Semiconductor Physics, Quantum Electronics & Optoelectronics. 2003. V. 6, N 2. P. 249-253.

PACS:

Synthesis, recording and metrology of laser beams with phase singularities

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Abstract. The main task of the work was obtaining the high efficient diffraction elements to generate high quality laser beams with phase singularities. The method of recording such diffractive structures on the organic photoresist and further replication to the transparent and reflective materials is described. Off-axis and on-axis holograms of optical vortices with different topological charges were computer generated and recorded. The exposure characteristics of the photoresist Shipley S1800 was investigated. The maximum achieved diffraction efficiency was 30 % (for the normal incidence case). The quality of the intensity and phase distribution was investigated. As criteria of the beam quality we accept the relative coincidence between experimental and theoretical data. We assume that ratio more than 0.8 indicates the good fitness. For this assumption over 90 % of the beam energy produced by our computer generated hologram (CGH) concur with theoretical distribution. Our diffraction elements recorded on photoresist are much better that ones recorded on silver emulsion. They were successfully used in the experimental investigations in our laboratory.

Keywords: optical vortex, computer-generated hologram, photoresist, quality of the intensity distribution.

Paper received 25.02.03; accepted for publication 16.06.03.

1. Introduction

In the recent years the beams with phase singularities are attend great attention to themselves. The helical wavefront beams play special role [1][3]. There are several methods of generation of beams with vortices: high laser mode generation, nonlinear interaction with media, zone plates etc. Such methods characterize with high efficiency and quality of transformation [3]. However, the significant disadvantage of these methods is either difficult realization or limited number of wavefront distribution topology that could be obtained.

From our point of view, the most versatile and simple method of generation of beams with predefined phase distribution is computer-generated hologram (CGH) [4]. The main task of our project was to develop the technology of obtaining such holograms on different materials by means of photolithography technique. In our very first experiments we synthesized simple beams with screw wavefront dislocation of charge one. But, the method allows to obtain the beams with predefined amplitude and phase distribution of highest complexity.

The complex amplitude of beam with screw dislocation could be given in the following form [2]

$$E(\rho,\varphi,z,t) = E_0 \frac{w_0}{w}\left(\frac{\rho}{w}\right)^{|m|} \exp\left(-\frac{\rho^2}{w^2}\right)\times$$
$$\times \exp i\left[-\left(|m|+1\right)\arctan\frac{z}{z_R}+\frac{k\rho^2}{2R(z)}+m\varphi+kz-\omega t\right], \qquad (1)$$

where ρ, φ, z are the cylindrical coordinates, k is the wave-number, w_0 is the waist parameter of the beam, $z_R = \frac{kw_0^2}{2}$ is the Rayleigh range where the cross size of the beam $w = w_0\left(1+z^2/z_R^2\right)^{1/2}$ increases $\sqrt{2}$ times and m is the topology charge of the beam. For $m = 0$ Eq. (1) describes the Gaussian beam.

If we add the reference flat wave that propagates under angle θ to the z-axis than we obtain interference fringes. The condition for interference maxima is:

$$\cos\Big[-m\varphi-\frac{k\rho^2}{2R(z)}-(|m|+1)\arctan\frac{kw_o^2}{2z}+$$
$$+k\rho\cos\varphi\sin\theta-2kz\sin^2\frac{\theta}{2}+(|m|+1)\frac{\pi}{2}\Big]=1\,. \qquad (2)$$

Eq. (2) could be used for diffractive devices calculation. When illuminated with reference wave they generate vortex beam with charge m [1].

2. Experiment methods

The technique we used was photolithography of binary mask (black/white). As the media for recording, we utilized the Shipley S1800 photoresist. This material has maximum of sensitivity in the blue range of spectrum. So, for the mask illumination He-Cd laser was used with the wavelength of 442 nm.

The binary masks were printed by photocomposer with resolution up to 3600 dpi (70 mm^{-1}) (Fig. 1). This is the highest resolution for this apparatus. The reduction factor of photolithography has been 10 times that made it possible to achieve the spatial frequencies up to $N = 700\ \mathrm{mm}^{-1}$. In our experiments the common resolution was about 200 mm^{-1}. For the sampling of the interference fringes we need to reserve not less than two samples for one spatial period (in our case we limited it to three).

