Direct Recording of Phase Plates in Holographic Material with Using of Probabilistic Amplitude Masks

Sergiy Mokhov, Marc SeGall, Daniel Ott, Vasile Rotar, Julien Lumeau, Boris Zeldovich, and Leonid Glebov
CREOL - The College of Optics & Photonics, University of Central Florida, P.O. Box 162700, Orlando, FL 32816-2700, USA
smokhov@creol.ucf.edu , msegall@mail.ucf.edu , dott@creol.ucf.edu , vrotar@creol.ucf.edu ,
jlumeau@creol.ucf.edu , boris@creol.ucf.edu , lbglebov@creol.ucf.edu

Abstract: Recording of robust permanent phase plate in photosensitive glass is proposed via contact method with probabilistic computer-generated amplitude mask with varying random binary transmission grid of micron size. Spatial light modulation is a possible application.

OCIS codes: (090.2890) Holographic optical elements; (160.5335) Photosensitive materials

1. Introduction to Photo-Thermo Refractive glass as holographic recording material

Photo-thermo-refractive (PTR) glass is photosensitive material developed [1] for the recording of volume holographic elements such as high efficiency volume Bragg gratings (VBGs) [2]. UV laser radiation causes chemical recombination processes in compounds of this glass and after subsequent thermal developing the permanent change of refractive index of glass matrix can be achieved up to $\delta n \approx 10^{-3} = 10^{3}$ppm. Robust optical elements made of this glass are characterized by low absorption and scattering in visible and IR spectral range and high tolerance to operating laser irradiation. VBGs recorded in PTR glass are widely using for spectral narrowing of radiation from laser cavities; they are promising candidates for realization of spectral beam combining. In this work we propose PTR glass for recording of transmission non-diffractive phase elements.

2. Probabilistic amplitude mask for recording of phase map in PTR glass plate

Let us consider typical PTR glass plate with aperture size of couple centimeters and thickness L of few millimeters, e.g. $L = 2$mm. We would like to record arbitrary change of phase $\Delta\varphi(x,y)$ across the aperture for operating wavelength λ, for example $\lambda = 1.06\mu$m. In order to achieve relative 2π-shift after propagation of laser beam through this phase plate we need relative refractive index change $\Delta n = \lambda/L = 530$ppm which is in range of linear sensitivity of PTR glass. Varying $\Delta\varphi(x,y)$ can be recorded with corresponding varying UV exposure during recording process which can be realized with use of amplitude mask with corresponding varying transmittance across aperture. For recording purposes we propose to use binary amplitude masks made by lithography with probabilistic distribution of transparant/notransparant micro-areas of small size, for example $a = 2\mu$m. So, for aperture size 2cm we can generate binary map with resolution $10^4 \times 10^4$ on computer, in case of such high resolution the lithographic equipment software is required to operate with files of 12Mb binary information memory and this value is reasonable now a days. Figure 1 shows central area of computer-generated amplitude binary mask for recording of vortex phase plate.

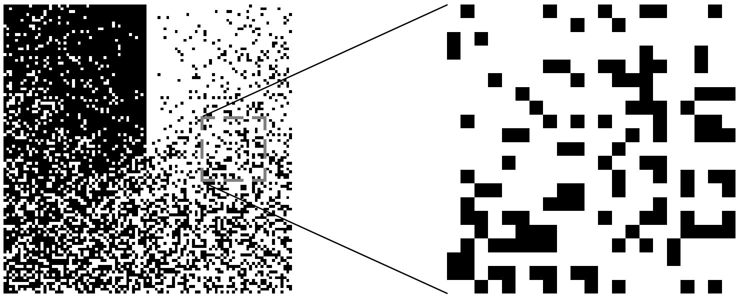

Fig.1. Central area of probabilistic amplitude mask for recording of vortex phase plate and local area with filling factor $\nu = 0.25$.

We consider recording of phase plates in PTR glass in close contact with amplitude mask. This method of contact recording is very robust and allows obtaining direct transmission phase elements with almost 100% efficiency. Probability filling factor $\nu(x,y)$ of mask transmittance can be not directly linearly proportional to $\Delta\varphi(x,y)$ in order to adjust nonlinear photosensitivity of holographic material and its value also can be realized in range narrower then from 0 to 1. If phase variation $\Delta\varphi(x,y)$ is slow then we can neglect diffraction on possible limited sharp amplitude edges corresponding to rapture in phase map, e.g. for vortex plate, during recording because of small thickness L of contacted PTR glass plate. On another hand, recording UV laser beam is highly coherent and we have to analyze complex field structure in plate volume in detail, which occurs due to beam propagation through amplitude mask consisting of regular square micro-areas with random binary transmittance. We will show in next two sections that such plate with recorded small local change of refractive index by coherent speckle field will operate as phase element with required phase variation $\Delta\varphi(x,y)$ across aperture due to averaging variations of refractive index along thickness L.

