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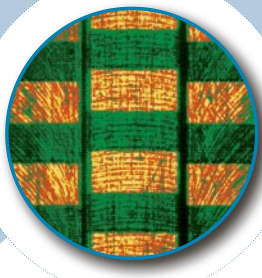
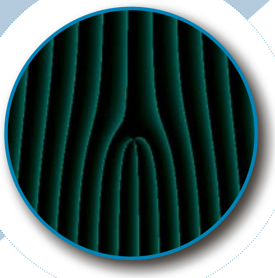
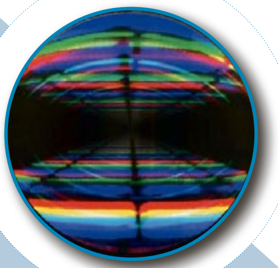
INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART







Universität Stuttgart

3D-Surface Metrology

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

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

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

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

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

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

Chromatic confocal spectral interferometry (CCSI)

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

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

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

The discrepancy of the limited axial-range in previously reported SI-schemes can be visualized as follows. The reference field contains a planar wave front, while the detection wave front acquires a rigorous curvature, when the object lies beyond the depth-of-focus, if aberration effects are neglected. Optical interference between those two fields leads to a reduced contrast of the modulated spectral signal. In the CCSI scheme presented here, the axial-range of the detector is expanded due to the chromatically-dispersed foci (25µm axial range with 0.95 NA were reported [3]) by means of a diffractive optical element – DOE (Fig. 1).

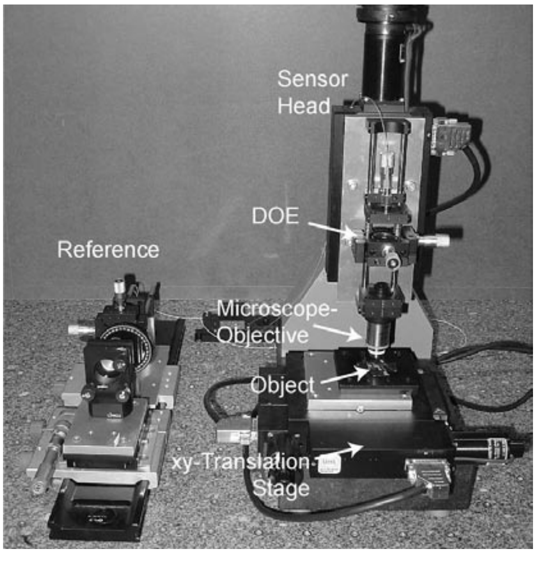


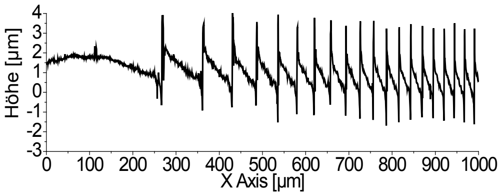
Fig. 1: CCSI sensor in fibre-based interferometer design.

If the object lies within the dispersed focus spectrum, a sharply focused spectral-component gets reflected and this induces a high-contrast wavelet in the spectral domain. The amplitude of this modulation remains constant within the entire range of the optical spectrum employed and the axial-range of the detector is decoupled from the limited depth-of-focus.

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

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

a) Chromatic-confocal measurement (reference arm blocked)



b) CCSI-measurement

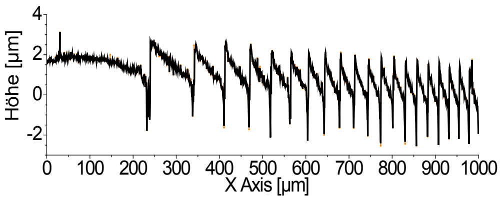


Fig. 2: Measurement of a diffractive optical element (DOE) with chromatic confocal microscopy **(a)** and CCSI **(b)** showing reduced overshooting in the CCSI-measurement.

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

References:

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

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

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

Influence of the object shape in white-light interferometry

R. Berger, K. Körner, W. Osten

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

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

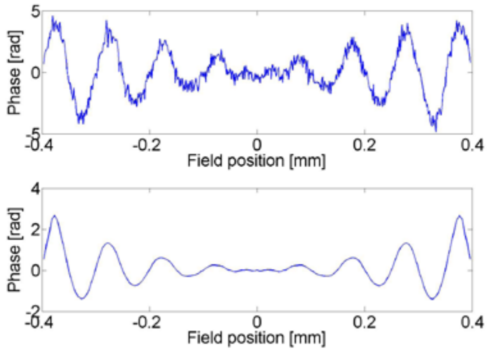


Fig. 1: Total phase at a mirrorlike, sinusoidal object.
Top: measurement,
bottom: simulation.