In our scheme we used the objective that has resolution of 1300 mm^{-1} (Fig. 2). The main obstacle that we have been faced to was the system focusing. The depth of focus is inversely as the square of system resolution $\Delta z \approx N^{-2}$ [5] and for 200 mm^{-1} it is only 78 mkm (Table 1).

Table 1. The focus depth dependence on system resolution [5].

N, mm^{-1}	Δz, mkm
100	300
200	78
400	19
500	12
650	7
1000	3

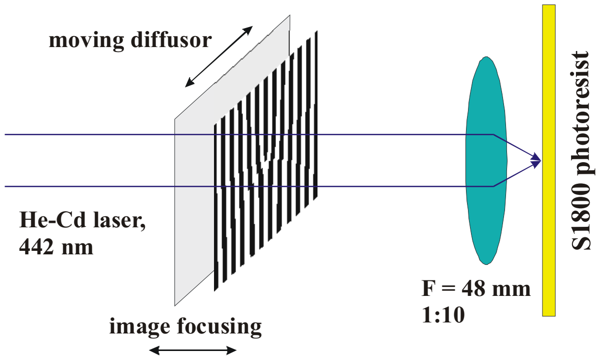


Fig. 2. The elementary scheme of CGH recording.

After developing process, the relief is formed on the surface of the photoresist. This relief is very sensitive to mechanical damages. But it could be replicated on the nickel by electroforming technique. In such a way we obtain reflective diffractive device that is resistant to the mechanical and high power laser's exposures. In case this nickel die could be used for embossing to obtain copies of the CGH on the transparent polymer film in any quantities. It should be noted that the optimal relief height for transparent devices is twice as for the reflective ones.

The vortex observation was realized by means of interference scheme. On the Fig. 3 there is pictures of vortex with topology charge 1 (Fig. 3a) and it's on-axis interference pattern (Fig. 3b).

To obtain the maximal possible efficiency of recorded CGH and thus the maximal brightness of the singular beam we should choose the correct exposure and developing parameters for the photoresist. On the Fig. 4 there is exposure curve for the Shipley S1800 photoresist. The height and the profile of the relief were measured by means of atomic force (AF) microscope (Fig. 5).

3. Results and their discussion

The main task of the work was recording the high efficient diffraction elements to generate high quality laser beams with phase singularities.

We achieved diffraction efficiency of 30 %. The maximum theoretically possible value of diffraction efficiency for this type of the hologram is 33.9 % [9][6]. The higher diffraction efficiency could be achieved on the gratings with non-symmetrical profile (kinoform). In the paper [7] Yoko Miyamoto and etc. used e-beam lithography technique for this. They recorded the gratings with diffrac-

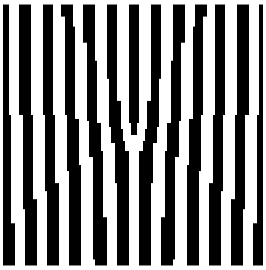
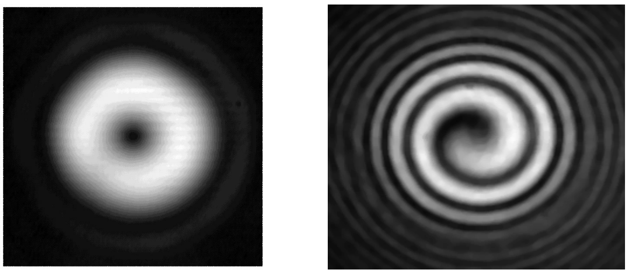


Fig. 1. Binary mask of computer generated hologram of vortex with charge m = 1.



a *b*

Fig. 3. Vortex with topology charge 1 (*a*) and its on-axis interference pattern (*b*).

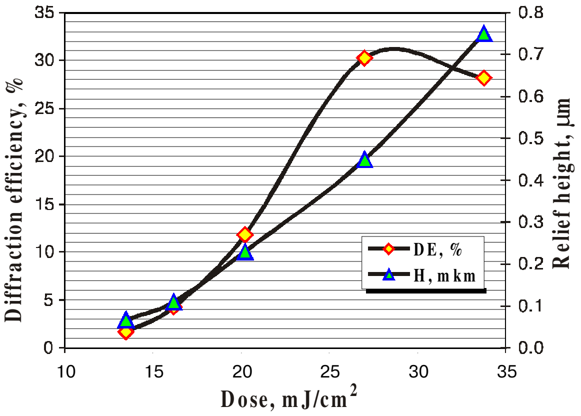


Fig. 4. The exposure curve for the Shipley S1800 photoresist.

