Thresholdless, hysteresis-free, V-shaped, electro-optical switching for a ferroelectric liquid crystal cell

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A ferroelectric liquid crystal (FLC) cell can be modeled as a combination of capacitors and resistors. In accordance with the properties of the FLC cell, external electric elements, such as capacitors and resistors, are usually connected to achieve a V-shaped performance at a driving inversion frequency f_i. However, the inversion frequency is strongly dependent on the external electric elements and the applied voltage. In this paper, the relation between the inversion frequency and the applied voltage is discussed. Additionally, the inversion frequency is found to be approximately proportional to $(R_{eq}C_{eq})^{-0.52}$, where R_{eq} and C_{eq} are equivalent resistance and capacitance, respectively. Based on the above properties, a useful driving scheme is proposed to achieve thresholdless, hysteresis-free, V-shaped characteristics for FLC cells at a driving frequency of 100 Hz. The driving scheme can be applied to fast-response FLC display.

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I. INTRODUCTION

Since the discovery of ferroelectric liquid crystals, a large number of investigations have been performed for fundamental understanding and technological applications. Recently, a thresholdless, hysteresis-free, V-shaped, electro-optical (EO) switching was discovered in the thin plane-parallel aligned cell of surface-stabilized ferroelectric liquid crystals (SSFLCs). The V-shaped switching has attracted considerable attention due to the advantageous possibility of an analog gray scale [1–5].

In Fig. 1, the optical transmittance shows a typical V-shaped characteristic when a triangular voltage wave form of ±10 V is applied to the cell at a frequency of 90 mHz. The EO transmittance appears W-shaped as a result of altering the frequency above or below the characteristic frequency, which is the so-called inversion frequency. Čopič *et al.* have constructed a model to explain the thresholdless V-shaped switching in ferroelectric liquid crystal (FLC) layers with alignment layers [6,7], but the mechanism for "V-shaped" switching is still under discussion. Recently, several ideas on the cause of a thresholdless, hysteresis-free, genuine V-shaped switching at inversion frequency and the equivalent circuit of FLC have been proposed by Blinov *et al.* [8]. However, the voltage dependence of inversion frequency is evident. The proposed circuit with the external electrical elements connected to FLC cells fails to remove the voltage dependence.

Up until now, only a few FLC materials reveal intrinsic V-shaped characteristics and the name "V-shaped FLCs (VFLCs)" are referred to these materials. The main advantage of these materials is low switching voltage and the presence of an analog gray scale. However, the intrinsic genuine V-shaped switching is observed only at very low frequency (<10 Hz) and usually far above room temperature [9]. Moreover, the EO transmittance of the so-called V-shaped materials often appears W-shaped rather than V-shaped, due to altering the driving voltage. The W-shaped characteristic is undesirable, because the driving procedure is very complicated and the driving circuit is difficult to design [10].

At present, to explore a VFLC for a fast-response display panel, there are three aspects that should be improved. The first one is to raise the inversion frequency f_i to an acceptable level (>60 Hz, the frame rate for a display panel). The second one is to remove the strong dependence of inversion frequency f_i on the applied voltage, such that the FLC panel can keep in V-shaped switching rather than W-shaped switching. The third one is to suppress the effect of the voltage and temperature dependence of the dynamical capacitance and resistance of the FLC layer [8]. In this paper we would like to propose a useful driving scheme to achieve these three characteristics. In Sec II we first give the detailed description of our experiment. In Sec. III we show that the W- and V-shaped electro-optic transmittance can occur, and then apply our designed circuit to achieve a true V-shaped EO transmittance operating at high frequency. Finally, a discussion and summary follow.

II. EXPERIMENT

In the experiment the SSFLC cells are of the sandwich-type, consisting of two glass plates covered by transparent conductive films of indium tin oxide (ITO). The parameters of the cell are the thickness of the gap $d=2$ μm, area $A=5\times 5$ mm^2, and two alignment layers each of thickness $d_p=40$ nm. FLC liquid crystal CS-1025 (Chisso) at room temperature is filled into the gap between the plates. Two wires are fixed separately to the ITO-coated glass plates of the SSFLC cell by silver paint.

