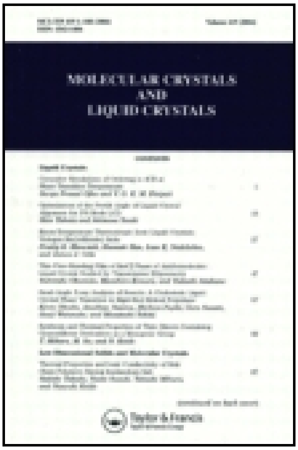

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HOLOGRAPHIC GRATING BASED ON DYE-DOPED SURFACE-STABLIZED FERROELECTRIC LIQUID CRYSTAL FILMS

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A surface stabilized ferroelectric liquid crystal (SSFLC) film, doped with an azo dye, methyl red (MR), is fabricated. A holographic grating is written in this film, using two coherent Ar^+ laser beams. Such a grating is formed by the re-orientation of the liquid crystal molecules caused by interaction with the photo-induced adsorption of the doped azo dyes. Experimental results show that the formed grating is permanent but electrically switchable, with a field of $\sim 0.08\,V/\mu m$.

Keywords: dye-doped; holographic grating; methyl red (MR); surface-stabilized ferroelectric liquid crystal (SSFLC)

INTRODUCTION

Photo-induced reorientation effects in dye-doped liquid crystals (DDLCs) have recently attracted significant attention. Janossy *et al.* found that photo-excited anthraquinone dye molecules induced a positive torque, facilitating the reduction of the threshold of the optical Freedericksz transition [1–3]. Gibbons *et al.* demonstrated that nematic liquid crystals (NLCs) were reoriented perpendicularly to the optical electric field, when the substrate, coated with an azo-dye doped polyimide, was excited by linearly polarized light [4–5]. The photo-excited dyes thus induce a negative torque in such a case. Khoo *et al.* indicated that the dye-induced space charge field could induce the reorientation of the nematic liquid crystal (photorefractive effect [6–7]). For azo-dye doped liquid crystals, recent studies [8–10] further verified that photo-excited dyes induce a transient

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three dimensional LC molecular rotation, and then diffuse and adsorb onto the substrates, generating a torque which aligns LC molecules.

Nematic LCs were used in all the aforementioned research mentioned above, but a few studies in the Ferroelectric LCs [11]. This article present the results obtained from studying holographic gratings formed in azo-dye doped surface-stabilized ferroelectric liquid crystal (SSFLC) films. Such a grating was formed by the interaction of adsorbed dye molecules and FLC molecules. This holographic grating boasts a fast response time and a low switching voltage, inherited from the SSFLC film.

EXPERIMENTS

The FLC material employed in this experiment was CS-1024 (Chisso). The FLC was firstly mixed with 1.0 wt.% azo dye, Methyl Red (MR, Aldrich). The dye-doped FLC material was introduced into a 2-μm-thick indium-tin-oxide (ITO) coated glass cell, via capillary action at a temperature of $\sim 95°C$, at which CS-1024 was isotropic. The cell was rubbed with PVA (poly(vinyl alcohol)) to promote the formation of a SSFLC film. It was then cooled to room temperature very slowly, under an applied DC voltage ($\sim 2\,V$). The quality of the sample in the SSFLC mode was confirmed using a polarized microscope (Olympus DH-2).

Figure 1 depicts the experimental set up. Two writing beams, derived from an Ar^+ laser ($\lambda = 514.5\,nm$), intersected at an angle, $\theta \sim 1.5°$. They were unfocused; each had a diameter of $\sim 6\,mm$ and a power of $\sim 5\,mW$. The beams were coherent, and therefore established an intensity interference pattern at the intersecting region, where the sample was placed. The writing beams were s–polarized, and the polarization direction

