Laser-lithography on non-planar surfaces

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Abstract: An extensively modified laser-lithography system specially developed for realization of micro-optical profiles on non-planar surfaces is presented. This extended system offers new possibilities of fabricating micro-optical elements without the technology related restriction of surface shape that existed so far. A diffractive lens on a convex spherical substrate is designed and fabricated as an example for hybrid achromatic refractive-diffractive elements to demonstrate the functionality of the system and the wide range of possible new applications.

OCIS codes: (220.3740) Lithography; (220.4000) Microstructure Fabrication.

References and links

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1. Introduction

Lithographic fabrication methods are well established and used for a multitude of applications in optics. Micro-optical elements such as binary or blazed gratings, microlens arrays, computer generated holograms or arbitrarily shaped diffractive optical elements (DOEs) can be fabricated by binary or gray scale lithography[1]. However, the restriction of standard lithography to planar substrates is a major drawback in modern optics technology and the evasion of this restraint is an important research topic. In the past, a lot of effort has been spent to obtain micro-structures on concave lenses by using conventional lithography techniques. Nevertheless, to avoid shape deviation from the desired structure these fabrication methods are limited to large radii of curvature in the range of hundreds of millimeters [2, 3].

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Another example for patterning non-planar surfaces is the fabrication of hybrid microlenses with small sag heights[4]. Here, microlenses generated by a reflow process of photoresist are structured in a laser lithographic step. The only requirement is the auto-focus system of the laser writer managing to keep in focus while moving the laser spot across the surface, so this concept is limited to sag heights well below one millimeter. To overcome these restrictions a new modified laser lithography system was developed in collaboration with the lithography systems manufacturer Heidelberg Instruments (HIMT). The novel system is introduced in detail in section 2 and enables the structuring of surfaces with high surface sag and small radii of curvature without being limited to rotationally symmetric designs. It allows for new applications like microlens arrays or spectrometer gratings directly being structured on refractive lenses. This possibility of combining different optical functions in one element can significantly reduce adjustment effort, size and price of any optical system. For example, the benefit of using the unique dispersion characteristics of diffractive structures for aberration control in hybrid refractive-diffractive elements has been known for about 20 years[5].
So far, fabrication of micro-structures has been restricted to planar substrates except for the process of diamond turning[6] which on the other hand has the drawback of being limited to rotationally symmetric designs. The advantage of using spherical substrates for arbitrary DOE designs is the possibility to substract the spherical part of the microstructure from the optical function if it is patterned onto a substrate with proper radius of curvature. This obviously leads to a wider range of producible designs. We demonstrate the structuring of a spherical substrate by directly patterning a diffractive lens onto a standard biconvex spherical lens. The design and fabrication issues are discussed in section 3 and its experimental verification is described in section 4.

2. The modified laser-lithography system

In most laser lithography systems the writing spot for exposure is formed by laser radiation that is focused by a fixed microscope lens. The substrate is mounted on a movable x-y-table for positioning the sample according to the predefined pattern to be exposed. For gray scale exposures the intensity of the laser beam is modulated in correlation with the actual position of the spot. Subsequently a wet-chemical development process removes the areas with higher dissolution rates, the exposed areas in case of a positive resist.
To realize lithographic processing of non-planar substrates like lenses, the lithography system has to meet special requirements that are not included in the standard equipment of the lithography system manufacturers. To ensure high quality of the desired structure, the exact positioning of the writing spot on arbitrary locations on the non-planar substrate has to be guaranteed. This requires the ability to tilt the substrate relative to the incident writing beam, so the local surface of the substrate is always perpendicular to the direction of exposure.
Another aspect to account for is the compatibility to the new possible substrate formats. In standard systems the range of substrate thicknesses is limited to a few millimeters, which is not enough to cover for example a range of spherical lenses. So, an additional requirement is to be able to address a wider range of possible sag heights connected to the new choice of substrates. In detail, two tiltable frames turning around perpendicular axes have been included in the standard x-y-substrate table for positioning. Their tilt angle is mechanically limited to $\pm 10^{\circ}$ for each frame. Additionally, the optics plate carrying the laser and the beam modulating optics can be tilted to allow for sag heights of up to 30 *mm* while keeping the optics path constant (see Fig. 1). The three tilting units are interferometrically controlled, and their actual positions have to be dynamically adapted throughout the exposure process.

