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Holographic Reversed-Mode Polymer-Stabilized Liquid Crystal Grating *

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We demonstrate the "reversed-mode" polymer-stabilized liquid crystal device. The incidence light goes through the film without the applied voltage and is diffracted with it. Because of relatively high liquid crystal percentage of 94%, the operating voltage of the device is less than 20 V. We explain this phenomenon using the molecular orientation model and the refractive index profile. The device can be used as display, optical switch, optical modulator and especially optical cross-connect deflector.

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Recently, polymer/liquid crystal (LC) has been extensively investigated for various electro-optical applications.[1−3] Polymer dispersed liquid crystal (PDLC) as a type of LC diffraction device is a thin composite film composed of micrometre-sized droplets of a nematic liquid crystal dispersed in a polymer matrix.[4] Holographic PDLC (HPDLC) is a variant of PDLC, which is a stratified composite of alternating layers of liquid and polymer.[5] HPDLC has potential applications in holographic and diffractive optics. Generally, a strong diffraction pattern is observed in the zero field state. For LC with a positive dielectric anisotropy ($\Delta\varepsilon > 0$) in the applied electric field, the incidence light transmit if the refractive index n_0 of LC is approximately equal to that of the polymer n_p,[6] which is called the "normal mode" HPDLC grating.

However, the reversed-mode device can be formed when the percentage of polymer monomer is small, for example, 3%–8%.[7] The "reversed-mode" means that the incidence light goes through the film without applied voltage and is diffracted with it. The few polymers form network or fabric that affects the LC alignment, which leads to its electro-optic property different from that of the normal mode device. The relatively high LC percentage allows a low operating voltage of the device. Therefore, its potential application is very attractive. In this Letter, we demonstrate this reversed-mode polymer stabilized LC (R-PSLC) using a holographic and photomask method.

As shown in Fig. 1, two different experimental methods are used to fabricate R-PSLC. The holographic method is shown in Fig. 1(a). It is a classical holographic recording method and a 488 nm Ar^+ laser is used in the experiment. The photomask method shown in Fig. 1(b) is to put the photomask composed of two vertical stripe-shaped templates in the expanding single 488 nm Ar^+ laser beam. The sample sticks to the back of the photomask closely. Under both conditions, polymerization occurs in the bright area and a polymer network or fabric is also formed in this area.

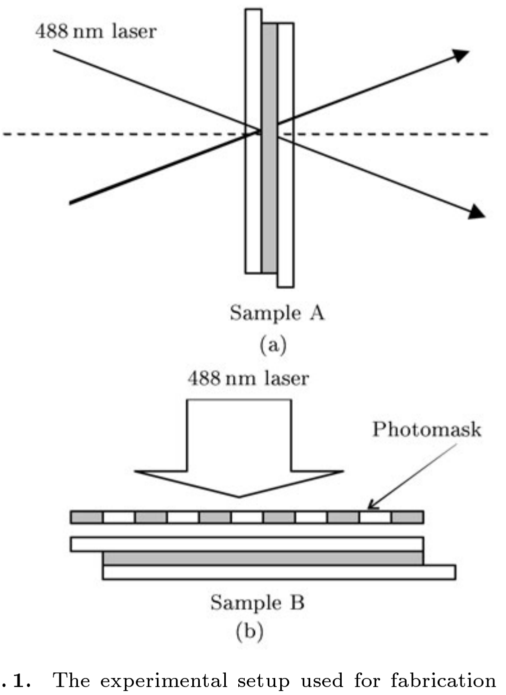

Fig. 1. The experimental setup used for fabrication R-PSLC grating: (a) holographic method, (b) photomask method.

