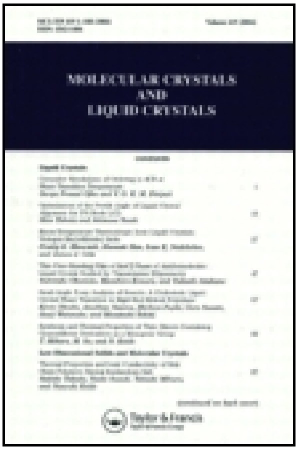

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We demonstrate a polarization-insensitive grating device based on a liquid crystal (LC) doped with azo-dyes in polymer networks. The polarization-insensitive diffraction is obtained by periodically modulating the optic axis of a homogeneously aligned nematic LC layer. The polymer networks formed in the doped LC medium play a critical role in achieving the optic axis modulation of the LC by a single pump irradiation. The optically induced effect in the dye-doped LC system is permanent, polarization-insensitive, and electrically controllable.

Keywords: dye-doped liquid crystals; optical reorientation; polarization-insensitive grating; polymer network

INTRODUCTION

Various types of liquid crystal (LC) grating devices have been developed for applications in optical modulating systems [1,2], optical communication systems [3], and three-dimensional display systems [4]. Most of the LC gratings possess the polarization-dependent diffraction that results in overall system losses. In order to solve this problem, the spatial light modulator based on ferroelectric liquid crystals (FLCs) showing two stable states has been recently proposed

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[5–7]. However, such approach inevitably involves the complexity in patterned electrodes and the difficulty in uniform alignment of the FLCs.

In this work, we demonstrate a polarization-insensitive grating device based on a dye-doped LC system in polymer networks. The polarization-insensitive diffraction is achieved by periodically modulating the optic axis of a homogeneously aligned nematic LC layer. Periodic domains are produced by a single pump beam onto a dye-doped LC where the polymer networks were periodically formed by the ultraviolet (UV) irradiation through a patterned photomask. The diffraction efficiency of our LC grating is electrically controllable and insensitive to the polarization of the input beam in the entire voltage range of operation.

EXPERIMENTS

In our study, a nematic liquid crystal of ZLI-2293 (E. Merck Industries), azo-dye of Methyl Red (MR, Sigma-Aldrich), and an UV-curable photopolymer of NOA65 (Norland Products Inc.) were used. The doped-LC composite system was prepared from a homogeneous mixture of 97 wt.% of ZLI-2993, 1 wt.% of MR, and 2 wt.% of NOA65. The mixture was injected into the sample cell, made with two indium tin oxide (ITO) coated glass substrates, at temperature above the clearing point of the LC. The inner surfaces of the substrates were coated with polyvinyl alchol (PVA) layers and rubbed unidirectionally so as to promote initial homogeneous alignment of the LC. The cell thickness was maintained using glass spacers of 6 μm thick.

The polarization-insensitive diffraction grating was fabricated through two processes, a patterned UV light exposure and an uniform pump beam irradiation. As shown in Figure 1, the cell was first irradiated with UV light from a Xe-Hg lamp at 10 mW/cm^2 for 50 minutes through an amplitude photomask to form polymer networks selectively in the bulk. The density of the polymer networks was modulated with the grating period of 100 μm. The illuminated region (region H) has the higher polymer concentration than the unilluminated region (region L). In the polymer stabilized state with the low concentration (2 wt.%) of the polymer, the uniform alignment of the LC along the rubbing direction was produced.

After the patterned UV exposure, an uniform pump beam was irradiated to induce the optical reorientation of the LC molecules in the periodically modulated polymer networks. As a pump beam source, an Ar-ion laser with wavelength of 488 nm and the power of 100 mW/cm^2 was used. The single pump beam was linearly polarized

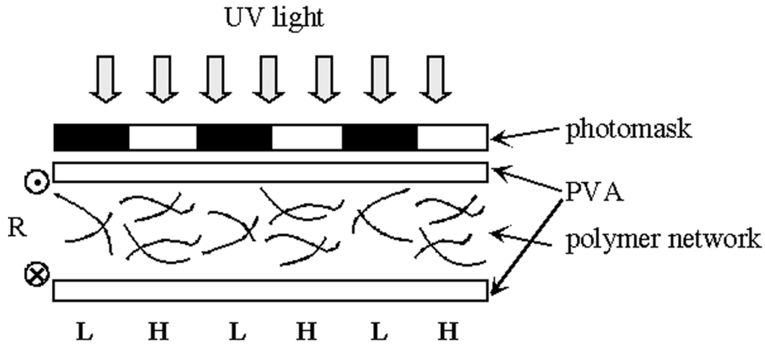

FIGURE 1 Fabrication process of periodically modulated polymer networks in the bulk. The period of the photomask is 100 μm. H and L represent the illuminated and unilluminated regions, respectively. R represents the rubbing direction of the PVA layers.

at an angle of 45° with respect to the rubbing direction so that the maximum optical torque was produced [8]. Figure 2 shows a microscopic texture of the periodically reoriented LC observed with a

