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Achromatic polarization switch using a film-compensated twisted nematic liquid crystal cell

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A broadband polarization switch consisting of an active twisted nematic liquid crystal cell and two passive uniaxial compensation films is analysed. The conjugate gradient method was used for optimizing the device parameters. Simulation results indicate that the polarization switch exhibits a broad bandwidth and high contrast ratio. The manufacturing tolerances on cell gap, twist angle and compensation films thickness are reasonably large.

1. Introduction

The polarization switch has important applications for colour-sequential displays [1], polarization-based stereoscopic 3D display [2] and fibre-optic communications [3]. The general requirements are broad bandwidth, fast response time, high contrast ratio, thinness, light weight, and low cost. The 90° twisted nematic liquid crystal (TNLC) cell [4] is a candidate for the broadband polarization rotator. In the voltage-off state, the incident linearly polarized light follows the twist of the LC director and is rotated by 90° after traversing through the cell. In a high voltage state, the LC directors are reoriented by the electric field. As a result, the incident light polarization is unaffected. The switching time of a TN cell depends on the cell gap and the LC material employed. Typically, a 5 μm TN cell has ~20–30 ms response time.

To enable a TN cell to function as a broadband polarization switch, the cell gap and birefringence product ($d\Delta n$) has to satisfy either the Mauguin limit, $\lambda \ll \Delta nd$ [5], or the Gooch–Tarry first minimum condition, $d\Delta n = (\sqrt{3}/2)\lambda$ [6]. To satisfy the Mauguin limit requires $d\Delta n \sim 20 \lambda$, i.e. a relatively thick LC layer must be used; as a result, the response time is sluggish. Strictly speaking, the Gooch–Tarry first minimum condition holds only for a single wavelength. Thus, there is an urgent need to develop a broadband polarization switch with fast response time.

A linear polarization rotator consisting of three LC

cells (two homogeneous cells and one TN cell) has been proposed based on the Poincaré Sphere method [7]. Results are encouraging except that the bandwidth is inadequate. A design optimization method was developed for improving the bandwidth of the linear polarization rotator using a TNLC cell and two uniaxial compensation films [8]. However, these two types of polarization rotators are intended for rotating, not switching, the polarization of the incident light.

In this paper, we demonstrate a broadband polarization switch using an active TNLC cell and two passive uniaxial compensation films. In the voltage-off state, the device works as a linear polarization rotator; in the voltage-on state, it does not affect the incoming polarization. We describe a new method for optimizing the device structure.

2. Operating principle

Figure 1 shows the device configuration and operating principle of the broadband polarization switch (in the dashed box). For the purpose of illustrating the calculation procedures, we place the polarization switch between crossed polarizers as shown in figure 1(a). When the LC cell is in the voltage-off state, the switch will rotate the input linear polarization by $\pi/2$. That means, it will convert the p -polarization to s -polarization, or *vice versa*. Under such circumstances, the incoming light is transmitted by the crossed polarizers. In a high voltage state, the LC directors are reoriented along the electric field so that the LC cell does not affect the input polarization. The input

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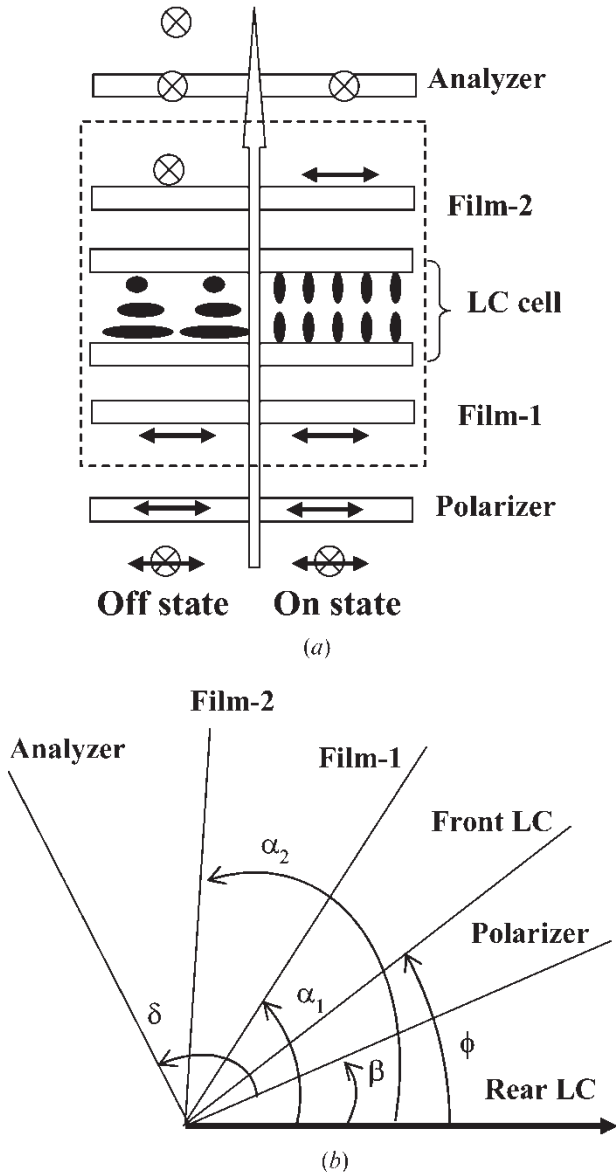


