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Circuit-Level Analysis on Opto-Electronic Characteristics of Ferroelectric Liquid Crystal

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Abstract: We propose an electronic model in Spice, instead of traditional mathematical analysis, for analyzing the performance of ferroelectric liquid crystal (FLC) under various working conditions. Using this equivalent circuit model, it is easy to simulate and analyze the behavior of an FLC layer in three different typical parameters, including temperature, input light wavelength, and the frequency of driving voltage. We conclude that the response velocity drops as the wavelength increases in the range of visible light, and for the parameter of temperature, the velocity reaches its lowest value when the temperature reaches a certain degree; meanwhile, the frequency of driving voltage exerts important effects on the response velocity only when the frequency is beyond a critical value. Excellent agreement is achieved between simulation and experimental results.

Key words: ferroelectric liquid crystal; circuit-level analysis; response characteristics; typical parameters
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1 Introduction

Since Meyer originally synthesized ferroelectric liquid crystal (FLC) compound in 1975, FLC has attracted much attention due to its characteristics such as fast response velocity, high resolution, low switching threshold, and good thermal stability. In 1980, the bistability of surface-stabilized FLC (SSFLC) demonstrated by Clark and Lagerwall paved the way to investigate FLC displays[1,2]. In 1989, researchers at the University of Colorado at Boulder developed a hydrogenated amorphous silicon/ferroelectric liquid crystal (a-Si:H/pin/FLC) optically addressed spatial light modulator (OASLM), which expedites the development of optical communication[3,4]. So far, FLC has been extensively utilized in many high-tech domains such as nonlinear optics, optical computing, and light information processing[5,6].

Ferroelectric liquid crystals are nonlinear, so when it comes to the study of their opto-electronic properties, researchers always employ mathematical analysis[7,8]. This paper presents an electronic model in Spice to help analyze the effect on FLC opto-electronic velocity of three typical parameters: temperature, ray wavelength, and frequency of driving voltage. This model effectively overcomes the problem of nonlinear analysis as well as parasitic elements introduced by nonlinearity, which mathematical computing cannot solve.

2 Physical model

An FLC layer is divided into many sublayers, and has a spiral structure[6]. If it is limited to a thin LC box (μm in thickness), the spiral structure will be effectively restrained. Then the FLC will exhibit two steady states. Due to its spontaneous polarization, when a driving voltage is applied to the LC box, the two states will switch at a high speed. As a result, FLC has a fast opto-electronic response velocity.

When FLC is in its steady state, it has the minimum potential energy.

If we break down an FLC layer into N sublayers as shown in Fig. 1, the free energy per unit area of an FLC layer of thickness d can be written as

$$F(\phi) = (F_{\mathrm{TS}} + F_{\mathrm{BS}}) + \int_0^d \left(\frac{1}{2}K\left(\frac{\partial \phi}{\partial y}\right)^2 + P_{\mathrm{S}}\cos\phi \frac{\partial V}{\partial y}\right)\mathrm{d}y \quad (1)$$

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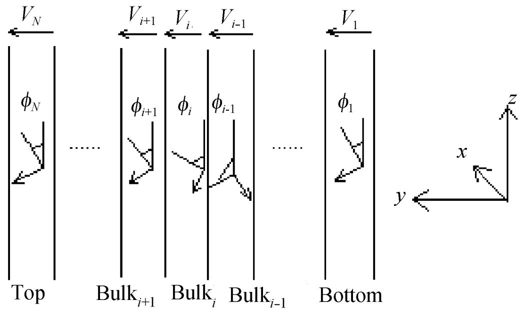

Fig. 1 Break-down of the FLC layer into N sub-layers

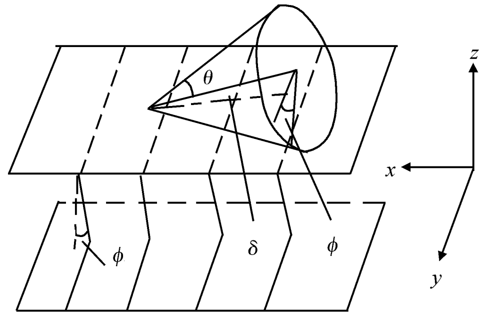

Fig. 2 Alignment of FLC cell molecular layers

where F_{TS} and F_{BS} describe the free energy at the top and at the bottom surfaces, respectively, K is the unique elastic constant, ϕ is the director rotation angle, P_S is the spontaneous polarization, and V is the driving voltage. According to Eq. (1), the rate of change of ϕ can be described as[9,10]

$$\gamma \frac{\mathrm{d}\phi}{\mathrm{d}t} = P_S E \cos\phi \cos\delta + K \cos\phi \tag{2}$$

where γ is the rotational viscosity, δ is the angle at which the layer is tilted due to the chevron structure, and E describes the external electric field produced by V. Figure 2 describes the alignment of FLC molecular layers. The optical power transmission can be derived from Fig. 2 as

$$I = \sin^2 2(\arctan(\sin\theta \sin\phi/(\cos\theta\cos\delta + \sin\theta\cos\phi\sin\delta))) \tag{3}$$

