Reflective homeotropic mode in a twisted nematic liquid crystal

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This letter reports on a novel liquid crystal (LC) display device capable of achromatic reflection in a twisted homeotropic configuration using a chiral nematic LC with negative dielectric anisotropy. Using the elastic continuum formalism, we arrived at simulated values for each parameter of interest, including external twist, cell gap, molecular chirality for the chiral pitch, and the surface anchoring energy. The experimental results correspond well with the calculated expectations, exhibiting EO properties that demonstrate excellent achromatic reflection, extinction, and a high contrast ratio. © 1998 American Institute of Physics. [S0003-6951(98)02934-9]

Recently, various liquid crystal (LC) reflective modes have been proposed in response to strong demands for low-power consumer displays. One particularly attractive structure in this reflective geometry is a single polarizer configuration, such as twisted nematic electrically controlled birefringence (TN-ECB) or a mixed twisted nematic (MTN). These structures exhibit promising electro-optic characteristics, possessing high brightness, enhanced contrast, and achromatic operation without requiring the use of a backlight. They also preserve other favorable features of a twisted nematic (TN) display such as the gray scale capability. However, despite improved electro-optic (EO) results, these reflective structures normally operate in a mode that produces no transmission in the off-state, called the "normally black mode." This mode proves far less advantageous than the normally white mode which often used in various reflective type portable displays such as mobile communication devices and computers. Furthermore, the reflective properties of a field-inactivated TN-ECB mode strongly depend on the wavelength of the incident light.

Of great interest to the current shortcomings experienced by these LC reflective modes is the recent development of a homeotropic to twisted-planar (HTP) structural transition in nematic liquid crystals. First investigated within the transmission mode, the HTP structure exhibited extremely high contrast with achromatic characteristics while providing a wide range of viewing angles. We demonstrate a novel LC device based on the HTP structure employing a chiral nematic LC with negative dielectric anisotropy within the reflective mode. The unique reflective HTP structure operates in the normally white mode, providing much greater ease of operation without requiring complex optical compensation. Moreover, due to the homeotropically aligned state in the field-inactivated mode, the HTP structure is capable of providing greatly enhanced reflection.

The transmission mode for twisted nematics usually operates at a point when the Gooch–Tarry conditions are satisfied, and the linearly polarized incident light is rotated by 90° by the twisted structure of the liquid crystal slab. While this may be a perfectly viable operation in the transmission mode using double polarizers, a single polarizer configuration in the reflective mode, operating at the Gooch–Tarry conditions, always restores the polarization rotation of light when it passes in the opposite direction, resulting in virtually no electro-optic modulation. The reflective mode therefore requires a different operating principal compared to the transmissive geometry.

Our first priority was then to establish, using a continuum elastic model, the optimal EO properties of a reflective-mode HTP structure. By varying several parameters—external twist, cell gap, molecular chirality, and anchoring energy—the calculated results yielded values that could later be compared to the experimental results. Comparing the calculated values with the experimental will provide information on several material parameters of interest, including azimuthal and polar anchoring of the homeotropic alignment layer. The experimental values will then test the accuracy of the simulated results while establishing the precise parameter values for optimal achromatic reflection, extinction, and highest contrast ratio.

In the following calculations the linearly polarized light is incident parallel to the molecular director of the liquid crystal. The first parameter of interest is the external twist angle (\(\Phi_T\)). The reflective property of the homogeneous twisted nematic structure with a single polarizer will have minima when the twist angle (\(\Phi_T\)) and the birefringence (\(\Delta n\)) satisfy the following conditions:

\[
\Phi_T = \frac{(2N-1)}{2}, \quad 2 \pi \Delta n d / \lambda = 2 \Phi_T, \tag{1}
\]

where \(N\) is a positive integer, \(\Delta n\) the birefringence of the liquid crystal, \(d\) the cell gap, and \(\lambda\) the wavelength of the incident light. The first and the second minima occur at \(\Phi_T = 63.6°\) and 190.8°, respectively, establishing what we project to be the desired external twist angle in experimentation. The next parameter is the chiral pitch, \(p\), which corresponds to the twist angle, \(\Phi_T\), and is given by \(p\)

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The symbol $I_0$ in Eq. (1) demarcates the experimental results, with each symbol representing a different value of $N$ in Eq. (1). The value of $p$ is uniquely determined by the birefringence and the wavelength. Comparing these criteria with the Gooch–Tarry condition for the twisted nematic operated in the first minimum, in the transmission mode, where $\Phi_T = 90^\circ$ and $\Delta n d/\lambda = \sqrt{3}/2$, the required cell gap for the first minimum in the reflective mode is $\phi (\approx 2.5)$ times smaller than transmissive case. However, it should be emphasized that the above criterion is applicable for only a homogeneously twisted nematic structure where the director is parallel to the surface.

