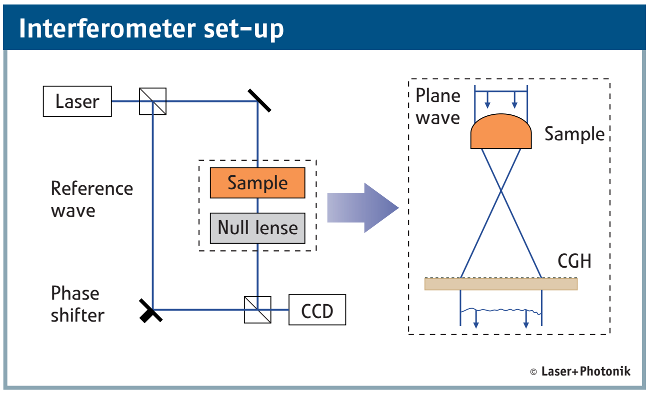
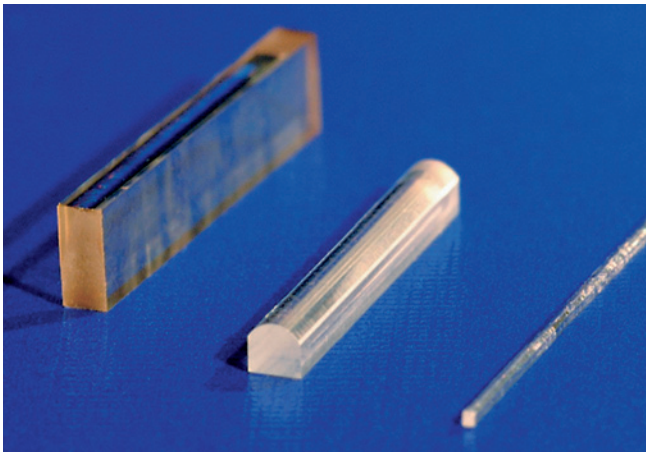
Cylinder Check

INTERFEROMETRICAL TESTING OF CYLINDRICAL LENSES WITH HIGH NUMERICAL APERTURE USING COMPUTER-GENERATED NULL ELEMENTS

Testing the shape of cylindrical FAC lenses is restricted by small dimensions and steep surface angles. The classical null-test in reflection arrangements using a computer generated hologram requires one individual hologram per acylindrical lens shape. Functional testing with transmitting light is a reasonable alternative.



1 Schematic set-up of a Mach-Zehnder-interferometer for testing FAC lenses utilizing a CGH



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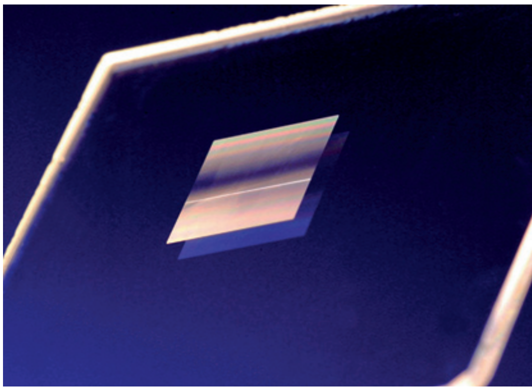
FAC (fast axis collimation) cylindrical lenes (**title picture**) are used for the beam-shaping in high-power diode lasers. Since the demands for beam quality are continuously increasing, the metrology for FAC lenses has to keep pace. The edge-emitting laser diodes output a large divergence angle in one of the two axes perpendicular to the beam direction. Thus, collimating such beams requires a cylindrical lens with a numerical aperture NA > 0.8. The typical length of such mostly plano-cylindrical lenses is about 12 mm allowing for the collimation of several single emitters at the same time. The emitters arranged in a line mainly emit in the near infrared (NIR) region from about 800 to 1000 nm. Common widths of such FAC lenses range to a few millimeters.

The classical test using reflected light and a wavefront adapted to the shape of the surface under test is everything but simple. Refractive null lenses as used for testing spherical or rotation symmetrical surfaces are not available. Hence, only computer generated holograms (CGH) come to question for adapting the wavefront.

