Transmissive Interferometric Display With Single-Layer Fabry–Pérot Filter

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***Abstract*—We present a transmissive-type interferometric display featuring a single layer of Fabry-Pérot (FP) filter using blue phase liquid crystal (BPLC) in tandem with a quantum-dot backlight. With this design, no polarizers and color filters are needed. The intensity modulation is implemented by electrically controlling BPLC's *Kerr* effect, while the color modulation employs a sequential color scheme. Based on numerical simulations, device performance has been studied in depth.**

***Index Terms*—Blue phase liquid crystal (BPLC), Fabry–Pérot (FP) filter, interferometric display, quantum dot (QD).**

I. Introduction

TODAY, the display industry has to accept a paradox—a panel with better performance and lower power consumption. This is because for a very long time, people made too many efforts to boost the specifications, but at the expense of natural resources. For a sustainable development in the long run, green displays are of great importance. In terms of energy efficiency, the current dominant display technology—liquid crystal displays (LCDs)—falls far short of being classified as a green display, as its light utilization is typically around 5% [1], mainly suffering from polarizers and color filters. To avoid polarizers and color filters, a number of approaches have been proposed. Polymer dispersed liquid crystal (PDLC) [2] is able to modulate the light intensity by manipulating the level of scattering. Usually, this kind of display comes without color filters and its contrast ratio (CR) is very poor. Cholesteric LCD [3] is based on the Bragg reflection, by which, light of certain wavelengths could be reflected, depending on the pitch. In order to produce full colors, three layers with different pitches have to be stacked together. After doing so, both the thickness and cost are tripled. Besides, any misalignment during stacking would cause serious parallax errors. Electrophoretic display [4] uses the concept of electrophoresis and it is now a commercialized technology, e.g. E-Ink. But the switching of this display is rather slow—on the order of hundreds of milliseconds—making it unsuitable for video applications. Interferometric modulation (IMOD) display [5]–[9] is sometimes synonymous with a trademark of Qualcomm, called “Mirasol”. Technically, this microelectromechanical systems (MEMS)-based technology has many edges over the former technologies, such as high CR, simple structure, super fast response etc [10]. However, it is still held back from being widely adopted. Among others, the color washout [11]—changes in color when the screen is viewed from an angle—is one of the issues that need to be overcome. In addition, due to the binary switching of MEMS, the methods of generating gray scale for such devices are known as spatial/temporal dithering, either deteriorating the resolution or the refresh rate.

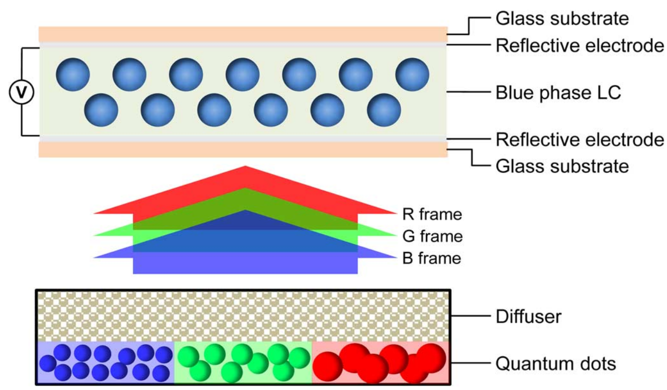

Fig. 1. Proposed structure of single-layer transmissive interferometric display.

Motivated by the above issues, we propose a transmissive-type interferometric display featuring a single layer of Fabry–Pérot (FP) filter using blue phase liquid crystal (BPLC) in tandem with a quantum-dot (QD) backlight, which is free of color washout and easy in generating the gray scale. By electrically controlling BPLC's *Kerr* effect and employing sequential color scheme, both intensity and color can be tuned, respectively.

