annual report
2013 / 2014

INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

Universität Stuttgart

INSTITUT FÜR TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

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ANNUAL REPORT 2013/2014

Dear Reader,

Another two years filled with many activities in different fields and enriched with fruitful national and global cooperation have passed since the ITO staff reported in 2013 about their current research activities. Thus it is again time to inform our partners, sponsors and customers about our recent advances in the field of Applied Optics.

The basic understanding that determines our work remains unchanged: striving for excellence in research and teaching, together with a good balance of continuity and systematic renewing. Ongoing activities are directed at both the continuous modernization of our infrastructure, and the profound investigation of our strategic research topics such as multi-scale sensor fusion, computational microscopy, resolution enhancement, model-based reconstruction of measurement data, asphere and freeform metrology, optical systems design, hybrid optics, digital holography, and inverse scattering. To complete our objective - the establishment of a sophisticated nano-fabrication and –measurement center, ITO participated in a call of the German Research Association for the installation of a Nano-Measurement and –Positioning Machine. We are very glad that we could win the grant in the value of 4,6 Mio Euro. This device NPMM 200, invented and constructed by the Technical University Ilmenau as the result of a long-term collaborative research center supported by the DFG, needs an especially designed environment to accomplish a resolution range of 0,08 nm for the positioning of different kind of sensors in a volume of 200x200x25mm^3. The design of the laboratory and the construction of the NPMM 200 are already on the way. We expect to open the new laboratory as an extension of our clean room where we already run the focused ion beam facility Helios Nanolab 600, two circular laser writing systems CLWS 300, and several sophisticated measurement tools, in the middle of the year 2017. Our aim to assure flexible structuring, positioning and measuring technologies with high resolution, precision and reliability not only for a few crucial experiments but for making dedicated optical components and to guarantee reliable measurements in the nano scale is on a good way.

To ensure that ITO can comply with its mission under changing boundary conditions, we support the cooperative network SCoPE[1] with many activities. On the one hand ITO is an active driver of the joint master course in Photonic Engineering that was established in spring 2013. This inter-faculty course shows a continuous increase in students from physics, mechanical and electrical engineering. On the other hand several joint research projects with different SCoPE members are in progress or on the way.

As a member of the Faculty of Mechanical Engineering, the Institute represents the University of Stuttgart in the field of Applied Optics in research and education. Together with our national and international partners, our research work focuses on the exploration of new optical measurement, imaging and design principles and their implementation in new components, sensors and sensor systems. One of our long-term 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 still on our agenda such as the implementation of a multi-sensor measurement system where the systematic cooperation of different classes of sensors is controlled by a sophisticated assistance system. With respect to the completion of the prototype of our tilted wavefront interferometer ITO could achieve very good results in cooperation with our partner Mahr. In 2014 a joint team received the AMA Innovation Award and the relevant IP was transferred meanwhile completely to Mahr. Mahr plans the market launch for the Mahr Surf TWI 60 for 2016.

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

- Active Metrology,
- Model-based Metrology,
- Remote Metrology,
- Resolution Enhanced Technologies,
- Computational Imaging,
- Sensor Fusion,
- Sensor Integration,
- Hybride Optics,
- Simulation, and
- Optical Systems Design.

The strong interaction between these directions gives the Institute the required depth across the broad range of our activities in optics. The considerable number of research projects that are referred to in this report reflects again the success of this approach.
Besides our wide research activities, an ongoing strong commitment of ITO is directed to high-quality teaching on different levels (bachelor, master, PhD). Our consecutive bachelor-master course in medical technology – a joint and challenging project of the University of Stuttgart and the Eberhard Karls Universität Tübingen – is running very successful in both the bachelor and the master level. Since the beginning in 2010, ITO is one of the drivers of that course.

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.

As it will be shown with this research report, ITO fulfils its mission successfully under partly complicated boundary conditions. One event in 2014 that influenced our daily work in remarkable way was the fire in our building that was caused by a technical defect in an upper floor. Although ITO was only affected by serious water damage, we had to evacuate the complete institute from one day to another for several months. Today we can report that neither our teaching nor our research activities and commitments were influenced in a negative way. This is primarily a result of the outstanding commitment of the entire staff and deserves our recognition.

Stuttgart, July 2015

W. Osten

Wolfgang Osten

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[1] Stuttgart Research Center of Photonic Engineering, http://www.scope.uni-stuttgart.de/

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Institute structure

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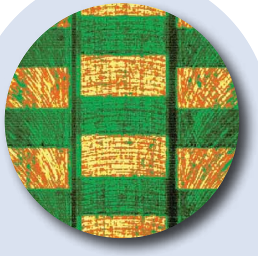
Colloquia & Conferences

Team and structure

Teaching
E. Steinbeißer

Chair
Prof.Dr. W. Osten
Prof. Dr. A. Herkommer

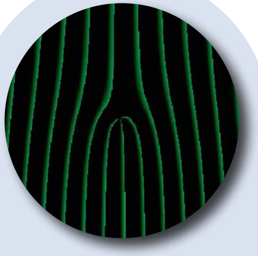
Deputy
Dr. T. Haist



3D-Surface Metrology

M. Gronle

- Macro and micro metrology
- White light and spectral interferometry
- Confocal microscopy
- Fringe projection
- Sensor-models and sensor-fusion



Active Optical Systems

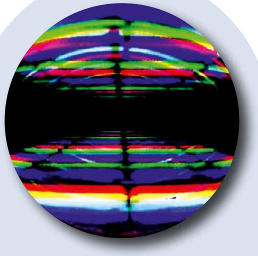
Dr. T. Haist

- Active wavefront modulation
- Active wavefront sensors
- Adaptive optics
- Computational imaging
- Dynamic holography

High Resolution Metrology

Dr. K. Frenner

- High resolution microscopy
- Scatterometry
- Light-surface interaction
- Modeling and rigorous simulation
- Model-based reconstruction



Interferometry and Diffractive Optics

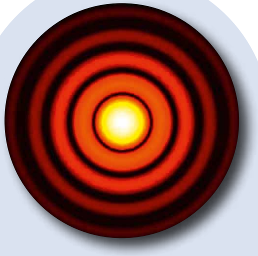
F. Schaal

- Technology and components
- Design and fabrication of diffractive optics
- Interferometry
- Testing of aspheres and freeform surfaces
- Micro-optics

Coherent Metrology

Dr. G. Pedrini

- Digital holography
- Phase retrieval
- Non-destructive testing
- Experimental stress analysis
- Medical imaging
- Remote laboratories and metrology



Optical Design and Simulation

Prof. Dr. A. Herkommer

- Optical design
- Illumination design
- Optimization methods
- Simulation of imaging- and illumination systems
- Optical systems in medical engineering

Administration, Software Engineering & Technical Support

Staff of the Institute

Status quo: June 2015

Director

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Scope

Margarita Riedel	left on 30.04.2014

Emeritus

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Research Assistants

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Dr. David Baureis	left on 30.11.2013	
Dr. David Fleischle	left on 30.11.2013	
Dr. Christian Kohler	left on 30.11.2013	
Dr. Wolfram Lyda	left on 30.11.2013	
Florian Mauch	left on 31.08.2014	

Active Optical Systems

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High resolution metrology and simulation

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Valeriano Ferreras Paz	left on 28.02.2015	
Holger Gilbergs	left on 31.01.2015	
Philipp Schau	left on 31.01.2015	

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Matthias Häfner	left on 31.01.2013	
Goran Baer	left on 31.05.2015	
Jan Beneke	left on 30.06.2015	

Coherent metrology

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Ahmad Faridian	left on 30.09.2014	
Peng Gao	left on 28.02.2014	
Henning Kästner	left on 31.12.2013	
Michael Morawitz	left on 31.08.2013	
Dinesh Naik	left on 31.12.2013	
Marc Wilke	left on 31.03.2015	

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Guest Scientists

Prof. Dr. Anhu Li	Tongji University, China	07/2012 – 01/2013
Prof. Dr. Huarong Gu	Tsinghua Univ., Beijing, China	01/2013
Ruslan Shimansky	IA&E SB RAS Novosibirsk, Rusia	01 – 02/2013
Prof. Dr. Mitsuo Takeda *	UEC, Tokio, Japan	since 03/2013
Prof. Dr. Changhe Zhou **	Shanghai Institute of Optics and Fine Mechanics, China	07 – 08/2013
Dr. Caojin Yuan	Nanjing Normal Univ., China	08 – 09/2013
Wei-Yao Chang	National Chiao Tung University, Taiwan	03 – 11/2014
Dr. Pavel Pavlicek	Palacký Univ., Joint Lab. of Optics, Olomouc, Czech Rep.	07/2014

Shinja Ishikawa	Utsonomyia University, Japan	10 – 11/2014
Prof. Dr. Ignacio Moreno Soriano	University Miguel Hernandez, Alicante, Spain	11 – 12/2014

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

Foreign Guests visiting the Institute: 2013 – 2014

Dr. C. Jones	NPL, Teddington, UK	January 2013
Dr. A. den Boef	ASML Veldhoven, Netherlands	January 2013
Prof. Dr. W. Coene	ASML, Veldhoven, Netherlands	January 2013
Dr. D. Claus	Univ. of Sheffield, GB	May 2013
Dr. P. Montgommery	CNRS Strasbourg, France	July 2013
Prof. Dr. R. Pryputniewicz	WPI Worcester, USA	September 2013
Prof. L. Li	Tsinghua Univ. Beijing, China	September 2013
Prof. B. Bai	Tsinghua Univ. Beijing, China	September 2013
Prof. J. Ma	Nanjing Univ. of Science and Technology, China	September 2013
Prof. R. Zhu	Nanjing Univ. of Science and Technology, China	September 2013
Prof. X. Peng	Shenzhen Univ., China	September 2013
Dr. C. Zuo	Nanyang Technical Univ., Singapore	September 2013
Dr. M. Zhao	Chinese German Center Beijing, China	December 2013
AIST Students Delegation	Univ. Tsukuba, Japan	March 2014
Dr. A. den Boef	ASML Veldhoven, Netherlands	March 2014
Prof. Dr. Y. Hayasaki	Utsunomiya Univ., Japan	April 2014
Prof. M. Duca	Academy of Sciences of Moldova, Chisinau, Moldova	June 2014
Dr. A. Glijin	Academy of Sciences of Moldova, Chisinau, Moldova	June 2014
Dr. E. Achimova	Academy of Sciences of Moldova, Chisinau, Moldova	June 2014
Dr. P. Stahl	SPIE President	July 2014
Dr. A. Brown	SPIE Senior Director, USA	July 2014
Dr. A. den Boef	ASML Veldhoven, Netherlands	July 2014
Dr. S. Mathisen	ASML Veldhoven, Netherlands	July 2014
Prof. K. Ishibashi	Univ. of Electro-Communications Chofu, Japan	October 2014
Prof. Dr. Y. Kanematsu	Osaka Univ., Japan	November 2014

Project partners

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

Aesculap AG	Tuttlingen
ASML Netherlands B.V.	Veldhoven, Netherlands
Carl Zeiss Meditec	Oberkochen
Carl Zeiss Microscopy	Jena
Carl Zeiss AG	Oberkochen
Carl Zeiss SMT AG	Oberkochen
Centre Spatial de Liege	Liege, Belgium
Centre Suisse d’Electronique et de Microtechnique	Zurich, Switzerland
Daimler AG	Stuttgart
DermoScan GmbH	Munich
ESTEC	Noordwijk, Netherlands
FOS Messtechnik GmbH	Schacht-Audorf
Fraunhofer ENAS	Chemnitz
Fraunhofer IOF	Jena
Fraunhofer IAP	Potsdam
Holoeye AG	Berlin
HSG-IMAT	Stuttgart
IAE SB RAS	Novosibirsk, Russia
ILM	Ulm
IMS Chips	Stuttgart
Laboratoire d'optique appliquée, IMT, EPFL	Neuchâtel, Switzerland
LaVision GmbH	Göttingen
Mahr OKM GmbH	Jena
Physikalisch Technische Bundesanstalt	Braunschweig
Polytec GmbH	Waldbronn
Robert Bosch GmbH	Gerlingen
Shenzhen University	China
Sick AG	Waldkirch
Siemens AG	München
Staatliche Akademie der Bildenden Künste Stuttgart	Stuttgart
Statice	Besancon, France
Trumpf GmbH + Co. KG	Ditzingen
Tsinghua University	Peking, China
Université de Franche-Comté	Besancon, France
University of Eastern Finland	Joensuu, Finland
VTT Technical Research Centre of Finland	Espoo, Finland

Studying optics

Traditionally our curriculum is primarily directed towards the students in upper-level diplom courses of **Mechanical Engineering, Cybernetic Engineering, Mechatronics, and Technology Management**. Since the academic year 2011/12 this courses are offered as master courses and an increasing number of master students is going to join our lectures.

This applies especially for the new master programme **"Micro-, Precision- and Photonics Engineering"** which enjoys great popularity also by students from other universities even from other countries.

Since the academic year 2009/10 we also offer our optics courses within the new bachelor and master program **"Medical Engineering"**, and since 2012 also within the new master program **"Photonic Engineering"**. We also welcome students from other courses, such as "Physics" and "Electrical Engineering" and "Information Technology".

The following list should give you an overview about the lectures given at the ITO. Be aware that not all lectures are suitable for all courses and that most lectures are held in German language.

Core subjects in Master Courses (6 ECTS - Credit Points):

- **Fundamentals of Engineering Optics**
  Lecture: Prof. Dr. W. Osten, C. Pruß
  Exercise: A. Bielke, E. Steinbeißer

- **Optical Measurement Techniques and Procedures**
  Lecture: Prof. Dr. W. Osten
  Exercise: Dr. K. Körner, E. Steinbeißer

- **Optical Information Processing**
  Lecture: Prof. Dr. W. Osten
  Exercise: Dr. K. Frenner

- **Fundamentals of Optics** (only for B.Sc.)
  Lecture: Prof. Dr. A. Herkommer
  Exercise: D. Rausch

- **Optical Systems in Medical Engineering**
  Lecture: Prof. Dr. A. Herkommer
  Exercise: D. Rausch

- **Development of Optical Systems**
  Lecture: Prof. Dr. A. Herkommer
  Exercise: S. Thiele

Elective subjects in Master Courses (3 ECTS - Credit Points):

- **Optical Phenomena in Nature and Everyday Life**
  Lecture: Dr. T. Haist

- **Image Processing Systems for Industrial Applications**
  Lecture: Dr. T. Haist, Dr. Ch. Kohler

- **Optical Measurement** (only for B.Sc.)
  Lecture: Dr. K. Körner, E. Steinbeißer

- **Fundamentals of Colorimetry and Digital Photography**
  Lecture: Dr. K. Lenhardt

- **Polarization Optics and Nanostructured Films**
  Lecture: Dr. K. Frenner

- **Introduction to Optical Design**
  Lecture: Dr. Ch. Menke, Prof. Dr. A. Herkommer

- **Advanced Optical Design**
  Lecture: Prof. Dr. A. Herkommer

- **Illumination Systems**
  Lecture: Prof. Dr. A. Herkommer

- **Current Topics and Devices in Biomedical Optics** (only for B.Sc.)
  Seminar: Prof. Dr. A. Herkommer

Additional studies:

- **project work and thesis within our fields of research**
  (you will find a list of all student project works at the end of this annual report)

- **practical course "Optic-Laboratory"**
  - speckle measurement
  - holographic projection
  - digital microscopy
  - computer aided design of optical systems
  - measurement of the spectral power distribution

- **practical course "Optical Measurement Techniques"**
  - high contrast microscopy
  - digital holography
  - 2D-interferometry and measurement
  - quality inspection of photo-objectives with the MTF measuring system
  - ellipsometry

- **common lab for mechanical engineering (APMB)**

The research groups

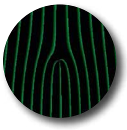
3D-Surface Metrology

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

Current research activities are:

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

Contact: **ofm@ito.uni-stuttgart.de**



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

Contact: **aos@ito.uni-stuttgart.de**

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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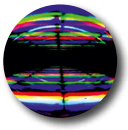

Interferometry and Diffractive Optics

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 elements and micro-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
- medical imaging

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Optical Design and Simulation

Focus of the group is the classical optical design of imaging and illumination systems, as well as ray-based and wave-optical system simulations. Main research targets are the development of novel tools for simulation and optimization and the design of innovative complex optical systems for industrial or medical purposes.

Current research topics are:

- imaging design
- illumination design
- optical simulations (ray-tracing and wave-optical)
- phase space methods in optical design and simulation
- complex surfaces in optical system design
- design and simulation of hybrid optical systems
- optical systems for biomedical applications

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RESEARCH PROJECTS

3D-Surface Metrology

Model-based sensor positioning and measurement in a multi-scale inspection system

M. Gronle, F. Mauch, W. Osten

In modern inspection and testing processes of technical objects fabricated in small batch series, there is an increasing demand for flexible, fast and precise inspection systems. For instance, the quality check of small gear wheels requires a detailed defect and form inspection of all faces whereas the crossover between the faces and the head must not contain any bumps. All these different demands can hardly be met in one single measurement step or with only one sensor in an effective manner.

All in all, an appropriate inspection system must comply with two main requirements: On the one hand, any specific part of the three-dimensional surface must be examined with respect to a lot of different features; on the other hand, the inspection must be done on large areas whereas the critical dimension of any feature may be much smaller. Both requirements can be overcome using a multi-scale inspection system. It consists of different optical sensors, all measuring with different relationships between optical resolution and field size, a high-precision positioning system and elaborated control software.

Fig. 1: *Demonstrator setup for the inspection of small gear wheels based on a modified Mahr MFU 100 machine. The mounted sensors are a zoom fringe projection stereo microscope and a chromatic confocal point sensor.*

We implemented a demonstrator system (fig. 1) that can be used to inspect technical objects with a complex three dimensional surface (like gear wheels) [1]. The challenge is then not only about choosing the right sensor for each inspection step but also about the optimal choice of suitable sensor poses such that any part of the surface is scanned within low time with an appropriate accuracy.

If a specific region of the object's model is marked for inspection, an appropriate sensor needs to be chosen for the necessary measurements. However, the quality of the acquisition mainly depends on the specific position and orientation of the sensor with respect to the object. Therefore a multi-sensor view planning system has been developed and implemented to determine the optimal pose.

The view planning system (fig. 2) contains simple models of all available (telecentric and endocentric) sensor systems and uses ray tracing to evaluate the visibility of measurability of desired surface regions from a huge set of possible sensor poses (denoted view point candidates). The ray tracing is implemented using the graphics processing unit (GPU) in order to allow an online optimization for various sensors, pose candidates and surface elements within few seconds.

The determination of the optimal sensor, its pose and parameterization depends on a freely selectable merit function. This can contain the estimated measurement time, the accuracy achieved by a sensor including its relative position to the inspected surface and many more parameters.

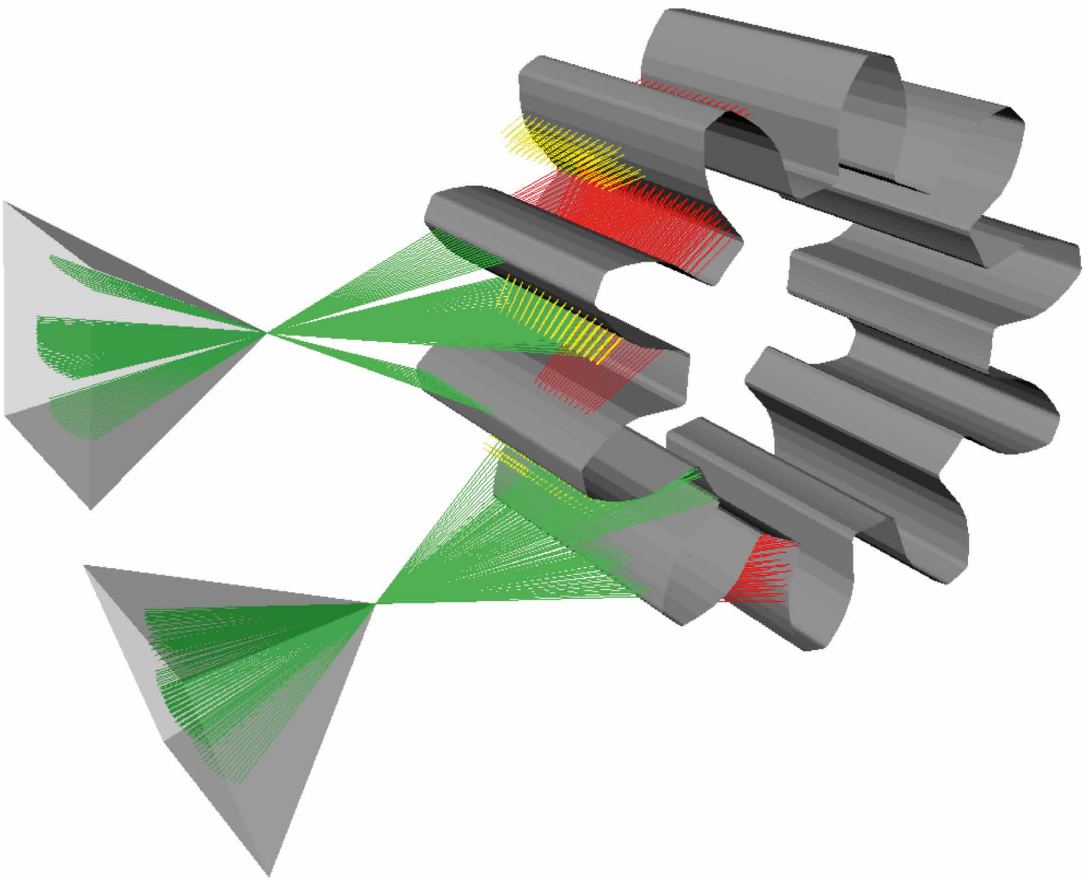


Fig. 2: *Visualization of the view planning system. Green rays symbolize that the surface patch is visible by the sensor's pose and lies within the measurement volume.*

Supported by: Baden-Württemberg Stiftung
Project: AMuPrüf
We thank our partners from "Institute for System Dynamics (ISYS), University of Stuttgart" for their cooperation in this project.

References:

[1] Gronle, M.; Lyda, W.; Osten, W. "Model-based, active inspection of three-dimensional objects using a multi-sensor measurement system", In: Proc. SPIE Bd. 8788 (2013) 87880Y-87880Y-9 .

[2] Keck, A.; Böhm, M.; Knierim K. L.; Sawodny, O.; Gronle, M.; Lyda, W.; Osten, W., "Multisensorisches Messsystem zur dreidimensionalen Inspektion technischer Oberflächen", Optomechatronische Messtechnik tm – Technisches messen 81.6 pp. 280-288 (2014).

Realistic simulation of camera images of local surface defects in the context of multi-sensor inspection systems

H. Yang, T. Haist, M. Gronle, W. Osten

A general problem for the design of hard- and software of an optical surface inspection system (OSIS) (fig. 1) is the lack of sufficient knowledge concerning the expected defects and the variety of permitted object or surface variations. A lot of different parameters of an OSIS have to be defined and the optimum definition of these parameters is rarely possible without being able to obtain realistic measurement images. Even more, automatic optimization of the image processing in this context is only possible, if enough realistic training data is available.

A virtual surface defect rendering method for multi-sensor surface inspection systems [1] is necessary to circumvent this problem. In this approach, various surface defects including the surface itself are virtually generated and the corresponding sensor image is simulated. The straight forward approach is to use ray tracing rendering methods. However, when the detection scale of the defects to be inspected becomes smaller, the traditional geometrical ray tracing method has its limitations and the wavelike nature of light becomes more important. Hence it is important to find the limiting scale of ray tracing rendering method for OSIS. We apply GPU based ray tracing [2] for simulating traditional 2D imaging in a multi-sensor surface inspection system and compare it with real measurements.

In order to simplify the simulation process for white light interacting with materials containing surface defects, BRDF models which are widely used in computer graphics are utilized. Here we use the Phong model, the Cook-Torrance Model and the Ashikhmin Shirley model (see results in fig. 3). In the experimental setup, the collimated white light is used as light source and the profiles of samples in the virtual inspection system were measured by confocal microscopy (fig. 2).

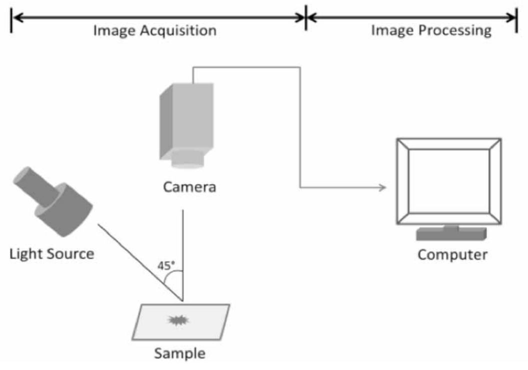


Fig. 1: *Schematic of typical optical surface inspection system.*

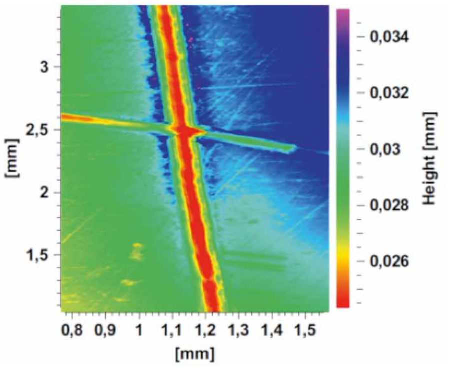


Fig. 2: *Profiles of samples measured by confocal microscopy.*

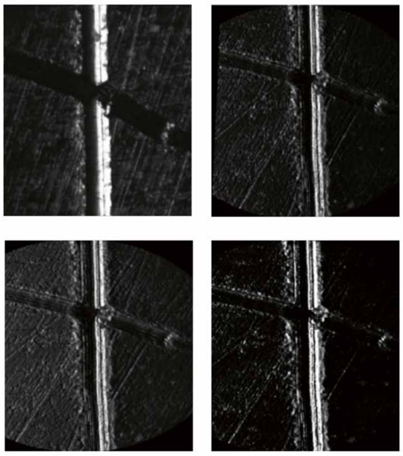


Fig. 3: *top left: image obtained by a digital camera, top right: Phong Model, bottom left: Cook-Torrance, bottom right: Ashikhmin Shirley.*

Supported by: Graduate School of Excellence advanced Manufacturing Engineering (GSaME), University of Stuttgart.

References:

[1] Lyda, W.; Burla, A.; Haist, T. et al. "Implementation and Analysis of an Automated Multiscale Measurement Strategy for Wafer Scale Inspection of Micro Electromechanical Systems", International Journal of Precision Engineering and Manufacturing 13(4), 483-489 (2012).

[2] Mauch, F.; Gronle, M.; Lyda, W. et al. "Open-source graphics processing unit-accelerated ray tracer for optical simulation", Optical Engineering 52(5), 053004 (2013).

Optical design and validation of a full field full-range optical coherence tomography system

J. Krauter, T. Boettcher, M. Gronle, W. Osten

The gold standard in clinics for skin cancer detection is a histopathological analysis. The project VIAMOS proposes an optical coherence tomography system (OCT), which profits from new fabrication techniques of wafer-based micro-optics. These techniques lead to a massive reduction of the system size and system costs, allowing to distribute more OCT systems in clinics. The concept of the system combines swept-source OCT with a full-field detection in a wafer-based multi-channel Mirau interferometer [1].

While the project objective is the development of an micro-optics OCT system, ITO developed a similar on-bench OCT system for the demonstration of the functionality. SS-OCT detects the Fourier-domain (FD) signal, whose Fourier-transform represents the object structure (A-Scan). However, the resulting signal is symmetrical with respect to the zero-delay position due to the ambiguity of the Fourier-transform. This halves the axial measurement range. To avoid this, the reference arm of the setup (fig. 1) is equipped with a piezo actuator allowing to establish phase shifting technique. This technique calculates the complex-valued signal, resulting in a highly reduction of the symmetrical part of the A-Scan by a suppression factor of 36 dB, which is at the signal's noise floor.

In OCT the sensitivity is one main characteristic factor for the OCT performance and depends on the signal-to-noise ratio (SNR). The first time-domain based systems showed sensitivity values in the range of 60 dB. Nowadays, FD-OCT is established, because of the sensitivity advantage by 20-30 dB. The measured sensitivity of this setup is constant over the measurement field of the sensor with a mean value of 96.8 dB.

In fig. 2, two measurements are shown. The first one is a membrane lens, which has a ~60 µm thickness. In the second measurement an onion slice shows the sensor's feasibility for imaging biological specimens. There are three layers visible in a range of 200 µm. Because of the limitation of the depth measurement range due to the numerical aperture, stitching of several z position measurements needs to be adapted.

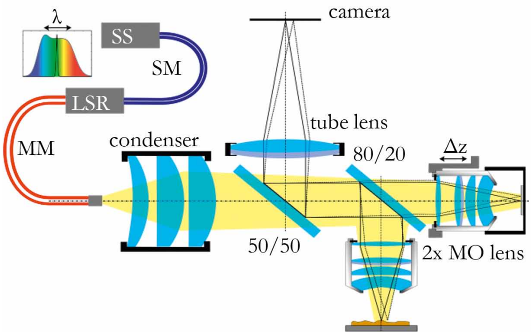


Fig. 1: *Layout of the OCT setup with a swept-source, Linnik interferometer and a tube lens for field detection.*

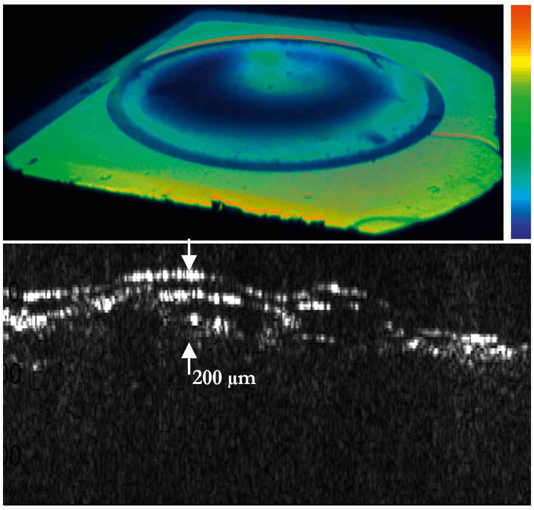


Fig. 2: *Measured membrane lens and onion slide.*

More information under **www.viamos.eu**

Supported by: EU (Call FP7-ICT-2011-8)
Project: Vertically Integrated Array-type Mirau-based OCT System for early diagnostics of skin cancer

References:

[1] Albero, J.; Perrin, S.; Bargiel, S.; Passilly, N.; Baranski, M.; Gauthier-Manuel, L.; Bernard, F.; Lullin, J.; Froehly, L.; Krauter, J.; Osten, W.; Gorecki, C. "Dense arrays of millimeter-sized glass lenses fabricated at wafer-level", Opt. Express Vol. 23 no. 9 pp. 11702 – 11712 (2015).

Development and numerical evaluation of an optical pressure sensor

S. Peterhänsel, K. Körner, T. Haist, W. Osten

In the scope of the European FP7 project "Pilot factory for 3D high performance mid assemblies" (3D-HiPMAS) the ITO performed a design study for optical pressure sensing based on a deformable membrane. Optical pressure sensing methods are used since more than 10 years in industrial applications. Their main advantage can be seen in the robustness in the long-term and under difficult environmental conditions. The application for high pressure and/or high temperature applications, e.g. within car engines, can be regarded today as a standard application. The emphasis for our design is put on tight space restrictions, low-cost and large temperature changes during operation (–40/+140°C). The principle of the focus sensor is shown in fig. 1.

For this, a lens with astigmatism is needed. Depending on the actual focus position to the object surface (here the membrane), we will get spot images with different elliptic shapes and orientations. These shapes and orientations can, for example be evaluated using the 4 signals of a 4 quadrants of the diode.

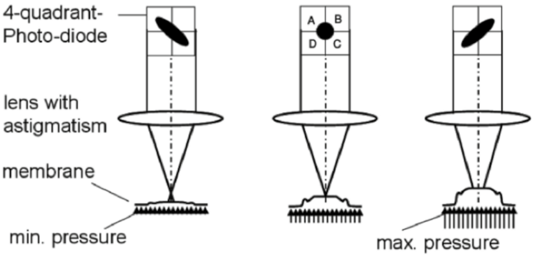


Fig. 1: *Principle of auto focus by astigmatism for an elongated membrane (deformed by pressure).*

The position of the membrane and therefore the pressure can be determined by the signal S defined by:

$$S = \frac{(B+D)-(A+C)}{A+B+C+D}$$

The drawback of this robust principle is that both a beam splitter and a lens with defined astigmatism are required. The first drawback collides with the space restriction and the later with the low cost. So we changed the design such that with a computer generated hologram (CGH) both the beam splitter and the lens could be avoided, while at the same time choosing only structures in the CGH that could be produced by direct laser writing. The final design is shown in fig. 2, along with the movement dependent spot diagram.

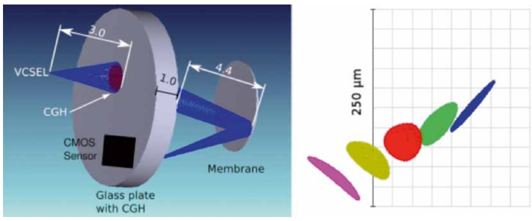


Fig. 2: *Design of the sensor with CGH (left) and spot diagram on sensor for whole range of membrane movement (right).*

As light source a Vertical-Cavity Surface-Emitting Laser (VCSEL OPV310 by OPTEK Technology) was chosen as it is operating in the whole temperature range and emits light in the near infrared (λ=850 nm) which allows for more relaxed feature sizes in the CGH. This design requires only a very small amount of space however, the signal is moving preventing the usage of a 4 element photo diode (fig. 2 (right)). Instead a small size quarter VGA cameras has to be used to allow to evaluate the resulting signal by first determining the centre of mass and afterwards selecting 4 regions of interest that correspond to the original four elements of the photo diode.

