

Fast Switchable Color Filter Based on Ferroelectric Liquid Crystals

Jingxuan Huang^{1,2}, Yipeng Huo², Zhibo Sun², Man Chun Tseng², Hoi Sing Kwok², Kristiaan Neyts^{2,3}

¹College of Optical Science and Engineering, Zhejiang University, Hangzhou, China

²State Key Laboratory of Advanced Displays and Optoelectronics Technologies, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

³Electronics and Information Systems Department, Ghent University, Ghent, Belgium

Abstract

Fast switchable color filter based on ferroelectric liquid crystals is a color sequential filter and can be used for field sequential color displays and colorization of the event-based vision sensors. The filters are structurally similar to polarization interference filters and show good spectral results. Due to fast response and low drive voltage of ferroelectric liquid crystals, they have a response time of 14–64 μs at 5–20 V driving voltages.

Author Keywords

Color filter; switchable color filter; ferroelectric liquid crystal; polarization interference filters; field sequential color display; event-based vision sensor.

1. Introduction

Field sequential color (FSC) display is a new type of display technology, the principle of which is to display color images by quickly switching red, green, and blue single source frames. In traditional LCDs, each pixel consists of three sub-pixels (red, green, and blue), as shown in Figure 1(a), and a color image is synthesized by controlling the brightness of each sub-pixel. In FSC-LCDs, each pixel has only one sub-pixel, as shown in Figure 1(b), and by quickly switching the three monochrome frames, human eyes can combine the three monochrome frames into one color frame to achieve color display. Due to its advantages of high contrast, high refresh rate, fast response, and low power consumption, FSC display has become a research hot topic in recent years.

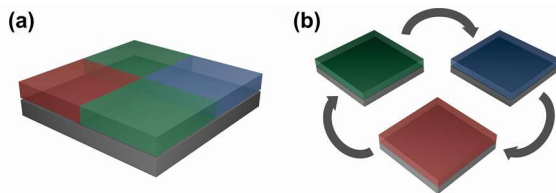


Figure 1. Schematic diagram of color display technology. (a) traditional color display. (b) field sequential color display

Color filters are extensively used in liquid crystal displays (LCD). Absorptive color filters are utilized for both direct view active matrix LCDs and super twisted nematic passive matrix LCDs. In contrast, interference filters are employed to generate colors in both LCD and light valve projectors, with reflected light being spectrally complementary to transmitted light. However, the optical path of ordinary interference filters poses a challenge in the design of the optical engine. Polarization interference filters (PIF) are based on the interference of polarizations and have been studied for a long time[1–4]. PIFs simplify the optical path design and show weaker angular dependence on the transmission spectrum compared to traditional interference filters. This results in a larger numerical aperture and higher luminous flux[1].

The vast majority of current PIF research work uses nematic liquid crystals (NLC) which are repellent for high-speed optical photonic devices due to their slow electro-optical response. Alternatively, the most promising candidates for development of the next-generation LC-based photonic devices are ferroelectric liquid crystals (FLC) with their microseconds response time and low power consumption. Due to these characteristics, fast switchable color filters based on ferroelectric liquid crystals can be used for FSC displays and colorization of the event-based vision sensors.

In this paper, we manufactured a fast switchable color filter using ferroelectric liquid crystals. Its structure is similar to the design of PIF. According to the simulation results, we found a suitable structure consisting of five liquid crystal layers placed between two crossed polarizers.

2. Simulation

The basic structure of the filter is shown in Figure 2. It consists of several waveplates placed between two polarizers.

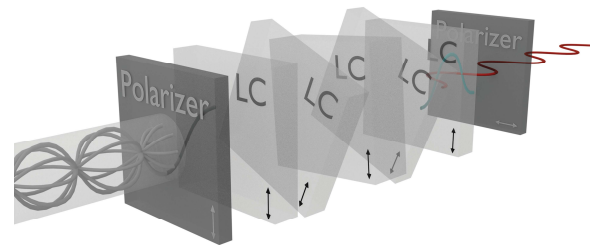


Figure 2. Schematic diagram of the design structure

It is well known that the Jones matrix can describe the exact polarization state of light for normal incidence. The retardation value of the plates is given by

