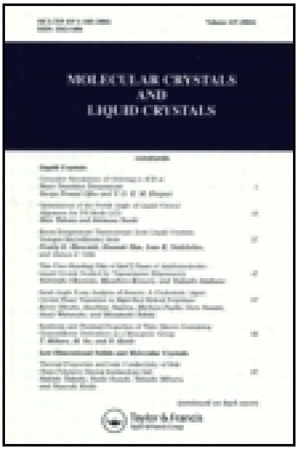

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The viewing characteristics of normally scattering polymer dispersed liquid crystal (PDLC) illuminated by guided light were studied. Luminance inversion occurred at viewing angles of more than 40° for the polarization component parallel to the plane of incidence, while the contrast ratio was more than 1 at all angles for the polarization component perpendicular to that plane. The luminance inversion was caused by the refractive index mismatch for the polarization component parallel to the plane of incidence even when an electric field was applied. By controlling the polarization of scattered light, we could suppress the luminance inversion.

Keywords: PDLC; light guide; viewing angle

INTRODUCTION

A display using light propagating in a planar light guide is expected to have high optical efficiency and high contrast [1]. We have used a polymer dispersed liquid crystal (PDLC) [2,3] cell as the device for controlling the release of guided light and demonstrated the display [4]. Since PDLC is adhesive, it is possible to tile panels seamlessly, so this type of display is expected to be used for large-area display applications. However, luminance inversion occurred at large viewing angles when we used a normally scattering PDLC, which consists of isotropic polymer and dispersed liquid crystal aligned randomly.

PDLC is a well-known material that can be switched between transparent and scattering states by applying an electric field and has been attentively studied for the transmission configuration, where the light incident angle is near 0°. Using PDLC for the display mentioned above, it is necessary to understand its optical characteristics for light incident at a large angle. In this paper, we discuss the scattering characteristics and demonstrate a module for a large-area display.

EXPERIMENTAL

Figure 1 shows the device structure and the configuration of the setup for measuring viewing-characteristics. We sandwiched a mixture of nematic liquid crystal (E7, Merck), optical adhesive (NOA 65, Norland), and spacers between ITO-coated glass substrates and cured it by UV-irradiation. The PDLC sample was stuck onto a planar light guide with optical immersion oil. Light emitting diodes (LEDs) illuminated a side edge of

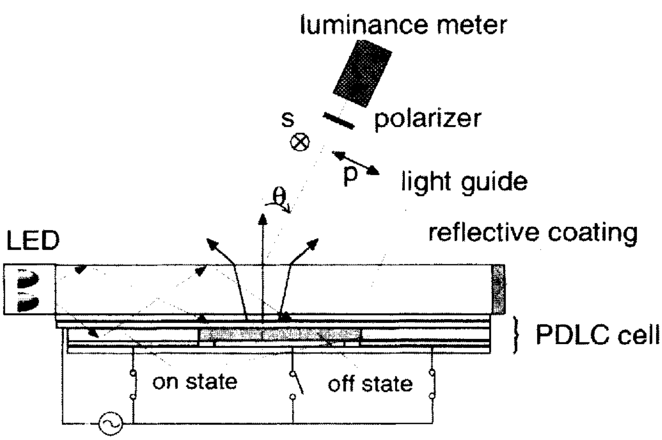

FIGURE 1. Schematic configuration of the device structure and setup for measuring viewing characteristics.

the light guide and light propagated within the light guide. When PDLC was in the scattering state, the light propagating within the light guide was scattered to the outside of the guide. When it was transparent, the light kept propagating inside the guide. The luminance was measured with a spectral radiance meter from the light guide side at various angles as shown in Fig. 1.

RESULTS AND DISCUSSION

Figure 2 shows how the luminance depends on viewing angle for each polarization. P- and s-polarizations, respectively, denote the components parallel and normal to the incident plane, which includes the incident ray and the direction of the electric field. When no voltage was applied (off state), the PDLC cell was bright for a wide range of viewing angle. When an electric field was applied (on state), both polarizations were dark enough at 0 degrees. However, for angles greater than 40 degrees the p-polarization