The robustness of this design was than evaluated by studying the signal dependence on production tolerances and temperature effects to ensure a low measurement uncertainty. Therefore simulations in Zemax were carried out taking into consideration a misplacement of the separate elements (x-,y-,z-shift and tilt) as well as thickness variations of the CGH substrate. For temperature effects two separate housings of the sensor have been tested, aluminium and plastic (Ketron 1000 PEEK by Quadrant EPP).

All studied parameter deviations influenced the exact signal S, making a calibration before first time use necessary. However, none of the studied deviations led to a decrease in signal that would prevent an accurate measurement.

Supported by: European Community FP7
Project: 3D-HiPMAS
Project partner: HSG-IMAT

Model-based approach for planning and evaluation of confocal measurements of rough surfaces

F. Mauch, T. Boettcher, M. Gronle, W. Osten

Optical methods like confocal microscopy are more and more commonly used as a tool for the inspection of technical surfaces. The measurement techniques and calculation of the measurement uncertainty are mainly defined by VDI/VDE Norm 2655 [1]. However, these rules disregard the measurement errors depending on the surface under test itself. Therefore, the BMBF funded project "OptAssyst" aimed for a software assistant, which helps the measurement technician to select the most suited sensor configuration for the respective task.

Object depending artifacts often occur on (locally) curved surfaces, like in measurements of rough surfaces. The actual intensity of each measurement point can be calculated by means of an overlap integral of the illumination field and the back-reflected field from the object as shown in [2,3].

Depending on the objective's numerical aperture, different wavefront curvatures are observed at different defocus positions. If a local surface curvature correlates with the curved wavefront at a defocused position, the detected intensity becomes at least as high at the one at the focus position and results in object depending measurement errors. The wavefront curvatures at different defocus positions are objective dependent (fig. 1).

The characteristic curves from fig. 1 can also be used to evaluate the trustworthiness of measured samples, shown in fig. 2 with respect to two different objectives. It is possible to locally fit a sphere and calculate the corresponding possible defocus [4,5]. By inserting a certain uncertainty threshold, one can mark all areas, where the obtained measurement error, induced by the surface curvature, exceeds the boundary value. If many areas are not trustworthy, the measurement has to be rerun with higher NA.

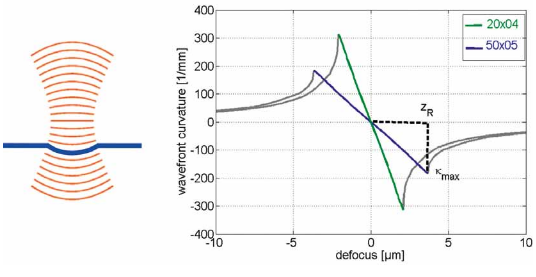


Fig. 1: *Best fit (wavefront/surface) curvature values depending on defocus position for different objective lenses / NA. Grey lines are neglected for rough surfaces, because these positions require macroscopic curved features, which are seldom found on rough surfaces.*

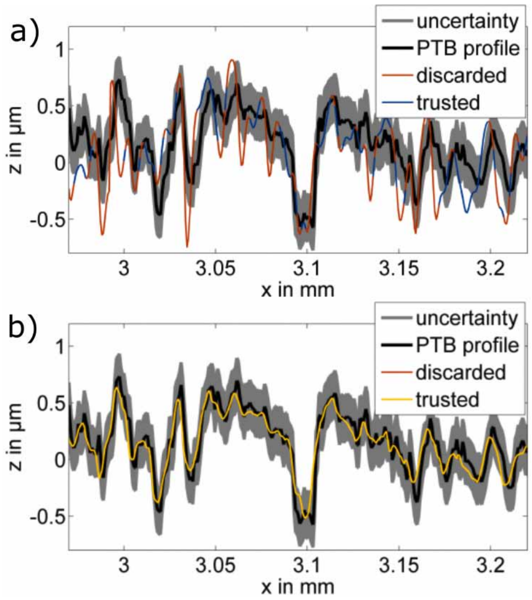


Fig. 2: *a) Measurement of roughness standard carried out with insufficient NA (20x0.4). Due to local curvature, many measurement errors are evident. The calculated local uncertainty exceeds the desired value (here: 200 nm), therefore many points are discarded.*
b) Same measurement with appropriately chosen objective (50x0.8).

Supported by: BMBF
Project: OptAssyst

References:

[1] VDI/VDE 2655 Optical measurement of microtopography: part 1.2. Calibration of confocal microscopes and depth setting standards for roughness measurement (2010).

[2] Mauch, F.; Lyda, W.; Gronle, M.; Osten, W. "Improved signal model for confocal sensors accounting for object depending artifacts", Opt. Expr. 18, 19936-19945 (2012).

[3] Mauch, F.; Lyda, W.; Osten, W. "Model based assistance system for confocal measurements of rough surfaces", Proc. of SPIE 8788, 87880U-1 (2013).

[4] Mauch, F.; Lyda, W.; Osten, W. "Object depending measurement uncertainty of confocal sensors", Fringe 2013, 957-964 (2013).

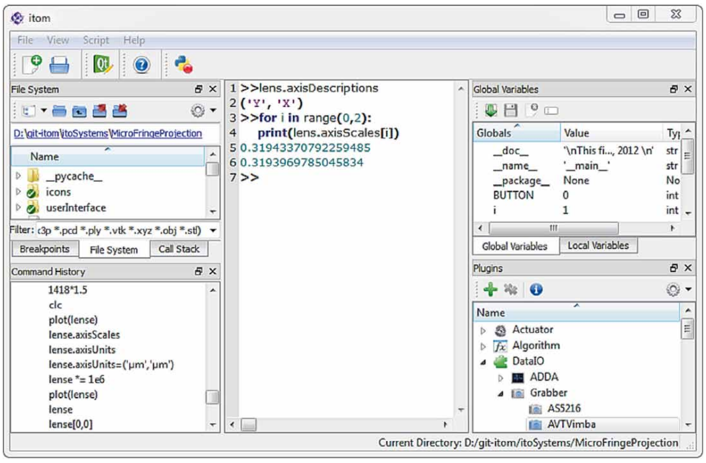
[5] Mauch, F.; Osten, W. "Model based approach for planning and evaluation of confocal measurements of rough surfaces", Meas. Sc. Tech. 25, 105002 (2014).

Open source measurement and evaluation software ”itom”

M. Gronle, C. Kohler, M. Wilke, W. Lyda, H. Bieger, W. Osten

itom is an open source software suite for operating measurements systems, laboratory automation and data evaluation. Its development has been started at ITO in 2011 in order to provide a software that can easily be used to control optical setups, create and execute data evaluation algorithms in Python and / or C++, communicate with hardware components or easily create individual user interfaces.

The software (fig. 1) has been designed considering various requirements: On the one side it should be used by non-experienced users to easily create an experimental setup in a lab and control cameras, displays or actuators. On the other side, the software has to be able to operate high-speed and complex measurement systems. While the rapid prototyping is provided by the fully integrated Python scripting language, performant algorithms and hardware connections can be added via a unified plugin interface. Hardware and software plugins are written in C++ and can integrate arbitrary 3rd party components as well as CUDA or other parallelization techniques.



```
>>lens.axisDescriptions
('Y', 'X')
>>for i in range(0,2):
    print(lens.axisScales[i])
0.31943370792259485
0.3193969785045834
>>
```

```
1418*1.5
clc
plot(lense)
lense.axisScales
lense.axisUnits
lense.axisUnits=('µm','µm')
lense *= 1e6
plot(lense)
lense
lense[0,0]
```

Globals	Value	Ty
__doc__	'\nThis fi..., 2012 \n'	str
__name__	'__main__'	str
__package__	None	No
BUTTON	0	int
i	1	int

Fig. 1: *Screenshot of the main window of itom.*

Besides the operation of hardware systems, **itom** can also be used for data evaluation purposes. Therefore it provides many algorithm plugins, can benefit from the wide range of Python packages and allows plotting data in multiple dimensions. These plots (fig. 2) are mainly adapted to the evaluation of measurement data.

If desired, users can also build their individual user interfaces with a huge set of different widgets including the **itom** specific plots and figures. While the design process is done in a WYSIWYG design tool, the interaction is added via Python methods. This allows creating modern and complex windows and dialogs in order to simply the operation of systems.

In the period under report, the functionality of **itom** has been continuously extended to provide a user-friendly software interface as well as a flexible and fast development and operating tool. Until now, more than 50 different plugins for various hardware components and algorithms have been created and published. For instance, the unified camera interface allows operating cameras from PointGrey, Ximea, Allied Vision, SVS Vistek, PCO, QImaging, Andor, IDS Imaging among others.

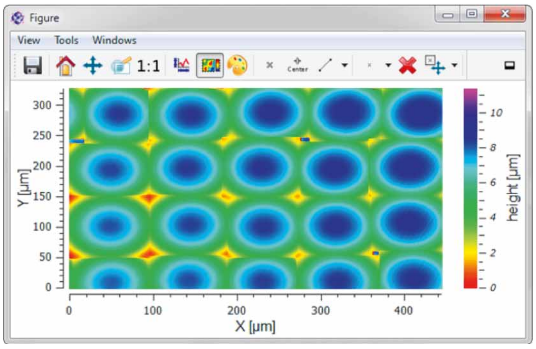


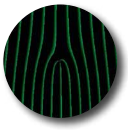
Fig. 2: *The 2d plot of itom shows the topology of a micro lens array. The height profile is colorized using false colors.*

The core application of **”itom”** is released under the open source license LGPL. The sources as well as setups for Windows can be freely downloaded under **http://itom.bitbucket.org**.

References:

[1] Gronle, M.; Lyda, W.; Wilke, M.; Kohler, C.; Osten, W. ”itom: an open source metrology, automation, and data evaluation software”, Appl. Opt. 53, 2974-2982 (2014).

Active Optical Systems and Computational Imaging



Programmable Microscopy

M. Hasler, T. Haist, W. Osten

A lot of different imaging techniques in microscopy are available. From superresolution to phase contrast imaging there is a whole zoo of methods that help to visualize and measure microscopic specimen. To make things even more complicated, all these methods have several parameters that considerably influence the image quality.

We try to realize programmable microscopy where spatial light modulators (typically LCOS microdisplays) are used in order to program the imaging. By this approach it is possible to change the whole imaging process (methods and parameters) without any mechanical motion, just by digital control. Different phase contrast and micromanipulation techniques have been shown in the past. We realized several experimental setups (see e.g. fig. 1) where the imaging as well as the illumination pupil can be programed.

By using a carrier frequency for the information to be incorporated it is possible to modify the phase and the amplitude of the light fields. One main disadvantage is the limitation of the space-bandwidth product of the light modulator which leads to a limitation of the object field. This limitation can be circumvented by the recording of two images and digital postprocessing (fig. 2).

We have shown the realization of stereo microscopy, different phase contrast methods, aberration correction and different confocal imaging schemes. Raman spectroscopy has been shown but is – due to the extremely low light levels – not very feasible.

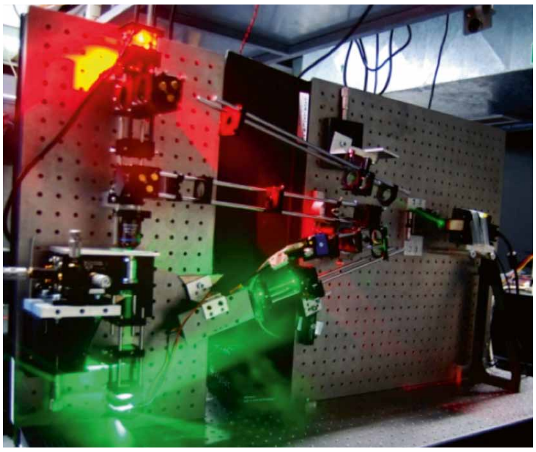


Fig. 1: *The setup, while applying all three possible illuminations.*

The main advantage is the extreme flexibility and the possibility to easily test new imaging methods and parameter settings. Also, the digital combination of multiple images obtained with different settings is of considerable interest. These advantages come with current light modulators at the price of reduced light sensitivity and a reduced object field.

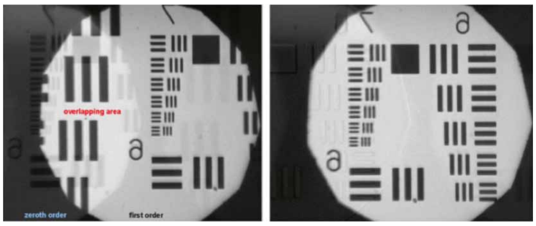


Fig. 2: *Correction example of overlapping diffraction orders in lightfield setup using a USAF-target.*

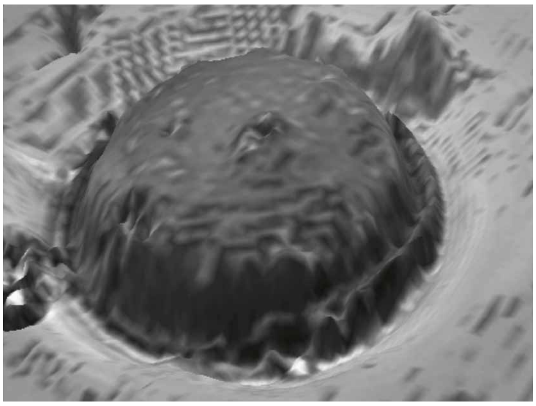


Fig. 3: *3D reconstruction of a styrene half sphere, acquired by a stack of defocused images and dekonvolution.*

Supported by: DFG German Science Foundation
Project: ProPupil (HA-3490 /2-1)

References:

[1] Haist, T.; Peter, A.; Osten, W. "Holographic projection with field-dependent aberration correction", Optics Express 23 (2015): 5590-5595.

[2] Hasler, M.; Haist, T.; Osten, W. "Object field expansion in spatial light modulator-based phase contrast microscopy", Optical Engineering 54 (2015): 043107-043107.

[2] Haist, T.; Baranek, M.; Hasler, M.; Osten, W. "Programmable microscopy", in: Multi-Dimensional Imaging (Ed.: B. Javidi) (2014): 153-173.

Holographic modal wavefront sensing

S. Dong, T. Haist, W. Osten

Holographic modal wavefront sensing is an interesting alternative to the conventionally employed wavefront sensors. The main advantages are the extremely fast operation without computational expense and the robustness against intensity variations in the wavefront to be measured. It can be employed for different applications in adaptive optics where point objects for the optimization are available.

Within a joint project, the Institut für Systemdynamik (ISYS) and ITO investigate the application of modal wavefront sensors (see fig. 1) for the control of membrane mirrors.

Instead of using Zernike modes for the description and measurement of the aberrated wavefronts we use the modes of the membrane mirror. This way, the measured voltages of the sensor can be directly used (without the typically employed reconstruction methods) to control the mirror. This helps to further reduce the computational cost and to adapt the system to the actuating element (membrane mirror).

Within the project we also tested combinations of modal holographic wavefront sensing with other sensor principles, especially Shack-Hartmann sensing (SHS) and curvature based sensors.

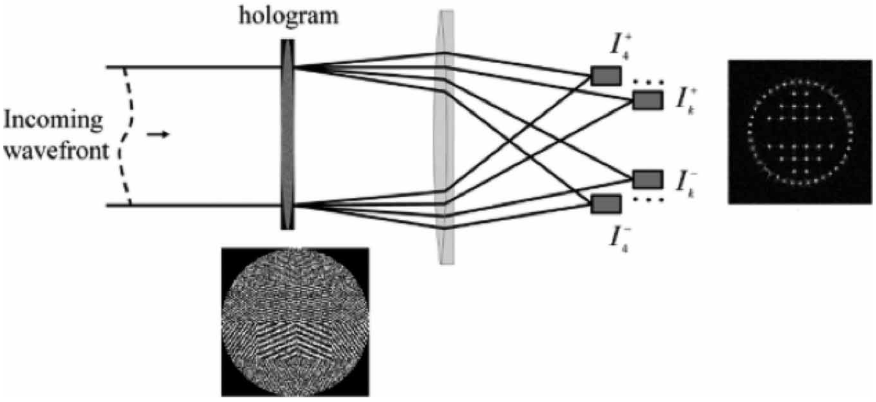


Fig. 1: *Principle of the combined SHS and modal wavefront sensor.*

The results for the curvature based sensing were not convincing. No real advantages compared to conventional SHS have been found. The number of iterations needed for the adaption to a typical atmospheric wavefront has been reduced by our approach, but only at the cost of a strong computational cost.

The combination with SHS makes more sense. Here, a low sampling (12 Sub-apertures) SH measurement is used to first set and determine the typically strong low frequency aberrations.

The remaining aberrations are within the dynamic range of the modal wavefront sensor and can be further optimized within a few iterations.

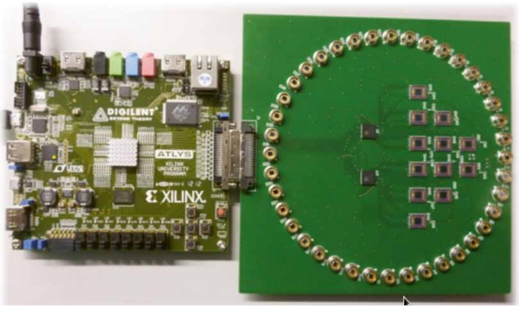


Fig. 2: *FPGA implementation of the combined SHS and modal wavefront sensor.*

The wavefront sensor has been implemented in We implemented two different versions: a) using an intelligent camera and b) using a FPGA-based evaluation (fig. 2). In general, the speed of the sensor is limited by the available light. The holograms have been fabricated at ITO.

Supported by: DFG German Science Foundation
Project: Systemanalyse und Methoden zum Reglerentwurf für verformbare Sekundärspiegel in der adaptiven Optik (OS 111/29-2)
In cooperation with Institut für Systemdynamik, University of Stuttgart

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References:

[1] Dong, S.; Haist, T.; Osten, W. "Hybrid curvature and modal wavefront sensor", Proc. SPIE 9227, 9227-02 (2014).

Benchmarking Approach of Phase Retrieval Algorithms

C. Lingel, T. Haist, W. Osten

The aim of the DFG Project "Benchmarks for Phase Retrieval Methods" was to develop a benchmark system consisting of defined phase objects, a collection of different criteria and a method to calculate the score for given phase retrieval algorithms.

Besides the classical methods for recovering the phase of an object (holography/interferometry), there are phase retrieval methods which work without a reference wave just by recording one or more intensity patterns in a special setup. Due to the huge amount of different approaches, starting in 1972 by Gerchberg and Saxton, it is difficult to keep the overview of all the different methods and hard to choose the proper one for a certain measurement task. Therefore, we proposed a system for the evaluation of the performance of different phase retrieval methods based on simulations.

First, we defined a set of different objects some having smooth phase steps, others having sharp phase edges and some are combined phase and amplitude objects. Thereafter, we implemented a selection of different phase retrieval algorithms which we applied to the different objects. There have been iterative (e.g. multiple plane algorithm) and non-iterative (e.g. transport of intensity (TIE) algorithm) algorithms among the tested methods. For judging the recovered phase we introduced the following benchmark criteria:

- Root mean square error (phase and intensity)
- Peak-to-Valley (phase and intensity)
- Correlation (phase and intensity)
- Repeatability
- Necessary image number
- Computational cost
- Setup complexity
- Alignment difficulty
- Automation
- Acquisition process

There are some values like the rms (root mean square) error or the calculation time, which can be determined by our simulation but also some "outer parameters" like the complexity of the necessary optical setup. After the calculation of the criteria we used a score table which defines how many points for a criterion value are given. These points together with a weighting factor result in the final score of the benchmark. The score table is one of the essential parts of the benchmark system and has to be adapted to the problem by the user. Thus, it is not possible to find the best phase retrieval method in general. It strongly depends on the particular measurement task.

The result can be plotted in a bar chart, see fig. 1. There the single values and resulting points are listed for each benchmark criterion. In this example we used the multiple plane algorithm and the overall score is 82 points or 62.1% of the maximally available points with the used score table.

As a result, our analysis of different phase retrieval methods shows that the quality of a specific method strongly depends on the object. The TIE algorithm for example works better for smooth phase changes in the object than for object with sharp phase steps.

In conclusion, we developed a benchmark system based on simulations which is applicable to many phase retrieval methods to rate their ability to recover the phase of different objects [1].

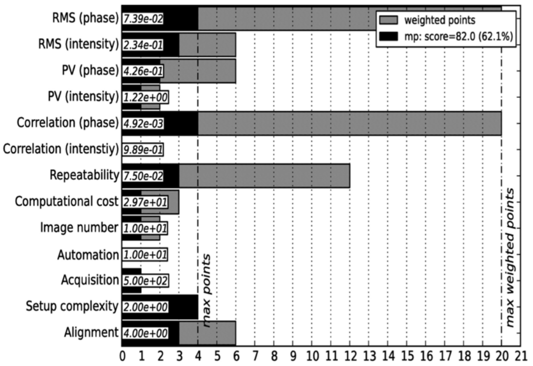

Fig. 1: *Example benchmark results of the multiple plane algorithm. For each criterion the value is printed and the points and weighted points are plotted as bars.*

Supported by: DFG German Science Foundation
Project: Benchmarks for Phase Retrieval Methods (OS 111/36-1)

References:

[1] Lingel, C.; Hasler, M.; Haist, T.; Pedrini, G.; Osten, W. "A benchmark system for the evaluation of selected phase retrieval methods", Proc. SPIE 9132, Optical Micro- and Nanometrology V, 91320R (May 1, 2014).

Accurate position detection based on holographic multi-point approach

M. Gronle, T. Haist, W. Osten

The accurate determination of positions is one of the basic tasks in optical measurement techniques. The measurement uncertainty of methods like Shack-Hartmann sensing, image processing-based geometry determination or autocollimation depends directly on the measurement uncertainty of position detection.

In the DFG-funded project DYNREF we investigate a new simple image-based technique for the determination of positions. Compared to today's high accuracy techniques like laser tracers it is potentially very cheap. The position of an actively illuminated target (e.g. a measurement head of a coordinate measurement machine) is measured using standard imaging with two cameras (fig. 1). Compared to the conventional photogrammetric approach we however use a hologram in front of the imaging optics, thereby replicating the point to multiple points on the image sensor (fig. 2). The positions of all the points are determined and (after correction for distortion) averaged. By this approach the statistical errors are reduced by the square root of the number of points.

In principle, using N photons for one center-of-gravity based measurement, the average position of the point can be determined up to a (one-sigma) measurement uncertainty of sigma / sqrt(N) if sigma denotes the standard deviation of the Gaussian (or Airy) intensity distribution. The number of photons is limited for a conventional image sensor by the quantum well capacity and we can enlarge it artificially by the proposed holographic multipoint technique or multiple exposures. Unfortunately, for multiple exposures we cannot reduce the discretization errors.

We have tested the method for laser as well as LED-based targets and achieved statistical measurement uncertainties down to 1/1000-th of a pixel using conventional industrial image sensors. This corresponds to uncertainties below 10 nm and it means that in principle one trillion different positions can be detected using a conventional sensor in combination with the simple multipoint approach.

For applications where an absolute position is to be detected it is necessary to have a camera calibration which achieves the same accuracy. Otherwise the systematic errors (camera calibration error) will be much larger than the statistical errors.

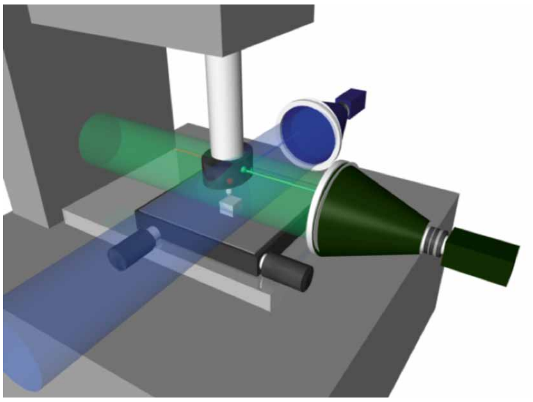

Fig. 1: *Envisioned system for measuring the position and the orientation of a head using two cameras with telecentric optics and the multipoint technique.*

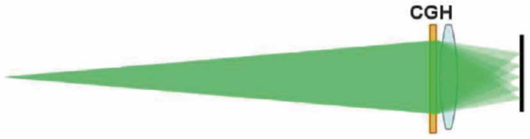

Fig. 2: *Principle of holographic multipoint generation.*

Supported by: DFG German Science Foundation
Project: Dynamische Referenzierung (OS 111/42-1)
In cooperation with Institut für Systemdynamik, University of Stuttgart

References:

[1] Haist, T.; Dong, S.; Arnold, T.; Gronle, M.; Osten, W. "Multi-image position detection", Optics Express 22, 14450-14463 (2014).

[2] Haist, T.; Gronle, M.; Schaal, F.; Jiang, B.; Pruss, C.; Bui, D.; Osten, W. "Towards one trillion positions", Proc. SPIE 9530, 9530-03 (2015).

[3] Haist, T.; Gronle, M.; Bui, D.; Osten, W. "Holografische Mehrpunktgenerierung zur Positionsanalyse", Technisches Messen 82, 273-279 (2015).

Hybrid system for telecentric imaging

B. Jiang, T. Haist, M. Gronle, W. Osten

Telecentric imaging is one of the corner stones of imaging in optical measurement techniques. Object-sided telecentricity leads to the independence of the lateral magnification with distance and image-sided telecentricity avoids problems due to local-varying pixel sensitivities (e.g. because of microlenses) for exact position measurements.

The main limitation for a lot of applications is the necessary size of the optical system. The front element has to be larger than the object field. For scenes with an extension of more than 100 mm this leads to quite expensive optical systems.

Within a joint project, the Institut für Systemdynamik (ISYS) and ITO investigate a new, potentially cheap method for accurately controlling the position of a measurement or tooling head within a large volume (300 x 300 x 300 mm). Telecentric imaging is achieved using a hybrid optical system with a DOE front element followed by a simple second group consisting of two catalog lenses (one plano-convex lens and one achromat, see fig. 1). The system has been designed for a circular object field of 200 mm and a ½ inch sensor at a wavelength of 515 nm.

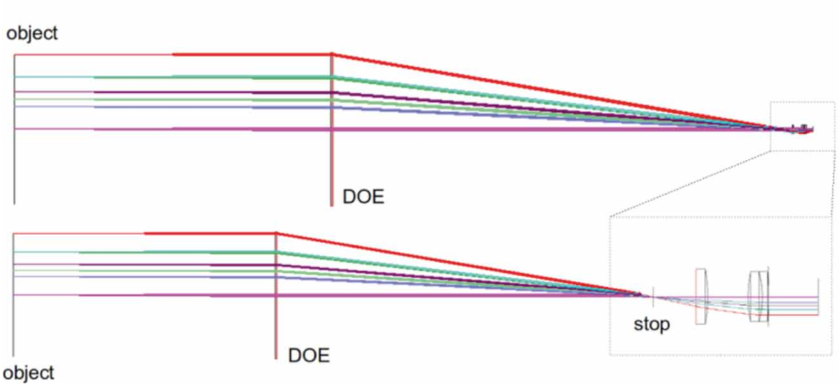

Fig. 1: *Optical design (lower part: zoomed in on the second group for better visualization).*

Due to the strong dispersion introduced by the DOE we limited the bandwidth to 3 nm (FWHM).

Experimentally, the system achieves a telecentricity error of 1.7 mrad over the whole field. At an F-number of 5 a contrast of 0.58 at a frequency of 53 lp/mm has been measured (compare fig. 2).

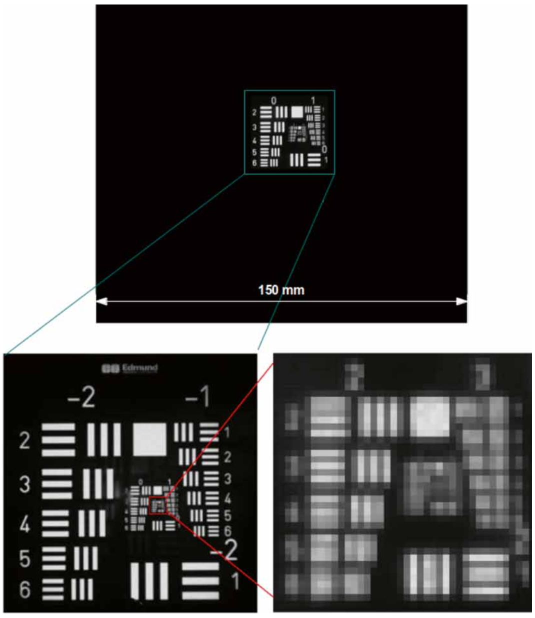

Fig. 2: *Imaging of a USAF test target in the central area of the object field.*

With appropriate replication techniques of the DOE, the approach can be used to achieve cost-effective telecentric imaging of large object fields for quasi-monochromatic applications. The image quality is currently limited by stray light due to unwanted diffraction orders of the DOE.

Supported by: DFG German Science Foundation
Project: Dynamische Referenzierung (OS 111/42-1)
In cooperation with Institut für Systemdynamik, University of Stuttgart

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References:

[1] Haist, T.; Gronle, M.; Schaal, F.; Jiang, B.; Pruss, C.; Bui, D.; Osten, W. "Towards one trillion positions", Proc. SPIE 9530, 9530-03 (2015).

Field dependent aberration correction in holographic projection

T. Haist, A. Peter, W. Osten

In projection applications aberrations can be introduced by the optical system or the object. Typical examples are the projection onto a curved freeform surface or locally varying aberrations introduced by microscopic samples. For a lot of applications, nevertheless high quality reconstruction of small patterns is necessary (e.g. in structured illumination microscopy). To this end we modified the iterative Fourier transform algorithm (IFTA) in order to achieve field dependent aberration correction.

For phase holograms, the correction of a global aberration is trivial because one just needs to multiply the hologram by the complex conjugate of the aberration. Unfortunately, this straight forward approach is not feasible for field dependent aberrations because each object point will be distorted by a different aberration.

For the correction we split the object field/volume into isoplanatic patches and simulate the aberrations for each patch using Zemax. The resulting Zernike coefficients for the patches are introduced in an IFTA optimization scheme where all the patches are processed in parallel, always taking into account the aberrations.

In order to reduce the undesired speckle-like appearance of the reconstruction due to the phase singularities that are always introduced by IFTA algorithms we compute the holograms with doubled resolution and setting the intensities at in-between positions to zero. The reconstruction quality can be further weighted against the diffraction efficiency and the reconstructed field size by two parameters during optimization.

Fig. 1 shows an optical reconstruction of the ITO logo using global aberration correction for a strongly tilted reconstruction system in the Fourier geometry. Fig. 2 shows the same reconstruction using the modified optimization approach.

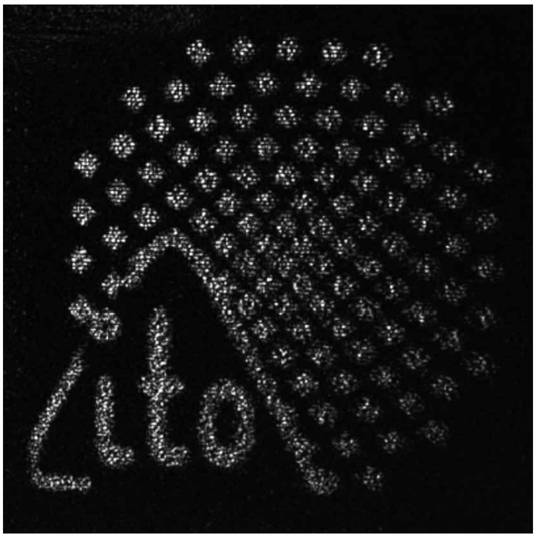


Fig. 1: *Optical reconstruction with global aberration correction.*

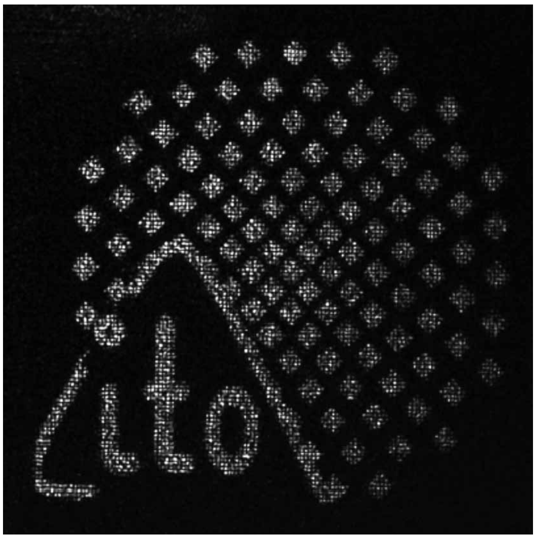


Fig. 2: *Optical reconstruction with field dependent aberration correction.*

Supported by: DFG German Science Foundation
Project: Programmierbare Mikroskopieverfahren basierend auf Lichtmodulator-gestützter Pupillenmanipulation (Ha 3490/2)

References:

[1] Haist, T.; Peter, A.; Osten, W. "Holographic projection with field-dependent aberration correction", Optics Express 23, 5590 (2015).

High Resolution Metrology and Simulation

Depth-sensitive fluorescence measurements for diagnostic investigations

J. Schindler, P. Schau, K. Frenner, W. Osten

Optical methods like optical coherence tomography (OCT) or confocal fluorescence microscopy play a key role in non-invasive medical diagnostics. One of the main difficulties is the scattering of biological tissue leading to a strong background signal and a decrease in contrast. Existing methods lack either the high interferometric depth resolution or cannot be adapted to fluorescence setups.

The aim of this work is the determination of the depth of fluorescent centers in a scattering material.

A combination of structured illumination and interferometric evaluation of the fluorescence signal is used. The setup is shown in fig. 1. A Sagnac interferometer coupled to a microscope allows adjusting the interference angle between the two separated beams. The main part of the excitation takes place in the intersection of the two beams. Additionally, the interference of the broadband source is restricted to a narrow region, see fig. 2. A shearing interferometer is used for the detection of the fluorescent signal. Analyzing the shearing interferograms yields information about the curvature of the wave front which is directly related to its distance to the focus of the microscope objective.