3. Speckle structure of coherent recording field after propagation of mask

First of all, let's estimate angular divergence of diffraction on aperture with hole size $a = 2\mu$m. For recording wavelength $\lambda_{\rm rec} = 325$nm it is $\Delta\theta_{x,y} = \lambda_{\rm rec}/a \approx 0.16$rad and corresponding Fresnel length is $a/\Delta\theta \approx 12\mu$m. Illuminating beam with the angular divergence $\Delta\theta$ leads to smudging of original distribution $\nu(x,y)$ by transverse resolution size $\Delta r \approx L\cdot\Delta\theta \approx 320\mu$m. Such transverse resolution appears to be reasonably good.

The incident field E_0, being transmitted trough randomly open and closed holes, may be represented as

$$E(\mathbf{r}) = E_0 \sum_\alpha u(\mathbf{r} - \mathbf{r}_\alpha)\, p_\alpha \,. \tag{1}$$

Here random variable $p_\alpha = 1$ if the hole #α is open, and $p_\alpha = 0$ if that hole is closed for transmission of light. The function $u(\mathbf{r})$ describes the result of diffraction of incident plane wave on a single aperture (hole). Because the size of the square hole is small enough, in almost all the space the function $u(\mathbf{r})$ is diffraction field in the far field zone:

$$u(\mathbf{r}) = f(\theta_x = \tfrac{x}{z}, \theta_y = \tfrac{y}{z}) \cdot \frac{e^{ikr}}{r}, \quad f(\theta_x, \theta_y) = \frac{k}{2\pi i} \iint_S e^{-ik(x'\theta_x + y'\theta_y)} dx'dy' = \frac{ka^2}{2\pi i} \frac{\sin t_x}{t_x} \frac{\sin t_y}{t_y}, \quad t_{x,y} = \frac{k\theta_{x,y} a}{2}, \tag{2}$$

Here integration was taken over the area $S = a^2$ of one hole.

Statistically average field (not intensity) $E_1 = \langle E(\mathbf{r})\rangle$ can be found by using $\langle p_\alpha\rangle = \nu$; here $0 < \nu < 1$, ν is average filling factor of local area. Considering $\nu(x,y)$ to be slow function of transverse coordinates, one gets

$$E_1 = \langle E(\mathbf{r})\rangle = E_0 \nu \,, \tag{3}$$

In this manner, we are able to represent $E(\mathbf{r})$ as

$$E(\mathbf{r}) = E_1 + E_0 \sum_\alpha (p_\alpha - \nu) u(\mathbf{r} - \mathbf{r}_\alpha) \equiv E_1 + E_2(\mathbf{r}) \,. \tag{4}$$

Field E_1 equals to the original plane wave, attenuated in amplitude by dimensionless factor ν.

Randomness of variables p_α and strong coordinate oscillations of the diffraction field $u(\mathbf{r})$ allows to consider $E_2(\mathbf{r})$ as speckle field with Gaussian statistics. Since $p_\alpha^2 = p_\alpha$, one has $\langle (p_\alpha - \nu)^2\rangle = \nu(1-\nu)$, so that the intensity $\langle |E_2|^2\rangle = |E_0|^2\cdot\nu(1-\nu)$ and angular intensity spectrum $j(\theta_x,\theta_y) = \text{const}\cdot(\sin(t_x)/t_x)^2(\sin(t_y)/t_y)^2$ [3,4].

Total intensity $|E_{\rm tot}|^2$ is the sum of that plane wave component, $|E_0|^2\nu^2$, and of speckle-component, $|E_0|^2\cdot\nu(1-\nu)$, i.e. $|E_{\rm tot}|^2 = |E_0|^2\cdot[\nu^2 + \nu(1-\nu)] = |E_0|^2\nu$, which allows to control the exposure of material $\propto |E_{\rm tot}|^2$ by slow varying $\nu(x,y)$, as was originally assumed.

Our result above,

$$|E|^2 = |E_0|^2 \cdot [\nu^2 + \nu(1-\nu)] \,, \tag{5}$$

allows to estimate fluctuations as the result of interference of attenuated plane wave with intensity $\propto\nu^2$ with the speckle wave with intensity $\propto\nu(1-\nu)$, as well as the fluctuation of intensity of speckle filed itself, see [4].

