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CONTINUOUS FERROELECTRIC SWITCHING IN TWISTED SMECTIC C* LIQUID CRYSTALS

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Abstract We report on the uniform alignment and continuous ferroelectric switching of a twisted smectic C* liquid crystals (LCs). In contrast to surface stabilized ferroelectric LCs, a twisted smectic C* (Sm C*) structure exhibits essentially no threshold field and produces intrinsic gray scales. For constructing such a twisted structure, the symmetry in molecular tilt with respect to the rubbing axis is externally imposed by the surface forces. The symmetry required for producing a uniformly twisted structure is that the twist angle between two rubbing axes on the substrates must be exactly twice of the molecular tilt. One important parameter is the existence of the smectic A state in the phase sequence, which facilitates to the uniform growth of the smectic layers. We perform numerical simulations to obtain the director profiles and the resultant electro-optic modulation as a function of the electric field in the twisted Sm C* structure. It is found that the experimental data agree well with the numerical results.

INTRODUCTION

Since the discovery of ferroelectric liquid crystals(FLCs),[1] FLCs have been paid much attention for their potential applications in various optical devices such as spatial light modulators and high-performance displays. Up to now, most of studies and applications have been concentrated on the surface stabilized geometry,[2–7] where the helicoidal structure in the chiral smectic C (Sm C*) state is suppressed by surface interactions in a thin cell. In a surface stabilized ferroelectric liquid crystal (SSFLC), there exist two uniformly oriented bistable states, i.e., *up* and *down* states of the spontaneous polarization. When an external electric field is applied, one of two

bistable states, of which polarization is parallel to the external field, is energetically favorable. Although the SSFLC has a fast switching speed of the order of 100 μs or less, it has the difficulty of achieving gray scales because of its intrinsic bistability. Several approaches to obtain the gray scales have been proposed.[8–12] One of them is to utilize an averaging scheme over the spatial or temporal states which still possesses the bistable nature. The other concerns a continuous distortion of the helix present in the Sm C* state with the variations of the external electric field.[11–13]

Very recently, it has been demonstrated[14] that a twisted Sm C* structure exhibits indeed the intrinsic gray scale. This twisted smectic (TS) structure was capable of producing a continuous optical transmission as a function of the electric field.

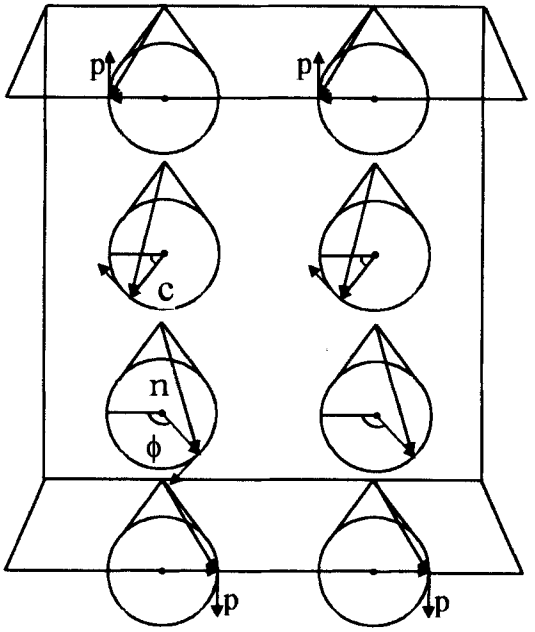

FIGURE 1 Schematic diagram of the twisted smectic C* structure.

The basic idea for constructing such structure is quite similar to that for a well-known twisted nematic (TN) structure. With an appropriate molecular tilt in the Sm C*

phase, the twist angle between two rubbing axes on the substrates is exactly twice of the molecular tilt. As shown in Fig. 1, the molecules become gradually twisted as in a typical TN case. However, they are constrained to maintain a constant angle on the cone-surface. In this case, the local polarization P would experience the total rotation of 180° in going from one surface to the other. In fact, this structure represents a combination of the fast speed of FLC and the continuous optical transmission of the TN structure. However, the basic physical mechanism for subtle changes in the optical modulation from material to material remains to be explored for practical applications.