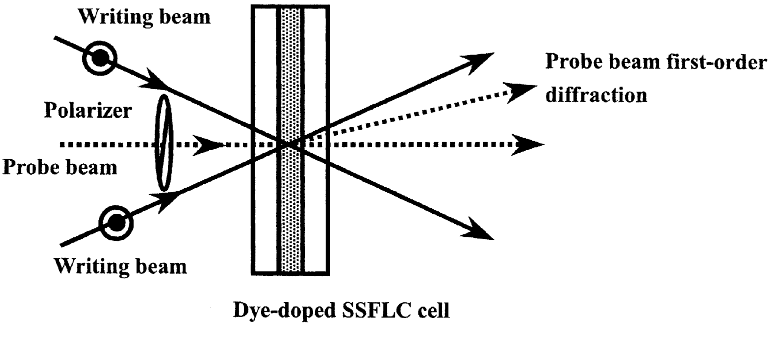

FIGURE 1 Experimental setup for fabricating a holographic grating in a dye-doped SSFLC film.

coincided with that of the director of the FLC molecules adjacent to the substrate's surfaces. A very weak s-polarized He-Ne laser ($\lambda = 632.8\,\text{nm}$) was introduced in the plane that contained the two writing beams, to probe the writing region of the sample. One of the first-order diffracted beam intensities was monitored as the grating was formed. The sample was written for 2000 s, and then the writing beams were switched off. A permanent holographic grating was formed in the dye-doped SSFLC film.

An unpolarized He-Ne laser was normally incident onto the writing region of the sample through a polarizer, which could be rotated to alter the polarization of the probe beam, to investigate the formed dye-doped SSFLC grating. φ is the angle made between the polarization direction of the probe beam and the rubbing direction of the alignment film. Notably, the zero-order beam passed through two polarizers, which were crossed. The first-order diffracted light did not pass through the analyzer. Variations in the angle φ of the zero-order and first-order diffracted intensities of the probe beam, were measured.

RESULTS AND DISCUSSION

1. Characteristics of Dye-Doped SSFLC Cell with PVA Alignment Film

Figure 2 displays the transmission (zero-order) of the dye-doped SSFLC cell as a function of angle φ, with and without an applied DC voltage (8 V). The results show that the transmission exhibits four maxima and minima as the angle φ changes from 0° to 360°. The high-contrast ratio of the transmission maxima to the transmission minima, shown in Figure 2, indicates that a good dye-doped SSFLC cell was fabricated. The tilt angle is $\sim 10^\circ$ with no voltage applied, and $\sim 20^\circ$ with an applied DC voltage (8 V). The latter is close to the inherent tilt angle (25°) of CS-1024 in the SmC* phase. This result implies that FLC molecules are not aligned at the maximum cone angle, when no voltage is applied. The effective cone angle is usually observed to be smaller than the intrinsic angle in a typical SSFLC cell [12].

Figure 3 shows the dynamic change in transmission intensity, when positive and negative DC voltage pulses are applied to the sample. The initial state is the dark state, in which FLC molecules are aligned with their director axes, parallel to the front polarizer. Transmissions at stages (1), (2) and (3), labeled in Figure 3, reveal that the dye-doped SSFLC cell still exhibits a bistable effect. The long response decay-time follows from the existence of ions inside the cell, as the FLC material is doped with dye.

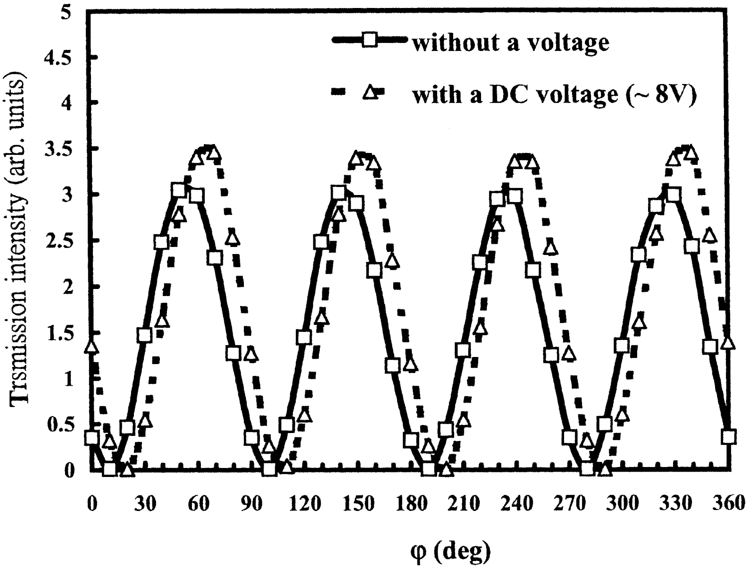

FIGURE 2 Measurements of the transmission intensity (the zero-order diffracted beam) as a function of angle φ made between the rubbing direction and the polarization direction of the probe beam, when a DC voltage (~8 V) is applied to the sample.