The modelling of the experiment is obtained in cooperation with the Institut für Lasertechnologien in der Medizin (ILM) at the University of Ulm. A combination of numerical solutions of the Maxwell equations and analytical approximations is used in order to simulate the propagation of light through the scattering material. Quantities of interest are the beam profile in different depths, the resulting fluorescence signal and the background in the detected signal due to scattering. The experimental data are used to parametrize the simulations and the numerical results allow to identify an optimal choice of the experimental parameters like the angle between the two intersecting beams.

Fig. 3 shows the phase maps of wave fronts in different distances to the focus of the microscope objective. The fringe spacing increases with the defocus indicating different amounts of curvature in the detected wavefront. This curvature is directly related to the distance of origin of the wavefront to the microscope objective, i.e. the depth of the fluorescent center.

The systematic characterization of the setup, the evaluation of the limitations concerning penetration depth and material properties as well as an assessment of the measurement uncertainty is work in progress.

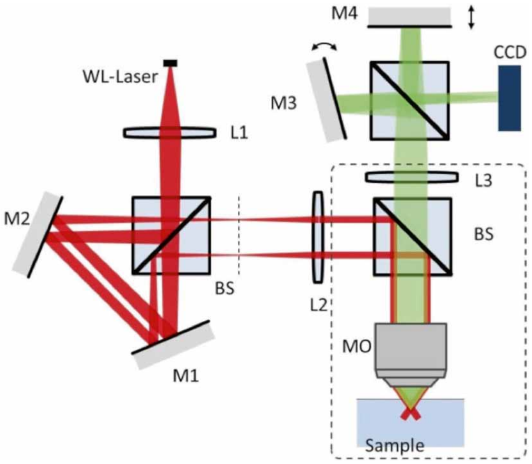


Fig. 1: *Experimental setup with structured illumination (red) and detection (green) attached to a microscope (dashed) in epi-illumination.*

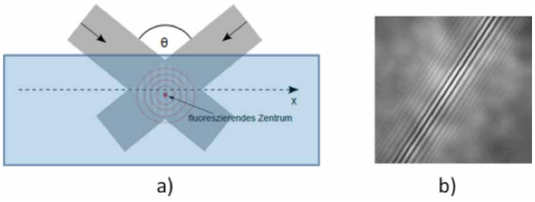


Fig. 2: *Structured illumination: Prinicple a) and recorded interferogram b).*

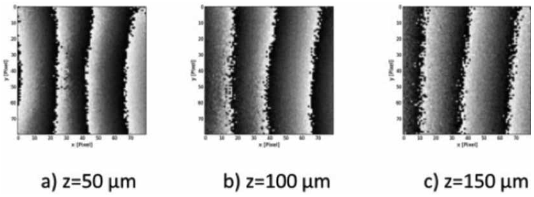

a) z=50 µm b) z=100 µm c) z=150 µm

Fig. 3: *Phase maps for different amounts of defocus.*

Supported by: Landesstiftung Baden-Württemberg
Project: FluoTis
In cooperation with Institut für Lasertechnologien in der Medizin (ILM).

References:

[1] Schau, P.; Brandes, A.; Frenner, K.; Kienle, A.; Osten, W. "Structured white-light illumination for diagnostic investigations", Proc. SPIE 8792, (2013).

Rigorous simulation of light scattering from general rough surfaces using surface integral equations and higher order quadrilateral element

L. Fu, K. Frenner, W. Osten

Wave scattering from irregular surfaces continues to be theoretical and computational challenges. It becomes especially difficult when waves are incident at low grazing angles or upon surfaces with strong roughness, while multiple backscattering may occur and analytical approximation becomes complicated. With the rapid advances in computer technology and fast computational electromagnetic algorithms, solving Maxwell's equations numerically allows us to simulate light scattering from random media without the limitations of analytical approaches and enable us to investigate fundamentally a wide range of rough surfaces of general media.

For this aim we have developed a rigorous simulation tool for light scattering from rough surfaces via surface integral equation (SIE) and boundary element method [1]. The surface is discretized with 8-noded 10-edge serendipity elements, with which the computation converges better and is widely used in commercial finite-element software-packages.

The coupled surface integral equations in Stratton-Chu's formulation were solved in terms of tangential electric and magnetic fields instead of induced surface currents. In our case, the tangential electric field $\mathbf{E_t}$ and magnetic field $\mathbf{H_t}$ are interpolated by a linear combination of 10-edge vectors $\mathbf{N_i}$ with unknown coefficents of S_{Ei} and S_{Hi}:

$$\mathbf{E_t} = \sum_{i=1}^{10} \mathbf{N_i} S_{Ei} \tag{1}$$

$$\mathbf{H_t} = \sum_{i=1}^{10} \mathbf{N_i} S_{Hi} \tag{2}$$

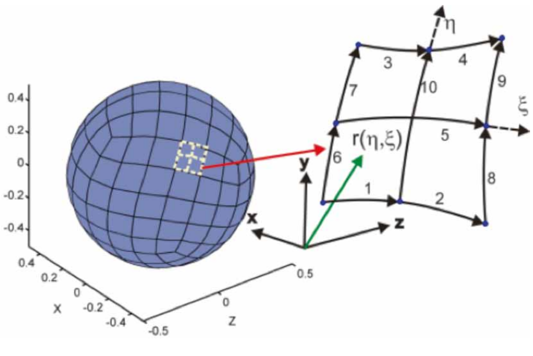


Fig. 1: *Meshed sphere with quadrilateral elements , each with 8 nodes and 10 edges.*

Replacing them into the surface integral equations and applying the Galerkin method, a set of linear matrix equations can be obtained. To calculate each element in the $2N \times 2N$ matrix (N is the edge number), complex inner product of field vectors from corresponding field elements has to be integrated. However, when the source element is overlapped with the field element, singularity with the integrand containing Green's function or gradient of Green's function occurs. This has to be treated specially, especially when a $O(1/r^2)$ order singularity occurs. The linear matrix equation was then solved by using LU-decomposition method. With the solved S_{Ei} and S_{Hi} coefficients, vector field anywhere in space can be calculated. To validate the implementation, we first applied the method to a silver sphere with a radius of 250 nm illuminated by a plane wave at normal incident with p-polarization at 600 nm wavelength.

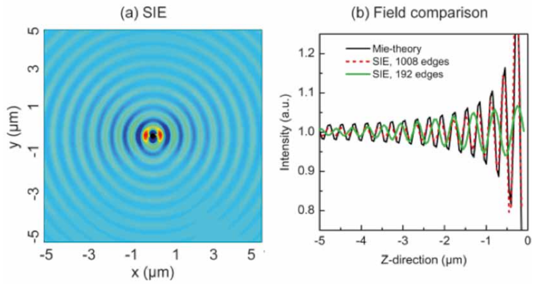


Fig. 2: *(a) Electric field (E_x) intensity at $z=0$ plane calculated using the surface integral equation method for an Ag-sphere with $r=250$ nm. (b) Back-scattered electric field intensity along the z-axis calculated by using the SIE method with different mesh numbers and by using the Mie-scattering theory.*

Fig. 2(a) shows the calculated field intensity of the E_x component in the $z=0$ plane for the sphere discretized with 165 elements (1008 indepedent edges). Compared with the back-scattered field at $x=0$ calculated from Mie scattering theory shown in fig. 2(b), good agreement was obtained except for the field very close to the surface of the sphere. However, this can be further improved by properly treating the nearly strong and weak singularities. Nevertheless, speckle field is calculated solely through the solved tangential electromagnetic fields on the surface and without the need for near field information. Therefore, we can still apply the implementation to far-field speckle simulation. In fig. 2(b) scattered field calculated via a discretization of only 32 elements (192 independent edges) is also shown. It deviates strongly from the Mie theory because of the coarse meshing.

We then applied the implementation to a rough surface with AFM measured profile, which is illustrated in fig. 3(a). It is a surface standard from Physikalisch Technische Bundesanstalt (R_z=1.55 µm, R_a=0.201 µm, λ_c=0.8 mm, R_{max}=1.84 µm). The surface is assumed to be silver and is also illuminated by 600 nm plane wave at normal incidence which is p-polarized with the electric along the -direction. To study the surface, a size of 50×50 µm^2 (within the white frame) was meshed with 256 elements. Fig. 3(b) shows the surface profiles along two selected lines in the x- and y-directions, respectively. The roughness is much stronger along the x-direction. The speckle fields at a plane 100 µm above the surface were calculated for both $\boldsymbol{E_x}$ (co-polarization) and $\boldsymbol{E_y}$ (cross-polarization) as shown in figs. 3(c,d), the latter of which is much weaker due to its weaker roughness.

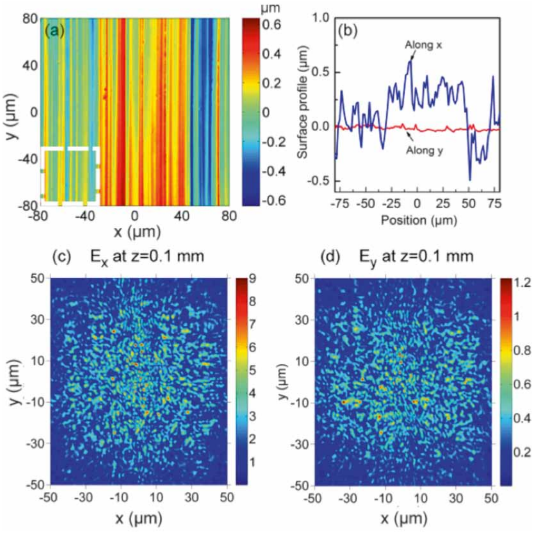


Fig. 3: *(a) Surface profile of a PTB surface standard sample. (b) Profiles along the* $\boldsymbol{x}$*-direction and the* $\boldsymbol{y}$*-direction. (c) Speckle field distribution of the* $\boldsymbol{E_x}$ *component at 100 µm above the rough surface under an illumination of p-polarized light at normal incidence. (d) Speckle distribution of the cross-polarized light with* $\boldsymbol{E_y}$ *component.*

In contrast to analytical approaches, without the statistical information of the surface or even when the surface roughness cannot be described by a simple statistical model, the speckle distribution scattered by the surface can still be calculated conveniently using our simulator.

In summary, we have developed a rigorous simulation tool to study light scattering from general rough surfaces using surface integral equations and higher order curvilinear edge elements. In principle, it can be applied to any kind of surfaces at arbitrary incident angle and polarization. Speckles in a much large view field and the cross-polarization effect can also be calculated flexibly. However, the size effect of the surface under study may induce diffraction in the far field. To obtain more accurate results, the surface under study has to be discretized in finer meshes, which increases the computation with an order of $N\times N$. To accelerate the calculation, Fast Multipole Method can be applied. Studies of rough surfaces should be carried out further and be compared with experimentally measured surface and with different analytical scattering approaches to check the application range of this simulator. Furthermore, through understanding the relationship of the rough surface and the near and far field speckle distribution, improved approximations in analytical approaches are expected.

Supported by: BMBF
Project: HoloVib (13N9339)
and the IZST project IOC104 under the
"Industry on Campus" initiation

References:

[1] Fu, L.; Frenner, K.; Osten, W., Opt. Lett. 39, 4104 (2014).

Characterization of Near- to Far-Field Transformers by Interferometric Fourier-Scatterometry

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

Plasmonic superlenses, which allow optical imaging below the diffraction limit, are subject of intense research. Features necessary for such plasmonic devices are a high transmittance through the metallic layers and a structure which is able to convert evanescent near-fields into propagating modes. This part of a superlens is called near- to far-field (NTFF) transformer. Plasmonic superlenses in the traditional sense, which are indeed not available yet, would allow to image sub-lambda samples directly with a conventional optical microscope. However, we use another feature of these structures to show that such

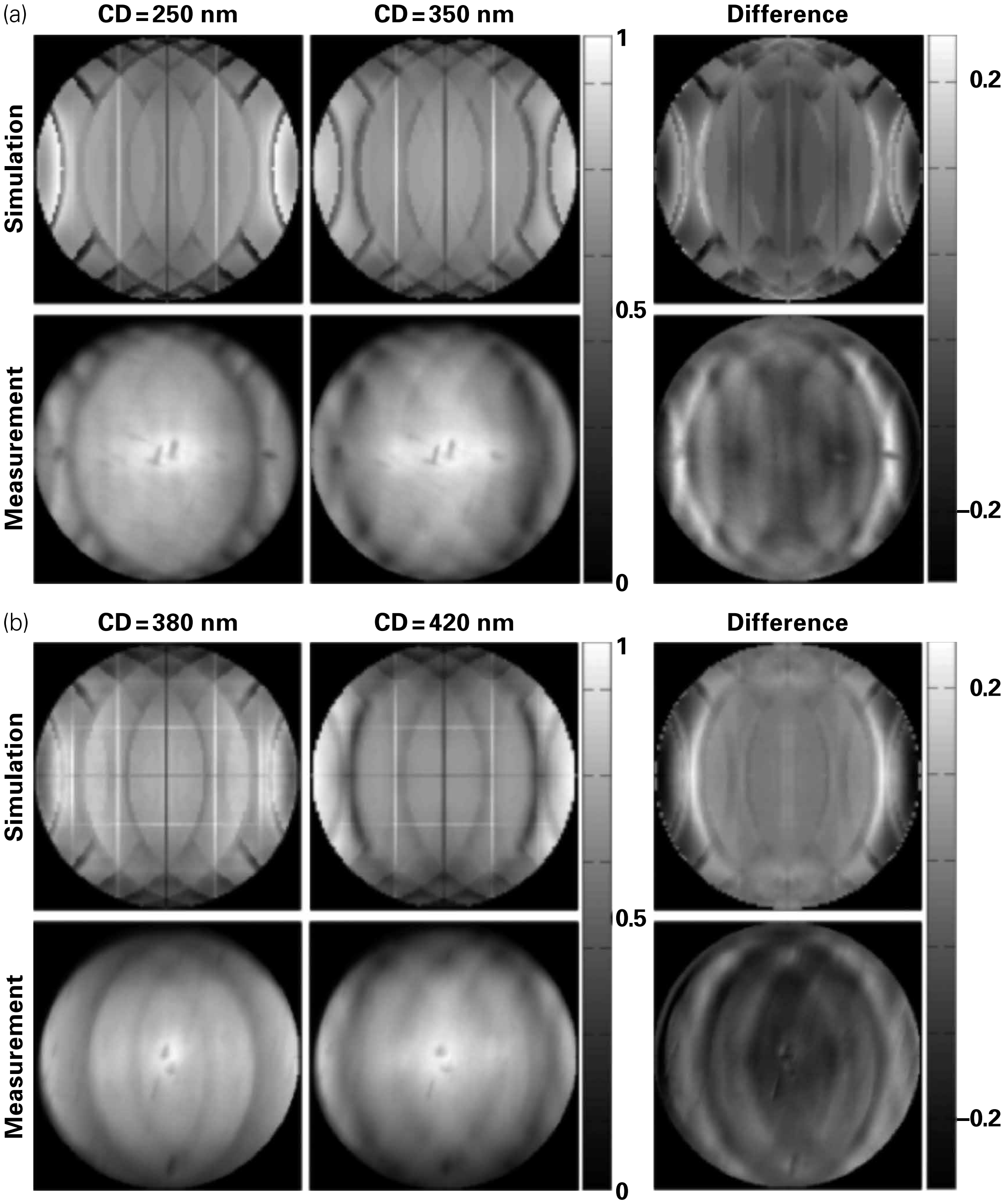


Fig. 1: *Fourier-scatterometry: a) line grating s-polarization, b) lines+rods s-polarization.*

a NTFF-element can be used to increase the sensitivity of a standard scatterometry setup which measures CD and pitch of an underlying line grating. The NTFF transforming structures used in our work consist of nano-rods with dimensions below 100 nm up to 300 nm. High aspect ratio NTFF structures could be obtained using two-photon polymerization (2PP)-techniques [1] and focused ion-beam lithography. We use a Fourier-scatterometer [2] to detect the backscattered light of test line gratings and to analyze the influence of nearfield structures on the sensitivity [3,4].

The experimental setup consists of a fiber-coupled, high power LED with a wavelength of 617 nm as a light source, which is imaged on the back focal plane of a high NA (0.95) microscope objective. A linear polarizer allows to select s- and p-polarized illumination. The reflected light is collected by the same objective in conjunction with a Bertrand-lens which images the back focal plane to a CCD with low aberrations. In addition to the illumination and imaging path of the Fourier-Scatterometer, a reference arm for a Linnik-type setup is included which gives access to the phase of the reflected diffraction orders.

Simulation of the Fourier scatterometry technique was done with our simulation tool "MicroSim" which is based on the rigorous coupled wave analysis (RCWA) method. An extended illumination pupil is discretized by planar waves on a grid, which is sampled with 99×99 equidistant points corresponding to different incident angles. To obtain the resulting pupil images, calculated fields for every incidence angle are coherently superposed. The grating was modelled with perfectly steep walls without roundings or line edge roughness.

Pupil images for the structures were measured for both s- and p-polarization with and without nano-rods between the lines. The measured and simulated results show comparable absolute differences in pupil intensity. From this it follows that the grating with rods is much more sensitive because the CD-difference is 40 nm for lines and rods compared to 100 nm for the line grating without rods. Thus it appears that metallic nano-rods show the desired NTFF-functionality.

Supported by: DFG SPP1327
Project: Optisch erzeugte Sub-100nm Strukturen für biomedizinische und technische Applikationen, OS111/28-2
In cooperation with Laser Zentrum Hannover

References:

[1] Reinhardt, C.; Kiyan, R.; Passinger, S.; Stepanov, A. L.; Ostendorf, A.; Chichkov, B. N. "Rapid laser prototyping of plasmonic components", Applied Physics A 89 pp. 321 – 325 (2007).

[2] Ferreras Paz, V.; Peterhänsel, S.; Frenner, K.; Osten, W. "Solving the inverse grating problem by white light interference Fourier scatterometry", Nature Light: Science & Applications 1(11), e36 (2012).

[3] Ferreras Paz, V.; Frenner, K.; Osten, W. "Increasing Scatterometric Sensitivity by Simulation Based Optimization of Structure Design", Fringe 2013 7th International Workshop on Advanced Optical Imaging and Metrology (2014), Springer Berlin Heidelberg, DOI: 10.1007/978-3-642-36359-7_62.

[4] Ferreras Paz, V.; Frenner, K.; Osten, W. "Simulation based optimization of scatterometric signatures by designed near field structures", Proc. SPIE 8789 Modeling Aspects in Optical Metrology IV, 87890S (13 May 2013) doi: 10.1117/12.2020569.

Phase sensitive structured illumination to detect nano-sized asymmetries in silicon trenches

A. Faridian, V. Ferreras Paz, K. Frenner, G. Pedrini, A. Den Boef, W. Osten

In semiconductor technology, the size of the structures is getting smaller and smaller, down to the scale of a few nanometres. As a result, nano-metrology is getting more and more demanding and the detection of the nano-sized imperfections and structural asymmetries during the fabrication process is of great importance. As the desired resolution to detect such asymmetries is below the diffraction-limited resolution of the optical imaging systems, a non-imaging approach should be utilized. One of the most widely used techniques for this task in semiconductor industry is scatterometry. A possible defect type in nanostructures is the asymmetry which can appear in the side-walls of a given nanostructure, such as different side-wall angle or rounding radius of the bottom corner (see fig. 1 (a)).

We propose a method [1] based on structured illumination to detect nano-sized asymmetries of a trench etched into a silicon wafer and demonstrate its feasibility by simulation. The simulations are performed with MicroSim [2], which is based on the rigorous coupled-wave analysis (RCWA). To create a structured illumination a π-phase plate has been introduced in the illumination path in which the singularity line was placed along the y-axis of the structure (see fig. 1 (b)). After being focused onto the structure, the intensity profile would be a dumbbell-shaped pattern, as shown in fig. 1 (c). Figure 1 (d) shows a cross section of the conventional spot focused on the same structure.

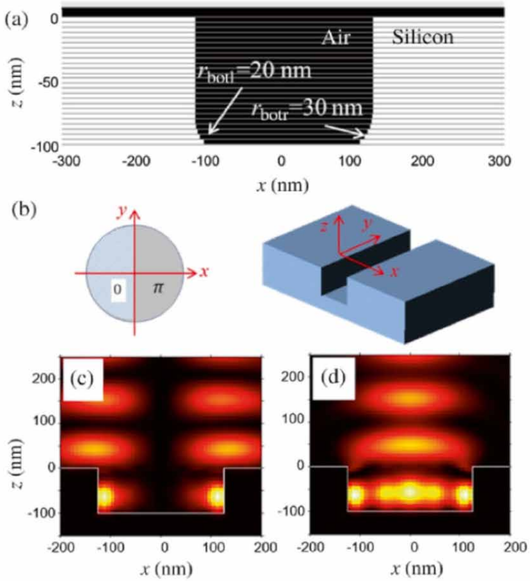


Fig. 1: *(a) Cross section of the simulated structure. (b) Phase modulation diagram of the illumination beam, relative to the structure axes. (c) Cross section of the structured illuminating- and (d) the conventional spot.*

The effect of asymmetry on the phase value at wafer scanning position $x_s=0$ (center of the structure) has been investigated for different bottom roundings radii of 10 to 50 nm for the left bottom rounding r_{botl} and right bottom rounding r_{botr} of 0 nm. Due to the phase singularity that lies along the y_i direction at $x_i=0$ in the image plane, the phase profile exhibits a beat signal around the centre of the image plane (see fig. 2). The difference between the maximum and the minimum peak values of the beat signal Δp is an indication for the presence of asymmetry. For figure 2 Δp is ranging from 0.13 rad for r_{botl}=10 nm to 2.86 rad for r_{botl}=50 nm. This means the magnitude of the beat-signal changes in correspondence to the asymmetry.

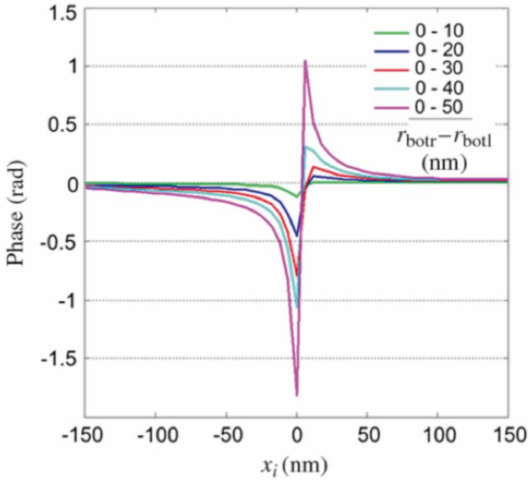


Fig. 2: *The phase profile of the spot along the x_i direction in the image plane, passing through the center of the spot at $y_i=0$, setting the wafer position at $x_s=0$ for a structure of width 250 nm. The curves obtained for asymmetries introduced on the left bottom roundings as $r_{botl}=10$, 20, 30, 40 and 50 nm and $r_{botr}=0$ for all cases.*

References:

[1] Faridian, A. et al. "Phase-sensitive structured illumination to detect nanosized asymmetries in silicon trenches", J. Micro/Nanolith. MEMS MOEMS 14(2) 021104 (2015).

[2] http://www.uni-stuttgart.de/ito/forschung/hms/modellierung_simulation/index.en.html

Imaging property of a cascaded plasmonic superlens with magnification

L. Fu, P. Schau, K. Frenner, W. Osten

Spatial resolution of a conventional microscope is fundamentally restricted by the diffraction limit due to the loss of waves with larger transverse wavevector. Plasmonic optics opens a novel science and technology regime to manipulate waves at nanometer scale due to its capability to couple and focus evanescent waves. Among them plasmonic superlenses for near field subwavelength imaging have been intensively studied over the past decade, which is the first step towards real-time imaging with super resolution. However, direct observation of subwavelength object in the far field at optical frequencies is still absent.

To solve this problem we designed a metalens [1] for observing subwavelength object in the far field at optical frequencies. It is composed of two cascaded plasmonic elements with realistic fabrication parameters, namely a plasmonic double layer meander cavity structure (DLMC, Element I in fig. 1) and a planar plasmonic lens (PPL, Element II in fig. 1). Element I is used to couple and support the propagation of waves with larger transverse wavevector from nano-objects (Cr-slit in this case), while Element II is used to couple the waves from the DLMC structure into free space with phase compensation to magnify the near field image.

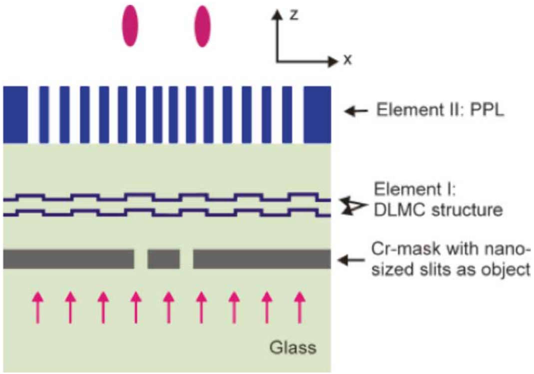


Fig. 1: *Cross-section of one-dimensional cascaded plasmonic metalens composed of a DLMC structure (Element I) and a planar plasmonic lens (Element II).*

As reported in our earlier studies, near field dispersion of a DLMC structure can be engineered for subwavelength imaging [2–4]. Fig. 2(a) shows the near field transmission coefficient of a DLMC structure located in air with structural parameters defined in the figure caption. In a large light frequency range and k_x range (in terms of k_0, the wavevector of free space), the DLMC structure has several bands with high transmission for evanescent waves, which is induced by surface plasmon excitation, grating scattering and coupling between the two layers [3]. At 640 nm, which is about 470 THz, the DLMC structure has a relative smooth dispersion due to the reduced transmission peak at $k_x = 1.2\,k_0$, as shown by the plot in fig. 2(b). When this is taken as a transfer function for a lens, a near field subwavelength image can be obtained theoretically (not shown here).

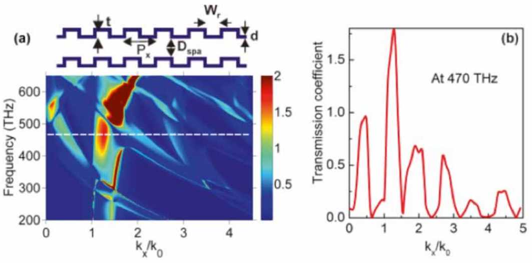


Fig. 2: *(a) Near field transmission coefficient of a DLMC structure in free space (schematic shown at the top of (a)) as a function of transverse wavevector k_x/k_0. The structural parameters are: P_x=400 nm, d=20 nm, **t**=50 nm, D_{spa}=80 nm and W_r=P_x/2-d. (b) Transmission dispersion at 470 THz (640 nm, working wavelength of our measuring system).*

For the planar plasmonic lens (Element II), it was designed to have a focus length of 3 µm and an aperture of 2 µm with a slit array in a 400 nm-thick Ag slab. The slit pitch is 200 nm and the slit width is varied from 34 nm to 88 nm. Numerically calculated field distributions at two incident angles for p-polarized plane wave are shown in fig. 3, confirming lens behavior of the PPL.

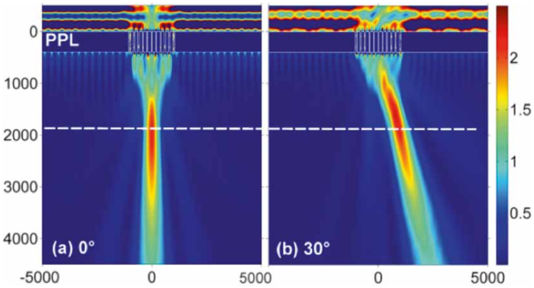


Fig. 3: *Field intensity distributions of a planar plasmonic lens (Element II in Fig. 1 with 11 slits and a pitch of 200 nm) illuminated by a plane wave at 640 nm with p-polarization at an incident angle of (a) 0° and (b) 30°.*

We then combined the two plasmonic elements together and studied numerically the imaging system embedded in glass as shown in fig. 4. With a coupling distance of 50 nm between them, subwavelength imaging with magnification is demonstrated. Field distributions of a 2-slit object (slit in a 100 nm Cr-layer each with 100 nm width), observed under a microscope with NA=1 behind the cascaded imaging system were calculated using Microsim. The results for slit distances of 200, 300 and 400 nm, respectively, are shown in fig. 4(a-c). High contrast images at imaging plane of $Z_{\mathrm{im}}=-600$ are obtained, which are located closely to the object plane.

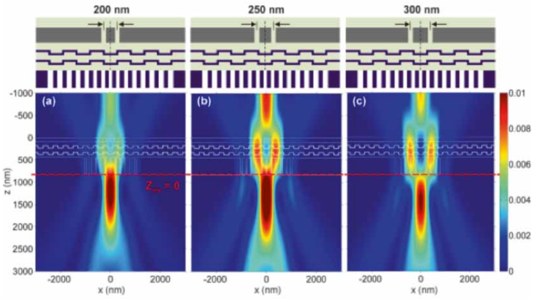


Fig. 4: *Imaging of the cascaded system for 2-slit objects with different slit distance X_D: (a) X_D=200 nm; (b) X_D=250 nm; (c) X_D=300 nm.*

With the increase of the coupling distance between the two elements, different imaging behavior was demonstrated, which reveals the important of near field information. In short summary, we have designed a metalens consisting of two plasmonic elements for far field observation of nano-object at optical frequencies.

Supported by: DFG German Science Foundation
Project: Design, Herstellung und Test einer kaskadierten plasmonischen Superlinse (OS111/40-1)

References:

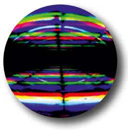
[1] Fu, L.; Schau, P.; Frenner, K.; Osten, W. 9526, 95260Z (2015).

[2] Fu, L.; Schau, P.; Frenner, K.; Schweizer, H.; Zhao, J.; Frank, B.; Wollet, L.; Gaiser, P.; Gompf, B.; Giessen, H.; Osten, W. Proc. SPIE 8423, 84232I–1 (2012).

[3] Fu, L.; Schau, P.; Frenner, K.; Osten, W.; Weiss, T.; Schweizer, H.; Giessen, H. Phys. Rev. B 84, 1–6 (2011).

[4] Schau, P.; Frenner, K.; Fu, L.; Schweizer, H.; Giessen, H.; Osten, W. Opt. Express 19, 3627–36 (2011).

Interferometry and Diffractive Optics



Tilted-Wave-Interferometry: Quick and flexible asphere and freeform metrology

J. Schindler, G. Baer, C. Pruß, W. Osten

The production of high-quality asphere and freeform surfaces is a field in which metrology plays a limiting role for the achievable performance. Aspheres and freeform surfaces offer a high degree of flexibility in optical design, but at the same time, accurate testing of their form is more involved due to the lack of spherical symmetry. Highly accurate and computer controlled production and finishing techniques like slow- and fast-servo tooling, magneto-rheological finishing and ion beam polishing have been established. Yet, the quality of the resulting surfaces can only be as good as the quality of the input data. In the production process, short setup and measurement times and a high degree of flexibility are desirable.

Several approaches for testing aspheres and freeforms have evolved: Compensation optics like CGHs, scanning the specimen and combining the obtained subaperture results or tactile testing with coordinate measurement machines. Yet, these techniques lack either flexibility or require long measurement times due to mechanical movement of either the specimen or parts of the instrument.

The Tilted-Wave-Interferometry has been developed at the ITO with the aim to offer both flexibility and high measurement speed together with a high accuracy in the range of several ten nanometers [1]. The basic setup is shown in fig. 1 and is based on a Twyman-Green interferometer. A diffractive element with microlenses and pinholes effectively creates an array of point sources which illuminate the specimen in parallel. Each of these wave fronts has a tilt and hence compensates for a certain amount of asphericity. This defines a patch on the surface with evaluable fringe densities for each source. This allows in principle to capture the whole surface in one shot leading to short data acquisition times of less than a minute.

As the rays to and from the specimen strongly deviate from the null test condition of perpendicular incidence, a calibration of all possible rays through the system including spatial and field dependency becomes necessary in order to take into account retrace errors. A sophisticated calibration procedure has been developed at the ITO [2]. Interferograms of known reference spheres are recorded at a set of suitably chosen positions in the test space. The state of the instrument is modelled by a polynomial description of the wave fronts in two reference planes. The system parameters are varied in a reverse optimization procedure such that the measured phases can be accurately reproduced. A correct choice of side conditions, a good sampling of all possible rays in the test space, taking into account positioning errors and the use of reference spheres with different well-known radii are essential to remove linear dependencies and achieve a precise calibration result.

An improved optics design has been worked out. In contrast to the earlier lab setup, improvements in mechanical stability, avoidance of reflexes, a simplified alignment and a reduced installation space could be realized. This leads to a better quality of the raw data such that short-time repeatabilities of less than 10 nm could be achieved.

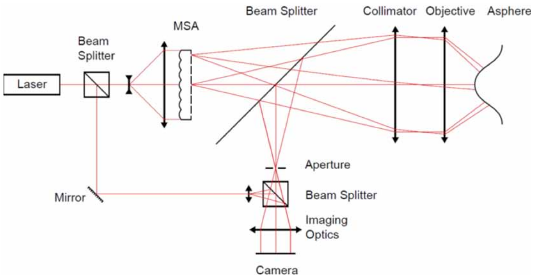


Fig. 1: *Experimental setup. Two wavefronts illuminating the specimen are shown.*

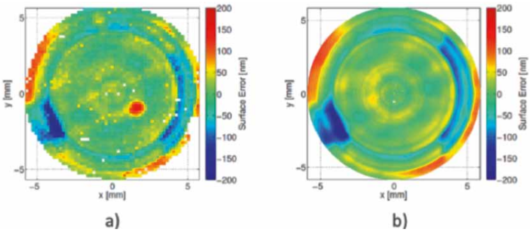


Fig. 2: *Experimental results of the polymer asphere A0775 measured by IBS Isara 400 a) and TWI b).*

Fig. 2 shows the results of a round-robin contest obtained by the TWI and a tactile measurement on the Isara 400 of IBS Precision Engineering. There is a good agreement concerning the form errors of the surface. The result of the TWI offers a much higher lateral resolution. The visual difference in fig. 2. is mostly due to this different resolution. The fact that this resolution can be obtained without prolonging the measurement time is one of the key advantages of the method.