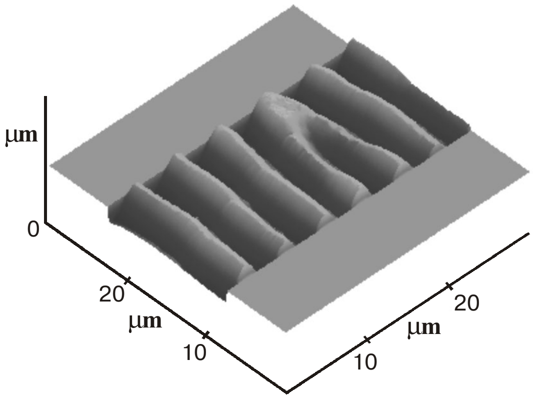


Fig. 5. The profiles of recorded diffractive structures taken by AF microscope.

tion efficiency as high as 57 %. It will be the next stage of our work to arise the diffraction efficiency of our CGH.

The measurements of the intensity distribution of the beam with optical vortex were carried out by means of CCD camera. To check how adequate is our method of measurement the test Gaussian beam was explored. The experimental data were compared to theoretical ones. On the Fig. 6 there is intensity distribution of the Gaussian beam: theoretical (*a*), experimental (*b*), cross-section (*c*). As it is evident we have high quality of the initial beam and adequate method of intensity distribution registration.

The similar measurements were carried out for the vortex beam with charge $m = 1$ that was generated by CGH (Fig. 7). There are some defects in the experimental beam that we would like to discuss. On the picture (Fig. 7b) is easy to see that experimental beam does not have perfect circle symmetry as theoretical beam do (Fig. 7a). On the top of the "donut" there is the valley area (Fig. 7d). We have made a number of measurements with different CGH, but this valley exited every time. On the Fig. 7c it is obvious that the central minimum of the experimental and theoretical beams do not coincide. Probably, the cause of these defects is the coherent noise that induces the shift of the vortex core.

Also, the less bright ring around the main beam could be noticed. This ring is related to the existence of the additional modes in the beam due to the binary initial mask of the CGH [8].

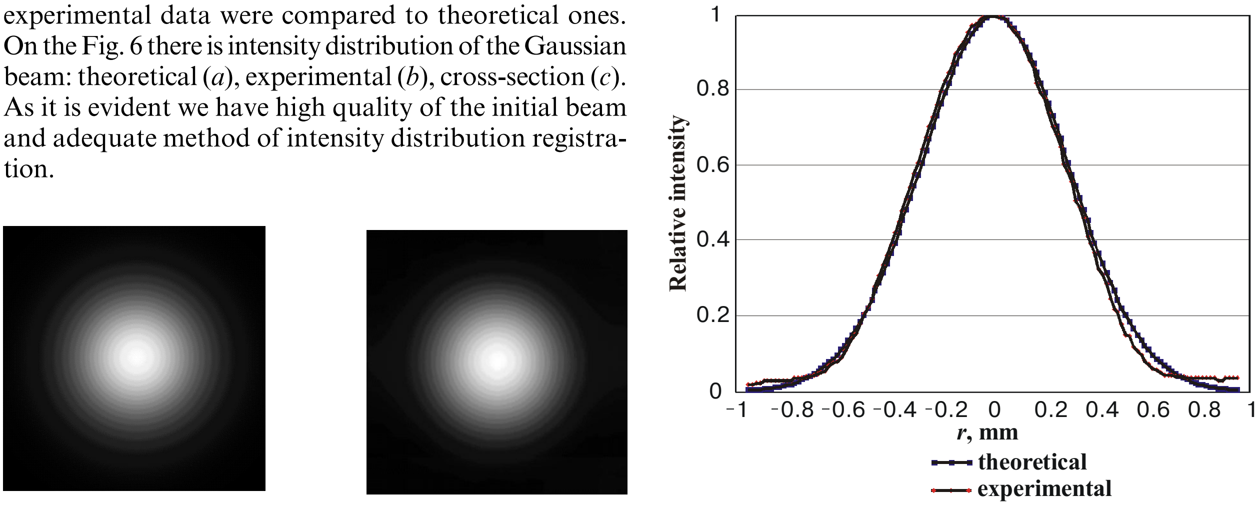
For the quality estimation of the singular beam the local relative deviation of experimental and theoretical intensity distributions was calculated (Fig. 8). Our experimental data are discrete. So, we worked with the samples or pixel of the CCD image. The procedure was the following. We take ring with the center in the vortex core, radius r and 2 pixels thickness. For the pixels that are in the ring the ratio was calculated:

$$\eta_i = \left| \begin{array}{ll} I_t / I_e, & \text{if} \quad I_e > I_t \\ I_e / I_t, & \text{if} \quad I_t > I_e \end{array} \right. , \tag{3}$$

where I_t is the theoretical intensity and I_e is the experimental intensity of the i-th pixel.

