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Reflective Liquid Crystal Display Using a Non-Twist Half-Wave Cell

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An optical configuration for a single-polarizer reflective liquid crystal display using a non-twist cell is proposed. Optimized optical configurations could be achieved by using a cell with a quarter-wave retardation or a half-wave retardation. Especially, a half-wave cell provides very high brightness in the bright state. The configuration can be applied to most of liquid crystal display modes with a non-twist cell. By fabricating an antiferroelectric liquid crystal (LC) cell and a vertically aligned cell, we demonstrated high brightness as well as high contrast of reflective half-wave cells.

KEYWORDS: liquid crystal display, reflective display, Poincare sphere, non-twist cell, single polarizer mode, quarter-wave film, half-wave cell

1. Introduction

With the increasing demand for hand-held devices with light-weight and low-power-consumption displays, reflective liquid crystal displays (LCDs) have been implemented in various configurations in order to achieve high brightness as well as high contrast.[1–8] Recently, the single polarizer mode has been considered as a suitable structure for reflective LCDs because it can provide high brightness.[4–8] However, the contrast of single-polarizer LCDs is lower than that of double-polarizer LCDs because of the light leakage in the dark state due to the phase dispersion. In order to enhance the optical contrast, a wide-band quarter-wave film could be used in refective LCDs because it lead the polarization of the reflected light to the linearly polarization over the whole visible spectra.[8] In this work, we propose optical configurations of single-polarizer reflective LCDs for high contrast and high brightness by using a non-twist half-wave retardation cell. The configuration can be applied not only to horizontal switching modes such as an in-plane switching mode (IPS) cell,[9] a ferroelectric LC cell,[10] an anti-ferroelectiric LC cell,[11] but also to vertical switching modes such as a homogeneous cell, a VA (vertically aligned) cell,[12] and a π-cell.[13]

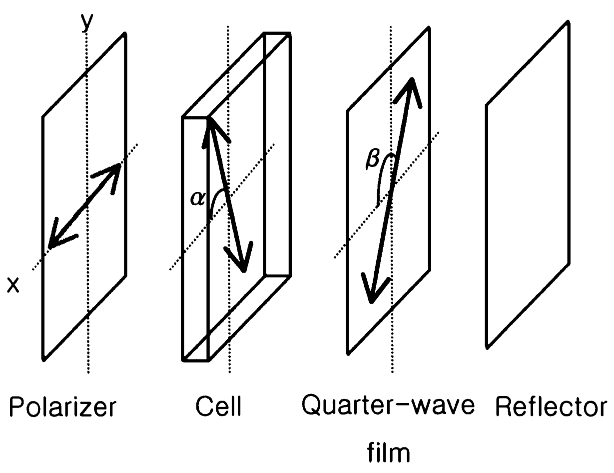

Fig. 1. Optical geometry of a single polarizer mode reflective cell.

A single-polarizer reflective cell is composed of a polarizer, a LC layer, a wide-band quarter-wave film, and a metallic diffuse reflector. In a reflective cell, in order to achieve the completely dark state, the polarization of the light passed through the LC cell twice should be rotated by 90° over the whole visible wavelength ranges. On the contrary, for the good bright state, it should be parallel with the transmission axis of the polarizer. To search for the optimum device configurations, we calculated the reflectance in the dark and bright state as a function of optical parameters, such as the retardation of the cell $d\Delta n$, and the angle of the LC director α with or without an applied electric field, and the optic axis β of the quarter-wave film. Here all the angles are defined with the transmission axis of the polarizer as the reference, as shown in Fig. 1.

