Fast polarization switching panel with high brightness and contrast ratio for three-dimensional display

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We propose a polarization switching device using optically compensated pi cell for polarization-glass-type three-dimensional display. This device shows good optical properties such as high transmittance and low cross-talk ratio because of its fast dynamic response characteristics. To improve the brightness and contrast ratio on the right- and left-hand sides, we attach optical retardation films on each side of the polarization glasses instead of attaching the films on the polarization switching panel. From the calculation and experiment, we obtain high contrast ratios, over 200:1, on both sides and a high brightness using only one film on each side. © 2011 American Institute of Physics. [doi:10.1063/1.3548863]

The flat-panel display technology has developed very fast in the past decade. Hence, this technology is attaining maturity and the market is approaching saturation. On the contrary, the market for three-dimensional (3D) display has been rapidly expanding worldwide. Many researchers have made various efforts to develop 3D displays with two-dimensional (2D)/3D switching, high brightness, and high resolution.¹⁻⁹ Among these technologies, the stereoscopic 3D display using 3D glasses has attracted industrial attention because it has neither the loss of spatial resolution nor the 3D moiré effect between pixels and barrier. Moreover, the stereoscopic 3D technology is suitable for realizing 2D/3D switching easily. The glass-type 3D displays are divided into passive retarder type using patterned retarder film⁵ and active retarder type using either liquid crystal (LC) shutter glasses^{6,7} or polarization switching (PS) panels.^{8,9} However, active retarder type with LC shutter glasses has poor brightness in the 3D mode because of the slow response time and writing speed of the LC panel and shutter glasses. Moreover, the shutter glass is too heavy and uncomfortable due to the presence of batteries, for an active operation. A 3D display with PS panel (3D-PS) uses polarization glasses that are lighter and more comfortable than LC shutter glasses, because they do not need batteries for operation. However, it also has drawbacks such as low brightness and 3D cross-talk because of slow response time of the PS panel.⁸ Moreover, without optical compensation, this device has low and asymmetric contrast ratio (CR). To overcome these limits, we suggested a 3D-PS using dual-frequency LC and two half-waveplate (HWP) films.⁹ However, it still has problems such as decrease in brightness due to the two HWPs, low CR under 200:1, and low cell gap under 3 μm . Hence, it is difficult to commercialize this technology.

In this letter, we propose a stereoscopic 3D display with a PS panel of high brightness and CR. The PS panel is a pi cell with very fast response time. To obtain high brightness and CR in the left- and right-hand sides simultaneously, we suggest a structure with optical compensation using one film on each side. We have measured the properties of the proposed cell, such as its electro-optical (EO) and dynamic re-

sponse characteristics, and have calculated the cross-talk ratios using the measured results. We have also measured the CR, and the results have been confirmed through calculation and experiment.

In previous 3D-PS,^{8,9} the transmission axes (TAs) of the right- and left-hand sides of the polarization glasses are orthogonal to each other, and optical films are attached on the PS panel. Thus, the optical film influences the optical properties of not only the left-hand side, but also the right-hand side. Moreover, two HWP films are required to obtain high CR on both sides. If we consider each side separately, then we can easily design a structure using optical retardation films. Therefore, we attached an optical film on each side of the polarization glasses, as shown in Fig. 1. The angle between the optical axis (OA) of the pi cell and the TA of the polarizer was set to be 45°. The right-hand side of the panel was designed as normally white mode. When we applied a voltage above a critical voltage, the LC alignment of the pi cell changed from splay state to low-bend state. When we increased the applied voltage, the LC alignment transitioned to a high-bend state. In the pi cell, we obtained the bright and dark states in low-bend and high-bend states, respectively. However, the dark state of the pi cell was not acceptable because of the residual phase retardation on the surface. To compensate the residual retardation, we needed a small retar-

FIG. 1. (Color online) Principle of the proposed 3D display with PS panel: (a) odd frame (V_{low}) and (b) even frame (V_{high}).

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FIG. 2. (Color online) Measured EO characteristics of the optical compensated pi cell for right-hand and left-hand sides.

dation film of 40 nm with an angle of 135° between the OA of the retardation film and the TA of the polarizer, as shown in Fig. 1(a). The left-hand side of the panel was designed as normally black mode, and we obtained bright and dark states in high- and low-bend states, respectively. As the TA of the polarizer on the left-hand side is of the same direction as that of the right-hand side, optical compensation is necessary. In the low-bend state, the phase retardation was around 275 nm as maximum brightness was obtained at this point. Therefore, to obtain the dark state at the low-bend state, we compensated the phase retardation using an HWP with an angle of 135° between the OA of the HWP and the TA of the polarizer, as shown in Fig. 1(b). In our proposed structure, the operating voltages for dark states of both sides were the key factors to obtain a high CR on both sides. Hence, we found it important to determine the voltage for the dark states both on the right-hand side (V_{high}) and the left-hand side (V_{low}). We confirmed that, at V_{high} , the right-hand side had a dark state and the left-hand side had a bright state; and, at V_{low} , the left-hand side had a dark state and the right-hand side had a bright state simultaneously.

