new methods and tools for data processing, resolution enhanced technologies, wide scale 4D optical metrology, hybrid measurement technologies, and new optical sensors and measurement systems. Thus after Berlin 1989, Bremen 1993, 1997 and 2001, Stuttgart was the third Fringe city where international experts met each other to share new ideas and concepts in optical metrology. And this was continued in 2009 where the city Nürtingen, a lovely medieval town nearby Stuttgart, was chosen as conference place.

The focus of the Stuttgart meeting was in particular directed to digital wavefront engineering, resolution enhanced technologies, 3D methods addressing applications from macro to nano considering dynamic changes, sensor fusion and new advances in the unification of modeling, simulation and experiment. Since optical metrology becomes more and more important for industrial inspection, sophisticated sensor systems and their applications for the solution of challenging measurement problems were chosen again as one of the central topics of the workshop. This extended scope was honored again by a great response on our call for papers. Scientists from all around the world offered more than 150 papers. The presented papers were summarized under 5 topics and published by Springer in a representative proceedings volume [1]:

1. New Methods and Tools for the Generation, Acquisition, Processing, and Evaluation of Data
2. Application Enhanced Technologies
3. 4D Optical Metrology over a Large Scale Range
4. Hybrid Measurement Techniques
5. New Optical Sensors and Measurement Systems

As in the former workshops, each dedicated session was introduced by an acknowledged expert who gave an extensive overview of the subject and a report of the state of the art.

The organizers and the whole audience appreciated the presentations of many internationally recognized scientists such as Mitsuo Takeda, Colin Sheppard, Joseph Rosen, Peter de Groot, Byongho Lee, Gerd Jäger, Ryszard Pryputniewicz, Heidi Ottevare, and Nadya Reingand. Since the early beginning of the Fringe series it has been a good tradition to distinguish deserved scientists with honorary lectures. In 2009 Jim Wyant was awarded with the honorary lecture while Charles Vest, President of the US National Academy of Engineering and former president of the MIT, was selected to present the key note at the banquet. On occasion of the Stuttgart conference the Hans Steinbichler award was presented for the second time by his son Marcus Steinbichler. The winner of the 2009 price was Michael Küchel, an internationally acknowledged expert in optical interferometry, for his numerous contributions to the field over many years of active scientific

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[1] Osten, W.; Kujawinska, M. (Eds.): Fringe 2009. Proc. Of the 6th International Workshop on Advanced Optical Metrology. Springer Heidelberg, Dordrecht, London, New York 2009

work. For all Fringe workshops a special event is the celebration of a new HoloKnight. The former Holoknight, Sir Charles of Washington (Charles Vest) honored Lady Nadya of St. Petersburg (Nadya Reingand) with the sword and the sealed parchment.

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

Looking forward to FRINGE 2013.

Fig. 1: *The program committee of Fringe 2009*

ITO celebrated its 50th anniversary

In 1947 the first preparations for the founding of an institute in the field of applied optics at the University of Stuttgart started. Apart from the scientific interest, the main motivation was to support the optical industries in Württemberg and Germany. It took more than 10 years until this institute, ITO, was finally founded in 1960 and, therefore, in 2010 we had the 50th anniversary of ITO.

More than 250 former ITO alumni and friends of ITO celebrated this event at our university. Prof. Osten gave an introductory presentation entilted "Wege zum Licht" where he talked about the importance of light and optical research starting from Genesis and ending with today's latest achievements. An emphasis, of course, was put on the last 50 years of research at ITO.

Prof. Leuchs of the Max Planck Institut für die Physik des Lichts in Erlangen, gave an introduction on quantum engineering in optics.

After the feastful lunch, presentations were given by former Ph.D. Alumni of ITO. Prof. Küchel took over and told about the optical characterization of surfaces. Dr. Dörband (responsible at Carl Zeiss SMT AG for the precision measurement of high-end optical components) reviewed interferometric testing of aspherical surfaces and Dr. Liesener of Zygo, USA completed the interferometry session with a presentation on optical measurement techniques in the semiconductor industry.

