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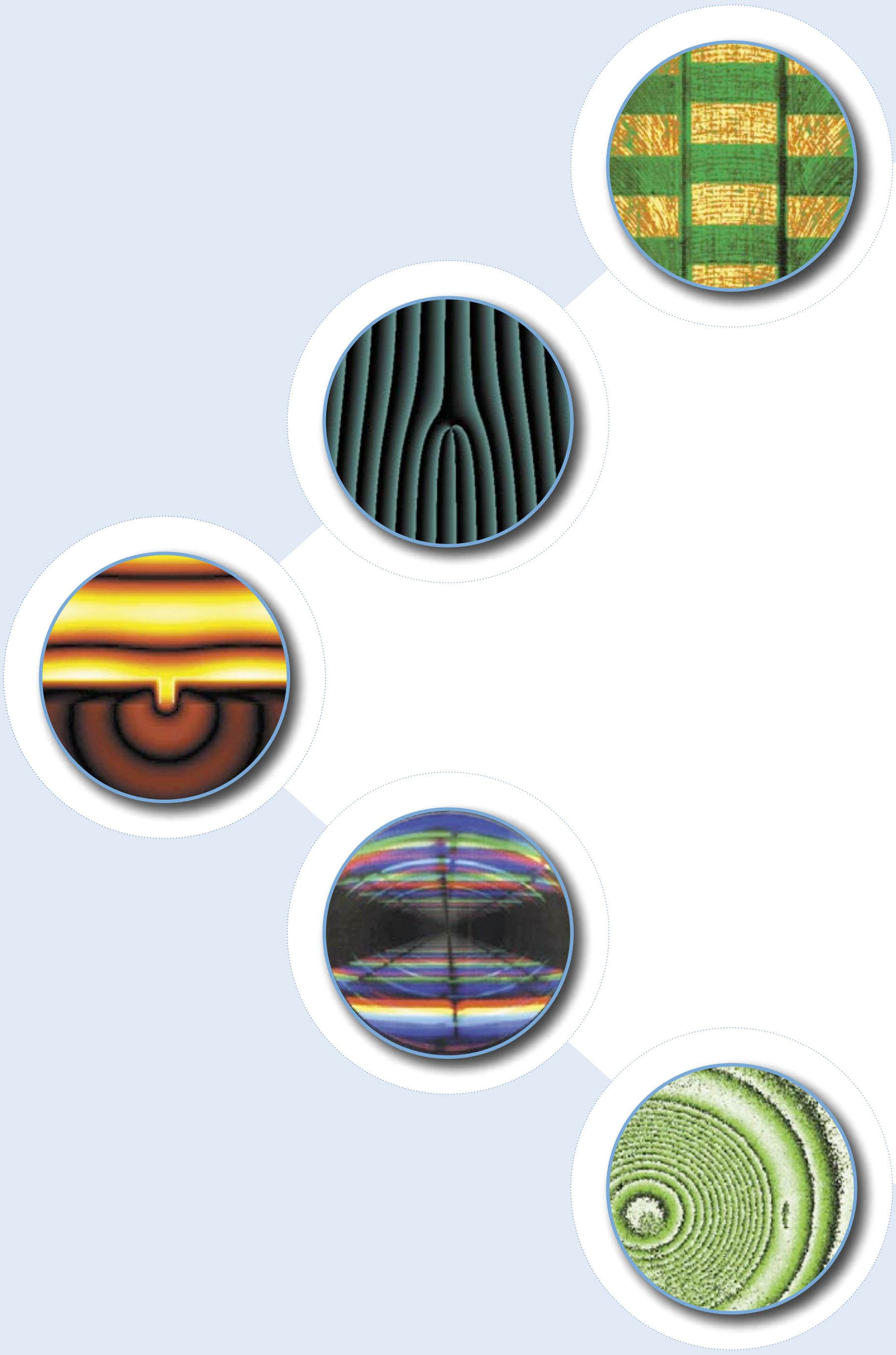

Universität Stuttgart

Active Optical Systems

High - resolution tomographic micro-interferometry
Supported by: DFG (OS 111/20-1)

Using consumer graphics boards in optics: hologram computation and ray tracing
Supported by: BMBF (FKZ 13N8809)

Active Micromanipulation using holographic optical tweezers and laser scissors
Supported by: Photonics BW

Active holographic cell sorting
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Low Cost Shack-Hartmann Sensor: Wavefront sensing with an aperiodic microlens array

High - resolution tomographic micro-interferometry

W.Gorski, W.Osten

Tomographic interferometer delivers as a result three-dimensional distribution of refractive index. The method is a combination of multidirectional transmission interferometry and tomographic reconstruction algorithms.

