Stitching errors in diffractive null-test elements

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For an interferometric null-test of aspheric lenses diffractive optical elements (DOEs) can be used as they offer the freedom of design to adapt easily to the desired sample under test. Like every other component in the measurement setup the DOE introduces systematic errors to the measurement. A study concerning the pattern distortions of the DOE due to the writing process used for the fabrication of the DOE was performed.

1 Introduction

An interferometric null-test of aspheric elements can be done with the help of a diffractive optical element (DOE) as null element, where the desired phase of the sample under test Ψ_{asp} can be easily imprinted. The structure deviations of the DOE due to the fabrication process Φ_{doe} and the aberrations of the substrate of the DOE Φ_{subs} then are added to the measured phase Φ_{meas}, which consist not only of the aberration of the sample under test Φ_{asp} but also of the aberration of the interferometer Φ_{int} and the misalignment Φ_{maf} between the null element and the aspheric lens. To remove the systematic errors from the measurement a multi-position test in combination with a dual-wavefront DOE could be used. A transmission null-test of an aspheric lens is presented in [1] and [2] where five measurement positions in a Mach-Zehnder Interferometer are used to eliminate the systematic errors of the setup.
Although an absolute test eliminates the errors introduced by the DOE, an estimation of the error budget of the DOE is advisable. The aberrations of the plane substrate plate Φ_{subs} can be measured separately and are not studied here. For the plates used for this study, which are $4''$ mask blanks with $0.06''$ thickness, the aberrations are below $\lambda/10$. By using an amplitude only DOE made of a chromium mask on a glass substrate the 0^{th} diffraction order could be applied to extract the aberration due to the DOE substrate.

2 Structure aberrations in the DOE

The structure aberrations of the finished DOE are dependent on the fabrication process and consist of pattern distortion, among others. Here, we study solely the pattern distortion which is influenced by the direct writing lithography used to structure the DOE. The pattern distortion depend only on the direct writing lithography if no additional replication process is involved.
Here, the exposure of the DOEs is done stripewise by a laser beam ($\lambda = 0.364\mu m$), where an acousto-optical deflector (AOD) is used to scan the beam over one stripe. Additionally, the whole DOE substrate is moved under the exposing beam on an interferometrically controlled table.
Pattern distortions occur due to systematic and random errors of the lithography system. We concentrate on the prominent systematic errors in this study.
Misalignement of the AOD leads to local pattern distortion in each writing stripe, which are usually summed up as stitching errors. The typical misalignment could be a rotation of the AOD, resulting in a stripe wise pattern rotation and a mismatch of the deflection angle, which leads to a stripe wise pattern scaling in the x-direction. Additionally, a global distortion of the underlying coordinate system can occur due to small errors of the positioning system.
Usually, the stitching errors of the lithography system are reduced by optical inspection of exposed test structures in a microscopic setup, which allows the local detection of stitching errors down to $\pm 100nm$. The errors of the positioning system can be measured at sampling points with the help of a golden plate standard. An estimation of the global distortion can be done by observing ghost structures in the Moiré of two exposed DOEs with rotationally symmetric high frequency pattern. None of those methods gives a direct information about the resulting phase aberration.

3 Error simulation

The pattern distortions, listed above were studied separately in simulations and their effect on the phase of the DOE was investigated. The phase of the distorted DOE is described by the phase of a DOE with distorted coordinate system $\Psi_{err}(\vec{r}) = \Psi(\mathbf{M_T}\,\vec{r})$. The global and local distortions of the coordinate system are combined in one global and one local transformation matrix $\mathbf{M_{T,G/L}}$ comprising the shear (s_x, s_y), the scaling (c_x, c_y) and the translation (t_x, t_y) of the coordinates $\vec{r} = (x, y)$

$$\mathbf{M_{T,G/L}}\,\vec{r} \overset{\text{Taylor}}{\longrightarrow} \begin{pmatrix} x + t_x + c_x x + s_y y \\ y + t_y + c_y y + s_x x \end{pmatrix} = \vec{r} + \vec{\epsilon}(\vec{r}) \quad . \quad (1)$$

The local pattern rotation due to AOD rotation is replaced by a combination of local pattern shearing and scaling.

