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Reduction of Viewing-Angle Dependent Color Shift in a Reflective Type Cholesteric Liquid Crystal Color Filter

Won-Gun Jang*, Tae Won Beom[1], Hao Cui[1], Jong Rak Park[1],
Seong Jin Hwang[2], Young Jin Lim[2], and Seung Hee Lee[2]

Korea Photonics Technology Institute, Wolchul-dong, Buk-gu, Gwangju 500-460, Korea
[1]*Department of Photonic Engineering, Chosun University, 375 Seosok-dong, Dong-gu, Gwangju 501-759, Korea*
[2]*BK-21 Polymer BIN Fusion Research Team, Research Center of Industrial Technology,*
School of Advanced Materials Engineering, Chonbuk National University, Chonju, Chonbuk 561-756, Korea

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The reflective type color filter for the liquid crystal displays (LCDs) was produced using cholesteric liquid crystal monomers whose phase is characterized by the unique optical features of *selective reflection*. Periodic micrometer scale hemi-spherical photoresist (PR) patterns were formed on glass substrates by thermal reflow method after photolithography. Cholesteric color filter films for red, green, and blue light reflections were then produced and the viewing angle dependence was investigated and compared with that of reflected light on the non-patterned substrates. Computer simulations using "*LightTools*" were also carried out, and it was confirmed that the color shifts were much smaller on the patterned substrates by bare eyes and Commission Internationale de'Eclairage (CIE) chromaticity coordination analysis qualitatively.

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In liquid crystal display (LCD) technology, although there have been tremendous improvements in image qualities such as viewing angle dependence, contrast ratio, and response time, there are still serious problems left for the best performance display applications. One of the problems is to inevitably utilize the polarizers and absorptive color filters since the polarization states of light are manipulated by LC molecules and primary colors are generated by color filters.1)

Presently the transmittance of polarizer is below 45% and color filter is less than 35% and overall transmittance of LCD panels drops less than 10% from backlight unit (BLU) intensity, which is quite serious in a light-efficiency point of view. For the light-efficient color filters in LCD panels, polymerized cholesteric liquid crystal (CLC) color filters which partially reflect light instead of absorbing it from BLU, is one of solutions.2–6) Cholesteric LC phase is characterized by unique helical LC molecular alignments along the substrate normal when properly treated. In a homogenously aligned helical structure of CLC, at normal incidence, the center wavelength λ_{o} of the reflected light is given by $\lambda_{\text{o}} = n \cdot p$, where p is the CLC pitch (a complete 360° turn of LC director) and n $(= \sqrt{(n_{\parallel}^{2} + n_{\perp}^{2})/2})$ is the average refractive index of $n_{\parallel}$ (ordinary) and $n_{\perp}$ (extra ordinary).7) The width of reflection band of CLC color filter $\Delta\lambda$ is expressed as $\Delta\lambda = \Delta n \cdot p$.8,9) Accordingly, right (or left) circular-polarized light is *selectively reflected* when the wavelength of incident light is comparable to the left (or right)-handed pitches of CLC. Partially reflected light from CLC can be reflected back from BLU and recycled, thus improving the light efficiency. Selective optical reflection is quite useful in optical film applications, such as reflective plates, reflective polarizers, etc.10,11) However, conventional selective-reflection color filter has shortcomings, i.e., reflected wavelength in viewing angle directions is considerably different from at 0° (right angle); the color leakage.12) Especially blue-shift of the reflection can be observed, which results in severe color shift problem. Here we report the studies on the dependence of color index change as the viewing angle varies and propose a new concept of "micro-patterned" CLC color filters to lessen the color-shift problems. We conjectured the viewing angle-dependent color shift would be reduced if color characteristics at normal direction are kept at same value as in viewing angle directions all over the cell. Therefore, we tried to produce the hemi-sphere type micro-structures comparable to each pixels in size using thermal reflow method after photolithography.

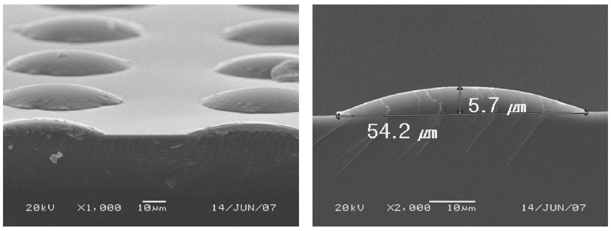

Fig. 1. Scanning tunneling microscope (SEM) images of produced glass substrates with PR coated.