The research has been conducted in close collaboration with the industry partner Mahr. As a result of this project, a first prototype has been designed and assembled by Mahr, see fig. 3. The introduction of the instrument to the market is planned. The current results and the demand of optics manufacturers of metrology equipment make the TWI a promising candidate for applications in asphere and freeform production.

Fig. 3: *Prototype of a Tilted-Wave-Interferometer built by the industry partner Mahr.*

In 2014 the Tilted-Wave-Interferometer has received the innovation award of the AMA association based on the advancement in development and its relevance to the market.

Future developments include the implementation of a stitching procedure for surfaces with larger diameter, the adaption to freeforms with a flat base shape and the development of a self-calibrating method.

Fig. 4: *Awarding the AMA innovation award at the Sensor+Test 2014 (photo: courtesy by AMA Service GmbH).*

Supported by: BMBF
Project: Multiskalige Messtechnikplattform
für die Qualitätssicherung optischer Freiformen
(FKZ: 13N10854)

References:

[1] Baer, G.; Schindler, J.; Pruss, C.; Osten, W. "Measurements of asphere and freeforms with the Tilted-Wave-Interferometer", Fringe 7th International Workshop on Advanced Optical Imaging and Metrology (2013).

[2] Baer, G.; Schindler, J.; Pruss, C.; Siepmann, J.; Osten, W. "Calibration of a non-null test interferometer for the measurement of aspheres and freeform surfaces", Opt. Express (2014).

[3] Baer, G.; Schindler, J.; Siepmann, J.; Pruss, C.; Osten, W.; Schulz, M. "Measurement of asphreres and free-form surfaces in a non-null test interferometer: Reconstruction of high-frequency errors", Proc. SPIE 8788 (2013).

[4] Baer, G.; Schindler, J.; Pruss, C.; Siepmann, J.; Osten, W. "Fast and flexible non-null testing of aspheres and freeform surfaces with the Tilted-Wave-Interferometer", International Journal of Optomechatronics, Vol. 8, p 242-250 (2014).

A simulation environment for uncertainty estimations of the tilted wave interferometer

G. Baer, C. Pruß, J. Schindler, W. Osten

The tilted wave interferometer (TWI) is an interferometer that was designed to combine measurement flexibility with high measurement speeds. High flexibility in this context means that the system can be used to measure steep aspheres and freeform surfaces with shape deviations of several hundred micrometers from their best fit sphere.

Two pillars form the basis for the TWI:

1. A setup that avoids vignetting even for large deviations of the surface under test from the best fit sphere
2. Calibration and measurement algorithms that go beyond the standard null test calibration scheme of interferometers and are capable of calibrating the whole 3D testing space.

The first point is achieved by replacing the standard point light source of an interferometer with a monolithic array of light sources such that the surface under test is illuminated with a set of mutually tilted wavefronts. At the interferometer aperture, only the best fitting wavefront of these is selected and recorded on the camera.

The second point requires a model of the interferometer. In recent years, we have developed a black box model that consists of three parts: a four dimensional polynomial description that returns the optical path length of any ray of the interferometer coming from the light source, a free space propagation and reflection off the surface under test in the test space and again a four dimensional polynomial description returning the optical path lengths from the test space to any pixel on the camera [1]. With this model and a thorough calibration of the system, we can separate the errors introduced by the interferometer from the measured errors of the surface under test.

Uncertainty estimations are a prerequisite for quantitative measurements. However, for such a flexible instrument as the TWI they are not straight forward due to the nonlinear and iterative algorithms that calculate the shape of the surface under test from the measured raw phase data.

The solution we developed in the scope of the EURAMET joint project IND10 together with our partners of the PTB (Physikalisch-Technische Bundesanstalt), Braunschweig, is a Monte Carlo approach to test the algorithms in computer simulations on a set of virtual interferometers in virtual measurements.

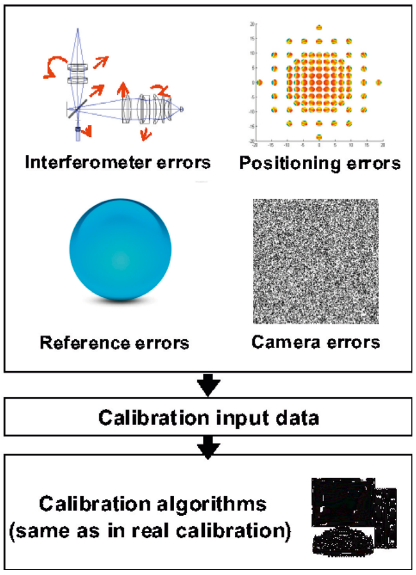


Fig. 1: *Virtual calibration experiment in our simulation environment. A realistically misaligned interferometer, positioning errors during calibration measurement, reference sphere errors and camera noise are simulated to produce realistic input data to test our calibration algorithms.*

Both the calibration procedure (see fig. 1) and the measurement process of a given surface under test can be simulated in our simulation environment. This allows to evaluate and compare calibration and measurement algorithms and their sensitivity to individual error sources. This forms the basis of uncertainty estimations for a given setup. Experimental results on known surfaces under test have shown the good agreement between the simulation model and real measurements, predicting e.g. for our lab setup an uncertainty in the range of a few 10 nanometers.

Supported by: EMRP
(European Metrology Research Programme)
Project: Joint project IND10 "Optical and tactile metrology for absolute form characterization"

References:

[1] Liesener, J.; Garbusi, E.; Pruss, C.; Osten, W. DE 10 2006 057 606 A1.

[2] Baer, G.; Schindler, J.; Pruss, C.; Siepmann, J.; Osten, W. "Calibration of a non-null test interferometer for the measurement of aspheres and free-form surfaces", Opt. Express 22, 31200-31211 (2014).

Optical design and experimental testing of an interferometric setup with a diffractive zoom-lens

A. Bielke, C. Pruß, W. Osten

Optical lithography is the basis for the production of virtually all electronic equipment in consumer and industry applications. Future generations of lithography equipment will use light with a wavelength of 13.5 nm, typically referred to as EUV (extreme ultra violet), to produce even smaller feature sizes on the computer chips. However, there are still scientific and technological challenges connected to this technological leap. The joint project ETIK addresses some of the most important issues such as coating and shape metrology of the optical mirror components. These mirrors require shape tolerances at a fraction of the wavelength used. Our goal is to develop a metrology approach for the measurement of different parts, e.g. the elements of an array of aspherical mirrors.

The approach we are following is to adjust the wavefront of the interferometer with the help of an adaptive optical system. The boundary conditions of the application dictate a compact design and a minimum of stray light. Our design [1] takes the very limited available construction space into account. Regular zoom lenses with an on axes set of spherical and aspherical lenses are focusing by shifting them parallel to the optical axes. This was not an option, both due to size and due to the center reflexes.

To avoid these issues, we used a combination of two diffractive optical elements (DOE) which produce a variable focal length when they are shifted in lateral direction with respect to each other. Additional astigmatism can be added by shifting the element in the other lateral direction. The setup is based on an idea of Alvarez and the diffractive implementation of Lohmann (AO 9/7, 1970).

The zoom-system is combined with a Fizeau-interferometer (fig. 1). The DOEs are placed after the transmission sphere between the Fizeau-surface and the focus plane. They are parallel to each other and orthogonal to the optical axis. By using the transmission sphere off axis, the wavefront is tilted with respect to the diffractive elements avoiding the center reflex.

To receive the effect of variable focus respectively astigmatism, the second DOE can be shifted laterally while the first element is fixed with respect to the transmission sphere. The focus plane is kept constant for all measured targets with different radii or astigmatism.

The diffractive elements were optimized by use of binary 1 surfaces in Zemax. They were produced as binary phase elements using direct laser writing with subsequent dry etching in the cleanroom of the institute. Their functionality was tested in an experimental lab setup.

The measured wavefront shows the expected behavior in terms of tuning focus and astigmatism. To verify that, the surface under test (SUT), a spherical mirror with a radius of 200 mm was located in the nulltest position of the interferometric setup.

The second DOE was shifted by ±1 mm in the horizontal respectively vertical direction. The resulting wavefront aberration was recorded every 500 µm. The expected variation of focus and astigmatism could be demonstrated (fig. 2).

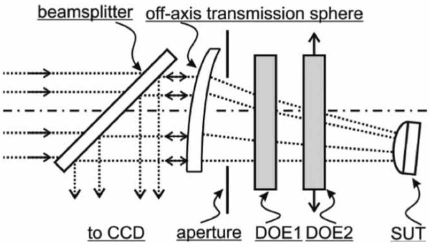


Fig. 1: *Light path of the diffractive zoom-lens.*

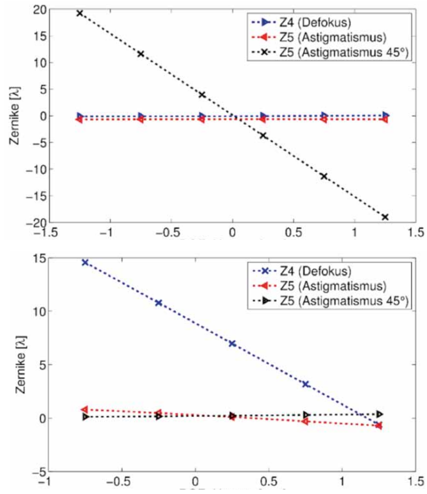


Fig. 2: *Experimental results: Variable defocus and astigmatism.*

Supported by: BMBF (FKZ 16N12258)
Project: EUV-Projektionsoptik für 14-nm-Auflösung (ETIK)

References:

[1] Bielke, A. et al. "Experimental demonstration of a diffractive zoom-lens for an interferometric setup", Classical Optics 2014, OSA, paper OTu4A.3 (2014).

Fabrication of Diffractive and Micro-Optical Elements

C. Pruß, F. Schaal, W. Osten

One of the major issues that prevented the wide use of diffractive elements in optical systems is still the availability of these high precision optical elements. At the institute we maintain a long tradition of design and fabrication of diffractive optical elements – our first writing system was installed in the 70s. In 1995 we started to produce high precision diffractive optical elements (DOE) in a laser direct writing process. Our fabrication capabilities are available for external partners.

Core of our microstructure fabrication are two circular laser writing systems, flexible high precision tools that work in polar coordinates, comparable to a DVD writer. This working principle offers the advantage of a high, continuous scanning speed and facilitated fabrication of rotationally symmetric structures. One of the systems is also capable to write on rotation symmetric curved substrates e.g. lens surfaces.

The writing is not limited to circles but allows writing arbitrary structures such as linear gratings or microlenses. Refractive microstructures and blazed gratings are written in grayscale mode where the writing beam intensity is varied with at the moment up to 256 levels.

The substrate size can vary from a few millimeters to 300 mm in diameter. The shape can be rectangular, round or any other reasonable outline. The system allows substrate thicknesses up to 25 mm.

The structures are written directly into photoresist. The resulting photoresist profile is then either used directly (e.g. for mastering) or is transferred into the fused silica substrate using dry etching (ICP).

Example applications that we have designed and developed with academic and industrial partners are:

- CGH for aspheric testing
- Custom made diffractive and refractive microlens arrays
- Beam shaping elements
- DOE for optical sensors
- DOE for imaging systems
- Custom phase structures
- Phase contrast plates
- Nipkow microlens disks
- Master fabrication for mass replication
- Writing on curved substrates e.g. for chromatic correction of optical systems

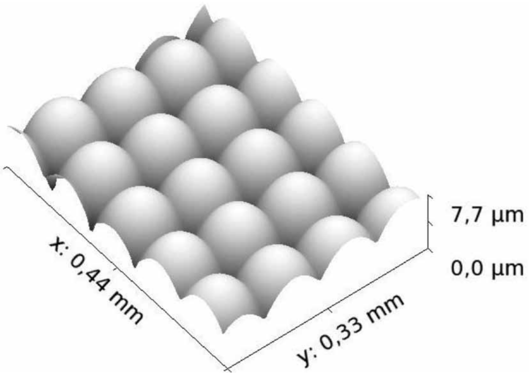


Fig. 1: *Aspheric refractive micro lens array.*

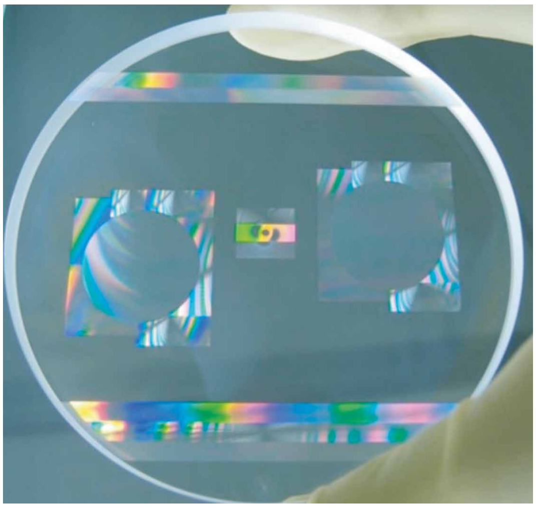


Fig. 2: *High precision DOE for a tunable interferometer.*

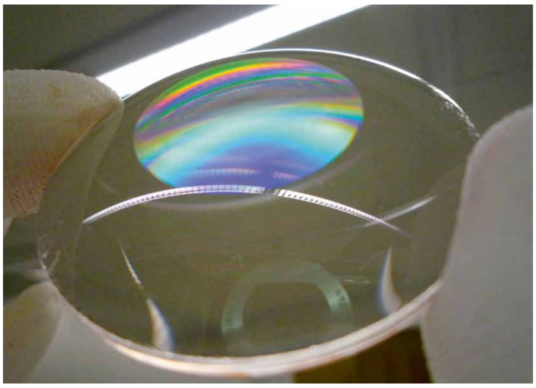


Fig. 3: *DOE on a lens surface.*

References:

[1] Häfner, M. "Neue Technologien zur Fertigung computergenerierter Hologramme mittels Laserdirektbelichtung", Dissertation ITO (2014).

Non-pixelated spatial polarization shaping for tunable phase contrast microscopy

F. Schaal, C. Pruß, W. Osten

We developed a compact micro optical device for non-pixelated spatial polarisation control (AMiPola device).

The operating principle is based on a photo-addressable cell. The birefringence of the cell is locally modulated due to the intensity of the ad-dressing light.

The benefit of optical addressing, compared to pixelated electronically addressing, is primary the reduction of spurious diffraction orders and therefore the enhancement of the efficiency.

To use the advantages of optical addressing it is necessary to have a compact optical addressing system. We developed a 200 channel optical addressing system with 19.5 mm diameter and 22 mm length. The micro optical addressing module uses a VCSEL array as light source (figure 1) and hybrid refractive/diffractive optical elements for beam shaping. Due to the small dimensions of the illumination system, several addressing channels can be realised in one device. The current through the 200 different VCSELs is digitally controlled by an integrated laser diode driver.

The whole system is integrated into a microscope objective (figure 2). The photo-addressable cell is located at the pupil plane of the objective.

There are several phase contrast methods for imaging transparent objects. Depending on object and application the phase contrast method and parameters are altered for optimal results. In conventional setups this is laborious, because several components must be changed and aligned.

The objective integrated AMiPola system is able to switch optically between different phase contrast methods. Also the parameters/orientation can be varied. It is possible to realize e.g. v-DIC, w-DIC (figure 3) or Zernike phase contrast.

The system can be also used e.g. as illumination system for spatial polarization patterns or for the characterisation of micro structures.

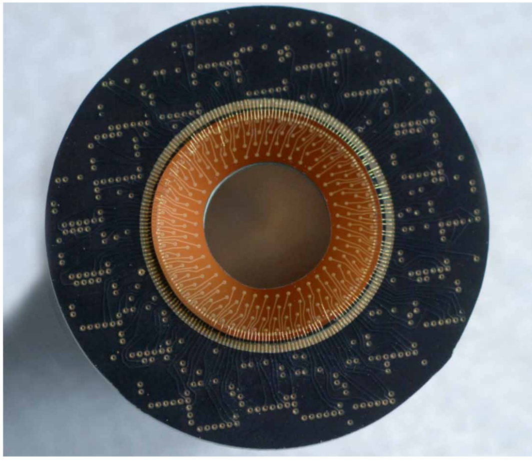


Fig. 1: *Ring shaped 200 VCSEL array, with integrated digital laser diode drivers, as light source for the optical addressing module.*

Fig. 2: *Microscope objective with integrated AMiPola spatial polarization shaping system.*

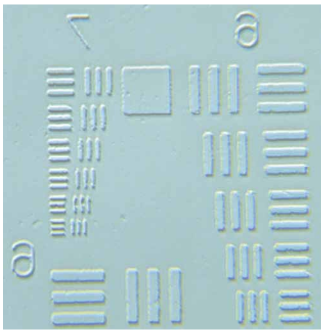


Fig. 3: *Phase contrast image of a phase fused silica USAF target (86 nm step height).*

Supported by: DFG OS111/35-1
This project is part of the DFG priority programme 1337 "Active micro optics" and is done in collaboration with the IHFG (University of Stuttgart), the University of Potsdam and others.

Replication of multilevel diffractive optical elements based on DVD technology

J. Beneke, F. Schaal, W. Osten

A wide range of applications, from beam shaping over chromatic correction to optical measurement systems can profit from the unique properties of diffractive optical elements. However, due to the high fabrication costs, their use is limited to high volume markets or special applications. For applications with small and medium number of pieces, the costs per element must be lowered.

Injection-compression is a fast and reliable method for the replication of optical microstructures. This technique offers an extraordinarily high level of technical maturity, driven by the requirements in optical data storage (e.g. CD, DVD, BluRay). It is therefore an ideal candidate for the cost-efficient replication of binary and multi-level diffractive optical elements (fig. 1). A remaining challenge is the efficient fabrication of gray scale structures that can be used as master elements for the replication process. We investigate their production using gray scale direct laser writing.

Laser direct writing introduces a rounding effect of the structure profile due to the used beam profile. The resulting energy distribution of a writing process can be described as a convolution of the intended energy profile with the writing beam profile. The resulting edge rounding is efficiency degrading. Our goal is to counteract these effects using proximity correction, i.e. a correction of the writing data to compensate the edge rounding.

We investigated techniques based on well-known deconvolution algorithms known from image processing that take the measured beam profile of the writing spot, the nonlinear grey scale properties of the photoresist, sampling of the structures due to the circular writing and stray light into account.

The developed algorithms introduce overshoots around edges that increase the steepness of emerged slopes (fig. 2). The resulting photoresist structures show steeper slopes, which leads to more efficient diffractive optical elements.

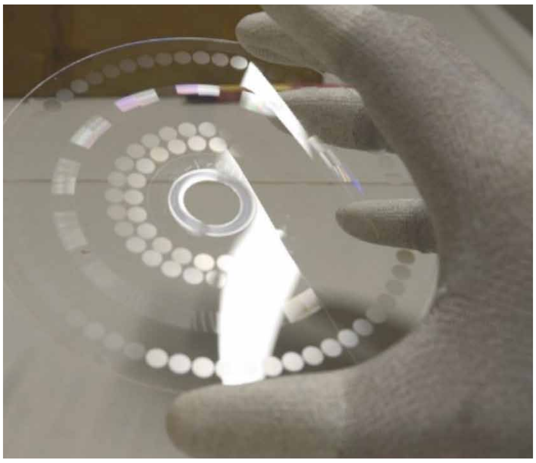


Fig. 1: *Replication of arbitrary multi-level diffractive structures by injection-compression.*

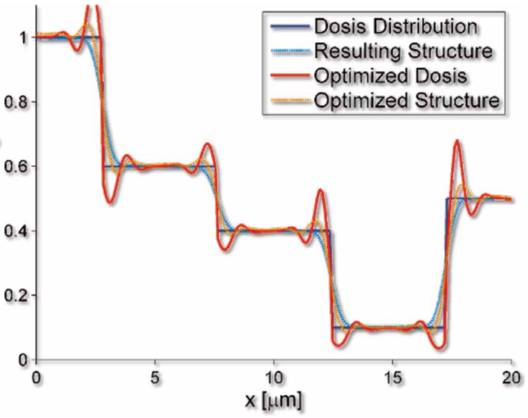


Fig. 2: *The normalized magnitude of a diffractive structure with and without optimization. Untouched design data (black) will lead to rounded structure profiles (blue). By using deconvolution algorithms, overshoots are introduced (red) that yield structures with steeper slopes (orange). We found that this method improves the diffraction efficiency of general 2D diffractive structures up to 7.5%.*

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

Supported by: BMWI (FKZ KF2281402AB2)
Project: Kosteneffiziente Grautonlithografie für diffraktive Multi-Level Elemente

Replication of diffractive optical elements on curved surfaces

J. Beneke, F. Schaal, W. Osten

When designing optical systems for imaging or metrology applications, hybrid optical elements that combine refractive and diffractive properties offer excellent correction capabilities with a compact size. Due to fabrication limitations, those elements are typically composed of a flat diffractive surface and a curved refractive surface. The combination of both functions into one surface will enhance the capabilities of these optical components even further. Fig. 1 shows a high frequency Fresnel zone plate on a plano-convex spherical lens.

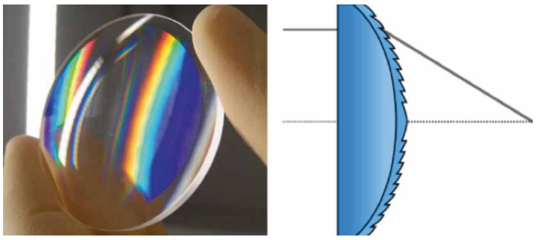


Fig. 1: *High frequency Fresnel zone plate written on a spherical lens (left). Schematic of a hybrid optical element, consisting of a spherical lens and a diffractive structure in photoresist (right).*

To make hybrid optical elements available for a broad range of products, highly efficient replication methods must be implemented. Together with our partner HSG-IMAT we are developing an injection molding process for the rapid replication of high quality hybrid optical elements. One of the tasks at ITO is the realization of the fabricaton technology for the micro-structured moulds.

We are investigating laser direct writing on curved substrates as a highly flexible technique capable of generating high resolution microstructures for the mould. The laser direct writing system we use was developed in house to work on strongly curved substrates (fig. 2). It creates a photoresist master on a glass substrate [1]. That is converted into a sturdy metal master via an electroplating process.

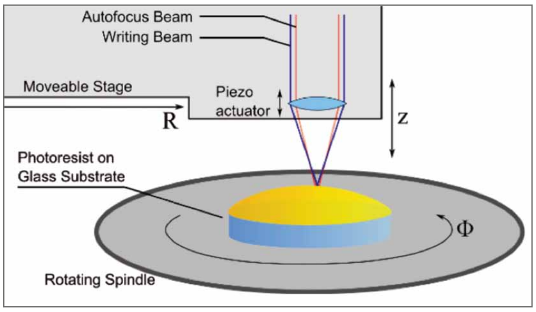


Fig. 2: *Schematic of a laser direct writing system for curved substrates. The continuous exposure of the photoresist takes place in polar coordinates and allows the fabrication of arbitrary diffractive structures.*

Using injection moulding we can fabricate monolithic elements as well as hybrid elements. Monolithic elements combine refractive and diffractive properties in one piece. A general problem of polymer optics are considerable dimensional deviations that can be introduced during the molding process, but also in the application due to environmental changes. A solution to this problem can be hybrid elements that are composed of a glass lens and an applied diffractive structure. In this case, the shape tolerances are defined mostly by the glass optics. One of the challenges of this approach is the alignment of the glass blank during the molding process.

The replicated monolithic or hybrid elements will be used for sensors in measurement applications like chromatic confocal microscopy or optical coherence tomography. The technology is especially suited for products with medium to high lot sizes.

Supported by: AiF (Vorhaben 18556N)
Project: Hybride optische Low-Cost Elemente für optische Sensoren (HOLEOS)
Partner: Institut für Mikroaufbautechnik der Hahn-Schickard-Gesellschaft für angewandte Forschung e.V.

References:

[1] Häfner, M.; Pruss, C.; Osten, W. "Laser direct writing: Recent developments for the making of diffractive optics", Opt. & Photonik. (2011) 40–43.

Limits of diffractometric reconstruction of line gratings when using scalar diffraction theory

S. Peterhänsel, C. Pruß, W. Osten

Computer generated holograms (CGH) are widely used for high precision asphere testing, with the interferometric Null test being one of the most common setups. In order to achieve the required precision, both the interferometer and the CGH have to be well calibrated. For the CGH this implies that phase errors in the generated wave fronts have to be well known, depending on the application down to $\lambda/100$ or better.

Both the design of a CGH and the calibration are frequently based on scalar approximation. In current setups for the calibration of binary line gratings the grating is illuminated by a coherent, single wavelength laser from one side and the intensity distribution of all transmitted diffraction orders is measured simultaneously by a camera. Using scalar approximation the inverse problem of determining the phase can be solved. However, the testing of steep aspheres requires high line densities in the CGH, which are well below 10 µm and hence the assumption for the scalar theory of λ being much smaller than the grating period Λ does not hold true anymore.

To solve this, rigorous simulations (here RCWA) were utilized to investigate phase errors introduced when reconstructing phase errors using scalar diffraction theory from diffractometric measurements. Line gratings with varying grating parameters were simulated and the resulting intensities were used as input for the scalar reconstruction. The error in both geometry characterisation and the resulting phase error were studied. As model binary line gratings with line width b and height h were used. For better comparability the duty cycle d, defined as the ratio b/Λ is used instead of the line width. As material fused silica was selected and all fabrication defects like rounding and side wall angle were ignored.

For readability the subscript sca denotes results gained by scalar approximation and the subscript meas denotes the results from the rigorous simulations that are treated here as measured values. For the reconstruction the following method was used: A scalar search matrix was calculated with parameters d and h for values of Λ between 1 and 10 µm. Assuming a known grating period the minimum difference between μ_{meas} and μ_{sca} is searched and the resulting reconstructed parameters are used to calculate the generated phase φ_{sca}. Due to Babinet's principle, scalar diffraction theory will yield the same results for values of d smaller or larger than $d = 0.5$. Likewise, same results will be obtained for h smaller or larger than $\lambda=[2(n - 1)]$.

The results of both reconstructed parameters changing Λ for a grating with h=500nm and d=0.43 made of fused silica and illuminated with λ of 632.82 nm are pictured in fig. 1.

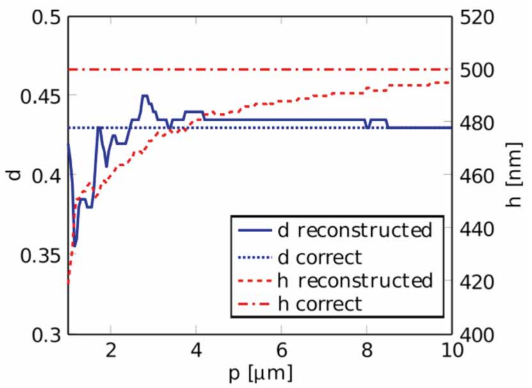


Fig. 1: *Dependence of reconstruction of parameters d and h on period p: While the reconstruction of d approaches the correct value rather quickly, for height reconstruction the deviation drops below 5 nm only for p > 8 µm resulting in phase differences larger than $\lambda/100$ even for periods of 10 µm.*

The reconstructed parameter d is converging rather quickly, suffering only from a small offset for periods larger than 4 µm. The reconstructed value for h is converging more slowly, with an error of less than 5 nm for periods larger 8 µm.

These results are vital for fabrication control, but for interferometric applications the generated phase of the grating is of much greater importance. Hence, we will now study the effect on the phase difference $\Delta\varphi=\mu_{meas}-\mu_{sca}$ defined as the difference between rigorously calculated one and calculated one from the reconstructed values, see fig. 2. The phase is divided by 2π, converting radians to the more commonly used waves.

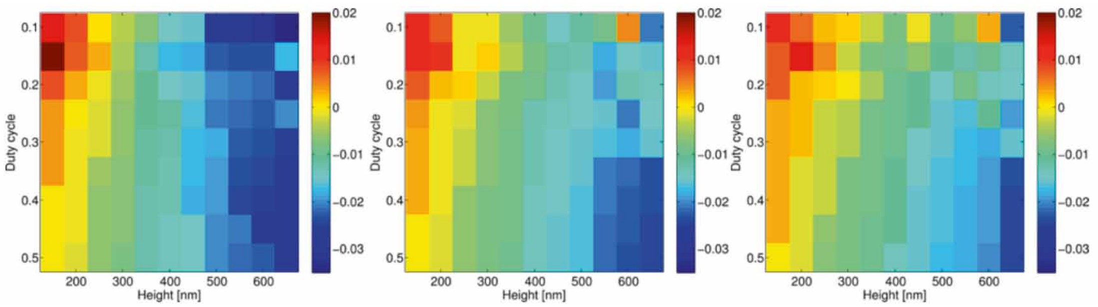


Fig. 2: *Comparison of the phase difference Δφ between simulated phase and calculated phase from the scalar reconstructed values for different grating periods: left - 4 µm, middle - 6 µm and right - 8 µm.*

Here we can see that for very flat gratings (h smaller 400 nm) the error in phase is in the range of ±λ/100. This range is improving slightly as p increases. On the other side, even for p of 8 µm the phase difference is 3λ/100 if the height is approaching values larger than 650 nm.

Again for very small heights of only 150 nm the error is increasing rapidly. The dependence of the error on d is marginal, resulting only in higher values for isolated structures (d in the range of 0.1...0.15), as for those structures rigorous effects play a more dominant role.

These results imply that scalar diffraction theory can be used for the geometry and phase reconstruction, if an error of a few λ/100 can be tolerated. As expected the error of this reconstruction will increase for smaller grating periods. In addition certain combinations of d and h will lead to an increasing error for both geometry and phase reconstruction [1].

Supported by: DFG German Science Foundation
Project: Inverse Source and Inverse Diffraction Problems in Photonics (OS 111/32-1)

References:

[1] Peterhänsel, S.; Pruss, C.; Osten, W. "Limits of diffractometric reconstruction of line gratings when using scalar diffraction theory", Opt. Letters 39(13):3764-66 (2014).

NPMM–200

K. Frenner, C. Pruß, W. Osten

With € 4,600,000 the Deutsche Forschungsgemeinschaft (DFG) has funded the acquisition of a nanopositioning and measuring machine NPMM–200. This device is a highly accurate positioning machine developed and manufactured at TU Ilmenau with a

- measurement range
  200 mm x 200 mm x 25 mm
- resolution 5 pm
- movement speed up to 10 mm/s reproducibility of position of ±1 nm over the entire measuring range
- vacuum operation with rough pump and turbo molecular pump

To achieve these performance parameters, the use of modern homodyne interferometers in vacuum is required. Such modern interferometers are characterized by the following properties:

- use of two-beam and three-beam interferometers minimizes frequency differences in 6D-measurements
- stability of the laser is higher than 10–9
- interferometers can be used in vacuum.

To illustrate the importance of environmental control and metrology, we have explicitly estimated the influence of temperature, pressure and humidity onto the measurement of one coordinate if measured interferometrically in air. If we assume a maximum allowable error of 1 nm for the position measurement we can calculate the maximum measurement error for environmental conditions. If we assume a length to be measured of 200 mm, a wavelength of 632.8 nm, temperature of 20°C and a pressure of 1013 mbar then we need a measurement accuracy of:

- temperature metrology:
  1 nm corresponds to dT = 0.00545 K
- pressure metrology:
  1 nm corresponds to dp = –1.89 Pa
- humidity metrology:
  1 nm corresponds to dh = 13.2%

This illustrates that for single nanometer requirements the influence of environmental conditions metrology is extremely severe. The vacuum approach of the NPMM–200 relaxes this problem by three orders of magnitude.

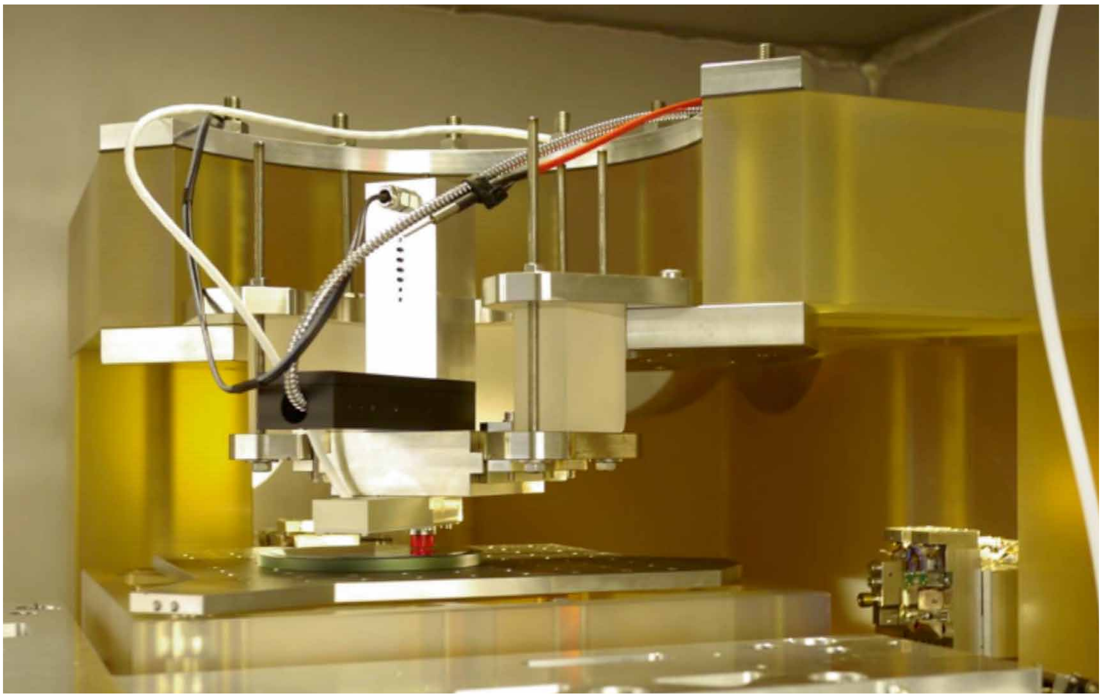


Fig. 1: *Central parts of the NPMM–200 at TU Ilmenau.*

The highly accurate repeatability and resolution of NPMM–200 will be used as a sensor platform for challenging projects like e.g.

