Quantitative phase measurement of direct laser written waveguides using differential phase contrast

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Focused ultrafast laser pulses induce refractive index changes on the micrometer scale in bulk glasses. The structural modifications can be used to design customized 3D diffractive optical elements. To characterize these changes, the phase of laser written waveguides and planes is measured using the differential phase contrast method. The method is verified by phase measurements of optical fibers with known properties.

1 Introduction

The interaction of focused ultrafast laser pulses causes structural changes in the refractive index near the focal volume inside bulk glasses. These structural modifications can be used in the direct laser writing of customized 3D diffractive optical elements [1]. For correct functionality of these DOES, these phase changes need to be known quantitatively. Differential phase contrast (**DPC**) microscopy allows the observation of these changes [2] and even enables the quantification by deconvolution of calculated phase transfer functions [3].

2 Experimental Setup

An existing, inverted microscope (Axio Vert, Zeiss) is used to capture the differential phase images. The illumination source is replaced by a programmable LED array to allow arbitrary illumination patterns. The setup is shown schematically in Fig. 1.

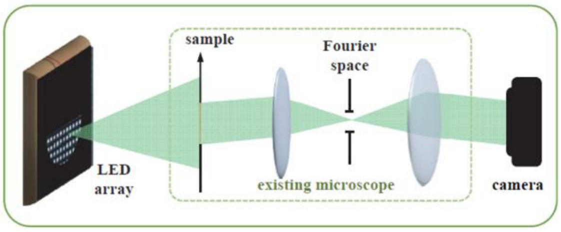

Fig. 1 *Optical setup. An LED array is used instead of the default illumination setup to allow for DPC [3].*

The illumination patterns shown in Fig. 2 are used to create the images needed by the DPC algorithm.

Fig. 2 *Illumination patterns generated on the LED Array to capture differential phase images.*

The differential phase contrast images needed for the DPC algorithm are calculated by subtracting the images of two complementary semicircle images, e.g., left and right, and then dividing it by the sum of the two image intensities.

$$I_{DPC} = \frac{I_{left}-I_{right}}{I_{left}+I_{right}} \qquad (1)$$

Using the DPC-algorithm proposed by Tian and Waller [3], the phase information can then be retrieved from the oblique illuminated images by calculating the phase transfer functions $H_{ph}(\boldsymbol{u})$, where $\boldsymbol{u}$ is the spatial frequency vector.

$$H_{Ph}(\mu,\nu) = i[\iint \mathrm{S}(\boldsymbol{u}')\mathrm{P}^*(\boldsymbol{u}')\mathrm{P}(\boldsymbol{u}'+\boldsymbol{u})\mathrm{d}^2\boldsymbol{u}'$$
$$-\iint \mathrm{S}(\boldsymbol{u}')\mathrm{P}^*(\boldsymbol{u}')\mathrm{P}(\boldsymbol{u}'-\boldsymbol{u})d^2\boldsymbol{u}'] \qquad (1)$$

Where $S(\boldsymbol{u})$ denotes the source intensity distribution and $\mathrm{P}(\boldsymbol{u})$ the pupil function. Finally, the phase $\Phi(x,y)$ can be retrieved by solving the following inverse Fourier transform

$$\phi(x,y) = IFFT\left\{\frac{\sum_j H_j^*(\boldsymbol{u})\cdot\tilde{I}_{DPC,j}(\boldsymbol{u})}{\sum_j\left|H_{Ph,j}(\boldsymbol{u})\right|^2+\alpha}\right\} \qquad (3)$$

where α is a regularization parameter and $\tilde{I}_{DPC,j}(\mu,\nu)$ the Fourier transformed DPC intensity for each illumination pattern indexed by j.

The laser emits pulses of pulse length τ = 100 fs at a central wavelength of λ = 800 nm (Spitfire Ace, *Spectra Physics)* and is focused by a microscope objective of NA = 0.45. The investigated samples are an optical fiber with known refractive indices, laser written waveguides as well as planes of modification consisting of laser tracks written closely together.

3 Experimental Results

The first object analyzed is an optical fiber (SM450, *Thorlabs*) immersed in glycerol to match the cladding index to the surrounding medium. The reconstructed phase is shown in Fig. 3. The inset shows the phase along the dashed line. Reconstruction artifacts at the interface between immersion to the optical fiber cladding exist. These show as black shadows in the interface region. The core of the fiber is reconstructed at the correct position, but the noise in the reconstruction renders a definitive quantitative measurement of the value uncertain Despite these problems the direct laser written samples are inspected using the DPC method.