In the experiment, the pre-polymer mixture consists of a nematic liquid crystal TEB30A (from Slichem, $\Delta n = 0.17$, $n_0 = 1.5221$) and 6 wt.% dipentaerythritol hydroxy penta acrylate monomer (DPHA, polysciences). A small amount of photoinitiator dye, Rose Bengal (RB) and coinitiator n-phenylglycine

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(NPG) are added to the mixture. To prepare a sample, a drop of the homogeneous mixture is injected into a cell that is made from two ITO-coated glass substrates separated by a 9-μm-thick spacer. The curing intensity is 2.8 mW/cm^2 and the exposure time is 10 min.

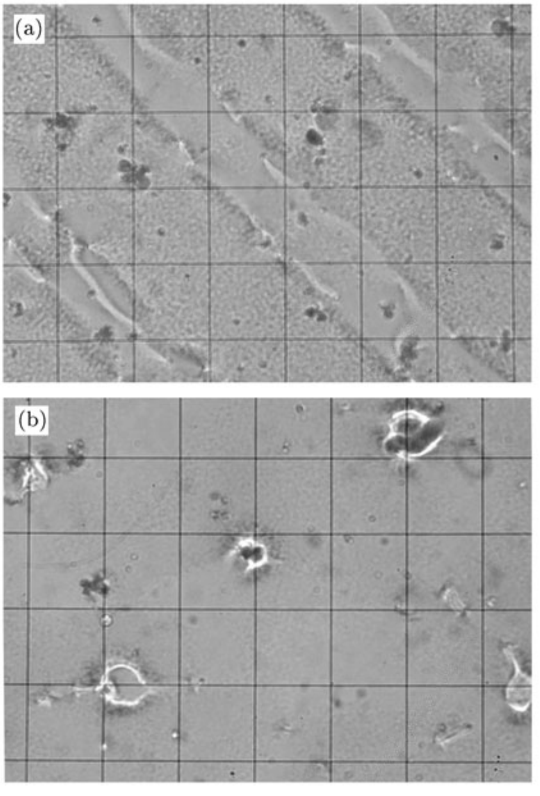

Fig. 2. Microscope photographs of the R-PSLC film: (a) sample A obtained using holographic method, (b) sample B obtained using photomask method.

Microscope photographs of the R-PSLC are shown in Fig. 2. The magnification is 125. The periodic polymer network or fabric in the LC matrix can be seen in the holographic R-PSLC grating (called sample A) photograph as shown in Fig. 2(a). Because the polymer percentage is low, it differs from the polymer grating and "wall" of HPDLCs. The micrograph of the sample using the lattice photomask method (see Fig. 2(b)) also shows the polymer lattice fabric in the LC matrix (called sample B). As a result, a sample with slight polymer concentration is fabricated. In the applied electric field its reversed-mode electro-optical property appears.

Figure 3(a) shows the diffraction pattern of sample A in different operation voltages. The He–Ne laser beam passes through sample A without applied voltage and very slight scattering occurs. When a voltage is applied to the film, the diffraction of incident light occurs at the voltage of 9 V. This is the threshold voltage of sample A. The intensity of the first-order diffraction light achieves the maximum at the voltage of 16 V. According to Eq. (1), we measure the diffraction efficiency η as a function of applied voltage as shown in Fig. 4(a).

$$\eta = T/I. \qquad (1)$$

In Eq. (1), T is the transmittance light intensity of the zero or the first-order beam and I indicates the incidence light intensity. For sample A, zero-order light almost passes through the film eliminating the scattering noise at $V = 0$. Above the threshold voltage ($V = 9$), the first-order diffraction efficiency increases with the increasing applied voltage. When the operation voltage is up to 16 V, η_1 can reach the maximum