In the first stage of the project the research was focused on resolution improvement in the tomographic reconstruction of optical phase microelements. Previous work in this field proved that there are two main factors, which affect the final resolution of the 3D measurement. The first is diffraction, which appears at the border of materials with different refractive indices. An additional difficulty in this respect, may come from the structure of the object, the structure may itself be diffractive. The second factor limiting the resolution is mechanical imperfection of the rotation, resulting in the radial run-out phenomenon.

A tomographic micro-interferometer for the measurement of micro-optical elements has been built (Fig.1). The system is based on a transmission multidirectional interferometer, combined with tomographic reconstruction. The implemented tomographic algorithms were filtered backprojection, diffraction tomography and algebraic reconstruction technique. The system was designed for the measurement of optical fibers and fiber devices, e.g. splices.

As a test object, a photonic crystal fiber was chosen because it has high spatial resolution, and additionally includes a diffractive structure. The fiber, as well as its internal channels, were immersed in an immersion liquid which has the same refractive index as the fiber (fused silica). The matching of the refractive index was aimed at minimizing the diffraction effects at the border between materials with different refractive indices. The results of the tomographic reconstruction using three different algorithms showed that diffraction tomography is best suited to objects such as photonic crystal fibers. The radial run out error was at first reduced numerically, however the results were still not satisfying. Therefore also a manual correction was applied, which required the interaction of the operator and was time consuming. However it delivered acceptable results (Fig.2).

Another investigated aspect of the extension of the resolution was the application of the synthetic aperture technique. It was realized in the setup a tilt of the imaging system, to a certain angle (e.g. α in Fig.1) could be used. By using a synthetic aperture in tomography, one can extend the depth of focus, increase the field of view and reduce aberrations and diffraction effects. The disadvantage is that one has to record and process at least 2 phase maps, corresponding to the single angular position of the object, while when a synthetic aperture is not used only one phase map is needed. The measurement was performed with a use low numerical aperture (NA=0.1) microscopic objective. The results confirm an increase of the resolution and the suppression of measurement errors when this synthetic aperture technique is applied.

In the next stage of the project, a compact measurement setup with LCD modulators, dedicated to high - resolution tomographic interferometry will be built.

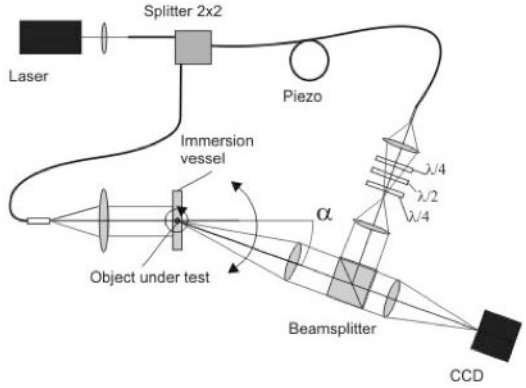

Fig. 1: Tomographic microinterferometer for optical microelements testing, with an optional extension to the synthetic aperture technique.

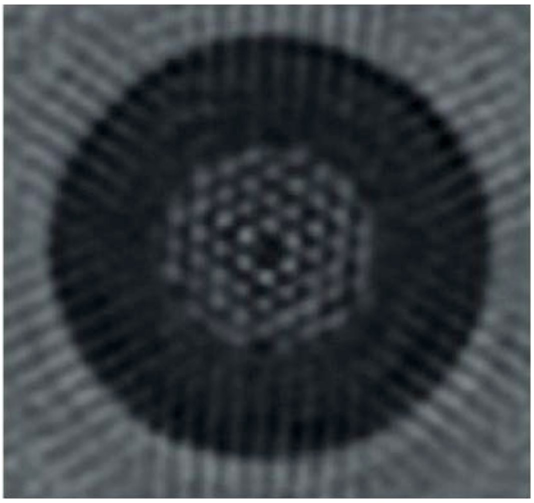

Fig. 2: The tomographic reconstruction of photonic crystal fiber, large mode diameter type (single layer tomogram).