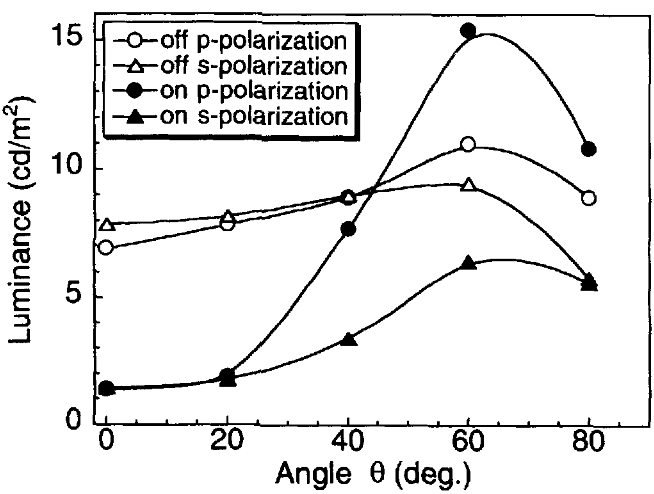

FIGURE 2. Viewing angle characteristics for various polarizations.

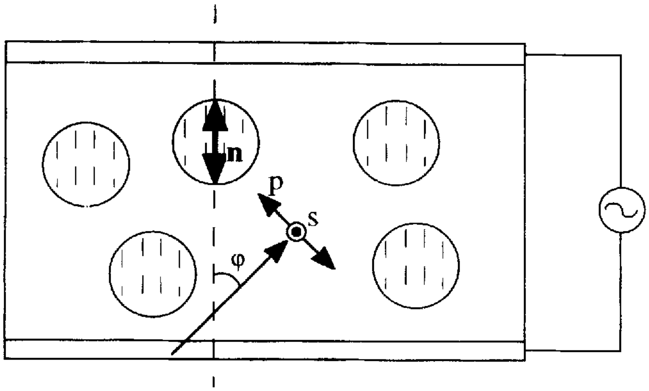

FIGURE 3. Relative orientation of director of alignment **n**, polarization definition of s- and p-rays, and propagation angle φ of the ray.

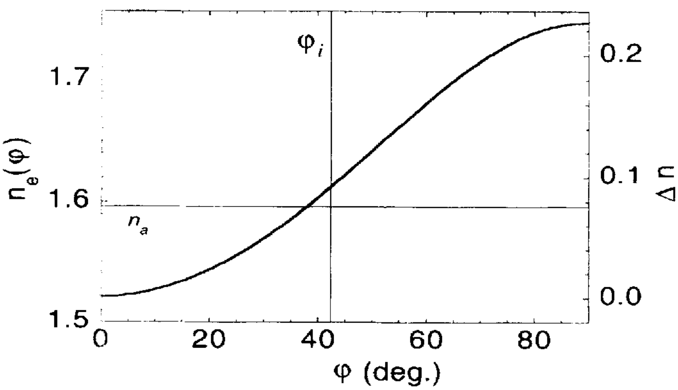

FIGURE 4. Dependence of refractive index of the extraordinary ray on φ. φ_i denotes the critical angle at the interface between acylic and air and n_a denotes the average refractive index of liquid crystal aligned randomly.

luminance was larger than when voltage was not applied. This luminance inversion was caused by the difference in refractive index for p-light between polymer and LC, which remained even when the electric field was applied. Under the electric field, LC molecules aligned in direction **n** shown in Fig. 3. It is well known that as the angle φ between the LC molecular alignment director **n** and the incident ray is changed, the direction of polarization of the ordinary ray, that is the s-ray, remains fixed and its refractive index is always n_o. The refractive index of polarization of the extraordinary ray, on the other hand, varies from $n_p(\varphi) = n_o$ for $\varphi = 0°$ to $n_p(\varphi) = n_e$ for $\varphi = 90°$. The refractive index $n_p(\varphi)$ of the extraordinary ray (p-ray) is give by

$$n_p(\varphi) = \frac{n_o n_e}{\sqrt{n_o^2 \sin^2 \varphi + n_e^2 \cos^2 \varphi}}$$

In this case, n_o and n_e are 1.52 and 1.75, respectively, and the refractive index of the optical adhesive is 1.52. Values of $n_e(\varphi)$ are shown in Fig. 4. Although the PDLC shows polarization-independent characteristics in the

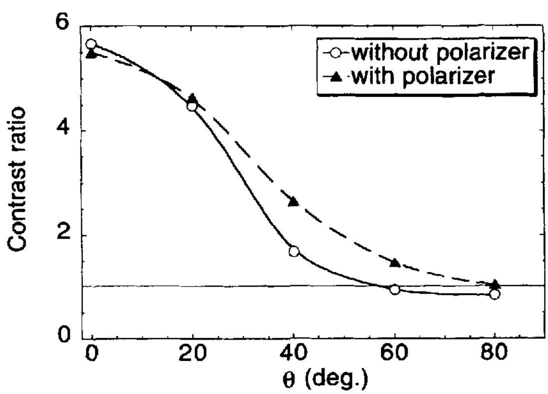

FIGURE 5. Dependence of contrast ratio on θ with and without polarizer.

