

A polarization insensitive 2×2 optical switch fabricated by liquid crystal–polymer composite

Y. J. Liu and X. W. Sun^{a)}

School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore

J. H. Liu, H. T. Dai, and K. S. Xu

State Key Lab for Advanced Photonic Materials and Devices, Department of Optical Science and Engineering, Fudan University, Shanghai 200433, China

(Received 24 September 2004; accepted 2 December 2004; published online 21 January 2005)

A polarization insensitive 2×2 optical switch was fabricated with liquid crystal–polymer composite by means of holography. The highest diffraction efficiency achieved was 85.7%. The rise time and the decay time measured were 36 and 160 μs, respectively, at an applied electric field of 18.2 V/μm. The polarization-dependent loss was 0.03 dB measured for *s*- and *p*-polarized light at the wavelength of 632.8 nm. © 2005 American Institute of Physics. [DOI: 10.1063/1.1857092]

Switchable diffraction gratings have attracted much attention for their potential applications in optical communications, information storage, and flat panel displays.^{1–4} Switchable diffraction gratings fabricated by various techniques, such as surface relief,^{5,6} mask-patterning,⁷ and polymer-stabilized liquid crystal,⁸ have been demonstrated. The gratings fabricated by these techniques are relatively straightforward to manufacture and require a reasonably low switching voltage. However, the switching time is generally slow (about 3–5 ms) and it is difficult to form a volume grating that operates in the Bragg regime. This letter reports a polarization insensitive 2×2 optical switch with fast switching time fabricated with liquid crystal (LC)–polymer composite by means of holography.

The materials used to fabricate the optical switch were monomer, trimethylolpropane triacrylate (TMPTA), cross-linking monomer, *N*-vinylpyrrolidone (NVP), photoinitiator, rose bengal (RB), coinitiator, *N*-phenylglycine (NPG), and surfactant, S-271 POE sorbitan monooleate, all from Aldrich. In prepolymer, the ratio of TMPTA/NVP/S-271/NPG/RB was 62/25/10/2/1 by weight. The refractive index of the cured polymer was 1.522 at 632.8 nm. The liquid crystal used was E7 from Merck with an ordinary refractive index of $n_o=1.521$, and birefringence of $\Delta n=0.225$. The prepolymer and LC were mechanically blended according to the appropriate weight ratio at 65 °C (higher than the clearing point of the LC) to form a homogeneous mixture. The mixture was sandwiched between two pieces of indium-tin-oxide (ITO) glass and placed behind the base of a right angle prism to record the hologram pattern, which was obtained by interference of two beams from an Ar⁺ laser operating at 514.5 nm. The thickness of the samples was 18 μm. After exposure, the samples were further cured for 5 min by mercury lamp. All samples were measured with polarized He–Ne laser at room temperature. For scanning electron microscopy (SEM) analysis, the test samples were broken with the ITO glass on one side removed, soaked in ethanol for more than 12 h to remove LC, and finally dried. The response time, recorded by an oscilloscope, was obtained by measuring the diffracted

light intensity variation triggered by square wave voltages applied on the grating.

The structure of the 2×2 optical switch is sketched in Fig. 1. With a cell thickness of 18 μm and grating spacing of 0.56 μm, the sample shows itself as a volume Bragg phase grating. By applying a proper electric field, the grating can be switched between ON and OFF states. The working principle of such a switch is fairly straightforward. A linearly polarized light beam incident on the switch will see the phase grating formed by the LC–polymer materials with different refractive index, and thus being diffracted. When an electric field is applied, the LC molecular director is reoriented, changing the refractive index seen by the incoming light. If properly designed, with a suitable voltage applied, $n_{LC}=n_{\text{polymer}}$ can be achieved, when the Bragg grating disappears. If and when the condition is met, the beam is no longer diffracted.

