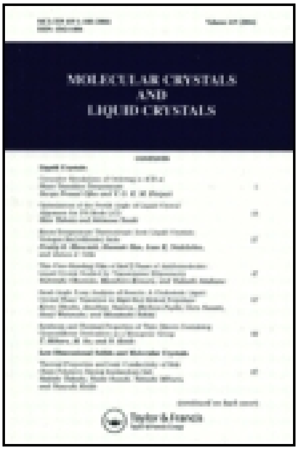

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Electrically and Optically Controllable Liquid Crystal Grating with a Patterned Surface-Command Layer

Eunje Jang [a], Hyoungwon Baac [a], Yeun-Tae Kim [a] & Sin-Doo Lee [a]
[a] School of Electrical Engineering, Seoul National University, Kwanak, Seoul, Korea

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Eunje Jang
Hyoungwon Baac
Yeun-Tae Kim
Sin-Doo Lee
School of Electrical Engineering, Seoul National University, Kwanak, Seoul, Korea

We propose a liquid crystal (LC) binary grating that can be controlled both electrically and optically in a simple scheme. The optical control scheme is obtained through the surface-induced reorientation of the LC molecules on a patterned surface-command layer by a single pump irradiation. The electrical control of the diffraction efficiency is achieved through the change in the phase retardation by the application of a bias voltage for given optically induced LC director distribution. In a coupled scheme of the optical and electrical control, the diffraction efficiency can be easily optimized.

Keywords: liquid crystal binary grating; optical control scheme; single pump; surface-induced reorientation

INTRODUCTION

A variety of liquid crystal (LC) gratings have been developed for practical applications such as a spatial light modulator, a diffractive optical element for holographic devices, a beam splitter, and a fiber-optic light modulator [1–4]. Most of the LC grating devices require an applied voltage to change the diffraction efficiency through an electro-optic effect. Recently, a purely optical control scheme of the LC grating based on a photo-sensitive polymer has been reported for photonic applications

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Address correspondence to Sin-Doo Lee, School of Electrical Engineering #032, Seoul National University, Kwanak P.O. Box 34, Seoul 151-600, Korea. E-mail: sidlee@plaza.snu.ac.kr

[2,5]. However, it needs the interference of two pump beams to induce the spatially periodic modulation of the LC director.

In this work, we propose a LC binary grating that can be controlled either electrically or optically in a simple scheme. The optical control scheme is achieved by the surface-induced reorientation of the LC molecules on a patterned surface-command layer consisting of one region with a photo-reactive polymer and the other with no photo-reactive polymer. The electrical control of the diffraction efficiency is achieved through the change in the phase retardation for given optically induced LC director distribution. Moreover, an external electric field provided by a pair of flat electrodes can be used to optimize the optically controlled diffraction efficiency in a wide range of the wavelengths.

DEVICE DESCRIPTION

Figure 1 illustrates two LC binary grating configurations with different hybrid LC distributions on a patterned surface-command layer. According to the polarization of a single pump beam, one of two grating configurations having either uniform optic axes or orthogonal optical axes is optically generated. It should be noted that the LC molecules only in the region with the photo-reactive polymer experience the optical reorientation by the single pump beam. In the uniform hybrid case, no considerable phase difference between two adjacent regions is expected. However, in the orthogonal hybrid case, a large phase difference will be appeared, implying that high diffraction

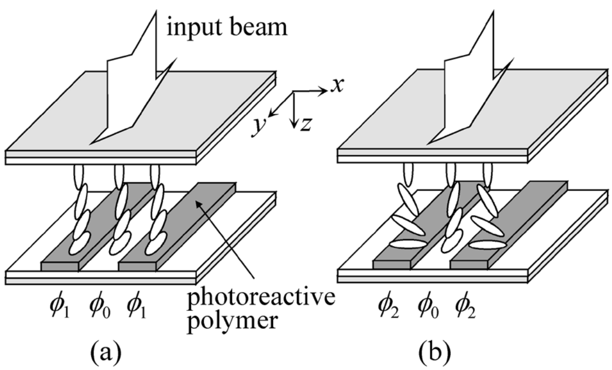

FIGURE 1 Schematic diagram of two LC binary grating configurations with different hybrid LC distributions on a patterned surface-command layer: (a) uniform optic axes and (b) orthogonal optic axes.

efficiency can be obtained. Moreover, the optically generated phase modulation can be precisely tuned by the application of a bias voltage.