In our experiments, we used the nematic LC mixture ZLI-2293 from Merck KGa ($\Delta\epsilon=10$, $\Delta n=0.1322$ at $\lambda=589$ nm, $K_{11}=12.5$ pN, $K_{22}=7.3$ pN, $K_{33}=17.9$ pN, and $\gamma_1=0.149$ Pa s). To promote homogeneous alignment, a homogeneous alignment layer (PIA-5310-GS10, Chisso Corporation) was spin-coated on the transparent indium tin oxide film of the top and bottom glass substrates and was rubbed to be parallel. The cell gap was controlled by ball spacers to be $3.8 \mu\text{m}$. When we measured the EO and the dynamic response characteristics, the TA of the polarizer was aligned at 135° with respect to the rubbing direction of the LC cell, and the TA of the analyzer was perpendicular to both sides. When we measured the EO characteristics of both sides, the angle between the OAs of the optical film and the LC layer was 90° , as shown in Fig. 1. All the measurements were performed using a xenon lamp (Photal, C4251), and a square wave voltage of 1 kHz was applied to the cells.

The EO characteristics of the optically compensated pi cell were measured for the left- and right-hand sides, respectively, as shown in Fig. 2. We found that $V_{\text{low}}=2.3$ V and $V_{\text{high}}=10$ V at dark states of both sides. The transmittances of the right- and left-hand sides were 32.6% and 31.5% at V_{high} and V_{low} , respectively. Figure 3 shows the dynamic response characteristics for a voltage between V_{low} and V_{high} . The thin and thick lines show the response characteristics of

FIG. 3. (Color online) Dynamic response characteristics at $V_{\text{low}}=2.3$ V and $V_{\text{high}}=10$ V.

the right- and left-hand sides, respectively. The rising and falling times of the right-hand side were 1.90 and 0.42 ms, respectively, on the thin line. On the other hand, the rising and falling times of the left-hand side were 0.44 and 1.70 ms, respectively, on the thick line. In the 3D display with glasses, the fast falling time indicates that the display image can be reset immediately and does not influence the next image. In addition, the fast rising time indicates that the brightness is high because of the large effective aperture in the time range of the LC response. Hence, a low cross-talk and a high brightness could be realized in our proposed structure. To support this, we calculated the cross-talk using a simple method,⁸ and the cross-talks of the left- and right-hand sides were 0.72% and 1.23%, respectively. The difference in cross-talks on both sides was due to the difference in rising and falling times in the pi cell.

Figures 4(a) and 4(b) show the calculated and measured optical performances of the left- and right-hand sides, respectively. To calculate the CR of both sides, we used the following equation:¹⁰

$$T = ||0 \quad 1| M_{\text{film}} M_{\text{LC}} [1 \quad 0]^t|^2, \quad (1)$$

where

$$M_{\text{LC}} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{i\Gamma/2} \end{bmatrix} \times \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix},$$

$$M_{\text{film}} = \begin{bmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} e^{-i\Gamma_1/2} & 0 \\ 0 & e^{i\Gamma_1/2} \end{bmatrix} \times \begin{bmatrix} \cos \beta & -\sin \beta \\ -\sin \beta & \cos \beta \end{bmatrix},$$

and T is the normalized transmittance. M_{LC} and M_{film} are the Jones matrices of the LC layer and the phase retardation film, respectively; α and β are the angles of OAs of the LC layer and the phase retardation film with respect to TA of polarizer, respectively; Γ and Γ_1 are the phase retardations of the LC layer and the retardation film; and $[1 \quad 0]$ and $[1 \quad 0]^t$ are the Jones vectors of the analyzer and the polarizer, respectively. In our calculation, α and β were set to be 45° and 135° on left- and right-hand sides, respectively. Γ_1 was set to be $8 \pi/55$ (40 nm) on the right-hand side and π (HWP) on the

FIG. 4. (Color online) Calculated and measured optical performances of the (a) right-hand side and (b) left-hand side.

left-hand side. We calculated the transmittances of the dark and bright states for the right- and left-hand sides by varying λ . Our proposed configuration showed small light leakage in the dark state and high brightness in the bright state, as shown in Fig. 4. In the case of both sides, excellent dark states and high brightness could be realized over the entire visible wavelengths. In the calculated results, CRs for the right- and left-hand sides were 1597:1 and 780:1, respectively, whereas in the measured results, CRs for right- and left-hand sides were 622:1 and 225:1, respectively. In this case, a difference in CR between both sides does not influence the visibility of the device because the CRs of both sides are enough high over than 200:1. A mismatch between the simulated and measured results can be attributed to the small variance of the polarizer, retardation films, and LC layer from the designed values. Moreover, the measured transmittance was lower than the calculated transmittance because, unlike the experiment, we were unable to calculate the decrease in transmittance by optical retardation film. Nevertheless, the experimental results show good agreement with the calculated results.

In conclusion, we proposed a fast response PS panel with high brightness and CR on both sides using a pi cell. We improved the optical properties in the right- and left-hand sides, respectively. We determined the operation voltages, $V_{\text{high}}=2.3$ V and $V_{\text{low}}=10$ V, through experiments. Transmittances of both sides were over 31% and the total dynamic response time was less than 2.5 ms. Furthermore, the cross-talk ratios were 0.72% and 1.23% in the left- and right-hand

sides, respectively. We used the Jones matrix method to calculate the CRs and found that the CRs for right- and left-hand sides were 1597:1 and 780:1, respectively. To confirm the calculated results, we measured the optical performances of both sides. The CRs for the left- and right-hand sides were 622:1 and 225:1, respectively. The simulated and experimental results showed some discrepancy, but they showed the same tendency.

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