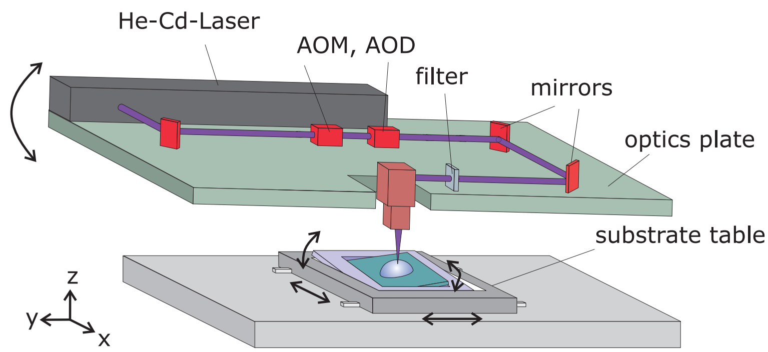

Fig. 1. Sketch of the main functional components of the modified laser lithography system allowing for structuring curved surfaces.

A further point to be considered is the substitution of the standard air-pressure-controlled autofocus system which would not work correctly on curved substrates. An optical autofocus was implemented instead, which operates at 650 *nm*. Finally, all the changes and newly implemented degrees of freedom have to be adequately controlled by the operating software. At least the last two points require a close collaboration with the supplier of the system. Together with the lithography systems developer HIMT the standard laser lithography system DWL400 was strongly modified to allow for the exposure of non-planar substrates. Figure 1 shows a sketch of the main functional components of the newly developed system and its capabilities. The technical data of the new system are summarized in Table 1.
However, the main focus of the current paper lies mainly in the discussion of the system performance and to point out the new possible freedoms in optical design.

Table 1. Technical data of the new laser-lithography system

basis system	DWL400 Heidelberg Instruments
laser	He-Cd, $\lambda = 442$ *nm*
max. writing field	200 *mm* $\times$ 200 *mm*
min. spot size	$\sim$ 1 μm
auto-focus system	optical
writing mode	variable dose, max. 64 level
substrate table	x-y motion and cardanic mount for tilt in 2 orthogonal axis
spot positioning	movement of substrate table and beam deflection
position accuracy: curved substrates planar substrates	 $\leq$ 150 *nm* $\leq$ 50 *nm*
min. radius of substrate curvature	$\sim$ 10 *mm*
max. surface tilt angle	10°
max. surface sag	$\sim$ 30 *mm*
max. writing speed (planar)	10 cm^2/h

The final thing to be modified according to the new features of the system is the software for data preparation and exposure control. Initially the input data to be exposed are defined on

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the tangential plane going through the vertex of the substrate (see Fig. 2). These data are then projected onto the real curved surface by the software, divided into sub-fields, and pre-distorted to make them fit onto the non-planar substrate.

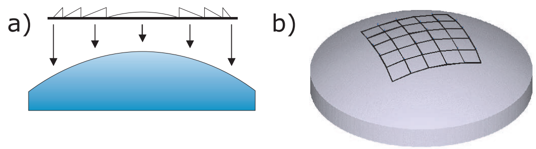

Fig. 2. Data preparation: data are defined in the tangential plane and projected onto the surface (a). The structure is divided into a number of subfields, where each subfield is pre-distorted and exposed separately (b).

Data preparation depends on whether the structure is periodic or not. For periodic designs only the data for one period of the design and the information about the sub-positions on the surface, including the corresponding tilt angles, are needed. The processing of non-periodic designs is time consuming and includes the segmentation of the design as a whole, according to the steps described above. During the exposure process each sub-field is addressed individually. The center of the field is moved into focus by motion of the x-y-table and tilt of the hinged frames. Then the structure of the sub-field is exposed in the same manner as on a planar substrate. The intermediate positioning processes make the exposure on curved surfaces significantly slower than the mentioned value of 10 cm^2/h, which the system reaches when exposing onto planar substrates at maximum resolution. The exact writing time depends on the specific structure geometry and increases for shorter radii and larger number of subfields.

3. Design and fabrication of an example structure

For demonstration of successfully patterning a diffractive structure onto a curved surface a hybrid element was created by adding a diffractive lens to a standard biconvex spherical lens. The aim was to improve the imaging performance and to reduce the chromatic aberrations of the standard lens with a radius of curvature of $R = 52.365$ mm in a simple 1:1 imaging setup shown in Fig. 3.