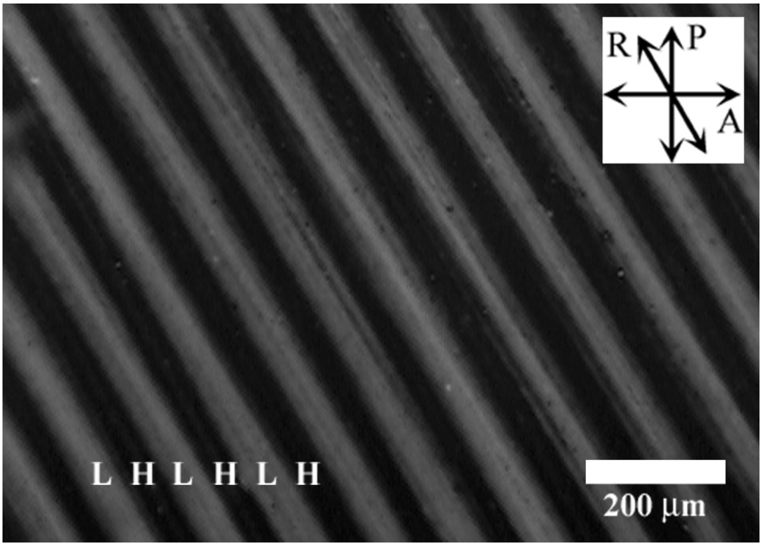

FIGURE 2 Microscopic texture of the periodically reoriented LC observed with a polarizing microscope under crossed polarizers. The texture was taken such that the rubbing direction is rotated by an angle of 30° with respect to the polarizer. R represents the rubbing direction.

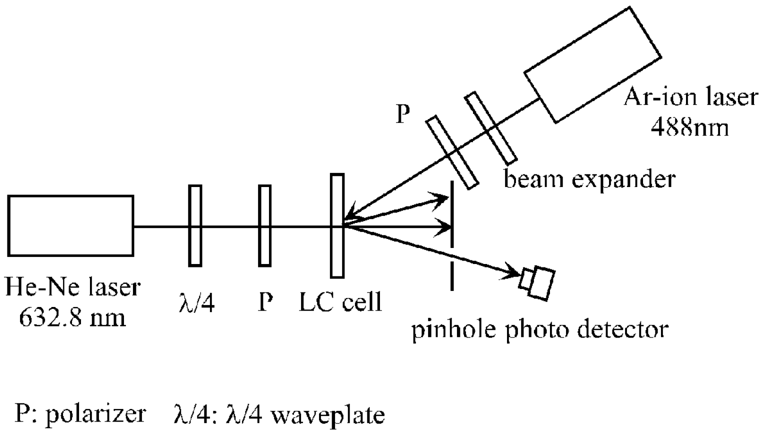

FIGURE 3 Experimental setup for measuring the diffracted intensity under a pump beam polarized linearly at an angle of 45° with respect to the rubbing direction.

polarizing microscope under crossed polarizers. The texture was sampled 24 hours after the Ar laser pumping for 300 seconds was completed. The region H was completely dark when the sample cell was rotated by an angle of 30° to the polarizer as shown in Figure 2. In other words, the optic axis of the dye-doped LC in region H was uniformly rotated by an angle of 30° with respect to the rubbing direction. The region L, where the density of the polymer networks was low, showed the optic axis rotated by an angle of 8° to the rubbing direction.

Figure 3 shows the experimental setup for measuring the diffraction of the dye-doped LC with periodic polymer networks upon a linearly polarized pump beam. The diffracted intensity was monitored using a He-Ne probe laser with wavelength of 632.8 nm. The probe beam was polarized parallel to the rubbing direction of the sample cell. The first-order diffracted intensity through a pinhole was measured with a photodetector in conjunction with a digitizing oscilloscope.

RESULTS AND DISCUSSION

Figure 4 shows the diffraction dynamics of the dye-doped LC where the polymer networks were periodically modulated. Before pumping, the LC molecules were uniformly aligned along the rubbing direction on the PVA layers. The phase difference between the region H and the region L was negligible due to the low concentration of the polymer. In this case, the diffracted intensity of the probe beam through the

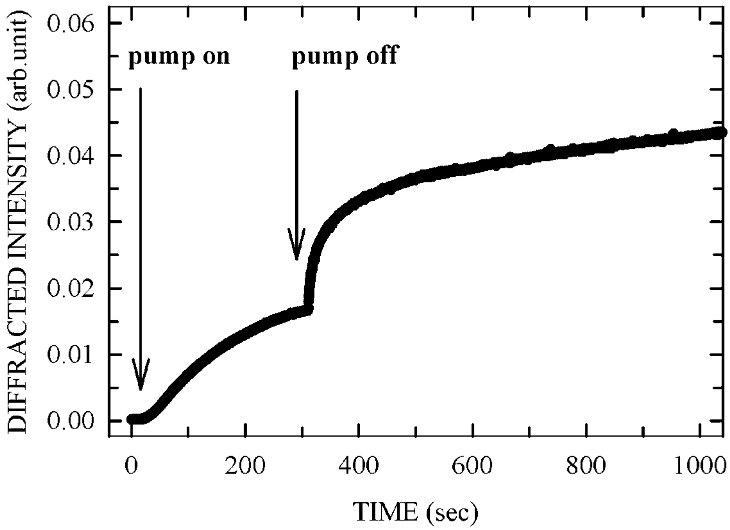

FIGURE 4 The diffracted intensity of the probe beam through the dye-doped LC cell with periodically modulated polymer networks as a function of time. The pump beam was on at the time of 10 sec and off at the time 310 sec.