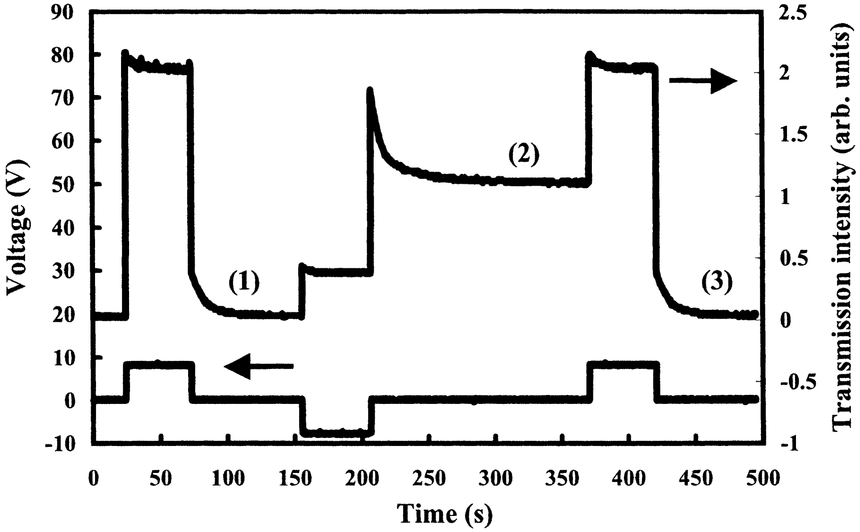

FIGURE 3 Changes in the transmission intensity (the zero-order diffracted beam) of the sample, with positive and negative DC pulses applied. Bistability of the dye-doped SSFLC cell is evident.

2. Dye-Doped SSFLC Gratings

Figure 4 displays the dynamic change in the first-order diffracted intensity during the formation of a grating in the sample. The grating was formed immediately following the writing beams were operational, at t = 0, and then the first-order diffracted intensity increased with time, and finally saturated at ~500 s. When the writing beams were turned off at ~2000 s, the diffracted beam intensity fell, and then became stable, revealing that a permanent grating was formed in the sample.

Recent investigations [8-10] have demonstrated that photo-excited MR dyes, doped in LC cells diffuse and then are adsorbed onto the substrates, inducing a torque to reorientate LC molecules. Figure 5 displays the morphology of the adsorbed MR dyes on the substrates, examined by scanning electron microscopy (SEM). The preparation of SEM samples was described in Ref. 13. Notably, the pattern of adsorption of dyes onto the substrates is identical to copy of the interference pattern established by the two writing beams. The fringe spacing is ~19 μm, showing that photo-excited MR dyes diffuse and then are adsorbed onto the substrates of the dye-doped SSFLC cells. After the Ar^+ laser beams are turned off, some adsorbed MR molecules may diffuse back into the bulk of the material. Therefore, the first-order diffracted intensity fell after the laser beams were turned off, as shown in Figure 4.

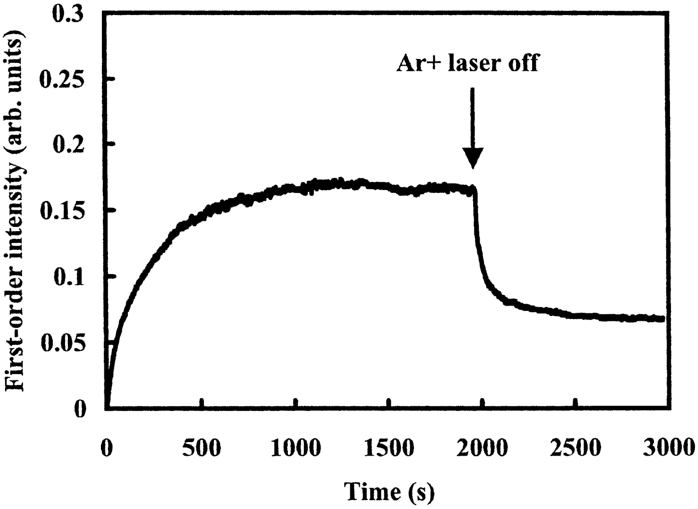

FIGURE 4 Dynamic changes in the first-order diffraction intensity while the gratings are formed in the dye-doped SSFLC film.

