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Limiting the number of quantisation levels of a harmonic lens as a method for improving the quality of the generated image

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Abstract. **The characteristics (modulation transfer functions) of harmonic lenses made by direct laser patterning of resist are experimentally studied. The influence of technological errors in the manufacture of lenses on the formation of the point spread function is modelled for harmonic lenses with 32 and 256 quantisation levels. Direct laser writing is used to produce lenses with these numbers of levels. It is experimentally shown that the modulation transfer function of the harmonic lens with 32 quantisation levels is significantly greater at high spatial frequencies (50 mm^{-1}).**

Keywords: *diffractive lens, harmonic lens, quantised microrelief, modulation transfer function.*

1. Introduction

The progress of the technology of direct laser writing of microreliefs higher than 1 μm has made it possible to make diffractive [1, 2] and harmonic [3] lenses which approximate practically any aspherical surface [4]. In the formation of images with such lenses, chromatic distortion is still quite large [4–6], but it becomes smaller with increasing relief height [3]; therefore, the obvious way to reduce chromatism is to increase the height of the microrelief. However, this gives rise to a new source of distortion – an appreciable increase in the absolute value of the deviation of this microrelief from the calculated one [7], which is due to the granularity and the nonlinearity of resist properties, the instability of laser power, as well as errors in the laser-beam power control system. The relative deviation of the microrelief height remains invariable and is only about 1% in areas with a smooth surface. This value of the relative error has the effect that the absolute deviation of the microrelief surface from the calculated one is 50–60 nm for a relief height of 6 μm. On the face of it, this error is small. However, given that the deviations are stochastic and change with each writing step (1 μm), the surface slope changes quite strongly. The calculation of the focusing in the ray approximation with such a lens shows a significant broadening of the point spread function (PSF). As an alternative to smooth microrelief we propose the use of a microrelief with a limited number of levels. In this case, the local microrelief slope is determined by the location of levels and hardly affects the PSF width.

However one cannot reduce the number of quantisation levels too much either. Since the microrelief height of a harmonic lens is equal to 6 μm, for a design wavelength of 550 nm the phase function changes approximately six times by 2π. Since an unambiguous definition of the wafefront slope necessitates at least three quantisation levels per each 2π of the phase function, their minimal number is 18. In this work we decided to use 32 quantisation levels as the minimal power of two greater than 18. Most likely, there exists some optimal number of quantisation levels, but its search requires additional investigation.

The effect of phase function quantisation on the performance of focusing diffractive optical elements (DOEs) was first described in Ref. [8] (in greater detail, in Chapter 5 of monograph [9]). To estimate the performance of focusing DOEs, Volkov et al. [9] used is the diffraction efficiency of focusing and the root-mean-square deviation (RMSD) of the resultant intensity distribution from the requisite one. For other DOE types, Volkov and Skidanov [10] proposed the use of the RMSD for intensity distributions obtained for a perfect optical element and the one under study. The estimate was performed employing the calculated light field in the DOE's operating domain. Volkov and Skidanov [11] studied the effect of quantised etching errors on the formation of intensity distribution by diffractive lenses. However, they considered the idealised case of equal errors in the formation of a set of levels in the quantised etching. When use is made of direct laser writing, the errors in the formation of individual levels will affect only the diffraction efficiency. In the present work we consider the effect of technological errors on the formation of intensity distribution and diffraction efficiency of diffractive lenses with different numbers of the levels.

2. PSF simulation for harmonic lenses

The PSF was simulated in the framework of geometrical optics by ray-tracing of the parallel rays passing through the lens aperture. To carry out the simulations, we calculated two harmonic lens surfaces (with 256 and 32 quantisation levels) with diameters of 10 mm and focal distances of 55 mm at the principal wavelength of 550 nm; the microrelief height was 6 μm. Figure 1 depicts the radial surface cross sections of the central regions of these lenses.

