# Bright color optical switching device by polymer network liquid crystal with a specular reflector

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**Abstract:** The color optical switching device by polymer network liquid crystal (PNLC) with color filter on a specular reflector shows excellent performance; white reflectance of 22%, color gamut of 32%, and contrast ratio up to 50:1 in reflective mode measurement. The view-angle dependence of the reflectance can be adjusted by changing the PNLC thickness. The color chromaticity shown by the device is close to the limit value of color filters, and its value nearly remains with respect to the operating voltage. These optical properties of the device can be explained from the prediction based on multiple interactions between the light and the droplets of liquid crystal. The high reflectance, vivid color image, and moderate responds time allow the PNLC device to drive good color moving image. It can widely extend the applications of the reflective device.



**OCIS codes:** (130.4815) Optical switching devices; (220.0220) Optical design and fabrication; (160.3710) Liquid crystals; (290.4210) Multiple scattering.

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## 1. Introduction

The reflective display has been attracting much attention due to the advantages of good image visibility in outdoor condition, low power consumption, and flexible feasibility. It can be applied to electronic paper, mobile device, and digital information display device. The several types of device for reflective display were recently suggested, such as electrophoresis type [1,2], electrowetting type [3–5], microelectromechanical type [6], and liquid crystal type [7–9]. Some of these types have shown color image in themselves while the others need to use color filters, which is simple method to convert from mono to color image. Unfortunately, these reflective devices have the common weakness; low color reflectance. To date, the highest value is 23%, obtained by interferometric modulation technology [6]. However, it has a view angle problem and a complicated device structure as a disadvantage. In the case of using color filters, the color purity can be good, but the reflectance becomes lower because the light passing through color filter reduces its intensity by 66% ideally. Consequently, it is hard to obtain bright color image for reflective device.

Polymer network liquid crystal (PNLC) as electro-optical material is a good candidate for reflective display. It has several advantages, comparatively fast response time to operate a movie [10,11], flexible feasibility [8], and many intermediate states between the opaque and the transparent state. But, as a mono device, a general PNLC device with absorption layer has the reflectance below 25% [12], and dye-doped PNLC has the reflectance below 40% although it is possible to have higher reflectance at near normal view angle [13,14]. When the color filter is used, the reflectance does not exceed 15% in both structures. Moreover, general PNLC device uses the backward scattering of PNLC so that the PNLC layer should be located between the upper color filter layer and the bottom absorption layer. Due to this structural design limit, the ultraviolet (UV) light needed to polymerize the PNLC is exposed to the cell structure at the side of the color filter layer. The absorption of UV light by color filter induces a poor polymerization of PNLC film, which causes poor optical characteristics and reliability. To improve the performance, it needs new structure without UV curing problem. In this report, we demonstrate the color optical switching device by PNLC with color filter on a specular reflector. This device shows high reflectance and vivid color image, and it also has an advantage of the simple manufacturing process.

## 2. Methods

To avoid the poor polymerization, the color filter layer was located at the bottom of PNLC material. However the structural change induces the problem of color notation. Therefore, an absorption layer was substituted with a specular reflector for color shutter function. The unique structural design can solve the poor polymerization and enhance the optical properties drastically. Figure 1 shows the operation principle of the device. The incident light is scattered by PNLC material. The light passed through color filter is reflected by specular reflector and is scattered by PNLC again. The scattered color light can reach a viewer, so that it shows color image. When the PNLC changes to the transparent state, the light passes

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through the PNLC without any scattering, and is reflected by the reflector with the specular angle. If the view point does not coincide with the specular angle, the viewer feels as black state. Because the loss of light is not mainly due to the light shutter modulation, but the color absorption, it is possible to realize bright color image compared to other types of reflective mode light shutter. For color image, the incident light needs to pass through the color filter. But some scattered light backward by PNLC material do not pass through the color filter, so that it can cause poor color purity. The degree of backward scattering and its effect on color purity were investigated. The PNLC used in our experiment was made by applying UV-polymerization induced phase separation method and using a mixture of nematic liquid crystal TL203 (Merck, $n_o$=1.529, $\Delta n$ =0.2) and a monomer PN393 (Merck, $n_p$ =1.499) at 80:20 wt% ratios. The intensity of ultraviolet light for curing the monomers is 20 mJ/cm$^2$. Indium-tin-oxide (ITO) coated glass was used as device substrate and the sputtered AlNd layer was coated to make specular reflector. The color filter layer has the thickness of 500 nm.