The contrast ratio (CR) and signal-noise ratio (SNR) of the switch can be defined as

$$\text{CR} = 10 \log \left(\frac{\text{DE}_{\text{max}}}{\text{DE}_{\text{min}}} \right)$$

or

$$\text{CR} = 10 \log \left(\frac{\text{TE}_{\text{max}}}{\text{TE}_{\text{min}}} \right), \quad (1)$$

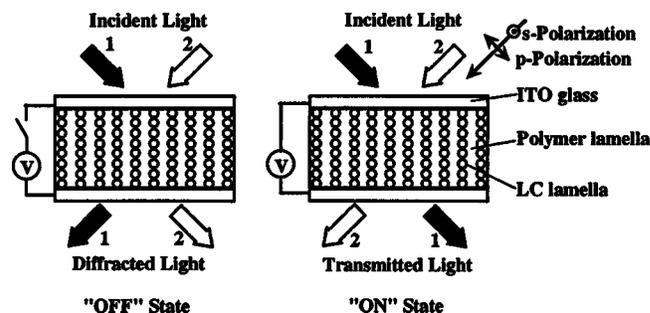


FIG. 1. Schematic of the LC–polymer composite 2×2 optical switch. The *p* and *s* polarization are also sketched.

^{a)} Author to whom correspondence should be addressed; electronic mail: exwsun@ntu.edu.sg

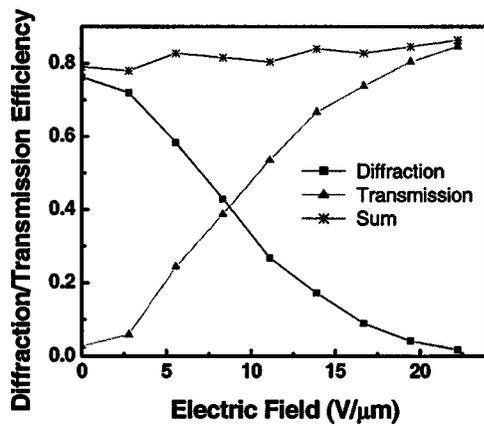


FIG. 2. Diffraction and transmission efficiency as a function of applied electric field. The sum refers to the sum of diffraction and transmission efficiencies.

$$\text{SNR} = 10 \log \left(\frac{\text{DE}_{\max}}{\text{TE}_{\min}} \right)$$

or

$$\text{SNR} = 10 \log \left(\frac{\text{TE}_{\max}}{\text{DE}_{\min}} \right), \quad (2)$$

where DE_{\max} is the highest diffraction efficiency, DE_{\min} is the lowest diffraction efficiency, TE_{\max} is the highest transmission efficiency, and TE_{\min} is the lowest transmission efficiency.

Figure 2 shows the diffraction efficiency and transmission efficiency as a function of the applied electric field. With an optimized ratio of various materials, the highest diffraction efficiency achieved was 85.7%. The corresponding CR and SNR were about 23.4 and 15.1 dB, respectively. In Fig. 2, the sum of the diffraction efficiency and transmission efficiency is also plotted. It can be seen that the sum increases slightly with the electric field, which indicates a decrease in the random scattering. When the diffraction efficiency is reduced to the minimum, the transmission efficiency reaches the maximum.

Figure 3 shows SEM image of the grating with the LC cell de-capped and LC removed. It can be seen from Fig. 3 that the pitch of the grating is about $0.56 \mu\text{m}$. Judging from the small holes (in narrower darker regions separating wider

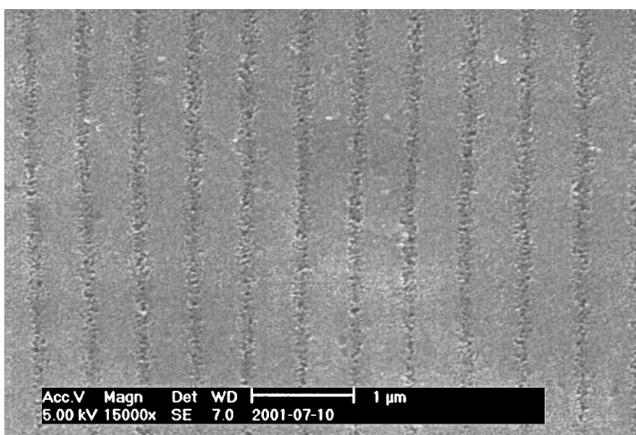


FIG. 3. The SEM image of the grating with LC removed.