For the experiment positive photoresist (PR) with high viscosity (30 cP) was spin coated on the glass substrate and photolithography was carried out. Thermal reflow process at 200 °C for 60 min was then conducted to form a hemi-spherical shaped PR patterns.13) Soft- and hard-baking processes at 80 and 200 °C were carried out for solvent removal and alignment layer followed by CLC coating. RMS 03-001 from Merck and chiral dopant were mixed together with a specific mixing ratios and UV-curable CLC monomers were obtained. UV exposure with the intensity of 350 W for 90–120 s. was applied and finally cholesteric color filters reflecting at R, G, B frequencies were formed and their micro-structures were checked through the scanning tunneling microscope observation and microscope focusing. Figure 1 shows SEM images of fabricated glass substrates with PR coated and unambiguously revealed the hemi-spherical patterns although the ratio of h/d (h: height, d: diameter of micro pattern) is lower than 1 (>5.7/54.2) experimentally.

The diameter of the fabricated hemispheres was 20–50 μm, depth was 5–10 μm and separation between indivi-

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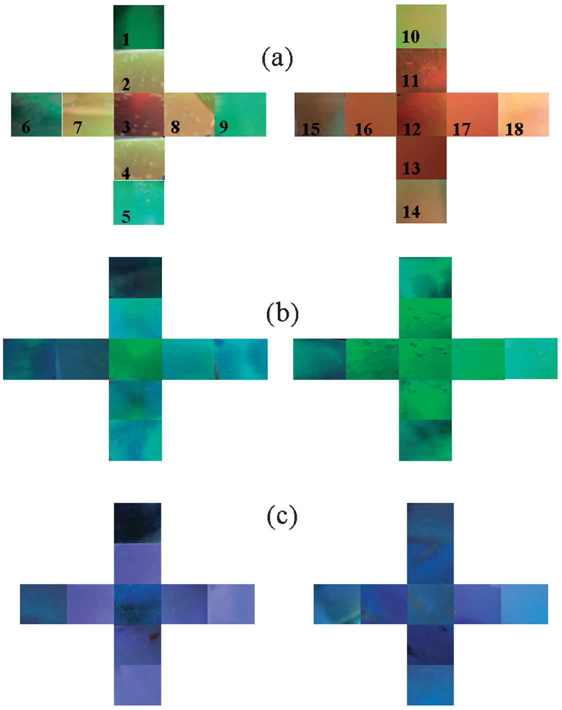
*E-mail address: wgjang@kopti.re.kr

dual patterns were $20-50\,\mu$m, comparable to actual size of pixels in LCD. It was sure that the size of micro structures corresponds to that of each color filters, and it was the main reason to focus on the specific size of micro structures. In other words, adjustable parameters were optimized to actual LC display conditions. Therefore same parameters were also employed in the simulational part later in this paper.

Optical characteristics of produced CLC color filters on micro patterned glass substrate were measured and compared results with non-patterned one. As mentioned above, wavelength of reflected light becomes shorter as viewing angle becomes greater. Colors reflected from CLC color filter were pictured by digital camera along the polar angles (viewing angle) at 0, 45, and 60°, 20 cm away from CLC and azimuthal angle as well under the laboratory fluorescent light. Figure 2 shows measured colors of produced films depending on the existence of pattern and on viewing angle for (a) red, (b) green, and (c) blue. Color shift from 0 up to 45° in viewing angle is unambiguously quite lower when the CLC films are produced on the patterned substrates. Red color shift on no-patterned substrate is especially serious ranging from red to dark green and blue one is lowest as we expected. We also varied the width of micro patterns (up to $\sim 20\,\mu$m) to see any effects of color shift changes, but could not observe substantial differences. Color shift becomes bigger over 70° regardless of the existence of micro-patterns on the substrate, which might be attributable to intrinsic property of CLC characteristics. In order to analyze the color characteristics qualitatively, we employed CIE $L^*a^*b^*$ together with CIE (x,y) color coordinates.[14,15] In Fig. 2 we indicated measured color indices in $L^*a^*b^*$ and (x,y) coordinates for the red color filter only and green and blue can also be expressed in a similar manner.



