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A Single-Cell-Gap Transflective Liquid Crystal Display With Complementary Common Electrodes and Reflectors

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***Abstract*—A single-cell-gap transflective liquid crystal display with complementary common electrodes on the top substrate and reflectors on the bottom substrate is demonstrated. These slit-patterned common electrodes and reflectors generate a strong longitudinal electric field in the transmissive region (T-region) and a weak fringe field in the reflective region (R-region). Both transmissive and reflective display modes show high optical efficiency and well-matched grayscales.**

***Index Terms*—Complementary electrode pattern, fringe field, transflective liquid crystal display (TR-LCD), vertical alignment.**

I. Introduction

TRANSFLECTIVE liquid crystal displays (TR-LCDs) have been widely used for mobile displays due to their outdoor and indoor readabilities. Because of the intrinsic difference in optical path between the transmissive (T) and reflective (R) regions, the simplest way to design a TR-LCD is to use the dual-cell-gap approach [1], [2]. However, the dual-cell-gap TR-LCD has some drawbacks, e.g., the R-region has faster response time than the T-region, cell gap uniformity is difficult to control, and defects occur near the T- and R boundaries.

Recently, several single-cell-gap TR-LCDs have been proposed [3]–[12]. Nevertheless, to compensate for the optical path difference between the T- and R-modes, the cell designs are usually rather complicated; many of them require in-cell retardation films. Among them, the single-cell-gap TR-LCD using partial switching mechanism in the R-region [13] exhibits some attractive features. For instance, the grayscale between the T- and R-regions overlaps reasonably well. However, if a metallic reflector is employed, then it should be isolated from the pixel electrode, otherwise no fringe field can be generated. These isolated reflectors would create a floating capacitor in the R-region and their charges are difficult to be released during frame refresh cycles. Although this problem can be solved by using discontinuous common electrodes, the electric field below the common electrode is still very strong in the R-region. As a result, the *LC* directors may be over switched.

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In this paper, we propose a single-cell-gap TR-LCD using specially designed electrode and reflector patterns [14]. Compared with other single-cell-gap TR-LCDs, our new design does not involve a complicated manufacturing process. Neither does it require any in-cell retardation films. More importantly, such a single-cell-gap TR-LCD exhibits a very good grayscale match between the T- and R-modes. The T-mode's optical efficiency reaches $\sim$98% and that of the R-mode exceeds 80%.

II. Device Structure and Working Principle

Fig. 1 shows the cross-sectional view of the new TR- LCD. A vertically aligned (VA) negative $\Delta\varepsilon$ *LC* layer is sandwiched between the top and bottom substrates and the cell gap is uniform throughout each pixel area. The common ITO electrode on the top substrate has a slit pattern, but the pixel ITO electrode on the bottom substrate is a whole piece within each pixel area. Above the pixel electrode, the reflector also forms a pattern. More specifically, the bottom reflector pattern is complementary to that of the top common electrode. In other words, there is no ITO common electrode right above the reflector region, and there is no reflector right below the ITO common electrode. Here, the bumpy reflector can be either a thin metal layer or a multilayer dielectric film. If a thin metal layer is used, the reflector and pixel electrode share the same electric potential. If a dielectric mirror is employed, then a light control film should be laminated to the top polarizer in order to avoid specular reflection and obtain a wide view angle. On the top and bottom sides of the *LC* panel, a half-wave film and a quarter-wave film are laminated to the inner side of the polarizer and analyzer to form a broadband circular polarizer. Such a circular polarizer is needed for the R-mode to obtain a good dark state. Based on this configuration, a crossed bottom circular polarizer is needed for the T-mode to achieve the same dark and bright states as the R-mode simultaneously.

Under such a complementary common electrode and reflector design, the electric field distribution is quite different between the T- and R-regions. Fig. 2 shows the simulated electric field distribution. In the T-region, a uniform longitudinal electric field is generated by the top common electrodes and the bottom ITO pixel electrode. In the R-region, however, a fringe field is generated since no common electrode exists right above the reflectors. If we design the cell gap, common electrode, and reflector patterns properly, we can make the average longitudinal component of the electric field in the R-region approximately one half of that in the T-region.

Since the electric field in the T-region is $\sim 2\times$ stronger than that in the R-region, the *LC* director's orientation angle (θ_T,

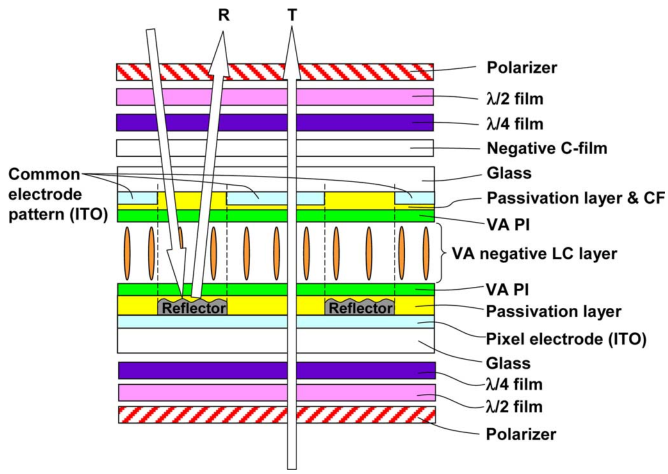

Fig. 1. Cross-sectional view of the new TR-LCD (one pixel area).