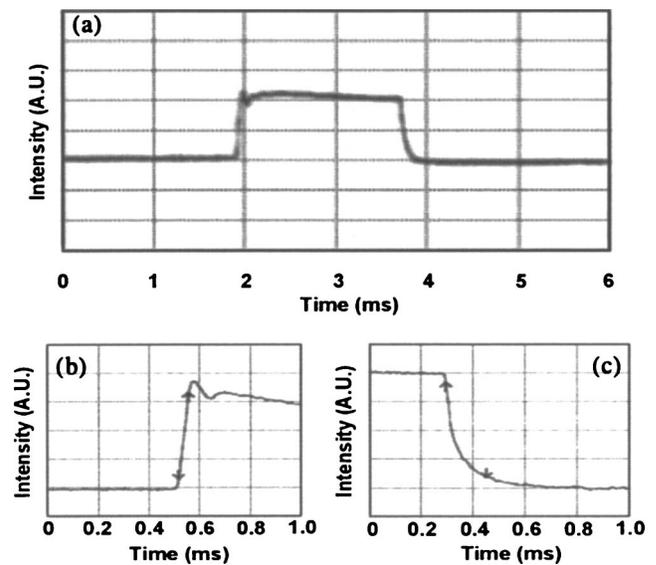


FIG. 4. Variation of diffracted light intensity corresponding to a square driving voltage (a), and the magnified rising edge (b), and the falling edge (c) of (a).

brighter stripes), where the LC droplet resides, the size of most LC droplets is in the range from 10 to 50 nm in diameter.

Driven by square wave signals, the rise and decay times were captured. Figure 4(a) shows the diffracted light intensity captured when the cell is driven by a 1.75 ms voltage pulse. Figures 4(b) and 4(c) show the rising edge and falling edge of the detected signal, respectively. The rise time (10%–90% intensity change) and the decay time (90%–10% intensity change), are 36 and 160 μs , respectively. The response time is faster than other optical switches, such as thermo-optical switches, whose response time is usually on the order of 1 ms.⁹ However, a drawback of the LC–polymer composite optical switch is that a high driving voltage is generally needed. In our experiment, the threshold electric field for the samples without surfactant was as high as $13 \text{ V}/\mu\text{m}$, which resulted in a threshold voltage of 234 V for an $18 \mu\text{m}$ cell. To lower the driving voltage, a small portion of surfactant, S-271 POE sorbitan monooleate, was added in the composite. After adding the surfactant, the threshold electric field was significantly reduced to about $2.5 \text{ V}/\mu\text{m}$, which was more than four times smaller than that without surfactant. This result agrees with the previous report by Yuan *et al.*¹⁰ It is worth mentioning that, besides adding surfactant, a high dielectric anisotropy material can also be added into the LC–polymer composite to reduce the driving voltage.¹¹ Another interesting thing to note is that, in Fig. 4(b), an optical bounce is clearly observed immediately after the electric field is applied. It is probably due to the backflow effect of liquid crystals.^{12,13}

For LC–polymer composite optical switch, polarization-dependent loss (PDL) is a big concern. Generally, the conversion of the monomer molecules into a polymer network is accompanied by a closer packing of molecules, which leads to contraction of the composite known as polymerization shrinkage. When the polymer shrinks, the LC droplets are compressed, which preferentially aligns the symmetry axis of the rod-shape LC molecules in the droplet along a common direction. This results in a polarization sensitive diffraction since the optical axis is on average along the same di-

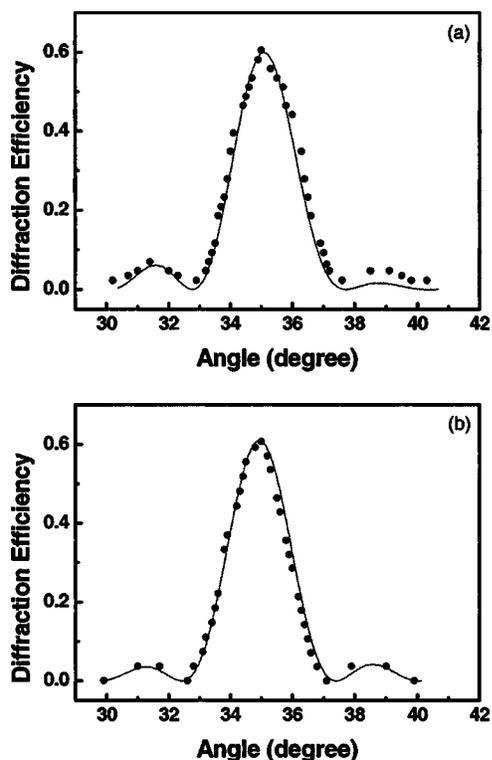


FIG. 5. Diffraction efficiency as a function of incident angle for *p*- (a) and *s*-polarized (b) light.