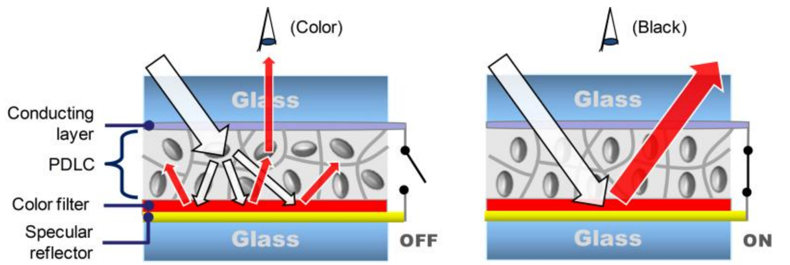


Fig. 1. Operation principle of color optical device switching by PNLC with color filter on a specular reflector.

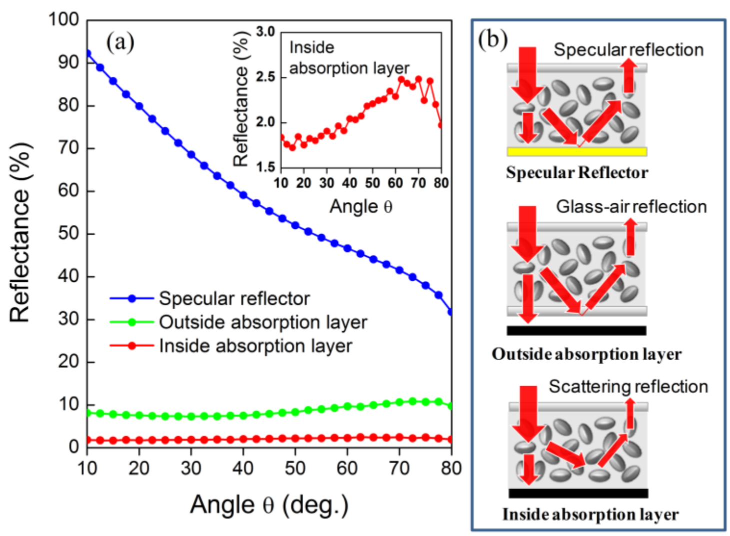


Fig. 2. (a) Measured reflectance of PNLC device with a specular reflector, an outside-absorption layer, and an inside-absorption layer. The reflectance with an inside-absorption layer was again shown in inset. (b) Schematics of light reflection in three types of cell.

To investigate the value of the backward scattering, the reflectance of PNLC with the thickness of 10 μm was measured in three types of cell structure; with a specular reflector, with an absorption layer outside cell, and with an absorption layer inside cell. The black color filter was used as an absorption layer. The operating voltage was not applied, so that PNLC can scatter the incident light in forward and backward directions. In the case of an absorption layer outside cell, the incident light is reflected by both backward scattering and a part of forward scattering due to the total internal reflection at the bottom glass-air interface, and in the case of a specular reflector is reflected by both backward and forward scattering. Figure 2(a) shows that the reflectance by the backward scattering of PNLC is less than 2.5%, and it increases to 10% including total internal reflection, and it finally increases to about 55% including specular reflection. As shown in Fig. 2(b), the reflectance with three types of cell structure is mainly influenced by specular reflection, total internal reflection at the glass-air interface, and backward-scattering reflection, respectively. When the operating voltage is applied, the PNLC becomes transparent. Because the light passing through PNLC without scattering is absorbed or reflected with a specular angle, the reflectance in all types of cell structure becomes very low, except a specular angle. Because very little light is only reflected backward by PNLC material scattering, in the suggested color shutter design, most light passes through color filter layer, even though the color filter layer is not located in the front side of cell structure. In addition, the shutter mechanism using scattering and specular reflection can have a high reflectance, which is close to the maximum value including the absorption of ITO layer and reflector. Therefore, the position of color filter on a specular reflector and PNLC working can make both high reflectance and vivid color image.

## 3. Experimental results

Two types of measurement conditions were used to investigate the optical characteristics of PNLC device with a specular reflector; specular collimated light source and integrating sphere light source. The experiment to measure view-angle dependence of reflectance was carried out in the geometry shown in Fig. 3(a). The intensity of reflected light from a sample was measured by a photodiode detector. The angle between an incident light and a sample was fixed as a normal incidence, while the detection angle is changed. The experiments to measure average reflectance were carried out in the geometry shown in Fig. 3(b). The reflected light was measured at normal angle under irradiation of the light in the integrating sphere. For this measurement, the commercial equipment (Minolta 1500d) was used. The reflectance measured in both types was normalized by a near perfect diffuser ($BaSO_4$) plate.