The second session was opened by Dr. Totzeck of Carl Zeiss AG. He gave an outlook about the future of optical measurement systems. Dr. Reichelt (SeeReal Technologies) gave a presentation about future 3D display technologies and finally Dr. Windecker from the European Patent Office talked about the role of intellectual property in optics. Finally, the banquet was followed by a social get-together night.

Fig. 1: *ITO alumni at the 50th anniversary*

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*

Fest-Kolloquium 2010: 50 Jahre ITO und gleichzeitig 25. Optik-Kolloquium

Photonik im Maschinenbau

am 10. September 2010, Teilnehmer: ca. 350

Begrüßung	Prof. Dr. W. Osten *ITO, Universität Stuttgart*
Grußwort	Prof. Dr.-Ing. Wolfram Ressel *Rektor der Universität Stuttgart*
50 Jahre ITO: Wege zum Licht	Prof. Dr. W. Osten *ITO, Universität Stuttgart*
Quantum Engineering in der Optik	Prof. Dr. Gerd Leuchs *Gastredner MPI Physik des Lichts, Erlangen*
Optische Vermessung von Präzisionsoberflächen	Prof. Dr. Michael Küchel *Oberkochen*
Messtechnik für High-End-Optikkomponenten der Lithographie	Dr. Bernd Dörband *Carl Zeiss SMT AG, Oberkochen*
Hochgenaue Messtechniken für die Halbleiterindustrie	Dr. Jan Liesener *ZYGO Corporation, Middlefield, USA*
Optische Messtechnik – Perspektiven aus Zeiss-Sicht	Dr. Michael Totzeck *Carl Zeiss AG, Oberkochen*
Future 3D-Vision	Dr. Stephan Reichelt *SeeReal Technologies, Dresden*
Die Rolle von Intellectual Property (IP) in der Optik	Dr. Robert Windecker *Europäisches Patentamt, München*

Optik-Kolloquium 2011

Mikro- und Nanooptik: Design, Herstellung, Prüfung und Anwendung

am 23. Februar 2011, Teilnehmer: ca. 200

Begrüßung und Einführung	Prof. Dr. W. Osten *ITO, Universität Stuttgart*
Mikrooptik als Schlüsseltechnologie: Von der DUV Lithographie zur Wafer-Level Kamera	Dr. R. Voelkel *SUSS MicroOptics SA, Neuchatel, Schweiz*
Planar-integrierte Mikrooptik: Entwurf, Fertigung, Anwendungen	Prof. Dr. J. Jahns *Lehrgebiet Optische Nachrichtentechnik, FernUniversität Hagen*
Fourier-Optik in der Integration: Breitstreifen-Halbleiterlaser mit monolithisch integrierten Fourier-optischen Transversalmodenselektoren	Prof. Dr. H. Fouckhardt *AG Integrierte Optoelektronik und Mikrooptik, TU Kaiserslautern*
Durchstimmbare Mikro- und Nanooptik	Prof. Dr. H. Zappe *IMTEK, Labor für Mikrooptik, Universität Freiburg*
Adaptive Mikrooptik für Ultrakurzpuls-Laser	Dr. R. Grunwald *Max-Born-Institut für Nichtlineare Optik und Kurzzeit-Spektroskopie, Berlin*
3D Laser-Lithographie – ein vielseitiges Werkzeug für die Nanotechnologie	Prof. Dr. G. von Freymann *AG Optische Technologien und Photonik, TU Kaiserslautern*
Perspektiven für die Subwellenlängen-Mikrooptik: Design, Herstellung und Anwendung	Dr. E.-B. Kley *Institut für Angewandte Physik, Friedrich-Schiller-Universität Jena*
Neue Fertigungstechnologien zur Herstellung diffraktiver Optiken mittels Laser-Lithographie	M. Häfner *ITO, Universität Stuttgart*
Inspektionskonzepte für die Detektion von Mikro/Nano-Defekten in großflächigen Strukturen	Dr. K. Gastinger *SINTEF ICT Optical Measurement Systems and Data Analysis, Trondheim, Norwegen*
3D-Metamaterialien	Prof. Dr. H. Giessen *4. Physikalisches Institut, Universität Stuttgart*
Superlinsen durch Metamaterialien: Visionen und Möglichkeiten	P. Schau *ITO, Universität Stuttgart*
Aktive Mikrooptik zur ortsaufgelösten Steuerung des Polarisationszustandes	F. Schaal *ITO, Universität Stuttgart*

SCoPE – Opening Ceremony

From basic research in photonics to engineering innovation

In March 2009, the University of Stuttgart established the Stuttgart Research Center of Photonics Engineering (SCoPE), as part of its new research strategy. This is the second major research center founded at the University of Stuttgart.