Figure 1. The device configuration and operating principle of the broadband polarization switch: (a) cell configuration; (b) orientation angles.

linearly polarized light goes through the switch without changing its polarization.

When the LC cell is in the voltage-off state, the TN cell has a twist angle ϕ and we use the Jones matrix method to calculate the transmission spectra. In a high voltage state, the bulk LC directors are reoriented nearly perpendicular to the substrate surfaces and the twist angle is zero. However, the boundary layers remain undisturbed due to the strong surface anchoring energy. Therefore we first use the continuum elastic theory [9] to calculate the director distribution and then use the Jones matrix method to calculate the transmission spectra.

In our coordinate system shown in figure 1(b), we define the rear rubbing direction of the TN cell as 0° . The incident linear polarization axis is at an angle β and the two polarizers are crossed, i.e. $\delta = \pi/2$. The polarization of the output light is in the $\gamma = \beta + \pi/2$ direction. The optical axes of the two uniaxial polymer films are oriented at angles α_1 and α_2 , and their thicknesses are d_1 and d_2 , respectively. During simulations, we only calculate the normalized transmittance of the polarization switch; all the absorption and reflection losses from polarizer, analyser, compensation films and substrates are ignored.

The normalized transmittance for the linear polarization component at an angle $\gamma = \beta + \pi/2$ can be obtained from the Jones matrix as [10, 11]:

$$T = \left| [\cos \gamma \ \sin \gamma] \mathbf{M}_{\text{film2}} \mathbf{M}_{\text{LC}} \mathbf{M}_{\text{film1}} \begin{bmatrix} \cos \beta \\ \sin \beta \end{bmatrix} \right|^2 \quad (1)$$

where

$$\mathbf{M}_{\text{LC}} =$$

$$\begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} \cos X - i(\Gamma/2)(\sin X/X) & \phi(\sin X/X) \\ -\phi(\sin X/X) & \cos X + i(\Gamma/2)(\sin X/X) \end{bmatrix}$$

$$\mathbf{M}_{\text{film1}} =$$

$$\begin{bmatrix} \cos \alpha_1 & -\sin \alpha_1 \\ \sin \alpha_1 & \cos \alpha_1 \end{bmatrix} \begin{bmatrix} \exp(-i\pi d_1 \Delta n_{\text{film}}/\lambda) & 0 \\ 0 & \exp(i\pi d_1 \Delta n_{\text{film}}/\lambda) \end{bmatrix} \begin{bmatrix} \cos \alpha_1 & \sin \alpha_1 \\ -\sin \alpha_1 & \cos \alpha_1 \end{bmatrix}$$

$$\mathbf{M}_{\text{film2}} =$$

$$\begin{bmatrix} \cos \alpha_2 & -\sin \alpha_2 \\ \sin \alpha_2 & \cos \alpha_2 \end{bmatrix} \begin{bmatrix} \exp(-i\pi d_2 \Delta n_{\text{film}}/\lambda) & 0 \\ 0 & \exp(i\pi d_2 \Delta n_{\text{film}}/\lambda) \end{bmatrix} \begin{bmatrix} \cos \alpha_2 & \sin \alpha_2 \\ -\sin \alpha_2 & \cos \alpha_2 \end{bmatrix}$$

Here, $X = [\phi^2 + (\Gamma/2)^2]^{\frac{1}{2}}$ and $\Gamma = 2\pi d \Delta n/\lambda$.