sample cell was essentially zero. During pumping by a linearly polarized beam of the Ar-ion laser, the photo-excited MR molecules were generated and thus the optical torque was exerted on the LC molecules so that the optic axis was rotated away from the rubbing direction toward a direction perpendicular to the pump polarization. The difference in the optical reorientation between two regions (H and L), induced by the density modulation of the polymer networks, produces the diffraction of the probe beam. When the pump beam was off, the dye-induced optical torque was no more exerted and thus the reoriented LC molecules was relaxed by the surface anchoring of the rubbed PVA layers. But, the diffraction intensity further increased due to the difference in the relaxation dynamics between the two regions with different polymer network density. In saturated state, well-defined alternating optic axes in the two regions were developed as shown in Figure 2. Although rubbed PVA layers produce strong anchoring of the LC at the surfaces, strong optical memory effect is generated in bulk since the polymer networks formed in the bulk provide the internal surface to anchor liquid crystalline order [9]. In other words, the optical reorientation of LC is sustained through the adsorption of the excited MR molecules on the polymer networks. This means that the region H with high density of the polymer networks possesses much less relaxation of the optical reorientation than the region L and thus the difference in relaxation results in the increase of the diffracted intensity when the pump beam is off. The optical memory effect in our LC grating device remains at least several months in the range of our observation in the case that the duration of pumping was 300 seconds.

Let us now describe the diffraction properties of the LC binary grating with the optic axis modulation and the phase retardation. With the Fraunhofer diffraction formalism for a binary anisotropic grating [10], the optical field of the first-order diffraction is given by

$$\mathbf{E}_{+1} = -\frac{2}{\pi}\sin\frac{\Gamma}{2}\sin\theta\begin{pmatrix} A_y \\ A_x \end{pmatrix}, \tag{1}$$

where A_x and A_y represent the x- and y-components of an incident light in coordinates intersecting equally two easy axes, Γ is the phase retardation, and θ is the angle between the two easy axes. It should be noted that the first-order diffraction efficiency is expressed as a function of the phase retardation and the optic axis modulation independently of the polarization of the incident light. In our case, the optic axis modulation θ of 22° was achieved through the single pump

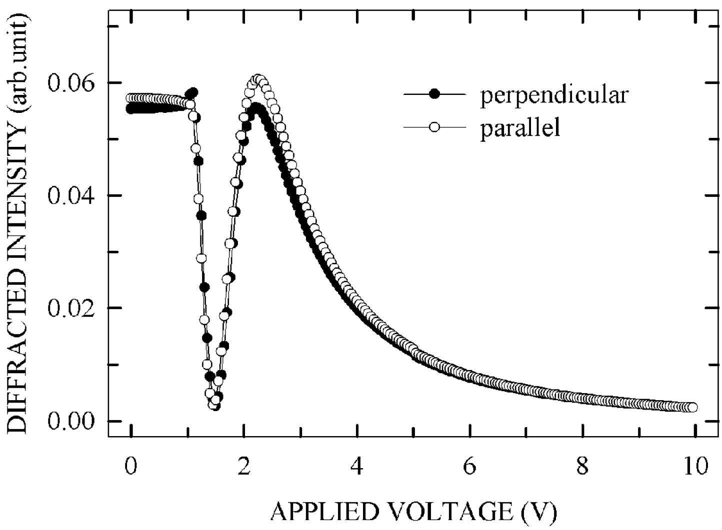

FIGURE 5 The diffracted intensity of our dye-doped LC grating device as a function of the applied voltage for two input polarizations. Filled and open circles represent the diffractions for the polarization perpendicular and parallel to the stripes, respectively.

irradiation as shown in Figure 4. The diffraction efficiency can be controlled by an applied voltage to reduce the phase retardation Γ.

Figure 5 shows the first-order diffraction as a function of the ac voltage at 1 kHz for two input polarizations, one perpendicular to the stripes and the other parallel to the stripes shown in Figure 2. The valley and peak of diffraction correspond to the phase retardation of 2π and π, respectively. At the applied voltage of 10 V, the phase retardation becomes nearly zero and the diffraction disappears. This tells us that the first-order diffraction is polarization-insensitive in the entire voltage range we studied.

CONCLUSION

We demonstrated a polarization-insensitive binary grating based on a dye-doped LC system with periodic polymer networks. The optic axis modulation was produced by optical reorientation of the dye-doped LC in periodically formed polymer networks by a single pump beam. The optical diffraction efficiency was electrically controllable and independent of the polarization of the input beam. The polarization-insensitive LC grating presented here is expected to be applicable for various optical systems.

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