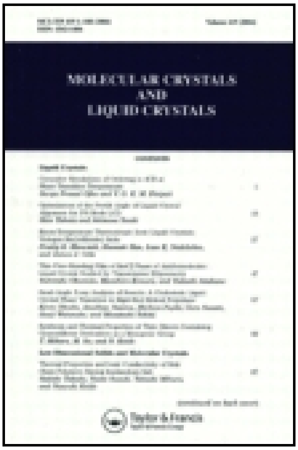

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

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Version of record first published: 31 Jan 2007

Mol. Cryst. Liq. Cryst., Vol. 434, pp. 87/[415]–95/[423], 2005

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400590957855

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Optical recording by smectic layer rotation is proposed and demonstrated. Smectic layer rotation is induced by the application of asymmetric voltage pulses, and the use of an amorphous silicon layer as a photoconductor allows the area for rotation to be selected by partial irradiation of the cell. The anisotropy of smectic layer rotation is clarified, and the recording resolution is found to differ between patterns oriented parallel and perpendicular to the smectic layer normal. This anisotropy is attributed to differences in the ease of boundary formation in the smectic layer.

Keywords: ferroelectric liquid crystal; layer alignment; optical recording; smectic layer rotation

INTRODUCTION

In antiferroelectric liquid crystal (AFLC) and ferroelectric liquid crystal (FLC), the liquid crystal molecules exhibit a smectic layer structure. Application of an external electric field deforms this structure on the axis vertical to the substrate, allowing the structure to

One of the authors (K. N.) was supported by the Suzuki Foundation.
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be alternated between a chevron structure and a bookshelf or quasi-bookshelf structure [1,2]. The alignment of the smectic layer in the plane parallel to the substrate can be changed by applying an alternating current (ac) electric field of sufficient amplitude. Our group has shown that the smectic layer can be rotated gradually and uniformly by applying an asymmetric ac electric field to chiral smectic C_A (SmC_A^*) [3,4], chiral smectic C (SmC^*) [5,6], and smectic A (SmA) phase [7,8]. Reorientation of the smectic layer, by which the dominant domain is switched between the two kinds of alignments with different smectic layer normals, has also been induced by applying an asymmetric ac electric field [9–15]. As these large changes in smectic layer alignment are generally considered to be undesirable in the application of FLCs and AFLCs to electro-optical devices, research on the suppression of such field-induced layer reorientation has been reported [16].

However, our group has suggested that control of layer alignment using this smectic layer rotation [3–8] may be advantageous as an active application. Alignment of the smectic layer can be controlled by the cumulative number of asymmetric voltage pulses applied [17], as this type of layer rotation is uniform, reversible and continuous, and is not the switching between two domain types. Optical recording using this form of smectic layer rotation was proposed as an application of this phenomenon [18,19] based on optical heating, that is, photothermal effect of the liquid crystal. However, that process required the liquid crystal to be doped with dye to enhance the absorption efficiency and the use of a high-power laser. That method was also expected to be affected by the anisotropy of thermal conductivity of the liquid crystal.

In the present paper, an optical recording system that utilizes smectic layer rotation in conjunction with an amorphous Si (a-Si:H) layer as a photoconductor to select the area for rotation is presented. The anisotropy of smectic layer rotation and the effects on recording resolution are also examined using the proposed device.

EXPERIMENTAL

The configuration of the cell used in the present study is shown in Figure 1. The cell consists of two glass plates; one coated with indium tin oxide (ITO) as a transparent electrode, and the other coated with both ITO and an overlying a-Si:H layer of 6–8 μm in thickness as a photoconductive layer. This a-Si:H photoconductor layer is responsible for converting the incident light distribution into an electric-field distribution acting on the FLC layer. The surfaces of the two glass plates

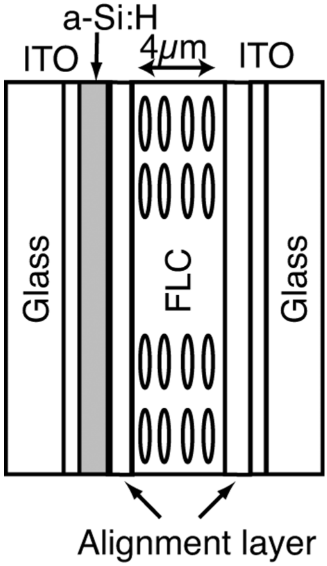

FIGURE 1 Schematic of experimental cell.

were coated with a rubbed polyimide layer (AL-1254, Japan Synthetic Rubber) to ensure uniform planar molecular alignment. The cell gap was 4 μm. The cell was set in a hot bath with heaters to provide temperature control. The optically addressed spatial light modulators used practically in the read/write cell also include a dielectric mirror layer to reflect "read" light (to allow reading of the state of the FLC layer), and a light-blocking layer to prevent "write" light (for recording light-intensity information on the a-Si:H layer) from reaching the "read" side of the device. In the present study, however, these layers were not included, as the aim of the present investigation was to check the basic properties and functionality of the cell. Consequently, light incident to the cell that is not absorbed by the a-Si:H layer propagates transparently to the opposite side and is used for observing the liquid crystal by transmission polarizing microscopy.