The reflectance characteristic of PNLC with a specular reflector was investigated by changing PNLC thickness. For white state of PNLC device, the operating voltage was applied. When the PNLC was thin, the reflectance has very high value at near normal angle, and it sharply decreases with view angle due to weak light scattering as shown in Fig. 3(c). However, in the case of the PNLCs, which have higher thickness than 20 $\mu m$, the reflectance was independent on the view angle as a paper due to sufficiently strong scattering effect. It shows that the view-angle dependence of reflectance can be selective according to the device application. Figure 3(d) shows the reflectance measured in the integrating sphere type. The reflectance has the highest value of 61% at the thickness of 5 $\mu m$, and decreases with thickness. It shows that the PNLC with thickness of 5 $\mu m$ most effectively scatters the ambient light to normal direction. The scattering effect of PNLC can also be adjusted by changing liquid crystal-polymer ratio, UV intensity [15], and temperature during polymerization [16]. The contrast ratio is the reflectance ratio of white to black state, and the reflectance of PNLC device in the black state was measured but is not shown. The operating voltage of PNLCs with various thicknesses was about 0.5 $V/\mu m$. In Fig. 3(e) and 3(f), the contrast ratio decreases with increasing thickness at all view angles. Although the PNLC is in the transparent state, the relatively weak scattering exists with respect to the view angle [17]. This weak scattering increases with PNLC thickness, so that the contrast ratio decreases. Moreover, in Fig. 3(e), the contrast ratio increases with view angle except near view angle of 10° and 80°. It is reason that the reflectance in black state more sharply decreases with view angle than that in white state. The reflectance measurements show that the mono PNLC

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device with a specular reflector can have the reflectance higher than 60% and the contrast ratio up to 50:1.

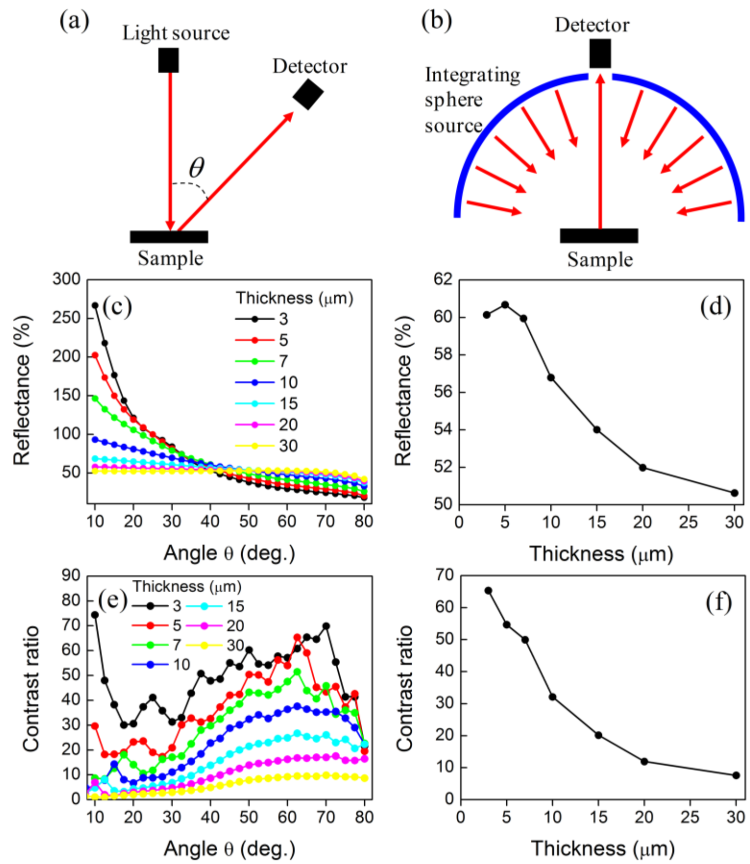


Fig. 3. Experimental setup for reflectance measurement with (a) specular collimated light source and (b) integrating sphere light source. Measured reflectance (c) in the specular geometry and (d) in the integrating sphere geometry. Measured contrast ratio (e) in the specular geometry and (f) in the integrating sphere geometry.