In this work, we present experimental results for continuous electro-optic (EO) properties of two different TS structures, and describe several important parameters for producing uniformly aligned structures. It was found that the existence of the smectic A (Sm A) phase and the proper combination of the twist and the molecular tilt in the Sm C* phase predominantly govern the uniformity of the alignment and the resultant optical modulation. Moreover, we performed numerical simulations to obtain the director profiles and the resultant EO properties of the TS structures in the continuum description, and discuss the main features of the experimental data compared with numerical results.

EXPERIMENTAL

We studied two different TS structures made up of commercial ferroelectric materials, CS1027 and CS2004, provided by Chisso Petrochemical Corp. The phase sequences of those materials are as follows.

- CS2004: I → (71°C) → N* → (62°C) → Sm C*.
- CS1027: I → (96°C) → N* → (88°C) → Sm A → (62°C) → Sm C*.

It should be noted that the main difference between the two materials is the existence of Sm A state in the phase sequence. As will be discussed later, this difference

significantly affects the uniformity of the alignment in the TS structures. The tilt angles for CS2004 and CS1027 in the Sm C* phase are 45° C and 20° C, respectively.

The TS cells were made with indium-tin-oxide coated glass substrates. The glass substrates were first coated with about 300 $\AA$ of polyimides and then unidirectionally rubbed. The cells were assembled such that two rubbing axes on the substrates make a twist angle of 90° for CS2004 and 45° for CS1027. The nominal cell spacing for the CS2004 and that for CS1027 were maintained by glass spacers of 6 μm and 5 μm, respectively. The twist angle in each TS cell was about twice of the molecular tilt in the Sm C* phase. In this geometry, the molecular director will stay on one side of the Sm C* cone at one surface and the other side of the cone at the other surface. With this type of the surface boundary conditions, continuously twisted layers would develop in the Sm C* phase as in the TN structure.

In relatively thick SSFLCs, it has been reported that several non-uniform (splayed) states can exist.[15] Particularly, Ouchi et. al[16] first proposed that there may exist at least six stable states in the SSFLCs, two of which are uniform and the remaining four splayed. These degeneracy necessarily induces some defect structures among various states and make it difficult to produce the uniform alignment. In our experiment, we attempt to stabilize only one of those states by a proper combination of the twist angle and the molecular tilt in the Sm C* phase. The state being stabilized is probably one of the six states described above.

Fig. 2 shows typical textures of our TS samples at room temperature. The CS1027, twisted by 45°, shown in Fig. 2(a) exhibits fairly uniform alignment, and it was quite transparent. Moreover, the structure of the twisted smectic layers was well preserved against an external shock or pressure. In contrast, the CS2004, twisted by 90°, in Fig. 2(b) has multi-domains, and the transparency was relatively poor. The apparent difference in the alignment quality between the two TS structures is presumably due to the difference in the phase sequences. i.e., the existence of the Sm A phase. For the CS2004, experiencing a direct cholesteric to the Sm C* transition, the uniform growth of the smectic layers will not be favorable. For the

CS1027, however, the smectic layers developed in the Sm A state will be preserved in the twist structure of the Sm C* state. In other words, the continuity of the layer structure will be conserved in the CS1027 case.