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

References:

[1] Gorski, W.; Osten, W. "Tomographic imaging of high-resolution phase structures", submitted to Opt. Letters.

Using consumer graphics boards in optics: hologram computation and ray tracing

T. Haist, A. Burla, F. Soyka, W. Osten

Many people think that the most powerful integrated circuit on their PC is the CPU. Chances are good that they are wrong. Today's consumer graphics boards incorporate highly parallel working processing units that outperform conventional CPUs for computational tasks with strong parallelism.

Within the BMBF project AZTEK real-time hologram computation is necessary to achieve the goal of a fully automated micromanipulation system based on holographic tweezers. Normal CPU based optimization of the holograms was found to be too slow for real-time operation. Therefore different hologram optimization methods were implemented on standard consumer graphics boards using a combination of Cg ("C for graphics"), OpenGL and C++. The most challenging part when writing such applications is to efficiently map the problem at hand to the hardware of the graphics board.

In fig. 1 the program flow for a iterative Fourier transform algorithm is shown. In order to fully exploit the available hardware it turned out that two holograms need to be computed at the same time. With a Nvidia 8800 GTX based graphics board it is possible to generate optimized (10 IFTA iterations) holograms for the holographic tweezers at a rate of 16 Hz. The main computational cost for this Fourier transform hologram optimization is associated with two-dimensional Fourier transforms. The 8800 GTX based board delivers for our application a performance of more than 360 complex (32 bit float) two-dimensional FFTs with 512 x 512 pixel per second and therefore strongly outperforms conventional CPUs. Other applications apart from hologram optimization (e.g. correlation, image processing) are of course possible.

As a technical demonstration, a program that captures part of the screen and computes holograms for the graphics found in the captured part in real-time has been implemented.

For many applications in optical design and simulation the available processing speed still limits optimization. One example is the simulation of the interferometric testing of aspheres. Another example is the design of illumination systems. We performed first experiments using the graphics board for optical raytracing. Benchmarks for tracing rays through systems with spheres and (polynomial) aspheres have been conducted after implementing a simple raytracing scheme.

On a 7800 GTX based card we achieved 200 million rays per surface per second for spherical surfaces and 50 million rays per surface per second for polynomial aspheres. The accuracy at the moment is 32 bit floating point precision.

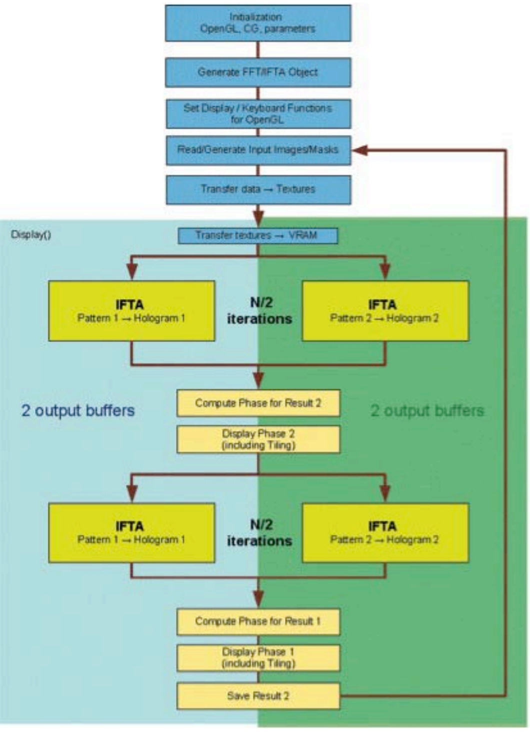

Fig. 1: flow diagram for the implementation of an iterative Fourier transform based hologram optimization on a graphics board. All boxes shown in yellow are completely processed on the graphics board.