4. Laser beam transformation after propagation through recorded phase plate

The use of thus fabricated element will consist in propagation of light wave through the medium with modified refractive index, while those changes contain smooth average part and fluctuating part. Average changes equal $\langle\Delta n\rangle = M\cdot\lambda/L$, where M is the number of "waves" of intended delay, $0 < M \le 1$; thus $\langle\Delta n\rangle \approx M\cdot 10^{-3}$ for $\lambda = 1.06\mu$m and $L = 2$mm. Fluctuations $\delta n(\mathbf{r})$ are about $\langle\Delta n\rangle$ itself. Their correlation length is about Fresnel length of recording diffraction pattern, $l_{\rm cor} \approx a/\Delta\theta \approx 12\mu$m. In this situation the fraction of scattered light at the usage stage may be estimated as

$$\delta I/I \approx (\Delta n \cdot l_{\rm cor}/\lambda)^2 \cdot L/l_{\rm cor} \approx 0.006 \,. \tag{6}$$

This shows that only small fraction of the work light will be scattered at propagation through the phase element.

6. Experimental results

The amplitude mask with probability varying factor azimuthally changing from 0 to1 was created lithographically on quartz substrate, the size of elementary square area is $a = 2\mu m$. Our first experiment is done with PTR glass plate of thickness $L = 1.8$mm exposed by UV radiation in contact through amplitude mask. After following thermal development obtained phase plate was observed in shearing interferometer, see Figure 2. The size of plate is about 15mm on this interferogram. Generated phase shift on edge between unexposed and maximally exposed area is estimated to be equal 1.5π for particular wavelength $\lambda = 633$nm, corresponding refractive index difference equals $\Delta n = 264$ppm. Additional thermal developing can increase this difference and then phase plate can be tuned for specific wavelength vortex generation by additional polishing for reducing of plate thickness. Obtained phase plate was illuminated by laser beam of the same wavelength with circular profile of diameter 4mm and far-field intensity distribution is presented on Figure 4.

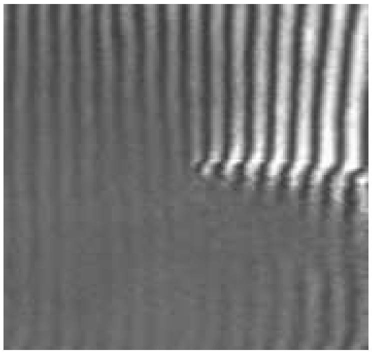

Fig.2. Interferogram of recorded phase plate.

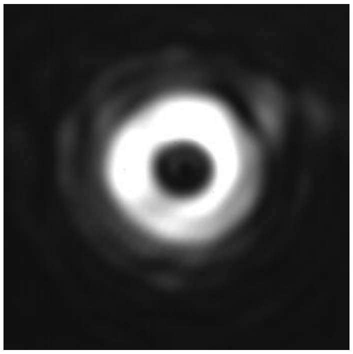

Fig.3. Far-field intensity distribution of circular beam after phase plate.

Thus we demonstrate the validity of proposed method which can be applied for recording of phase plates for wide range of different applications.

7. Conclusions

We proposed to record phase plates made of PTR glass by uniform expose transmitted through amplitude masks with varying transmittance across aperture. This variation can be realized by varying of probability distribution of small areas with binary transmittance and such binary mask master form can be fabricated with well-developed lithography technology. Computer-generated amplitude map with varying randomness consists of binary elements with size few times larger then wavelength of recording. This map distribution can be adjusted for photosensitivity dependence of particular holographic material. We have analyzed speckle structure of recording intensity in plate volume and we came to conclusion that the recorded refractive index change even due to coherent recording speckle pattern will reproduce assumed phase variation $\Delta\varphi(x,y)$. We have recorded the first transmission phase mask for generation of optical vortex beams with this method; the experimental results are in good agreement with theoretical expectations. Due to relatively small cost of this recording process such phase elements can compete with existed lithographic techniques of regular glass plate fabrication with varying thickness. Also in some experiments, proposed permanent phase plates can substitute spatial light modulators because of their robustness and theoretically higher transverse smoothness of varying phase distribution.

8. References

[1] L. B. Glebov, "Volume hologram recording in inorganic glasses," Glass Science and Technology **75** C1, 73-90 (2002).

[2] O. M. Efimov, L. B. Glebov, V. I. Smirnov, "High efficiency volume diffractive elements in photo-thermo-refractive glass," United States Patent **6,673,497**. January 6, 2004.

[3] B.Ya. Zeldovich, N. F. Pilipetsky, and V. V. Shkunov, *Principles of Phase Conjugation*, Sect. 5.7.1, Springer-Verlag, 1985.

[4] B.Ya. Zeldovich, A. V. Mamaev, and V. V. Shkunov, *Speckle-Wave Interactions in Application to Holography and Nonlinear Optics*, CRC Press, 1995.