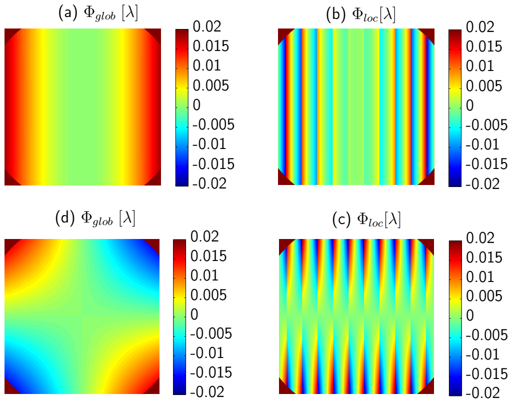

Fig. 1 *Simulated deviation from the ideal spherical wave front due to DOE structure errors. (a) Scaling of the global coordinate system by* $c_x = 0.000025$*; (b) Stripe wise local scaling by* $c_x = 0.0001$*; (c) Shear of the global coordinate system by* $s_y = 0.000025$*; (d) Stripe wise local shear by* $s_x = 0.0001$

The wavefront aberration of the DOE $\Phi_{doe}(\vec{r}) = \Psi(\vec{r}) - \Psi(\vec{r} + \vec{\epsilon}(\vec{r}))$ is approximated by

$$\Phi_{doe}(\vec{r}) \approx -\vec{\nabla}\Psi(\vec{r}) \cdot \vec{\epsilon}(\vec{r}) \quad . \qquad (2)$$

For a spherical wave front DOE the aberration results in

$$\Phi_{doe}(\vec{r}) = \frac{(c_x x^2 + c_y y^2 + t_x x + t_y y + (s_x + s_y)xy + r^2)}{\sqrt{f^2 + r^2}} \,, \qquad (3)$$

where f is the focal length.The simulated aberrations of a spherical wave front DOE for different structure deformations are presented in Fig.1(a)-(d). The diameter of the simulated DOE is $2r_{max} = 20mm$ and the focal length $f = 40mm$. The width of the writing stripes $d_s = 2mm$ was chosen $20\times$ bigger than the real stripe size to visualize the local aberrations.

Stretching the coordinate system in x-direction by a factor of $c_x = 0.000025$, which corresponds to a length error of $500nm$ over the whole diameter, lead to a astigmatic error with a PV of 0.02λ (see Fig.1(a)). A global shear in x-direction by a factor of $s_y = 0.000025$ results in an by $45°$ rotated astigmatic error with a PV of 0.04λ (see Fig.1(c)).

A stripewise scaling in x-direction by a factor of $c_x = 0.0001$, which in a real element leads to an overlap between the stripes of $\pm 100nm$, results in a sawtooth like error with increasing magnitude at higher DOE frequencies (see Fig.1(b)). A local shear in y direction of $s_x = 0.0001$ results in a local astigmatism in each stripe with a PV of 0.04λ (see Fig.1(d)). and corresponds to a displacement of $\pm 100nm$ at the stripe ends.

4 Measurement

To calculate the aberration due to the pattern distortion Φ_{doe} the phase measurements using the $\pm 1^{st}$ diffraction order of a spherical wavefront DOE were subtracted similar to [3]. The global error was extracted by LSQ-fitting the structure polynomial from eq.(3). As the stripe width in the fabricated DOE could only be increased up to $160\mu m$ the local errors are very roughly sampled and therefore, the local errors were extracted by LSQ fitting of a second order polynomial in x and y direction after subtracting the fit of the global error.

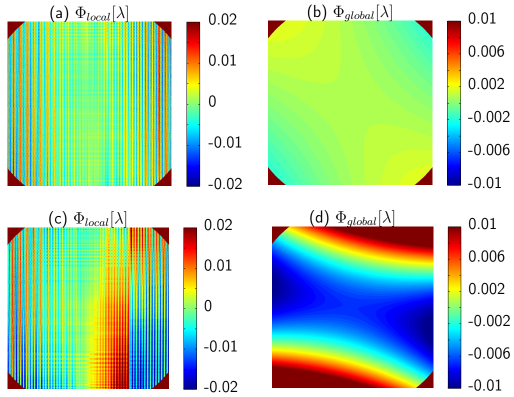

Fig. 2 *Fit of global and local deviations to the measured deviation from the ideal spherical wave front due to DOE structure errors of a typical DOE. The focal length of this DOE was* $f = 40mm$ *? and the diameter* $20mm$.

Fig.2(a-b) shows one exemplary measurement of a DOE with typical alignment of the lithography machine. The local aberrations Fig.2(a) are hampered by spatial filtering so they mainly show a sinusoidal profile with a PV up to 0.04λ in areas with high frequencies in the DOE. It corresponds mainly to a local scaling of the writing stripes. The global aberrations Fig.2(b) show a small astigmatism. Regarding all studied DOEs the typical phase aberration due to pattern deviation is small ($< \lambda/20$).

Fig.2(c-d) shows the measurement of a DOE which was written some weeks before the failure of the positioning system of the machine. Although at that no error was visible with the normal methods, the phase aberration already shows a random positioning error leading to a discontinuity in the local aberration and a strong global error.

References

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