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Research Article

Electrically Tunable Diffraction Grating Based on Liquid Crystals

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A periodic electric field is generated in the grating-like electrodes cell by an applied voltage and results in the reorientation of liquid crystals. The linearly polarized probe beam experienced periodic distribution of refractive index and formed a phase grating. He-Ne laser was used as the probe beam to detect the zeroth-order (o) and first-order (+1) diffraction intensities. The experimental results showed that the diffraction grating can be switched on by applying a small voltage. The optimal first-order diffraction efficiency is about 12%. The dependence of the first-order diffraction efficiency on the polarization of the probed beam is also discussed herein.

1. Introduction

Liquid crystal (LC) phase grating has numerous applications, such as laser beam steering, beam shaping, fiber-optic communications, highly efficient projection displays, wide-viewing and direct-view displays, and other modifications of light intensity or phase [1–9].

For nematic liquid crystals (NLCs) based phase grating, because the operation voltage changing the orientation of the molecular director is usually lower, depending on the dielectric anisotropy ($\Delta\varepsilon$) of LCs, an effective refractive index (Δn) of the medium is experienced by a propagating beam and has become an ideal candidate as an electrically controllable device due to the large optical birefringence [3, 10–15].

There are several ways to fabricate the liquid crystals diffraction gratings. Gibbons et al. have shown liquid crystal grating by exposing a dye-doped polymer layer to an ultraviolet interference pattern. Chen et al. have shown a hybrid liquid crystal configuration to create a double-rubbed polyimide layer for polarization-independent grating [16–20]. Honma et al. have demonstrated multidomain alignment regions liquid crystal gratings through a microrubbing technique [12, 13]. Wen et al. have shown a dual-domain polarization grating which consists of right- and left-handed twisted regions created from scribing a polyimide layer [5].

In this paper, we propose a simple phase grating with tunable diffraction efficiency by applying a small voltage. The grating-like patterning of the electric field for the alignment of liquid crystals is easy to achieve and results in the periodic distribution of refractive index. The physical mechanisms for the first-order diffraction efficiency versus polarization angles of the probed beam are also discussed.

2. Experiment

We studied the liquid crystals phase grating in 25 μm-thick LC cell containing homogenously aligned E7. The cell is with grating-like electrode width $w = 15\ \mu$ m. An LC mixture (E7) with $\Delta\varepsilon = 14.4$ (dielectric constants at 1kHz) and Δn=0.218 (refractive indices difference at λ=633 nm and T=20°C) was injected into the cell via capillary flow. Figure 1(a) shows the experimental setup for characterizing the liquid crystals phase grating. He-Ne laser ($\lambda = 633$ nm) was used as the probe beam. The transmission axis of the linear polarizer was set in the x-direction. An AC power supply (~1 KHz) applied voltage to the grating-like electrode cell and produced the periodic electric field on the cell and resulted in the periodic

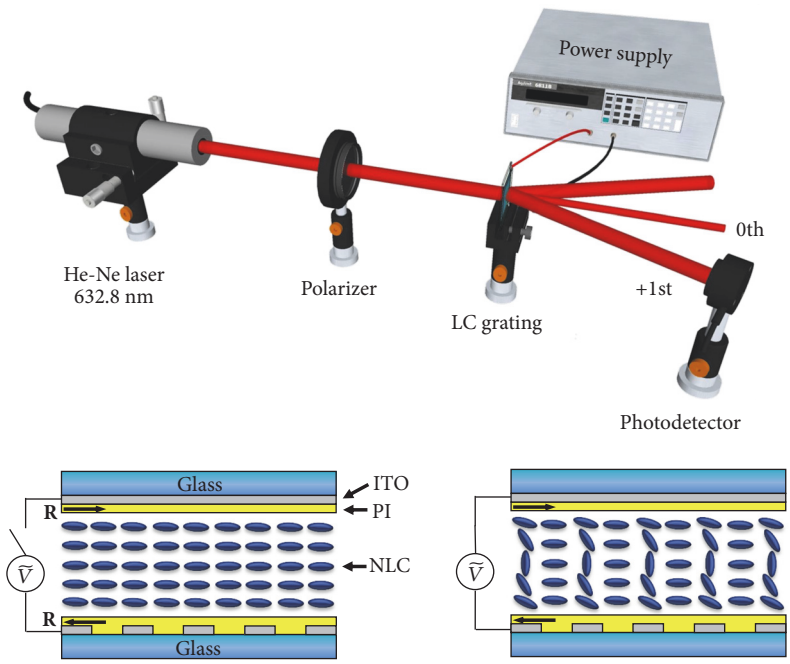


Figure 1: (a) Experimental setup for characterizing the performance of the phase grating. (b) The periodic distribution of refractive index of liquid crystals with an external *ac* voltage.

distribution of the refractive index of liquid crystals, as shown in Figure 1(b). The measured diffraction signals for the zeroth and the first order were detected by the photodetectors and recorded by the computer.

