Display Technology Letters

A Transflective Liquid Crystal Display Using an Internal Wire Grid Polarizer

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***Abstract*—To obtain high transmittance and reflectance simultaneously, a single cell gap transflective liquid crystal (LC) display using internal wire grid polarizer (WGP) is proposed. For the reflective mode, the imbedded WGP serves as a polarization-dependent reflector for the ambient light. For the transmissive mode, no achromatic quarter-wave film is needed. This device can be used as a normally black mode (using vertical alignment) and a normally white mode (using twist-nematic alignment), based on the initial LC cell alignment. Detailed electro-optic performance, such as voltage-dependent light efficiency and viewing angle of these two device configurations, is investigated.**

***Index Terms*—Liquid crystal display (LCD), transflective, wire grid polarizer (WGP).**

THE rapid advance of portable electronics, such as mobile phones, e-books, and personal digital assistants, generates a growing demand of displays with low power consumption, good outdoor readability, and compact size. Among various display technologies, transflective liquid crystal display (LCD) is a good candidate due to its capability to meet these requirements. The pixels in a transflective LCD are normally divided into transmissive and reflective regions to meet different ambient conditions. A simple method, the dual cell gap design, can be used to compensate for the optical path difference between the transmissive and reflective parts [1], [2]. The dual cell gap method achieves good optical performance, but the transmissive and reflective modes exhibit different response times due to the cell gap difference. More importantly, its fabrication process is quite complicated, resulting in a low yield and high cost. To overcome these drawbacks, single cell gap transflective LCD designs have attracted much research attention [3]. However, single cell gap transflective LCDs generally experience the difficulty of obtaining high transmissive and reflective light efficiency simultaneously, if same LC cell configuration is employed.

In this paper, we report a single cell gap transflective LCD configuration using wire grid polarizer (WGP) as the reflector. The transflective cell is divided into transmissive and reflective regions with same LC cell configuration. This device can achieve high light efficiency for both transmissive and reflective modes.

Fig. 1 shows the typical structure of a WGP where metal (e.g., aluminum) ribs are periodically formed on the glass substrate. For an unpolarized incident light, the light component whose electric field vector is parallel to the wire grids will be almost fully reflected by the WGP. Conversely, most of the light with electric field vector perpendicular to the wire grids will transmit through the WGP. Detailed explanation for this polarization-dependent reflection of the WGP in visible spectrum can be found in [4] and [5]. Exploiting this unique polarization-dependent reflection, Hansen *et al.* applied the WGP into the entire cell region and use an external controller to switch between the transmissive and reflective modes [6]. But an inversion between transmissive and reflective images is observed. To overcome this image inversion, we suggest two transflective LCD configurations in Figs. 2 and 3 with internal WGP for a normally black vertical alignment (VA) cell and a normally white twisted-nematic (TN) cell, respectively [7]. In both Figs. 2 and 3, the LC cell is sandwiched between two crossed linear polarizers, and the WGP is formed on the lower substrate with its wire grids aligned with the transmission axis of the bottom polarizer.

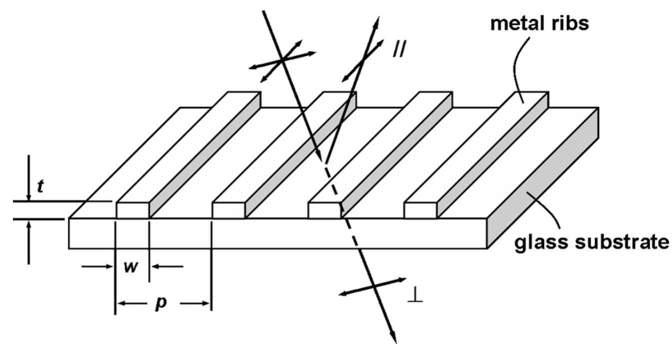

Fig. 1. Schematic illustration of WGP.