3 Equivalent circuit model

According to Eq. (2), when in an electronic circuit, FLC can be regarded as a combination of resistors and capacitors. In order to simulate the FLC model in an equivalent circuit, a variable G_{in} is introduced, which represents the change of electrical current caused by the rotation of the director[9].

$$G_{in} = P_S \cos\phi \cos\delta \frac{\mathrm{d}\phi}{\mathrm{d}t} \tag{4}$$

As the function DDT provided by Spice cannot accurately determine results of differential coefficients, the nonlinear relation of voltage and current on a capacitor with some leakage and series resistance, in parallel with a variable current sink, is used to describe the derivative term in Eq. (4). The equivalent circuit is illustrated in Fig. 3.

V_{in} is the driving voltage and R_{in} is the series resistor introduced by current leakage. The controlled current sources G_r, G_k, G_{ps}, and G_{in} satisfy Eq. (5)～Eq. (8), respectively.

$$G_r = P_S V_{R2}/\gamma d R_{out} \tag{5}$$

$$G_k = \kappa(V_{Cout}) \tag{6}$$

$$G_{ps} = V_{R1} \cos V_{Cout} \cos\delta \tag{7}$$

$$G_{in} = P_S \cos V_{Cout} \cos\delta \frac{\mathrm{d}V_{Cout}}{\mathrm{d}t} = P_S \cos V_{Cout} \cos\delta \frac{V_{Rout}}{R_{out}} \tag{8}$$

where the voltage on C_{out} can equally represent ϕ, and the current through it is the value of $\mathrm{d}\phi/\mathrm{d}t$.

4 Results and discussion

The driving source used in the simulation is a ± 15V symmetrical square wave voltage. In sections 4.1 and 4.2, the frequency of the driving voltage is 300Hz. The variable V in the curves corresponds to optical power W. The main parameters of FLC are set as follows[5,9]: cone angle $2\theta = 21.5°$, input polarizer orientation $\alpha = -24°$, cell thickness $d = 1.5\mu m$, cell area $S = 10cm^2$, $\delta = 18.6°$, and $\gamma = 65mPa \cdot s$. Other parameters will have different values in various sections.

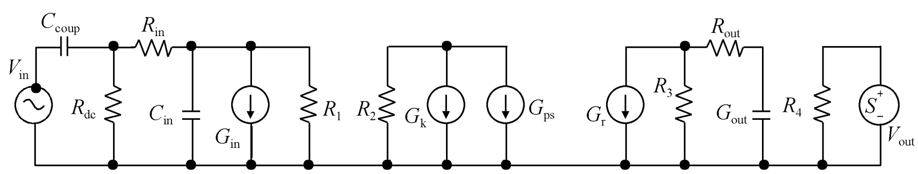

Fig. 3 Equivalent circuit of FLC cell

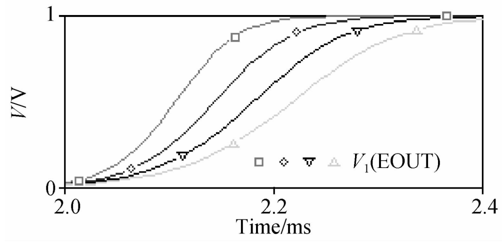

Fig.4 Dependence of the response velocity on wavelength Wavelengths corresponding to the symbols are 350, 450, 550, and 650nm, respectively.

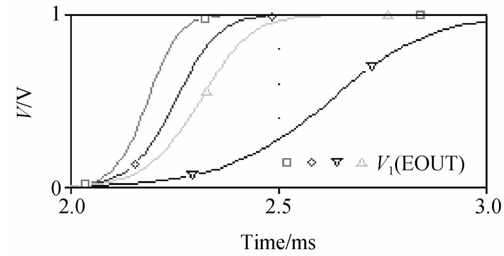

Fig. 5 Dependence of the response velocity on temperature Temperatures corresponding to the symbols are 80, 82, 84, and 86℃, respectively.

4.1 Effect of wavelength on response velocity

When incident light goes through an FLC, its transmission power can be described as[7]

$$I = I_0 \sin^2(4\theta)\sin^2(\Delta/2) \tag{9}$$

where I_0 is the incident light power and Δ represents the phase delay[2].

$$\Delta = \frac{2\pi}{\lambda}\Delta n \times d \tag{10}$$

In order to have the best transmission effect, $\Delta/2$ should be equal to $\pi/2$, and then we have $2\Delta nd = \lambda$. When the ray wavelength λ varies in the visible light range, the relation between transmission power I and λ is shown in Fig. 4. In this section, P_S and Δn have their typical values: $P_S = 6.4\text{nC/cm}^2$, $\Delta n = 0.15$[3~5].