- sensor development for extreme resolution lithography
- synthetic quantum systems
- 3D-measurements with different macroscopic, microscopic and nanoscopic sensors
- multi-modal sensor-fusion

High resolution and fast detection of local properties like imperfections, faults or deviations from design can be adapted to extended optical components and systems much more flexible with a multi-scale measurement strategy and sensor fusion than probing with one individual sensor. Sensor fusion combines high precision absolute shape measurement with additional information on the nanoscopic scale below the resolution limit of optical systems using e.g. plasmonic near-field sensors and optical metamaterials. Selection of suitable sensors in such a multisensor system and determination of their parameters will be performed automatically by an assistance system. Key element in the final finishing step of high precision fabrication, where the error of the optical surface is reduced to the 10 nm level (rms) or below, is the absolute measurement. Such a high precision characterization of optical functional surfaces like e.g. aspheres, free forms, DOEs and hybride elements can be improved by combining optical full field methods with NPMM–200 measurements. Integration of such an expensive and unique device will be realized at ITO within a remote laboratory concept. Based on such a concept and referring to a systematic access procedure, the NPMM could be applied by remote users. The implementation of a virtual nano-processing and nano-measurement center is objective of these investigations.

Supported by: DFG Os 111/44-1
Nanopositionier- und Messmaschine

Coherent Metrology

Optical Methods for Damage Assessment of Artworks

D. Buchta, G. Pedrini, W. Osten

Artwork is an important part of our culture and should be prevented from any damage. But a continuous decay due to ageing can lead to different changes. Furthermore transports and the occurring vibrations or fast variation of climate accelerate this decay. To avoid irreversible damaging of artwork an early and complete detection of these defects is necessary. In addition to obvious defects, non-visible deteriorations like changes of surface in micrometer range or defects under the surface like delaminations should be detected reliably.

To get access to all of the mentioned defects we are developing a multimodal measurement system, combining fringe projection and shearography.

The fringe projection uses structured illumination to generate a 3D point cloud containing the information about the shape of the object [1]. As example in fig. 1b) the point cloud of a canvas painting (fig. 1a) is shown.

The shearography is an interferometric technique, which uses a comparison of two phase maps to detect subsurface damages. Between the recordings of these phase maps, the object is stressed by a loading device for example by an infrared lamp [2]. Defects can then be recognized as irregularities in the phase map, as can be shown for the canvas painting in fig. 1c), where larger cracks on the surface as well as subsurface cracks are detected.

To simplify the recognition and the localization of defects for the conservator we combined the point cloud and the shearogram with a daylight photo. In the resulting representation, the irregularities in the shearogram are colored and mapped on the photo and afterwards on the point cloud. The result for the canvas painting is shown in fig. 2. In the zoomed window the advantage of the combination of the two measurement techniques become clear. While the cracks (on surface and subsurface) can only be detected with shearography others like small holes can be easily recognized by the fringe projection. The use of the daylight photo allows furthermore the identification of discolorations. Moreover, cross correlation is applied to compare two states for example before and after a transport. This enables the possibility to detect changes of the surface also in micrometer range [3]. So the system can be used to distinguish between transport and ageing induced defects and therefore to improve the rules for a save transport of artwork.

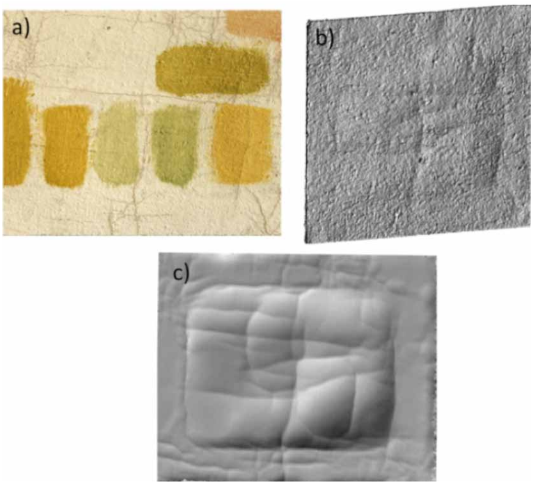


Fig. 1: *a) Daylight photo of canvas painting. b) 3D point cloud recorded with fringe projection c) Phase map with detected defects recorded with shearography.*

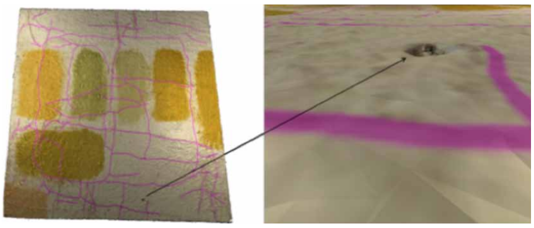


Fig. 2: *Result of the combination of daylight photo, 3D point cloud and phase map. In the zoomed and tilted representation the complementary properties of the two techniques become clear.*

Supported by: DFG German Science Foundation
Project: Die materielle Veränderung von Kunst durch Transporte (OS 111/34-1)
In cooperation with Staatliche Akademie der Bildenden Künste Stuttgart

References:

[1] Hein, N.; Krekel, C. "3D-Weißlicht-Streifenprojektionsscanner zur Untersuchung von Transportschäden an Skulpturen", Zeitschrift für Kunsttechnologie und Konservierung 24(1), 146159 (2010).

[2] Buchta, D. et al. "Artwork Inspection by Shearography with adapted loading", Experimental Mechanics, doi: 10.1007/s11340-015-0070-9 (2015).

[3] Buchta, D. et al. "Combination of topology and structural information for damages and deterioration analysis of artwork", Proc SPIE 9527 (2015).

Opposed-view digital holographic microscopy

A. Faridian, G. Pedrini, W. Osten

In the opposed-view approach the holograms are captured concurrently from the top and bottom views of the imaging system. Each hologram is analyzed separately and the intensity images, obtained for each layer from each view, are fused together to create the final multilayer images. Figure 1 shows a schematic of an opposed-view dark-field DHM. The system is a symmetric combination of two off-axis dark-field DHMs. Two Nikon bright/darkfield microscope objectives with 20× magnification and NA = 0.45 are placed face to face for imaging from both views. As the object is illuminated simultaneously using the objectives, both transmitted and reflected light from the structures make contribution in image formation. A camera is installed in each view to concurrently record the dark-field (DF) images.

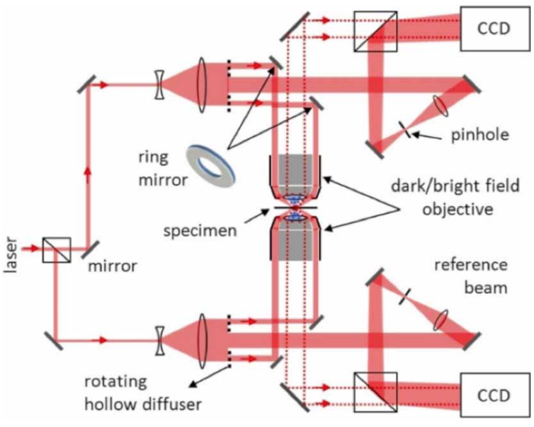


Fig. 1: *Setup of an opposed-view dark-field digital holographic microscope.*

To easily extract the fine structures from each image view, dark-field imaging mode is favourable. To combine the information obtained from the opposed views, first the counterpart images for each specific object layer, obtained from both views, should be selected and the image combination should be applied to each corresponding pair. The images are fused together using a pixel-based approach. For each pixel, a region of 10×10 pixels, centred by the initial pixel point, is selected. The standard deviation (Std) of the intensity distribution over the selected region is calculated and compared with the same value for the corresponding pixel in the opposed-view image. The pixel value with the larger calculated Std is then set to the corresponding pixel position in the final image. This process is done for each single pixel of both images to derive the final image, which is shown in fig. 2(a) for a given layer of a Drosophila embryo. Sub-figures in fig. 2(b) represent the highlighted images of the regions marked by numbers in fig. 2(a), which are separately obtained from top and bottom views. For the sake of better visibility, some structures have been marked with arrows in fig. 2(b), which are present in one of the views while missing in the other. The fused sub-images of the same regions have been shown in fig. 2(c). The structures presented in both views are visible together in the fused images, without reducing the image quality.

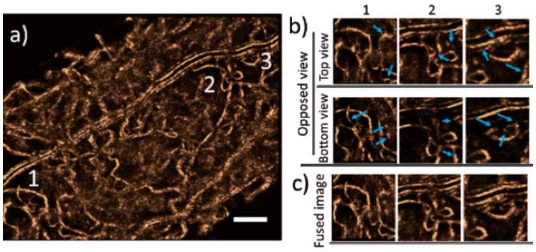


Fig. 2: *The reconstructed image of a Drosophila embryo. (a) The fused image obtained using the pixel-based approach. (b) The top and bottom view images of the regions marked with numbers in (a). The arrows represent some of the structures visible in one view, while missing in the other. (c) The images of the same regions as (a) after performing image fusion process. The scale bar in (a) is 25 µm.*

Supported by: DFG German Science Foundation.
Project: High resolution 3D microscopy using opposed-view dark-field digital holography (OS 111/32-1)

References:

[1] Faridian, A.; Pedrini, G.; Osten, W. "Opposed-view dark-field digital holographic microscopy", Biomedical Optics Express 5 (2014) pp. 728-736.

[2] Faridian, A.; Pedrini, G.; Osten, W. "High-contrast multilayer imaging of biological organisms through dark-field digital refocusing", Journal of Biomedical Optics 18 (2013) 8 pp. 086009.

[3] Osten, W.; Faridian, A.; Gao, P.; Körner, K.; Naik, D.; Pedrini, G.; Singh, AK; Takeda, M.; Wilke, M. "Recent advances in digital holography", Applied Optics 53 (2014) pp. G44-G63.

Quantitative phase imaging using a deep UV LED source

A. K. Singh, A. Faridian, P. Gao, G. Pedrini, W. Osten

Imaging with deep-ultraviolet (DUV) light sources has many practical advantages. According to the Abbe's criteria, the diffraction-limited lateral resolution is given by $0.61\lambda/\mathrm{NA}$, where λ is the wavelength of the light source and NA is the numerical aperture of the imaging system. Thus, the lateral resolution can be increased by reducing the wavelength.

DUV digital holography was successfully applied for high resolution imaging using a short coherence laser source with wavelength 193 nm [1]. Although, the system performance proved promising for high resolution imaging, the presence of a separate reference beam and the use of an Excimer laser made the setup expensive and sensitive.

Recently, some digital holographic systems utilizing LEDs in the visible range were reported; however, compensating for the optical path difference between the object and the reference wave in such systems requires many optical elements, which increases the complexity of the system and makes it very sensitive to vibration.

We report a single beam phase imaging system that avoids the shortcomings of the existing techniques using an incoherent DUV LED source. Thanks to recent technology developments, LEDs are now available in this spectral range and are cost effective. For the phase retrieval, we apply a technique using intensity diffraction patterns recorded at different planes and an iterative algorithm and thus a reference beam is not necessary [2, 3].

Figure 1 shows the experimental setup for the applied phase retrieval method using the DUV LED source. The emitting area of the source is less than 0.3 x 0.3 mm^2 and the central wavelength is 285 nm and the FWHM is 12 nm. To increase the spatial coherence for phase imaging, a lens of diameter 10 mm with the focal length of 15 mm was inserted between the LED and the sample and the light was loosely focused onto the sample. The temporal coherence of the light source is calculated to be 6.77 µm and the spatial coherence region for this configuration is 40 µm which is measurable using a Michelson interferometer. The magnified image of the sample is then projected onto the CCD camera using a microscope objective (MO), having the NA 0.75. No additional component e.g. pinhole or spatial filter is necessary to increase the spatial coherence of the source. The separation between the camera and the MO is kept relatively large (80 cm in this case) so that a very small area of the sample is imaged onto the CCD with a magnification of more than 200 times and the field of view is approximately 35 µm. Since the coherence region is larger than the field of view, this method can be used for retrieving the phase.

We have performed experiments on a nano-structured template. The SEM image of the sample is shown in fig. 2(a) to provide a better visual comparison with the obtained results. Because of its ultra-small size and low power illumination source, a very small amount of the LED light could transmit through the sample. Therefore, higher integration time is required for the camera (4 seconds in this case). Here, only five on-axis images were acquired at an interval of 10 mm for retrieving the phase and the initial guess of the phase varies between 0 to 2π. Figs. 2(b) and 2(c) show the obtained amplitude and phase in the image plane. Because of the low irradiance the intensity image is not so sharp but the phase image is providing finer details. The phase profile of the dashed line segment shown in fig. 2(c) is plotted in fig. 2(d). The width of the lines are 500 nm, and are well resolved. The phase information can be used to show the surface profile in 3-D as is shown in fig. 2(e).

The proposed system can be used for imaging technical structures as well as biological samples.

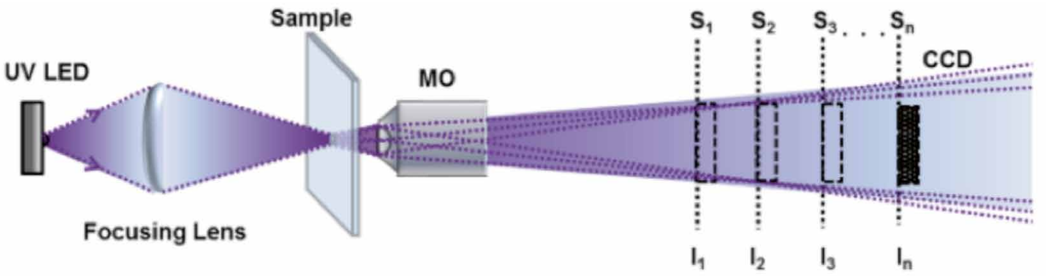


Fig. 1: *Experimental setup with Deep UV LED as the light source. The ray diagram is shown to visualize the imaging of the object using MO (microscope objective).* I_1, I_2, I_3…I_n *are the intensity samplings at* S_1, S_2, S_3…S_n *planes, respectively.*

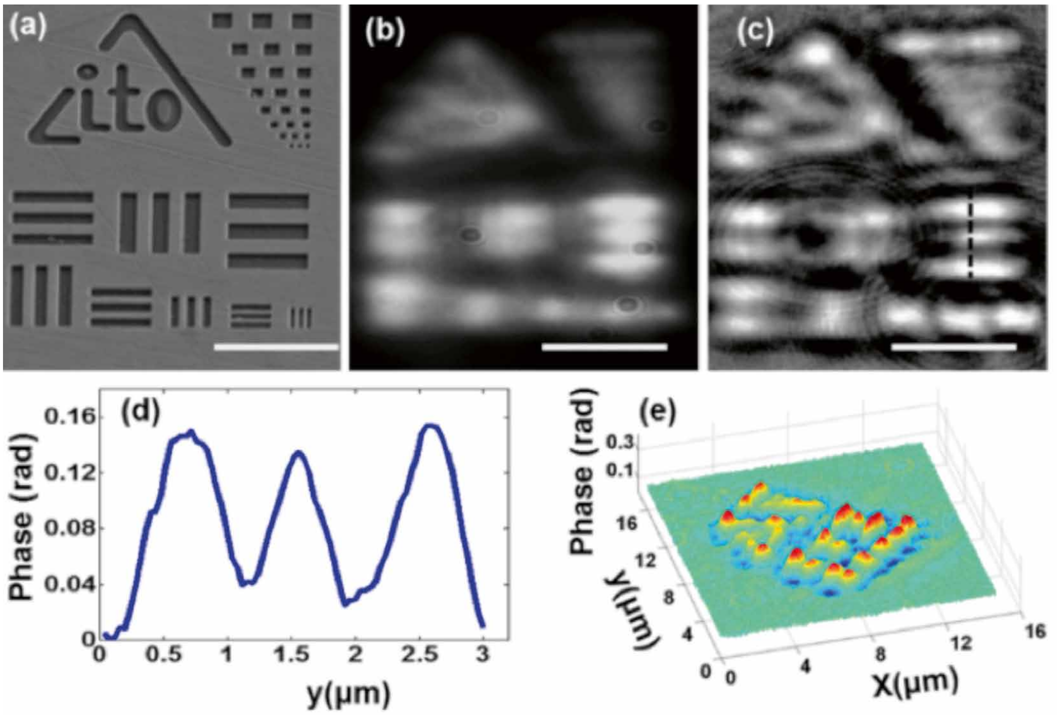


Fig. 2: *(a) The SEM image of 'ITO logo', (b) amplitude image in the image plane, (c) the phase image, (d) the height variation of the dashed line segment shown in (c) and (e) the phase profile of the sample in 3-D. The scale bar is 3 µm.*

Supported by: DFG German Science Foundation
Project: Holographie mit adaptiver Wellenfrontformung zur hochauflösenden Untersuchung von 3D-Mikrostrukturen im tiefen UV-Bereich (OS111/19-3)

References:

[1] Faridian, A.; Hopp, D.; Pedrini, G.; Eigenthaler, U.; Hirscher, M.; Osten, W. "Nanoscale imaging using deep ultraviolet digital holographic microscopy", Opt. Express18, 14159 (2010).

[2] Singh, A. K.; Faridian, A.; Gao, P.; Pedrini, G.; Osten, W. "Quantitative phase imaging using a deep UV LED source", Opt. Lett. 39, 3468-3471 (2014).

[3] Osten, W.; Faridian, A.; Gao, P.; Körner, K.; Naik, D.; Pedrini, G.; Singh, A. K.; Takeda, M.; Wilke, M. "Recent advances in digital holography", Applied Optics 53 (2014) pp G44-G63.

Phase retrieval by using spatially modulated illumination

P. Gao, G. Pedrini, W. Osten

Phase imaging is of fundamental importance for technical and biomedical investigations, since the phase contains information about the 3D shape and the inner structure of transparent or translucent samples. Holography is the most commonly used approach to retrieve the phase, where an additional reference wave is superimposed to the object wave and the phase is reconstructed from the generated interference pattern. This approach has high accuracy, but the use of an independent reference wave make it sensitive to external perturbations, such as vibrations, temperature changes, etc., and leads to an increase in the setup complexity. The beam propagation based methods estimate the phase by iteratively propagating of the wave among a sequence of diffraction patterns. The diffraction patterns may be recorded at different axial planes; with different wavelengths; by flipping the sample; modulating the object wave with different phase patterns or by scanning an aperture over the object wave. There are as well deterministic methods retrieving the phase by using the transport of intensity equation (TIE). The TIE method records two or three diffraction patterns at closely spaced planes and reconstructs the phase without iteration process and without the need of phase unwrapping.

We propose a phase retrieval method by using time-sequential spatially modulated illuminations [1, 2]. For wave fronts with smooth phase, a deterministic phase retrieval is performed by solving the phase gradient instead of the phase second derivative (Laplacian). Thus, the boundary condition problem of the traditional TIE method, is avoided. An iterative process is used to reconstruct the phase of wavefronts having discontinuities and at the same time enhance the spatial resolution. Unlike the traditional TIE which records the object wave intensities in two or more axially spaced planes, this method records the intensity patterns in a single plane.

Figure 1 shows the setup used for the phase retrieval, where a collimated beam is modulated by a spatial light modulator (SLM) and imaged to the sample by a telescopic system composed by the lenses L1 and L2. Another telescopic system composed by the lenses L3 and L4 reconstructs an inverted and magnified image of the sample in the plane IM located at the axial distance dz from the CCD sensor. We use a sequence of illuminations and the resulting intensities (with and without inserting the sample) are processed by a using an optimized TIE equation in order to retrieve the phase of the wavefront transmitted by the sample (for more details see Ref. [1]).

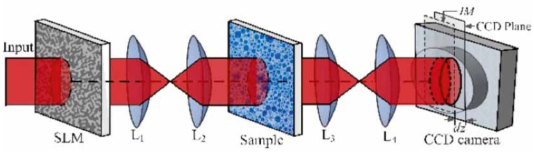


Fig. 1: *Setup of the phase retrieval by using spatially modulated illuminations; SLM, Spatial light modulator; L1–L4, achromatic lenses; IM, Image plane; dz is the distance between imaging plane and CCD plane.*

Based on the configuration shown in fig. 1, an experiment has been carried out to demonstrate the feasibility of the method. The obtained results are shown in fig. 2. Five random patterns (fig. 2(a)) were loaded sequentially on the SLM to generate spatially modulated illuminations. The diffraction patterns of the sample under these illuminations are shown in fig. 2(b). The recorded intensity obtained when a plane wave is used to illuminate the sample and the phase derivatives of the sample in x direction are shown in figs. 2(c) and 2(d), respectively. The phase distribution of the sample (fig. 2(e)) is reconstructed from the derivatives along the x and y directions. For comparison, the same sample was also investigated by digital holographic microscopy (fig. 2(f)). The consistence between the results shown in figs. 2(e)–2(f) demonstrates the feasibility of the proposed method.

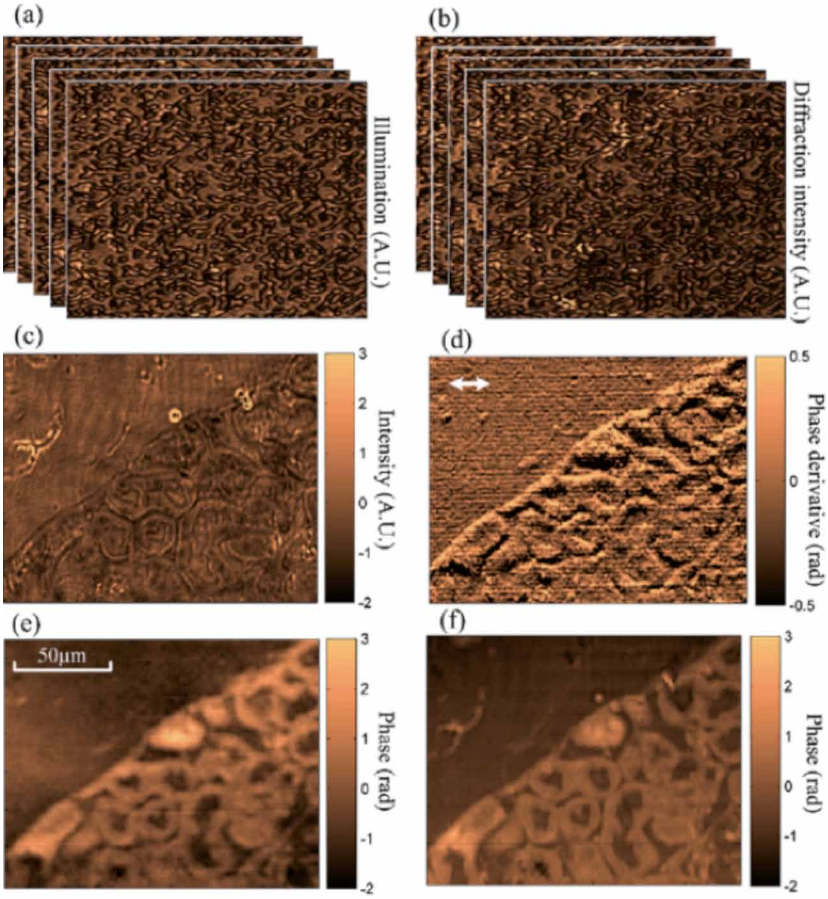


Fig. 2: *Reconstruction results of a slice of mouse kidney; (a) intensity distributions of five illuminations; (b) intensity distributions of five generated diffraction patterns; (c) intensity image of the sample under plane wave illumination; (d) reconstructed phase derivative of the object wave in x direction; the reconstructed phase distributions obtained by the proposed method (e) and by digital holographic microscopy (f). The arrow in the fig. 2(d) denotes the direction of the phase derivative.*

Supported by: Alexander von Humboldt foundation for P. Gao

References:

[1] Gao, P.; Pedrini, G.; Zuo, C.; Osten W. "Phase retrieval using spatially modulated illumination", Opt. Lett. 39, 3615-3618 (2014).

[2] Osten, W.; Faridian, A.; Gao, P.; Körner, K.; Naik, D.; Pedrini, G.; Singh, A. K.; Takeda, M.; Wilke, M. "Recent advances in digital holography", Applied Optics 53 (2014) pp G44-G63.

Incoherent digital holography

D. Naik, D. Claus, G. Pedrini, W. Osten

Digital holography holds many advantages over conventional imaging techniques such as non-destructive full field measurement, numerical refocusing to enable the recovery of a 3D scene, single shot recovery of quantitative phase information and the ability to multiplex information. It has therefore been applied to many different fields among others optical metrology and biomedical imaging. However, due to the coherent nature of the light sources employed, digital holography suffers from coherent noise artefacts also known as speckles, which decrease the image quality of the reconstructed hologram. Many attempts have been made to reduce the speckle noise in the reconstructed hologram, most of which are based on speckle de-correlation. This has either been implemented by reducing the spatial coherence via the introduction of a rotating diffuser or via the averaging of multiple holograms recorded at different wavelengths. Our approach addresses both, spatial and temporal coherence, via the usage of a partially coherent broadband light source or a self-luminous object (fluorescence). In that manner the averaging of speckle de-correlated holograms already takes places in the recording process. In order to enable the recording of incoherent holograms, self-referencing schemes can employed. The underlying theoretical principle addressing the spatial incoherence is based on the analogy of the diffraction integral with the van Cittert-Zernike theorem. The van Cittert-Zernike theorem states that the Fourier transform of an incoherent source's planar intensity is proportional to the spatial coherence function measured in the far field.

The temporal incoherence is addressed via the Wiener-Khintchine theorem, which refers to the Fourier transform relation between the spectral density function and real correlation function.

Other than applying the tedious and time consuming Young's double pinhole point wise measurement approach to obtain the spatial coherence function, a full field measurement system is used, which obtains the spatial coherence function as the contrast and phase distribution of interference fringes.

Such a system, which in addition also enables the application of temporally incoherent light, can be implemented via a phase shifting radial shearing interferometer, as shown in fig. 1.

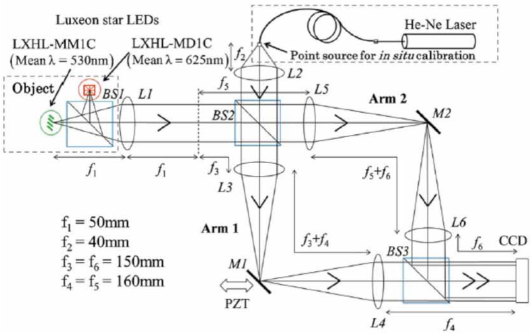


Fig. 1: *Experimental setup for the recording of a spectrally resolved incoherent-object hologram, taken from [5].*

Radial shearing enables the recovery of 3D information and adds equal weight to all spatial frequencies (orientation independent) compared to other shearing arrangements such as rotational shearing (no depth information) and lateral shearing (orientation dependent), respectively. It is advantageous to record the interference patterns in the far field region. Here the optical field is shift invariant, so that every object point has the same impulse response, which significantly reduces the numerical effort, as pointed out in. Radial shearing is implemented via a Mach-Zehnder interferometer, whereas a different magnification is applied to the optical system in each arm. Phase stepping is made possible via the introduction of a piezo mounted mirror (arm 1 in fig. 1). In that manner a series of incoherent phase stepped holograms can be recorded e.g. 1024 incoherent holograms. The reconstruction scheme, which is then employed, is depicted in fig. 2, where the star of a 1 cent Euro coin has been used as the object under investigation. The temporal interference signal along one pixel column is Fourier-filtered, to result in a stack of wavenumber corresponding holograms. The reconstruction of each wavenumber corresponding hologram is obtained via the application a 2D Fourier transformation. Hence, compared to the other incoherent/short coherence digital holography approaches implemented by ITO [1–4], the spectral information can also be recovered, which in combination with the recovery of 3D information, made possible via numerical refocusing, completes the description of the object under investigation [5,6].

The recovery of spectrally filtered holograms is demonstrated in fig. 3, where a toy airplane composed of different colours is used as the object under investigation.

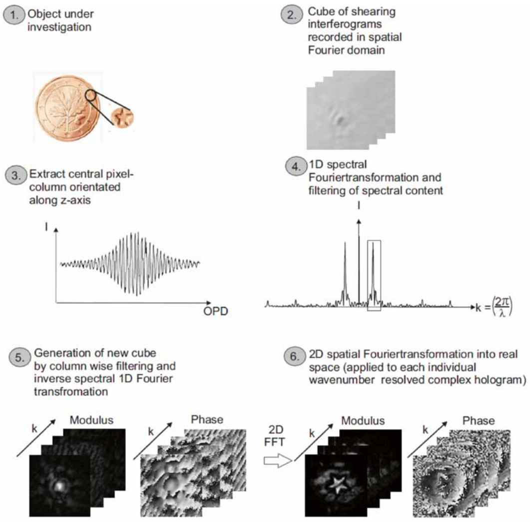


Fig. 2: *Flowchart diagram displaying the different image processing steps applied to the recorded phase stepped shearing interferograms.*

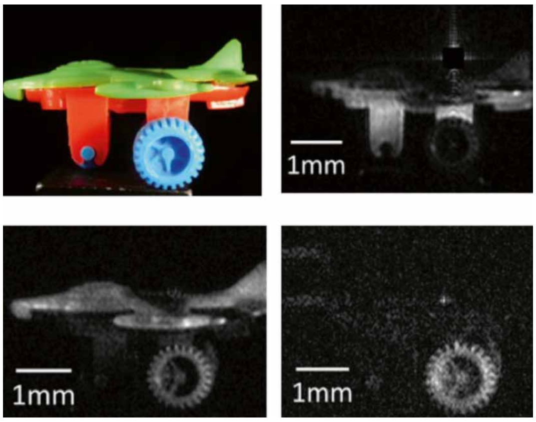


Fig. 3: *Images have been taken from reference [5], the individual subfigures display (a) a toy aircraft as polychromatic object, (b) the reconstruction for 635 nm, (c) the reconstruction for 530 nm and (d) the reconstruction for 450 nm.*

In summary, alongside the aforementioned advantages of digital holography, spectrally resolved holography furthermore offers a speckle noise reduced reconstruction and the recovery of spectral information, which opens the passage to new applications.

Supported by: Alexander von Humboldt foundation for D. Naik

References:

[1] Martínez-León, L.; Pedrini, G.; Osten, W. "Applications of short-coherence digital holography in microscopy", Appl. Opt. 44, 3977-3984 (2005).

[2] Pedrini, G.; Li, H.; Faridian, A.; Osten, W. "Digital holography of self-luminous objects by using a Mach-Zehnder setup", Opt. Lett. 37, 713–715 (2012).

[3] Naik, D. N.; Pedrini, G.; Osten, W. "Recording of incoherent-object hologram as complex spatial coherence function using Sagnac radial shearing interferometer and a Pockels cell", Opt. Express, 21, 3990-3996 (2013).

[4] Zhang, Y.; Situ, G.; Pedrini, G.; Wang, D.; Javidi, B.; Osten, W. "Application of short-coherence lensless Fourier-transform digital holography in imaging through diffuse medium", Opt Commun, 286, 56-59 (2014).

[5] Naik, D. N.; Pedrini, G.; Takeda, M.; Osten, W. "Spectrally resolved incoherent holography: 3D spatial and spectral imaging using a Mach-Zehnder radial-shearing interferometer", Opt. Lett. 39:1857-1860 (2014).

[6] Osten, W. et al "Recent advances in digital holography", Appl. Opt 53: G44-G63 (2014).

Determination of Material Parameters of Biological Tissue

D. Claus, P. M. Schumacher, M. Wilke, G. Pedrini, W. Osten

Minimally invasive surgery has for many applications replaced open surgery, since the amount of tissue, which has to be cut, is reduced to a minimum, resulting in a quicker recovery of the patient connected with reduced post operational stress. Moreover, it offers some aesthetical advantages in particular for exposed parts of the human body e.g. face. However, minimal invasive surgery has restricted the working environment of the surgeon due to the loss of two mayor human senses, three dimensional vision and haptic feedback. The haptic feedback is an important tool which helps the surgeon in localizing tumors due to the increased stiffness compared to healthy tissue (palpation). Tumorous tissue is 7–14 times stiffer than healthy tissue. Our goal is to re-establish the surgeon's sense of touch in minimally invasive surgery, albeit with an increased sensitivity, increased lateral resolution and the new feature of depth localization, made possible by the information from preoperational data and template matching with FE-simulation.

Our working principle is based upon the combination of multiscale and multimodal elastographic measurement techniques and a soft tissue applicable FE-Model, which correlates well with the measurement. From the FE-model a large data bank will be created, which can be used to solve the under-defined measured data in real time. Therefore, the project involves different partners combining different expertise and facilities (IAP at University of Tübingen, Klinikum at University of Tübingen, IMWF at University of Stuttgart, ISYS at the University of Stuttgart).

ITO has been involved in the development of a large scale (organ level) elastographic real time measurement tool. For this purpose a roll indenter, enabling lateral movement across the sample combined with a feedback loop controlled force or indentation depth, has been designed and manufactured at ITO's electrical and mechanical workshops, which is displayed in fig. 1. A two dimensional displacement field was measured employing image correlation technique.

At first, silicon phantoms without [1] and with stiffness inclusions [2], characterized by well-defined geometry and elastic behavior have been studied in order to generate a ground truth and to validate the system.