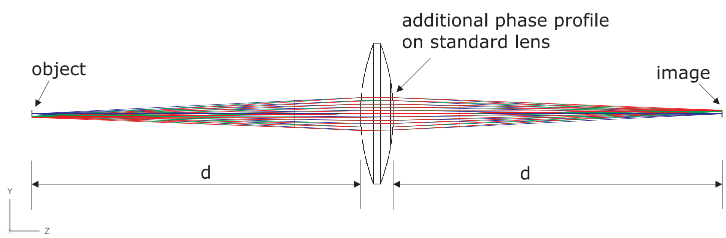

Fig. 3. Design of a simple optical 1:1 imaging setup.

Standard ray tracing software was used to model and optimize the system for a wavelength range of 500 $nm - 600$ nm and a field of view of 2 $mm \times 2$ mm in the image plane. The initial value of the distance from the object to the lens and from the lens to the image was set to $d = 100$ mm. An additional diffractive phase profile of the form $\varphi(r) = \alpha_1(rb)^2 + \alpha_2(rb)^4$ was added to the image facing facet of the lens, with r being the normalized radius, and b the extent

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of the structure (in Millimeters). This leads to a surface profile of the diffractive structure of $\Delta z = \frac{\lambda_0}{(n-1)} \times \frac{\varphi(r)}{2\pi}$ mod1, where λ_0 and n equal the central wavelength of the spectral range and the refraction index of the exposed photoresist, respectively. The parameters d, α_1 and α_2 were left to change during the optimization.

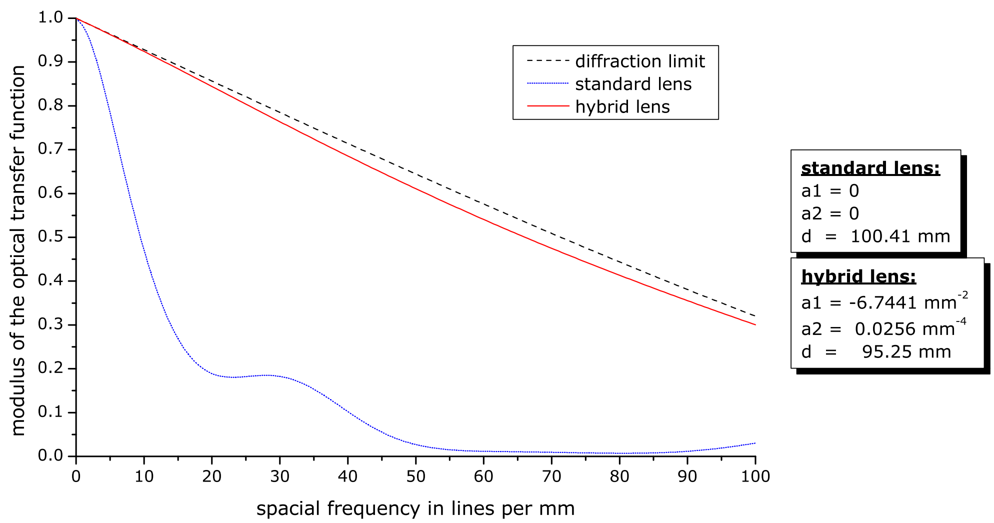

Fig. 4. Comparison of MTF for standard lens (blue, dotted line) and hybrid lens (red, plain line) to diffraction limited performance of an ideal lens (black, dashed line) for a field of view of 2 $mm \times 2$ mm in the image plane. The table on the right shows parameters of the simulation.

The optical performance of the hybrid lens was then compared to the standard lens by evaluating the MTF for polychromatic illumination. Figure 4 shows the simulated values of the MTF and the parameters of the optimization for both lenses in the setup of Fig. 3 compared to diffraction limited performance of an ideal lens. The standard lens shows a rapidly dropping MTF for higher spatial frequencies due to chromatic and spherical aberrations. In contrast, the hybrid lens works close to the diffraction limit because both aberrations could be significantly reduced by the diffractive structure.

The maximum possible diameter b of the diffractive element is determined by the radius of curvature of the bulk lens R and the maximum tilt angle φ of the laser lithography system according to $b = 2\pi R\varphi/180°$, resulting in $b = 18.28$ mm. As the final step in data preparation the complete structure was divided into 31×31 subfields each 600 $\mu m \times 600$ μm in size and pre-distorted by the special conversion software. The standard lens equal to the unstructured one serves as spherical substrate which is spin-coated with photoresist AZ4562.