To imitate technological errors, deviations equal to 1% of the microrelief height were artificially added to the design cross sections. The resultant surface cross sections are not given in the paper, because there is no way to visually discern

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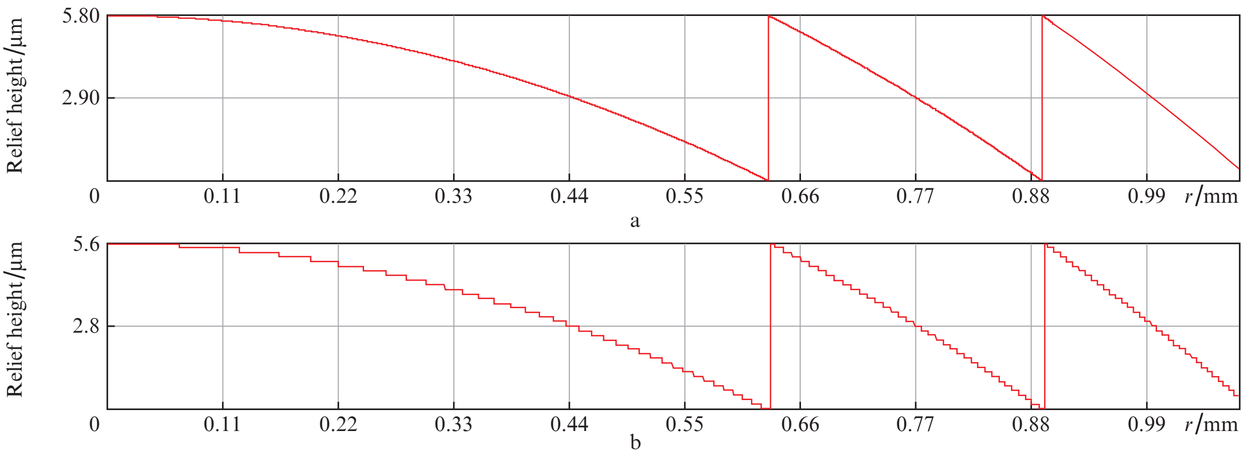

Figure 1. Radial surface cross sections of the central regions of harmonic lenses with 256 (a) and 32 (b) quantisation levels.

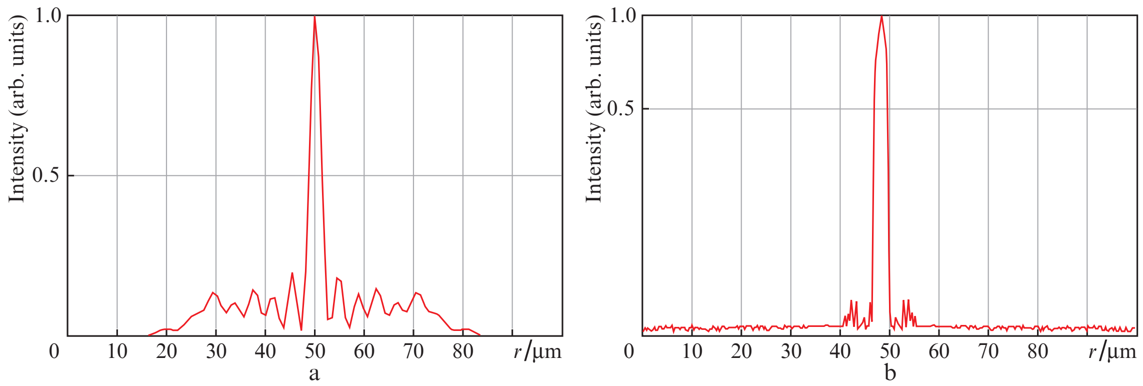

Figure 2. Radial PSF cross sections in the focal planes of harmonic lenses with (a) 256 and (b) 32 quantisation levels.