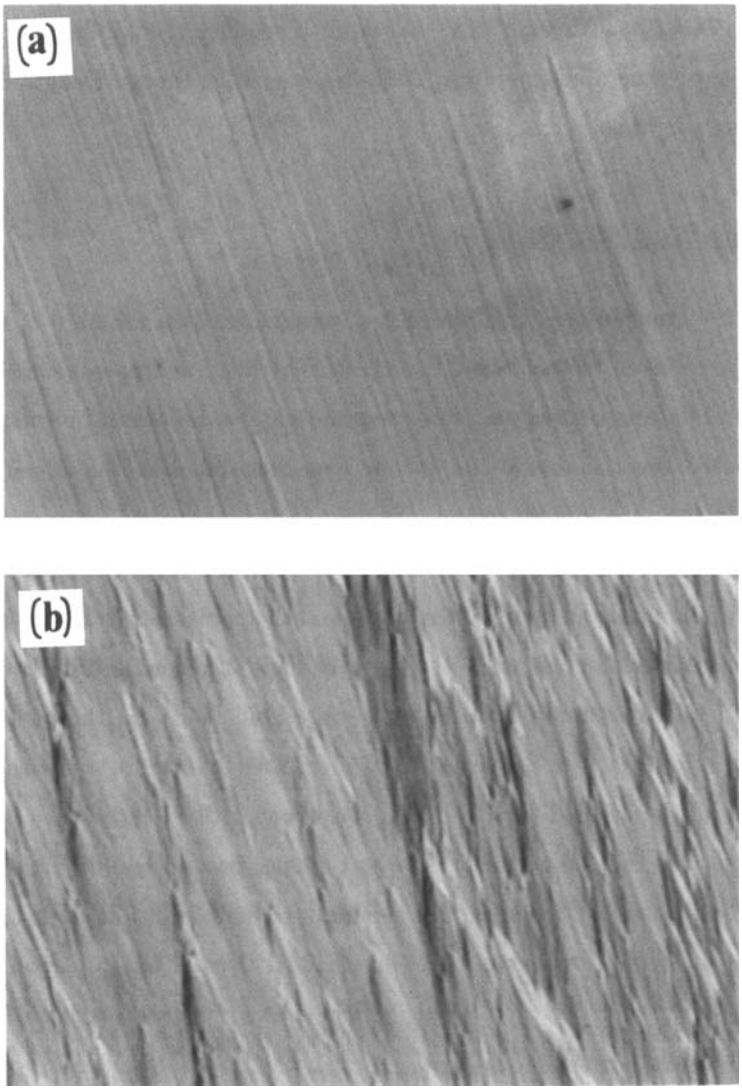

FIGURE 2 Typical textures of two twisted smectic C* structures, photographs taken under crossed polarizers; (a) CS1027 and (b) CS2004. One of the two rubbing axes is parallel to the striped patterns. See Color Plate VI.

For the EO measurements, the twisted Sm C* sample cells were placed between crossed or parallel polarizers. The measurements were carried out at room temperature. The transmitted light intensity through the cell was monitored with a photodiode and a digitizing storage oscilloscope (Tektronix TDS420). An arbitrary waveform generator (Wavetek 75A) was used to produce the applied voltage of variable amplitude generated randomly. A He-Ne laser with the wavelength of 632.8 nm was used as a light source.

RESULTS AND DISCUSSION

In Fig. 3 the transmitted light intensities were shown as a function of the applied field for two types of twisted Sm C* samples. The filled and open squares represent experimental data measured under crossed and parallel polarizers, respectively. The solid lines are the theoretical fits to our experimental data, based on numerical results obtained in a simple model. Details of the numerical simulations will be described later on. For both CS2004 and CS1027, one of the polarizers coincides with the rubbing axis at one surface, and the other polarizer (analyzer) is parallel or perpendicular to the first one. As shown in Figs. 3(a) and (b), both the CS2004 and CS1027 share common features of no threshold field and the continuous EO modulation. However, the EO response of the CS2004 is symmetric with respect to the polarity of the applied field, which is consistent with the previous result.[14] This is simply because the cell geometry for the CS2004, twisted by 90°, is symmetric to the crossed polarizers. Of course, this symmetry is nothing to do with the intrinsic property of molecular switching. For the CS1027, twisted by 45°, good extinction and high transmission were achieved, which makes the twisted Sm C* structure promising for optical devices.

In both cases, the transmitted light intensities monotonically vary with changing the applied voltage up to +2 V, producing a continuous gray scale, and then become saturated beyond that value. In the limit of high voltages, the spontaneous polarization of the molecules will be perfectly aligned along the field direction. Un-

der crossed polarizers, the molecular director makes an angle of 45° for the CS1027 and 90° (or 0°) for the CS2004 with respect to the polarizers.