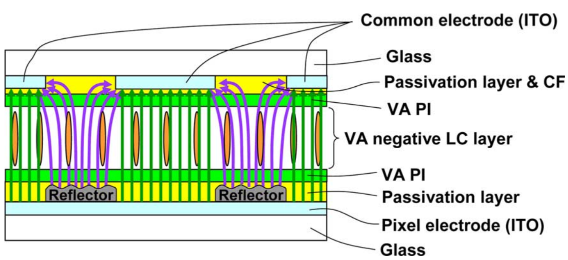

Fig. 2. Electric field distribution in the T– and R-regions of the new TR-LCD (one pixel area).

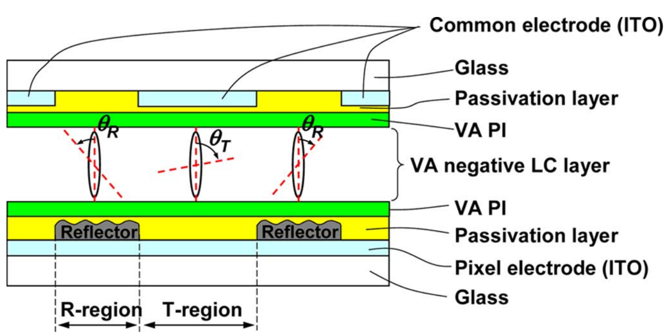

Fig. 3. *LC* director orientation angle in a voltage-on state. The tilt angle in the T-region θ_T is about twice as large as that in the R-region θ_R.

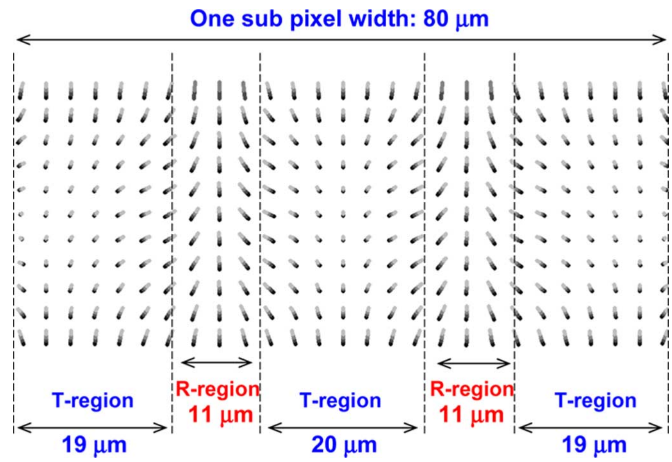

Fig. 4. Simulated *LC* director profile at $\mathrm{Von} = 4\ \mathrm{V_{rms}}$ with cell gap $\mathrm{d} = 5\ \mu\mathrm{m}$.

tilted from the normal direction) in the T-region is also about twice larger than that in the R-region (θ_R), as depicted in Fig. 3. Under such a circumstance, in a voltage-on state, the *LC* layer's phase retardation in the T-region is roughly twice as large as the R-region. Since the back light passes through the T-region once, while the ambient light passes through the R-region twice, the overall accumulated phase retardation in the T-region is comparable to that in the R-region. Consequently, their grayscales can overlap with each other quite well.

In Fig. 1, in the voltage-off state, the VA *LC* layer does not impose any phase change to the incoming polarized light. In the T-region, the incident unpolarized backlight becomes circularly polarized after it passes through the bottom circular polarizer. Since the VA *LC* layer causes no phase change, the outgoing light is blocked by the top circular polarizer. Thus, a dark state is obtained. In the R-region, the incident circularly polarized ambient light sees no phase retardation after traversing through the VA *LC* layer. Upon reflection from the bumpy reflector, a π phase change occurs so that the outgoing light is blocked by the top circular polarizer, resulting in a dark state. In a voltage-on state, the *LC* directors are reoriented and the *LC* layer is equivalent to a half-wave phase retarder in the T-region and a quarter-wave phase retarder in the R-region. Consequently, both T- and R-regions are in bright state.

Surface treatment is crucial to form stable domains in the T- and R-regions. In our simulation, if the rubbing in Figs. 1–3 is along the elongated electrode direction, i.e., perpendicular to the paper, we found that the domains are stable in both T- and R-regions. However, if the rubbing is perpendicular to the elongated electrode direction, i.e., parallel to the paper, the domains are unstable due to the push-and-pull interactions across the T- and R-regions.

III. Simulation Results

To prove the concept, we performed 2-D computer simulations using a 2dimMOS program (from autronic-MELCHERS, Germany). The simulated *LC* director profile at 4 $\mathrm{V_{rms}}$ is shown in Fig. 4. The negative *LC* material used is MLC-6608 (from Merck) and surface rubbing direction points into the paper. In order to obtain optimal electro-optic performance, we chose a 5-μm cell gap and 11-μm reflector width.