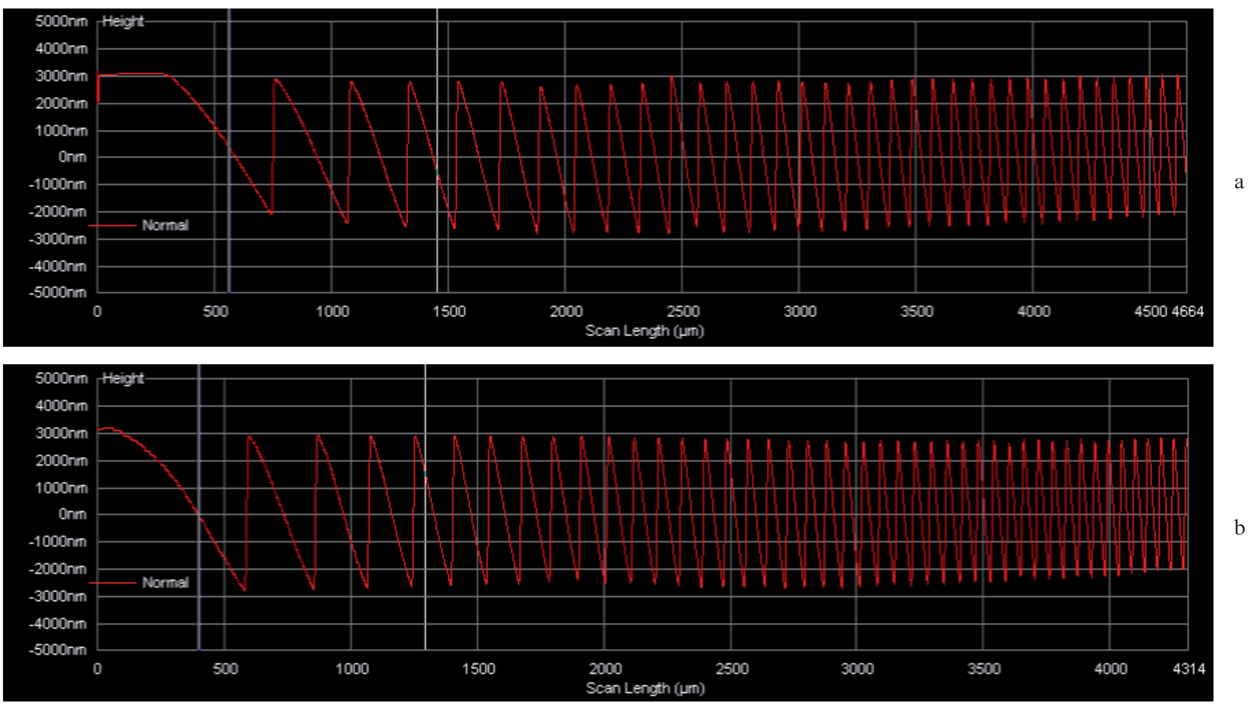

Figure 3. Surface microrelief profilograms for harmonic lenses with (a) 256 and (b) 32 quantisation levels measured with a Tencor profilometer with a resolution of 1 μm.

the curves with this relative error level. The resultant surfaces were employed for the subsequent ray-tracing with a large number ($\sim 10^7$) of parallel rays with the use of the software developed specially for harmonic lens simulations. The lens simulation data are given in the form of the radial cross sections of the PSFs in Fig. 2 (in Fig. 2b, use is made of the logarithmic ordinate scale to demonstrate the existence of background illumination around the central peak). On the ordinary scale, the average level of the background illumination amounts to less than 0.1% of the maximum value and is not discernable in the drawing.

As follows from Fig. 2, the lens with 32 quantisation levels exhibits, on the whole, a better PSF, since the technological surface irregularities scatter light almost evenly over a large area. Because of technological errors, the lens with 256 quantisation levels produces a broad light spot about the central maximum, which is comparable in intensity with the maximum itself. This PSF form should lead to impairment of the modulation transfer function for the lens with 256 quantisation levels. We carried out an experiment to verify this effect.

3. Fabrication of harmonic lenses with 32 and 256 quantisation levels and experimental comparison of the modulation transfer functions of both lenses

To perform experiments, two harmonic lenses with the design surfaces were made by direct laser writing. Figure 3 shows the lens profiles measured with a Tencor profilometer.

As stated above, the existence of technological microrelief errors for a small relative error has a significant effect on the PSF. By way of illustration, the first derivative of the profilogram with respect to the radial coordinate is plotted in Fig. 4a for the entire lens size and in Fig. 4b only for the central region.

As is seen in Figs 3 and 4, by and large, the resultant microrelief is almost void of noticeable errors, while the plot of the first derivative with respect to the radius shows that the microrelief slop error is comparable with the slope itself, especially so in the central regions of the lens (see Fig. 1b). This signifies that different areas of the lens will focus the light at distances that do not coincide with the design focal distance. In this connection, we conceived the idea to artificially limit the number of harmonic lens levels, so that the technological errors will result only in an increase in the light scattering coefficient of the lens but will not change the PSF width.