CIE (L*a*b*)

1. 0.2889, 0.4945 (46,-40, 28)	10. 0.4041, 0.4543 (69,-8, 50)
2. 0.3814, 0.4251 (69,-7, 37)	11. 0.5330, 0.3688 (49,42, 42)
3. 0.4938, 0.3542 (47,37, 29)	12. 0.5557, 0.3666 (35,37, 37)
4. 0.3814, 0.4188 (66,-5, 34)	13. 0.3814, 0.4188 (66,-5, 34)
5. 0.2827, 0.4048 (91,-45, 20)	14. 0.4239, 0.4029 (58,11, 34)
6. 0.2864, 0.3836 (53,-23, 9)	15. 0.4400, 0.3947 (35,12, 24)
7. 0.3839, 0.4380 (71,-10, 42)	16. 0.4854, 0.3843 (47,27, 35)
8. 0.4013, 0.3987 (68,7, 33)	17. 0.4784, 0.3717 (56,33, 35)
9. 0.2834, 0.4205 (74,-42, 21)	18. 0.4174, 0.3882 (78,17, 37)
No pattern	**Patterned**

Fig. 2. Measured colors of produced films depending on the existence of pattern and on viewing angle for (a) red, (b) green, and (c) blue. Measured color indices in $L^*a^*b^*$ and converted CIE coordinates for the red color filter is also shown. G, B can also be expressed in a similar manner.

Computer simulations using a commercial optical modeling tool "LightTools" (Optical Research Associates) were also executed. In the simulation, pitch, width, and the depth of the micro-patterns were ~70, ~55, and $\sim 5.7\,\mu$m respectively. An appropriate coating property, which was obtained using Berreman's 4×4 matrix method, was assigned to the top surface of the structure for each color filters (red, green, and blue). Spectral and angular luminous characteristics of the source for the simulations were set according to the experimental conditions, i.e., white spectrum and ±10° – diverging intensity profile.

Simulation results (Fig. 3) show that color shifts in R, G, B were quite large when color filters were made on the non-patterned substrate. Especially, bandwidth of red color shift was wide and color changes from red to even blue depending on the viewing angle. However, one can find that color shift characteristics are considerably improved when patterned substrates were used. The color changes are much more gradual and almost no change in color could be observed up to 45° of viewing angle. We plotted simulational and experimental results for the color shift together in Fig. 4. They show a fairly good agreement for the tendency in the color shift. Through simulations we have found that the patterned structure reported in this letter was effective up to ±30° – diverging intensity profile through computer simulations. In order to implement the patterned structure to a real device, however, optimization of the structure should be performed considering real ambient illumination conditions. Employment geometry of CLC color filter is same as that of conventional LCD except an additional 1/4-plate on top of CLC since it transforms the transmitted circular polarization into linear one. We infer the principle of color-shift suppression as "normal-angle effect", i.e., off-normal angle colors are reflected back and diminishes and solely normal angle color is viewed. Finally micro pattern helps us reduce the color shift noticeably, but there are still viewing angle characteristics remaining to be improved and it is necessary to develop more favorably coatable materials for the easy process and commercial productions. Nevertheless, we insist that this concept of patterned CLC filter itself is quite meaningful as one of improvement technique for color characteristics of CLC color filters.

In summary, we could produce CLC color filters for R, G, and B and reduce the color shifts considerably by employing hemi-spherical micro-patterned substrates with alignment layer coated. Trend of color shift is more continuous and predictable in patterned color filter than that in non-patterned one. Simulations of color characteristics of CLC color filters at various viewing angles also turned out to be in good agreement with experimental data.