The liquid crystal material used was the commercial mixture EN-37 with a negative dielectric anisotropy ($\varepsilon_{an} = -3.0$), obtained from Chisso Petrochemical Corp. The birefringence of this material is 0.095 ($\lambda = 632.8$ nm). The chiral additive used was S-811 obtained from Merck. Homeotropic alignment was produced using polyimide JALS-203 from Japan Synthetic Rubber Co. The polyimide was spin coated on the substrates, followed by unidirectional rubbing required to break the azimuthal symmetry. The rubbing process is necessary for stabilizing the twist deformations and for producing a monodomain sample in the field-activated state. Each HTP cell was assembled such that the angle between the rubbing directions on the top and bottom surfaces produces the desired twist. Nine different samples grouped into three sets of the HTP cells were prepared in an effort to test the various parameters. In each set, two of the parameters under investigation remained fixed while the third was varied three times, constituting the three samples per set. The first set (I) reported a fixed cell gap, $d = 2.9 \mu m$, along with a fixed chiral pitch, $p = 13.0 \mu m$, while the twist angle was varied. The second set (II) reported fixed both $\Phi_T = 63^\circ$ and $p = 13.0 \mu m$, while the cell gap was varied. The final set (III) reported fixed $d = 2.9 \mu m$ and fixed $\Phi_T = 63^\circ$, while the pitch was changed such that $p = 10.0, 13.0, \text{and } 18.0 \mu m$. For all EO measurements, each HTP cell was placed between a single input polarizer and a mirror (reflector) located outside the cell. The polarizer was adjusted to coincide with the rubbing axis on the top surface of the cell. The mirror was slightly tilted (about 1°) with respect to the direction of the incident beam in order to allow detection of the reflected beam. A He–Ne laser of 632.8 nm was used as the light source. A square wave voltage at 1 kHz of varying amplitude was applied to the cell. All the measurements were carried out at room temperature.

Figure 1 shows both the calculated and experimental reflected intensities of the HTP cells as a function of the applied voltage for various external twist angles, $\Phi_T$’s (set I). The symbols demarcate the experimental results, with each symbol representing a different $\Phi_T$, while the solid lines represent the numerical fits performed using the continuum theory. Three significant conclusions can be wrought with a close inspection of Fig. 1. First, all three HTP cells have the same threshold voltage (≈2.2 V). Below the threshold, all three exhibit excellent reflectance in the homeotropic geometry, independent of the wavelength of light. Second, even a cursory observation of Fig. 1 shows excellent agreement between theory and experiments. Finally, those simulated parameter values expected to provide the greatest LC effects in the HTP cell are accurate, as evidenced by the excellent EO characteristics and the minimal reflectance (less than 1% of the input light above 6 V) when the twist angle is around 63.6°. This accords nicely with the calculated expectations. Likewise, in regard to the smallest twist examined (i.e., 45°), the reflectance never goes to zero even in the high field regime. For the 90° twist, the reflectance reaches a minimum of about 10% at 4 V and then increases with increasing the voltage. It is noteworthy that the gradient of the EO curve becomes steeper as the twist angles increase—an important consideration for multiplexed displays.

The effect of variation of the cell gap is shown in Fig. 2, which again shows a good fit between theory and experiments. Furthermore, an inquiry into the EO performance of the simulated optimal value for cell gap, i.e., $d = 2.9 \mu m$, is clearly evident in Fig. 2, where the greatest extinction (i.e., >1%) occurs after 6 V. Some explanation concerning this cell gap value is in order. The first minimum in the reflection mode of TN occurs at $\Delta n d = \lambda / 2$ for the twist angle $\Phi_T = \pi / 2$, ($\approx 63.6^\circ$). In our case, the cell gap $d = 2.36 \mu m$ corresponds to the condition for first minimum, provided that $\Delta n = 0.095$ and $\lambda = 632.8$ nm. However, despite the 2.36 $\mu m$ value for optimum cell gap, we discovered experimentally an optimum performance at cell gap $d = 2.9 \mu m$, indicating that about 0.3 $\mu m$ region at each end of the surface is immobile. Taken together, this susceptible region, along with the 0.3 $\mu m$ “dead” region at each cell surface, where the LC is perfectly immobile, yield an optimal cell gap value at $d = 2.9 \mu m$.