2. Quarter-Wave Cell

For horizontal-switching LC cells, two kinds of configurations may be used for a normally black (NB) mode reflective cell. One configuration uses a LC layer with the retardation $d\Delta n = (n \pm 1/4)\lambda$, where $\lambda = 550$ nm and n is an integer. With the optical condition of $\alpha = 0°$, and $\beta = 45°$, we can obtain the lowest brightness at the dark state. Since the angle α of the LC director is in parallel with the transmission axis of the polarizer, linearly polarized incident light will keep the state of polarization when the light propagates through the LC layer. Figure 2 shows the Poincare sphere representation[14] of the polarization path for the dark state in a quarter-wave cell ($n = 0$). The transmission axis of the polarizer and the angle α of the LC director are located at the point P1 and the optic axis β of the quarter-wave film is located at the point P2. Linearly polarized incident light becomes circularly polarized by passing through the quarter-wave film whose optic axis is aligned at an angle $\beta = 45°$. Path 1 represents the polarization path when the light passes through the quarter-wave film. The reflected light is rotated by an angle 90° by passing through the film once more, as shown by the path 2. 90°-rotated reflected light will maintain the state of polarization during the propagation through the LC layer, since the polarization is perpendicular to the angle α of the LC director. Finally, the polarization of the reflected light is perpendicular to the transmission axis of the polarizer, so that the polarizer will block the reflected light. Since the brightness in the dark state only depends on characteristics of the quarter-wave

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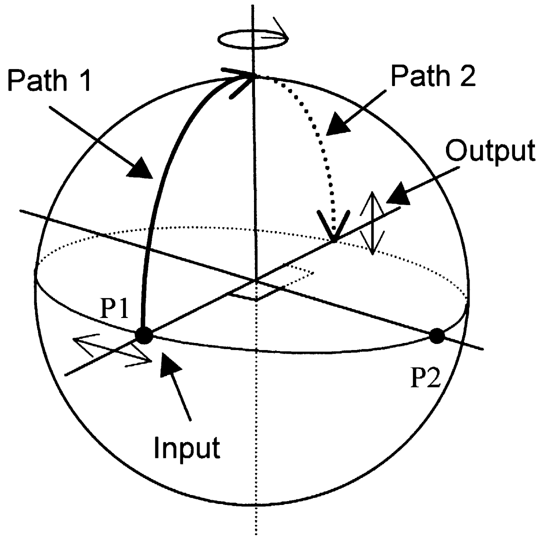

Fig. 2. Poincare sphere representation of the polarization path of the dark state in a quarter-wave and a half-wave reflective cell.

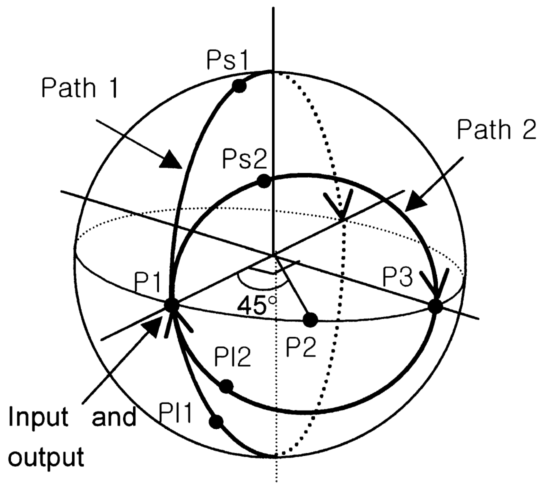

Fig. 3. Poincare sphere representation of the polarization path of the bright state in a quarter-wave and a half-wave reflective cell.

film, a wide-band quarter-wave film is required for the lowest brightness in this configuration.

For the bright state, we rotate the angle of the quarter-wave LC director to $\alpha = 45°$ by applying appropriate electric field to the cell. Path 1 in Fig. 3 represents the polarization path for the bright state in a quarter-wave cell on the Poincare sphere. Now, the angle α of a LC director is moved to P3 from P1. The linearly polarized incident light will be rotated by 90° by propagating through the LC layer and the quarter-wave retardation film. Then, the reflected light with the 90°-rotated polarization will propagate these layers once more, so that the final polarization of the reflected light will be coincident with the transmission axis of the polarizer. As a result, the bright state is obtained.

3. Half-Wave Cell

The other configuration uses a LC layer with the retardation $d\Delta n = (n + 1/2)\lambda$, where n is an integer. The dark state can be obtained by the same principle as in a quarter-wave cell. For the bright state, we rotate the optic axis of the half-wave LC layer to an angle α by applying appropriate electric field to the cell. The linear polarization of the incident light will be rotated by an angle 2α by propagating through the half-wave LC layer. If the polarization angle 2α is in parallel with the optic axis β of the quarter-wave film, the light will maintain the polarization during the double pass through the quarter-wave film. And then, the polarization of the reflected light will be rotated by an angle -2α by propagating through the LC layer once more. Finally, the polarization of the reflected light will return to the original polarization state, so that bright state is achieved. Since we have to fix the angle $\beta = 45°$ for the perfect dark state, $\alpha = 22.5°$ and $\beta = 45°$ is an optimized configuration for the bright state in a half-wave cell.

