Optical Simulation of Multicolor Cholesteric Liquid Crystal Displays Using Finite-Difference Time- Domain (FDTD) Method

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Abstract

The Finite-difference time-domain (FDTD) method is used to directly solve Maxwell's equations, and the techniques required for optical simulation of Bragg reflections of cholesteric liquid crystal (ChLC) displays are introduced in this paper. The simulated results show that the color gamut of a ChLC display can be broadened by using of a circular polarizer on top surface of the ChLC film, and are examined by experiments.

1. Introduction

The cholesteric liquid crystal (ChLC) is chosen as one of the candidates for reflective display material, because of its bistability, alignment layer free, and high reflectivity properties. Several types of flexible display devices using ChLC have been reported recently[1-3].

To produce multi-color ChLCDs, we try to deal with two approaches in the present – to design a multi-color display structure with easier and faster manufacturing processes, and to improve the display performances.

Two methods can be adopted to manufacture a multi-color ChLC display. One is an array type design which pixelize the ChLC materials reflect the three primary colors in display area[4-7]. Another is a stacked multi-layer structure[8,9] that set these three ChLC display layers with different pitch lengths to stack on top of each other. The former display structure can only be one-third as bright as stacked multi-layer cells, but simpler construction, and fewer electronic interconnects are its advantages.

The real ChLC displays may consist of many layers: substrates, ITO electrodes, and ChLC. The reflection of a ChLCD in the planar texture is affected significantly by the reflections from the interfaces between these layers, as well as the interference between these reflections[10]. To improve the display performances, cell structures can be designed to decrease the light reflected from the interfaces[11].

In this work, the finite-difference time domain (FDTD) method[12] which can be used to accommodate multidimensional inhomogeneity of the dielectric tensor, are adopted to solve the Maxwell's equations directly. A broadband pulse wave source and total field-scattered field (TF-SF) formulations are used. The computational space terminations are provided by a combination of the perfectly matched layer (PML) and periodic boundary conditions (PBC). Cell structure with circular polarizer design is investigated numerically to broaden the color gamut of the Bragg reflection of the ChLC displays, and is examined by experiments.

2. FDTD method description

The FDTD method is an efficient technique to solve the Maxwell curl equations numerically. Yee grid[13] is the most used FDTD formulations. The general layout of our computational space used in the FDTD method is shown in Fig. 1.

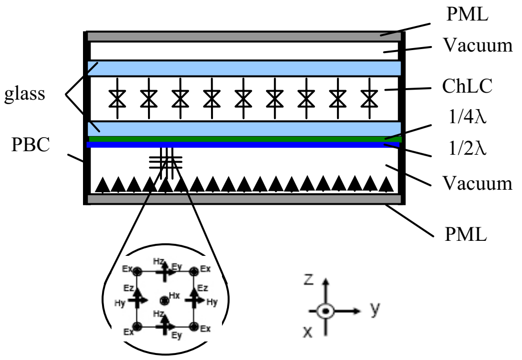


Figure 1. General layout of the computational space used in the FDTD method. An indicative Yee cell used to fill the computational space is also shown.

The discretization of the equations to yield the electric and magnetic field time derivatives in the Maxwell's equations are shown in Eq. (1) and (2) with the help of central difference eqiations[12].

$$E^n = \frac{1-(\sigma\Delta t)/(2\varepsilon)}{1+(\sigma\Delta t)/(2\varepsilon)}E^{n-1} + \frac{\Delta t/\varepsilon}{1+(\sigma\Delta t)/(2\varepsilon)}\nabla\times H^{n-1/2}, \quad (1)$$

$$H^{n+1/2} = H^{n-1/2} - \frac{\Delta t}{\mu}\nabla\times E^n, \quad (2)$$

where n stands for the time points. Note that the electric fields are updated at the "integer" time points and the magnetic fields at the "half" time points.

After the local material parameters are set and the dielectric tensor relative to the director distribution of liquid crystal at every grid point is defined, one can obtain the light propagation sequences in the corresponding liquid crystal devices. Note that, in the article we assumed that all the materials are non-conductive and non-magnetic media.

A broadband pulse $p(t)$ shown in eq. (3) is applied as the wave source in the FDTD program,

$$p(t) = \alpha^2 \cdot \exp[-\alpha(t-t_o)^2] \cdot \sin[\omega_c(t-t_0)] \quad (3)$$

where $\alpha = 3.7351\times10^{29}$, $t_0 = 3.2725\times10^{-15}$, and $\omega_c = 3.456\times10^{15}$. The total field-scattered field (TF-SF) formulation is used to introduce the broadband pulse plane into the computational domain. This formulation can prevent any nonphysical reflection toward the material of interest from the position of wave source, and offer the scattered field directly.

The function of perfect matched layer (PML) is to prevent outgoing waves from reflecting back to the main computational space. It is an artificial medium having fictitious exponential conductivities that vary from the normal to the tangential electric components. Any wave leaving the main domain will enter a PML and be absorbed exponentially without any reflection. On the other hand, we considered only normal incidence of illumination in this work, the field patterns from period to period will replicate by themselves. Then, implementing the FDTD method under PBC is quite straightforward.