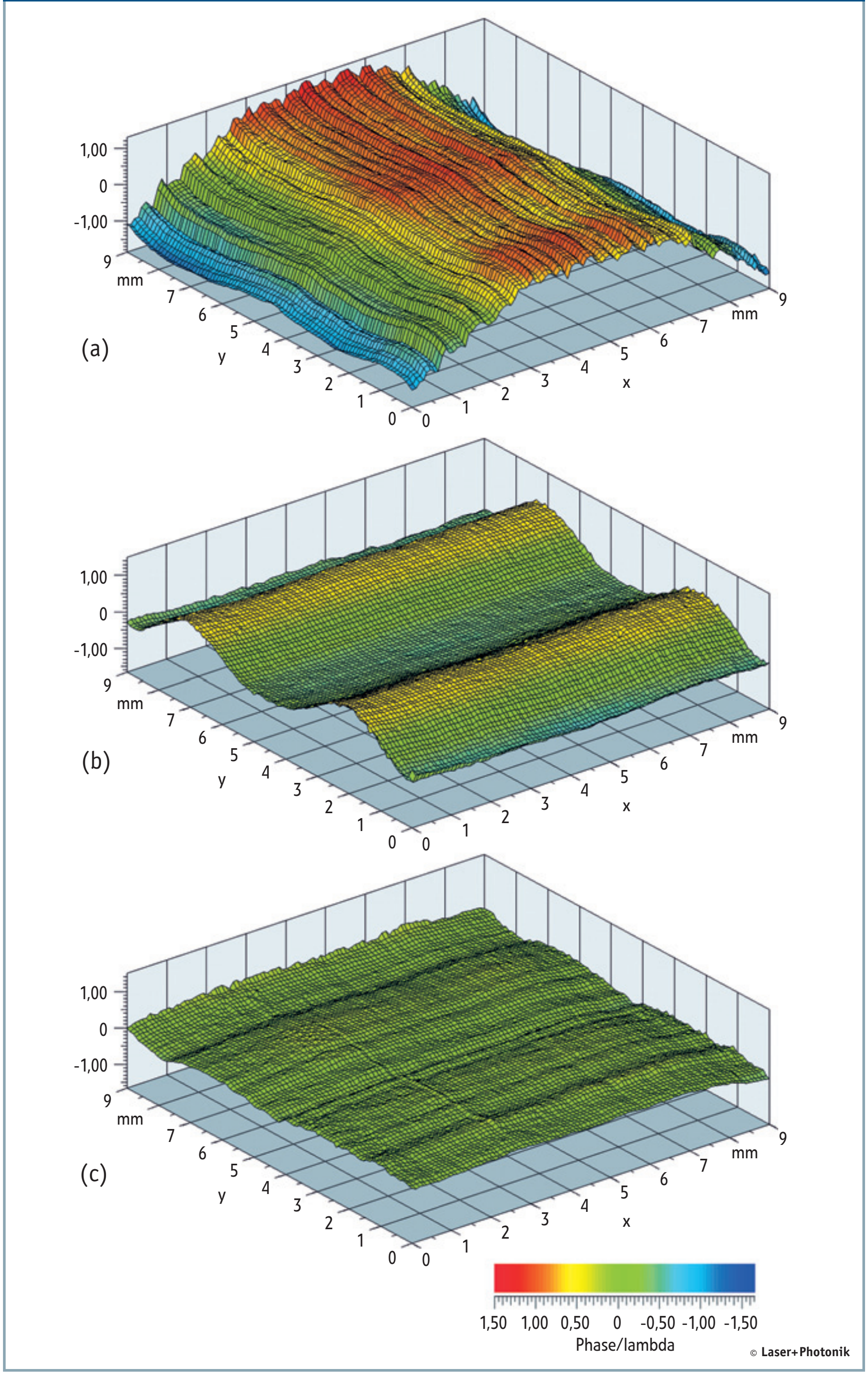
For tests at the classical wavelength of 632.8 nm, grating periods of about 0.73 µm are necessary in the CGH. This is due to the large surface angles of up to 60° at the rim of the FAC lens. The accuracy of lithographically illuminated diffractive optics drops for decreasing grating periods which therefore should be avoided.