Supported by: BMBF (FKZ 13N8809)

References:

[1] Reicherter, M.; Zwick, S.; Haist, T.; Kohler, C.; Osten, W. "Fast digital hologram generation and adaptive force measurement in LCD based holographic tweezers", Applied Optics 45(5), pp. 888-896 (2006).

Active Micromanipulation using holographic optical tweezers and laser scissors

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

The aim of the Photonics-BW funded project AMIMA (Aktive MikroManipulation) was to build up a flexible tool, composed of holographic optical tweezers and holographically steered scissors. Such a tool enables the simultaneously movement and processing of micro-scaled objects with very high precision. It is much less expensive than mechanical systems for this application and it opens up a range of new applications in biology and micromechanics using automation.

Optical tweezers enable the trapping and movement of micro-scaled objects within the focus of a laser beam (1064nm) by transferring the momentum. Steering is carried out by a hologram, which is displayed on a liquid crystal display (LCD, LC-R 2500, Holoeye) which works as a spatial light modulator (SLM) and is situated in the Fourier plane of the object plane. By changing the hologram, it is possible to arbitrarily and independently move the tweezers in three dimensions. Thus high-precision-steering with a high repetition rate is possible without the movement of any mechanical parts.

Holographically steered optical scissors work a similiar way. As they work in the ultraviolet (λ=355 nm) a digital micromirror device (DMD; Texas Instruments) is required, since liquid crystals may be damaged by the UV-light. Optical Scissors enable the cutting, welding or destruction of biological or non-biological objects in the micro-scale.

We have combined these two tools in one versatile system, which is shown in figure 1.

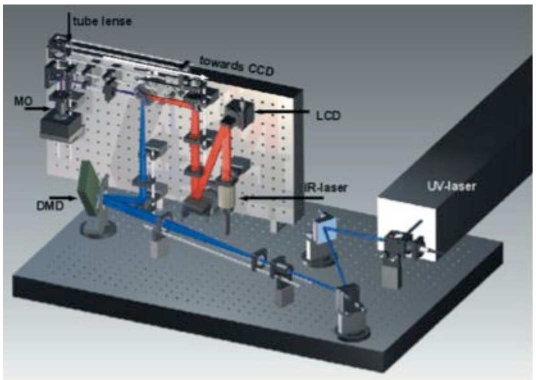

Fig. 1: Complete setup with optical tweezers (red ray path) and laser scissors (blue ray path)

As there are many sources that introduce aberrations into the optical setup, it is important to correct for them. Several different methods of aberration correction were developed and tested and two of them turned out to be practicable:

Optical tweezers are very sensitive to beam spot quality. To correct for specimen-introduced aberrations an automated iterative algorithm was developed, which calculates a new hologram by correcting a random aberration. Depending on the resulting spot intensity, another hologram would be calculated, until no improvement can be achieved.

The most deformed element in the laser scissors setup is the DMD itself. To correct for these aberrations, the wavefront deformation introduced by the DMD was measured with a Twyman Green Interferometer. Based on this measurement, a correction hologram was calculated, which was superimposed onto the holograms used for steering. Fig. 2 shows a holographically written circle on a photo resist. By correcting for aberrations, we could make the redundant -1 diffraction order less intense and thus giving no effect on the resist.

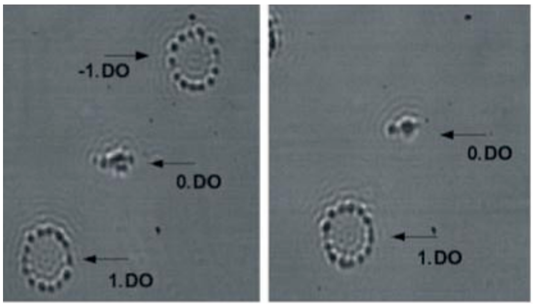

Fig: 2: Holographically written circles in photoresist. Left: without aberration. Right: with aberration control.

We have built the first completely holographically steered processing tool in the microscopic range. Figure 3 shows a human erythrocyte, being moved and destroyed by this tool.

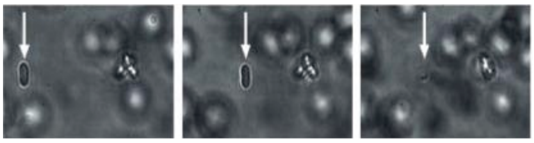

Fig. 3: Human erythrocyte, which first was moved and than destroyed by the laser scalpel.