The FLC used in the experimental cell was CS-1024 (Chisso), with an isotropic-chiral nematic (N^*)-SmA-SmC* phase sequence. Voltage pulses were generated by an arbitrary waveform generator (33120 A, Agilent) and were amplified by a voltage amplifier (F20A, FLC Electronics). The asymmetric waveform shown in Figure 2 was used as the voltage pulse. The "write", or patterning, light source was a He-Ne laser with wavelength of 632.8 nm and output power of 10 mW.

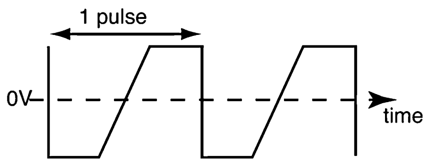

FIGURE 2 Waveform of asymmetric voltage pulses for smectic layer rotation.

PRINCIPLE OF OPERATION

One of the techniques that have been applied in optically addressed devices is the use of a photoconductor, which exhibits low resistance under light irradiation and high resistance in darkness. The introduction of this photoconductor layer between the liquid crystal and the electrode (Fig. 1) makes it possible to control the electric field applied to the liquid crystal by controlling the irradiation of the cell.

For optical recording, the cell is maintained at a temperature at which the liquid crystal is in the SmC* phase. The cell is partially irradiated as shown in Figure 3(a), causing the resistance of the irradiated a-Si:H photoconductor layer to decrease. When asymmetric voltage pulses are applied to the ITO electrodes of both glass plates in this state, only the liquid crystal in the irradiated area is affected by the asymmetric voltage pulses, resulting in rotation of the smectic layer in the irradiated area, as shown in Fig. 3(b).

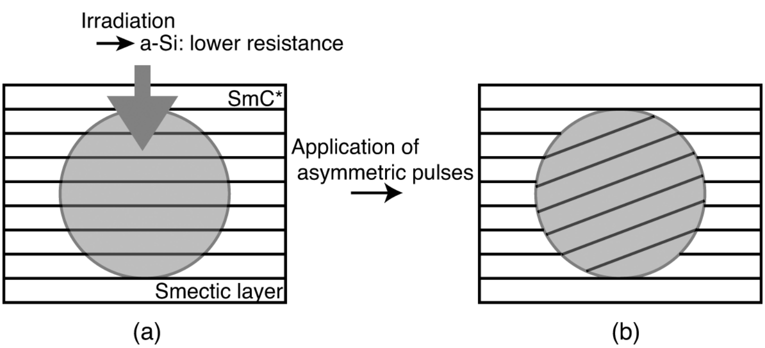

FIGURE 3 Schematic of optical recording procedure. (a) Smectic layer is aligned uniformly and the resistance of the a-Si:H layer is reduced by irradiation. (b) Liquid crystal in the irradiated area is affected by the asymmetric voltage pulses resulting in rotation of the smectic layer in the irradiated area. Gray regions represent the areas irradiated with write light.

RESULTS AND DISCUSSION

Optimization of Temperature

The temperature dependence of smectic layer rotation was examined first to establish the optimum operating conditions for the experimental cell. An asymmetric voltage waveform of amplitude 45 V and frequency 5 Hz was applied to the cell, and the cell was irradiated at 2.1 mW/cm^2, which was sufficient to lower the resistance of the a-Si:H layer.

Figure 4 shows the results for temperatures of 5 and 15°C below the phase-transition temperature ($T_{A\text{-}C}$) from SmA to SmC*. The smectic layer rotated by 5.5° after 1000 pulses at 5°C below $T_{A\text{-}C}$, but rotated by only 1.3° after 5000 pulses at 15°C below $T_{A\text{-}C}$. Based on these results, the experimental temperature was set at 5°C below $T_{A\text{-}C}$.

Optimization of Voltage Amplitude

The amplitude of the voltage waveform was also optimized to obtain the best recording characteristics. A stripe pattern with stripe width of 446 μm and stripe pair width of 892 μm was produced using a USAF 1951 target filter as the write light. The intensity of the write light at the cell was 0.9 mW/cm^2. The asymmetric pulses were applied at a frequency of 3 Hz. Polarizing microphotographs were taken while applying a direct current (dc) voltage of 20 V and irradiating the sample with visible light from a halogen lamp to reduce the resistance of the a-Si:H layer and allow observation using the transmission polarizing microscope.