Additionally, the lens surface is not a partial area of a cylinder anymore. Consequently, a new individual CGH is needed for each lens type or acylindrical surface shape when testing FAC lenses in reflection. Moreover, the sizes of the CGH structures are already approaching the wavelength, i.e., de-



2 The diffractive null lens (CGH) has a dimension of about 12 x 12 mm^2 and very small grating periods (~ 1 µm)

Wavefront errors of FAC lenses



3 Wavefront errors of different FAC lens samples: The wavefront shows a strong bend and grooves (a, top), one dimensional ›spherical‹ aberration (b, middle) and good planarity (c, bottom). All results have the same scaling along the z-axis

signing the CGH requires taking into account rigorous diffraction effects.

It should be mentioned, that there is another method for testing cylindrical lenses in reflection: gracing incidence interferometry allows for arbitrarily high surface angles. However, this method comprises a reduced and inhomogeneous lateral resolution and requires a pair of CGHs for each acylindrical lens type.

Squaring the rectangle

All FAC lenses collimate light in one direction. Thus, a metrology approach that allows for testing this particular function is universal. One can think of creating an artificial light source with radial characteristics in one dimension by means of a CGH. This ›light line‹ could be used to illuminate the FAC. However, the measurement of the plane wave output of the FAC has a disadvantage. The wavefront shows an unfavourable width-to-height ratio of about 1 : 10. Since the measurement should characterize the complete lens at once, the lateral resolution will be low in the direction of collimation, i.e., perpendicular to the cylinder axis.

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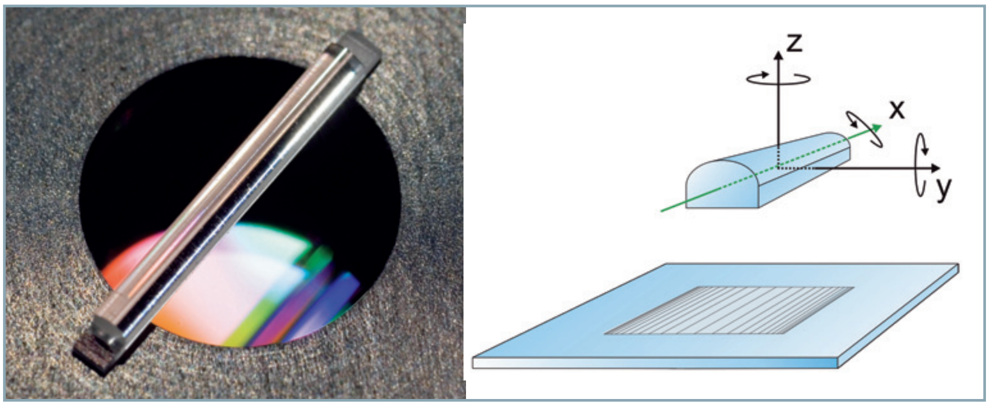
Reversing the light path enables the wavefront propagating through the ›line focus‹ and diverging on the further way. Now it is possible to retransform the diverging cylindrical wave into a plane one using a computer generated (reference) lens or a CGH, respectively. The plane is chosen where the width-to-height ratio is 1 : 1 for example, i.e., where it fits to the sensor chip. The plane wave is now much more easy to measure. Consequently, only one CGH is necessary for all different lens types. The unit comprising the FAC lens and the CGH is built into one arm of a Mach-Zehnder interferometer (**figure 1**). This interferometer type is the first choice for transmission measurements. Evaluating the interferograms and calculating the wavefront errors generated by the lens is made by means of phase-shift interferometery, i.e., moving a mirror in the reference arm. A telescope inside the interferometer is used for both, imaging the wavefront and adaptating the cross section of about 12 mm x 12 mm onto the camera chip. The measurement is preferably performed at the design wavelength in order to avoid systematic wavefront errors. The application of NIR wavelengths has the advantage that the grating periods in the CGH increases proportionally with the wavelength for a given maximum deflection angle. This facilitates the fabrication of the CGH.