Path 2 in Fig. 3 represents the polarization path for the bright state in a half-wave cell on Poincare sphere ($n = 0$). The optic axis of a half-wave LC layer is located at the point P2. The phase retardation of a cell with $d\Delta n = 275$ nm is a half wave exactly at $\lambda = 550$ nm, so that polarization of the reflected light at $\lambda = 550$ nm returns to the original position P1 after 360° rotation through the path 2 on the Poincare sphere. However, polarizations at wavelengths other than 550 nm are not focused on the point P1, since phase retardations at other wavelengths are different from a half wave. For example, the polarization at $\lambda = 450$ nm moves to the point Ps2, while the polarization at 650 nm to Pl2. Similarly, in a quarter-wave cell the polarization at 450 nm moves to Ps1 through the path 1, while the polarization at 650 nm moves to Pl1. As shown in Fig. 3, the path difference of a half-wave cell (Ps2–Pl2) is smaller than that of a quarter-wave cell (Ps1–Pl1). This implies that the phase dispersion of a half-wave cell is smaller than that of a quarter-wave cell, which results in high reflectance over the whole visible wavelength ranges.

By using the 2×2 Jones matrix method, we calculated reflection spectra in the bright state with $d\Delta n$ of the LC layer at $\lambda = 550$ nm as a parameter. As shown in Fig. 4, a half-wave cell provides reflectance higher than a quarter-wave cell over the visible wavelength ranges. Moreover, since $d\Delta n$ of a half-wave cell is the twice that of a quarter-wave cell, a half-wave cell can be fabricated more easily with commercially available LC materials. However, large retardation cells ($n = 1, 2, \ldots$) exhibits lower reflectance and coloration because of the large phase dispersion.

The NW (Normally White) mode can also be obtained with a half-wave cell, if we prepare the initial configuration of $\alpha = 22.5°$ and $\beta = 45°$ for the bright state. The dark state could

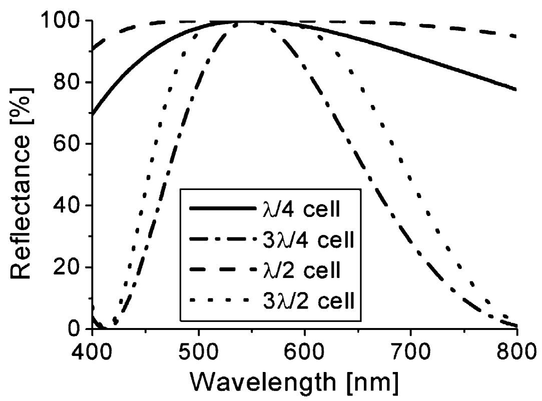

Fig. 4. Calculated reflectance of the optimized bright states with the retardation of a cell as a parameter.

be obtained by rotating the angle of the LC director to $\alpha = 0°$ by applying an appropriate electric field.

We can also optimize the optical configuration of vertical-switching reflective cells with a non-twist LC layer, such as a homogeneous cell, a VA cell, a π-cell, and so on. For the dark state, we have to align the LC director vertically with the optic axis of the quarter-wave film at an angle $\beta = 45°$. The highest brightness in the bright state could be achieved with the half-wave retardation of a cell. For the bright state, we have to align the LC director horizontally along an angle $\alpha = 22.5°$ by the rubbing process. The principle of operation is the same as that of the bright state in a horizontal-switching cell.

4. Experiments

To check the validity of our design, we fabricated a reflective half-wave anti-ferroelectric LC (AFLC) cell as an example of a horizontal-switching cell and a half-wave VA cell as an example of a vertical-switching cell.