Within the Fraunhofer diffraction formalism for a binary phase grating [6], the diffraction efficiency of the first-order is given by

$$\eta_{\pm 1} = \frac{4}{\pi^2} \sin^2\left(\frac{\Delta\phi}{2}\right), \tag{1}$$

where the relative phase difference between two adjacent regions, $\Delta\phi = \phi_0 - \phi_1$ in Figure 1(a) and $\phi_0 - \phi_2$ in Figure 1(b). For an ideal binary phase grating, the diffraction efficiency of the first-order has the maximum of $\eta_{\pm 1} = 0.4$ at $\Delta\phi = (2n+1)\pi(n = \text{integer})$. In our case, the optically induced phase modulation is fixed at a certain value $\phi_0 - \phi_2$, which is determined by the LC cell parameters and the wavelength of the input beam. Hence, in order to obtain the maximum diffraction efficiency, a bias voltage V corresponding to $\phi_0(V) - \phi_2(V) = (2n+1)\pi$ should be applied to the optically generated LC grating.

EXPERIMENTS

The photo-reactive polymer for producing the patterned surface-command layer was an azobenzene copolymer of poly-[(methyl-methacrylate)-co-(Disperse Red 1 acrylate)] (Sigma-Aldrich). The azobenzene copolymer dissolved in tetrahydrofuran was spin-coated on a transparent indium-tin-oxide (ITO) glass substrate coated with a homogeneous alignment layer and then baked at 60°C for 1 day. The polymer layer was exposed by an ultraviolet excimer laser through an amplitude photomask to obtain binary patterns. The unexposed, non-etched polymer produced a periodic array of rectangular patterns of 100 µm wide and 500 nm thick. The other ITO substrate was coated with a homeotropic alignment layer so as to promote hybrid alignment of the LC. The gap of the LC cell was maintained using glass spacers of 13.6 µm thick. A nematic LC of ZLI-2293 (E. Merck Industries) was filled into the cell at room temperature. The LC molecules on the homogeneous alignment layer with no photo-reactive polymer were aligned along the flow direction. The ordinary and extraordinary refractive indices of ZLI-2293 are given as $n_o = 1.4797 + 6737/\lambda^2$ and $n_e = 1.5941 + 13271/\lambda^2$ where λ is the wavelength of light in nm. The dielectric anisotropy and the elastic constants are $\varepsilon_a = 10$, $K_1 = 12.5 \times 10^{-12}\,\text{N}$, $K_2 = 7.3 \times 10^{-12}\,\text{N}$, and $K_3 = 17.9 \times 10^{-12}\,\text{N}$.

Figure 2 shows the experimental setup for measuring the diffraction properties of our LC binary gratings upon a single pump beam

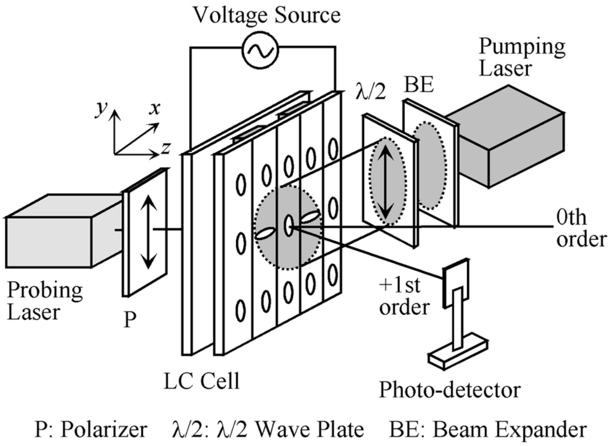

FIGURE 2 Experimental setup for measuring the diffraction properties upon a single pump beam and a bias voltage.

and a bias voltage. As the pump beam source, an Ar-ion laser with wavelength of 488 nm and the power of 200 mW/cm^2 was used. The single pump beam was linearly polarized along the *y* direction (or the *x* direction) for switching-on (or switching-off) the diffraction [7]. For the electrical control of the diffraction, a square wave voltage of 1 kHz was applied to the LC cell. The diffracted intensity was monitored using two He-Ne probe lasers of 632.8 nm and 544 nm in wavelength to study the dependence of the diffraction efficiency on the input wavelength. The probe beam was polarized parallel to the *y* direction and low enough to avoid any appreciable effect on the photo-reactive polymer. The first-order diffracted intensity through the LC cell was measured with a photodetector in conjunction with a digitizing oscilloscope.