The displacement field obtained has then been compared with the FEM-simulations, based on the Arruda-Boyce model, created by our partners from the IMWF. As a result a good agreement between the FEM simulation and experimental data was obtained, as displayed in fig. 2 for silicon phantom with stiffness inclusion.

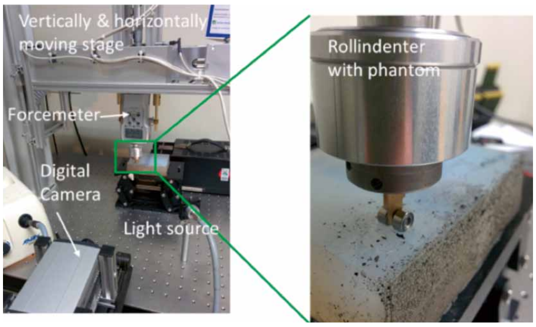


Fig. 1: *Experimental setup for roll-indentation and optical imaging system.*

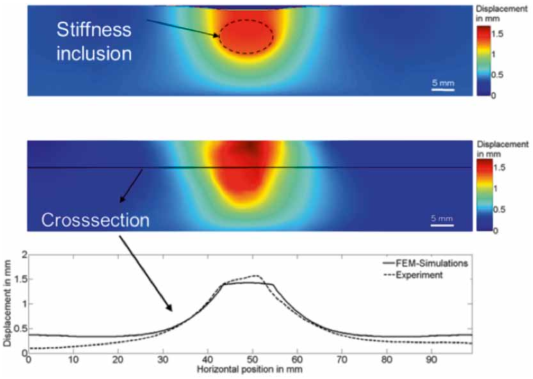


Fig. 2: *Displacement maps obtained, top to bottom: FE-Modell, experimental results, cross-section plot (good match at central position).*

Supported by: Industry on Campus Project
Project: IoC105 – In cooperation with Aesculap AG

References:

[1] Claus, D. et al "Intraoperative model based identification of tissue properties using a multimodal and multiscale elastographic measurement approach", Proc. SPIE, Biomedical Optics, Munich (June 2015).

[2] Claus, D. et al "Intraoperative model based identification of tissue properties based on multimodal and multiscale measurement", Proc. SPIE BIOS San Francisco (Feb. 2015).

Navigation During Laparoscopic Abdominal Surgery

M. Wilke, D. Claus, P. M. Schumacher, G. Pedrini, W. Osten

During minimally invasive surgery a surgeon is dependent on a detailed anatomical orientation to achieve the goal of the procedure (e.g. to locate and remove a tumour). While available pre-operation data such as MRI (Magnetic resonance imaging), X-Ray, or CT (X-ray computed tomography) images can support the surgeon, matching its information to the changed orientation of the patient on the operating table poses a challenge due to the shift of inner organs, the occlusion of the target by interposed tissue, and the degradation of the endoscopic image due to interference inherent to the surgical procedure itself (blood, smoke from electrical cutting and cauterization). A navigation system capable of identifying anatomical markers gained in the pre-operation data during the actual operation and making it available to the surgeon in the endoscopic image would accelerate surgical procedures, limit the tissue damage to the patient, increase the chance of success and improve the recovery of the patient.

The approach taken in this project involves three stages: 1) the creation of a 3D-model of the patient based on pre-operation CT data, 2) the registration of the absolute position and orientation of the patient and the surgical tools in the fixed coordinate system of the surgical theatre using optical, inertial, and ultrasonic tracking, and 3) matching the image of the endoscope to the 3D model (fig. 1). The project involves the ISYS (optical, inertial, and ultrasonic tracking) and the ITO (3D Model from CT data) at University of Stuttgart, as well as the Institute for Cognitive Systems (tracking markers in the endoscopic image and blending the CT data into images) and the UKT (medical expertise, test Ops and provision of CT data) at the University of Tübingen.

The role of the ITO consisted of the segmentation of CT/MRI data to identify relevant anatomical structures for the creation of a pre-operative, patient-internal coordinate system and corresponding 3D model. Since the segmentation and 3D modelling of CT data is a well-researched field with powerful, free and commercial software solutions available, we chose 3D Slicer for this task. In a first step, the skeleton was segmented using a simple thresholding algorithm applied to the Hounsfield coefficients of the CT data set. The skeleton plays a key role in the 3D model as it provides easily identifiable anatomical markers (the pelvic bone or the lower ribs) and a relatively rigid framework. In a second step, the general position of the kidneys was marked manually and the kidneys themselves segmented using a robust statistics segmenter starting with those manually placed seeds. The final 3D model combines these two features and is stored in VTK, PLY, or STL format for further processing (fig. 2).

A test surgery creating one fully consistent data set of CT, registering of the body and the surgical tools in the surgical theatre, and recording the endoscopic image has been performed to test the current state of the the system to be developed in this project.

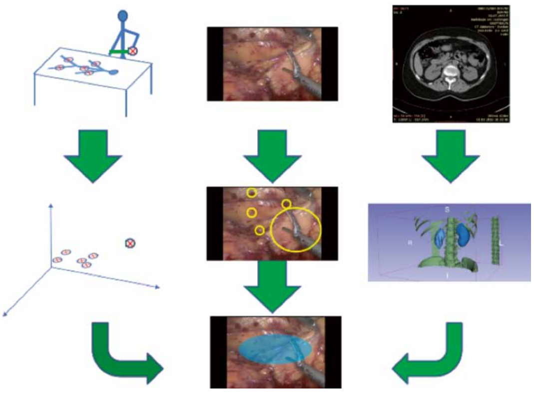


Fig. 1: *The Registration Problem.*

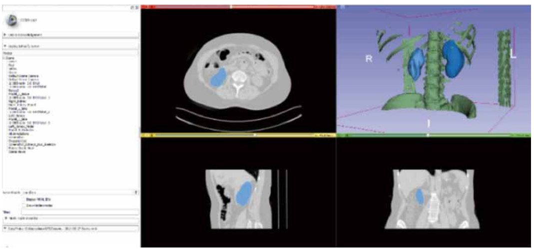


Fig. 2: *Segmentation and 3D Model of Kidneys in 3D Slicer.*

Supported by: Industry on Campus Project
Project: IoC104 – In cooperation with: Aesculap AG, ISYS (University of Stuttgart), Cognitive Systems (University of Tübingen), UKT (University of Tübingen)

Residual stress analysis of ceramic coatings

G. Pedrini, W. Osten

Ceramic coatings are commonly used to improve the wear or heat resistance of many technical components, but due to their deposition process, e.g. plasma or high velocity oxygen fuel spraying, rather high residual stresses can build up within the coating and underneath. The reason for that are differences in the coatings and substrates expansion coefficients, inhomogeneous temperature distribution during the process and the quenching of splats. The mechanical hole drilling technique can be used for the detection of residual stresses in coatings. The residual stresses are locally relieved due to the material removal process, which leads to a deformation of the surface around the hole. These deformations, measured as relaxed strains through strain gauges rosettes, in combination with appropriate calibration data (separately determined by simulation for the layer composite), allows the quantitative determination of the residual stress depth profile. The disadvantage of the strain gauges is that they can only be used on flat and relatively smooth surfaces, where the rosette is applied.

We propose an approach to avoid the mechanical drilling operation and the application of strain gauges, where a pulsed laser is used for the object machining (ablation process) leading to 3D residual deformation by stress relaxation which are measured by an optical system based on digital holographic interferometry. For the validation of the method, test plates were prepared, where aluminium/titan oxide coatings are deposited by atmospheric plasma spraying technique on aluminium substrates.

The experimental setup for residual stress analysis (fig. 1) can be divided into two parts one for the machining of the object and the other for the measurement of the resulting 3D deformations. The harmonic separator (HS), transmits the infrared light for the laser machining (wavelength: 1064 nm) and reflects the visible green light (wavelength: 532 nm), for the deformation measurement, allowing at the same time machining and deformation measurements. Laser pulses with a power density higher than 109 W/cm^2 are used for the ablation of material, in order to obtain such density a laser beam of a few nanoseconds pulse length is focused by a lens on the sample surface. Complex structures are machined by using a spatial light modulator (SLM), where a given light distribution is produced by writing a phase/amplitude pattern (computer generated hologram) on the SLM. The release of residual stresses by the laser machining system produces 3D deformations that are measured by the system based on digital holography shown in the bottom part of fig. 1. Light from a laser is divided into two beams by the beam splitter BS, one is coupled into a single mode optical fibre and serves as the reference beam and the other one is further divided into four beams illuminating the object sequentially from four different directions. The phase of the object scattered wave changes as a function of the deformation and by processing holograms recorded from different illumination directions it is possible to measure the 3D deformation around the machined surface.

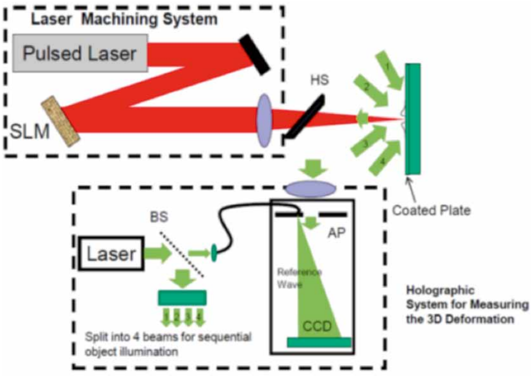


Fig. 1: *Setup for laser machining and measurement of the 3D object deformation by digital holography. SLM: Spatial Light Modulator, HS: harmonic separator; BS: Beam splitter; AP: Aperture.*

The SLM based system was used for machining structures with different shape and depth on the coated surface. Figure 2.a shows a milled horizontal bar obtained after 64000 laser pulses, the depth of the machined structure is 130 µm. Figures 2. b–g shows the wrapped phase and the corresponding 3D deformations produced by the milling. By incremental loading structures (bars, crosses, rings) having different depth are produced and the resulting 3D deformations are measured. The residual stresses at different depth of the coating are calculated from the deformations together with the profile (shape, depth) of the machined surface and the material parameters. The coating used for the investigations shown in fig. 2 had a thickness of 70 µm, at this depth the residual stress was –250 MPa.

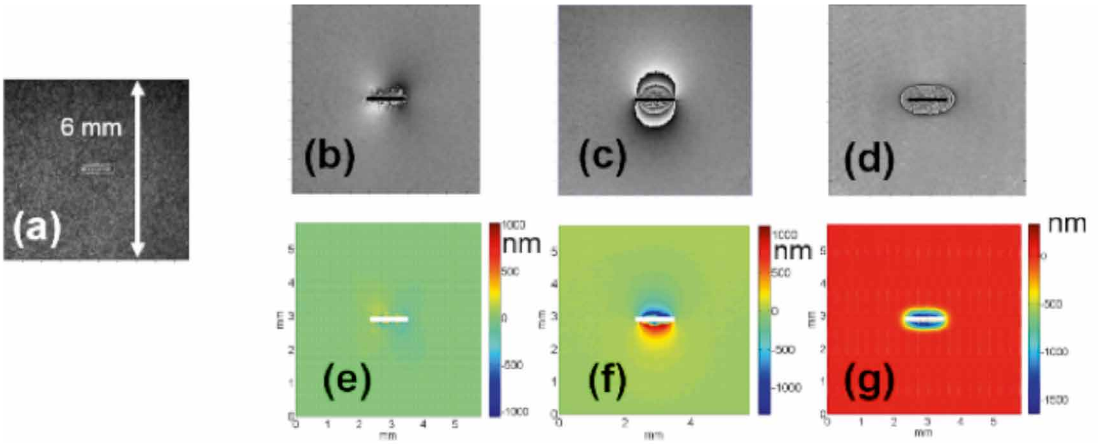


Fig. 2: *Image of the bar shaped machined structure after 64000 laser pulses (a). Phase modulo 2π (wrapped phases) and calculated displacements along the x (b, e), y (c, f) and z (d, g).*

Supported by: DFG German Science Foundation
Project: Ermittlung von Eigenspannungen in beschichteten Oberflächen (OS 111/37-1)
In cooperation with: "Institut für Fertigungstechnologie Keramischer Bauteile" and "Institut für Materialprüfung, Werkstoffkunde und Festigkeitslehre".

References:

[1] Pedrini, G.; Martínez-García, V.; Weidmann, P.; Wenzelburger, M.; Killinger, A.; Weber, U.; Schmauder, S.; Gadow, R.; Osten, W. "Residual stress analysis of ceramic coating by laser ablation and digital holography", submitted for publication in "Experimental Mechanics".

3D single shot deformation measurements by using a remote controlled system

A. K. Singh, A. Prakash, G. Pedrini, W. Osten

Deformation can be attributed to the change in the shape of an object in presence of load, heat, gravity etc. The measurement of deformation at micro and macro level is equally important for various applications. Many techniques have been proposed for the same in past but NDT techniques have an edge over others mechanical techniques, and are applicable for measuring the nano-metric changes in the surface. Also, the non-destructive measurement techniques are applicable to biological samples, which could be useful for bio-medical studies. The deformation in a surface can be divided into two components (1) in-plane and (2) out of plane. For years Holography is providing a fitting solution for measuring the out-of-plane deformation by calculating the phase difference but measuring in-plane deformation is another challenge. Interferometric techniques were proposed to measure the same, based on multidimensional measurements. Such methods either need multiple references which makes the setup quite complicated or required to record multiple holograms in a sequential way from different directions. Such methods could make the measurements quite slow and are prone to errors.

The change in phase due to the change in path length is an inherent property of holography, which makes the out-of-plane deformations measurement quite easy and can be done using a single illumination beam. The intensity information in such experiments are usually a waste product. We propose a setup using single illumination beam to measure full-field deformation. For such measurement system we will utilize the phase as well as intensity information. The schematic diagram is shown in fig. 1. The holographic interferometric technique is employed for measuring the out of plane movements and the in-plane deformation are measured using the correlation of intensity distribution before and after the deformation. The proposed setup can be used for sub nano-metric deformation measurements.

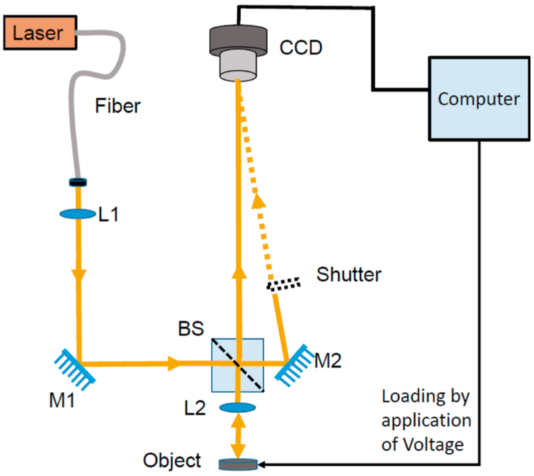


Fig. 1: *The schematic diagram of the setup for deformation measurement.*

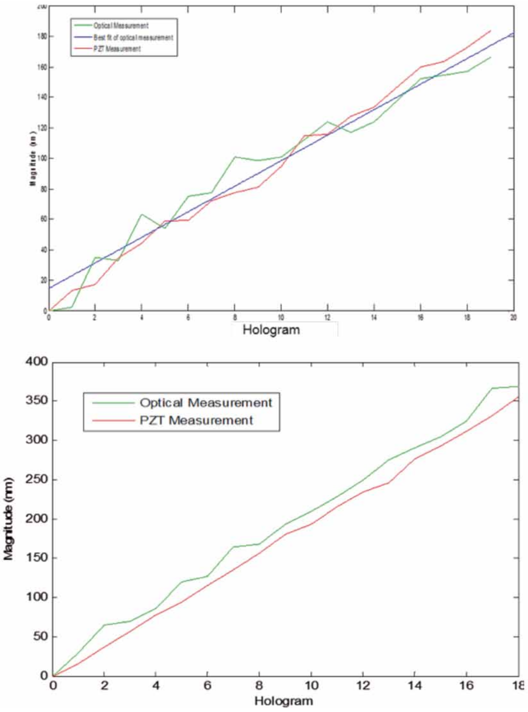


Fig. 2: *Deformation measurement; (a) in-plane measurement with a resolution of 10 nm was achieved with the help of subpixel interpolation. Red, green and blue curves in the plot are showing the PZT measurement, the optical measurement and the best fit to the experimental data, respectively, (b) out-of-plane deformation, red and blue color curves are showing PZT measurement and the optical measurement, respectively. The PZT measurements were obtained with the help of a feedback loop.*

An off-axis holographic setup was arranged and a He-Ne laser was used for illumination. The beam outgoing from the laser is coupled into a single mode fibre and the output beam is collected by the lens L1 and further reflected by the mirror M1 towards the beam splitter BS, which splits the incoming beam into two parts, the reflected beam passes through the lens L2 (f=4.7 mm) and illuminates the sample. In order to illuminate the sample with a parallel beam, the lens L1 is adjusted to produce a converging beam focusing in the back focal plane of L2. The light reflected by the sample is collected again by L2 which images the sample surface on the CCD sensor with a magnification of 48x. A reference beam obtained from the light transmitted by the BS is superimposed on the beam scattered by the object surface. There is an angle of few degrees between these two waves and thus their interference forms an off-axis hologram, which is recorded by the CCD. The image sensor used in the setup was a PCO Pixelfly with dynamic range 12 bit, 1392×1024 pixels and pixel size 6.45×6.45 μm^2. A shutter was inserted in the setup to block the reference wave, the setup without reference was used to obtain the in-plane deformation. The setup was calibrated using a PZT nano positioner system from Physik Instrumente, with a resolution of 2 nm and a repeatability <10 nm. The setup can be remotely controlled via internet and was utilized to measure the out-of-plane and in-plane deformations of MEMS structures. The calibration measurements for in-plane and out of plane deformations are shown in fig. 2(a) and (b), respectively.

Supported by: German Science Foundation (DFG) and the Sino German Center
Project: Remote Laboratory for Optical Micro Metrology (DFG-OS111/39-1 and GZ 760)
In cooperation with the University of Shenzhen

References:

[1] Osten, W.; Faridian, A.; Gao, P.; Körner, K.; Naik, D.; Pedrini, G.; Singh, A. K.; Takeda, M.; Wilke, M., "Recent advances in digital holography", Applied Optics 53 (2014) pp G44-G63.

Looking Through a Diffusing Medium and Around a Corner

A. K. Singh, D. N. Naik, G. Pedrini, M. Takeda, W. Osten

Is there a way to see an object obscured by a strong diffuser such as a transmissive ground glass or an opaque plate with a reflectively scattering surface? Such a question has long been addressed in the context of inverse scattering problems, and a technique has been known that can detect a 2-D periodic grating structure hidden by a diffuser. Recently a technique of ultrafast time-of-flight 3-D imaging that can look around the corner using diffusely reflected light was demonstrated. Also SLM-based technique that compensates the random phase and permit imaging a 3-D object through a diffuser have been reported. The applications of such technique ranges from medical imaging through turbid medium or cell to rescue operations in hazardous condition.

We propose two different techniques for the imaging of 3D object obscured by a diffuser or hidden around a corner. We interpret that the obscuration of the object image is due to the loss of phase information caused by the scattering due to the diffuser. Then we note that the clue to the solution is to find an imaging technique that can cope with the loss of phase information. Indeed, holography is the technique that can recover phase information that is lost by intensity recording in conventional photography. Intensity correlation is another way to reconstruct the object as the mutual intensity of the diffracted field. The reconstruction scheme of the Intensity correlation involves the fourth order correlation of the optical field.

Though our approach based on holography is functionally more restrictive than time-of-flight 3-D imaging, but is much simpler and requires no special equipment such as a femtosecond laser and a high-speed streak camera. We use a reference beam for holography, just as a reference point source used for the SLM-based random phase compensation. Our techniques can be realized easily by the combination of a common CW laser and a conventional camera and does not even require a SLM and the iterative search of the phase distribution that compensates the random phase introduced by the diffuser. The schematic diagram of the setup and the reconstructed object through a scatterer are shown in fig. 1(a) and (b) respectively.

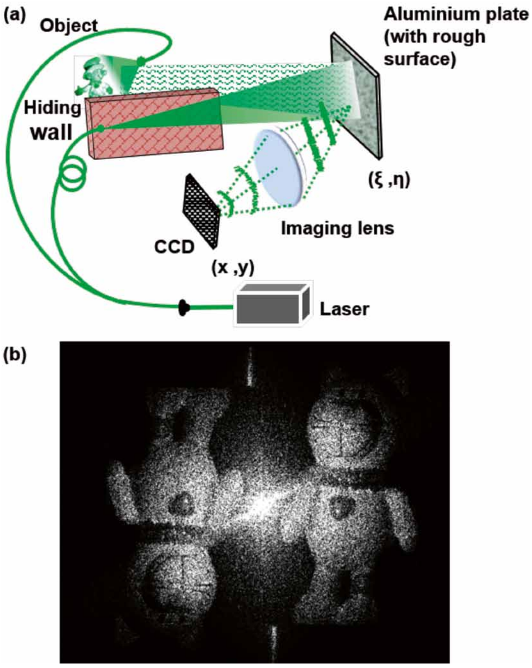


Fig. 1: *(a) Reflection mode schematic of the holographic setup, (b) reconstructed object.*

We proposed another technique which is based on intensity correlation for imaging through the diffusing medium and around the corner. The schematic diagram of the setup is shown in fig. 2(a). The object and the reference point source are kept in the same plane in front of the diffuser in a way that they satisfy the condition of isoplanatism, which states that the light from two point sources, lying within the range of memory effect, after propagating through a diffusing media will produce shifted but correlated speckle patterns. Thus the light from the object and the reference produce similar speckle patterns. The image sensor which is kept on the other side of the diffuser records the scattered light as speckle pattern. To reconstruct the object we performed the averaging operation over the speckle pattern by using spatial averaging by means of auto correlation of the intensity distribution. Thus the proposed technique is a single shot, Lensless and real-time imaging technique. By virtue of limited depth of field optical sectioning and the 3D reconstruction is also possible.

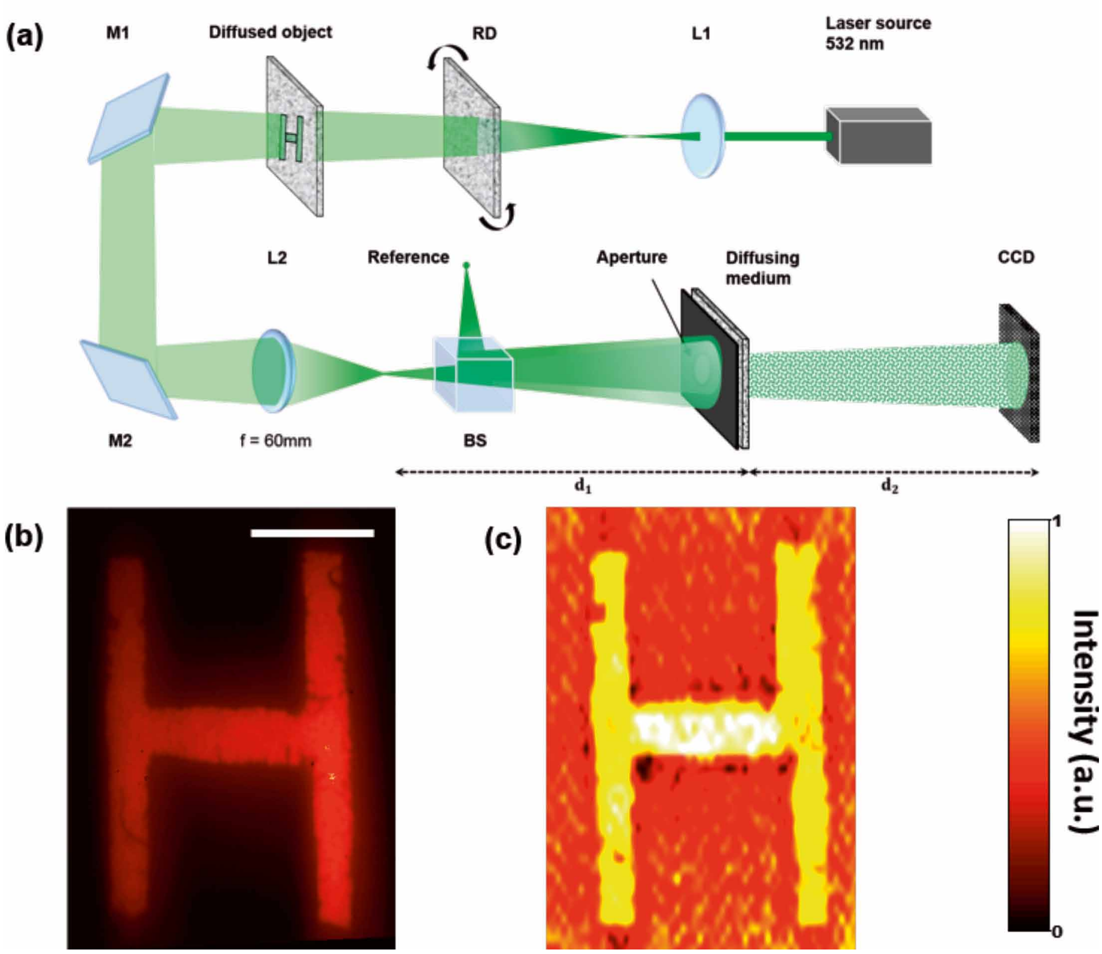


Fig. 2: *(a) The schematic diagram of the setup to image through the diffusing medium using intensity correlation method, (b) the 2 mm long and 3 mm wide letter 'H' was pasted on a thin diffuser and was used as object, (c) the reconstructed object through the diffusing medium. L1 is a converging lens which is used here as beam expander, RD is the rotating diffuser to destroy the spatial coherence of the laser beam, L2 is the imaging leans, BS is the beam splitter, d1 and d2 are the distances between the object pane and the diffusing sample and CCD and the sample, respectively. The scale bar in (b) is 1.5 mm.*

Supported by: Alexander von Humboldt foundation for D. Naik and M. Takeda

References:

[1] Singh, A. K.; Naik, D. N.; Pedrini, G.; Takeda, M.; Osten, W. "Looking through a diffuser and around an opaque surface", Opt. Exp, 22, 7694-7701 (2014).

[2] Osten, W.; Faridian, A.; Gao, P.; Körner, K.; Naik, D. N.; Pedrini, G.; Singh, A. K.; Takeda, M.; Wilke, M. "Recent advances in digital holography", Applied Optics 53 (2014) pp G44-G63.

Data Compression for the Transmission of Digital Holograms

M. Wilke, G. Pedrini, W. Osten

This project investigates the application of data compression techniques to digital holography. Advances in computational power and the decreasing pixel pitch of high-end cameras are moving real-time capable, digital holography into the realm of near future feasibility. Physical limitations impose large detectors with small pixels, resulting in very large images (typically 12 Mega-Pixels at 10 bit depth). Holographic video has been proposed. These large sets of data suggest the use of compression techniques to reduce the storage size or transmission bandwidth required in applications like holographic remote laboratories. However, while they are recorded on the same hardware (CCD or CMOS detectors) as natural images, holograms differ significantly from these. Holograms store information about both the amplitude, as in a normal image, and the phase in interference fringes. This difference requires a reevaluation of the standard compression techniques before they can be applied to holograms.

The holograms used in this investigation are Phase Shifting (PSI) holograms. It has been shown, that a JPEG2000 style compression scheme works best in the plane of reconstruction. To account for this, the algorithm being developed in this project applies a Fresnel transformation and separates the phase and amplitude for independent processing (fig. 1). The results of the statistical analysis have shown that the statistics of the wavelet coefficients for the amplitude of the reconstructed wavefront in the object plane show a distinct two-component behavior. One component, with the coefficient distributed Gaussian, represents the speckle field, while the other, with an approximately Laplacian distribution, correspond to the macroscopic shape of the object (fig. 2). The wavelet coefficients for the phase are Gaussian distributed, although the distribution is very noisy. This noise is the result of numerical instabilities in calculating the phase for amplitudes close to zero. We have shown that the noise can be suppressed using a mask based on the amplitude of the wavefront. These results indicate, that standard compression algorithms can be applied successfully to Fresnel propagated and wavelet analyzed PSI holograms, especially to the amplitude coefficients which are Laplace distributed. The results also indicate that a separation of the wavefront into a speckle field and a remainder representing the macroscopic shape would be advantageous.

Current work is aimed at designing a compression algorithm based on these results. An efficient filter separating the speckle field from the rest of the hologram based on a max-likelihood algorithm is being implemented. New quality measures are under investigation to define a hologram-optimized rate distortion theory for Fresnel propagated and wavelet analyzed complex-valued wavefronts to be used in a rate allocation algorithm and a corresponding compression algorithm.

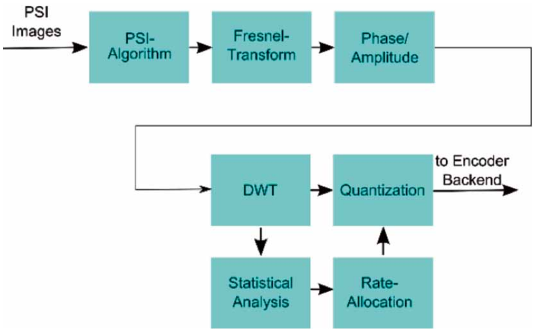


Fig. 1: *Encoding Process.*

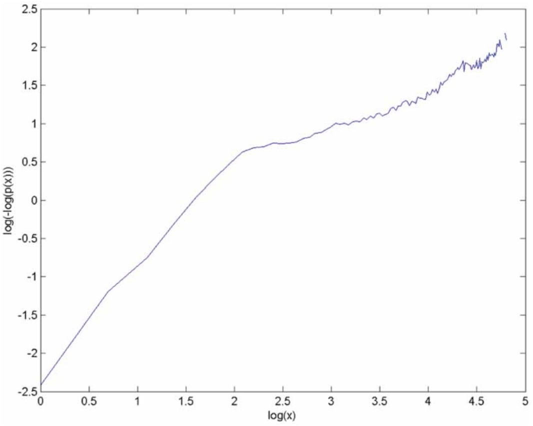


Fig. 2: *Histogram of the intensity wavelet coefficients in logarithmic scale.*

References:

[1] Proc. SPIE 8499, Applications of Digital Image Processing XXXV, 849904 (15 October 2012); doi: 10.1117/12.929745.

[1] Osten, W.; Faridian, A.; Gao, P.; Körner, K.; Naik, D.; Pedrini, G.; Singh, A.; Takeda, M.; Wilke, M. "Recent advances in digital holography [Invited]", Appl. Opt. 53, G44-G63 (2014).

Optical Design and Simulation

Optical design and simulation: An overview of the status and current activities of the group

A. Herkommer

In 2011 the endowed chair for "Optical Design and Simulation" was established at the ITO and I had the great honour to be selected for this position. After four years of continuous work I would like to look back and give a short overview about the status of the group, as well as current topics in teaching and research. However before that I need to express my deepest appreciation to all of my sponsors for making this possible.

The group currently consists of a total of four PhD students, only one of them being financed by the university, while the rest is funded via national research projects or stipends. In addition, two more PhD-thesis are currently being supervised and supported in cooperation with companies.

Most of my teaching is situated within the very successful medical engineering programs (BSc and MSc) at the University of Stuttgart, which were established in cooperation with the University of Tübingen in 2010. In this program an "Introduction to Optics" is a mandatory part of the study and the students can later specialize on optical systems in medicine. Within the specialization field I offer courses as: "Optical Instruments", "Introduction and Advanced Optical Design", "Illumination Systems" and "Development of Optical Systems". Those courses tend to be very successful in attracting students and in consequence more than 20 BSc-thesis have already been supervised by my group, with an increasing tendency. My teaching is accompanied by engagement in various academic committees of this program. In addition to the medical engineering program in 2013 we successfully established a master program in photonic engineering within the Stuttgart Research Center SCoPE. Here I serve as a dean of studies and also participate in teaching.

The research in my group aligns well with the other ITO research groups and a lively exchange and good cooperation between all groups is established. The core competency of the group is classical optical design, design methods and optical simulations based on ray and wave-optical principles. We have access to most commercial software codes as ZEMAX, CodeV, ASAP or VirtualLab, however in parallel improve and employ our own ray-tracing code MacroSim. The more specific research directions can be classified into the following main three areas, where in each area we also refer to one major publication:

- **Complex Optical Surfaces**
  Within modern optical systems there is a clear tendency to increase surface complexity, e.g. in form of freeform surfaces or diffractive surfaces. We try to support this by developing methods, tools and novel design types, which are able to use the advantages of such components [1].
- **New Design / Simulation Methods**
  Novel components (such as freeform) or novel light sources (as LED) require adequate ways to find design forms for optimized imaging and illumination performance. We believe that phase space methods are a good and novel access to modern imaging and illumination designs, as well as computational imaging systems [2].
- **Hybrid / Holistic optical systems**
  Another tendency in today's optical systems, especially for medical applications, is to combine many different modalities into one optical system (e.g. multispectral, multi-channel). Also often more than one simulation technique is required to predict the performance of the system. We therefore try to combine modalities and simulation methods within optical systems [3].

All above research topics are presented at national as well as international conferences and the work is starting to be recognized by the optical community. In consequence the number of invited or key-note presentations is increasing and scientific cooperation is more and more established. Moreover we employ our methods in various industry cooperation projects.

Overall I am quite happy which what has been achieved, however challenges remain, especially in getting the required funding for future activities.

So in other words: After four years I feel like I have arrived at the ITO and in academic research.

References:

[1] Herkommer, A. M. "Advances in the design of freeform systems for imaging and illumination applications", Journal of Optics 43 (4), 261, (2014).

[2] Herkommer, A. M. "Phase space optics: an alternate approach to freeform optical systems", Optical Engineering 53 (3), 031304 (2014).

[3] Thiele, S.; Seifert, A.; Herkommer, A. M. "Wave-optical design of a combined refractive-diffractive varifocal lens", Optics Express 22 (11), 13343, (2014).