In a half-wave AFLC (Chisso CS4001) cell, the two rubbed substrates were separated by spacers to maintain the uniform cell thickness $d = 1.8\,\mu$m. By applying electric fields vertically, we can rotate the angle of the LC director to $\alpha = 24.9°$ from the rubbing direction. It provides reflection spectra in the bright state slightly worse than that with the original design value of $\alpha = 22.5°$, as shown in Fig. 5. When the incident angle of the light source was $-30°$, measured viewing angle dependent reflectance of a reflective half-wave AFLC cell with a wide-band quarter-wave film (Nitto Denko) is shown in Fig. 6. Maximum brightness can be observed at 30°. For this direction, however, the contrast is very low because of the high reflection from the surface of the cell. Maximum contrast can be achieved by observing the image from the direction normal to the surface. We achieved high brightness as well as high contrast ratio of 20:1.

We also fabricated a half-wave VA LC cell with the cell gap $d = 3.7\,\mu$m. By rubbing the cell along an angle $\alpha = 22.5°$, we can achieve not only the perfect dark state under the initial homeotropic state but also the high bright state by applying a vertical electric field. In order to obtain the initial vertical alignment of the negative anisotropic LC (Chisso EN 35) layer, polyimide SE-1211 from Nissan was used. When a voltage is applied to the cell, the LC director will tilt down along the rubbed direction homogeneously. By using the setup the same as that used for the AFLC cell, we measured viewing angle dependent reflectance of a reflective half-wave VA cell with a wide-band quarter-wave film, as shown in Fig. 7. We obtained high contrast ratio of 24:1.

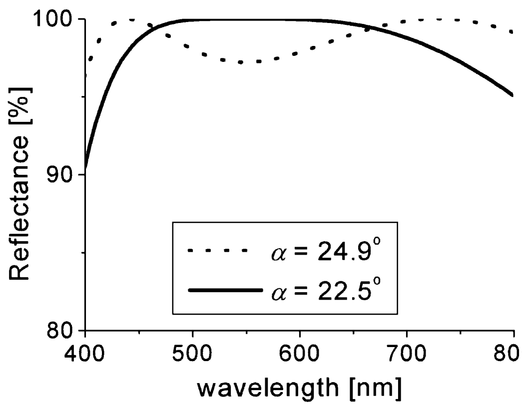

Fig. 5. The reflection spectra in the bright state. (a) an AFLC cell ($\alpha = 24.9°$), (b) a original design ($\alpha = 22.5°$).

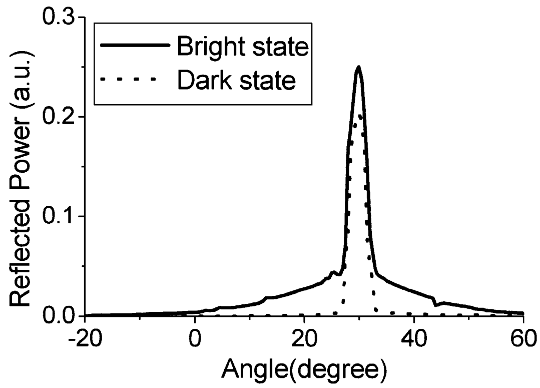

Fig. 6. Measured viewing-angle-dependent reflectance of a half-wave AFLC cell. The maximum contrast ratio is 20:1.

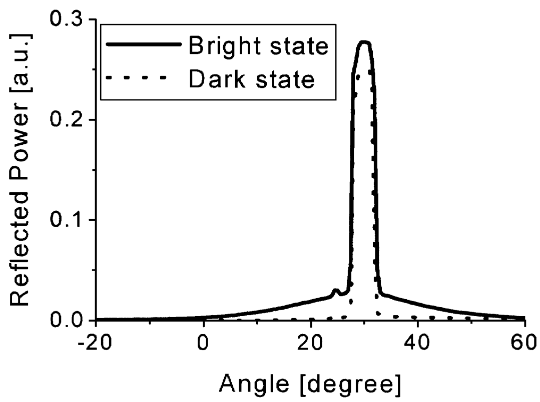

Fig. 7. Measured viewing-angle-dependent reflectance of a half-wave VA cell. The maximum contrast ratio is 24:1.

5. Conclusion

We proposed an optical configuration for a single-polarizer reflective LCD with a non-twist half-wave cell. We described the optical switching principle on the Poincare sphere. A half-wave LC cell with a wide-band quarter-wave film provides very high brightness in the bright state as well as the lowest brightness in the dark state. We demonstrated good optical performances of a reflective cell with a non-twist half-wave LC layer. The proposed configurations can be applied most of single-polarizer reflective LCD modes with the non-twist state.

Acknowledgment

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