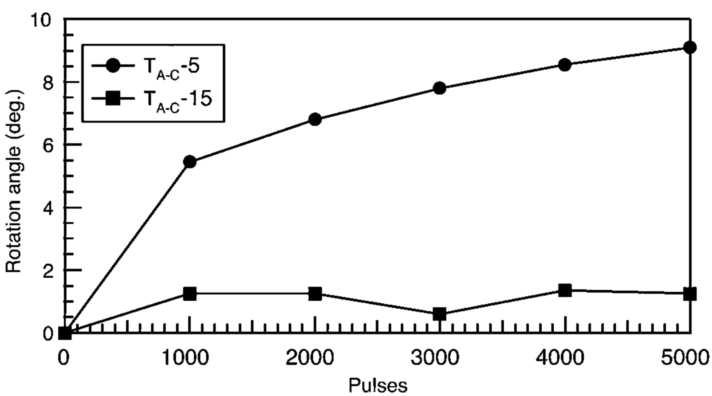

FIGURE 4 Rotation angle as a function of number of applied pulses.

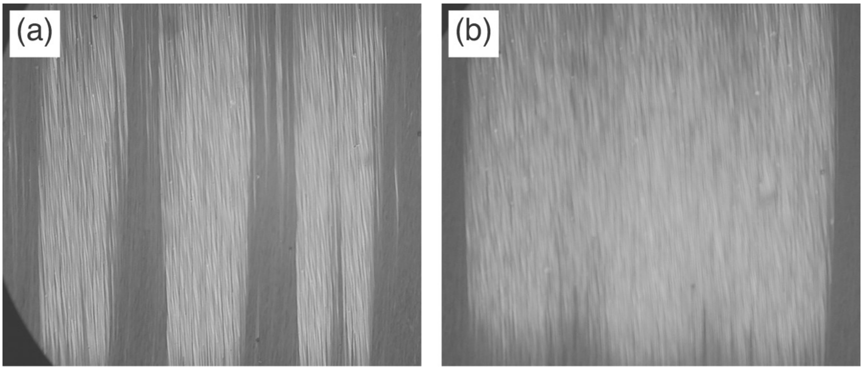

FIGURE 5 Polarizing microphotographs under an applied dc voltage of 20 V for asymmetric voltage pulses of (a) 55 and (b) 60 V.

Figure 5 shows the polarizing microphotographs of the liquid crystal after 3000 asymmetric voltage pulses at 55 and 60 V. The dark domains represent the areas in which the smectic layer alignment did not changed from the initial state, and the bright domains indicate the areas in which the layer alignment was rotated by the recording process. At 55 V, the recorded pattern is produced with distinct bright and dark areas, whereas the stripe pattern was not successfully produced at 60 V. At 60 V, both the irradiated and non-irradiated areas rotated due to the application of an excessively high voltage. Therefore, under the present conditions, a pulse voltage of 55 V provides better recording performance than 60 V. The optimal amplitude, however, will be dependent on factors such as the sensitivity of the a-Si:H, the intensity of the write light, and the rubbing intensity.

Anisotropy of Smectic Layer Rotation

In our previous paper on optical recording by optical heating [19], the recording resolution exhibited some anisotropy. However, as the method proposed in that study was based on local heating of the liquid crystal by irradiation, and considering the anisotropy of thermal conductivity in liquid crystal, the anisotropy of resolution may have been caused by thermal conductivity and not the anisotropy of smectic layer rotation. In the present method, however, the local layer rotation is induced not through the phenomena that exhibit anisotropy. To investigate this anisotropy, experiments were performed using voltage pulses of 55 V and 3 Hz and a cell temperature of 5 °C below $T_{\text{A-C}}$. The first experiment was conducted with the stripe pattern for recording oriented parallel

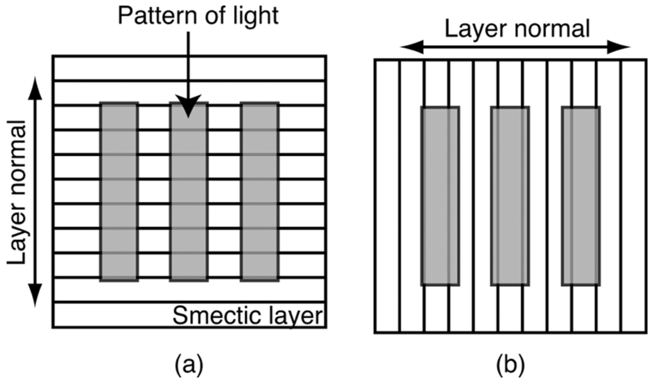

FIGURE 6 Experimental configuration of smectic layer and recording stripe pattern. The relative scale between the smectic layer and the pattern is exaggerated for clarity. Configurations are shown for (a) parallel and (b) perpendicular alignment between the stripes and the smectic layer normal.