The PNLC devices with red, green, and blue (RGB) color filters on a specular reflector were made respectively and its color optical property was investigated. We first checked an operating voltage of the device. As shown in Fig. 4(a), normalized reflectance shows that color filter layer almost does not affect the electrical driving operation of PNLC device. As mentioned previously, the color purity of PNLC device can decrease with the increase of backward scattered light, not passed through color filter. However, although the measurement has been done using PNLC with thickness of 20 $\mu m$, the color chromaticity in CIE 1931 color space was near value of only color filter, and was not much shifted with respect to the operating voltage, as shown in Fig. 4(b). The color reproduction shown by the devices was 32%, and the device can show the consistent color image regardless of image brightness. Thus it is possible to have a good performance of color purity although the color filter layer is located at the bottom of PNLC material. At the 5 $\mu m$ thickness of PNLC showing the highest reflectance, the reflected light by devices had RGB color spectrum shown in Fig. 4(c), and the device had the reflectance of 14%, 35%, and 18%, respectively. If the device consists of RGB color filter array, the reflectance in white state can be 22.3%. In Fig. 4(d), the images of device show a vivid color and a good visibility. In this case, the color reproduction was 33%,

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which is almost same as that of color filter. The device had the responds time of 50 msec at switching voltage of 5 V.

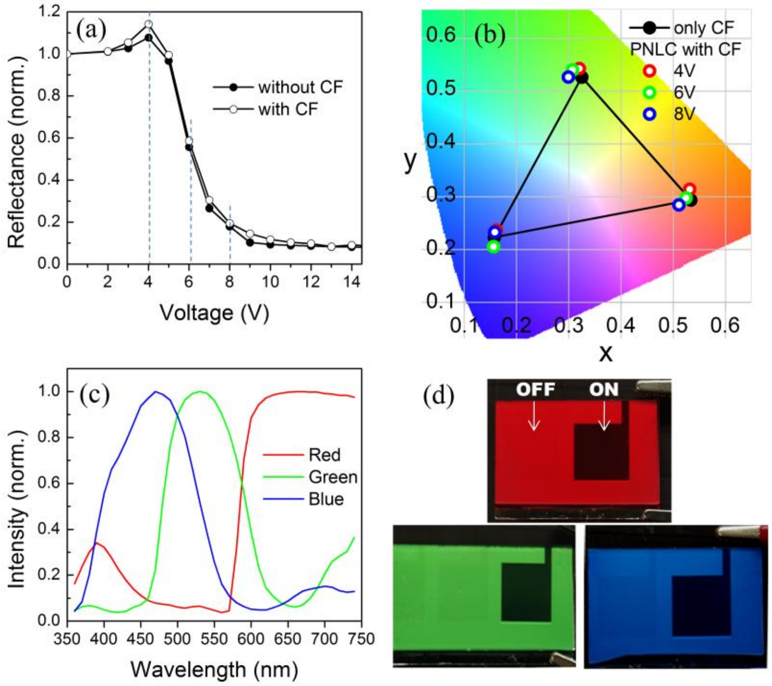


Fig. 4. (a) Comparison between the normalized reflectance of PNLC device without color filter and with color filter. (b) Color chromaticity of color PNLC device in CIE 1931 color space with respect to the voltages. (c) Spectrum of color PNLC devices. (d) Images of color PNLC device. The PNLC with 20 μm thickness was used in (a) and (b), but with 5 μm thickness in (c) and (d).

## 4. Discussion

To verify the measurement of the optical property of PNLC device, the light scattering of PNLC material was theoretically investigated. For more precise estimation, the multi-scattering of PNLC material was calculated from modifying the single scattering formulas. According to the anomalous diffraction approach [18], given by the angle between the electric field vector of incident light and the plan defined by the wave vector of incident light and the droplet direction of liquid crystal, $\alpha_o$, and the angle between wave vectors of incident light and scattered light, $\theta$, the differential scattering cross section for a single droplet can be expressed as

$$\frac{d\sigma}{d\Omega}=\frac{R^4k^2}{4}[|H(iv_e,kR\sin\theta)|^2\cos^2\alpha_o+|H(iv_o,kR\sin\theta)|^2\sin^2\alpha_o]. \qquad (1)$$

$H$ is a complex function as $H(iv,z)=2\int_0^1(1-\exp[iv(1-x^2)^{1/2}])J_0(xz)xdx$, $J_0$ is the Bessel function of zeroth order, $v_e$ is given by $v_e=2kR(\frac{n_e(\phi)}{n_p}-1)$, $n_p$ is the refractive index of polymer, effective refractive index $n_e(\phi)$ is given by $n_e(\phi)=(\frac{\cos^2\phi}{n_o^2}+\frac{\sin^2\phi}{n_e^2})^{-1/2}$, and $\phi$ is the angle between the wave vector of incident light and the droplet direction of liquid crystal. The effective differential cross section of PNLC material, $\sigma_0(\theta)$, is given by the average over the