Than we average these ratios over the ring:

$$\eta = \frac{1}{N} \sum_i \eta_i , \tag{4}$$



a *b* *c*

Fig. 6. The intensity distribution comparison of the theoretical Gaussian and experimental He-Ne laser beams: theoretical (*a*), experimental (*b*), cross-section of theoretical and experimental beams (*c*).

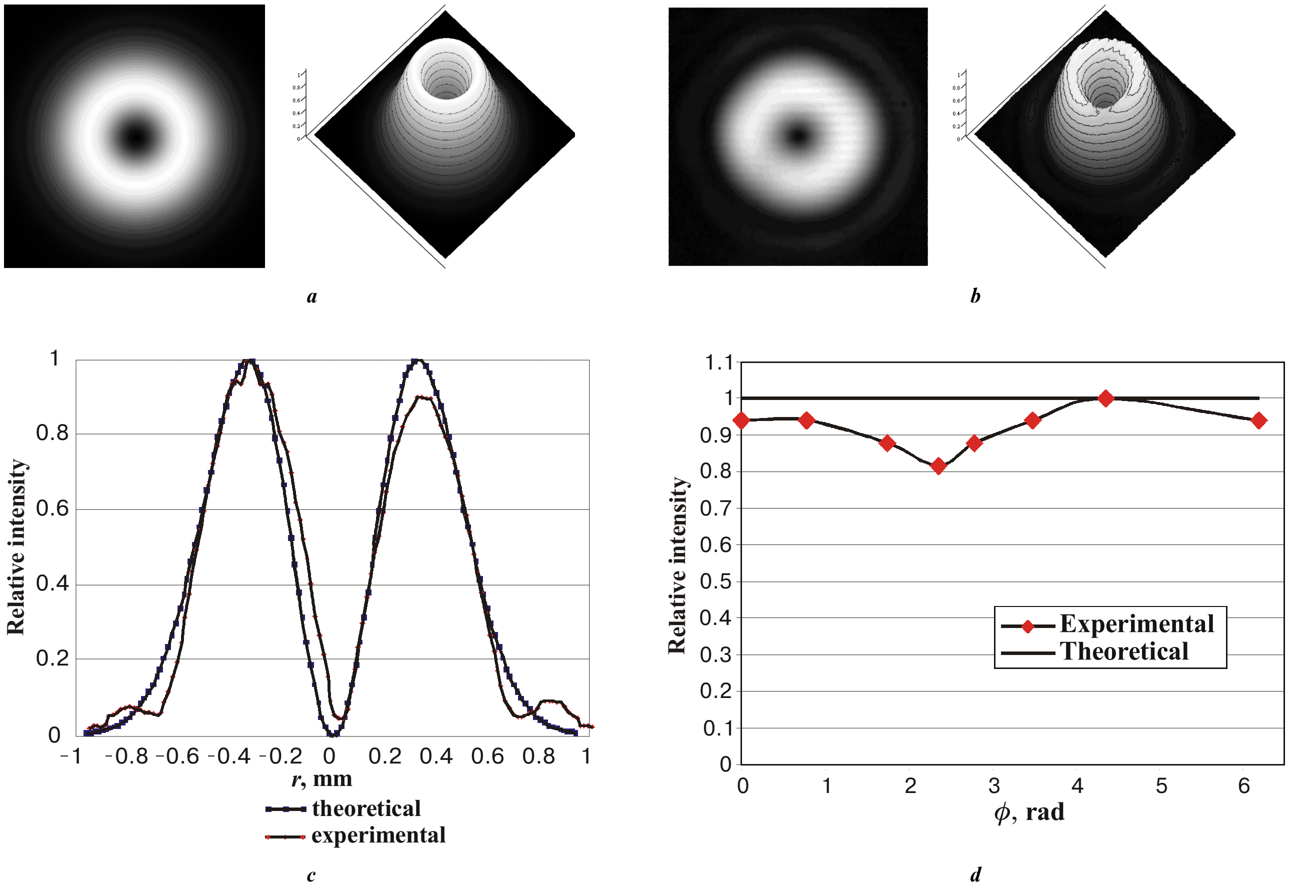


Fig. 7. The intensity distribution comparison of the experimental and theoretical singular beams: theoretical (*a*), experimental (*b*), cross-section of theoretical and experimental beams (*c*), intensity distribution of the vortex beam top (*d*).

