Wave-front Coding for increased depth of field of optical systems

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Wave-front Coding is used for increasing the depth of field of optical systems. We demonstrate the functionality by using a cubic phase plate. We present design considerations, the fabrication process of the refractive phase plate as well as experimental results with a specific focus on fabrication errors.

1 Introduction

Using microscopy the depth of field (DOF) is a major issue limiting the image quality. Conventionally an extended depth of field can be achieved by reducing the aperture size or by multiple-imaging scanning techniques for 3-dimensional objects. In this case however the depth of field is achieved at the expense of light efficiency or recording time. Wave-front coding (WFC) offers a way to avoid these disadvantages. To this end the optical transfer function is modified to become more defocus resistant. An additional computational postprocessing allows to correct the distortion generated by the modified transfer function. For the coding we use a cubic shaped phase plate [1] designed for a 5x microscope objective (*NA*=0.14) at $\lambda = 630$ nm. The element was fabricated as a refractive surface in PMMA. Its characterization and performance within a microscope setup at a 2D-imaging process will be shown.

2 Design of a Cubic Phase Plate

The DOF of the optical system can be described by the variation of the PSF with increasing defocus distance. The similarity of the defocused and the focused PSF can be evaluated in Hilbert space angle units [2]. The larger the Hilbert space angle the more similar are the PSFs. This corresponds to a large parameter α of the normalized cubic profile function.

$$z = \alpha \cdot \left(x^3 + y^3\right) \tag{1}$$

However with an increasing parameter α the resolution of the system decreases. As a trade-off we determined a best value of $\alpha = 0.005$ for covering the full spatial frequency spectrum at a defocus distance of 200 µm.

3 Fabrication and Characterization

The phase plate was fabricated as a refractive element in PMMA using ultraprecision micromilling. The dimensions of the element are 8 x 8 mm² with a profile height of about 40 µm. Figure 1a shows a 3D-scan of the surface using an autofocus sensor measurement. The fit through the measured data points shows slight differences to the specified curve as can be seen in Eq. 2 and 3. However simulations show very small effects of these variations on the optical performance.

$$z_{PMMA-spec.} = 1.640 \cdot 10^{-4} \cdot \left(x^3 + y^3\right) \quad \text{in mm} \tag{2}$$

$$z_{PMMA-meas.} = 1.894 \cdot 10^{-4} \cdot x^3 - 1.693 \cdot 10^{-4} \cdot y^3 \quad \text{in mm} \tag{3}$$

Caused by the milling strategy with a ball shaped milling tool meandering across the substrate the roughness of the surface depends on the direction of scanning (Fig. 1b). The roughness values are $R_{a\text{-}x}$=10.95 nm in and $R_{a\text{-}y}$=29.81 nm measured with white light interferometry.

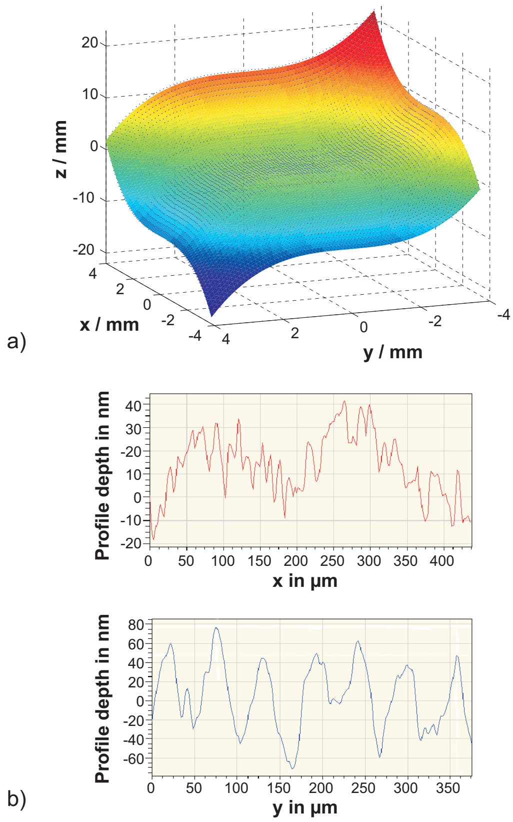

Fig. 1 *Measured data points with fit (a) and profile scan with white light interferometry in x- and y-direction (b)*

The PSFs of the on-axis and four off-axis spots in the corners of the object field are shown in Fig. 2a with the MTFs in Fig. 2b. The shape of the curves are very similar but for higher spatial frequencies the contrast drops down to nearly zero. This causes difficulties for the postprocessing since the high frequent noise signal becomes amplified and reduces the image quality. The main reason for this contrast reduction can be found in the spectral bandwidth of the light source which is a red LED with a peak wavelength of $\lambda = 627$nm.