Figure 5 shows the optical setup used in the experiment. Figure 6 shows the image of a conventional black-and-white pattern deposited on a transparency for testing the lenses.

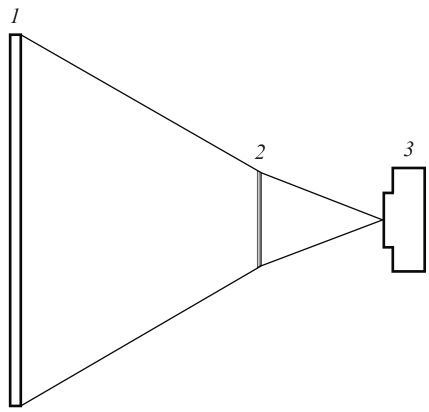

Figure 5. Optical setup for image formation with harmonic lenses: (*1*) patterned transparency; (*2*) harmonic lens; (*3*) ToupCam UCMOS03100KPA recording camera.

The images of inclined strips in the lower part of the pattern served as the target area. The modulation transfer functions (MTFs) of both lenses were determined from precisely these strips. Figure 7 depicts the target areas of the pattern shown in Fig. 6.

As is seen in Figs 7c and 7d, the lens with 32 quantisation levels provides a slightly higher-contrast image of the high-frequency areas of the striped image. With the use of the images in Figs 7a and 7b, we measured the MTFs of the lenses

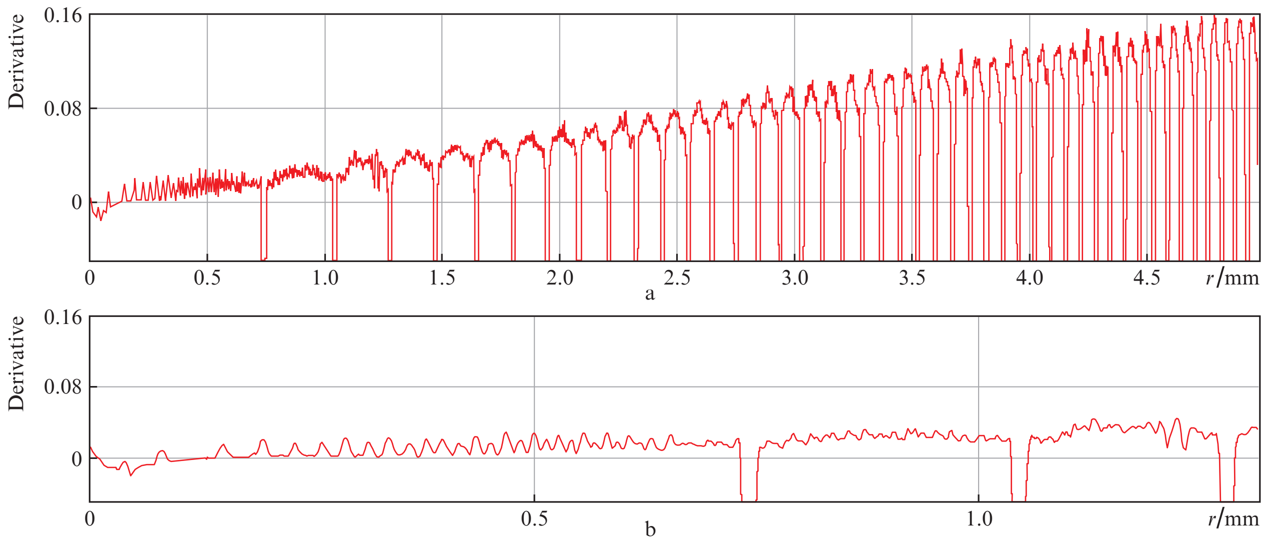

Figure 4. First radial derivative of the microrelief profilogram for a harmonic lens with a focal distance of 55 mm and a microrelief height of 6 μm (the peaks correspond to zone boundaries) (a) and a part of dependence *a* for the central lens region (b).