where N is the total number of the pixel in the ring. The value η we called local relative coincidence. This value shows how experimental data is close to the theoretical ones. About 91.4 % of beam energy concur with theoretical distribution and have local relative coincidence not less than 0.8.

We also carried out the qualitative analysis of the vortex beam phase distribution (Fig. 9). For this purposes the on-axis interference pattern with the sphere reference wave was measured (Fig. 9b). The experimental fringes could be found from the equation [9]:

$$I(\rho,\varphi,z) \sim \cos\left(-m\varphi - \frac{k\rho^2}{2R(z)} + \frac{k\rho^2}{2R_0}\right), \quad (5)$$

where the R_0 is the radius of the reference wave curvature.

If we overlap the experimental and theoretical fringes than we could see that their maxima and minima concur very well. So, our singular beam has helicoidal phase distribution.

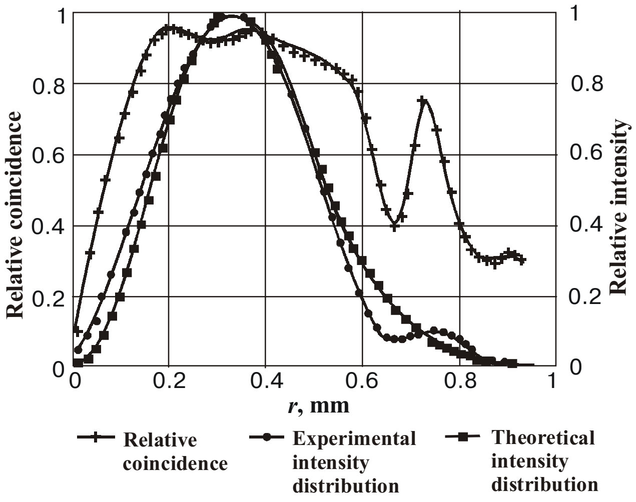


Fig. 8. Local relative coincidence of the theoretical and experimental intensity distribution of the singular beam.

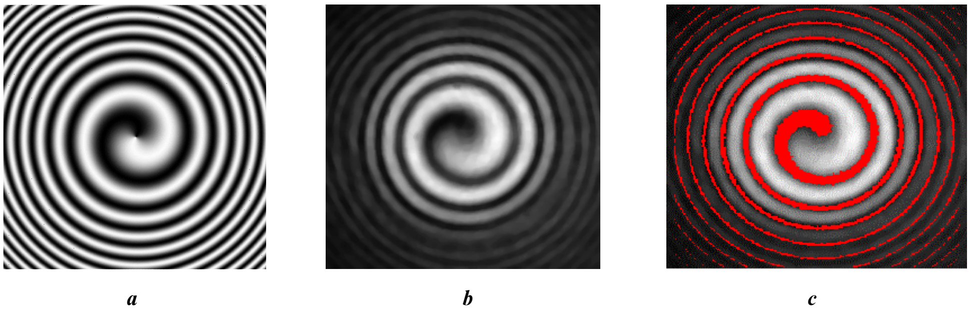


Fig. 9. Comparison of the on-axis interference pattern of the vortex beam: *a* – theoretical, *b* – experimental, *c* – overlapping of the *a* and *b*.

4. Conclusion

During the investigation the technology for the singular diffractive devices was worked out. The described method combine availability and comparative simplicity in realization together with number of amplitude and phase distribution of singular beams that could be generated. Our diffraction elements recorded on the photoresist generate singular beams that have much better quality and efficiency than ones recorded on the silver halide photoemulsion. They were successfully used in the experimental investigations in our laboratory.

Acknowledgment

The authors wish to express their thanks to the colleague from the Institute of Semiconductor Physics, NAS of Ukraine, Kostyukevich S. A. for his assistance in measurements.

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