Optically inscribed surface-relief zone plates in azo polymer films

Jun Yang (杨 军)[1,3], Bin Guo (郭 斌)[2], Douguo Zhang (张斗国)[3],
Pei Wang (王 沛)[3], and Hai Ming (明 海)[3]

[1] *Academe of Optoelectronic Technology, Hefei University of Technology, Hefei 230009*
[2] *College of Information Science and Technology, Nanjing Forestry University, Nanjing 210037*
[3] *Department of Physics, University of Science and Technology of China, Hefei 230026*

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We describe a simple and cost-effective holographic method for the fabrication of surface-relief zone plates. The zone plate is inscribed by interference between the first- and second-order diffracted waves from an ion-etched Fresnel zone plate. The inscribed surface-relief zone plates are observed by atomic force microscope (AFM). The formation process of the surface grating and the mass diffusion in azo polymer are analyzed.

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Fresnel zones and zone plates are classic topics in optics and have received wide spreading attention. Conventional zone plates made with glass present disadvantages such as poor transmission in the ultraviolet (UV) and infrared part of the spectrum. Also their fabrication process is long. Owing to these facts, alternative methods and materials have been proposed[1]. Diffractive optical elements can be fabricated by several techniques, such as lithography, diamond turning, laser or electron-beam pattern generators, and recording of interference patterns[2]. Materials used in these techniques are, for example, photoresist, electron-beam resist, photopolymers, and dichromated gelatin[3−5].

Azobenzene polymers have received increasing attention due to their interesting properties and possible applications in optical storage, optical communication, nonlinear optics, and diffractive optical elements[6,7]. The azo group in azobenzene polymer liquid crystal is one kind of photoactive group, which can change from trans to cis and from cis to trans, under the action of linearly polarized light and heat. With this character, we can illuminate azobenzene polymers by a given wavelength of light to make them carry out photo-alignment by trans-cis-trans isomerization cycles. Azobenzene falls perpendicularly to the direction of the electric field vector of the linearly polarized light. This reorientation induces anisotropy and the difference of refractive index parallel and perpendicular to the irradiating laser polarization direction.

In 1994, Rochon *et al.* found that large surface relief gratings could be directly recorded at room temperature on azobenzene-containing polymer films using two interfering polarized Ar ion laser beams[8]. Holographic grating formation in azobenzene polymer based on light-induced surface relief hologram (SRH) by trans-cis photoisomerization has received a lot of attention.

In this paper, we describe a simple and cost-effective holographic method for the fabrication of surface-relief zone plates. Azo polymer materials were used and obtained through chemical synthesis as described in Ref. [9]. When the ion-etched Fresnel zone plate is illuminated by a collimated beam of 532-nm semiconductor laser, a holographic zone plate for the laser wavelength is obtained by recording the interference pattern between the first- and second-order diffracted waves.

The surface-relief zone plate is inscribed using the system described in Fig. 1. A collimated linear continuous-wave (CW) laser beam illuminates perpendicularly the original Fresnel zone plate ZP. The diameter of zone plate ZP is D, and the focal length is f.

Here, Cartesian axes r-x are taken. The origin is at a distance of $f/2$ from the zone plate ZP. The first-order diffracted spherical wave from the zone plate is expressed as[2]

$$A_1 \exp(i\varphi_1) = A_1 \exp\left[\frac{-ikr^2}{2(f/2-x)}\right]. \tag{1}$$

The second-order diffracted wave is

$$A_2 \exp(i\varphi_2) = A_2 \exp\left[\frac{-ikr^2}{2(f/6+x)}\right]. \tag{2}$$

The intensity distribution resulting from interference between the first- and second-order diffracted waves is

$$I = A_1^2 + A_2^2 + 2A_1A_2\cos\{kr^2 f/[3(f/6+x)(f/2-x)]\}. \tag{3}$$

This is recorded on a holographic plate and a holographic

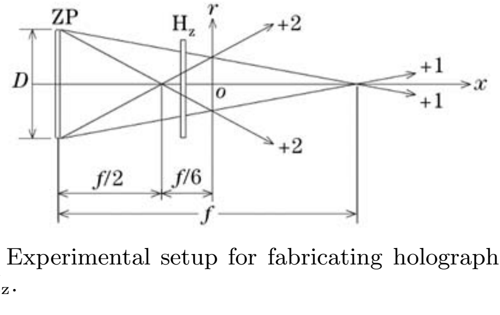

Fig. 1. Experimental setup for fabricating holographic zone plate H_z.