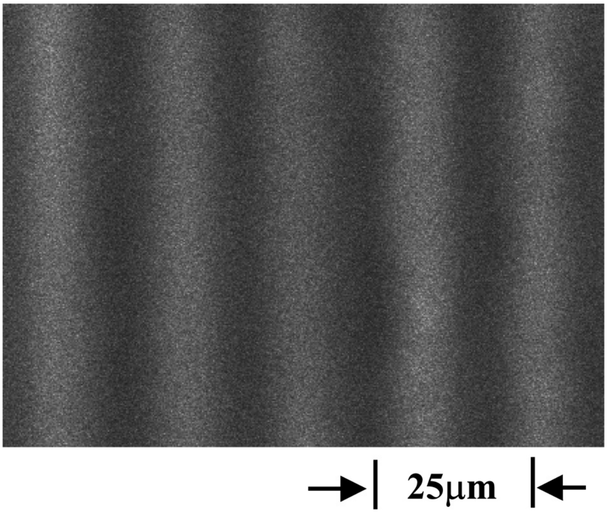

FIGURE 5 SEM image of the adsorbed MR dyes on the substrates.

Figure 6 presents the changes in zero- and first-order intensities of the formed dye-doped SSFLC grating, as a function of φ. The change in the zero-order intensity is similar to that shown in Figure 2, and the change in the first-order diffracted intensity exhibits two minima at $\varphi \sim 20^\circ$ and 200°. A separated experiment was conducted to explain this result. A single Ar^+ laser beam (s-polarized, 10 mW) was normally incident on the dye-doped SSFLC cell. Also, the director axes of FLC molecules were set to coincide with the polarization of the Ar^+ laser. An unpolarized He-Ne laser beam (~1 mW), used as a probe beam, passed through two crossed polarizers, and the cell placed at the intersection. The transmission of the probe beam was determined as a function of the angle, φ. Figure 7 shows the results.

The initial state was dark. The transmission intensity increased sharply after the Ar^+ laser was turned on. The Ar^+ laser was turned off when the transmission was saturated. The transmission then fell slightly before reaching a stable value. The crossed polarizers were then simultaneously rotated, while the transmission of the probe beam was monitored. The lowest transmission was obtained when the polarizers were rotated ~4° from the original position, as shown in Figure 7. For comparison, the transmissions were also measured when the polarizers were rotated by 2° and 8°. In Figure 7, the photo-diode was blocked while the polarizers were rotated. The finding shows that the director axes of the FLC molecules are reorientated by ~4° after the dye-doped SSFLC cell is illuminated by an Ar^+ laser. Furthermore, the order of FLC molecules in the

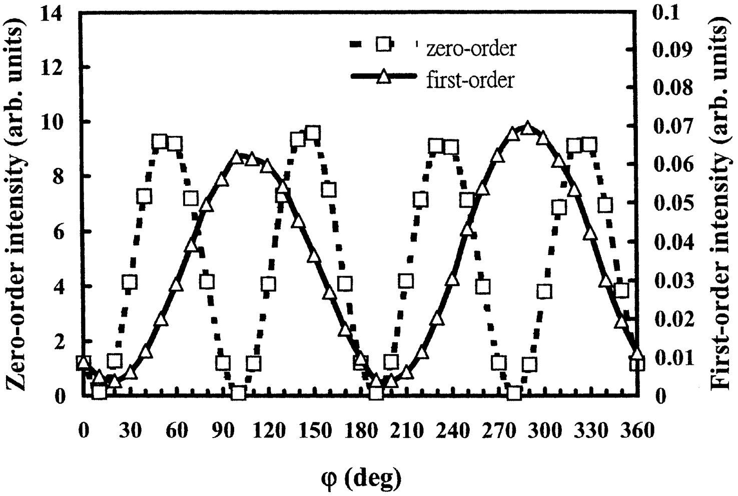

FIGURE 6 Zero-order and the first-order diffracted intensities functions of the angle φ.