As shown in Fig. 4, when λ equals 350nm, the response velocity reaches its peak, and with the increase of λ, the velocity decelerates. This phenomenon demonstrates that when the wavelength varies within the range of visible light, the FLC opto-electronic response velocity declines while λ increases.

4.2 Effect of temperature on response velocity

According to Landau theory, the temperature dependence of spontaneous polarization is fitted to a power law equation[8,11],

$$P_S(T) = P_0(T_{AC} - T)^{\alpha} \tag{11}$$

where T_{AC} is the transition temperature from smectic A to smectic C^*, P_0 is a constant, and α is a critical exponent. The fit values of T_{AC}, P_0, and α are, respectively, 84.2℃, 3.5nC/cm^2, and 0.5[11].

Figure 5 explicitly illustrates the effect of temperature on the opto-electronic response velocity. When $T < 84$℃, the response velocity declines as temperature rises; while $T > 84$℃, the result is fitly the opposite. It can be concluded that the temperature parameter has a certain value, at which the response velocity reaches its lowest, and when T gradually varies from the critical point, the response velocity accelerates with the change of T.

4.3 Effect of frequency on response velocity

In this section, the frequency of driving volt-

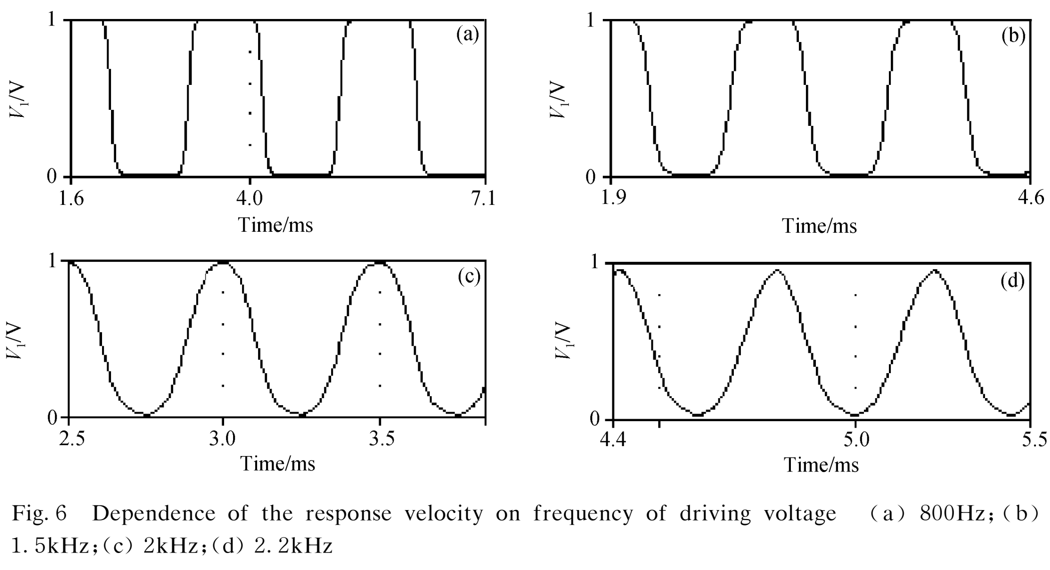

Fig. 6 Dependence of the response velocity on frequency of driving voltage (a) 800Hz; (b) 1.5kHz; (c) 2kHz; (d) 2.2kHz

age is changed to simulate FLC opto-electronic-characteristics under different driving sources, as shown in Fig. 6. P_S is set to its critical value $6.4 nC/cm^2$[5]. In Figs. 6 (a) and (b), curves have distinct rising and falling edges, while in Figs. 6 (c) and (d), the edges are not as steep as the former two; they become slighter as the driving frequency increases. This result as well as many more simulation curves with even higher driving frequencies leads to the conclusion that the driving frequency has an upper limit of 2kHz. When and only when the frequency in application exceeds this point, the opto-electronic response velocity will be affected on a large scale. Figure 6 corresponds well to the report of Ref. [8].

5 Conclusions

An equivalent circuit model is proposed in this paper to simulate effects on the FLC opto-electronic response velocity of three typical parameters: input light wavelength, temperature, and frequency of driving voltage. When wavelength varies within the range of visible lights, response velocity declines while wavelength increases. Temperature has an extremum and frequency has an upper limit. The results obtained correspond to experimental curves. The introduction of a Spice model conveniently overcomes the problem of parasitic components, which traditional mathematical analysis cannot solve.

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铁电液晶光电特性的电路级分析

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摘要： 建立了铁电液晶的 Spice 等效电路模型，并基于此模型，分析了温度、光波长以及电压频率 3 个典型参量对铁电液晶光电响应特性的影响．仿真结果表明，以上 3 个参量的变化对铁电液晶光电响应有明显的控制作用，该结果与 Matlab 数值分析结果以及实验结果相符．

关键词： 铁电液晶；电路级分析；响应特性；典型参量

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