In the normally black VA cell shown in Fig. 2, the boundary LC directors are initially rubbed at 45° with respect to the transmission axis of the top polarizer. At the voltage-off state, the linearly polarized light from the top polarizer keeps its polarization after the homeotropic LC cell. With its polarization perpendicular to the wire grids, this light passes through the WGP and is further absorbed by the bottom polarizer. For the transmissive part, the backlight passed by the bottom polarizer is blocked by the crossed top polarizer. Thus a common dark state is achieved for both the transmissive and reflective modes. After the applied voltage exceeds the threshold voltage, the LC directors are reoriented by the applied electric fields. Under proper reorientation, the cell can be tuned to reach a state that is functionally equivalent to a $\lambda/2$ plate. In the reflective mode, the polarization axis of the incoming ambient light from the top polarizer is rotated 90° by the LC cell and becomes parallel to the wire grids, thus is reflected back by the

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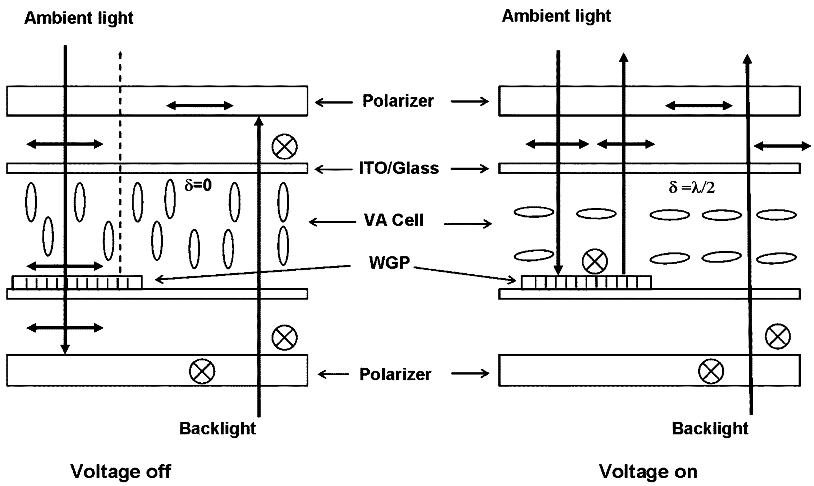

Fig. 2. Schematic illustration of a normally black VA transflective LCD mode.

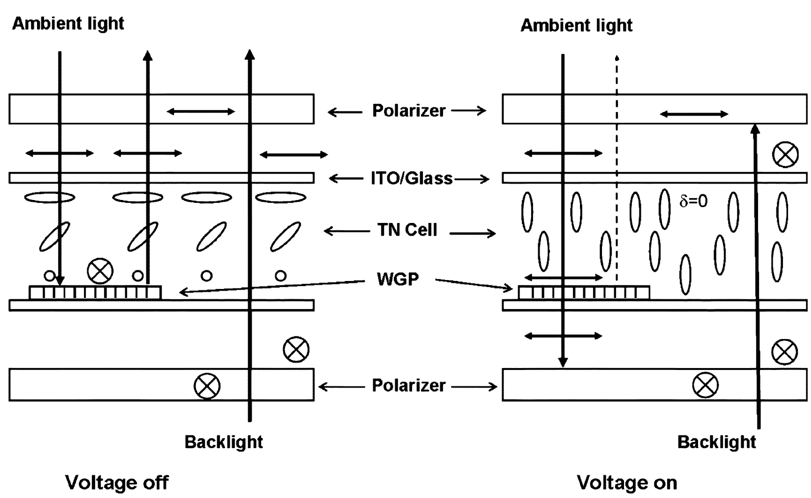

Fig. 3. Schematic illustration of a normally white TN transflective LCD mode.

WGP. And it further transverses the $\lambda/2$ LC cell and exits the top polarizer. Similarly in the transmissive mode, the backlight from the bottom polarizer is also rotated by the LC cell to transmit the top polarizer. As a result, a common bright state is achieved.

Fig. 3 shows a normally white transflective LCD using a 90° TN cell as the polarization rotator. At the voltage-off state, the ambient light from the top polarizer experiences a polarization rotation by the TN cell and becomes parallel to the wire grids. After it is reflected by the WGP, its polarization state experiences a second conversion by the TN cell and it further exits the top polarizer at maximum light efficiency. In the transmissive mode, the backlight from the bottom polarizer is rotated by the TN cell and is transmitted by the polarizer. Thus without voltage, the cell is at a bright state. In the high voltage regime, the LC directors are reoriented perpendicular to the substrates. Neither the ambient light nor the backlight sees any phase retardation resulting in a black state.

