Interferometry and Diffractive Optics

Tilted-Wave-Interferometry: Quick and flexible asphere and freeform metrology
Supported by: BMBF
Project: Multiskalige Messtechnikplattform für die Qualitätssicherung optischer Freiformen (FKZ: 13N10854)

A simulation environment for uncertainty estimations of the tilted wave interferometer
Supported by: EMRP (European Metrology Research Programme)
Project: Joint project IND10 “Optical and tactile metrology for absolute form characterization”

Optical design and experimental testing of an interferometric setup with a diffractive zoom-lens
Supported by: BMBF (FKZ 16N12258)
Project: EUV-Projektionsoptik für 14-nm-Auflösung (ETIK)

Fabrication of Diffractive and Micro-Optical Elements

Non-pixelated spatial polarization shaping for tunable phase contrast microscopy
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 Stuttgart), University Potsdam and others

Replication of multilevel diffractive optical elements based on DVD technology
Supported by: BMWi (FKZ KF2281402AB2)
Project: Kosteneffiziente Grautonlithografie für diffraktive Multi-Level Elemente
Partner: Holoeye Photonics AG

Replication of diffractive optical elements on curved surfaces
Supported by: AiF (Vorhaben 18586N)
Project: Hybride optische Low-Cost Elemente für optische Sensoren (HOLEOS)
Partner: Institut für Mikroaufbautechnik der Hahn-Schickard-Gesellschaft für angewandte Forschung e.V.

Limits of diffractometric reconstruction of line gratings when using scalar diffraction theory
Supported by: DFG German Science Foundation
Project: Inverse Source and Inverse Diffraction Problems in Photonics (OS 111/32-1)

NPMM–200
Supported by: DFG Os 111/44-1 Nanopositionier- und Messmaschine
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 al and TWI bl.

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.

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 adaptation to freeforms with a flat base shape and the development of a self-calibrating method.

References:


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 straightforward due to the non-linear 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.

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:
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 reflexes.

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 Zémax. 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:
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 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

References:

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 (68 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: 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.

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 fabrication 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.

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:

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 $\mu$m and hence the assumption for the scalar theory of $\lambda$ being much smaller than the grating period $\Lambda$ 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 $b/\Lambda$ 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 $\Lambda$ between 1 and 10 $\mu$m. Assuming a known grating period the minimum difference between $\mu_{\text{meas}}$ and $\mu_{\text{sca}}$ is searched and the resulting reconstructed parameters are used to calculate the generated phase $\phi_{\text{sca}}$. 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 $\Lambda$ for a grating with $h=500$ nm and $d=0.43$ made of fused silica and illuminated with $\lambda$ of 632.82 nm are pictured in fig. 1.

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

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 $\Delta \phi = \mu_{\text{meas}} - \mu_{\text{sca}}$ defined as the difference between rigorously calculated one and calculated one from the reconstructed values, see.
The phase is divided by $2\pi$, converting radians to the more commonly used waves.

Fig. 2. Comparison of the phase difference $\Delta\phi$ between simulated phase and calculated phase from the scalar reconstructed values for different grating periods: left - 4 $\mu$m, middle - 6 $\mu$m and right - 8 $\mu$m.

Here we can see that for very flat gratings ($h$ smaller 400 nm) the error in phase is in the range of $\pm \lambda/100$. This range is improving slightly as $p$ increases. On the other side, even for $p$ of 8 $\mu$m the phase difference is $3\lambda/100$ 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 $\lambda/100$ 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].

References:

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 11144-1
Nanopositionier- und Messmaschine