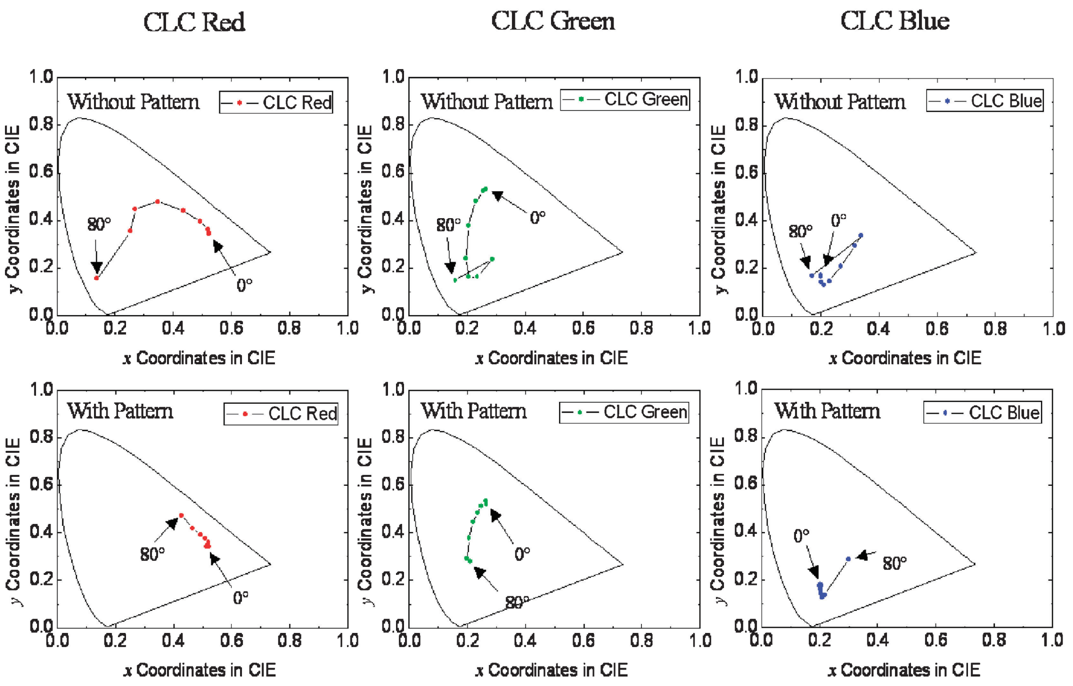


Fig. 3. Simulated color shift in red, green, and blue CLC color filters in CIE coordinate.

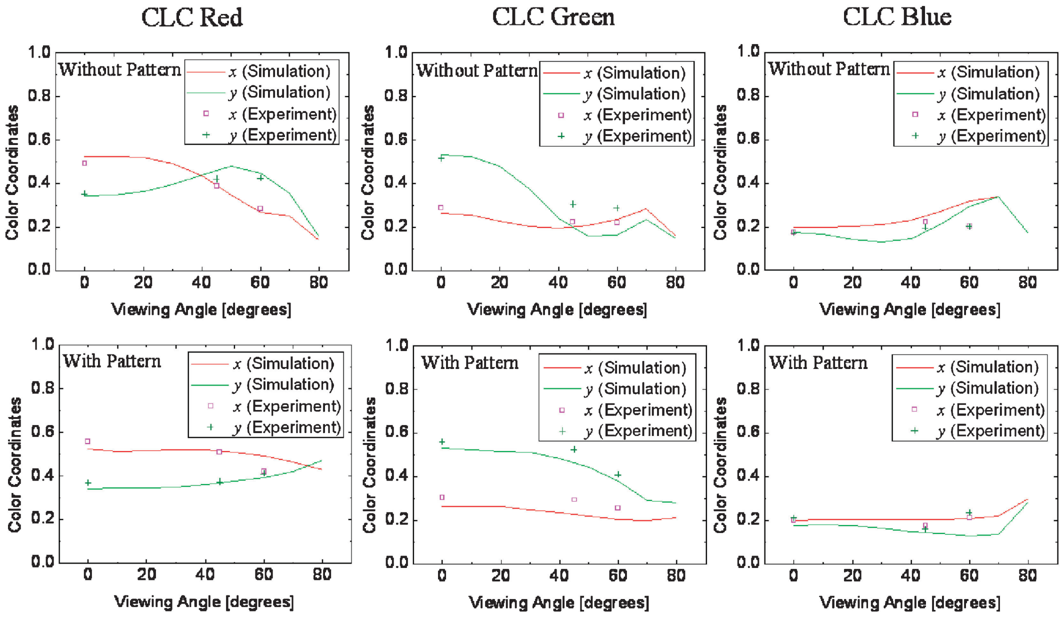


Fig. 4. Comparison between simulational and experimental results for color shift.

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