All measurements are carried out in the smectic C^* phase of the FLC. The FLC cell is set between the crossed polarizer

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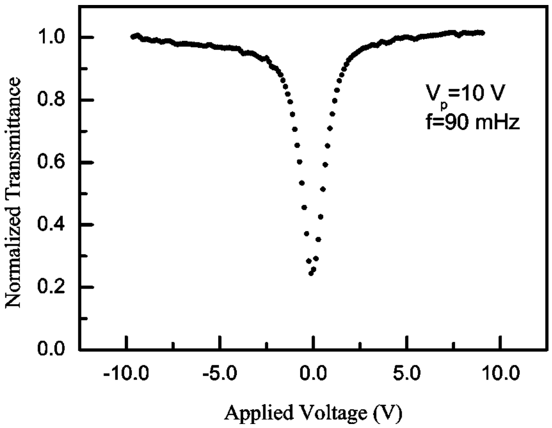

FIG. 1. Transmittance of the FLC cell driven by a triangular wave voltage form ±10 V at frequency $f=90$ mHz, temperature 25°C.

and analyzer perpendicular and parallel to the normal of the smectic layers, and driven by the triangular voltage with amplitude $\pm V_p$. The EO transmittance of the FLC is investigated using a low-frequency function generator Instek GFG-8020H with a homemade power amplifier, a He-Ne laser of 632.8 nm, a photodetector, and a digital oscilloscope TDS2002 (Tektronix).

III. RESULTS AND DISCUSSION

In Fig. 1, the optical transmittance of the cell induced by a triangular wave form voltage of the amplitude ±10 V at 90 mHz shows an intrinsic thresholdless electro-optical behavior at 25°C. There are no external elements connected to the FLC cell. The genuine V-shaped switching corresponds to the threshold voltage $V_{\mathrm{th}}=0$.

Figure 2(a) shows the equivalent electric circuit for SSFLC. With the dielectric constant of the polymer $\varepsilon_p=3.8$ and specific resistance $\rho=10^{14}$ Ω m, the polymer layer capacitance $C_{\mathrm{p}}=0.5\varepsilon_p A/d_p(\approx 10$ nF) and resistance $R_p=2\rho d_p/A(\approx 3\times 10^9\ \Omega)$, respectively. The resistance R_p can be ignored compared to the dynamical impedance of the polymer capacitor at the frequency higher than 10 mHz. Thus, we adopt the simplified circuit [Fig. 2(b)] for FLC cell. The magnitudes of the capacitance and the resistance of the cell are measured at the bias voltage 1.0 V and frequency 100 Hz using an LCR meter. The corresponding capacitance $C_{\mathrm{LC,1V}}=0.02$ nF of the FLC layer via the equivalent circuit Fig. 2(b) is obtained. The capacitance C_{LC} of the FLC decreases as voltage increases. Since we are interested in the amplitude larger than 1 V, C_{LC} is negligible compared to C_{p}. Therefore, the *RC* constant of FLC cell becomes $C_p R_{\mathrm{LC}}$.

To elevate the inversion frequency to 100 Hz, an optimized capacitor with $C_{\mathrm{ext}}=2.64$ nF and a resistor $R_{\mathrm{ext}}\ll R_{\mathrm{LC}}$ are selected to connect to the FLC cell, as shown in Fig. 2(c). The equivalent capacitance and resistance are $C_{\mathrm{eq}}\approx 2.64$ nF $\approx(1/4)C_p$ and $R_{\mathrm{eq}}\approx R_{\mathrm{ext}}\approx 500$ kΩ, respectively. Because of the external electric elements, the inversion frequency can be shifted from 90 mHz to 100 Hz. As shown in Fig. 3(a), the inversion frequency f_i is the function of the external resistance R_{ext} and voltage V_p. In Fig. 3(b), $\log_{10}(f_i)$ is plotted as a function of $\log_{10}(\mathrm{R_{eq}})$ for different voltages. It is fitting to a straight line with intercept $\log_{10}(f_i)=-\eta\log_{10}(R_{\mathrm{eq}})+b$ by least-squares fitting. The parameters η's for different voltages in the assumption $f_i=A(R_{\mathrm{eq}}C_{\mathrm{eq}})^{-\eta}$ are indicated in Fig. 3(b) and the values are between 0.52 and 0.6, which are very close to 0.5 predicted from the theory for intrinsic inversion frequency[8]. The dynamical resistance $R_{\mathrm{LC,10V}}\approx 7.58\times 10^7$ kΩ of the FLC layer for operating voltage $V_p=10$ V is obtained from the straight line function with the corresponding inversion frequency $f_i=90$ mHz. It is obvious that the constant $R_{\mathrm{eq}}C_{\mathrm{eq}}$ is decreased by the factor $h=1.64\times 10^{-6}$ with the electrical elements C_{ext} and R_{ext} connected to the FLC cell. From the approximation, we estimate the inversion frequency would be elevated by the factor $h^{-0.52}(\approx 1019)$, which agrees with our optimized circuit that raises the inversion frequency from 90 mHz to 100 Hz. We indeed give a numerical analysis to estimate the dynamical resistance R_{LC} of FLC layer explicitly. It is helpful to select the external elements R_{ext} and C_{ext} to raise the inversion frequency efficiently.