II. Operational Principle

A. Proposed Structure

Fig. 1 is a schematic drawing of the cross section of the proposed structure, where a layer of BPLC is sandwiched in between two reflective, conductive electrodes to form an FP filter. The molecular self-assembly of BPLC could save the alignment layers required by other types of liquid crystals (LCs) [12]. The top electrode is grounded, whereas the bottom electrode is driven by thin-film transistors (TFTs). Underneath the FP filter, a QD backlight is laminated to emit the unpolarized red (R),

Manuscript received March 12, 2015; revised April 26, 2015; accepted May 08, 2015. Date of publication May 18, 2015; date of current version August 11, 2015. This work was supported in part by 973 Program under Grant 2013CB328804, the National Natural Science Foundation of China under Grant 61307028, and the Science and Technology Commission of Shanghai Municipality under Grant 13ZR1420000. *(Corresponding author: Lei Qian)*.

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Digital Object Identifier 10.1109/JDT.2015.2432111

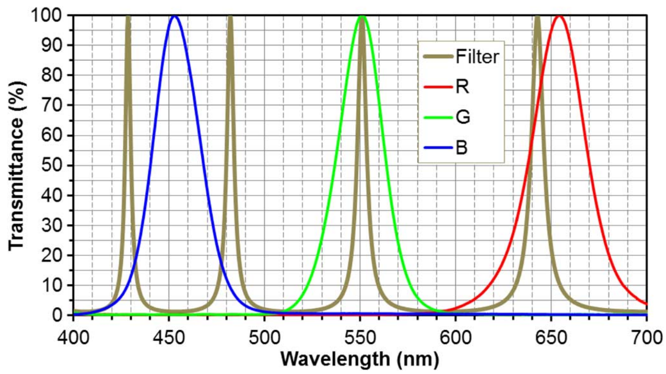


Fig. 2. Spectra of QD backlight and FP filter when $n_{LC} = 1.607$.

green (G), and blue (B) colors in sequence. With the R/G/B QDs provided by *Nanophotonica*, their spectra are measured respectively, as shown in Fig. 2.

B. Blue Phase Liquid Crystal

In the voltage-off state, BPLC is optically isotropic and its refractive index can be given by [13]

$$n_{\text{iso}} = \sqrt{\frac{(2n_o^2 + n_e^2)}{3}} \tag{1}$$

where n_o and n_e are the ordinary and extraordinary refractive indices of the LC composite, respectively. If exposed to an external electric field E, n_o and n_e will be subject to the following changes [13]:

$$n_o(E) = n_{\text{iso}} - \Delta n(E)/3 \tag{2}$$

$$n_e(E) = n_{\text{iso}} + 2\Delta n(E)/3 \tag{3}$$

$$\Delta n(E) = \Delta n_{\text{sat}} \left(1 - \exp\left[-\left(\frac{E}{E_s}\right)^2\right]\right) \tag{4}$$

where $\Delta n(E)$ stands for the induced birefringence by the external field, Δn_{sat} is the saturated induced birefringence, and E_s is the saturation field. For a wavelength λ, *Kerr* constant K can be obtained from [13]

$$K = \frac{3\Delta n_{\text{sat}}}{\lambda E_s^2}. \tag{5}$$

Since the BPLC lattices are stretched along the vertical electric field, for the case of normal incidence, both s-wave and p-wave encounter the same refractive index $n_o(E)$. In other words, this device is independent of the polarization. For oblique incidence, s-wave continues to encounter $n_o(E)$, while p-wave encounters the effective refractive index n_{eff}, which can be written as [14]

$$n_{eff} = \frac{n_o n_e}{\sqrt{n_o^2 \sin^2\theta + n_e^2 \cos^2\theta}}. \tag{6}$$

C. Intensity Modulation

The intensity modulation is implemented by controlling the overlapped area between FP filter's spectrum and QD's spectra. As QD's spectra are settled, the modulation is simply to tune the filter's spectrum. According to *Airy* function [15], transmittance of a single FP filter with a BPLC interlayer can be written as

