Modified method of direct laser writing radially symmetric structures

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Abstract. We proposed and modeled a modified direct laser photoresist recording method. The method is based on using a planar-parallel plate to shift the writing beam. We carried out an experimental study on the recording of radially symmetric structures by a beam with a shifted focusing.

1. Introduction
Methods of laser recording microrelief are the most widespread and universal for forming the topology of photomasks of different purposes: diffraction elements, angular scales, grids, etc. The laser recording technology makes it possible to form diffraction microstructures in lithium niobate crystals [1,2], photoresist [3-5], in chrome films [6-8], molybdenum films [9,10], silica [11].

Direct laser recording is applied both for 1D [2], 2D and 3D structures [1]. In article [1] the universality of the direct femtosecond laser recording method for microstructures with iron impurity in lithium niobate crystals is demonstrated. Non-destructive photomodification allows you to completely or partially erase/delete/remove or modify previously recorded structures. In article [2], phase diffraction structures are formed in lithium niobate crystals with surface doping/alloying by photorefractive impurities. They used the procedures of point-wise sequential exposure of the photosensitive region by laser radiation and its parallel exposure through a one-dimensional amplitude transparency. Electron beam lithography is one of the technologies that make it possible to achieve ultrahigh resolution. The resist is exposed by deflecting the beam and does not require the use of masks, which is the main advantage of this technique. In article [3] the method of microrelief formation by direct electron-beam etching of the resist is proposed. This method makes it possible to obtain a masking image in a resistive dry one-stage vacuum exposure process, accompanied by a simultaneous development of the image. This is achieved by direct etching of the resist and turning it into volatile products directly when exposed to the electron beam in the exposed areas. The method is suitable/appropriate for obtaining micro- and nanostructures with a rounded cross-section profile and for obtaining 3D spatial structures with good accuracy of vertical image dimensions and low surface roughness [4]. The main disadvantage of electron lithography is its low productivity. Thermochemical oxidation of chrome is the most developed and widely used method of fabrication lithographic masks and diffractive optical elements (DOE) [6-8]. Work on the further development of the additive method of manufacturing the microrelief of phase gratings on molybdenum film appeared relatively recently [9, 10]. The proposed technology consists in the thermal oxidation of a mask based on a thin metallic layer of molybdenum (15-70 nm). Then the substrate is etched through the resulting mask. The main disadvantage of recording structures with the technologies considered is a small size.

Currently, one of the best recording methods for a large raster is the recording of radial structures by direct laser recording. A circular laser writing station (CLWS) was developed in Novosibirsk. The
principle of operation of the station is based on the formation of a pattern by a focused laser beam on a rotating glass substrate with chrome film or photoresist film [12]. The new generation of CLWS allows to record diffraction optical elements (DOE) on spherical surfaces with a wavefront error less than $\lambda/100$ [13]. The recording of a multilevel microrelief of phase DOEs on photoresist films and amplitude photomasks on thin chrome films is realized with the help of two lasers.

2. Modified method for recording radially symmetric structures

There is a problem of obtaining vertical surfaces for the recording of radially symmetric structures due to the characteristics of the CLWS. As a result, the aperture ratio of lens decreases and a limiting aperture ratio of lens for short-focus systems appears.

Figure 1 shows the microrelief deviations at the points of abrupt profile change. Deviations are less than 50 nm in other places, which corresponds to the optical quality of the surface (less than $\lambda/10$).

![Figure 1. Profilogram of the manufactured lens (a free line) and the curve of the modeled profile (broken line).](image)

It is necessary to modify the recording method by shifting the laser beam entering the microobjective to record vertical surfaces in the microrelief. The symmetrical focusing cone should turn into an asymmetric cone as a result of this displacement (Fig. 2). The vertical surface of the resist will not be exposed to light when recording in a certain direction. The simplest and fastest way to shift the beam without radical changes in the design of the CAM is the installation of a plane-parallel plate at an adjustable angle (Fig. 2) in front of the lens to shift the recording beam. Figure 2 shows the displacement of the beam as the tilt angle of the plate changes.

Light refracts twice passing through a plane-parallel plate. As a result, the beam displaced in such a structure is parallel. The beam displacement in such a structure is determined by the formula (1):

$$x = h \sin(\alpha)$$

(1)
Unfortunately, we lose some of the energy due to Fresnel reflection when installing the plate. The ratio of reflected light depends on the displacement of the laser beam, which must be obtained.

Figure 3 shows that the minimum displacement is determined by the beam size (the beam is displaced by half the size), and the maximum displacement is determined by the aperture size (the beam is shifted to the edge of the aperture). We calculated the minimum and maximum tilt angles of the plate (the size of the entrance pupil is 5.05 mm, the laser beam at focusing is 2.1 mm (parameters of the CLWS)). The tilt angle variation range of the plate is from 32° to 57°.