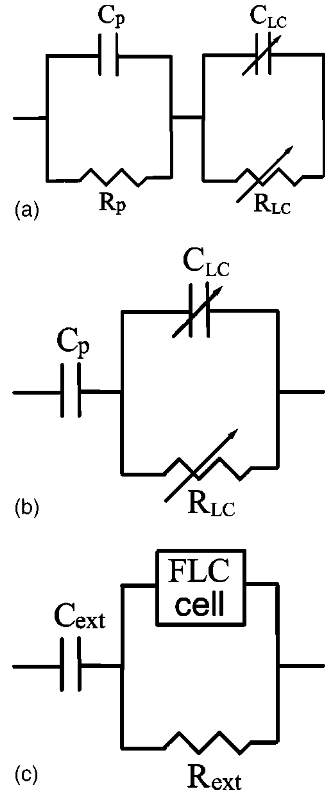

FIG. 2. Equivalent circuit (a) FLC cell, with C_{p} and R_{p} the capacitance and resistance of the polymer layer. C_{LC} and R_{LC} are the capacitance and resistance of the FLC layer. (b) The same cell with R_{p} neglected. (c) The circuit of the cell connected to external resistor R_{ext} and capacitor C_{ext}.

From Fig. 3(a) it also suggests that the parallel external resistor is a pretty good choice for removing the voltage dependence of the inversion frequency and furthermore setting the constant inversion frequency. In our case, the specific inversion frequency 100 Hz is chosen from Fig. 3(a) for a V-shaped driving wave form. Firstly, we plot R_{ext} as func-

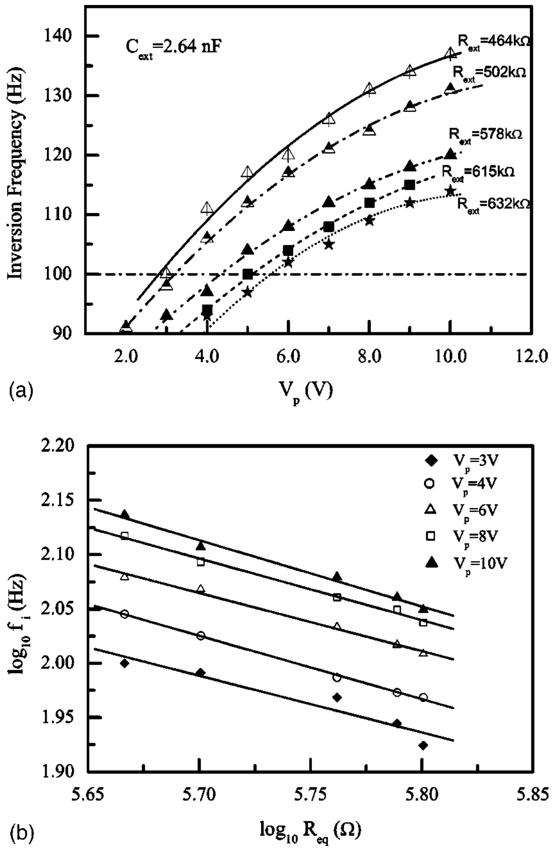

FIG. 3. (a) Inversion frequency f_i as a function of the triangular voltage amplitude V_p for different external resistances 464, 502, 578, 615, and 632 kΩ. (b) $\log_{10}(f_i)$ is plotted as a function of $\log_{10}(R_{eq})$ for different voltage amplitudes. A straight line with intercept $\log_{10}(f_i)=-\eta\log_{10}(R_{eq})+b$ is fitted. The corresponding η's for voltages 3, 4, 6, 8, and 10 V are 0.52, 0.58, 0.53, 0.56, and 0.60, respectively.

tion of V_p in Fig. 4 and decide the corresponding suitable external resistances 480, 549, 606, and 648 kΩ for four specific voltage amplitudes 3,4,5 and 6 V, respectively. Therefore, we design an optimized circuit shown in Fig. 5. The FLC cell is designed to connect to one of the suitable exter-