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individual differential cross section, and is independent on the azimuthal angle because the droplets of PNLC material are randomly orientated;

$$\sigma_0(\theta) = \left\langle \frac{d\sigma}{d\Omega} \right\rangle_{\alpha_o,\phi} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} \frac{d\sigma}{d\Omega} \sin\phi d\phi d\alpha_0. \tag{2}$$

We assume that the differential cross section can be used as the angle distribution of the incident light for next scattering; for (i+1)-th scattering, the angle distribution of incident light, $p_i(\theta)$, is proportional to the effective differential cross section $\sigma_i(\theta)$ obtained by i-th scattering with correction factor $c$ as $p_i(\theta) = c\sigma_i(\theta)$. Consequently, the effective differential cross section, $\sigma_{i+1}(\theta)$, can be calculated by

$$\sigma_{i+1}(\theta) = \int \left( \sum_n \sum_m c\sigma_i(\theta_n, \varphi_m)\sigma_0(\theta', \varphi') \right) \sin\varphi d\varphi. \tag{3}$$

Given by three dimensional rotation matrix, $R(\theta_n, \varphi_m)$ [19], the angle $\theta'$ and $\varphi'$ can be obtained from the relation between wave vector $\vec{k}'(\theta', \varphi')$ and wave vector $\vec{k}(\theta, \varphi)$; $\vec{k}'(\theta', \varphi') = \vec{R}(\theta_n, \varphi_m) \cdot \vec{k}(\theta, \varphi)$. This formula is simple to perform the calculation, compared with the previous simulation reported by Kelly *et al.* [20]. To compare with the measurement, the angle in PNLC material, $\theta$, was converted to the angle in air, $\theta_{air}$, by the Snell's law, $\theta_{air} = \arcsin(n_p \sin\theta)$. For this calculation, the droplet radius of 1 μm and the light wavelength of 550 nm were used.

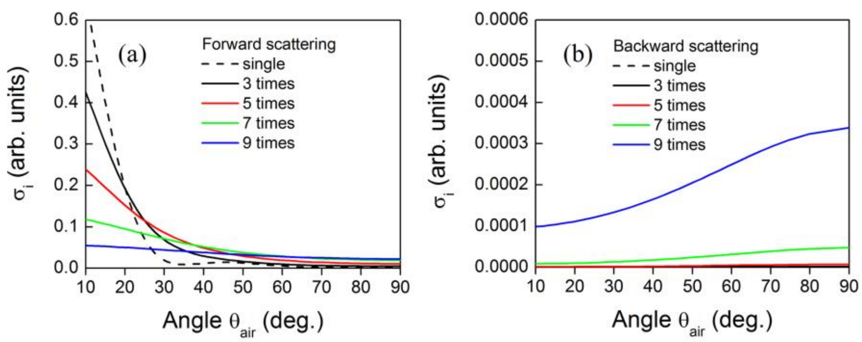


Fig. 5. Angle dependence of effective differential scattering cross section with respect to the number of scattering times (a) for forward direction and (b) for backward direction.

From the above formula, the angle dependence of scattering for forward and backward cases was calculated. The values with respect to the number of scattering times were normalized to give the same total cross section. Figure 5(a) shows the effective differential scattering cross section for forward case. The single scattering is sharply decreased with the angle, but the multi-scattering distribution becomes independent on the angle when the number of scattering times increases. The probability to happen the multi-scattering with higher number increases with the PNLC thickness. This calculation result shows the qualitative agreement with measurement shown in Fig. 3(c). Thus, it shows that the light scattering of PNLC is mainly influenced from multi-scattering rather than single scattering. For backward scattering, as shown in Fig. 5(b), the effective differential scattering cross section has very low value compared to forward scattering, and its value increases with view angle. This view angle dependence agrees with measurement shown in inset of Fig. 2(a). The weak backward scattering of PNLC material can realize vivid color appearance of the device.

The calculation of the multi-scattering supports good optical properties of our color optical switching device.

## 5. Conclusion

We demonstrated the color optical switching device by PNLC with color filter on a specular reflector. The device structure makes use of the forward scattering effect of PNLC, contrary to other PNLC devices, and so that it is possible to have high reflectance and high contrast ratio. Moreover, the device has good advantages to adjust the view-angle dependence of reflectance, to have wide color reproduction similar to that of color filter, and to be almost no color shift with respect to the operating voltage. The optical measurements have qualitative agreement with the prediction based on light multi-scattering of PNLC material. As the PNLC material has moderately fast responds time, the bright color optical switching device can be applied to reflective display in a wide range.


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