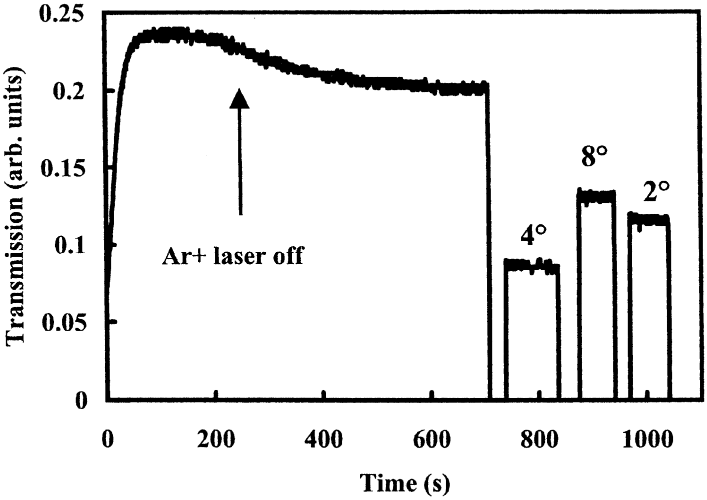

FIGURE 7 Dynamic changes in the transmission intensity (zero-order) of the sample when illuminated by a single Ar^+ laser beam. The sample was placed between two crossed polarizers, that were initially set to give the dark state. When the Ar^+ laser was turned off, and the transmission of the probe beam reached a stable value, both the crossed polarizers were simultaneously rotated while the transmission of the probe beam was monitored. Transmissions at rotations of 2°, 4°, and 8° were measured.

photo-illuminated region is thought to decrease, since the state that corresponds to the minimum transmission is not as dark as the original state. Accordingly, the dye-doped SSFLC grating depends on the fact that the FLC molecules in the high-intensity regions (dye-adsorbed regions) of the interference are reorientated by ~4°, while those in the low-intensity regions remain in their original orientation.

For a typical LC, the birefringence, Δn, is proportional to the order parameter, $S^{1/2}$, that is $\Delta n = n_e - n_o \propto S^{1/2}$, where n_e, n_o are the extraordinary and ordinary refractive indices of FLCs, respectively. Thus, if S decreases to S', then the birefringence becomes $\Delta n' = n'_e - n'_o$. For a linearly polarized incident beam, the effective index of refraction is,

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

where θ is the angle between the polarization of the incident beam and the director axis of the LC molecules.

Hence, the effective index of refraction in the low-intensity regions (dye-unadsorbed regions) of the interference pattern is,

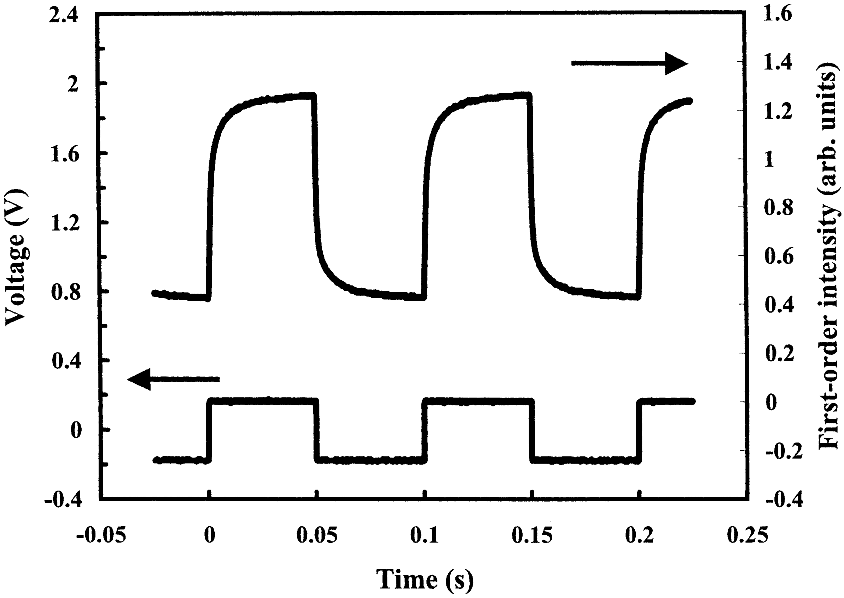

FIGURE 8 Dynamic change in the first-order diffracted intensity when a 10 Hz AC voltage (~0.08 V/μm) is applied to the sample.