to the smectic layer normal (Fig. 6(a)), and the second was conducted with the two features in perpendicular (Fig. 6(b)). These experiments provide information on the resolution of recording in these two directions. The stripe widths were 355 μm in the parallel case and 446 μm in the perpendicular case.

Figure 7 shows the results of recording after 3000 pulses. The recorded stripe texture in the parallel case can be observed clearly. However, even though wider stripes were used in the perpendicular

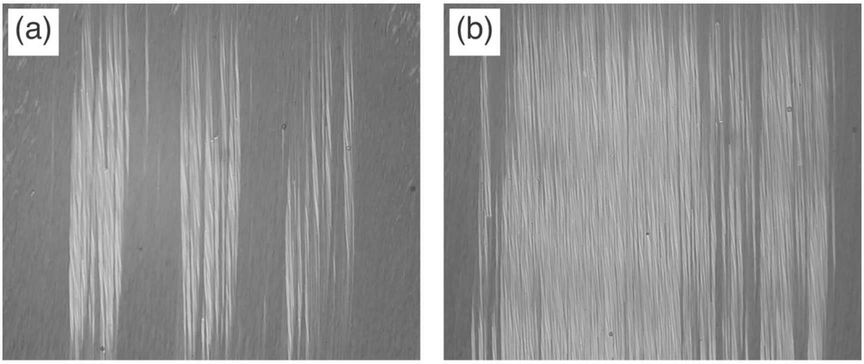

FIGURE 7 Polarizing microphotographs under an applied dc voltage of 20 V for (a) parallel and (b) perpendicular alignment between the stripes and the smectic layer normal.

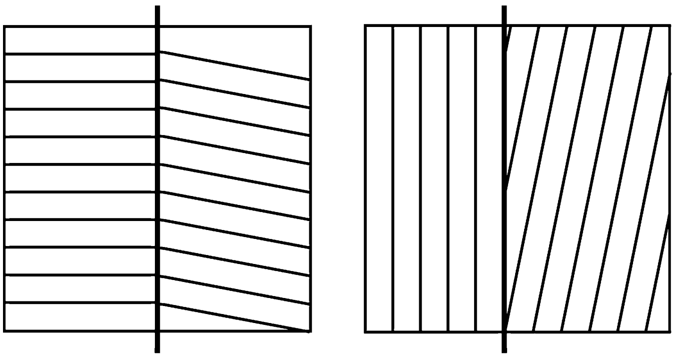

FIGURE 8 Schematic of smectic layer structure at the boundary for (a) parallel and (b) perpendicular alignment of the layer normal with respect to the boundary.

case, the stripe texture is not visible, indicating that the smectic layer rotation occurred over the entire area. These results clearly show that there is some intrinsic anisotropy in the rotation of the smectic layer.

A possible explanation for this anisotropy of smectic layer rotation is the nature of the boundary between the rotated domain and the non-rotated domain. The boundary present after recording the stripe pattern shown in Figure 6(a) is shown in Figure 8(a). This boundary can be readily formed by bending of the smectic layer. However, in the perpendicular case as shown in (Fig. 8(b), a boundary cannot be formed by simple deformation of the smectic layer structure. In this case, it is necessary to sever the smectic layer structure, forming a discontinuous layer. The bending boundary occurs more easily than the destruction in the smectic layer structure, allowing for the formation of a sharp boundary. Discontinuous boundaries are much more difficult to form, as the generation of defects is unfavorable in terms of energy. Accordingly, the smectic layer in the non-irradiated area will rotate to avoid defect formation, effectively blurring the boundary.

CONCLUSION

An optical recording cell based on smectic layer rotation was proposed and demonstrated. The resolution of recording was optimized through appropriate selection of the temperature, voltage of the applied asymmetric pulses and intensity of the write light. The anisotropy of smectic layer rotation was clarified, and the resolution of the recording in the cell was found to be higher using stripe textures oriented parallel to the layer normal. The origin of this anisotropy of resolution was discussed from the viewpoint of deformation of the smectic layer structure. The resolution of recording can be improved moreover by optimization of the cell gap, rubbing process and so on.

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