Supported by: Photonics BW

Active holographic cell sorting

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

Drug development is a statistical process. The aim is to filter out genetically modified cells that produce a desired protein. Up till now, to isolate these cells, cells have to be repeatedly diluted and bred, which is a long process when dealing with a high number of cells. To shorten this process, we can separate non-relevant from relevant cells.

In drug development, where there is a need to sort a smaller number of cells but with high accuracy, optical tweezers are an appropriate tool. Optical tweezers enable us to trap and move micro-scaled objects in the focus of a laser beam (λ=1064 nm) by transfer of momentum.

Holographic optical tweezers are an important extension of this tool. The setup includes a spatial light modulator (SLM) in the fourier plane of the object plane. There, a hologram is displayed to steer the object into position and to generate the desired number of traps. By changing the hologram, it is possible to move the tweezers arbitrarily and independently in three dimensions. Thus, high-precision-steering with high repetition rate is possible without moving any mechanical parts.

In the BMBF-founded project AZTEK (Aktive Zellsortierung Transfizierter EuKaryonten), in cooperation with two German companies (Innovatis and Holoeye), there are two aims. One is the realisation of a flexible two-step cell sorting system. The other is to build a holographic tweezers add-on module for a standard research microscope.

For the cell sorting, first a passive pre-sorting by a static light field, which separates cells by attributes like size or refractive index is employed (s. Fig. 1). Second an active sorting by attributes defined by the operator and which are identified by image processing is used. The identification of the relevant cells is done by our partner Innovatis, a specialist in cell analysis by image processing.

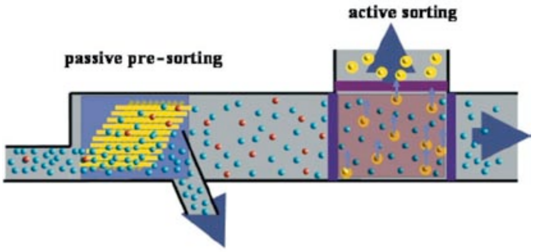

Fig 1: Schematic of a passive pre-sorting and active cell sorting combined with a micro fluidic system. The identification of relevant cells in the active sorting is done by image processing, whereas passive pre-sorting reacts on cell attributes like size.

The add-on module is designed for a Zeiss Axiovert 200M and includes a new phase-only LCOS modulator developed by Holoeye.

Since the parallel ray path is not accessible with a Zeiss Axiovert, the diffraction limited design of the system is not trivial. A detailed simulation had to be performed, in order to achieve an easy-adjustable and compact setup, which produces diffraction limited tweezers. For this purpose, a telescope to enlarge the laser beam diameter was designed in order to illuminate the SLM. Imaging of the hologram into the microscope is done by a 3-lens-system, which can be easily adjusted to the non-parallel ray path.

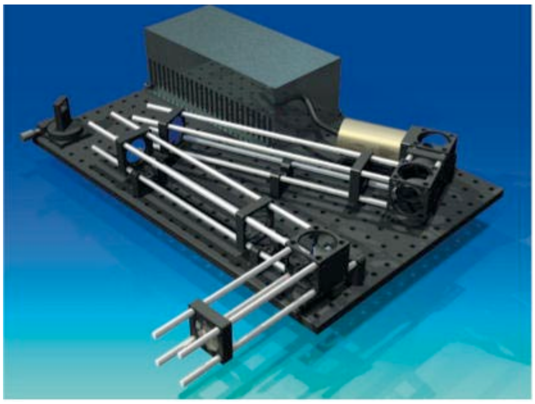

Fig. 2: Compact add-on module for holographic optical tweezers for a Zeiss Axiovert 200M.

Fig. 2 shows the complete and compact add-on module, which enables us to move and sort cells in combination with a microscope and a micro fluidic system. The micro fluidic system enables cells to travel through the device allowing separation. As this system has to be adapted to a sorting process, a special channel alignment is required. Development of such a system is in process.