$$\Gamma = \frac{2\pi\Delta n d}{\lambda} \quad (1)$$

where Γ is the retardation values, $\Delta n = n_e - n_o$ is birefringence, d is the thickness, λ is the wavelength of incident light. n_e and n_o are the extraordinary and ordinary indices, respectively. Without loss of generality, the x-axis can be defined as the direction of the input polarizer. Then the Jones vector of the input is given by

$$E_{in} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (2)$$

Here, we assume that the retardation values of all the waveplates are the same. Thus, the Jones matrix of each waveplate is given by

$$W_i = \begin{bmatrix} \cos \varphi_i & -\sin \varphi_i \\ \sin \varphi_i & \cos \varphi_i \end{bmatrix} \begin{bmatrix} e^{-i\Gamma} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \varphi_i & \sin \varphi_i \\ -\sin \varphi_i & \cos \varphi_i \end{bmatrix} \quad (3)$$

where Γ is the retardation values and φ_i is the optical axis orientation of the i-th waveplate relative to the x-axis. The polarizer is placed at the end, then the output Jones vector will be given by

$$E_{out} = \begin{bmatrix} E_u \\ E_v \end{bmatrix} = \begin{bmatrix} \cos\varphi_p & \sin\varphi_p \\ -\sin\varphi_p & \cos\varphi_p \end{bmatrix} \prod_{i=1}^N W_i \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (4)$$

where φ_p is the angle of the output polarizer relative to the original x-axis. Thus, E_u is the real output and E_v is the complementary function. E_u can be viewed as a function of wavelength.

$$E_u(\lambda) = C_0 + \sum_{k=1}^N C_k \cdot e^{-i\frac{2\pi\Delta nd_k}{\lambda}} + \sum_{\substack{1 \leq m < n \leq N \\ \dots}} C_{m,n} \cdot e^{-i\frac{2\pi\Delta n(d_m+d_n)}{\lambda}} + \dots + C_{1,2,\dots,N} \cdot e^{-i\frac{2\pi\Delta (d_1+d_2+\dots+d_N)}{\lambda}} \quad (5)$$

where the coefficients $C_0, C_k, C_{m,n}, \dots, C_{1,2,\dots,N}$ are functions of angle φ_i of the waveplates and polarizers. The transmittance spectrum of the output light is the square of E_u and can be viewed as a function of wavelength.

$$T(\lambda) = |E_u|^2 \quad (6)$$

MATLAB was used to calculate the transmittance spectrum and fit it to the target spectrum. The error function is the root mean square error (RMSE) between the fitted and target spectrum. Optimization was performed to minimize the error function using the FMINCON function (find a minimum of a constrained nonlinear multivariable function), with initial guesses and boundary constraints. FMINCON is a function included in MATLAB's Optimization Toolbox which seeks the minimizer of a scalar function of multiple variables, within a region specified by linear constraints and bounds. In the process of calculation, the program will start from the initial guess and find the optimal solution according to the gradient descent.

For a simple structure of five waveplates placed between two crossed polarizers, the retardation values and angles of the five waveplates make up the entire parameter space. To ensure that the existing materials can achieve the designed results, we fixed the birefringence to 0.17 and controlled the thickness range to discrete values between 1000 and 5000 nm with an interval of 250 nm, which is determined by the size of the existing spacer material.

To minimize the change of LC angles when the filter switches between different color filter modes, we consider fixing the angle of some LC layers. The final simulation results are shown in Table 1 and the spectrum calculated from the results is shown in Figure 3. The angles of LC 3 and LC 4 are fixed and switching between any two modes only requires changing two angles. For example, switching between red and green modes only requires changing the angle of LC 2 and LC 5.

Table 1. Structure of fast switchable color filters

Layer	d	Δn	φ_{Red}	φ_{Green}	φ_{Blue}
Polarizer	/	/	0°	0°	0°
LC 1	1250nm	0.17	0°	0°	-40°
LC 2	2500nm	0.17	23°	-65°	-65°
LC 3	5000nm	0.17	-5°	-5°	-5°
LC 4	2500nm	0.17	23°	23°	23°
LC 5	2500nm	0.17	0°	35°	0°
Polarizer	/	/	90°	90°	90°