TABLE I
SIMULATION PARAMETERS

Object	Parameter	Value
Electrode	R	80%
	A	2%
BPLC	d	1200 nm
	n_o	1.490
	n_e	1.818
	n_{iso}	1.607
	Δn	0.328
	Δn_{sat}	0.290
	E_s	7 V/μm
	K	32.23 nm/V^2

$$T = \left(1 - \frac{A}{1-R}\right)^2 \frac{1}{1 + F\sin^2\left(\frac{\delta}{2}\right)} \tag{7}$$

where

$$F = \frac{4R}{(1-R)^2} \tag{8}$$

and

$$\delta = \left(\frac{2\pi}{\lambda}\right) 2n_{LC} d \cos\theta. \tag{9}$$

Herein R and A are the reflectance and absorbance of the reflective electrodes, reflectively. F is defined as fineness, which determines the transmission bandwidth of an FP filter. δ denotes the phase difference between two successive reflections. n_{LC} and d are the refractive index and cellgap of the BPLC interlayer, respectively, and θ is the angle of refraction. By applying a voltage to the BPLC interlayer, the refractive index n_{LC} of the BPLC can be varied, so as to change the phase differenceδ and the filter's spectrum. The maximum transmittance occurs when one of the peak wavelengths of the filter coincide with the central wavelength of QD's spectra. Moreover, the tunable range of transmittance hinges on one third of the maximum induced birefringence of BPLC, as seen in (2).

D. Color Modulation

Since the BPLC is best known for its submillisecond response [16], our device is eligible for a field sequential color (FSC) scheme [17], [18], in which each color of QD backlight is turned on in sequence. For this reason, color washout faced by the conventional IMOD displays is no longer an issue for this device, as the color of QD backlight is so saturated, normally with a full-width at half-maximum (FWHM) between 20–40 nm [19]. Instead, the other problem known as color breakup [17] arises for this type of display. Preferably, with a so-called stencil-FSC method [17], this problem can be dramatically suppressed. Furthermore, another obvious benefit of using FSC scheme for color modulation is the tripled resolution.

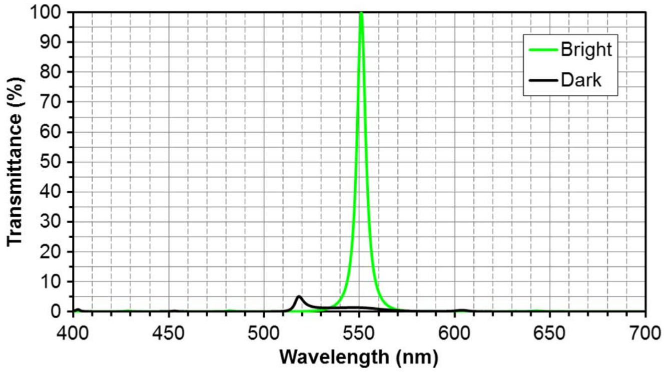


Fig. 3. Spectra of light emerging from the device for both bright and dark states (reference wavelength = 550.93 nm).

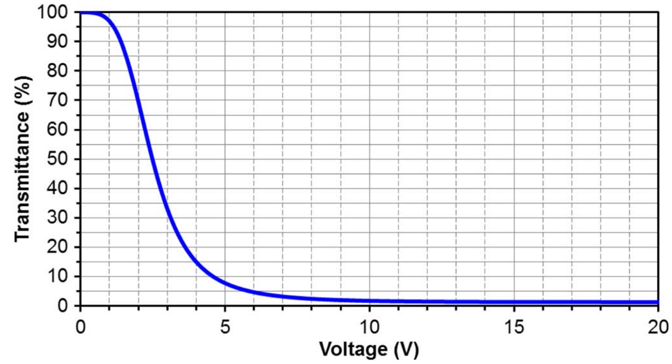


Fig. 5. Voltage-transmittance (V–T) curve (reference wavelength = 550.93 nm).

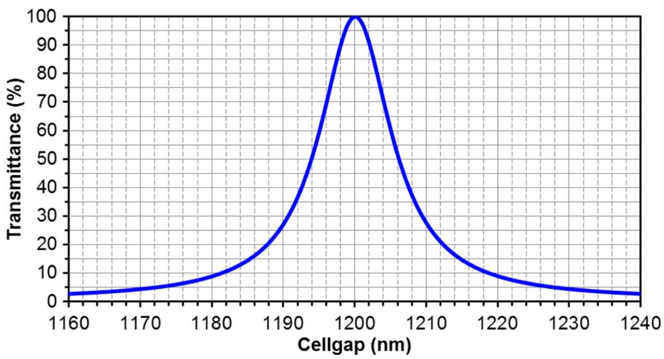


Fig. 4. Variation of transmittance against cellgap (reference wavelength = 550.93 nm).