In our design, we have taken the LC and polymer material dispersions into consideration [12]:

$$n_e = A_e + \frac{B_e}{\lambda^2} \quad (2a)$$

$$n_o = A_o + \frac{B_o}{\lambda^2} \quad (2b)$$

In equations (2), A_e , B_e , A_o , and B_o are fitting parameters. For the Merck E7 LC mixture we used, $A_e = 1.6718$, $B_e = 24460.2 \text{ nm}^2$, $A_o = 1.4983$, $B_o = 8612.6 \text{ nm}^2$, $n_e = 1.7527$, $n_o = 1.5268$ and $\Delta n = 0.2259$ at $\lambda = 550 \text{ nm}$. Let us assume that the uniaxial films are

made of polycarbonate (PC) and have $n_e=1.5856$, $n_o=1.5569$ and $\Delta n=0.0287$. The fitting parameters for the PC film are $A_e=1.5637$, $B_e=6624.8 \text{ nm}^2$, $A_o=1.5367$, and $B_o=6110.4 \text{ nm}^2$.

In the optimization method, the cost function is taken to be:

$$\text{Cost} = - \int_{400 \text{ nm}}^{700 \text{ nm}} T(\lambda) d\lambda \quad (3)$$

which is minimized in search of β , ϕ , α_1 , α_2 , d , d_1 and d_2 for the polarization switch at voltage-on and -off states. The optimization method used in this work is known as the conjugate gradient method [13].

3. Results and discussion

Figure 2 shows the simulation results of the voltage-dependent transmittance for the polarization switch at $\lambda=650$, 550 and 450 nm. The LC parameters are: $\varepsilon_{\parallel}=19.6$, $\varepsilon_{\perp}=5.1$, $K_{11}=12 \text{ pN}$, $K_{22}=9 \text{ pN}$, $K_{33}=19.5 \text{ pN}$ and pitch = 300 μm . The upper and lower pretilt angles are 3° . The optimal values of the TN cell are found to be: $\phi=90.12^\circ$, $d=6.20 \mu\text{m}$ and $\beta=1.64^\circ$, while the film orientation angles $\alpha_1=89.96^\circ$, $\alpha_2=-89.91^\circ$, and thickness $d_1=45.29 \mu\text{m}$, and $d_2=4.83 \mu\text{m}$.

We also calculated the wavelength-dependent transmittance of the polarization switch at $V=0$ and $5 V_{\text{rms}}$. Results are plotted as solid lines in figure 3. From Figure 3, the polarization switch has a bandwidth spanning the entire 400–700 nm range in the voltage-off state and high contrast ratio in the voltage-on state.

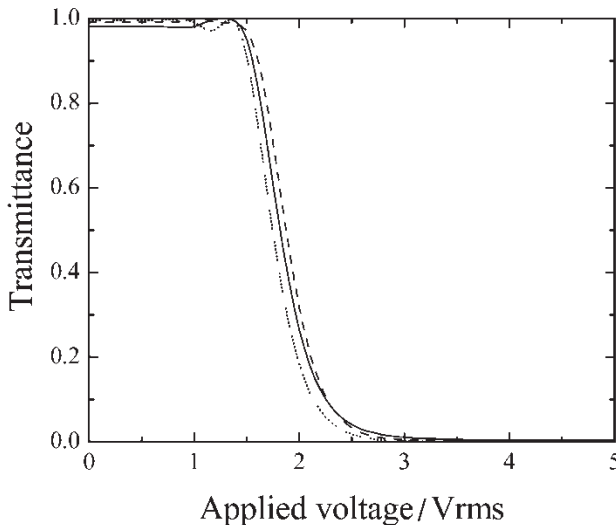


Figure 2. The simulated voltage-dependent transmittance of the polarization switch at $\lambda=650 \text{ nm}$ (dotted line), $\lambda=550 \text{ nm}$ (solid line) and $\lambda=450 \text{ nm}$ (dashed line). The parameters used for simulations are listed in the text.

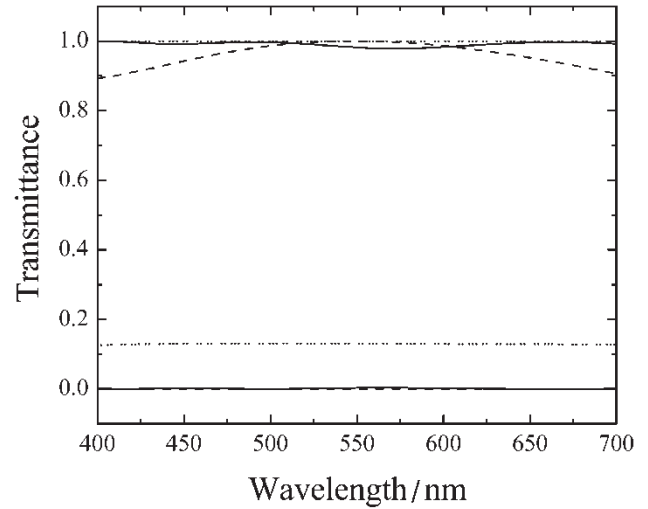


Figure 3. The simulated transmission spectra of the proposed polarization switch (solid lines), Gooch-Tarry 90° TN LC cell (dashed lines) and a broadband polarization rotator (dotted lines) between crossed polarizers. Upper curves: $V=0$, lower curves: $V=5 V_{\text{rms}}$.