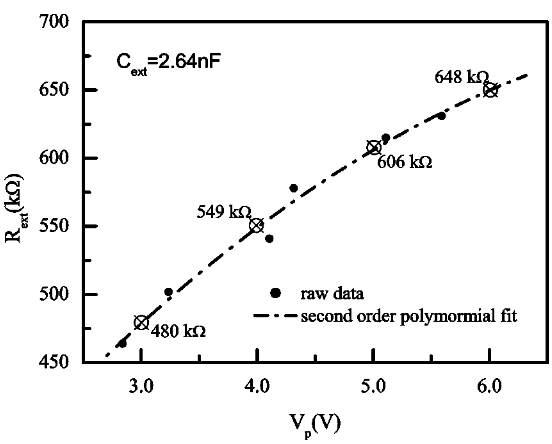

FIG. 4. The selected external resistance R_{ext} as a function of the triangular voltage amplitude V_p at $f_i=100$ Hz.

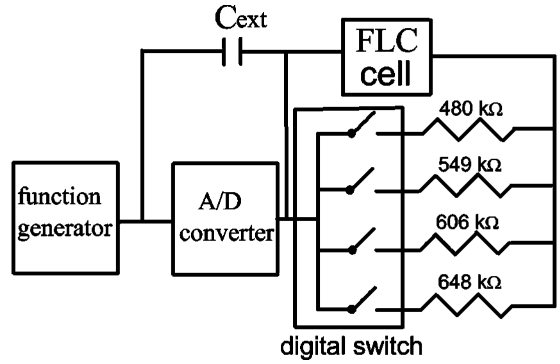

FIG. 5. The optimized circuit with $C_{ext}=2.64$ nF, the A/D converter and digital switch will automatically select a suitable external resistor connected to a FLC cell according to the driving voltage from the function generator.

nal resistors mentioned above in parallel to the FLC cell corresponding to the four specified voltages V_p's from the function generator. In other words, using an A/D converter and a digital switch, automatic gray level selection can be achieved. Figures 6(a) and 6(b) show the EO transmittance without any external elements for $V_p=3$ and 6 V, respectively. Both are in W shape and are not coincident. It will thus make the driving circuit much more complicated [10]. With our proposed circuit shown in Fig. 5 to select the opti-

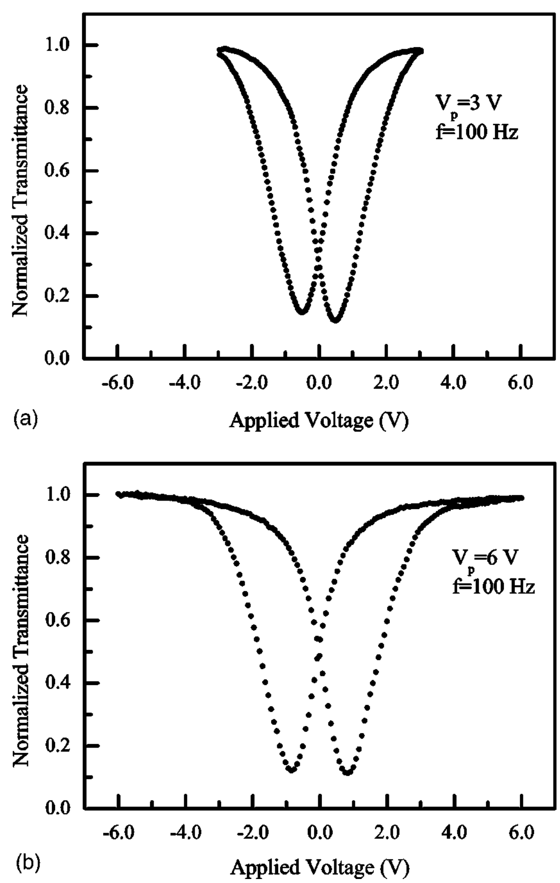

FIG. 6. The EO transmittance of a FLC cell without external electrical elements for the amplitude of the triangular voltage (a) $V_p=3$ V and (b) $V_p=6$ V.