RESULTS AND DISCUSSION

Figure 3 shows the first-order diffraction efficiency of two optically generated LC configurations shown in Figure 1 as a function of the applied voltage for fixed input wavelength of 632.8 nm. The uniform and orthogonal hybrid configurations were produced by a single pump beam polarized along the *x* direction and the *y* direction for 40 seconds, respectively. The diffraction efficiency in the uniform hybrid configuration is nearly zero in the entire voltage range we studied. This means that variations of the effective voltage due to the dielectric surface relief grating in the patterned photo-reactive polymer layer are

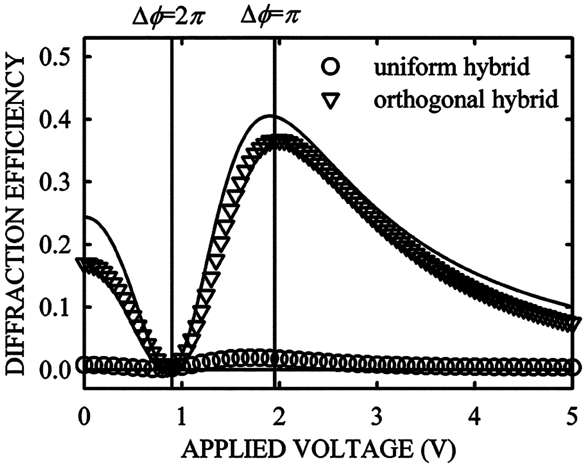

FIGURE 3 The first-order diffraction efficiencies in two optically generated LC configurations shown in Figure 1 as a function of the applied voltage for fixed input wavelength of 632.8 nm. The open symbols and the solid lines denote the experimental data and theoretical predictions, respectively.

negligible [8]. The solid lines in Figure 3 represent one-dimensional numerical results [9] calculated from Eq. (1) under the assumption of the no relief grating effect. In the orthogonal hybrid configuration, the diffraction efficiency has the minimum at 0.90 V and the maximum at 1.95 V, which correspond exactly to the case of $\Delta\phi = 2\pi$ and that of $\Delta\phi = \pi$ in Eq. (1), respectively. Under no applied voltage, the phase difference is between 2π and 3π. Note that the difference between the experimental and theoretical results is attributed to the LC distortions at domain boundaries.

Figure 4 shows the diffraction dynamics of the optically controlled LC grating with or without a bias voltage for two different wavelengths of 632.8 nm and 544 nm. Four cycles of switching-on and switching-off the diffraction between the orthogonal and uniform hybrid configurations were carried out by changing the polarization state of the input beam for 40 seconds. In the absence of the bias voltage, the relative phase difference generated optically, $\phi_0(0) - \phi_2(0)$, was found to be between 2π and 3π for both input wavelengths. The phase difference for 544 nm was larger than that for 632.8 nm. The maximum diffraction efficiency was obtained under the bias voltage of 1.95 V for 632.8 nm and that of 2.20 V for 544 nm. This corresponds exactly to the case of $\Delta\phi(V) = \pi$. The nonzero diffraction efficiency for 544 nm in the switch-off state results from the