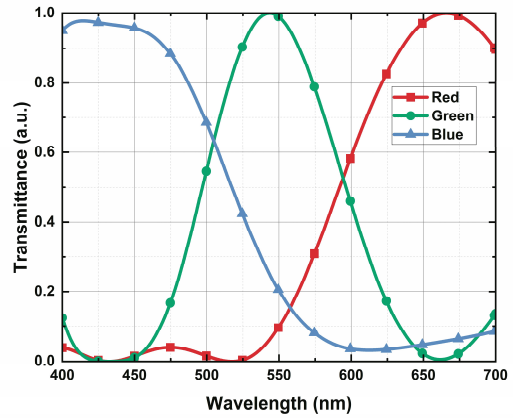


Figure 3. Spectrum of simulated results

We analyzed the effect of the thickness and angle of LC 2 on the spectrum. The calculated spectral results of each solution of the entire parameter space were compared with the target spectrum. RMSE is used to represent the error between the solution and the target and the results are shown in Figure 4. The result in Table 1 is the optimal solution that minimizes the RMSE in the entire parameter space.

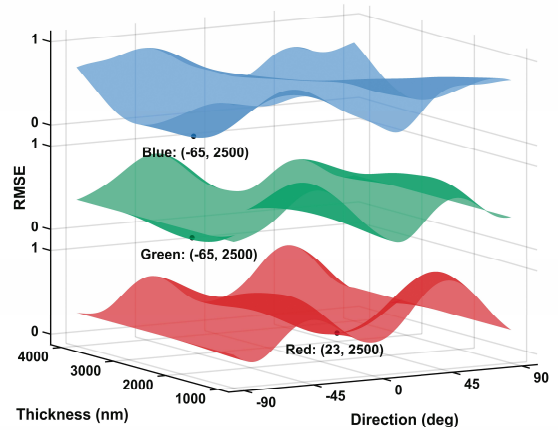


Figure 4. Effect of LC 2 on spectrum

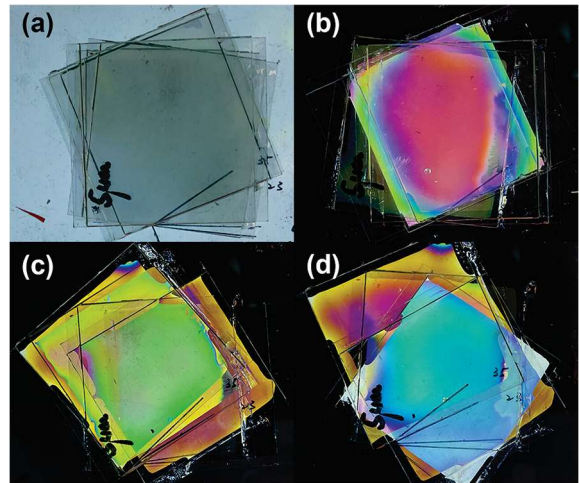


Figure 5. Prototype of fast switchable color filter. (a) w/o polarizer, (b) red filter, (c) green filter, (d) blue filter

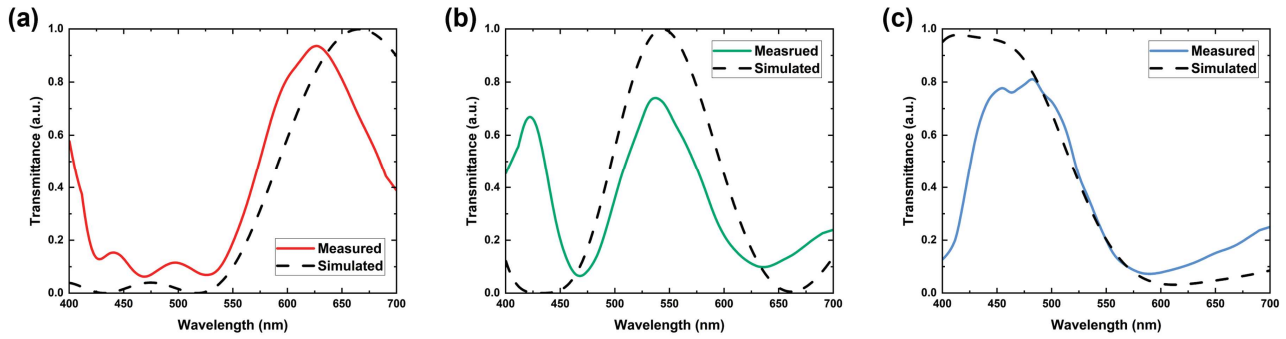


Figure 6. Comparison of measured and simulated spectrum. (a) red filter. (b) green filter. (c) blue filter.