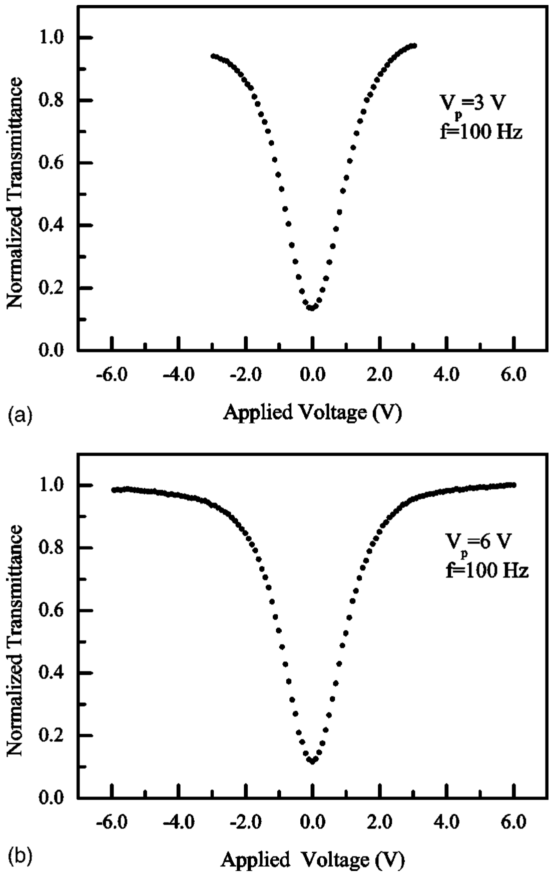

FIG. 7. The EO transmittance of a FLC cell with the optimized circuit shown in Fig. 5 for the amplitude of the triangular voltage (a) V_p=3 V and (b) V_p=6 V.

mized resistor, the EO transmittances become V shaped and are in complete accordance with each other, as shown in Figs. 7(a) and 7(b). The situations are the same for the amplitudes 4 and 5 V. Figures 7(a) and 7(b) clearly show that our proposed circuit has accomplished both symmetric (V-shaped) EO performance and lower switching voltage at high frequency 100 Hz. In the fine structure of the V-shape, the EO transmittance increases monotonically with increasing the applied voltage from 0.2 to 2.5 V. It is obvious that the applied voltage in this range can modulate the gray levels of a SSFLC linearly.

The electric power is estimated by applying the equivalent electronic circuit [Fig. 2(c)] to conventional circuit simulators such as SPICE. It is about 10.0 μW for R_{ext}=500 kΩ when a triangular voltage wave form of ±5 V at a frequency of 100 Hz is applied. Even though the more power is required to drive the proposed circuit, it is still acceptable.

IV. CONCLUSION

From the results of our experiments described above, we can see that both the external capacitor and resistor play crucial roles in increasing the inversion frequency. Although the dependence of inversion frequency on the external resistance and capacitance is quite complicated, the reliable way to estimate the dynamical resistance R_{LC} of the FLC layer is given in Sec. III. Furthermore, it can be approximated that the inversion frequency f_i is proportional to $(R_{\text{eq}}C_{\text{eq}})^{-\eta}$, where η is between 0.5 and 0.6, which is in correspondence with the theoretical approximation [8]. Then we can follow Sec. III to select the suitable external capacitor and compensated resistor connected to the FLC cell to raise the inversion frequency by this approximation.

For continuous gray scale capability, the FLC cell should operate at the specific frequency and keep in V shape for different driving voltages. In Blinov's work, the external electric elements are suggested to connect to the cell to raise inversion frequency and to achieve the thresholdless, hysteresis-free, V-shaped, electro-optical switching in SSFLC. However, with the external electric elements being connected to the cell, the voltage dependence of inversion frequency is noticeable enough to be taken into consideration. But until now, not much attention has been paid to deal with it. In this paper, we design the optimized circuit to select the corresponding suitable external resistance connected in parallel to an FLC cell for different voltages from a function generator. The EO transmittances of an FLC cell induced by a triangular voltage form of different amplitudes at 100 Hz reveal V shapes, and all the V shapes are identical. It is evident that we have removed the voltage dependence of inversion frequency to produce gray scale modulation of the ferroelectric liquid crystal cells.

In addition to the merits mentioned above, the temperature and voltage dependence of FLC resistance is minimized by connecting the external resistor in parallel to an FLC cell, since the external resistance is quite smaller than R_{LC} and the equivalent resistance $R_{\text{eq}} \approx R_{\text{ext}}$. Although the proposed circuit needs more power for driving, it is still acceptable in practical design.

On the basis of our optimized circuit, our research group extends the gray scale capability without a threshold and the voltage dependence of the inversion frequency in SSFLC at high frequency ($\geqslant$100 Hz) to explore the probability of practical applications on fast-response FLC display panels.

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