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

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

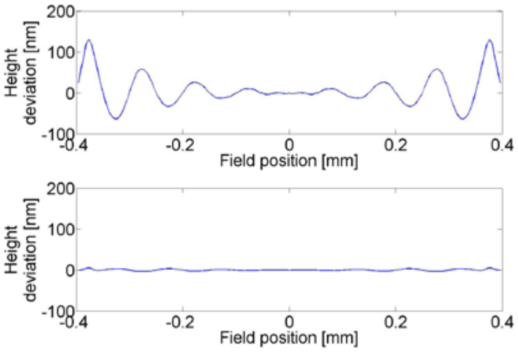


Fig. 2: Height deviation of the simulated sinusoidal profile.
Top: result after envelope evaluation,
bottom: result after phase evaluation.

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

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

References:

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

[2] Berger, R.; Körner, K.; Osten, W. „Chromatische Aberrationen in der Weißlichtinterferometrie", DGaO-Proceedings, A30, 2008.

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

R. Berger, K. Körner, W. Osten

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

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

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

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

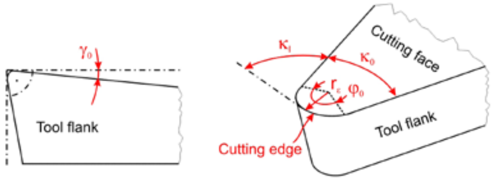


Fig. 1: View of a Diamond tool with the parameters to be measured.

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

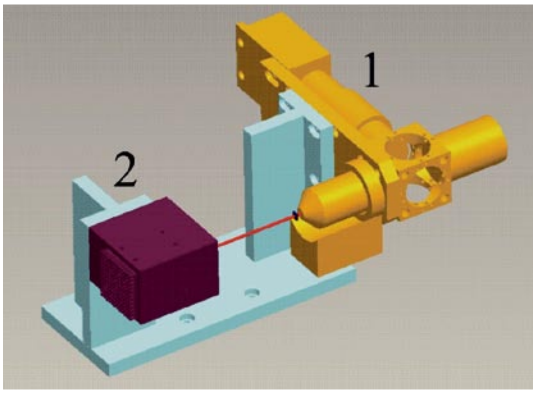


Fig. 2: Optical measurement system consists of a white-light interferometer **(1)** with a transmitted light device **(2)** for digital image processing.

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

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

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

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

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

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

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

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

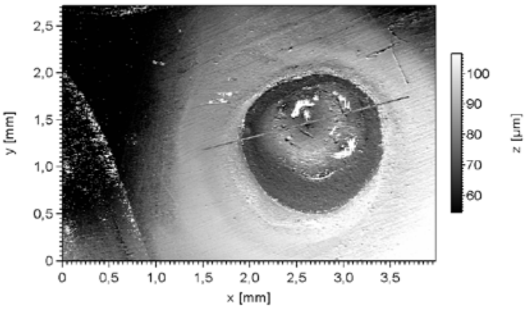


Fig. 1: Topography of a welding point measured with the new stereo-microscope-setup.

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

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

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

References:

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

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

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

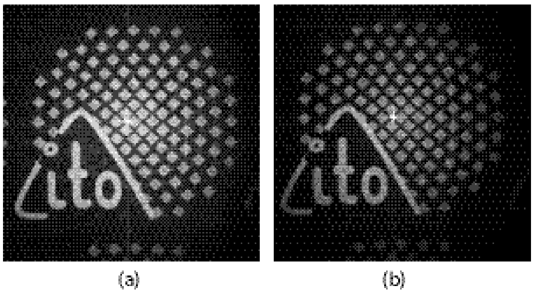
LCoS displays are widely used in optical measurement systems. The two main purposes they are applied for are amplitude modulation and phase modulation. Most modulators are designed as amplitude modulators, e.g. for projection devices, hence using them in their previewed manner yields few problems. The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

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

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

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

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



(a) (b)

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

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

References:

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

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

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

In process measurement of micrometer scaled tools

C. Kohler, T. Wiesendanger

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

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

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

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

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

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

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

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

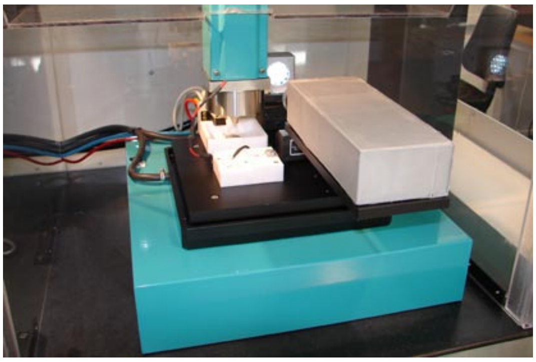


Fig. 1: Machine tool with integrated measurement setup on the right side.