From Fig. 4, the directors in the T-region have a fairly uniform tilt angle. This is because the electric field in the T-region is always uniform and longitudinal. Such a uniform tilt-angle distribution results in a nearly flat transmittance in T-region under crossed circular polarizer configuration as shown in Fig. 5. In the R-region, however, the electric field is a nonuniform fringe field; the closer to the center, the weaker the electric filed becomes. Thus, the tilt angle (with respect to the normal) in the center is smaller than that near the edges, as shown in Fig. 4. Such a nonuniform tilt angle distribution produces a nonuniform reflectance profile in the R-region, as depicted in Fig. 5. Here, the width of one subpixel is 80 μm and the incident light wavelength is 550 nm. Also shown in Fig. 4, the *LC* directors form multidomains in both T- and R-regions. These multidomain structures help to enlarge the viewing angle for both T- and R-modes.

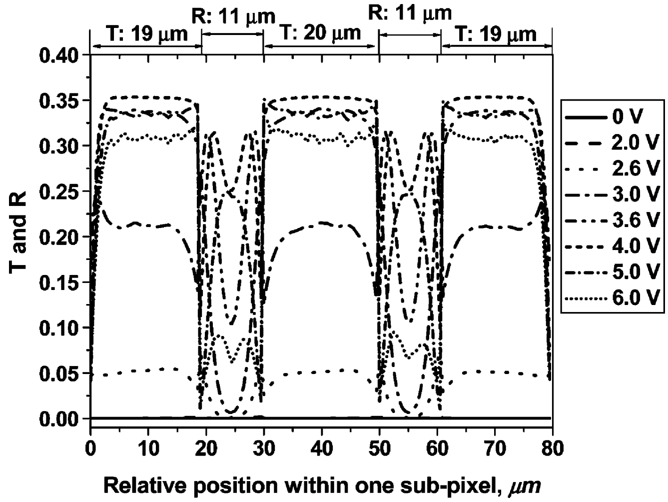

Fig. 5. Simulated transmittance and reflectance profile across one sub-pixel area at different voltages. Here one subpixel width is 80 μm and $\lambda = 550$ nm.

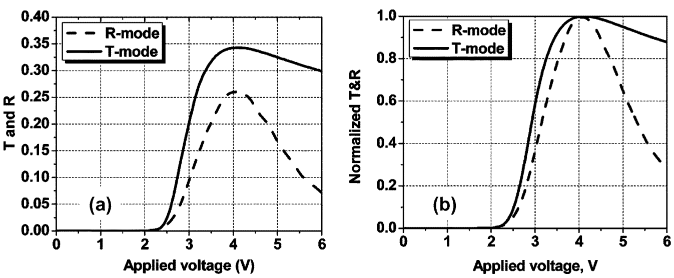

Fig. 6. Simulated VT and VR curves under normal incidence: (a) before normalization and (b) after normalization. $\lambda = 550$ nm.

Fig. 6(a) shows the simulated voltage-dependent transmittance (VT) and reflectance (VR) curves under normal incidence. Because of the nonuniform *LC* director profiles, we average the transmittance and reflectance values over the entire T- and R-regions, respectively. Both the T- and R-modes reach their respective maximum at $\mathrm{V} \sim 4\ \mathrm{V_{rms}}$. However, the optical efficiency of the R-mode is only ~80% in comparison with the T-mode. The reasons are twofold: 1) in the R-region, the aluminum reflector has only about 91% reflectivity, and 2) the *LC* directors in the R-region are not uniform because of the nonuniform fringe fields. Therefore, the reflectance profile over the entire reflective pixel region is not flat (shown in Fig. 5) even under the crossed circular polarizer configuration, which slightly lowers the light efficiency.

For a TR-LCD, the absolute intensities of backlight source and ambient light are usually not equal. Thus, it is more representative to compare the normalized transmittance and reflectance as Fig. 6(b) shows, rather than the absolute values. From Fig. 6(b), both T- and R-modes have a threshold voltage of about 2 $\mathrm{V_{rms}}$ and both reach maximum at $\sim 4\ \mathrm{V_{rms}}$. In the intermediate grayscales, the R-mode curve is slightly more linear than the T-mode curve. Overall, their grayscales match with each other quite well. As a matter of fact, the common electrode patterns on the top substrate and the reflector patterns on the bottom substrate do not need to complement each other perfectly. A certain degree of mismatch or gap in between is allowable. This provides another degree of freedom for optimizing the VT and VR curves.

IV. Conclusion

A new single-cell-gap TR-LCD is demonstrated. This design does not require any in-cell retardation films. To compensate for the optical path difference between the T- and R-regions, we use pixilated complementary common electrodes on the top substrate and reflectors on the bottom substrate. Such a complementary pattern design generates a strong longitudinal electric filed in the T-region and a weak fringe field in the R-region. By optimizing the device parameters, we can make the grayscales of the T- and R-modes match with each other quite well. Moreover, the manufacturing process of this design is completely compatible to the current mass production manufacturing technologies. A widespread application of this new TR-LCD is foreseeable.

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