In close cooperation with the industry SCoPE will strengthen research and development, from basic research on photonics to photonic innovation and interdisciplinary collaboration between physicists and engineers at the University of Stuttgart.

ITO was one of the initiators of SCoPE and together with seven other institutes founded the research center in March 2009. Currently, 11 institutes from two engineering departments (the department of Construction, Industrial Engineering, Automotive Engineering and the department of Informatics, Electrical Engineering and Information Technology), as well as the department of physics collaborate on the SCoPE center. It is planned to integrate other institutes and research facilities in the near future.

Primary scientific objectives in SCoPE's interdisciplinary research are:

- Modelling, simulation, fabrication and characterization of structured photonic components with critical dimensions in the sub-wavelength range
- Integration of photonic components into active optical devices and systems,
- Modelling and technical implementation of photoninduced and photon-based processes and components for photonic machines with special emphasis on process safety in industrial manufacturing.

One of the most important aims of SCoPE is to increase excellence and visibility of the research in photonic technologies at the University of Stuttgart. This is achieved by:

- Improvement of interdisciplinary collaborations between scientists and engineers
- Improvement of the width and coherence of research and education
- Establishment of mid and long term research foci

SCoPE has an interdisciplinary and interfaculty research structure, collaborating with national and international research and industry partners, including Alcatel-Lucent, Bosch, Daimler, Trumpf and Zeiss.

SCoPE was officially founded in November 2009, with wide participation of industry, academia and politics. During the opening ceremony, the structure and mission of

SCoPE

STUTTGART RESEARCH CENTER OF PHOTONIC ENGINEERING

SCoPE were presented, together with the following three keynote speeches:

- Photonic crystal fibres: mastering the flow of light, Prof. Dr. Philip Russell, MPI, Erlangen
- Future Photonic Production – wissenschaftlichtechnische und strukturelle Perspektiven eines Schwerpunktes an der RWTH-Aachen, Prof. Dr. R. Poprawe, FhG ILT, Aachen
- Die Graduiertenschule "Karlsruhe School of Optics & Photonics": Ausbildungskonzepte für die Optischen Technologien, Prof. Dr. U. Lemmer, KSOP Universität Karlsruhe.

SCoPE is not only an interdisciplinary research consortium, but has evolved into a team-oriented interfaculty organization of physicists and engineers.

In addition to the scientific work a beach volleyball tournaments is organized each Year. The most recent took place on July 3rd 2010, when 15 teams from eight institutes played at the university sports facilities. One of the two ITO teams reached the second place in this tournament.

For more information on SCoPE:
www.scope.uni-stuttgart.de

Organized International Conferences: 2009 - 2010

W. Osten, M. Kujawinska, P. Ferraro:

SPIE Europe Optical Metrology Conference 2009

June 15 -18, 2009, Munich, Germany

P. Lehmann, W. Osten:

Optical Measurement Systems for Industrial Inspection VI

SPIE Congress, June 15 – 18, 2009, Munich, Germany

W. Osten, M. Kujawinska:

Fringe 2009

The 6th International Workshop on Advanced Optical Metrology, September 13 – 18, 2009, Stuttgart, Germany

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C. Gorecki, A. Asundi, W. Osten:

Optical Micro- and Nanometrology III

April 13 – 14, 2010, Brussels, Belgium

Z. Füzessy, S. Krüger, W. Osten:

HoloMet 2010

3rd International Workshop on Advanced Imaging and Metrology, June 13 – 17, 2010, Balatonfüred, Hungary

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