III. Results and Discussion

A. Simulation Parameters

Due to the unavailability of electrodes and BPLC with parameters required below, device performance is studied based on the simulations. All parameters used for simulations are listed in Table I. We shall mention that these values are optimized for central wavelength of G, i.e., 550.93 nm, which is selected as the wavelength of interest hereafter.

B. Transmittance

As can be seen from (7), the efficiency of our device is largely decided by the R and A of the electrode. When $R = 80\%$ and $A = 2\%$, the maximum transmittance is 81%. In practice, those values are very difficult to achieve with opaque, metallic electrodes [20], but possible with a stacking of multiple layers of dielectric materials [21] and transparent, non-metallic electrodes. Fig. 2 plots the spectrum of FP filter along with QD's spectra in the visible regime, when BPLC's refractive index equals to 1.607. In this case, there are four peak wavelengths of filter, one of which matches with the central wavelength ($\lambda =$ 550.93 nm) of the green color of QD backlight. Thus, this case is referred to as bright state. On the contrary, dark state is obtained when BPLC's refractive index is decreased to 1.510, depending on the saturated induced birefringence. The spectra of light emerging from the device for both bright and dark states are given in Fig. 3, where it can be seen that FWHM of light of bright state is only about 6 nm, accounting for 22% of FWHM of green QD. This indicates that color gamut of this device should be very broad, but at the cost of light utilization, which as a total of the device is about 18%. The compromise could be done by lowering the reflectance of electrode to widen the filter's bandwidth, but color gamut as well as CR will inevitably go down. This is because too wide filter's bandwidthis unable to block off all wavelengths within the tunable range of BPLC, as depicted by the black line (dark state) of Fig. 3. Hence, as a rule of design, the bottom line is to have BPLC with larger *Kerr* constant and QDs with narrower FWHM.

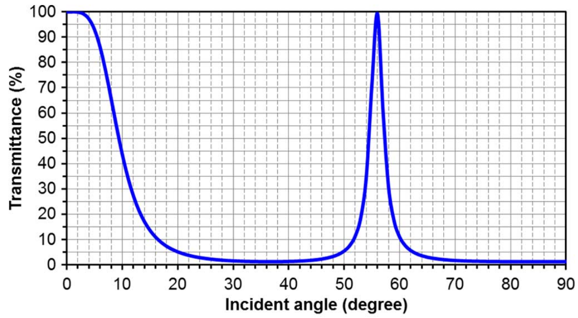
From the perspective of manufacturing, the variation of transmittance against cellgap is shown in Fig. 4, where it is noticed that this device is rather sensitive to the cellgap in that a ±6-nm deviation from the center will translate into a drop in the transmittance by 50%.

C. Contrast Ratio (CR)

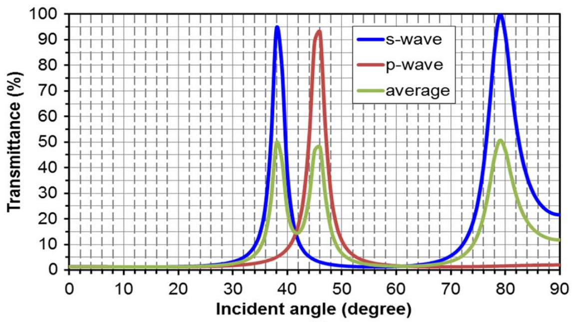
Following from the extended *Kerr* model [13], voltage-transmittance (V–T) curve can be calculated, as shown in Fig. 5. The dark state is achieved when voltage $V = 19.8$ V, corresponding to $n_{LC} = 1.510$. Besides, CR—the ratio of maximum transmittance to minimum transmittance—is 76:1 at this point. If the specification for CR would be relaxed to 10:1, then driving voltage could be only 4.6 V. If central wavelengths of R/G/B QDs would be aligned with different filter's peaks, respectively, and spectra profile of them would be finely adjusted, it could be very interesting and possible to drive R/G/B pixels with the identical V–T curve, remarkably simplifying the driving circuit.