To obtain the far-field amplitude or intensity distribution, one can collect the near-field results and transform them. Note that the thickness of the glass substrates are assumed to be 30 μm, and the ChLC layer is single-domain planar texture with 12 pitches thick. The circular polarizer consists of a polarizer parallel to the rubbing direction of the ChLC cell (represented by a linear polarized wave source), a half wave plate has +17.5° to the rubbing direction, and a quarter wave plate has +80° to the rubbing direction.

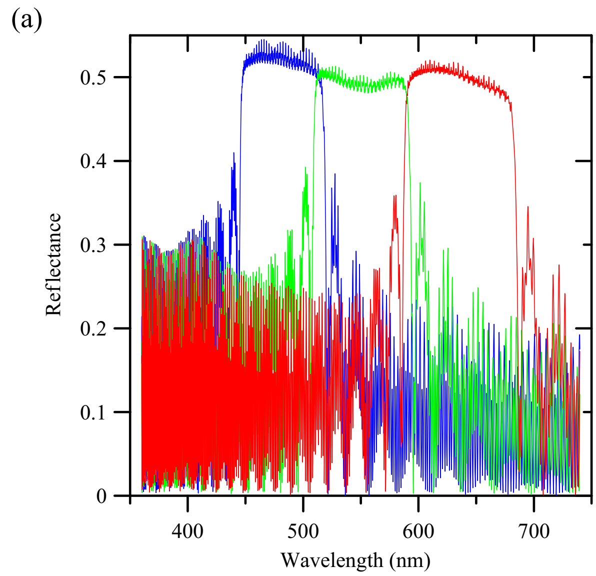
3. Experiment

The ChLC is a chiral-nematic mixture of BL001 (Merck) and chiral [mixture of CB15 (Merck) and ZLI4572 (Merck)]. The compositions reflect red (strongly reflect light with wave length of 640 nm), green (550 nm), and blue (480 nm) light comprised of 31.08w%, 31.9w%, and 32.75w% chiral, respectively.

The homogeneous alignment material SE7492 (NISSAN) is coated on the surface of top substrate and rubbed. The cell gap is controlled to 5 μm by using of photo spacer. The LC material is then vacuum filled. The construction of circular polarizer (NITTO DENKO) is described in the previous section. The reflection spectra for the ChLC cells are measured by OTSUKA LCD5100. Both the illumination and viewing angles are set to 30° from the normal. The reference is a mirror.

4. Results and discussion

In Fig. 2, the numerical results for the reflection spectra of the ChLC displays in three major peaks are shown. Figure 2(a) depicts the reflection spectra for ChLCDs without the circular polarizers on top surfaces of the displays, and fig. 2(b) depicts those for displays with circular polarizer. The results show that, before attaching the circular polarizer on top surface of the ChLCDs, the peak reflections are shown in wavelength 480, 550, and 640 nm with the values about 50%. The tremendous brightness results from the assumption of single domain planar texture in mathematical scheme. The reflections with undesired wavelength show great intensities in fig. 2 with the reflectance about 20~30%. This might come from the interference between the light reflected from the liquid crystal and the light reflected from the interfaces between the vacuum, the glass substrate and the liquid crystal[14]. Also, it might be the reason for the excessive peak reflectance (>50%) of the spectra, and the poor color gamut of a ChLCD.



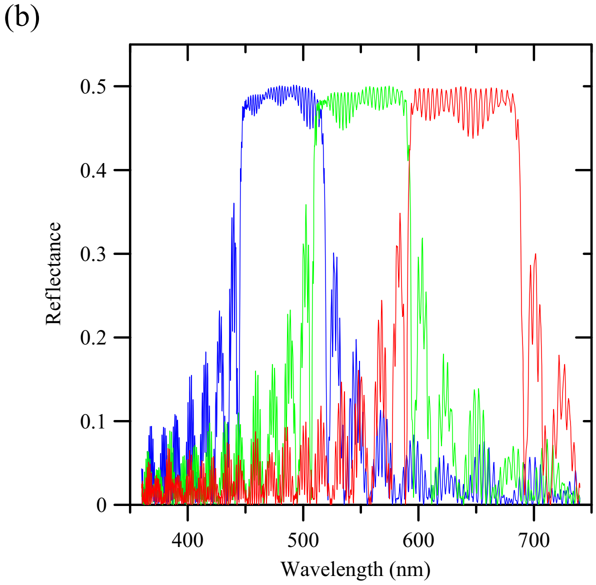


Figure 2. The calculated results for reflection spectra of the ChLCD (a) before and (b) after the circular polarizer is applied.