Double bent optical path

The functional diffractive surface of the null CGH is fabricated as a binary phase mask (**figure 2**) by means of a litho- ▶



4 Cylindrical lens on adjustment stage above the CGH. In the metrology device, the lens will be adjusted relative to the fixed CGH (left side). Depiction of the relative adjustment of cylindrical lens towards CGH (right side)

▶ graphic process. Besides generating the wanted diffraction order, such binary phase masks also induce additional spurious diffraction orders. Multi-level or quasi continuous phase masks widely reduce higher orders, however such masks do not reach the same wavefront accuracy of binary structures. Moreover, due to small errors in both, duty cycle and etching depth in the hologram structure, the zeroth diffraction order is always slightly present and lets the light pass the CGH without deflection. In particular, the zero diffraction order would significantly disturb the interferometric measurement due to its coherence to the order actually used.

One method to circumvent these disturbances was developed early in the field of holography. The introduction of a carrier frequency along the direction of the cylinder axis will add an additional and individual deflection angle to all diffraction orders and are all spatially separated. The direction of this separation is perpendicular to the effective focussing direction of the CGH. Thus, the different diffraction orders can be easily filtered out by means of an aperture stop in the Fourier plane of the imaging telescope mentioned above. In particular, the used first diffraction order is deviated, i.e., the optical axis is bent. For easy correction of this bending angle, a prism is inserted into the beam path.

The correct lens turn

If diffractive optics like CGHs are applied in interferometers, some aspects have to be taken into account in order to reach high accuracy. The deflection angle a of a CGH is connected to the wavelength λ and the local grating period p via $\sin \alpha = \lambda/p$. Simulations show that especially for CGHs with high NA, the stability and absolute accuracy of the wavelength is critical for the accuracy of the null optic's function. Consequently, the wavelength should have an accuracy close to 0.05 nm. In the visible wavelength range, such values can be reached with e.g. HeNe lasers without difficulty, whereas in the NIR, initially less frequency-stable diode laser sources have to be used.

However, recently, robust and stable DFB diode lasers became available in the required wavelength range. The diffraction effects mentioned above, which cannot be described by scalar approximation anymore, are in principle also occurring in the CGH design used here: An FAC with NA = 0.85 requires deflection angles of approximately 60°. Therefore, the maximum grating period in the CGH will be close to 1 µm for the used NIR wavelength. Simulations using rigorous diffraction theory showed that the error effects in good approximation (better than $\lambda/50$) only result in a small defocus. The defocus is removed during the adjustment process for the measurement of a FAC lens, anyway.

Regarding the symmetry of FAC lens and CGH, it is obvious that five degrees of freedom have to be adjusted during the measurement (figure 3). Besides the shifts along the optical axis and transverse to the cylinder axis direction, all three rotational degrees of freedom have to be adjusted in a way that the interferogram has least fringes. Aberrations due to remaining false adjustment will be removed in the measured wavefront by means of fitting and subsequent subtraction of suitable mathematical functions. The accuracy of the nulling optics (CGH and prism) has been tested at the university of Erlangen-Nuremberg by means of a modified so called 3-positions test. Very good values of better than $\lambda/10$ peak-to-valley could be reached.

Good and Bad

In the following measurement results, it can be be seen that the method can reliably distinguish bad and good FAC lens samples: Figure 4a shows a lens with a strong bend of the transmitted wavefront along the cylinder axis. Moreover, grooves from the manufacturing process are visible in the traverse direction. The sample measured in figure 4b has less roughness, however a one dimensional ›spherical aberration‹ can be clearly seen. A very good lens sample is shown in figure 4c. Here, the RMS wavefront error is around $\lambda/10$. Assuming that the plane backside of the FAC lens only marginally contributes to that errors, the acylindrical front surface can be optimized. These measurements used a NA of 0.78 and a wavelength of 780 nm. ■

Summary: Testing lens designs reliably

The presented Mach-Zehnder interferometer offers a high lateral and axial resolution for the measurement of cylindrical FAC lenses having high numerical aperture. The application of a CGH inside the tool allows for function testing of different lens designs in one metrology system without changing the null optics.

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