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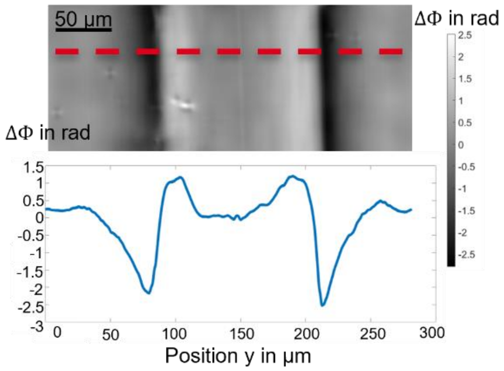

***Fig. 3** Reconstructed phase of an optical fiber using the DPC method. The inset shows the phase along the dashed line.*

Next, the DPC method is applied to laser written waveguides. The phase of one waveguide, written with a scan velocity of $v = 2\ \frac{\mathrm{mm}}{\mathrm{s}}$, at a repetition rate of $f = 10$ kHz, corresponding to a pulse-to-pulse distance of $0.2\ \mu\mathrm{m}$, a pulse energy of $E = 150$ nJ in a depth of $z = 100\ \mu\mathrm{m}$, is shown in Fig. 4. Since the change of refractive index induced is low ($< 10^{-3}$) and continuous, fewer reconstruction artifacts phase are observed. The inset shows a magnification of the marked region.

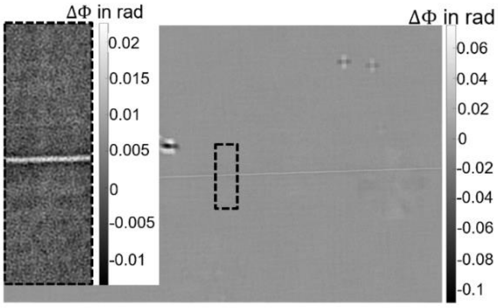

***Fig. 4** DPC phase reconstruction of a laser written waveguide in fused silica. The inset shows a magnified image of the marked area.*

Plotting the reconstructed phase across the laser written waveguide shows the profile of the phase. The waveguide exhibits a phase peak-to-valley value of around $\Phi = 20\ \mathrm{mrad}$. The reconstructed phase in dependence of the position on the sample, is shown in Fig. 5.

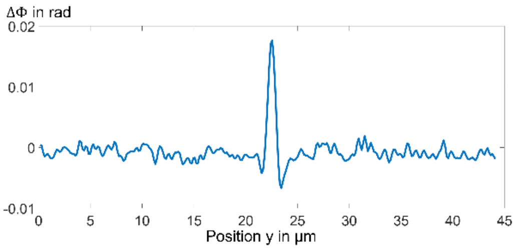

***Fig. 5** DPC phase reconstruction along an orthogonal cut through waveguide. The waveguide is clearly visible between position y=20 and y=25 µm.*

Lastly, the phase of a laser written plane is reconstructed using DPC. The plane is composed of laser tracks written in a distance of 0.2 µm to each other, The tracks are written with the same parameters as the previously shown waveguide. The phase reconstruction is shown in Fig. 6.

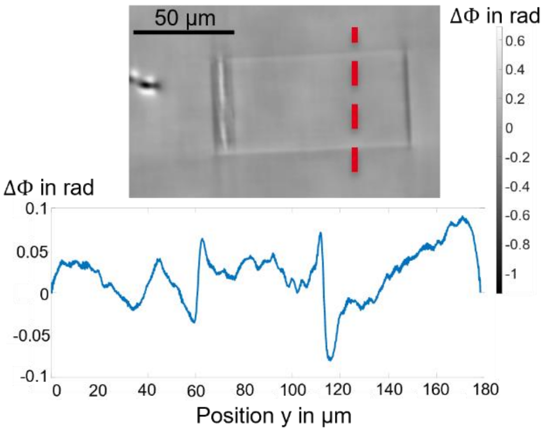

***Fig. 6** DPC phase reconstruction of a laser written plane. The inset shows the phase along the dashed line.*

The area of high phase on the left-hand side is caused by an error in the fabrication process. The cut across the plane shows, that the phase of the plane suffers from artifacts on the inner region, which is located between 60 µm < x < 120 µm.

4 Summary

The DPC method allows the reconstruction of phase objects, even inside bulk material. While the phase reconstruction of objects of continuous phase change, e.g., laser written waveguides and edges of planes, is possible, the reconstruction of discrete phase changes, e.g., cladding and core of optical fiber, suffers from artifacts. Improving the algorithm and setup could lead to removal of these artifacts.

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