transmission configuration ($\varphi = 0$), the difference between the polarizations become large as φ become large. When no electric field is applied, the directions of LC molecules are random, so the average refractive index of LC (n_a) for both p- and s-rays is

$$n_a = \frac{2n_o + n_e}{3}$$

In this case, n_a is 1.60.

As a light guide, we used an acrylic plate, whose refractive index is 1.49, so the critical angle at the interface between the acrylic plate and air is about 42.2°. Therefore, only rays of $\varphi > 42.2$ propagate in the light guide. Because the refractive index difference between LC and matrix polymer for the p-ray within the light guide is significant, the p-ray is scattered. We think that the increase in luminance at angles of more than 40° in Fig. 2 when an electric field was applied results from the increase in refractive index difference as shown in Fig. 4.

In the s-light case, luminance inversion did not occur anywhere in the range because of the good index match between LC and polymer. Therefore, s-light operation, for example by using a polarizer, improves the viewing angle characteristics of the display. Figure 5 shows the contrast ratio with and without a polarizer that is transparent for s-rays. When the polarizer was used, the ratio stayed more than 1, which means that luminance inversion did not occur anywhere in all the entire range of viewing angles.

We fabricated this type of display module using PDLC sandwiched between a glass plate with an ITO-electrode and a printed-circuit board with 16 x 12 electrodes. The size of the pixel electrodes was 2.8 mm x 2.8 mm. LEDs illuminated a light guide from the right side of the module and the colors were achieved by the field sequential technique. Figure 6 shows the module from the viewing angles of 0° and 60° with and without a polarizer transparent for vertically polarized light. At 0°, colors were recognized both when a polarizer was and was not used though it was difficult to distinguish the colors without polarizer at 60°. This improvement in viewing-angle characteristics by using a polarizer can be explained by the scattering characteristics of the PDLC.

For a large-area display, the need for precise fabrication processes, e.g., for TFTs, prevents existing flat panel displays from being made bigger.

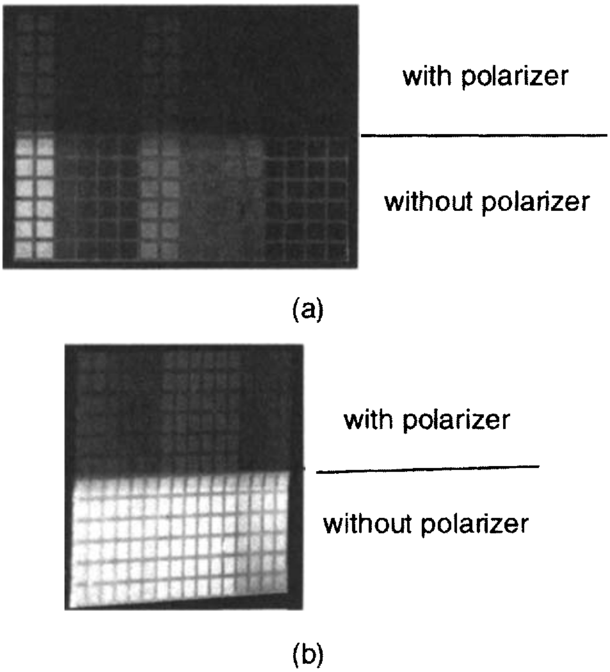

FIGURE 6. The 16 x 12 bit-mapped display observed when the viewing angle was (a) 0° and (b) 60° with and without a polarizer.
See Color Plate II at the back of this issue.

However, since this module can be made by using a conventional PC board process and the driver ICs and electronic circuits are mounted on the rear of the display, this module can be tiled seamlessly, so it is promising for large-area display applications.

CONCLUSION

We studied the scattering characteristics of PDLC illuminated by a planar light guide. The good luminance-switching characteristics were obtained at right angles, while luminance inversion occurred at large viewing-angles. This inversion was caused by the refractive index mismatch for the polarization component parallel to the plane of incidence even when an electric field was applied.

We demonstrated a 16 x 12 pixels display that produced color by using the field sequential technique as a tilable module for large-area displays.

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