3. Results and Discussions

First, the diffraction intensities of the liquid crystal gratings in the zeroth and the first orders were recorded as a function of time, with an applied voltage of ~4.0V, as shown in Figure 2. The x- linearly polarized light from a He-Ne laser light source is normally incident on the sample; the zeroth-order diffraction rapidly decayed and the first-order diffraction was raised as the voltage was in "on" state. The diffraction intensities rise or decay to a stable level at t=250 ms. Next, the voltage was in "off" state at t=3250 ms; the zeroth-order diffraction was gradually increased and the first-order diffraction was gradually raised to an initial state at t=~3800 ms.

Figure 3(a) plots the first-order diffraction intensity versus voltage for a liquid crystal phase grating formed from the periodic grating-like electrodes cell. The threshold voltage occurred at 2.0 V. After 2.0 V, the diffraction intensity gradually grew. The shape of the first-order diffraction versus voltage curve was indicated; as the voltage is increased to 4.0 V, the liquid crystal director orientation may tend to be homeotropically aligned in the electrical field, and the linearly polarized probe beam in the x-direction experienced the difference in refractive index modulation between electrode and nonelectrode stripes zones, which was significant. From 4.0 V to 10.0 V, the diffraction intensity gradually decays. The phenomenon is speculated to be the result of the disordering of the alignment of liquid crystals in

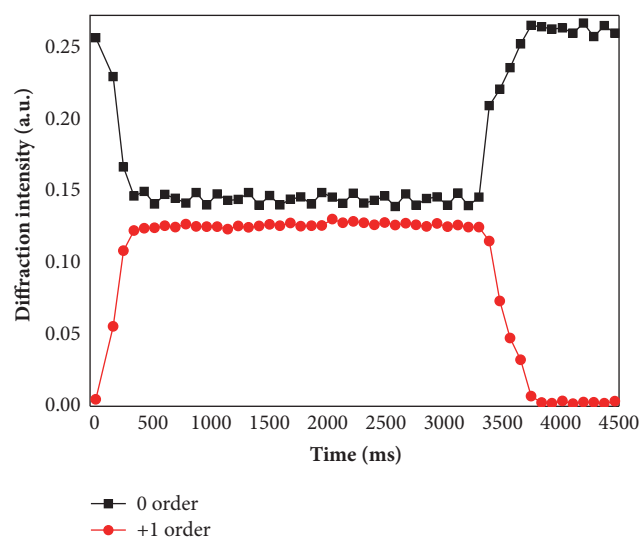
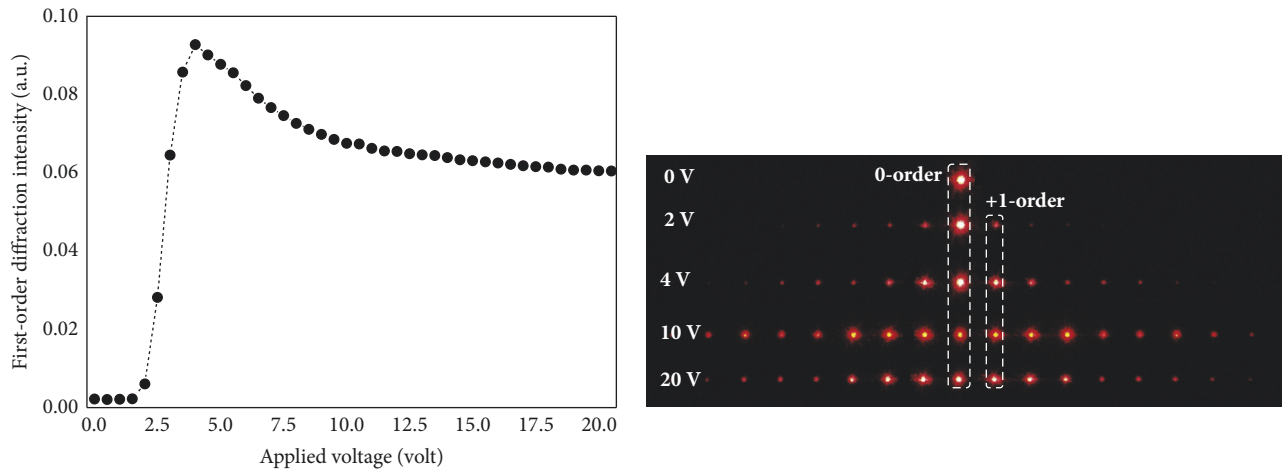


Figure 2: The diffraction intensities of the liquid crystal gratings in zeroth and the first orders were recorded as a function of time, using an applied voltage of ~4.0V.