To validate this device concept and investigate its performance, the electro-optic performance such as voltage-dependent transmittance (V-T) curve, voltage-dependent reflectance (V-R) curve, and iso-contrast plots for above configurations are calculated. For the VA cell, a negative $\Delta\varepsilon$ Merck LC mixture MLC-6608 is used. Its physical properties are listed as follows: extraordinary and ordinary refractive indices $n_e = 1.5578$, $n_o = 1.4748$ (at $\lambda = 589$ nm), parallel and perpendicular dielectric anisotropy $\varepsilon_{\parallel} = 3.6$, $\varepsilon_{\perp} = 7.8$, elastic constants $K_{11} = 16.7$ pN, and $K_{33} = 18.1$ pN. And a positive $\Delta\varepsilon$ LC material ZLI-4792 (from Merck) is employed for the 90° TN cell, with its parameters as $n_e = 1.5763, n_o = 1.4794\,(\lambda = 589\,\text{nm})$, $\varepsilon_{\parallel} = 8.3$, $\varepsilon_{\perp} = 3.1$, $K_{11} = 13.2$ pN, $K_{22} = 6.5$ pN, and $K_{33} = 18.3$ pN. The pretilt angles in the VA cell and the TN cell are set at 88° and 2°, respectively. In calculations, the extended Jones matrix method [8], [9] is used for both transmissive and reflective modes. Since the WGP reflects the electric fields parallel to grids and transmits the perpendicular components, it can be characterized by a transition matrix $J_{\rm TR}$ in correlating the incident and reflected electric field vectors on the WGP surface. More specifically, the incident electric field vector $[E_x^i, E_y^i]^T$ to the WGP surface and the reflected vector $[E_x^r, E_y^r]^T$ by the WGP can be correlated by

$$\begin{bmatrix} E_x^r \\ E_y^r \end{bmatrix} = J_{TR} \cdot \begin{bmatrix} E_x^i \\ E_y^i \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} E_x^i \\ E_y^i \end{bmatrix}. \quad (1)$$

Here in the WGP surface plane, the direction perpendicular to the wires is defined as the x-axis, and that parallel to the wires is set as the y-axis. Detailed derivations of the extended Jones matrix

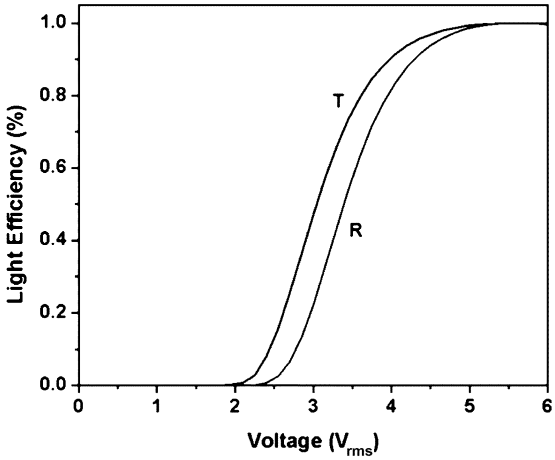

Fig. 4. V-T and V-R curves of the VA cell at $d\Delta n = 0.36\,\mu$m for $\lambda = 550$ nm.

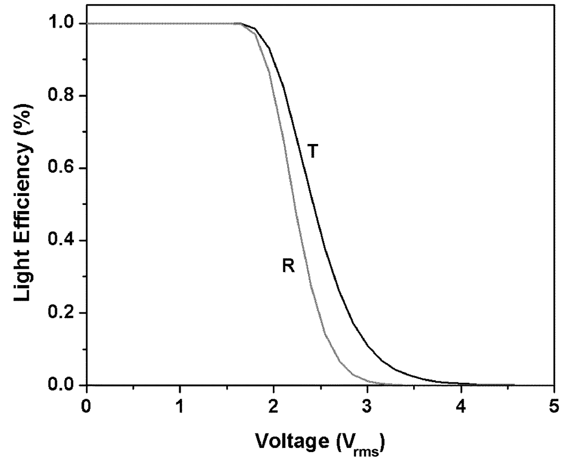

Fig. 5. V-T and V-R curves of the TN cell at $\mathrm{d}\Delta\mathrm{n} = 0.48\,\mu$m for $\lambda = 550$ nm.