D. Viewing Angle

As predicted by (6), (7) and (9), the transmittance is strongly dependent on the incident angle, as shown in Fig. 6, where a 10-degree deviation from the normal will translate into a drop in the transmittance by 56%. The region of transmittance above 10% covers two segments: (1) 0°–16° and (2) 52°–60°. Apparently, if taking into account all wavelengths of the bandwidth of green QD, the viewing angle shall be much wider. Similar to transmittance, CR is strongly dependent on the incident angle as well, as shown in Figs. 7 and 8, where a 10-degree deviation from the normal will translate into a drop in the CR by 54%. The region of CR above 10:1 covers two segments: (1) 0°–15° and (2) 54°–59°. Most importantly, despite that the peak wavelength differs all the time, the overall color remains the same due to the sequential color scheme as discussed above. This would



(a)



(b)

Fig. 6. Variation of transmittance against incident angle at (a) bright state and (b) dark state (reference wavelength = 550.93 nm).

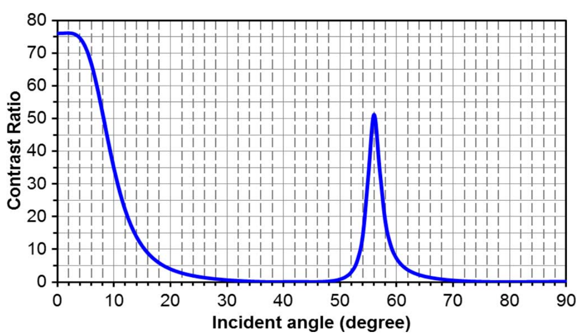


Fig. 7. Variation of CR against incident angle (reference wavelength = 550.93 nm).

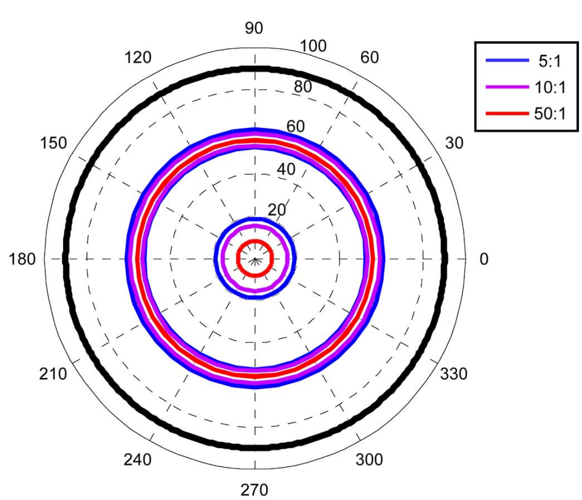


Fig. 8. Iso-CR contour (bright/dark = 0 V/19.8 V).

be a big advantage over other interferometric displays [8], [9], which are vulnerable to color shifts.

IV. Summary

In conclusion, we have demonstrated a transmissive interferometric display with a simple structure featuring a single-layer FP filter using BPLC and a QD backlight. Its operational principlesare elaborated, followed by simulation results. The intensity modulation is realized by manipulating BPLC's *Kerr* effect, whereas color modulation employs the sequential color scheme. Compared other interferometric displays, our LC-based solution is free of color washout, easy in generating gray scale, and higher in resolution. The main challenges identified include strict cellgap tolerance, electrode reflection, and sensitivity to the viewing angle. Hopefully, this type of display would become a potential candidate for the green display applications.

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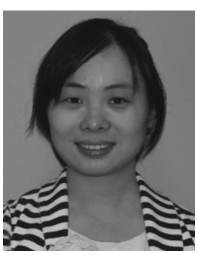

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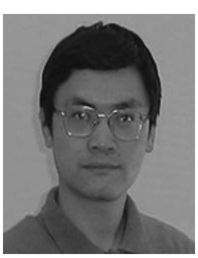

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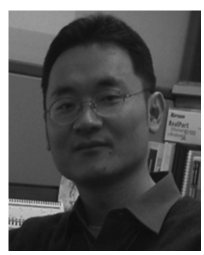

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