The method of spin-coating is applicable, because for a ratio of substrate radius to radius of curvature below 0.816 the thickness of the film is nearly homogenous over the sample [7], and in our case good homogeneity is only needed in the area covered by the diffractive structure (resulting in a ratio of about 0.35). The resist coated lens is lithographically exposed by variable dose writing using the modified laser lithography system. In order to save exposure time, the resolution was reduced to 16 dose levels which yielded a total writing speed of about 2 cm^2/h. Subsequently a wet-chemical development process follows, resulting in the desired micro-structured surface profile. Figure 5 shows a photograph of the resulting hybrid element (a) and a microscope image (approximately 5.4 $mm \times 4$ mm in size) of the diffractive element on the spherical substrate (b). Fabrication errors like exposure dose inhomogeneities are visible where the sub-fields connect especially in Fig. 5a), even though their maximum width is well below 2 μm.

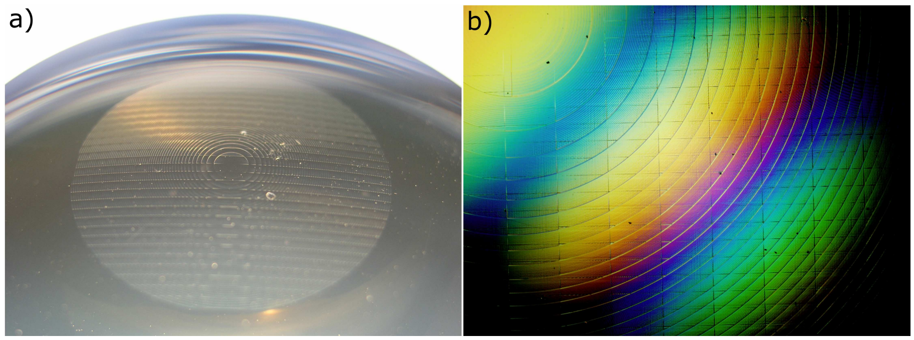

Fig. 5. (a) Photograph of the diffractive element on a biconvex lens. (b) Microscope picture of the hybrid element taken in differential interference contrast mode.

4. Optical testing of the sample structure

The performance of the hybrid element was experimentally tested in the same simple optical setup as shown in Fig. 3. Sinusoidal transmission gratings with frequencies ranging from 1 to 80 cycles per Millimeter serve as objects which are imaged onto a CCD camera by the lens under test. The initial simulation was done assuming the distribution of power of the design wavelengths to be homogenous. However, a measurement of the spectrum of the halogen lamp used as a light source revealed a different situation. The power at 600 *nm* is 5 times and the one at 550 *nm* about 3 times as high as the measured power at 500 *nm*. This result was included into the simulation, so the values of the theoretical MTF change towards higher modulation values. The results of the measurement compared to the adapted simulation are shown in Fig. 6.
A significant improvement of the MTF for the hybrid element compared to the one of the pure lens is observable.

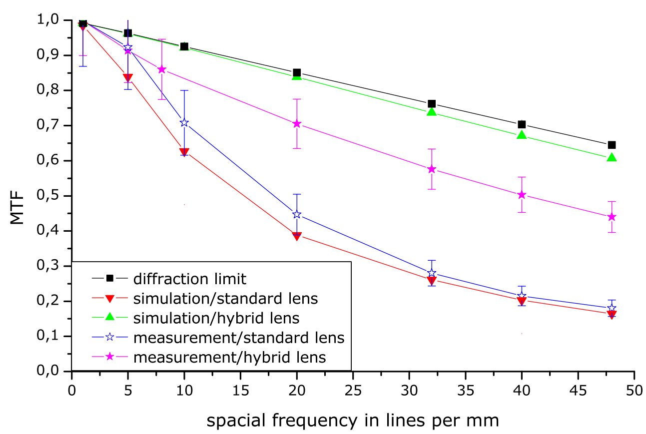

Fig. 6. Comparison of theoretically and experimentally obtained polychromatic MTF for the standard and the hybrid lens.