In practice, the analyser shown in figure 1 is removed. Therefore, if the polarization switch transmits the s-polarization in the voltage-off state, it will transmit the p-polarization in the voltage-on state, or *vice versa*.

Also included in figure 3 for comparison are the results of the Gooch-Tarry 90° TNLC cell (dashed lines) and the broadband polarization rotator (dotted lines) [8]. As expected, the Gooch-Tarry TNLC cell reaches $T=1$ at $\lambda=550 \text{ nm}$ in the voltage-off state but gradually drops to $T\sim 0.9$ at $\lambda=400$ and 700 nm . This implies that the polarization state is impure. On the other hand, the 90° TN polarization rotator has an excellent voltage-off state transmittance except that its voltage-on state has about 12% light leakage. Thus, such a polarization rotator is good for rotating the linear polarization in the voltage-off state. In the voltage-on state, its outgoing polarization is impure. In contrast, our broadband polarization switch has $T>97.8\%$ in the voltage-off state and little light leakage ($<0.35\%$) in the voltage-on state.

Although the proposed polarization switch is not aimed for direct-view display application, a wide acceptance angle is still desirable for improving the device extinction ratio. Our film-compensated TN cell maintains a 100:1 contrast ratio within the $\sim 15^\circ$ viewing cone.

In the example illustrated here, we have used E7 with $\Delta n\sim 0.226$. As a result, its cell gap is $d=6.20 \mu\text{m}$. To improve response time, a thinner cell gap with higher Δn LC could be considered. Several high Δn and low viscosity LCs have been developed [14]; for example, if

we choose $\Delta n=0.3$, then the cell gap is reduced to $d=4.67\mu\text{m}$. The response time should be in the 20–30 ms range.

Tolerance is an important concern from manufacturing viewpoint. Figures 4(a) and 4(b) depict the tolerance of our designs when the cell gap and twist angle vary by $\pm 5\%$ from their optimal designs. From figure 4(a), when the cell gap increases (or decreases) by

5%, the off-state transmittance shifts to a longer (or shorter) wavelength. However, its overall transmittance remains higher than 97.5% and dark state transmittance remains lower than 0.35%. From figure 4(b), the twist angle has a large effect on the dark state performance of the proposed polarization switch. Fortunately, the twist angle of the LC cell can be controlled with a better precision.