$$n_{\mathrm{eff}} = \frac{n_o n_e}{\left(n_e^2 \sin^2(\varphi - 10^\circ) + n_o^2 \cos^2(\varphi - 10^\circ)\right)^{1/2}}, \tag{2}$$

while that in the high-intensity regions (dye-adsorbed regions) is

$$n'_{\mathrm{eff}} = \frac{n'_o n'_e}{\left(n_e'^2 \sin^2(\varphi - 14^\circ) + n_o'^2 \cos^2(\varphi - 14^\circ)\right)^{1/2}}, \tag{3}$$

If $\Delta n_m \ll 1$, such that $\eta \propto \Delta n_m = n_{\mathrm{eff}} - n'_{\mathrm{eff}}$, then the diffraction efficiency, η, is proportional to the index modulation Δn_m, and the difference between the indices of the dye-adsorbed and the dye-unadsorbed regions. Δn_m can be calculated to be a minimum at $\varphi \approx 20^\circ$. The measurements, shown in Figure 6 are thus consistent with those in Figure 7.

Finally, the switching characteristics of a dye-doped SSFLC grating were evaluated. Figure 8 shows the results. The grating can be switched on or off by applying a small voltage (~0.08 V/μm). The response time is around a few ms, and the contrast is ~3. However, the grating is switched very differently if a higher voltage, ~2 V/μm, is applied. Figure 9 shows the corresponding results. Switching with a response time of ~μs occurs when the polarity of the driving voltage changes, yielding the results of Figures 8 and 9 for the following reason. When the driving voltage is low, FLC molecules in the dye-unadsorbed regions are thought to be reorientated. Those in the dye-adsorbed regions, anchored by the dyes, maintain their orientation, changing the index of modulation. However, when

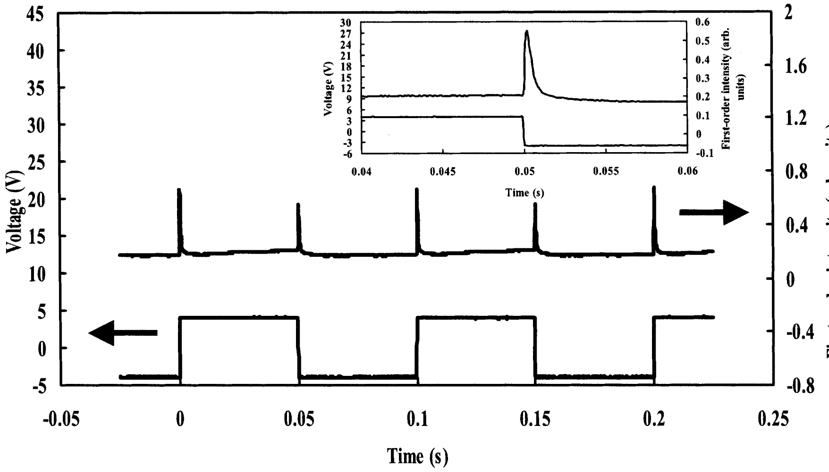

FIGURE 9 Dynamic change in the first-order diffracted intensity when a 10 Hz AC voltage (~2 V/μm) is applied to a sample.

driven at a high voltage, the FLC molecules in both the dye-adsorbed and –unadsorbed regions are identically reorientated, except in that their response times differ, producing spike-like switching, as shown in Figure 9.

In conclusion, the feasibility of inducing a holographic grating in a dye-doped SSFLC film has been demonstrated. Such a grating is caused by the reorientation effect of FLC molecules, due to the interaction with the photo-induced adsorption of the doped azo dyes. Experimental results show that the grating thus formed is permanent but electrically switchable by a small voltage ($\sim 0.08\,\mathrm{V/\mu m}$). Fast switching ($\sim\mu$s) can be performed using a field of $\sim 2\,\mathrm{V/\mu m}$.

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