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The MTF values of the standard lens show good agreement to the theoretical values, whereas the hybrid element produces lower modulation values than predicted by the theory. This might be due to the difficulties in adjusting the lens in the measurement setup but also because the micro-structure is not perfectly centered on the substrate lens, which is crucial for good performance. The centering can be improved by using a special substrate holder. An additional effect degrading the modulation values of the hybrid lens is the diffraction efficiency ε of the structure. It is lower than unity due to inhomogeneities inherent to the laser-lithography process and the fact that the structure height can only be matched exactly for one wavelength of the spectral range (preferably the center wavelength).
The maximum achievable diffraction efficiency for blazed gratings produced by our laser lithography system was measured for sample gratings fabricated on planar substrates. The result for standard direct writing mode is shown in Fig. 7 for a range of grating periods. Due to the sampling with a discrete number of pixels with a minimum size of 200 *nm* and the finite size of the writing spot the efficiency for high frequency gratings with a period length of 5 μm is only $\varepsilon = 0.59$. Rising the period to 100 μm results in an enhancement of performance up to $\varepsilon = 0.94$. The minimum and maximum grating period of the designed diffractive lens is 80 μm at the edge and about 360 μm in the center of the structure, respectively, resulting in an averaged efficiency of about $\varepsilon = 0.95$. It is assumed that the efficiency does not decrease when structuring curved surfaces because within the subfields the change in size of the writing spot is negligible.

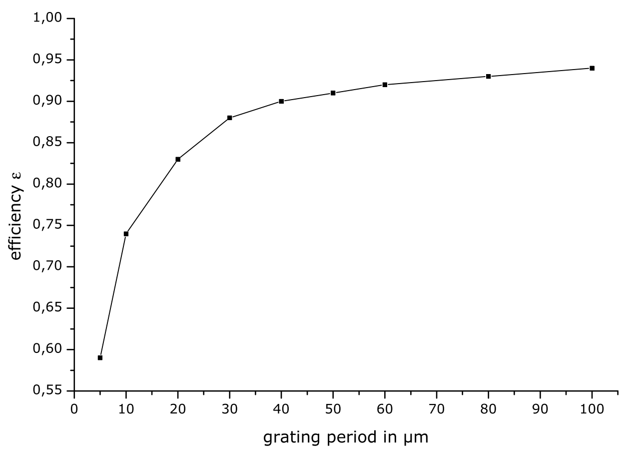

Fig. 7. Maximum diffraction efficiency for blazed gratings with varying grating period which were fabricated by our laser lithography system on planar substrates.

To account for the wavelength dependence, the efficiency of blazed gratings in the small-angle approximation can be calculated using Eq. (1) [8]:

$$\varepsilon(m,\lambda) = sinc^2 \left\{ \pi \left[m - m_o \frac{\lambda_o}{\Delta n(\lambda_o)} \frac{\Delta n(\lambda)}{\lambda} \right] \right\}, \tag{1}$$

with m being the diffraction order, λ the wavelength and Δn the difference of the refractive indices of the material and the surrounding medium. m_o and λ_o indicate the values of the parameters for which the system is designed to be 100% efficient. Ideally for the diffractive part of the hybrid lens this would be at the center wavelength of 550 *nm*. However, due to a mismatch in structure depth (1 μm instead of 900 *nm*) λ_o was set to 610 *nm*. The values for 500 *nm*, 550 *nm* and 600 *nm* were weighted with the spectral intensity distribution of the used light source, resulting in an average efficiency of $\bar{\varepsilon} = 0.96$ for the diffractive structure. Both effects, the reduction of efficiency due to writing spot size and wavelength mismatch, result in a theoretical value of about $\varepsilon = 0.91$ for the expected maximum total efficiency. Stray light measurements using an integrating sphere reveal that only about 93% of the light passing the hybrid element are directed into the first diffraction order of the lens. The rest is mainly scattered into a solid angle of about $\pm 10^\circ$ around the optical axis. This measurement shows good correlation with the expected efficiency value.

The effect of the stray light on the MTF-values can be estimated to be in the order of magnitude of 10% by accounting for the stray light by an offset value in the contrast calculation given by $(I_{max} - I_{min})/(I_{max} + I_{min})$. Thus, including the effect of stray light yields a better match of the theoretically expected and experimentally observed results.

In summary the performance of the hybrid lens is reduced by a stray light level. However, it shows a significantly better performance than the uncorrected lens, the modulation in image space has doubled for spacial frequencies from about 20 to 50 cycles per millimeter.

5. Conclusion

A strongly modified laser lithography system was presented that allows the implementation of standard lithographic fabrication methods on non-planar substrates for realization of high quality optical microstructures. For demonstration purposes a color-corrected hybrid lens composed of a refractive and a diffractive element was created, which offers the possibility of achromatic and aspheric correction in a single element.

Other conceivable applications include gratings on concave lenses used for spectrometric tasks or microlens arrays on non-planar surfaces. In order to produce durable elements with higher optical quality than resist structures the applicability of replication techniques to non-planar surfaces has to be investigated in further research work.

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