Wave-optical design of hybrid diffractive-refractive varifocal lenses

S. Thiele, A. Herkommer

As a part of the Baden-Württemberg Stiftung project "Hybride optische Technologien für die Sensorik", this work aims at the development of a miniaturized zoom system which combines both, imaging and tomography. In this joint research project our project partner IMTEK (University of Freiburg) is improving and developing microoptical components, while the work at the ITO is focused onto the optical system design.

One aspect of our joint work is the aberration correction for tunable membrane lenses used in the endoscopic zoom system. These devices consist of a PDMS membrane which is deflected by internal fluid pressure, forming a tunable refractive surface. Due to boundary effects, the membranes do not exhibit a perfectly spherical shape, but regions close to the fixture of the membrane lead to significant spherical aberration. In order to avoid the penalty of stopping down the aperture one possibility is to correct for spherical aberration directly on the membrane. Spherical aberration as well as chromatic aberration can be corrected simultaneously by using a diffractive optical element (DOE). To achieve the most integrated solution, the DOE is designed to be imprinted directly onto the membrane of the refractive tunable lens (fig. 1).

The pressure induced effect of the hybrid membrane lenses was simulated with a finite-element package and cross-checked with experimental results. As preliminary investigations showed, the projected shape of the DOE (period and height) can be assumed to be constant over a reasonable tuning range of the lenses [1]. In order to find a phase element which simultaneously corrects for spherical as well as chromatic aberration and includes diffraction efficiencies, a wave-optical approach was necessary. To avoid relying on the thin element approximation, a direct integration algorithm using the scalar Fresnel-Huygens diffraction integral was implemented. By utilizing axial symmetry, the problem was reduced to 2D, significantly speeding up the calculations. To find an optimum solution, a genetic algorithm was used, solving for the DOE parameters to achieve the best possible correction of spherical and chromatic aberration over a certain tuning range.

The results show that imprinted phase structures can significantly improve the performance of varifocal membrane lenses. Both, spherical and chromatic aberrations were considerably reduced. The resulting diffractive profiles can be fabricated by standard methods such as direct laser writing or grey tone lithography, combined with a casting process.

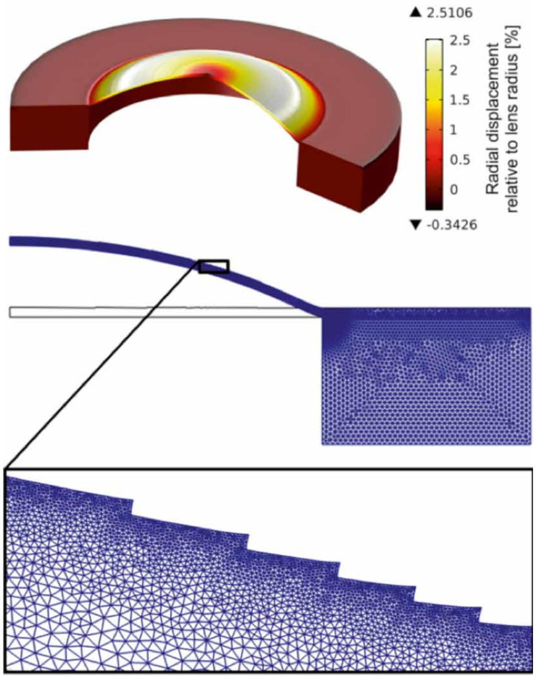


Fig. 1: *Mechanical FEM model of the elastic membrane, deflected by a positive pressure.*

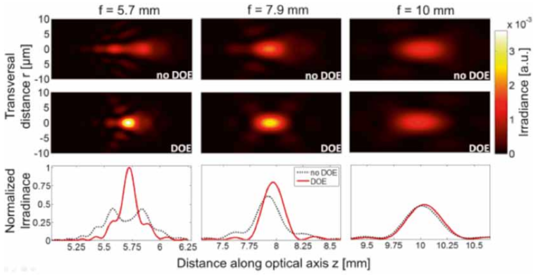


Fig. 2: *2D cross sections through the focal spot for different focal lengths and corresponding line scans along the optical axis.*

Supported by: Baden-Württemberg Stiftung
Project: Hyazint
Cooperation: Gisela-und-Erwin-Sick-Lehrstuhl für Mikrooptik, Institut für Mikrosystemtechnik (IMTEK), University of Freiburg

References:

[1] Thiele, S.; Seifert, A.; Herkommer, A. M. "Wave-optical design of a combined refractive-diffractive varifocal lens", Optics Express 22 (11), pp. 13343-13350 (June 2014).

Design of TIR collimators for LED lighting

T. Talpur, A. Herkommer

Most light sources used in our everyday life employ one or the other form of collimation optics. With ever-increasing efficiency and output flux of LED light sources, the collimator design is vitally important to completely utilize the light output along with increasing the light quality in terms of homogeneity, colour temperature, and colour rendering.

Total internal reflection (TIR) collimators are most widely used due to their high efficiency and low losses. The general criteria for TIR collimator design include efficiency, dimensions, output homogeneity, beam shaping, light mixing, and so on. Various design methods have been developed such as tailoring method [1], mapping and feedback method [2], optimization method [3], and simultaneous multiple surface (SMS) method [4]. The different design methods allow improved control of one or the other parameter, therefore, selection of the design method is crucial in achieving the desired performance. Therefore it is our goal within this project to investigate, implement and test various design methods for TIR-reflectors:

Numerical optimization of the surfaces is possible, but subject to slow or no convergence, due to the large number of free parameters and the statistical nature of the non-sequential ray tracing. Therefore, an efficient design process needs more accurate methods requiring less or no optimization. The point source mapping methods allows designing the collimator quickly along with a good control of the output field pattern. The performance, however, drops as extended sources are implemented. The performance for extended sources can be regained with either optimization algorithms or routines for multiple iterative design with feedback. The simultaneous multiple surface (SMS) method, on the other hand, incorporates the source extension and the shape of multiple surfaces iteratively. Typically either edge rays or a number of points are used, resulting in high-performance extended-source designs. The final SMS designs require no or minimum optimization.

The collimator designs with SMS method and mapping method are shown in fig. 1 and the corresponding outputs are depicted in fig. 2. The SMS method provides good beam control. It simultaneously designs multiple curves, making the curves interdependent, which allows little control over individual curve shapes. The mapping methods, despite lower beam control, allows better grip over the curve shapes, which is very beneficial in validity the preliminary idea and fulfilling the collimator dimensional requirements.

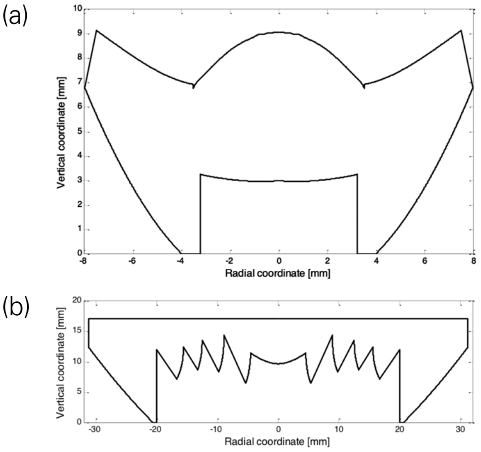


Fig. 1: *Collimator design via (a) SMS method and (b) mapping method.*

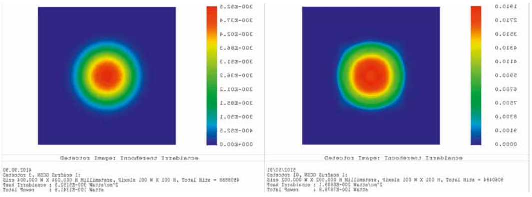


Fig. 2: *Collimator output for (a) SMS design and (b) mapping design.*

Supported by: AIF, Fö. KF 2281403DF3.
Project: Entwicklung eines energieeffizienten Operationsleuchtensystems mit intelligenter Lichtverteilung.
In cooperation with SIMEON Medical Tuttlingen

References:

[1] Winston, R.; Ries, H. "Nonimaging reflectors as functionals of the desired irradiance", J. Opt. Soc. Am. A, Vol. 10 No. 9 pp. 1902–1908 (1993).

[2] Parkyn, W. a. "The design of illumination lenses via extrinsic differential geometry", in Proc. SPIE, 1998, Vol. 3428 No. July pp. 154–162.

[3] Kudaev, S.; Schreiber, P. "Automated optimization of non-imaging optics for luminaries", in Proc. SPIE 2005 Vol. 5962 p. 59620B–59620B–9.

[4] Miñano, J. C.; González, J. C. "New method of design of non-imaging concentrators", Appl. Opt. Vol. 31 No. 16 pp. 3051–3060 (1992).

Phase space methods for imaging and illumination design

D. Rausch, B. Chen, A. Herkommer

In the last few years, the demand for high performance optical systems with a high accuracy increased for a lot of different industrial application fields like medical science, automotive technologies or high efficiency solar concentrators. Therefore, the need of more complex optical designs forces the designer to follow new paths.

An effective method to evaluate the performance of an optical system is to use the concept of phase space. Especially, in the design of complex surfaces for imaging and non-imaging applications, phase space provides a new access:

For illumination systems it is important to have access to the relevant illumination quantities like irradiance, radiance, etendue and energy to check the performance of the optical system. These quantities can directly be derived from the radiance distribution in phase space. Also the propagation of this distribution can be studied for a detailed understanding of the illumination functionality [1].

To investigate the phase space distribution directly by an experiment we use the concept of a light field analyzer. If a one dimensional line-like light distribution is propagated through special optical elements like several prisms lying upon another or a quadrupole lens, the resulting irradiance on a detector surface directly shows the phase space distribution of this input beam. Figure 1 illustrates a simulated phase space distribution of a one dimensional input beam generated by a line grating and propagated through a quadrupole lens. The concept of this phase space analyzer should now be verified experimentally and possibly expanded to more dimensions.

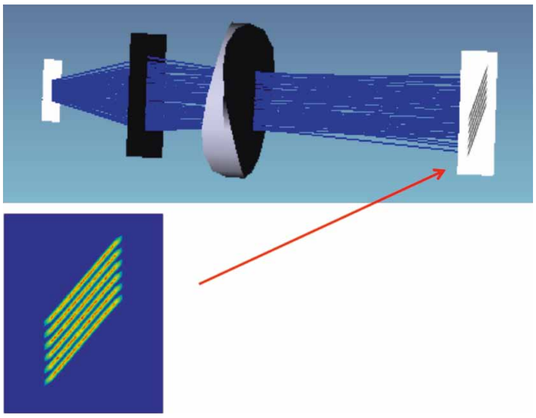


Fig. 1: *Phase space distribution on the detector surface of a line-like input beam generated by a line grating, simulated with the Design Software Zemax.*

For imaging optical systems the phase space distribution is able to reveal detailed information about the aberration characteristics and individual surface aberration contributions [2]. Since the concept of phase space does not reley on rotational symmetry this approch is especially usefull in calculating and visualizing the aberrations of so-called freeform-systems [3]. Figure 2 illustrates a freeform prism element used for Head-Mounted-Displays. The lower part of the Figure illustrates the phase space deformations as a color code, allwing to gain access to individual aberrations.

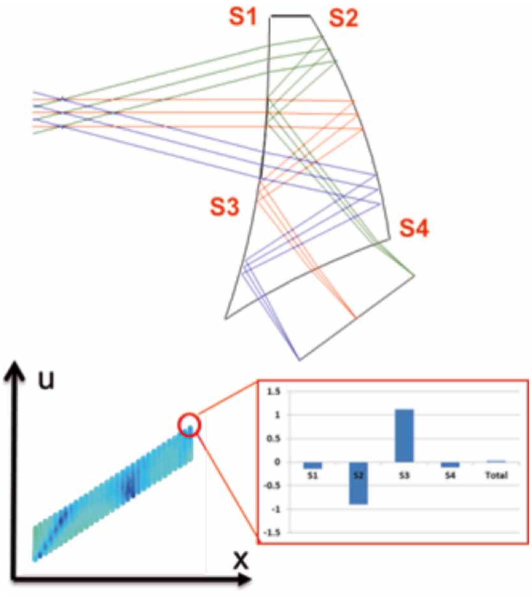


Fig. 2: *Phase space distribution of a freeform optical system. The colour code indicates the aberration value, which can be decomposed for surface contributions*

References:

[1] Rausch, D.; Herkommer, A. M. "Phase space approach to the use of integrator rods and optical arrays in illumination systems", AOT Vol.1 (2012).

[2] Herkommer, A. M. "Phase space optics: an alternate approach to freeform optical systems", Opt. Eng. 53(3) (2013) 508-510, Elsevier 2005.

[3] Herkommer, A. M. "Advances in the design of freeform systems for imaging and illumination applications", Journal of Optics 43 (4), 261-268.

Invited lectures on international conferences

W. Osten

Making, Testing, Applying –
Some Progress in the Field of Microoptics

ICOPEN 2013, International Conference on Optics in Precision Engineering and Nanotechnology Singapore, April 09–12,2013

G. Pedrini

Interferometrical techniques for the investigation of dynamic events

ICOPEN 2013, International Conference on Optics in Precision Engineering and Nanotechnology, Singapore, April 09–12, 2013

D. Naik, W. Osten

Unconventional Digital Holography

Conference: Digital Holography & 3-D Imaging 2013, Kohala Coast, Hawaii, USA, April 21–25, 2013

W. Osten

Remote Laboratories for Optical Metrology: From the Lab to the Cloud

WPI, Worcester, USA, April, 2013

A. Herkommer

Freeform Surfaces: Engineering standard or still exception to the rule?

EOS Manufacturing of Optical Components, Munich, Germany, May 15, 2013

C. Pruss, W. Osten

Das Prinzip der verkippten Wellenfronten: Vorteile und Herausforderungen für die Asphärenmesstechnik

114. DGAO Tagung, Braunschweig, May 21-25, 2013

W. Osten

Optical Metrology: From the Laboratory to the Real World

OSA Conference "Applied Industrial Optics: Spectroscopy, Imaging, and Metrology (AIO)", Arlington, USA, June 23–27, 2013

K. Gastinger, W. Osten

Finding the Needle in the Haystack – Approaches for Detecting Small Defects on a Large Object

OSA Conference "Applied Industrial Optics: Spectroscopy, Imaging, and Metrology (AIO)", Arlington, USA, June 23–27, 2013

L. Fu, K. Frenner, W. Osten

Light scattering from rough surfaces and rigorous speckle simulation

CO'13 – 11th International Conference on Correlation Optics, Chernivtsy, Ukraine, September 18-21, 2013

W. Osten

How to transfer the advantages of optical metrology from the laboratory to the factory floor?

2nd Intern. Conf. "Optical Techniques and Nano-Tools for Materials and Life Sciences ONT4MLS, Dresden, September 30 – October 2, 2013

W. Osten

What Optics can do for the Inspection of Micro and Nano Component?

MEMUNITY MEMS Testing and Metrology Workshop 2013, Dresden, October 9, 2013

W. Osten

Optical Metrology: From Lab to Fab

Photonex 2013, Coventry, GB, October 17, 2013

G. Pedrini

Phase retrieval techniques for optical metrology

International Conference on Optical Instrument & Technology, Beijing, China, November 17-19, 2013

W. Osten

Unconventional Implementations and Applications of Digital Holograpy

OPTIC 2013, Taoyuan, Taiwan, December, 2013

W. Osten

Optical Metrology: The long but successful way from the Laboratory to the Factory Floor

Optical Society of Korea (OSK) Winter Annual Meeting, Daejon, Korea, February, 2014

W. Osten

Remote Laboratories: Prospects for the Embedding of Experimental Facilities in a Cloud Computing Environment

Forum Osaka Univ., Nara, Japan, March, 2013

D. Naik, W. Osten:

Progress in Digital Holography: New Implementations and Applications

International conference on Optics & Opto-electronics (ICOL-2014), Dehradun (India), March 05-08, 2014

A. Herkommer

Advances in the design of freeform systems for imaging and illumination applications

International Conference on Optics and Optoelec-tronics, March 6, 2014, Dehradun, India

K. Frenner:

Scatterometry-based CD-Metrology

METROMEET 2014;10th International Conference on Industrial Dimensional Metrology; Bilbao (Spain), March, 27, 2014

J. Schindler, G. Baer, C. Pruss, W. Osten:

The tilted-wave-interferometer: free-form surface reconstruction in a non-null setup

International Symposium on Optoelectronic, Technology and Application 2014 (IPT2014), Beijing, China, May, 13–15, 2014

W. Osten, F. Schaal:

Optical Nondestructive Testing: From the laboratory to the Factory Floor

ICCES, Changwon, South Korea, June 12–17, 2014

C. Pruss, G. Baer, J. Schindler, W. Osten:

Flexibility and Rapid Measurement: Asphere and Freeform Metrology with Tilted Wave Interferometry

OSA Optical Fabrication and Testing, Kohala Coast, United States, June 22–24,2014

G. Pedrini:

Phase retrieval methods for optical imaging and metrology

Workshop on Information Optics, Neuchatel, Switzerland, July 7–11, 2014

W. Osten

Remote Laboratories: A Challenge for Digital Holography and Modern Metrology

OSA Conference ”Digital Holography and 3D Imaging”, Seattle, USA, July 13–17, 2014

W. Osten

What Optical Metrology can do for Non-Destructive Testing and Experimental Stress Analysis?

Univ. Florianopolis SPIE Chapter, Florianopolis, Brazil, September, 2014

A. Herkommer:

The Lagrange Invariant- a bridge between imaging and illumination design

EOS Conference on Advanced Manufacturing, September, 17, 2014, Berlin, Germany

G. Pedrini:

Phase retrieval for optical metrology

SPIE.COS, Photonics Asia, Beijing, China, October 9–11, 2014

F. Schaal, T. Haist, C. Pruss, W. Osten:

Applications of diffractive optical elements for optical measurement techniques

SPIE COS Photonics Asia, Beijing China, October 9–11, 2014

W. Osten

Different Approaches to overcome existing Limits in Optical Micro and Nano Metrology

The International Conference on Photonics and Optical Engineering and the Annual West China Photonics Conference 2014, Xian, China, October 13–15, 2014

W. Osten

What Optical Metrology can do for the Inspection of Micro and Nano Components?

Experimental Mechanics (SEM) Fall Conference, Peking, China, October 31, 2014

W. Osten

Remote Labs for Optical Metrology: From the Lab to the Cloud

LAOP 2014, Cancun, Mexico, November, 2014

W. Osten

Different Approaches to overcome existing Limits in Optical Micro and Nano Metrology

LAOP 2014, Cancun, Mexico, November, 2014

Editorial work

W. Osten (Ed.)

Fringe 2013 – 7th International Workshop on Advanced Optical Imaging and Metrology

Springer, Heidelberg 2013

Lehmann, P., Osten, W.; Albertazzi, A. (Eds.):

Optical Measurement Systems for Industrial Inspection VIII. Part 1 & Part 2

Proc. SPIE Vol. 8788, Bellingham 2013

Gorecki, C.; Asundi, A.; Osten, W. (Eds.):

Optical Micro- and Nanometrology V

Proc. SPIE Vol. 9132, Bellingham 2014

Osten, W. (Ed.):

Special Issue on Advances in Optical Imaging and Metrology-Selected Papers from the Conference Fringe 2013

Int. Journal of Optomechatronics, 8 (2014) 3–4, pp. 229-399, Taylor & Francis 2014

Kim, M.; Cheng, C.-J.; Kim, J.; Osten, W.; Picart, P.; Yoshikawa, H. (Eds.):

Special Issue on Digital Holography and 3D Imaging

Applied Optics 53 (2014) 27

Awards

W. Osten

Honorary Professor of the Shenzhen University, China, 2014

W. Osten:

Fellow of the Optical Society OSA, 2014

W. Osten:

Fellow of the Society for Experimental Mechanics SEM, 2014

A. M. Herkommer:

Winner of the International Optical Design Contest ”Illumination Design” at the IODC Conference 2014 in Hawaii

G. Pedrini:

Honorary Associate Professor of the Shenzhen University, China, 2014

G. Baer, C. Pruss, and J. Schindler (ITO) and J. Siepmann, and M. Lotz (Mahr GmbH, Jena)

Winner of the AMA Innovation Award 2014, Nuremberg, 2014

Membership of Advisory Boards

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Director of SPIE 2015-2017

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Steering Comm. Member of the Conference "Laser – World of Photonics"

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"Holography and Speckle"

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Member of the Editorial board of the Journal
"Optica Applicata"

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Member of the Editorial board/Topical Editor of the Journal "3D Research"

W. Osten

Associate Editor of the Journal
"IEEE Transactions on Industrial Informatics"

G. Pedrini

Topical Editor of the Journal
"Applied optics"

Reviewed papers, books and book chapters

2013

Alexeenko, I.; Vandenrijt, J.F.; Pedrini, G.; Thizy, C.; Vollheim, B.; Osten, W.; Georges, Marc P.

Nondestructive testing by using long-wave infrared interferometric techniques with CO_2 lasers and microbolometer arrays

Applied Optics 52 (2013) 1 pp. A56-A67

Almoro, P.; Pedrini, G.; Osten, W.; Narayanamurthy, C. S.

Analysis of Bessel beam propagation in free space using digital holographic microscopy

Optik 124 (2013) 14 pp. 1882-1885

Baer, G.; Schindler, J.;Pruss, C.; Osten, W.

Correction of misalignment introduced aberration in non-null test measurements of free-form surfaces

Journal of the European Optical Society - Rapid publications JEOS:RP 8 (2013) pp. 13074

Faridian, A.; Pedrini, G.; Osten, W.

High-contrast multilayer imaging of biological organisms through dark-field digital refocusing

Journal of Biomedical Optics 18 (2013) 8 pp. 086009

Fleischle, D.; Lyda, W.; Gronle, M.; Mauch, F.; Körner, K.; Osten, W.

Herausforderungen und Lösungsansätze für die fertigungsnahe Qualitätskontrolle mittels optischer 3D-Messtechnik

Technisches Messen 80 (2013) 1 pp. 3-8

Gao, P.; Pedrini, G.; Osten, W.

Structured illumination for resolution enhancement and autofocusing in digital holographic microscopy

Optics Letters 38 (2013) 8 pp. 1328-1330

Gao, P.; Pedrini, G.; Osten, W.

Phase retrieval with resolution enhancement by using structured illumination

Optics Letters 38 (2013) 24 pp. 5204-5207

Haist, T., Lingel, C., Osten, W., Winter, M., Giesen, M., Ritter, F., Sandfort, K., Rembe, C., Bendel, K.

Multipoint vibrometry with dynamic and static holograms

Review of Scientific Instruments 84 (2013) 121701

Joenathan, C.; Bernal, A.; Pedrini, G.; Osten, W.

Radial shear interferometer with holographic lenses coupled with a spatial Fourier transform method suitable for static and dynamic measurements

Optical Engineering 52 (2013) 3 pp. 035603

Li, A.; Peng, X.; Yin, Y.; Liu, X.; Zhao, Q.; Körner, K.; Osten, W.

Fringe projection based quantitative 3D microscopy

Optik - International Journal for Light and Electron Optics 124 (2013) 21 pp. 5052-5056

Lingel, C.; Haist, T.; Osten, W.

Optimizing the diffraction efficiency of SLM-based holography with respect to the fringing field effect

Applied Optics 52 (2013) 28 pp. 6877-6883

Ma, J. ; Yuan, C.; Situ, G.; Pedrini, G.; Osten, W.

Resolution enhancement in digital holographic microscopy with structured illumination

Chinese Optics Letters 11 (2013) 9 pp. 090901

Mauch, F.; Gronle, M.; Lyda, W.; Osten, W.

Open-source graphics processing unit–accelerated ray tracer for optical simulation

Optical Engineering 52 (2013) 5 pp. 053004

Naik, D. N. ; Pedrini, G.; Osten, W.

Recording of incoherent-object hologram as complex spatial coherence function using Sagnac radial shearing interferometer and a Pockels cell

Optics Express 21 (2013) 4 pp. 3990-3996

Osten, W.; Wilke, M.; Pedrini, G.

Remote laboratories for optical metrology: from the lab to the cloud

Optical Engineering 52 (2013) 10 pp. 101914

Peterhänsel, S.; Pruss, C.; Osten, W.

Phase errors in high line density CGH used for aspheric testing: beyond scalar approximation

Optics Express 21 (2013) 10 pp. 11638-11651

Pehnelt, S.; Dollinger P.; Osten, W.; Seewig, J

Topografiebeurteilung von Zylinderlaufbahnen

MTZ - Motortechnische Zeitschrift 04 (2013) pp. 320-325

Ruppel, T.; Dong, S.; Rooms, F.; Osten, W.; Sawodny, O.

Feedforward Control of Deformable Membrane Mirrors for Adaptive Optics

IEEE Transactions on Control Systems Technology 21 (2013) 3 pp. 579-589

Singh, R. K.; Naik, D. N.; Itou, H.; Brundabanam, Maruthi M.; Miyamoto, Y.; Takeda, M.

Vectorial van Cittert-Zernike theorem based on spatial averaging: experimental demonstrations

Optics Letters 38 (2013) 22 pp. 4809-4812

Takeda, M.

Spatial stationarity of statistical optical fields for coherence holography and photon correlation holography

Optics Letters 38 (2013) 17 pp. 3452-3455

Tiziani, Hans J. ; Pedrini, G.

From speckle pattern photography to digital holographic interferometry

Applied Optics 52 (2013) 1 pp. 30-44

Vandenrijt, Jean-Francois; Thizy, C.; Alexeenko, I.; Pedrini, G.; Rochet, J.; Vollheim, B.; Jorge, I.; Venegas, P.; Lopez, I.; Osten, W.; Georges, M. P.

Mobile speckle interferometer in the long-wave infrared for aeronautical nondestructive testing in field conditions

Optical Engineering 52 (2013) 10 pp. 101903

Zhang, Y.; Situ, G.; Pedrini, G.; Wang, D.; Javidi, B.; Osten, W.

Application of short-coherence lensless Fourier-transform digital holography in imaging through diffusive medium

Optics Communications 286 (2013) pp. 56-59

2014

Anand, A.; Faridian, A.; Chhaniwal, V. K.; ; Mahajan, S.; Trivedi, V.; Dubey, S.K.; Pedrini, G.; Osten, W.; Javidi, B.

Single beam Fourier transform digital holographic quantitative phase microscopy

Applied Physics Letters 104 (2014) Article Number: 103705

Baer, G.; Schindler, J.; Pruss, C.; Siepmann, J.; Osten, W.

Fast and Flexible Non-Null Testing of Aspheres and Free-Form Surfaces with the Tilted-Wave-Interferometer

International Journal of Optomechatronics 8 (2014) 4 pp. 242-250

Baer, G.; Schindler, J.; Pruss, C.; Siepmann, J.; Osten, W.

Calibration of a non-null test interferometer for the measurement of aspheres and free-form surfaces

Optics Express 22 (2014) 25 pp. 31200-31211

Faridian, A.; Pedrini, G.; Osten, W.

Opposed-view dark-field digital holographic microscopy

Biomedical Optics Express 5 (2014) 3 pp. 728-736

Fortmeier, I.; Stavridis, M.; Wiegmann, A.; Schulz, M.; Osten, W.; Elster, C.

Analytical Jacobian and its application to tilted-wave interferometry

Optics Express 22 (2014) 18, pp. 21313-21325

Fu, Y.; Pedrini, G.; Li, X.

Interferometric Dynamic Measurement: Techniques Based on High-Speed Imaging or a Single Photodetector

Scientific World Journal (2014) Article Number: 232906

Fu, L.; Frenner, K; Osten, W.

Rigorous speckle simulation using surface integral equations and higher order boundary element method

Optics Letters 39 (2014) 14 pp. 4104-4107

Georges, M. P.; Vandenrijt, J-F; Thizy, C.; Alexeenko, I.; Pedrini, G.; Vollheim, B.; Lopez J.; Jorge I.; Rochet, J.; Osten W.

Combined holography and thermography in a single sensor through image-plane holography at thermal infrared wavelengths

Optics Express 22 (2014) pp. 25517-25529

Gao, P; Pedrini, G; Zuo, C.; Osten. W.

Phase retrieval using spatially modulated illumination

Optics Letters 39 (2014) pp. 3615-3618

Gronle, M.; Lyda, W.; Wilke, M.; Kohler, C.; Osten, W.

itom: an open source metrology, automation, and data evaluation software

Applied Optics 53 (2014) 14 pp. 2974-2982

Haist, T.; Gronle, M.; Bui, D.A.; Osten W.

Holografische Mehrpunktgenerierung zur Positionsanalyse

Technisches Messen 82 (2014) 5 pp. 273-279

Haist, T.; Dong, S.; Arnold, T.; Gronle, M.; Osten, W.

Multi-image position detection

Optics Express 22 (2014) 12 pp. 14450-14463

Haist, T.; Hasler, M.; Osten, W.; Baranek, M.

Programmable Microscopy

In: Javidi, B., Tajahuerce, E., Andrés, P. (Eds.): Multi-Dimensional Imaging. WILEY (2014), pp. 153-173

Haist, T.; Lingel, C.; Adler, R.; Osten, W.

Parallelized genetic optimization of spatial light modulator addressing for diffractive applications

Applied Optics 53 (2014) 7 pp. 1413-1418

Haist, T.; Gronle, M.; Arnold, T.; Bui, D.A.

Verbesserung von Positionsbestimmungen mittels holografischer Mehrpunktgenerierung

Forum Bildverarbeitung - KIT Scientific Publishing (2014) pp. 239

Herkommer, A. M.

Advances in the design of freeform systems for imaging and illumination applications

Journal of Optics 43 (2014) 4 pp. 261-268

Herkommer, A. M.

Phase space optics: an alternate approach to freeform optical systems

Optical Engineering 53 (2014) 3 pp. 031304-031304

Keck, A.; Böhm, M.; Knierim, K.L.; Sawodny, O.; Gronle, M.; Lyda, W.; Osten, W.

Multisensorisches Messsystem zur dreidimensionalen Inspektion technischer Oberflächen

Technisches Messen 81 (2014) 6 pp. 280-288

Li, X.; Pedrini, G.; Fu, Y.

Optical Metrology under Extreme Conditions

Scientific World Journal (2014) Article Number: 263603

Mauch, F.; Osten, W.

Model-based approach for planning and evaluation of confocal measurements of rough surfaces

Meas. Sci. Technol. 25 (2014) pp. 105002

Naik, D.; Pedrini, G.; Takeda, M.; Osten, W.

Spectrally resolved incoherent holography: 3D spatial and spectral imaging using a Mach-Zehnder radial-shearing interferometer

Optics Letters 39 (2014) 7 pp. 1857-1860

Osten, W.; Faridian, A.; Gao, P.; Körner, K.; Naik, D.; Pedrini, G.; Singh, AK; Takeda, M.; Wilke, M.

Recent advances in digital holography [Invited]

Applied Optics 53 (2014) 27 pp. G44-G63

Peterhänsel, S.; Pruss, C.; Osten, W.

Limits of diffractometric reconstruction of line gratings when using scalar diffraction theory

Optics Letters 39 (2014) 13 pp. 3764-3766

Peterhänsel, S.; Laamanen, H.; Kuittinen, M.; Turunen, J.; Pruss, C.; Osten, W.; Tervo, J.

Solving the inverse grating problem with the naked eye

Optics Letters 39 (2014) 12 pp. 3547-3550

Singh, A. K.; Faridian, A.; Gao, P.; Pedrini, G; Osten, W.

Quantitative phase imaging using a deep UV LED source

Optics Letters 39 (2014) 12 pp. 3468-3471

Singh, A. K.; Naik, D.; Pedrini, G.; Takeda, M. Osten, W.

Looking through a diffuser and around an opaque surface: A holographic approach

Optics Express 22 (2014) 7 pp. 7694-7701

Stumpe, J.; Sakhno, O.; Gritsai, Y.; Rosenhauer, R.; Fischer, Th.; Rutloh, M.; Schaal, F.; Weidenfeld, S.; Jetter, M.; Michler, P.; Pruss, C.; Osten, W.

Active and Passive LC Based Polarization Elements

Molecular Crystals and Liquid Crystals 594 (2014) 1 pp. 140-149

Thiele, S.; Seifert, A.; Herkommer, A.

Wave-optical design of a combined refractive-diffractive varifocal lens

Optics Express 22 (2014) 11 pp. 13343-13350

Conference proceedings and journals

2013

Baer, G.; Schindler, J.; Pruss, C.; Osten, W.

Comparison of alignment errors in asphere metrology between an interferometric null-test measurement and a non-null measurement with the tilted-wave-interferometer

Proc. SPIE 8884 (2013) pp. 88840T – Optifab 2013

Baer, G.; Schindler, J.; Pruss, C.; Osten, W.

Measurement of Aspheres and Free-Form Surfaces with the Tilted-Wave-Interferometer

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 87–96

Baer, G.; Schindler, J.; Siepmann, J.; Pruss, C.; Osten, W.; Schulz, M.

Measurement of aspheres and free-form surfaces in a non-null test interferometer: reconstruction of high-frequency errors

Proc. SPIE 8788 (2013) pp. 878818
Optical Measurement Systems for Industrial Inspection VIII

Boettcher, T.; Lyda, W.; Gronle, M.; Mauch, F.; Osten, W.

Robust signal evaluation for Chromatic Confocal Spectral Interferometry

Proc. SPIE 8788 (2013) pp. 87880W
Optical Measurement Systems for Industrial Inspection VIII

Faridian, A.; Pedrini, G.; Osten, W.

Contrast Enhancement in 3D Microscopic Imaging of Microorganisms Immersed in a Liquid Medium

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 595–598

Faridian, A.; Pedrini, G.; Osten, W.

Opposed View Digital Holographic Microscopy

Proc. DGaO 114. Tagung (2013) B 23

Ferreras Paz, V.; Frenner, K.; Osten, W.

Increasing Scatterometric Sensitivity by Simulation Based Optimization of Structure Design

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 345-348

Ferreras Paz, V.; Frenner, K.; Osten, W.

Simulation based optimization of scatterometric signatures by designed near field structures

Proc. SPIE 8789 (2013) pp. 87890S
Modeling Aspects in Optical Metrology

Fu, L.; Frenner, K.; Osten, W.