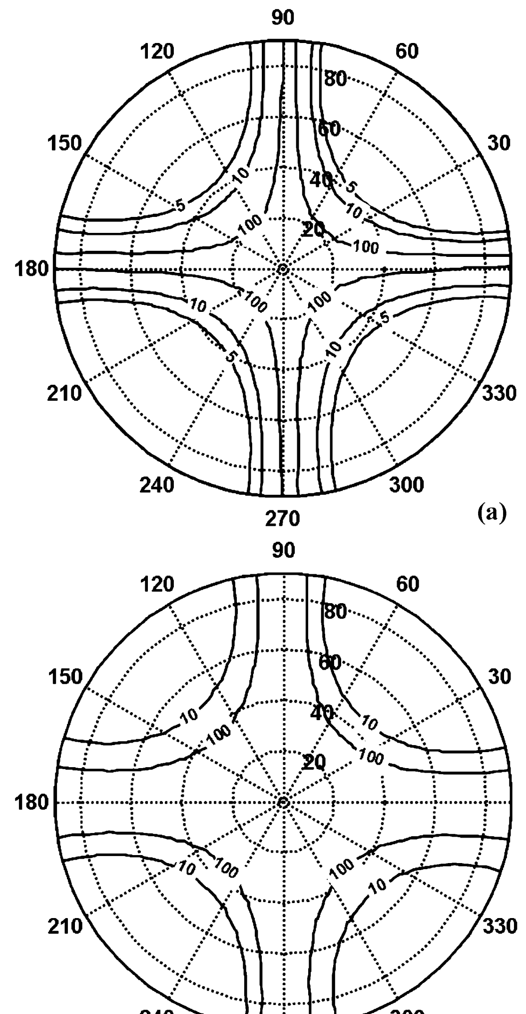

Fig. 6. Iso-contrast plots for the (a) transmissive and (b) reflective modes of a transflective VA cell.

forms for other layers, such as the LC cell can be found in [9]. However, a more realistic model of WGP should be referred to [5].

To reduce the driving voltage of the VA cell below 5 V_{rms} for TFT applications, the $d\Delta n$ (product of birefringence and cell gap) is set at ~360 nm. Fig. 4 plots the calculated V-T and V-R curves at normal incidence and $\lambda = 550$ nm. The light efficiency is normalized to the maximum light efficiency (~38%) between two parallel sheet polarizers. Besides, the WGP here is assumed to perform as a pure metallic mirror to the polarization parallel to the wire grids. As we can see from this figure, both T and R modes can reach 100% light efficiency at $V_{on} = 5\,V_{rms}$. A detailed view of the V-T and V-R curves shows that both curves have almost same light efficiency at the voltage-off state and the state when voltage is much higher than the threshold voltage. But the V-R curve rises more slowly than the V-T curve at a same intermediate driving voltage. This is because at the intermediate gray levels, the LC cell is no longer equivalent to a $\lambda/2$ plate. Therefore, the entrance light passing through the LC cell will have electric fields with polarization both parallel and perpendicular to the wire girds. Thus only a portion of the light is reflected by the WGP and the rest transmits the WGP and is further absorbed by the bottom polarizer. Consequently, there is always additional loss for the reflective mode on the WGP, until the LC cell is fully turned on to be equivalent to a $\lambda/2$ plate. This phenomenon is also observed in the normally white TN cell.

For the 90° TN cell shown in Fig. 3, once the $d\Delta n$ is greater than the Gooch–Tarry first minimum condition [10], it will have an effective polarization rotation. For our simulations, the $d\Delta n$ value is set at 480 nm. Fig. 5 shows the V-T and V-R curves with same cell parameters. The transmissive and reflective modes both have 100% light efficiency at $V = 0$ and reach good dark state at a high voltage. Similarly, because of the additional loss at the WGP at the intermediate gray levels, the reflective mode drops faster than the transmissive mode. In addition, because the positive LC material has a larger $\Delta\varepsilon$, the driving voltage in the TN cell is lower than that of the VA cell, which is good for low power consumption in mobile displays.