3. Experiment

We prepared the samples according to the design results of the simulation. The LC layers are stacked at specific angles of simulated results, and crossed polarizers are placed in front and back. We prepared the red, green, and blue filters, and the prototype image is shown in Figure 5.

Each LC layer is a LC box consisting of two glass substrates. The glass substrates are deposited with patterned ITO film on the inner surface. Polyimide (PI) is spin-coated on ITO and then the softbake and hardbake process are performed on the glass substrates. To determine the direction of the LC layer, the glass substrates are mechanically rubbed at same direction. Spray the spacers on the inner surface of a glass substrate and cover another one on the top. In this process, it is necessary to ensure that the inner surfaces are all facing inward, that the ITO electrodes are exposed to the outside for the power supply, and that the spaced gaps are uniform. The

thickness of LC layer is determined by the size of spacers. Then fix them together with UV-curing glue and UV light, and fill the empty LC box with LC material.

To observe the properties of the filter, the transmission spectrum is measured under the microscope. The measured and simulated spectra are shown in Figure 6. The filters work very well for the visible spectrum. The part below 450 nm of the spectrum differs from the simulation results due to the dispersion of the liquid crystal material, whose birefringence is higher than 0.17.

We prepared the filters with the same parameters using NLC and FLC with the same birefringence and tested their response times, as shown in Figure 7. The response time of FLC is much lower than that of NLC. NLC has a response time of approximately 30 ms, whereas the response time of the FLC ranges from 14 to 64 μ s, depending on the peak voltage of the drive signal.

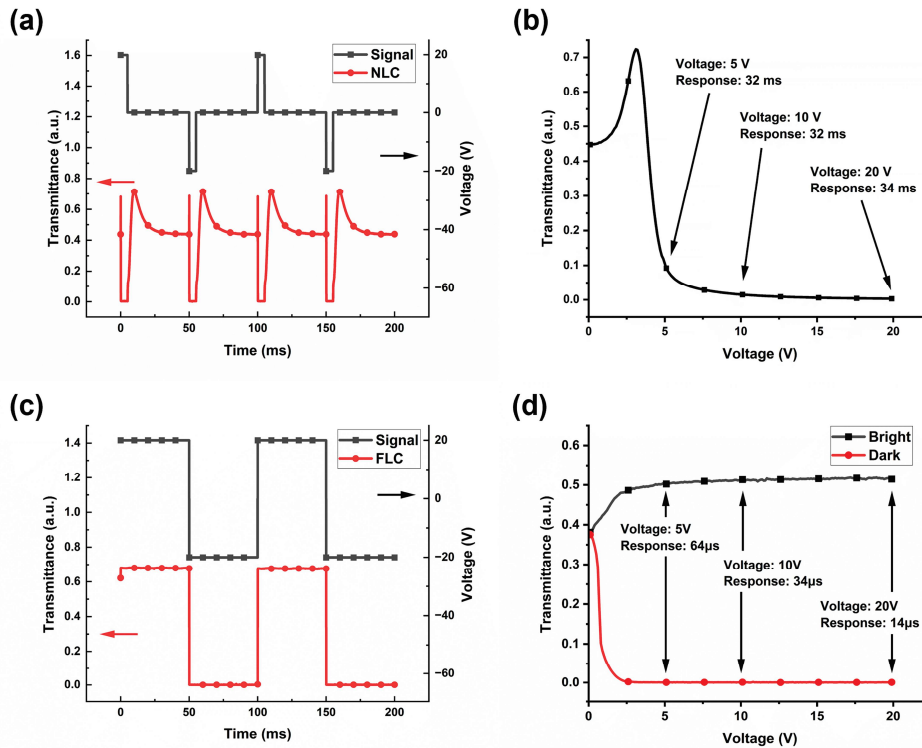


Figure 7. Waveform and response time of nematic liquid crystal and ferromagnetic liquid crystal. (a) signal waveform and response waveform of NLC. (b) transmittance and response time of NLC under different voltages. (c) signal waveform and response waveform of FLC. (d) transmittance and response time of FLC under different voltages.

4. Conclusion

In a word, the fast switchable color filters based on ferroelectric liquid crystals show good spectra and have microsecond response time. It can be used for FSC displays and colorization of the event-based vision sensors. The simulation process mentioned in the paper can be repeated for any other similar structure. In the future, we may continue to use the filters to manufacture FSC display devices or make color event-based vision sensors.

5. Acknowledgment

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6. References

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