Supported by: BMBF (FKZ 13N8809)

References:

[1] Haist, T.; Zwick, S.; Warber, M.; Osten, W. "Spatial Light Modulators – Verstile Tools for Holography", Holography and Speckle 2006, Vol. 3, No. 2, pp. 125-136.

Low Cost Shack-Hartmann Sensor:
Wavefront sensing with an aperiodic microlens array

T. Ruppel, L. Seifert, T. Haist, T. Schoder, W. Osten

Shack-Hartmann sensors are commonly used as wavefront sensors in a wide field of applications, such as adaptive optics, beam characterization and non-contact measurements. They are popular because of the ease of use and the robustness of the sensor. We introduce here a new way to improve the performance of these miniaturized and mass-producible optical wavefront sensors for industrial inspection applications.

A commonly used SHS consists of a microlens array and a detector with the same size. The measurement aperture is usually limited by the detector size. Because large detectors are expensive, the measurement diameter is normally in the range of 5-15 mm.

By using an aperiodic diffractive element, it is possible to design a sensor with different microlens array and detector sizes. This is interesting because CCD cameras with smaller detectors are much cheaper and therefore a SHS can be build at a lower price. To demonstrate this, we have built a SHS with a low cost webcam as the detector.

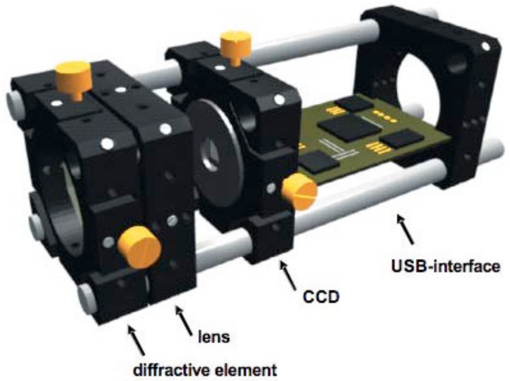

Fig. 1: Our low-cost Shack-Hartman Sensor can measure a 20 mm diameter wavefront using a 4.6x4.0 mm CCD chip from a webcam.

The basic component of this Shack-Hartmann sensor is the microlens array. The number of microlenses is identical to the number of slope measurements made over the aperture. Common SHS often use about 400 microlenses. Due to the low resolution of the chosen camera, in this case the number of microlenses is limited to about 200 lenses.

The measurement aperture of the sensor is circular but the detector area is rectangular. All pixels of the detector should be used. Therefore the assignment from microlens to spot position can not be uniform. Because all microlenses should have the same dynamic range, the path length for all microlenses should also be the same. We choose a remapping scheme in which the path length variation over all microlenses is minimised. Because of the small CCD chip, the phase function of the microlenses contains an additional phase tilt, so that the spots are focused on the detector. This can be seen in Figure 2.

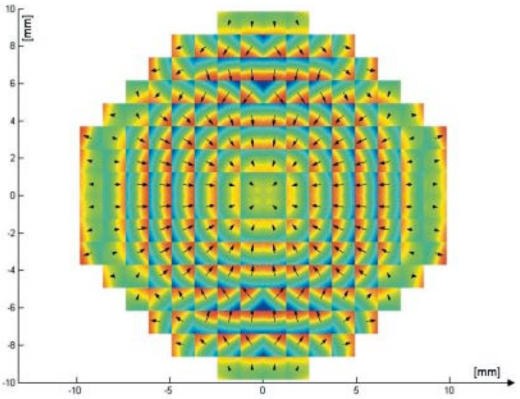

Fig. 2: Phase front picture of the microlens array. The arrows show the direction and amplitude of the tilt.

To enlarge the minimal size of the diffractive structure for simpler and cheaper fabrication, we added a biconvex lens (f=30.3 mm) between the microlens array and the detector.

A known reference wave is needed for the determination of the sensor accuracy. The simplest wavefront for this task is a spherical wave. We compared the measured wavefront of spherical waves with a radius between 4600 mm and 5300 mm. According to these results the average phase error of our low cost Shack-Hartman sensor is below 0.1λ.

References:

[1] Seifert, T. Ruppel, T. Haist, and W. Osten, "Wavefront sensing by an aperiodic microlens array", Proc. SPIE 6293, 2006

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