Besides the high light efficiency for both transmissive and reflective modes, viewing angle is another important requirement for transflective LCDs. The iso-contrast plots for the transmissive and reflective modes of the VA cell without any compensation film are shown in Fig. 6(a) and (b), respectively. The reflective mode shows a better view angle ($CR > 10:1$ within a 50° viewing cone) than the transmissive mode ($CR > 10:1$ within a 35° viewing cone). Similar phenomenon is observed in the iso-contrast plots for the transmissive and reflective TN modes shown in Fig. 7(a) and (b). Two reasons contribute to the better viewing

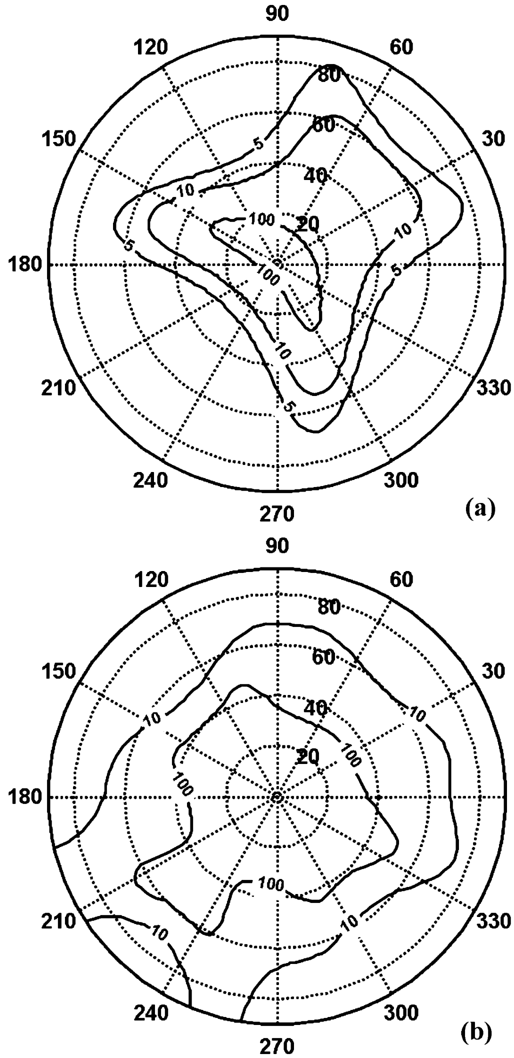

Fig. 7. Iso-contrast plots for the (a) transmissive and (b) reflective modes of a transflective TN cell.

angle of the reflective mode: 1) the reflective mode is equivalent to a two-domain structure because of the mirror image effect [11] and 2) during simulations the surface reflection is completely neglected (e.g., by adding anti-reflection films) and an ideal WGP is assumed, i.e., the WGP completely transmits light with its polarization perpendicular to the wire grids. In other words, the WGP in a reflective mode performs similar to an O-type reflective polarizer with its extraordinary reflection axis along with the wire girds [12]. Consequently, in the dark state of the reflective mode, because the small entrance ambient light at an oblique incident angle has both polarization components, it is further attenuated by the WGP, resulting in a weaker light leakage, thus a better dark state than the transmissive mode. In real environment, both surface and internal reflections from the WGP might not always be negligible. Thus the viewing angle of the reflective mode might be deteriorated. However, because the reflective mode is mainly used in outdoor ambient, the viewing angle design is always emphasized for the transmissive part. Owing to the simple structure without any achromatic quarter wave film, both the VA cell and TN cell here can be easily compensated without much difficulty. Typical compensation for the normally black VA cell can be achieved by adding a negative C film [13] between the top polarizer and the LC cell. And the normally white TN cell can be partially compensated by the wide view discotic Fuji film [14].

Compared to other transflective designs, the WGP also offers a potential fringing benefit of further enhancing the brightness of transmissive pixels in both VA and TN designs. After backlight passes through the bottom polarizer and reaches the WGP, the WGP will reflect most of light back. This mechanism offers a possibility of recycling and redistributing backlight to transmissive pixels. Thus, power consumption may be further reduced by enhancing backlight brightness available to the transmissive pixels. Note that from the energy saving point of view an imperfect light leakage through WGP (from the backlight) is perfectly allowed. Because of the same LC configuration and single-gap structure, the reflective pixels behave like their counter transmissive pixels and contribute to the overall output intensity.

In summary, the proposed single cell gap transflective LCD devices using the WGP as the polarization-dependent reflector show high light efficiency for both the transmissive and reflective modes. With a single cell configuration, the treatment of the LC cell is simple and the transmissive and reflective modes could have a similar response time. Furthermore, in this transflective LCD mode, no achromatic quarter wave films are necessary, which makes the optical compensation fairly easy. With the advance of nano fabrication of WGP, the suggested device can be a promising technology for future mobile displays.

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