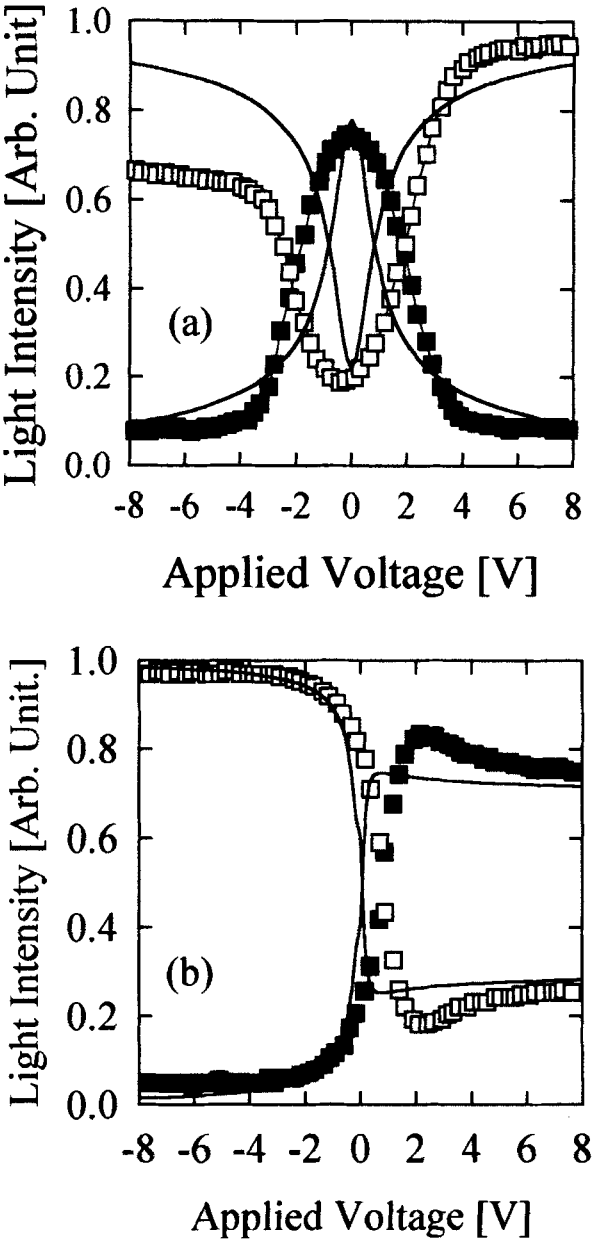

FIGURE 3 The transmitted light intensities as a function of the applied voltage;

(a) CS2004 and (b) CS1027. The filled and open squares represent experimental data measured under crossed and parallel polarizers, respectively. The solid lines are the theoretical fits to experimental data, based on the numerical results.

In this case, the CS1027 will behave as a retardation plate, and thus the maximum transmission will be obtained. For CS2004, however, no transmission will be observed, which is quite similar to a typical TN case. In the absence of the applied voltage, the CS1027 will waveguide, and the polarization of the incident light becomes rotated by 45°, and the transmission will be about one half of the incident beam. In the intermediate range of the applied voltage (-2 to $+2$ V), the twisted state becomes gradually transformed into a uniform state by the unwinding process. This makes the waveguiding effect changed, and thus the transmitted intensity will be continuously changed with varying the field.

The experimental results for the continuous EO modulation can be understood in a simple model where the gradual unwinding of the TS structure was introduced. For numerical simulations, we adopt the total free energy density as a combination of the nematic-like elastic and the ferroelectric field parts.[2,4]

$$F = \frac{k_1}{2}(\nabla \cdot \underline{n})^2 + \frac{k_2}{2}(\underline{n} \cdot \nabla \times \underline{n} + q_t)^2 + \frac{k_3}{2}(\underline{n} \times \nabla \times \underline{n} + q_b\ \underline{b})^2 - \underline{P} \cdot \underline{E} \quad , \quad (1)$$

where $\underline{n}$ denotes the molecular director, $\underline{P}$ the spontaneous polarization, and E the applied electric field. Here, k_1, k_2, and k_3 are the splay, twist, and bend elastic constants, respectively. q_t and q_b represent the wave numbers associated with the inherent twist and bend distortions, respectively. In our case, the dielectric effect is ignored since it turns out to play no significant role in the essential features of the EO modulation in the TS structures.