The reflection coefficients for s-polarization and p-polarization are determined by the formulas:

\[ R_s = \frac{\sin^2(\gamma - \theta)}{\sin^2(\gamma + \theta)} \]  
\[ R_p = \frac{\tan^2(\gamma - \theta)}{\tan^2(\gamma + \theta)} \]  

The ratio of reflected light are from 9 to 15% (depending on the polarization) when the beam is shifted to the minimum angle, and at a maximum angle of about 25%. In this case, the thickness of the standard substrate is not enough to shift the beam to the edge of the aperture.

We simulate the photoresist recording process by shifting the recording beam with a plane-parallel plate.

Figure 4a shows that the axis of the laser beam passes through the center of the lens. Neither the right side nor the left side of the exposed area is vertical. We have displaced the axis of the laser beam along the x axis so that the beam with the smallest x coordinate passes through the center of the lens, that is, \( x_0 = 3 \) (Fig. 4b).

The cant of the left side of the exposed area became a reverse tilt angle after displacement compared to the previous position (Figure 4b). We raised the lens to minimize the sharp slope on the upper layers of the photoresist (Figure 4c). It can be seen from figure 4 that there is no sharp slope on the upper layers of the photoresist, but there is still a imperceptible cant to the left. However, the inclination angle of the left side almost does not change when the axis of the laser beam is displaced to the left and the micro-lens height is adjusted (Figure 4d).

We consider the photosensitivity of the resist to simulate the recording process. Photosensitivity is a quantity that is inverse to the amount of absorbed light energy required to obtain a certain photochemical effect in a given photoresist layer (loss of solubility of exposed areas in a negative photoresist or the acquisition of solubility of exposed areas in a positive photoresist):

\[ S = \frac{1}{I \cdot t} = \frac{1}{H} \]  

where I is the exposition intensity of the photoresist layer of thickness h, in which the required photochemical effect occurred; t is the exposure time; H - exposure. The physical meaning of this criterion is that the less exposure is required to change the solubility of the layer to a depth of h, the more photoresist is photosensitive. Most photoresists have a photosensitivity to the ultraviolet region of the spectrum in the range from 300 to 500 nm.
Figure 4. Ray tracing and the energy distribution absorbed by the photoresist for the parameters given in Fig. 2 (a), for the displaced beam by $x_0 = 3$ (b), for the displaced beam by $x_0 = 3$ and the lens at $y_1 = 4.6$, for the beam with $x_0 = 2.8$ and lenses with $y_1 = 4.6$.

In this paper, the photoresist is exposed by radiation with a wavelength of 355 nm. We can obtain an accurate characterization of photosensitivity with consideration of the processes of both exposure and manifestation. The exposure process influences the photoresist photosensitivity, since the developer chemically interacts with the exposed and unexposed areas of the photoresist. The photoresist photosensitivity as a function of its thickness is shown in Fig. 5.

Figure 5. Dependence of the threshold dose for photoresist AZ 3027 on the thickness of the film.

Figure 6 shows the results obtained in the dynamic model with consideration of the photoresist AZ 3027 parameters and the recording parameters of the binary microrelief.
Fig. 6 shows that the process of recording a displaced beam forms a microrelief with almost vertical surfaces. Deviations from the vertical are only in the lower part of the microrelief (this is due to the low power of beam).

We performed an experimental recording with a shifted beam using simulation results. We added a device with a plane-parallel quartz plate 2 mm thick (Fig. 7) to the optical circuit of the CLWS. We can change the tilt angle to shift the beam with this device.

The profilogram of the axicon obtained after recording by the displaced beam is shown in Figure 8.

Fig. 8 shows the effect of increasing the tilt angle from the side opposite to the displacement of the recording beam. This is qualitatively consistent with the results of modeling. In Fig. 9, the tilt angles of the surfaces are schematically indicated.

The values of the tilt angles on the left and on the right differ when the recording beam is deflected by 6 degrees. The right angle is 28% greater than angle on the left, $\alpha = 36.4$, $\beta = 26.4$. We have demonstrated a qualitative effect of increasing the tilt angle of the surface approximating the vertical when recording with a displaced beam.
3. Conclusions

The method of direct laser photoresist recording based on the use of a plane-parallel plate for the displacement of the writing beam is modified. Decrease of efficiency is compensated by a change in the area of exposure of the photoresist (the volume of the photoresist is reduced). Therefore, the ratio of reflected light have almost no effect on the recording speed. The modeling of the recording process in a shifting beam is carried out and the principal possibility of obtaining an almost vertical surface in the resist is shown. The results of the natural experiment qualitatively confirm the results of the simulation.

4. References

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