Rigorous Speckle Simulation Using Surface Integral Equations and Boundary Element Methods

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 361–364

Fortmeier, I.; Stavridis, M.; Wiegmann, A.; Schulz, M.; Baer, G.; Pruss, C.; Osten, W.; Elster, C.

Sensitivity analysis of tilted-wave interferometer asphere measurements using virtual experiments

Proc. SPIE 8789 (2013) pp. 878907
Modeling Aspects in Optical Metrology IV

Fortmeier, I.; Stavridis, M.; Wiegmann, A.; Schulz, M.; Baer, G.; Pruss, C.; Osten, W., Elster, C.

Results of a Sensitivity Analysis for the Tilted-Wave Interferometer

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 701–706

Gao, P.; Pedrini, G.; Osten, W.

Phase Retrieval with Resolution Enhancement by Using Random-Phase Illumination

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 369–372

Gao, P.; Pedrini, G.; Osten, W.

Resolution enhancement and autofocusing in digital holographic microscopy by using structured illumination

Proc. SPIE 8788 (2013) pp. 878809
Optical Measurement Systems for Industrial Inspection VIII

Gastinger, K.; Osten, W.

Finding the Needle in the Haystack - Approaches for Detecting Small Defects on a Large Object

Proc. OSA Conference "Applied Industrial Optics: Spectroscopy, Imaging, and Metrology (AIO)", Arlington, USA, June 2013, AIO-2013-ATu2B.1.pdf

Gronle, M.; Lyda, W.; Osten, W.

Automated Multi-sensor Inspection of 3D Objects

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 711–714

Gronle, M.; Lyda, W.; Osten, W.

Model-based, active inspection of three-dimensional objects using a multi-sensor measurement system

Proc. SPIE 8788 (2013) pp. 87880Y
Optical Measurement Systems for Industrial Inspection VIII

Gronle, M.; Kohler, C.; Wilke, M.; Lyda, W.; Bieger, H.; Osten, W.

itom – An Open Source Measurement, Automation and Evaluation Software Suite

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 957–964

Haist, T.; Lingel, C.; Osten, W.; Bendel, K.; Giesen, M.; Gartner, M.; Rembe, C.

Characterization and demonstration of a 12-channel Laser-Doppler vibrometer

Proc. SPIE 8788 (2013) pp. 87881V
Optical Measurement System for Industrial Inspection VIII

Hasler, M.; Haist, T.; Osten, W.

Programmable Microscopy

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 365–368

Herkommer A. M.; Rausch D.

Phase space transformations-a different way to understand freeform optical systems

OSA Topical on Freeform Optics (2013), FT2B. 5.

Mauch, F.; Lyda, W.; Osten, W.

Model-based assistance system for confocal measurement of rough surfaces

Proc. SPIE 8788 (2013) pp. 87880U
Optical Measurement Systems for Industrial Inspection VIII

Mauch, F.; Lyda, W.; Osten, W.

Object Depending Measurement Uncertainty of Confocal Sensors

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 465–470

Morawitz, M.; Hein, N.; Alexeenko, I.; Wilke, M.; Pedrini, G.; Krekel, C.; Osten, W.

Detection of transport and age induced damages on artwork: an advanced concept

Proc. SPIE 8790 (2013) pp. 879004
Optics for Arts, Architecture, and Archaeology IV

Morawitz, M.; Hein, N.; Alexeenko, I.; Wilke, M.; Pedrini, G.; Krekel, C.; Osten, W.

Optical Methods for the Assessment of Transport and Age Induced Defects of Artwork

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 951–956

Naik, D. N.; Pedrini, G.; Osten, W.

Digital holography for recording of incoherent-object hologram as complex spatial coherence function

Proc. SPIE 8776 (2013) pp. 87760B
Holography: Advances and Modern Trends III

Naik, D.; Pedrini, G.; Takeda, M.; Osten, W.

Recording of 3D Spatial and Spectral Information of Self-luminous Objects Using a Mach-Zehnder Radial Shearing Interferometer

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 715–720

Osten, W.; Baer, G.; Häfner, M.; Lyda, W.; Pruss, C.; Reichle, R.; Schaal, F.

Making, testing, applying: some progress in the field of micro-optics at ITO

Proc. SPIE 8769 (2013) pp. 876905 – International Conference on Optics in Precision Engineering and Nanotechnology

Osten, W.

Optical Metrology:
From the Laboratory to the Real World.

Proc. OSA Conference "Applied Industrial Optics: Spectroscopy, Imaging, and Metrology (AIO)", Arlington, USA, June 2013, AIO-2013-JW2B.4.pdf

Partanen, H.; Peterhänsel, S.; Pruss, C.; Osten, W., Tervo, J.; Turunen, J.

Broad Area Laser Diode Coherence Measurement and Modeling

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 879–882

Pedrini, G.; Alexeenko, I.; Osten, W.

Interferometrical techniques for the investigations of dynamic events

Proc. SPIE 8769 (2013) pp. 876915 – International Conference on Optics in Precision Engineering and Nanotechnology

Peterhänsel, S.; Pruss, C.; Osten, W.

An Inverse Measurement Strategy to Determine Phase Errors Introduced by Rigorous Effects in CGH

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 355–360

Peterhänsel, S.; Pruss, C.; Osten, W.

Studying fabrication induced phase errors in CGHs using RCWA

Proc. DGaO 114. Tagung (2013) B 4

Pruss, C.; Osten, W.

Das Prinzip der verkippten Wellenfronten: Vorteile und Herausforderungen für die Asphärenmesstechnik

Proc. DGaO 114. Tagung (2013) H 2

Rausch, D.; Herkommer, A.

Illumination Optics in Phase Space

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 373–376

Schaal, F.; Pruss, C.; Osten, W.

Objektivintegrierter differentieller Interferenzkontrast

Proc. DGaO 114. Tagung (2013) B 28

Schau, P.; Brandes, A.; Frenner, K.; Kienle, A.; Osten, W.

Structured white-light illumination for diagnostic investigations

Proc. SPIE 8792 (2013) pp. 879208 – Optical Methods for Inspection, Characterization, and Imaging of Biomaterials

Schindler, J.; Baer, G.; Pruss, C.; Osten, W.

Freiformmessungen an einem Tilted-Wave-Interferometer

Proc. DGaO 114. Tagung (2013) A 10

Schindler, J.; Baer, G.; Pruss, C.; Osten, W.

Estimating the Accuracy of Different Parametric Freeform Surface Descriptions

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 349–354

Singh, A.; Naik, D.; Pedrini, G.; Takeda, M.; Osten, W.

Holographic Imaging of a 3D Object Hidden behind a Diffuser or around a Corner

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 377–384

Thiele, S.; Blattmann, M.; Zappe, H.; Seifert, A.; Herkommer, A. M.

Design of a Hybrid Miniaturized Zoom Imaging System

In: Fringe 2013, Proceedings of the 7th International Workshop on Advanced Optical Imaging and Metrology (2013) pp. 947-950

Thiele, S.; Herkommer, A. M.

Aberrationskorrektur bei durchstimmbaren Membranlinsen mittels Mikrostrukturierung der Membran

Proc. DGaO 114. Tagung (2013) P 31

Tornari, V.; Pedrini, G.; Osten, W.

Remote photonic metrology in the conservation of cultural heritage

Proc. SPIE 8790 (2013) pp. 87901H
Optics for Arts, Architecture, and Archaeology IV

2014

Bielke, A.; Pruss, C.; Osten, W.

Variables Interferometer-Objektiv für die Messung von Asphären und Freiformflächen

Proc. DGaO 115. Tagung (2014) A 23

Boettcher, T.; Gronle, M.; Mauch, F.; Osten, W.

A more robust and flexible approach to laterally chromatically dispersed, spectrally encoded interferometry (LCSI)

Proc. SPIE 9132 (2014) pp. 913211
Optical Micro- and Nanometrology V

Dong, S.; Haist, T.; Dietrich, T.; Osten, W.

Hybrid curvature and modal wavefront sensor

Proc. SPIE 9227 (2014) pp. 922702
Unconventional Imaging and Wavefront Sensing 2014

Faridian, A.; Pedrini, G.; Osten, W.

High-contrast 3D microscopic imaging of deep layers in a biological medium

Proc. SPIE 8949 (2014) pp. 89490H
Three-Dimensional and Multidimensional Microscopy: Image Acquisition and Processing XXI

Geiger; F. B.; Koerdel, M.; Schick, A.; Heimann, A.; Matiasek, K.; Herkommer, A. M.

Concept and setup for intraoperative imaging of tumorous tissue via attenuated total reflection spectrosocopy with quantum cascade lasers

SPIE Medical Imaging (2014), 94125F-94125F-13

Georges, M. P.; Vandenrijt, J.-F.; Thizy, C.; Alexeenko, I.; Pedrini, G.; Rochet, J.; Vollheim, B.; Jorge, I.; López, I.; Osten, W.

Speckle interferometry at 10 micrometers wavelength: a combined thermography and interferometry technique and its application in aeronautical nondestructive testing

Proc. SPIE 9204 (2014) pp. 92040F
Interferometry XVII: Advanced Applications

Haist, T..; Dong, S.; Arnold, T.; Osten, W.

CGH-basierte Verbesserung der Messunsicherheit von Positionsbestimmungen mittels pixelierten Bildaufnehmern

Proc. DGaO 115. Tagung (2014) B 35

Herkommer, A. M.; Yang, H.

Tackling freeform aberrations by ray-mapping analysis

International Optical Design Conference (2014), 92930K-92930K-5

Krauter, J.; Boettcher, T.; Lyda, W.; Osten, W.; Passilly, N.; Froehly, L.; Bargiel, S.; Albero, J.; Perrin, S.; Lullin, J.; Gorecki, C.

Optical design of a vertically integrated array-type Mirau-based OCT system

Proc. SPIE 9132 (2014) pp. 91320L
Optical Micro- and Nanometrology V

Lingel, C.; Hasler, M.; Haist, T.; Pedrini, G.; Osten, W.

A benchmark system for the evaluation of selected phase retrieval methods

Proc. SPIE 9132 (2014) pp. 91320R
Optical Micro- and Nanometrology V

Mauch, F.; Gronle, M.; Osten, W

GPU-accelerated ray tracing for optical simulation and design

in: Classical Optics 2014, OSA Technical Digest (online) (Optical Society of America, 2014), paper IW1A.4.

Osten, W.

Remote Laboratories: A Challenge for Digital Holography and Modern Metrology

Proc. OSA Conference "Digital Holography and 3D Imaging", Seattle, USA, July 2014, DH-2014-DTu3B.1.pdf

Pedrini, G.; Faridian, A.; Singh, A. K.; Osten, W.

Phase retrieval for optical metrology

Proc. SPIE 9276 (2014) pp. 927602 – Optical Metrology and Inspection for Industrial Applications III

Rausch, D.; Herkommer, A. M.

Phase space imaging in optical design

Proc. SPIE 9193 (2014), Novel Optical Systems Design and Optimization XVII, 919305 – doi: 10.1117/12.2061763

Schaal, F.; Haist, T.; Peter, A.; Beeck, A.; Pruss, C.; Osten, W.

Applications of diffractive optical elements for optical measurement techniques

Proc. SPIE 9271 (2014) pp. 927105
Holography, Diffractive Optics, and Applications VI

Schaal, F.; Rutloh, M.; Weidenfeld, S.; Stumpe, J.; Osten, W.

Tunable non-pixelated spatial polarization shaping including an integrated optical addressing unit

Proc. SPIE 9181 (2014) pp. 91810H
Light Manipulating Organic Materials and Devices

Schindler, J.; Baer, G.; Pruss, C.; Osten, W.

Modellierung von Wellenfront-Aberrationen: Fitfehler und Retrace-Fehler

Proc. DGaO 115. Tagung (2014) A 10

Schindler, J.; Baer, G.; Pruss, C.; Osten, W.

The tilted-wave-interferometer: freeform surface reconstruction in a non-null setup

Proc. SPIE 9297 (2014) pp. 92971R – International Symposium on Optoelectronic Technology and Application 2014: Laser and Optical Measurement Technology; and Fiber Optic Sensors

Singh, A. K.; Naik, D. N.; Pedrini, G.; Takeda, M.; Osten, W.

Looking around an opaque surface and through a diffused media: a holographic approach

Proc. DGaO 115. Tagung (2014) B 37

Singh, A. K.; Naik, D. N.; Pedrini, G.; Takeda, M.; Osten, W.

Looking around the corner and through a diffuser: different approaches

Proc. OSA Conference "Digital Holography and 3-D Imaging", Seattle, USA, July (2014) DTu3B.3.pdf

Thiele, S.; Herkommer, A. M.

Wave optical optimization of a high NA fiber tip TIR lens

Optical Fabrication and Testing (2014), JTu5A. 14

Patents

Patent Applications

Körner, Klaus; Herkommer, Alois; Osten, Wolfgang

Verfahren und Anordnung, insbesondere auch zur bildgebenden Fourier-Transformations-Spektroskopie im mobilen Einsatz; Method and arrangement, in particular also for imaging Fourier Transformation spectroscopy in mobile use

WO 2014067651 A1
Date of publication: 08.05.2014

Körner, Klaus; Herkommer, Alois; Osten, Wolfgang

Verfahren und Anordnung zur FT-Spektroskopie, insbesondere auch zur bildgebenden Strahlungsquellen- und Stoff-Analyse sowie Tumorgewebe-Diagnostik

DE 102012023248 A1
Date of publication: 30.04.2014

Körner, Klaus; Osten, Wolfgang; Pedrini, Giancarlo; Pruss, Christof

Method and arrangement for short coherence holography

GB 2505106 A
Date of publication: 19.02.2014

Körner, Klaus; Osten, Wolfgang; Pedrini, Giancarlo; Pruss, Christof

Method and arrangement for short coherence holography

US 20140022553 A1
Date of publication: 23.01.2014

Granted Patents

Baer, Goran; Osten, Wolfgang

Justage einer zu prüfenden optischen Fläche in einer Prüfvorrichtung; Adjustment of an optical surface to be tested in a test device

EP 2525188 B1
Date of publication: 20.08.2014
Assignee: Baden-Württemberg Stiftung GmbH

Bilski, Bartosz Jan; Frenner, Karsten; Osten, Wolfgang

Inspection method and apparatus, lithographic apparatus, lithographic processing cell and device manufacturing method

US 8804123 B2
Date of publication: 12.08.2014
Assignee: ASML Netherlands BV, NL

Körner, Klaus; Berger, Reinhard; Osten, Wolfgang

Verfahren und Anordnung zur robusten Interferometrie; Method and assembly for robust interferometry

EP 2526373 B1
Date of publication: 11.12.2013

Körner, Klaus; Osten, Wolfgang

Method and apparatus for interferometry

US8605289B2
Date of publication: 10.12.2013

Körner, Klaus; Osten, Wolfgang,

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

DE 102010046907 B4
Date of publication: 31.01.2013

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

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

DE 102006007172 B4
Date of publication: 17.01.2013

Doctoral thesis, Diploma thesis, Master & Bachelor thesis and Student research thesis

Doctoral thesis 2013–2014

Fleischle, David

Konzepte und Implementierung für die prozessnahe Integration optischer Sensoren

07/2013

Lyda, Wolfram

Sensorkommunikation in multiskaligen Messsystemen

08/2013

Burla, Avinash

Assistant Systems for Multiscale Sensor Fusion Technologies in Automated Optical Surface Inspection

11/2014

Häfner, Matthias

Neue Technologien zur Fertigung computergenerierter Hologramme mittels Laserdirektbelichtung

oral examination: 10/2014

Diploma thesis 2013–2014

Ukalovic, Dubravka

Tiefenaufgelöste Fluoreszenzdetektion für die medizinische Diagnostik

09/2013

Jia, Haifei

Herstellung und Charakterisierung plasmonischer Metamaterial-Superlinsen

09/2013

Zhou, Ming

Design und Herstellung von Depolarisatoren mit plasmonischen Metamaterialien

09/2013

Sabbagh, Ahmad

Charakterisierung und Optimierung eines OCT-basierten Formmesssystems

09/2014

Master thesis 2013 – 2014

Lutz, Christian

Wellenfrontanalyse von Fluoreszenzzentren mittels Shearing-Interferometrie für die medizinische Diagnostik

07/2014

Fernholz, Felix

Transmissive Vermessung progressiver Optiken

07/2014

Stahl, Janek

Objektfelderweiterung in SLM-basierter Mikroskopie durch Superposition der Beugungsordnungen

08/2014

Peter, Alexander

Optimierung computergenerierter Hologramme unter Einfluss feldabhängiger Aberrationen

11/2014

Bachelor thesis 2013 – 2014

Weida, Sebastian

Simulation einer neuartigen Sonnenkollektor-Optik

02/2013

Ketata, Montassar

Charakterisierung eines kombinierten CCSI- /CCM-Sensorsystems und Bewertung des Fehlerbudgets beider Verfahren

04/2013

Adler Yanez, Rodolfo Ignacio

Experimentelle Optimierung der Kennlinie dynamischer SLM-basierter Hologramme

05/2013

Schwanke, Oliver

Entwicklung und Realisation eines Vorbelichters für die Grautonlithographie

07/2013

Joas, Sebastian

Design einer Bertrand-Optik für ein Mikroskopiesystem

09/2013

Vöhringer, Sandra

Evaluation of a PET-based motion correction method for examinations of cerebral metabolic mechanisms in awake small animals

09/2013

Faulhaber, Andreas

Design und Konstruktion einer Vollfeld-Laserbeleuchtung für die Mikroskopie

10/2013

Reichert, Carsten

Beleuchtungsdesign und Streulichtanalyse eines miniaturisierten OCT-Sensors zur Frühdiagnose von Hautkrebs

10/2013

Schmitt, Jascha

Optimierte Berechnung computergenerierter Hologramme für die Nulltestprüfung von Freiformflächen

10/2013

Edelmann, Mirjam

Experimentelle Untersuchungen zur dynamischen Raman-Spektroskopie

10/2013

Brodhag, Nicole

Simulation und Optimierung einer korrelationsbasierten Sensorik in der Raman-Spektroskopie

10/2013

Huber, Rebecca

Untersuchung eines Prototypen-Objektivs für ein In-Situ Mikroskop

11/2013

Wempe, Alexander

Variable Fokussierung mit Hilfe diffraktiver optischer Elemente

12/2013

Schmid, Peter

Entwicklung einer TIRF-Mikroskopie-Beleuchtung mit Lichteinkopplung über das Deckglas

01/2014

Paramsothy, Keerthanaa

Signalentstehung und Signalauswertung eines OCT Sensors mit Phasenschiebemethoden

03/2014

Bilazer, Elif

Neue Ansätze zur Laser-Tattoo-Entfernung

04/2014

Libuda, Lars

Herstellung eines optischen Freiform-Elementes mittels Rapid Prototyping für spezifische Beleuchtung

06/2014

Czochracz, Claudia

Prozessgestaltung von Complaint Management am Beispiel Pentero 900

09/2014

Hahn, Robin

Charakterisierung eines OCT-Laboraufbaus

10/2014

Ehret, Mirka

Optisches Design einer mikroskopischen Smartphone-Vorsatzoptik

10/2014

Ramos, Scarlett

Untersuchung von komplexen ATR-Prismengeometrien für MIR-Laser-Spektroskopie

12/2014

Schäfer, Max

Entwicklung eines kostengünstigen multispektralen Abbildungssystems

12/2014

Student research thesis 2013 – 2014

Jiang, Bofan

Verbesserung der Messunsicherheit triangulationsbasierter Messtechniken durch den Einsatz computergenerierter Hologramme

09/2013

Schiele, Philipp

Design eines holografischen Raman-Mikroskops

11/2013

Axthelm, Christoph

Entwicklung eines Bildverarbeitungsalgorithmus zur automatischen Erkennung von Zellen und Zellkernen im Hellfeld-Mikroskopbild

11/2013

Stahl, Janek

Performance-Analyse von Phaseretrieval Algorithmen

11/2013

Dietrich, Tom

Simulation und Analyse eines krümmungsbasierten Wellenfrontsensors

01/2014

Grumbrecht, Mario Till

Erstellung einer prüflingsorientierten Prüfraumbeschreibung eines Tilted Wave Interferometers

01/2014

Grün, Eduard

Modellbasierte Fehleranalyse der chromatisch-konfokalen Spektral-Interferometrie (CCSI)

02/2014

Hertling, Philipp

Integration eines Piezo Walk Linearmotors zur Ansteuerung einer Laserdirektbelichtungsanlage

04/2014

Beeck, Andreas

Optimierung dynamischer computergenerierter Hologramme in Kombination mit hochauflösenden statischen Phasenmasken zur Erweiterung des Rekonstruktionsbereichs

04/2014

Li, Huan

Digitale Holographie von partiell kohärent beleuchteten und selbstleuchtenden Objekten

04/2014

Arnold, Thomas

Korrelationsbasierte Shack-Hartmann Wellenfrontsensorik

04/2014

Putze, Sebastian

Automatisiertes Lohmann-Objektiv: Konstruktion und Erprobung

05/2014

Rotte, Simon

Untersuchung der optischen Eigenschaften von biologischen Geweben

08/2014

Alvarez Echeverri, Santiago

Untersuchung von Dekonvolutionsalgorithmen in der Mikroskopie

10/2014

Fringe 2013

The 7th International Workshop on Advanced Optical Imaging and 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 for the first time 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.

For the Fringe 2009 we decided to stay in this region but to make a slight shift of the conference place from Stuttgart to Nürtingen. Nürtingen – a lovely medieval village – offered everything needed for a good conference: a nice conference hotel, attractive surroundings and a stimulating atmosphere. The topics have undergone a refreshment again: digital wavefront engineering and sensor fusion. Due to the very good experience with the conference place Nürtingen, we decided to organize the 7th Fringe Workshop again in Nürtingen. This brought back a moment of stability but we extended the scope markedly by accentuating the bridge between optical imaging and metrology. While the previous workshops were dedicated to optical metrology, the scope of the Fringe 2013 was extended to include advanced technologies in both disciplines, optical imaging and optical metrology. On the one hand, optical imaging and optical metrology are self-standing topics with a long tradition. On the other hand, the current trends in both disciplines show increasing dynamics stimulated by many fascinating innovations such as high resolution microscopy, 3D imaging and nano-metrology. Consequently, both are getting even younger every day and are stimulating each other more and more. Thus, the main objective of the workshop was to bring experts from both fields together and to bridge between these strongly related and emerging fields. New topics were computational imaging, model-based reconstruction, compressed sensing, solutions to inverse problems, multimodality, in-line performance and remote technologies. This extended scope was honored again by a great response to our call for papers. Leading scientists from all around the world submitted more than 200 papers. The complete record of the presented papers was published again by Springer [1].

The papers are summarized in the very attractive volume under 5 topics:

- New methods and tools for the generation, acquisition, processing, and evaluation of data in optical imaging and metrology,
- Application-driven technologies in optical imaging and metrology,
- High dynamic range solutions in optical imaging and metrology,
- Hybrid technologies in optical imaging and metrology, and
- New optical sensors, imaging and measurement systems.

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[1] W. Osten (Ed.): Fringe 2013 – 7th International Workshop on Advanced Optical Imaging and Metrology. Springer, Heidelberg 2013

As in the former workshops, each topic was introduced by an acknowledged expert who gave an extensive overview of the topic and a report of the state of the art. The organizers and the whole audience appreciated the presentations of Jari Turunen, Jeremy Coupland, Kevin Kelly, Katsura Otaki, Arnold Nicolaus, Miguel Alonso, Jörg Wrachtrup, Olliver Cossairt, Christoph Krekel, and Chris Koliopoulos. Since the early beginning of the Fringe series it has been a good tradition to distinguish deserved scientists with honorary lectures. In 2013 Joseph Goodman was awarded with the honorary lecture while Eugene Arthurs and Thomas Tyc were invited to present the welcome address and the key note, respectively, at the banquet. On occasion of the Fringe 2013 the Hans Steinbichler award was presented for the third time by the deputy ceo of Steinbichler Optotechnik, Manfred Adlhart. The winner of the 2013 award was Ichirou Yamaguchi, an internationally acknowledged expert in speckle metrology and digital holography, for his numerous contributions to the field over many years of active scientific work. For all Fringe workshops a special event is the celebration of a new HoloKnight. The recent Holoknight, Lady Christina of Vigo (Christina Trillo), honored Sir Jim of Arizona (James Wyant) 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 exciting topics as modern optical imaging and metrology.

Looking forward to the FRINGE 2017.

Fig. 1: *International Program Committee and Invited Lecturers of the Fringe 2013*

Optik-Kolloquium 2013

Optics for Space (Optische Technologien zur Erforschung des Weltraums)

am 27. Februar 2013, Teilnehmer: ca. 150

Begrüßung und Einführung	Prof. Dr. W. Osten *ITO, Universität Stuttgart*
Beobachten wie aus dem Weltraum: Adaptive Optik für Sonnen-Teleskope	Prof. Dr. O. von der Lühe *Kiepenheuer-Institut für Sonnenphysik, Freiburg*
Ultrapräzise Metallspiegel mit exzellenter Form und Rauheit für Astronomie und Raumfahrt	Dr. S. Risse *Fraunhofer-Institut für Angewandte Optik und Feinmechanik, Jena*
NIRSpec – Ein IR Spektrometer für das James Webb Teleskop	Dr. W. Holota *Holota Optics, Bad Tölz*
Astronomische Polarimetrie	Prof. Dr. C. U. Keller *Leiden Observatorium, Universität Leiden, Niederlande*
SOFIA - Ein fliegendes Observatorium	Prof. Dr. J. Wagner *Deutsches SOFIA Institut, Universität Stuttgart*
Infrarot-Astronomie mit SOFIA	Dr. B. Stecklum *Thüringer Landessternwarte Tautenburg, Karl-Schwarzschild-Observatorium, Jena*
eROSITA – Eine neue Himmelsdurchmusterung im Röntgenbereich	Dr. P. Predehl *Max-Planck-Institut für extraterrestrische Physik, Garching*
LISA: Laser-Interferometrische Gravitationswellen Weltraum-Antenne	Dr. G. Heinzel *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Inst.), Hannover*
Optische Intersatelliten-Datenübertragung: das Tesat Laser Communication Terminal	Dr. F. Heine, Dr. H. Zech *Tesat-Spacecom GmbH & Co. KG, Backnang*
Polarisations-Scrambler auf Basis von Metamaterialien für Weltraumanwendungen	Ph. Schau *ITO, Universität Stuttgart*
Modale Regelung verformbarer Sekundärspiegel für erdgebundene Teleskope	Dr. T. Ruppel *Corporate Research and Technology, Carl Zeiss AG, Jena*
Wellenfront-Sensorik für die Erfassung hochfrequenter Störungen	S. Dong *ITO, Universität Stuttgart*

Optik-Kolloquium 2014

Optische Technologien für die Medizintechnik

am 27. Februar 2014, Teilnehmer: ca. 180

Begrüßung und Einführung	Prof. Dr. W. Osten und Prof. Dr. A. Herkommer *ITO, Universität Stuttgart*
Das Operationsmikroskop: Historie und Zukunftstrends	Dr. A. Högele *Carl Zeiss Meditec AG, Oberkochen*
Multimodale radiologische Bildgebung in Diagnostik und Therapiemonitoring	Prof. Dr. C. Claussen *Universitätsklinikum Tübingen, Tübingen*
Molekulare Endobildgebung für eine sichere und präzise Tumordiagnose in der Neurochirurgie	Dr. W. Göbel *Karl Storz GmbH & Co. KG, Tuttlingen*
Lichtausbreitung in biologischem Gewebe: modellbasierte Simulation für das Sensordesign	Prof. Dr. A. Kienle *ILM, Universität Ulm*
3D-Bilderfassung und –Darstellung in der modernen medizinischen Endoskopie	A. Hofer *Schölly, Denzlingen*
Dreidimensional messende Endoskopie für die minimal-invasive Chirurgie	Dr. A. Schick *Siemens AG, München*
Mikrofluidische Plattformen zum Nachweis einzelner Moleküle in der patientennahen Diagnostik und der Biologie	Prof. Dr. R. Zengerle *IMTEK, Universität Freiburg*
Biomedizinische Anwendungen optischer Korrelationstechniken: zeitaufgelöste Fluoreszenz- und Speckle-Methoden	Prof. Dr. J. Schreiber *NUGA LAB GmbH, Dresden*
Multimodale ortsaufgelöste Spektroskopie im mikroskopischen Fern- und Nahfeld zur markierungsfreien Charakterisierung von Chromosomen und Geweben	Prof. Dr. R. W. Kessler *Hochschule Reutlingen*
Entwicklungen in der Rastersondenmikroskopie mit biomedizinischen Anwendungen	Prof. Dr. T. Schäffer *Institut für Angewandte Physik, Universität Tübingen*
Mikrooptisches Zoom-System für den Einsatz in endoskopischen Sonden	S. Thiele *ITO, Universität Stuttgart*
Nichtinvasive Messung des Blutzuckerspiegels mittels Puls-Differential-Spektroskopie	F. Schaal *ITO, Universität Stuttgart*

Stuttgart Scientific Symposium 2015 "Light for the future"

dedicated to the 30th Stuttgart Optics Colloquium
and the International Year of Light 2015

am 25. Februar 2015, Teilnehmer: ca. 250

Opening	Prof. Dr. Wolfgang Osten *Institute for Applied Optics (ITO) of the University of Stuttgart*
Welcome address	Prof. Dr. Wolfram Ressel *Rector of the University of Stuttgart*
Welcome address	Ministerialdirigent Günther Leßnerkraus *Abteilungsleiter Industrie, Innovation und wirtschaftsnahe Forschung im Ministerium für Finanzen und Wirtschaft Baden-Württemberg*
"High-performance research infrastructures as basis for economic success in lasers and photonics"	Prof. Dr. Andreas Ostendorf *President WissenschaftlicheGesellschaft für Lasertechnik WLT e.V.*
"Light in SCoPE: Optics research at the University of Stuttgart"	Prof. Dr. Wolfgang Osten *Institute for Applied Optics (ITO) of the University of Stuttgart*
"2015 International Year of Light under UNESCO auspices – celebrating the importance of light and light-based technologies in shaping the society"	Dr. Jean-Paul Ngome Abiaga *International Basic Sciences Programme (IBSP) of UNESCO*
Welcome address "Germany – a country with a bright tradition in optics"	Dr. Frank Höller *President Deutsche Gesellschaft für Angewandte Optik DGaO*
"Light – a bridge between research, industry and society"	Prof. Dr. Edward G. Krubasik *President of the German Physical Society DPG*
Welcome address "Recent highlights of photonics research in Europe"	Prof. Dr. Seppo Honkanen *2015 President of the European Optical Society EOS* Prof. Dr. Jyrki Saarinen *Executive Director at EOS*
"Challenges and trends in the german photonics industry sector"	Prof. Dr. Andreas Tünnermann *Director Fraunhofer Institut für Angewandte Optik und Feinmechanik, Jena, Germany*
"Light as a perspective to strengthen the european economic backbone"	Dr.-Ing. Michael Mertin *President and CEO of JENOPTIK AG and President of Photonics21, Jena, Germany*
"Optics and photonics as the backbone of physics in Europe"	Dr. Luc Berge *European Physical Society EPS – Chair of the Quantum Electronics and Optics Division*

"Selected emerging areas of optics and photonics"	Prof. Dr. Philip Russell *2015 President of the Optical Society OSA and Director at the Max Planck Institute for the Science of Light, Erlangen, Germany*
"Raising awareness of optics and photonics to the general public"	Elizabeth A. Rogan *OSA CEO, Washington DC, USA*
"Society advocacy on behalf of the community: SPIE's view of its growing importance"	Prof. Toyohiko Yatagai *2015 President of International Society for Optics and Photonics SPIE and Director of CORE – The Center for Optical Research and Education, Utsunomiya University, Japan* Dr. Eugene Arthurs *CEO at SPIE, Bellingham, USA*
"Modern teaching in optics at the College of Optical Sciences of the University of Arizona"	Prof. Dr. James C. Wyant *Founding Dean of the College of Optical Sciences, University of Arizona, USA*
"Photonic quantum technology and future applications"	Prof. Dr. Gerd Leuchs *University Erlangen-Nürnberg and Director at the Max Planck Institute for the Science of Light*
"Light sources for EUV lithography"	Dr. Michael von Borstel *CEO of TRUMPF Lasersystems for Semiconductor Manufacturing*
"Building new scientific communities and European cohesion through the world's largest laser research facility"	Prof. Dr. Wolfgang Sandner *Director General and CEO, ELI-DC International Association AISBL, The European Extreme Light Infrastructure ELI*
"Optical and laser engineering at COLE, Singapore"	Prof. Dr. Anand Asundi *Director of COLE – Center for Optical and Laser Engineering, MAE, Nanyang Technological University, Singapore*

Organized international conferences: 2013 – 2014

W. Osten:

SPIE Congress Optical Metrology 2013

May 13 – 16, 2013, Munich, Germany

W. Osten:

SPIE Conference "Optical Measurement Systems for Industrial Inspection VIII"

May 13 – 16, 2013, Munich, Germany

W. Osten:

Fringe 2013 – 7th International Workshop on Advanced Optical Imaging and Metrology

September 8 – 11, 2013, Nürtingen, German

W. Osten:

SPIE Conference "Optical Micro- and Nanometrology V"

April 15 – 17, 2014, Brussels, Belgium

Impressum:

Publisher:	Institut für Technische Optik (ITO) Universität Stuttgart Pfaffenwaldring 9 D – 70569 Stuttgart www.uni-stuttgart.de/ito
Editor:	Dipl.-Ing. (FH) Erich Steinbeißer, ITO ac.Cent werbeagentur gmbh, Leonberg (Layout)
Printing:	Breitschuh & Kock GmbH, Kiel
Print run:	250
	ISBN 978-3-923560-78-3

ISBN 978-3-923560-78-3