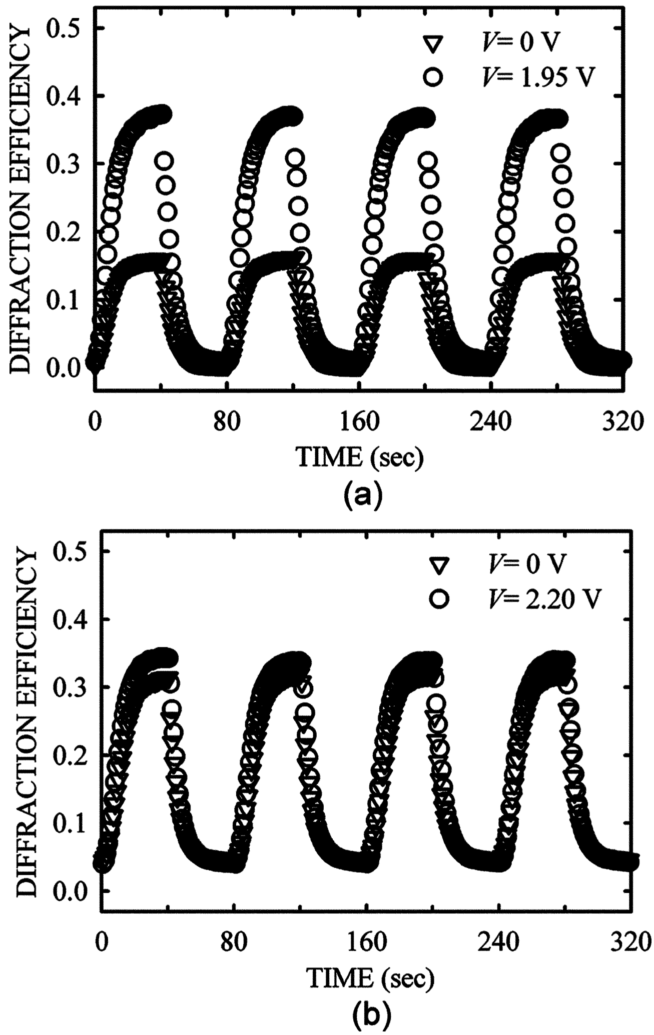

FIGURE 4 The diffraction dynamics of the optically controlled LC grating with or without a bias voltage for two different wavelengths of: (a) 632.8 nm and (b) 544 nm. The single pump beam polarized linearly along the y direction (or the x direction) was irradiated for switching-on (or switching-off) diffraction for 40 seconds.

absorption spectrum of the photo-reactive polymer. Moreover, the first-order diffraction efficiency is somewhat smaller than the predicted value of $\eta_{\pm 1} = 0.4$.

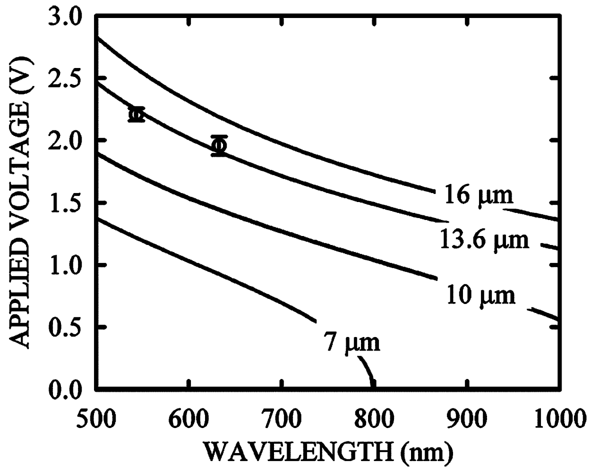

FIGURE 5 The bias voltage required for the maximum diffraction efficiency in our LC binary gratings for several cell gaps as a function of the input wavelength. Open circles and the solid lines denote the experimental data and theoretical predictions, respectively.

The bias voltage required for obtaining the maximum diffraction efficiency depends on the cell parameters such as the cell gap and the wavelength of the input beam. In Figure 5, the required bias voltages of the LC gratings with different cell gaps are shown as a function of the wavelength of the input beam. For short wavelength application, the bias voltage should be relative high. It is also predicted that a thick LC cell is desirable to obtain the maximum efficiency in the wide range of the wavelength. However, a high bias voltage is needed and the switching time is slow for the thick cell. This is consistent with the experimental results in Figure 4.

CONCLUSION

We demonstrated an electrically and/or optically controllable LC binary grating with a patterned surface-command layer. The diffraction efficiency was controlled optically by a single pump beam and electrically by an applied voltage across a pair of flat electrodes. Under a bias voltage, the optically generated diffraction can be controlled to obtain the maximum efficiency in a wide range of the wavelength. The LC binary grating configuration with two control schemes presented here will provide great flexibility in implementing it into various optical systems that are operated either optically, electrically, or simultaneously.

REFERENCES

[1] Davis, J. A., Adachi, J., Fernandez-Pousa, C. R., & Moreno, I. (2001). *Opt. Let.*, *26*, 587.
[2] Cipparrone, G., Mazzulla, A., & Russo, G. (2001). *Appl. Phys. Lett.*, *78*, 1918.
[3] Park, J.-H., Yu, C.-J., Kim, J., Chung, S.-Y., & Lee, S.-D. (2003). *Appl. Phys. Lett.*, *83*, 1918.
[4] Jeong, Y., Kim, H.-R., Baek, S., Kim, Y., Lee, Y. W., Lee, S.-D., & Lee, B. (2003). *Opt. Eng.*, *42*, 964.
[5] Yamamoto, T., Yoneyama, S., Tsutsumi, O., Kanazawa, A., Shiono, T., & Ikeda, T. (2000). *J. Appl. Phys.*, *88*, 2215.
[6] Doucen, M. L. & Pellat-Finet, P. (1998). *Opt. Commun.*, *151*, 321.
[7] Gibbons, W. M., Shannon, P. J., Sun, S.-T., & Swetlin, B. J. (1991). *Nature*, *351*, 49.
[8] Yoon, T.-Y., Park, J.-H., Sim, J., & Lee, S.-D. (2002). *Appl. Phys. Lett.*, *81*, 2361.
[9] De Gennes, P. G. *et al*. (1993). *The Physics of Liquid Crystals*, Oxford U. Press: New York.