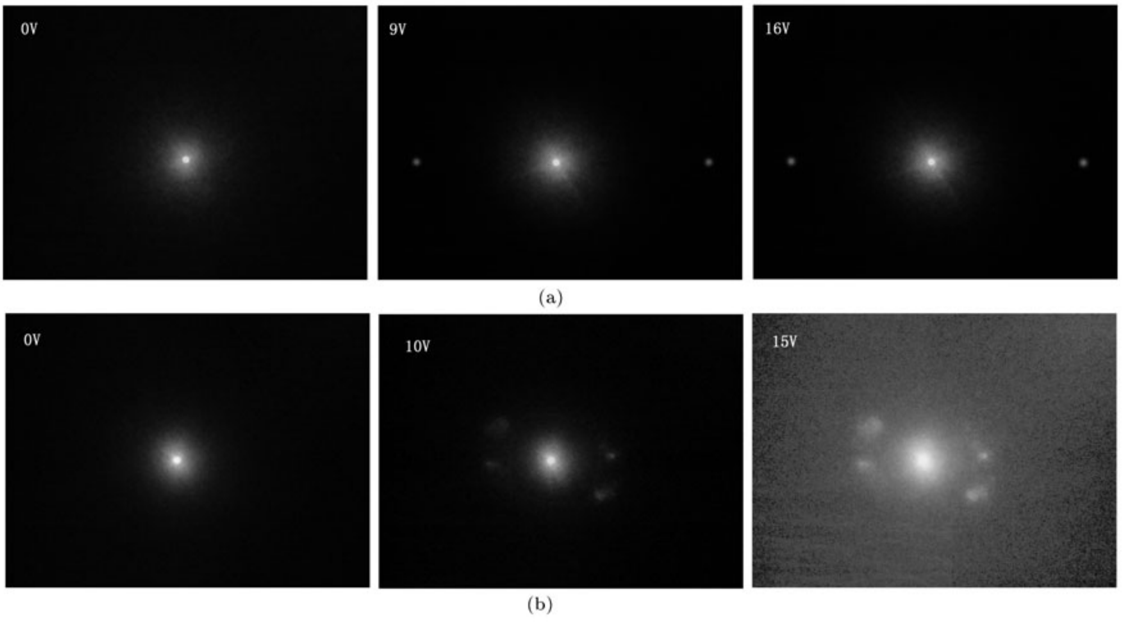

Fig. 3. Photographs of the diffraction patterns at different operating voltages: (a) sample A, (b) sample B.

value of 0.29%. From our point of view, the adjustment range of η can be expanded if the fabrication conditions is optimized.

Employing the same method we obtain the photographs and diffraction efficiency curve of sample B as shown in Figs. 3(b) and 4(b), respectively. The polymer lattice fabric forms because of the photomask pattern. Correspondingly, sample B has the character of a two-dimensional grating. One bunch of incidence light becomes four bunches of about equal intensity to the first-order light by diffraction in the applied voltage. In particular, it can be used as a multiple-path all-optical cross-connect device. Sample B also realizes the reversed-mode application. As seen in Fig. 4, η of sample B is higher than that of sample A. We believe that this phenomenon may be due to the different extent of their phase separations. The extent of phase separation of sample B exhibits more clearly than that of sample A as shown in Fig. 2, which determines a higher η of sample B than that of sample A. In addition, as seen in Fig. 2, slight polymer occurs in the dark area where LC centralizes. The result suggests that the low phase separation extent of sample A is mainly due to the small fringe contrast of the interference light field. The effective method to increase the η value of sample A is to prevent the polymer in the dark area from occurring by increasing the fringe contrast of the interference light field.