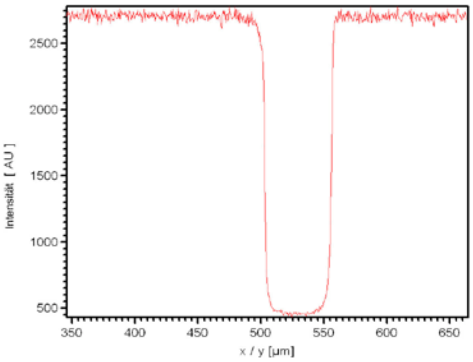


Fig. 2: Line cut through the image of a tungsten tool with a diameter of 50µm.

Application of phase retrieval for the characterization of LCoS displays

C. Kohler, F. Zhang, W. Osten

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

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

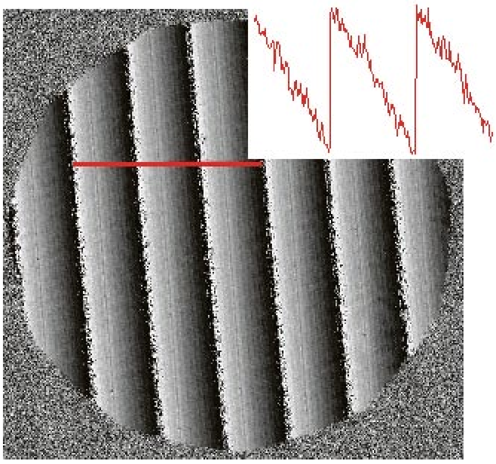


Fig. 1: Blazed phase grating written into the LCoS display measured with the phase retrieval method.

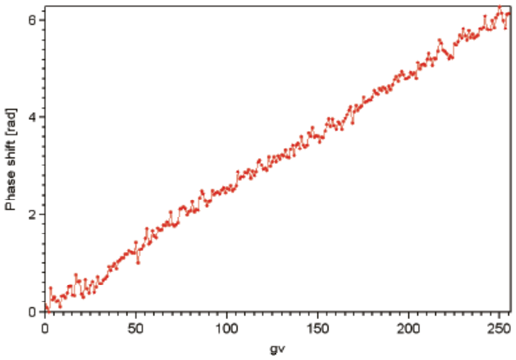


Fig. 2: Phase shift over the gray level written into the display, measured with a double slit like method.

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

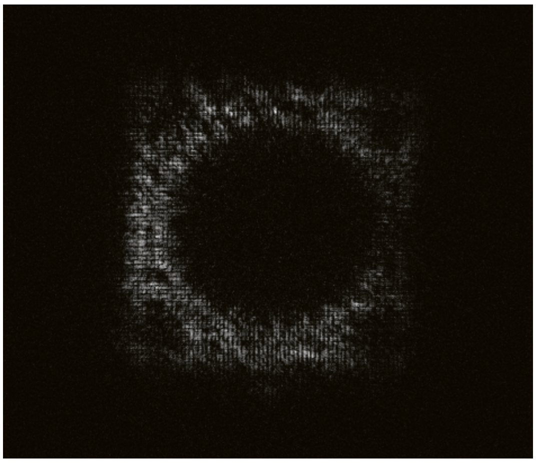


Fig. 3: With the LCoS display as a modulator retrieved intensity distribution of a mounting plate.

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

References:

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

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

Optical Simulations of a Biomolecular and Medical Diagnostic Sensor

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

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

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

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

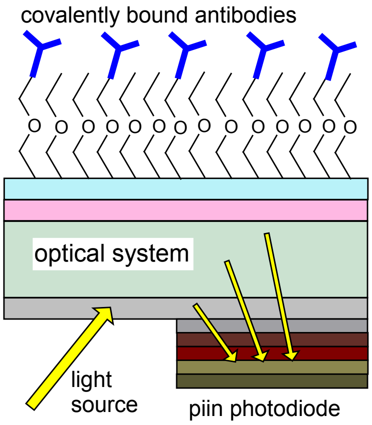


Fig. 1: The MoDekt sensor.

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

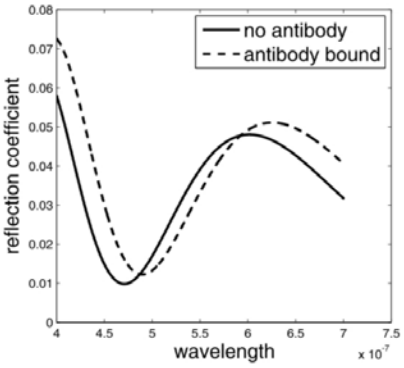


Fig. 2: The shift of the RIfS signal as seen when an antibody or an antigen binds to the detector surface.

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

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

References:

[1] Gauglitz, G. Rev. Sci. Instrum., 76 (6) (2005), 062224.

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[3] Pfäfflin, A.; Schleicher, E. Anal. Bioanal. Chem., (2008), DOI 10.1007/s00216-008-2561-3.

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