the nonelectrode domains due to the edge effect of the electric field, reducing the difference in the refractive index modulation. After 10.0V, the first-order diffraction decays to a stable level. Figure 3(b) shows the images of the diffraction signals taken at 0, 2, 4, 10, and 20 V. At 0 V, only the zeroth-order diffraction signal exists; at 2 V, the first-order diffraction appears and the high order diffraction signals (4th-order diffraction) can be observed; at 4 V, the first-order diffraction becomes the brightest and the 6th-order diffraction signals can be observed; at 10.0 V and 20.0V, the



(a) (b)

Figure 3: (a) The first-order diffraction intensity versus voltage for a liquid crystal phase grating formed from the periodic grating-like electrodes cell. (b) Diffraction patterns at different applied voltages: 0, 2, 4, 10, and 20 V, respectively.

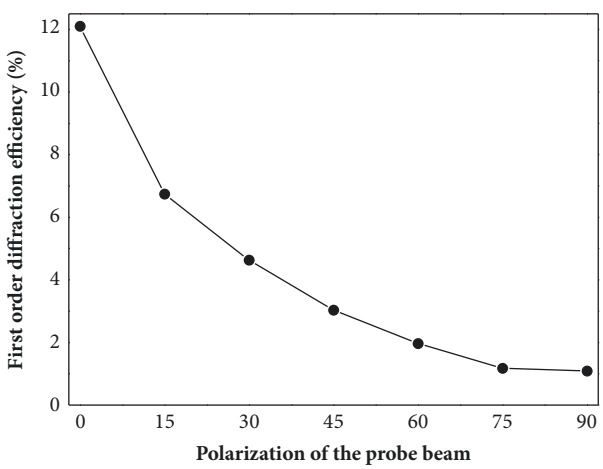


Figure 4: The diffraction efficiency of the first-order beams versus polarization of the probe beam with applied voltage ~4.0V.

first-order diffraction signal decays, and 8th-order diffraction signals can be observed.

Figure 4 shows the measured diffraction efficiency of the first-order beams with various polarization of the probe beam with applied voltage ~4.0V. The first-order diffraction efficiency η_1 is defined as the ratio between the intensity of 1st diffracted order and the total intensity at $V = 0$, described by

$$\eta_1 = \frac{I_1}{I_0} \tag{1}$$

The polarization of the probed beam is adjusted by rotating a polarizer from 0° to 90° corresponding to the adjustment of the polarization of the probe beam from x polarized to y polarized. The intensity of the probe beam maintains a constant value as the polarization is adjusted. The polarization angles of the probed beam are 0°, 15°, 30°, 45°, 60°, 75°, and 90°, respectively. When the polarization angle is at 0°, the probe beam experiences ordinary (n_o) and extraordinary (n_e) refractive indices in the regions with and without the grating-like electrode stripes of the liquid crystal grating, respectively. The modulation of the refractive indices $\Delta n = ne - no$ causes the phase grating effect in liquid crystals. The first diffraction efficiency η_1 *is ~12.0%*. In considering the polarization angle other than the x polarization (0°), the effective refractive index experienced by the probed beam is a function of the polarization angle, according to [21]

$$n_{\text{eff}}(\theta) = \left(\frac{n_o n_e}{n_o{}^2\cos^2\theta} + n_e{}^2\sin^2\theta\right)^{1/2} \tag{2}$$

where θ is the angle between the x-axis and the polarization of the probe beam. As the polarization angle is adjusted from 0° to 90°, the effective refractive index n_{eff} experienced by the beam in the regions without the electrode stripe is reduced; the refractive index is constant in the regions with the electrode stripe. The modulation of the refractive index influences the phase grating. Therefore, the decrease in the anisotropy of the refractive index weakens the phase grating effect. The phase grating effect gradually decays as the polarization angle is increased. When the probe beam is linearly polarized in the y direction (90°) it experiences almost the same ordinary refractive index in the regions with and without the electrode stripe. The first diffraction efficiency η_1 *is ~1.1%*. The results reveal that the phase grating effect is directly influenced by the polarization of the probe beam and can be switchable by adjusting the polarization of the probe beam.

4. Conclusions

In summary, the reorientation of liquid crystals can be obtained by applying external voltage in the grating-like electrodes cell; the linearly polarized probe beam experienced periodic distribution of refractive index, resulting in the

liquid crystal phase grating. The zeroth-order and the first-order diffraction intensities were probed by a He-Ne laser. The diffraction grating can be switched on by applying a small voltage (~2.0 V). The optimal first-order diffraction efficiency is about 12%. The first-order diffraction efficiency can also be tuned from 12.0% to 1.1% by adjusting the polarization of the probe beam.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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