rection for all droplets, therefore making diffraction efficiency sensitive to the input polarization. However, in our experiment, the shrinkage was only about 2%, which is significantly smaller than the reported data—usually 5%–10%.^{14,15} The smaller polymerization shrinkage reduces the PDL remarkably. The main reason for the lower shrinkage in our experiment is that smaller exposure intensity and longer exposure time were used to decrease the shearing strength in the polymerization process. Figures 5(a) and 5(b) show the diffraction efficiencies measured for *p*- and *s*-polarized light with a wavelength of 632.8 nm, respectively. Using the diffraction efficiency obtained in Figs. 5(a) and 5(b), the PDL was calculated to be 0.03 dB, by comparing the insertion loss difference between *p*- and *s*-polarized

light. It is worth mentioning that Karasawa *et al.* have reported that diffraction efficiency for *p* polarization is much higher than that for *s* polarization in acrylate systems.¹⁶ From Fig. 5, the angular bandwidth (full width at half maximum) is approximately 2°. According to the Kogelnik's coupled-wave theory,¹⁷ with increased thickness of LC-polymer composite films, the bandwidth will become narrower.

In conclusion, we have fabricated a polarization insensitive 2 × 2 optical switch with LC-polymer composite by holographic technique. The highest diffraction efficiency achieved was 85.7%. The corresponding CR and the SNR were 23.4 and 15.1 dB, respectively. The rise time and the decay time were 36 and 160 μs, respectively. The PDL was 0.03 dB for *s*- and *p*-polarized light at 632.8 nm.

¹R. L. Sutherland, L. V. Natarajan, and V. P. Tondiglia, *Chem. Mater.* **5**, 1533 (1993).

²P. Mach, P. Wiltzius, M. Megens, D. A. Weitz, K. H. Lin, T. C. Lubensky, and A. G. Yodh, *Europhys. Lett.* **58**, 679 (2002).

³V. P. Tondiglia, L. V. Natarajan, R. L. Sutherland, T. J. Bunning, and W. W. Adams, *Opt. Lett.* **20**, 1325 (1995).

⁴R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, S. A. Siwecki, S. Chandra, and T. J. Bunning, *Proc. SPIE* **4463**, 1 (2001).

⁵S. Sainov, M. Mazakova, M. Pantcheva, and D. Tontchev, *Mol. Cryst. Liq. Cryst.* **152**, 609 (1987).

⁶M. Stalder and P. Ehbets, *Opt. Lett.* **19**, 1 (1994).

⁷P. F. McManamon, E. A. Watson, T. A. Dorschner, and L. J. Barnes, *Proc. SPIE* **1969**, 2 (1993).

⁸H. W. Ren, Y. H. Fan, and S. T. Wu, *Appl. Phys. Lett.* **82**, 3168 (2003).

⁹X. J. Wang, L. Xu, D. X. Li, L. Y. Liu, and W. C. Wang, *J. Appl. Phys.* **94**, 4228 (2003).

¹⁰H. Yuan, J. Colegrove, G. Hu, T. Fiske, A. Lewis, J. Gunther, L. Silverstein, C. Bowley, G. Crawford, L. Chien, and J. Kelly, *Proc. SPIE* **3690**, 196 (1999).

¹¹J. Colegrove, H. Yuan, S. T. Wu, J. R. Kelly, C. C. Bowley, and G. P. Crawford, *Proceedings of the Sixth International Display Workshops*, 1999, p. 105.

¹²C. Z. van Doorn, *J. Appl. Phys.* **46**, 3738 (1975).

¹³D. W. Berreman, *J. Appl. Phys.* **46**, 3746 (1975).

¹⁴L. V. Natarajan, C. K. Shepherd, D. M. Brandelik, R. L. Sutherland, S. Chandra, V. P. Tondiglia, D. Tomlin, and T. J. Bunning, *Chem. Mater.* **15**, 2477 (2003).

¹⁵G. T. Warren, M. Desarkar, J. Qi, and G. P. Crawford, *SID 2001 International Symposium Digest of Technical Papers*, p. 866.

¹⁶T. Karasawa and Y. Taketomi, *Jpn. J. Appl. Phys., Part 1* **36**, 6388 (1997).

¹⁷H. Kogelnik, *Bell Syst. Tech. J.* **48**, 2909 (1969).