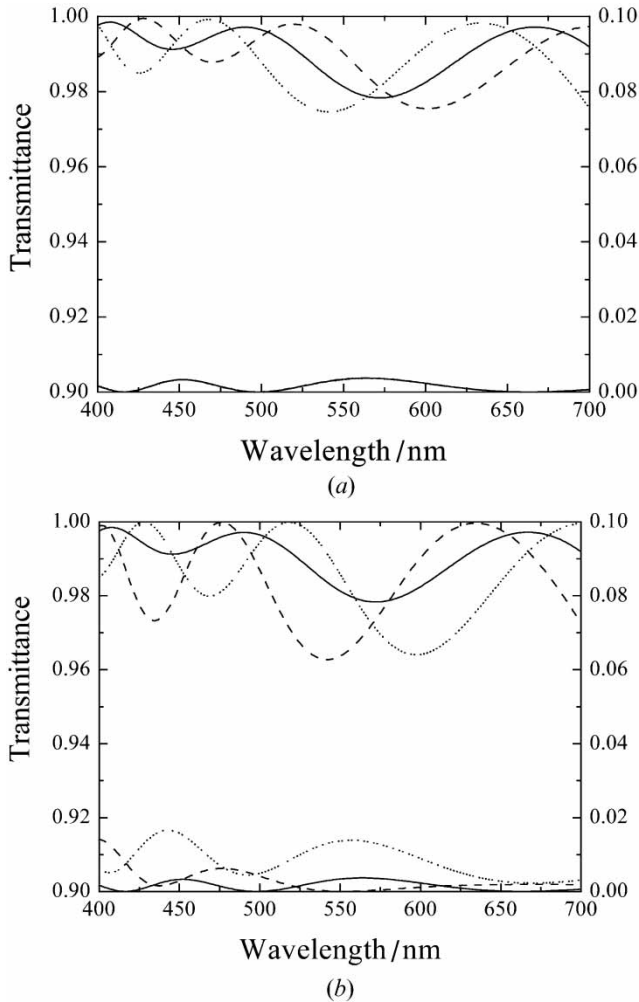


Figure 4. (a) Cell gap tolerance of the polarization switch. Solid lines indicate optimal values, dashed lines indicate 5% higher than the optimal values, and dotted lines indicate 5% lower than the optimal values. The remaining parameters are the same. Left scale: upper curves for the LC at $V=0$; right scale: lower curves for the LC at $V=5V_{\text{rms}}$. (b) Twist angle tolerance of the polarization switch. Solid lines indicate optimal value, dashed lines indicate 5% higher than the optimal value, dotted lines indicate 5% lower than the optimal value. The remaining parameters are the same. Left scale: upper curves for the LC at $V=0$; right scale: lower curves for the LC at $V=5V_{\text{rms}}$.

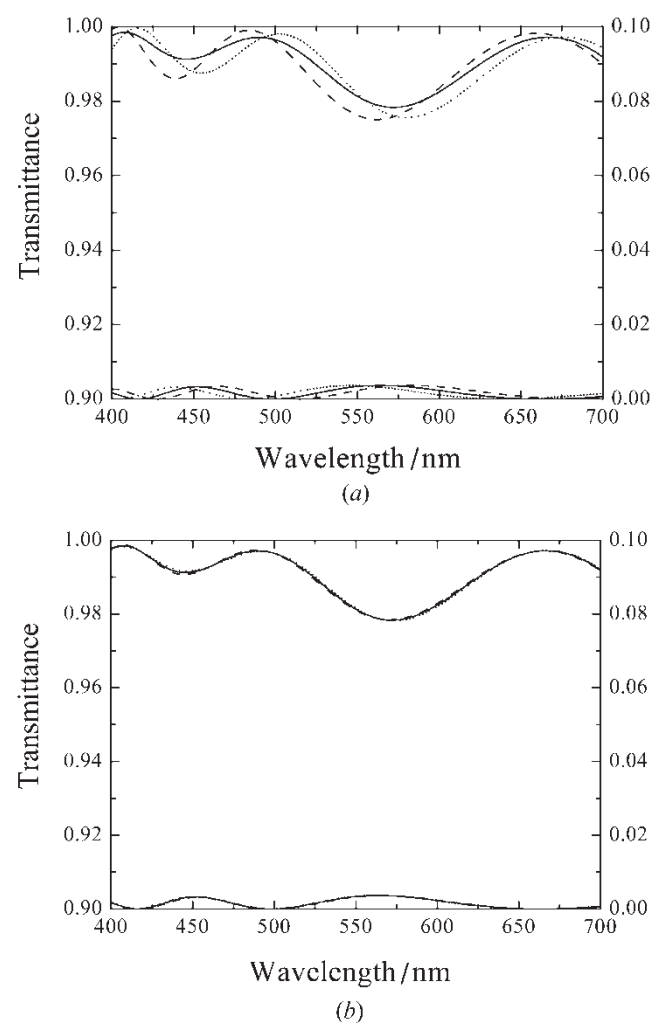


Figure 5. (a) Thickness tolerance of the compensation film-1. Solid lines indicate optimal value, dashed lines indicate 5% higher than the optimal value, dotted lines indicate 5% lower than the optimal value. The remaining parameters are the same. Left scale: upper curves for the LC at $V=0$; right scale: lower curves for the LC at $V=5V_{\text{rms}}$. (b) Thickness tolerance of the compensation film-2. Solid lines indicate optimal value, dashed lines indicate 5% higher than the optimal value, dotted lines indicate 5% lower than the optimal value. The remaining parameters are the same. Left scale: upper curves for the LC at $V=0$; right scale: lower curves for the LC at $V=5V_{\text{rms}}$.

Figures 5(a) and 5(b) plot the thickness tolerance of the compensation films 1 and 2, respectively, while keeping the cell gap and twist angle at their optimal conditions. The thickness tolerance of the two uniaxial films is not too noticeable.

4. Conclusions

We have demonstrated a broadband polarization switch using an active TNLC cell and two passive uniaxial compensation films. We used the conjugate gradient method to optimize the device parameters. Such a polarization switch exhibits a broad bandwidth and high contrast ratio. Its response time depends on the choice of LC material and cell gap. The manufacturing tolerances for cell gap, twist angle and compensation films thickness are analysed and results are quite acceptable.

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