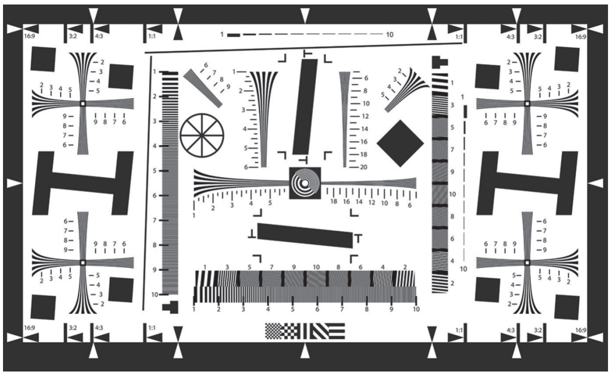

Figure 6. Image of the black-and-white pattern used for lens testing.

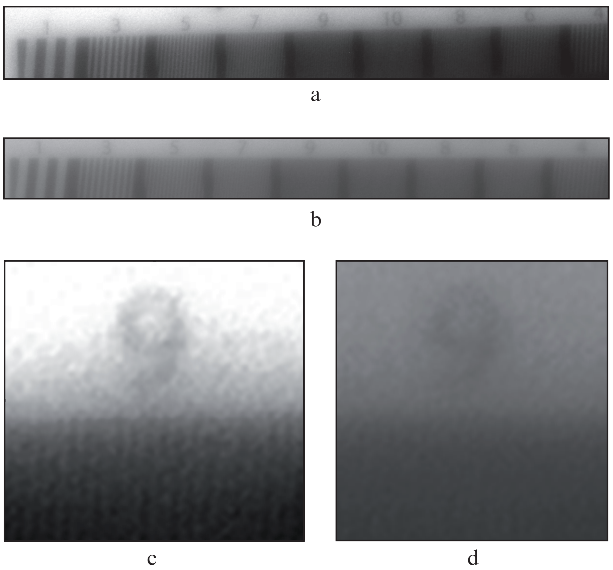

Figure 7. Images of the target pattern areas formed using the lenses with (a, c) 32 and (b, d) 256 quantisation levels.

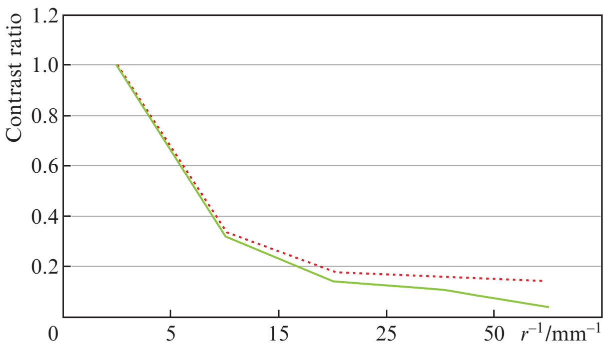

Figure 8. MTFs for the lenses with 32 (dotted line) and 256 (solid line) quantisation levels.

with 32 and 256 quantisation levels. The MTFs are plotted in Fig. 8.

As is seen in Fig. 8, the MTF of the lens with 32 quantisation levels is significantly better than the MTF of the lens with 256 quantisation levels. The greatest difference in the values of the modulation transfer functions is observed at high frequencies: specifically, at a frequency of 50 mm^{-1}, for the lens with 32 quantisation levels this function is equal to 0.14, while for the lens with 256 quantisation levels it is only 0.04.

4. Conclusions

The simulations of light focusing by harmonic lenses with 32 and 256 quantisation levels suggest that the PSF of the harmonic lens with 256 levels shows a broad domain in which the intensity is comparable with that of the central maximum. For the harmonic lens with 32 levels this broadening is not observed. This gave grounds to believe that employing the harmonic lens with 32 levels will improve the MTF at high frequencies. Our experimental comparison study of the modulation transfer functions of the harmonic lenses with 32 and 256 quantisation levels bore out the conclusions drawn in the simulation of imaging by harmonic lenses with different numbers of quantisation levels. Specifically, when using the harmonic lens with 32 quantization levels, the image quality is undoubtedly better than in the case of 256 levels. The strongest influence is observed in the domain of high spatial frequencies: at a frequency of 50 mm^{-1} there is an almost fourfold difference between the MTF levels (0.14 for a lens with 32 levels and 0.04 for a lens with 256 levels).

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