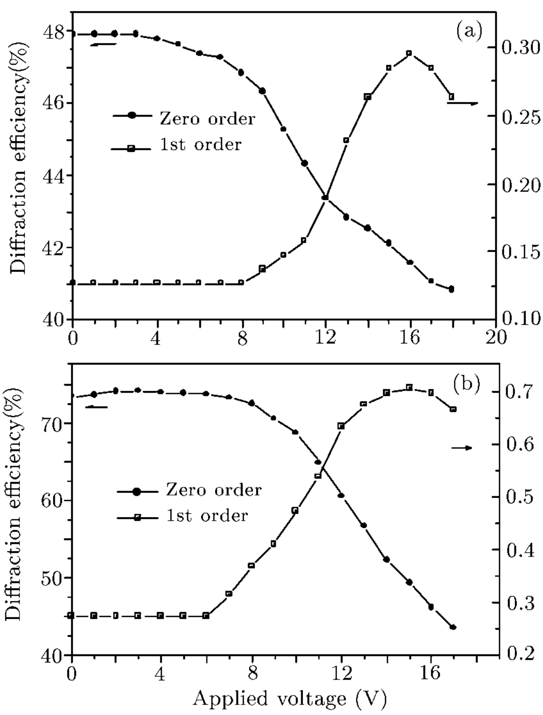

Fig. 4. Diffraction efficiency as a function of applied voltage: (a) sample A, (b) sample B.

According to the photographs of polymer fabric in the LC matrix and the diffraction efficiency as a function of applied voltage, we can determine that the polymer records the distribution of the light intensity under holographic and photomask conditions. Polymer concentration tends to take place in the light areas. Contrarily, LC matrix localizes in the dark areas. Thus, phase separation occurs. Consequently, polymer fabric affects the device for reversed-mode applications.

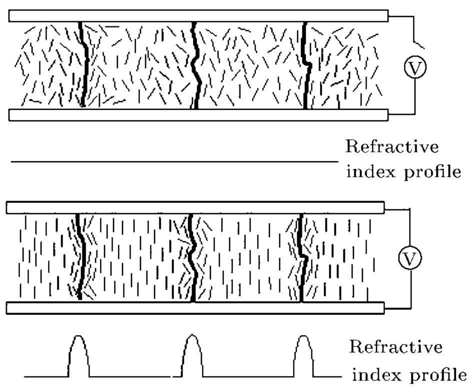

Fig. 5. The molecular orientation and the refractive index profile of sample A in the zero field and in the electric field.

We present the molecular orientation model and the refractive index profile of sample A in Fig. 5 to explain this reversed-mode phenomenon. In the zero-field state the director of LC domain is governed by elastic energy, which leads to its random distribution. However, the LC director around the polymer fabric is mainly governed by anchoring energy of the inhomogeneous polymer fabric surface where it is also random. Averagely, all the LC director distribution is random. The total refractive index can be expressed as

$$n_{\text{eff}} = (n_{LC}^2 \phi_{LC} + n_p^2 \phi_p)^{1/2} \approx 1.572, \qquad (2)$$

where ϕ_{LC} and ϕ_p are the percentage of LC and polymer respectively, $n_{LC} = (2n_o + n_e)/3 \approx 1.578$ and n_p is the refractive index of polymer ($\sim$1.5). Hence the refractive index profile is relatively smooth and the device has no obvious diffraction property. With the applied low electric field, the LC directors in the LC domain are oriented to the electric-field direction. The refractive index in these areas tends to n_o. Because the polymers have anchoring effect on the surrounding LC, the refractive index profile is undulated. Consequently, the refractive index modulated grating forms. In fact, the LC microdrops in the polymer fabric do not participate in the refractive index modulation because of the relatively strong anchoring effect at low voltage. When the maximum modulation is obtained, the first order diffraction efficiency becomes maximum. Following the same principle, photomask makes polymer fabric be distributed in certain areas in the sample B and the diffraction pattern is different from that of sample A. We can control the diffractive pattern by changing the shape of photomask. In this experiment, the low electric field is a considerable parameter. All LC would be oriented to the electric field direction in the high applied voltage. The anchoring capacity would descend relatively, which makes the diffraction efficiency descend correspondingly.

In conclusion, we have demonstrated a reversed-mode device using the holographic and photomask method. Because of low operating voltage and reversed-mode effect, it can be used in many electro-optical applications. Various diffraction devices can be obtained using the holographic and different patterned photomask method. If optimizing the anisotropy of LC, the variety and percentage of monomer, the laser intensity and exposure time, the reversed-mode PSLC can reach higher diffraction efficiency. It can be used as display, optical switch, optical modulator and especially optical cross-connect deflector.

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