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zone plate is fabricated. The focal length f of the zone plate is given by

$$f_{\mathrm{z}} = 3(f/6 + x)(f/2 - x)/2f. \tag{4}$$

To obtain a holographic zone plate with high visibility, we usually put a holographic plate $\mathrm{H_z}$ in the region where $-f/16 < x < 0$, since the light intensities of the first- and second-order diffracted waves do not differ much in this region (based on formulas for computing the paraxial diffraction of phase zone plates, $A_1 = A_2$). Note that a holographic zone plate has a shorter focal length and smaller diameter than the original zone plate. Compared with conventional manufacturing process of zone plates and equipments, this optical setup is simple and cost-effective. Also their fabrication process is shorter.

In our experiments, azo polymer films as described in Ref. [9] was used as a recording material, and the original Fresnel zone plate was made by electron-beam scanning and deep UV lithography. Its thickness is 0.02 mm, and the diameter is 3 mm. Figure 2 shows the image of the original Fresnel zone plate observed by microscope. A linear CW laser (diode-pumped, frequency-doubled, Nd:$\mathrm{YVO_4}$) at 532 nm was used as the light source of the system. The laser beam was expanded to a diameter of 3 mm. In the experiment, the laser irradiation power was 30 mW. After about 20 minutes of illuminating time, surface-relief zone plates have been clearly inscribed in azobenzene polymer films.

Figure 3 shows the image of the SRH zone plate fabricated in the setup of Fig. 1, which was observed by a polarization microscope. An atomic force microscope (AFM) image of the surface relief zone plate is shown in Fig. 4. The surface-relief grating period and the height of profile are about 1.3 and 3 μm, respectively.

We find that the notch forms at the high-intensity area and heave at low-intensity area[9], which is in coincidence with the model proposed by Barrett *et al.*[10]. We recognize that the mechanism at the origin of surface-relief zone plates connects with the mass diffusion in azo polymer films. When azo polymer is illuminated by two laser beams, the phase addition of the two beams in the interference pattern leads to regions of high trans-cis-trans isomerization by the absorbing azo groups, and other regions have low isomerization. Because the geometrical isomerization requires free volume in excess of that available in the films, the photoisomerization in these areas produces a laser-induced internal pressure. It is proposed that the resulting viscoelastic flow from these high-pressure areas to lower-pressure areas. Namely, the mass of the polymer at high-intensity area expands, diffuses and deposits above the low-intensity area, and leads to the formation of the surface-relief zone plates.

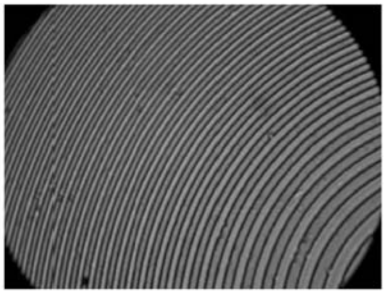

Fig. 2. Original Fresnel zone plate.

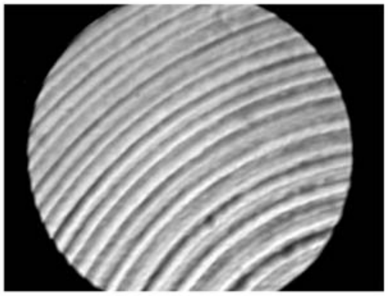

Fig. 3. SRH zone plate $\mathrm{H_z}$ fabricated in the setup of Fig. 1.

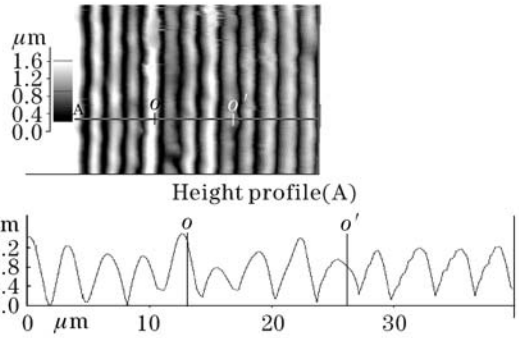

Fig. 4. Surface profile of zone plates.

In conclusion, we investigated an organic zone plate based on light-induced surface grating hologram in azo polymer films. The novel methods of fabricating holographic zone plates were proposed by using diffracted waves from an ion-etched Fresnel zone plate. Surface-relief zone plate has been clearly inscribed in azo polymer films. In observation areas, the surface-relief grating is with a height of about 1.3 μm and the period is about 3 μm.

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