We first minimize the above free energy to find the director profiles in a equilibrium configuration. Fig. 4 shows the resultant director profile for the CS2004 as a function of the scaled distance in the TS structure at several applied voltages. In the absence of the applied voltage, the azimuthal angle, ϕ defined in Fig. 1, increases almost linearly with the scaled distance y/d. Each line represents the director pro-

files in a step of 1 V up to 4 V. As the applied voltage increases, the TS structure becomes gradually unwound, and it is transformed into a uniform state.

Now, we calculate the transmission of the light propagating through such a structure using 2×2 Jones matrix method with the help of the director profiles obtained above. In the calculations, a small amount of the biaxiality was taken into account. The solid lines in Figs. 3(a) and 3(b) are the theoretical fits using the numerical results. Note that the numerical results follow fairly well our experimental data.

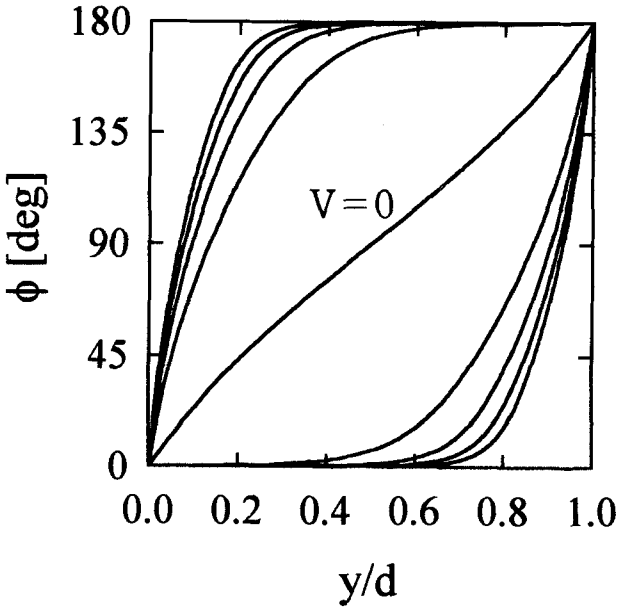

FIGURE 4 The director profiles for CS2004, twisted by 90°, in the TS as a function of the applied voltage. ϕ is the twist angle of the director and y/d represents the scaled distance along the surface normal.

The spontaneous polarization for both the CS1027 and the CS2004, $P \approx 6$ nC/cm^2, measured by the triangular wave method,[17] was used in the calculations. Other

materials parameters used were collected in Table 1.

Table 1 Materials parameters being used.

	CS2004	CS1027
k_1	3.0×10^{-11} N	1.0×10^{-11}N
k_2	8.0×10^{-11} N	6.0×10^{-11}N
k_3	12.0×10^{-11} N	8.0×10^{-11}N
n_1	1.45	1.45
n_2	1.45	1.49
n_3	1.59	1.57

As already noticed in Figs. 3(a) and 3(b), it was found that the disparities among the three elastic constants and the amount of the biaxiality play an important role in correctly describing the magnitude as well as the shape of the EO modulation in the TS structure.

CONCLUDING REMARKS

We have presented the experimental results for the alignment properties and the continuous ferroelectric switching properties of the twisted Sm C* structures. By symmetry, the twist angle, imposed by external surface forces, should be exactly twice of the molecular tilt in the Sm C* phase. In such a TS structure, it is possible to select only one stable state among various splayed and uniform states. The existence of the Sm A phase in the phase sequence predominantly governs the alignment quality, which was supported by the results for CS1027. The twisted Sm C* structure gradually unwound with increasing the applied electric field, and thus produces a continuous EO modulation. This twist unwinding process results in essentially no threshold and the continuous ferroelectric switching at relatively low voltages. Particularly, the CS1027, twisted by 45°, was found to produce a high contrast ratio ($\approx$ 100) and good gray scale capability.

Our preliminary results for the dynamics show that the response time is on the order of 100 μs. In addition, a peculiar field-dependence of the ferroelectric switching has been found. Further studies on the dynamics as well as surface properties of the twisted Sm C* structures would be required for obtaining rather a complete picture of the continuous ferroelectric switching described here.

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