After attaching a particular handedness circular polarizer on top surface of the ChLCD, this optical film cooperates with the ChLC to decrease the light reflected from the interfaces between vacuum, glass, and ChLC. As a result, the reflection in undesired wave length range is decreased, and the excessive peak reflection is eliminated. Because the reflection from the liquid crystal and the reflection from the interfaces have different handedness circular polarizations. The light reflected from the interfaces cannot go through the circular polarizer on top surface of the displays.

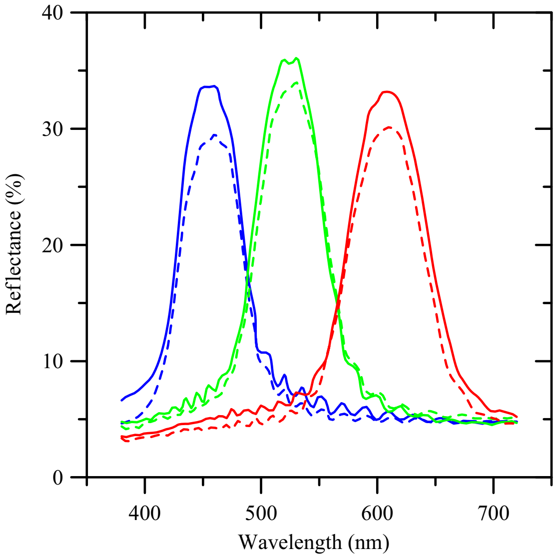


Figure 3. The measurement results for reflection spectra of the ChLCD before (solid lines) and after (dashed lines) the circular polarizer is applied.

In Fig. 3, the measurement results for the reflection spectra of the ChLC cells in three major peaks are shown. Solid lines represent the reflection spectra for ChLC cells without the circular polarizer on top surface of the glass substrate, and dashed lines represent those for a display with circular polarizer. The results show that, before attaching the circular polarizer, the peak reflections appear in wavelength 450, 530, and 620 nm with the values greater than 30%. The shift of peak reflections may result from the measurement geometry mentioned in the previous section. The values of peak reflections are smaller than calculated results for real samples show multi domain planar texture. The reflections of reflect lights with the undesired wavelength in fig. 3 are only about 3~7%. After attaching a particular handedness circular polarizer on top surface of the ChLC cells, the reflections are slightly decreased, but we do not observe a great effect to eliminate the undesired reflections.

Figure 4 demonstrates the results of the color representations for ChLC displays obtained from FDTD method and sample measurement. The thick solid lines represent the calculated color gamut for ChLCDs, and the thick dashed lines represent those for ChLCDs with circular polarizer. The thin solid lines represent the color gamut for ChLC cells, and the thin dashed lines represent those for a ChLC cells with circular polarizer. Simulated results show that with the help of the optical film, the color saturation, as well as the color gamut are improved tremendously. However, the color saturation and color gamut reveal a few differences from the experiment results. The performances of real samples lie in between two simulated cases.

5. Summary

In the work, we use the Finite-difference time-domain (FDTD) method to solve Maxwell's equations directly, and the techniques required for optical simulation of Bragg reflections of cholesteric liquid crystal (ChLC) displays are introduced. The calculated results show that the color gamut of a ChLCD can be broadened by using of circular polarizers attached on top surfaces the ChLC cells. But the experiment results show limited difference when the circular polarizer is applied.

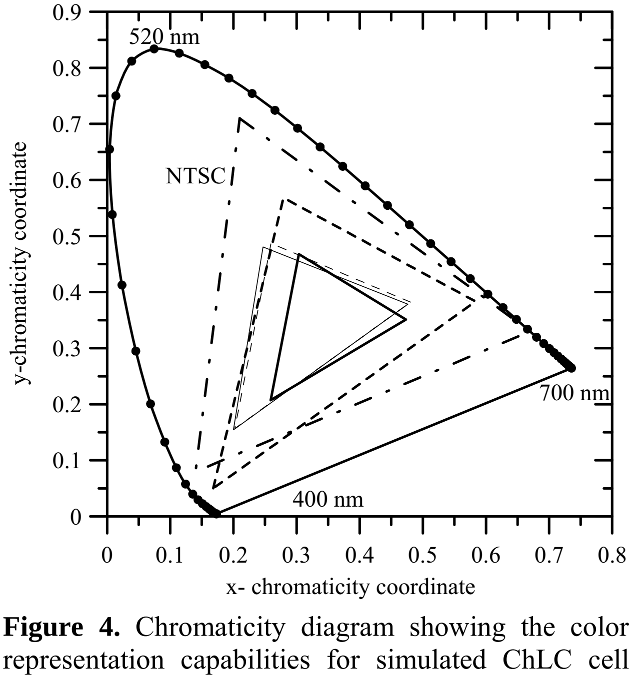


Figure 4. Chromaticity diagram showing the color representation capabilities for simulated ChLC cell (thick solid and dashed lines) and real ChLC cells (thin solid and dashed lines)

The inconsistencies between the numerical results and experimental results reveal that the numerical scheme used in this study should be modified. The color performance of the ChLCD needs to be further studied theoretically and experimentally.

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