Last we deal with the effect of chirality on the EO properties of the reflective HTP cell through a study of the chiral pitch, $p$ (set III). Figure 3 shows the reflectance of the HTP cells as a function of the applied voltage for three differing values of pitch. Again we will note excellent reflectance below the threshold value and high accord between experimental and simulated results. As expected, the cell with chiral pitch $p = 13.0 \mu m$ exhibits the best EO characteristics. Using Eq. (1), the optimum pitch, corresponding to the natural
twist, is determined by \( p = 2 \lambda / \Delta n \). In our case, this condition corresponds to \( p = 13.3 \, \mu \text{m} \) corresponding to \( \Delta n = 0.095 \) and \( \lambda = 632.8 \, \text{nm} \). Notice that the change in equivalent natural twist caused by molecular chirality is greater than change of surface twist angle shown in Fig. 1. However, the resultant EO characteristics of the reflective HTP cell seems less sensitive to molecular chirality compared to the effect of external twist angle imposed by rubbing. This indicates that the actual twist involved in the HTP transition under an applied voltage depends strongly on the external anchoring terms, the director profiles can be subsequently obtained. Using the literature values of the dielectric constants, and the birefringence of EN-393, we determined the elastic constants, as well as the azimuthal anchoring energy \( F_a(\theta, \varphi) \). We now turn our attention to the anchoring energy.

Following the free energy formalism including the surface anchoring terms, the director profiles can be calculated and the resultant EO properties can be subsequently obtained. In the homeotropic geometry, we adopted the surface anchoring energy, \( F_s(\theta, \varphi) \), consisting of the polar \((\theta)\) and the azimuthal \((\varphi)\) parts as follows:

\[
F_s(\theta, \varphi) = \frac{1}{2} W_p \sin^2 \theta + \frac{1}{2} W_a \sin^2 \theta \sin^2(\varphi - \varphi_0),
\]

where \( \theta \) is the polar angle defined as the deviation from surface normal direction, \( \varphi \) is the in-plane azimuthal angle, and \( \varphi_0 \) represents the easy axis of \( \varphi \) imposed by rubbing. \( W_p \) and \( W_a \) are the polar and azimuthal anchoring strengths, respectively. Using the literature values of the dielectric constants and the birefringence of EN-393, we determined the elastic constants, \( K_1 = 14.5 \times 10^{-12}, K_2 = 6.2 \times 10^{-12}, \) and \( K_3 = 12.7 \times 10^{-12} \, \text{N} \), the ordinary and extraordinary refractive indices, \( n_o = 1.486 \) and \( n_e = 1.391 \), from the numerical fits of the data for three HTP cells with different \( \Phi_T^{\prime} \)'s. For the surface anchoring energies, \( W_p = 3.0 \times 10^{-4} \) and \( W_a = 2.0 \times 10^{-6} \, \text{N/m} \), are independent for within the experimental error for the data shown here. It is generally believed that azimuthal anchoring is about one to two order(s) of magnitude smaller than the polar one.

In summary, the specific parameter values expected to optimize the reflective LC device were determined for the external twist angle, the cell gap, molecular chirality for the pitch, and the surface anchoring energy. The experimental results verified the numerical simulations while also exemplifying excellent achromatic reflection (greater than 99%) as well as extinction (less than 0.5%) for all HTP cells under investigation. In the course of experimentation, an immobile surface region of about 0.3 \( \mu \text{m} \) thick on each cell substrate was found to play a significant role in achromatic reflection. Advantages of this reflective HTP architecture include its operation in the normally white mode without the use of retardation plates. The proposed structure is a promising candidate for low-power displays and portable applications such as personal digital assistants and wireless communication devices. It may also be applicable in various reflective spatial light modulators and light valves.

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