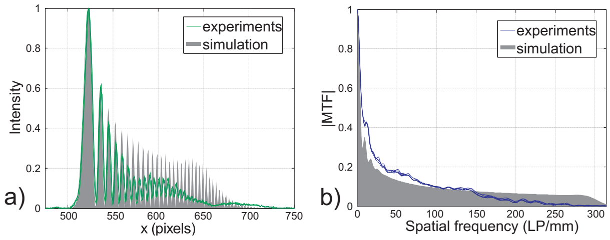

Fig. 2 *Comparison of wave-front coded experimental and specified PSF (a) and MTF (b)*

In Fig. 3a and b we show how the spot quality changes with increasing spectral bandwidth. Up to a bandwidth of $\Delta\lambda = 10$ nm there is no significant change to the ideal monochromatic PSF. Therefore we are using a *FWHM* = 8 nm band-pass filter for the following experimental results.

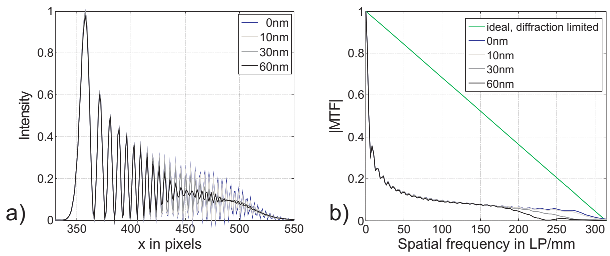

Fig. 3 *Simulation of PSF (a) and MTF (b) with contrast reduction for increasing spectral bandwidth*

4 Experimental Results

For the experimental verification of the performance of the cubic phase plate we use a 2D-USAF-target as object. The images for the focused case and a defocus of 200 µm are shown in Fig. 4a and b. The corresponding wave-front coded images (Fig. 4c-d) are much more blurred but very similar to each other. The inverse filter we apply to the coded images is calculated from the experimental images. The use of the ideal filter results in unacceptable artifact due to the non-ideal shape of the phase plate and its roughness. The features in the postprocessed image (Fig. 4e) have sharp edges compare to the focused image but there is still background noise visible. We assume that the reason for this noise is still the roughness of the element combined with noise of the CCD-camera.

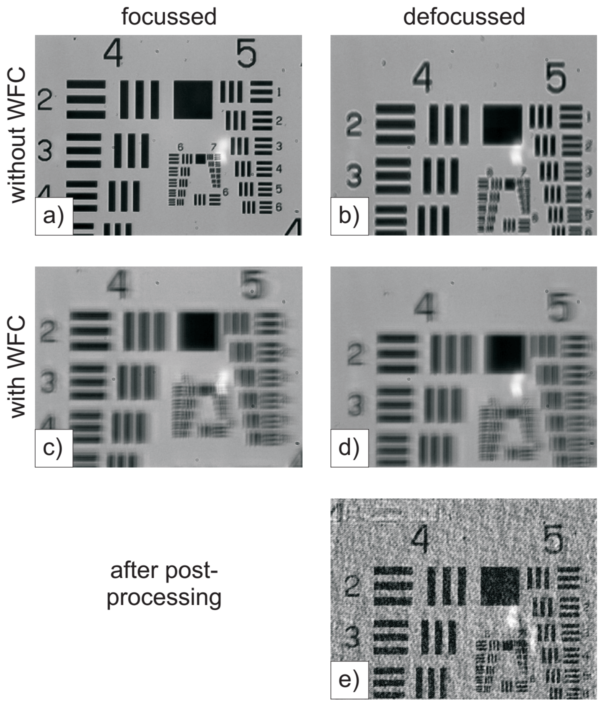

Fig. 4 *WFC-process with 2D-USAF-target with a defocus distance of 200 µm*

5 Conclusion and Outlook

We presented the design and fabrication of a cubic phase plate including its influence on the 2D-imaging process with wave-front coding. There are still issues for the future in reducing the background noise as well as the spectral influence for applications with white light.

References

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