Display Technology Letters

Transmissive and Transflective Blue-Phase LCDs With Enhanced Protrusion Electrodes

Yan Li and Shin-Tson Wu, *Fellow, IEEE*

***Abstract*—An enhanced protrusion electrode is proposed for both transmissive and transflective blue-phase liquid crystal displays. For transmissive displays, the new design increases transmittance while keeping a low operating voltage. For transflective displays, it exhibits high transmittance and reflectance and a well-matched gamma curve with a single cell gap.**

***Index Terms*—Blue phase, protrusion, single cell gap, transflective liquid crystal display (LCD).**

I. Introduction

POLYMER-STABILIZED blue-phase liquid crystals (PS-BPLCs) [1]–[6] exhibit several attractive features, such as submillisecond response time, no need for molecular alignment layer, and cell gap insensitivity. In particular, fast response time not only reduces motion blur but also enables color sequential displays using RGB LEDs. The elimination of color filters triples the optical efficiency and resolution density. However, some technical obstacles remain before widespread application of this promising technology can be realized, such as high operating voltage ($\sim 50V_{\rm rms}$), relatively low transmittance (~65%), hysteresis [7], and residual birefringence which lowers the contrast ratio.

The operation voltage of a polymer-stabilized blue-phase LCD is governed by both device configuration and Kerr constant (K) of the employed material [8], [9]. From a material viewpoint, a large Kerr constant is favorable. Recently, a BPLC material with $K \sim 13.7$ nm/V^2 has been developed [10]. This new material will undoubtedly accelerate the emergence of blue-phase LCDs. On the device standpoint, some device structures such as protrusion electrode [8], [11], wall-shaped electrode [12], corrugated electrode [13], and double-penetrating fringe fields [14] show a very positive trend to lower the driving voltage to 10 $V_{\rm rms}$, except that the transmittance is sacrificed. Therefore, an urgent task is determining how to lower the operation voltage while keeping a high transmittance.

Manuscript received February 18, 2011; revised March 24, 2011; accepted April 04, 2011. Date of current version June 07, 2011. This work was supported by AU Optronics (Taiwan).

The authors are with the College of Optics and Photonics, University of Central Florida, Orlando, FL 32816 USA (e-mail: yanli@creol.ucf.edu; swu@mail.ucf.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JDT.2011.2141115

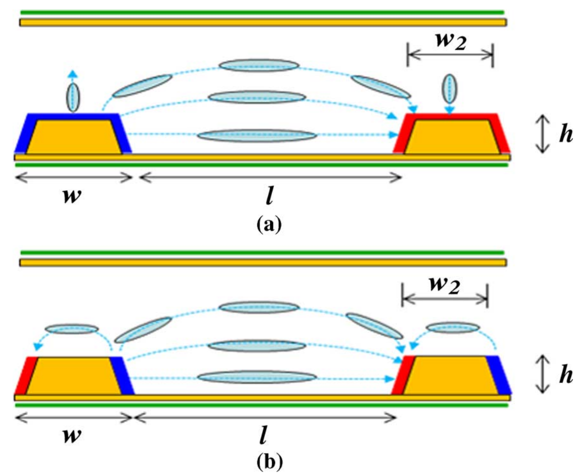


Fig. 1. BPLCD (a) with conventional protrusion electrodes and (b) with enhanced protrusion electrodes.

In this paper, we propose an enhanced protrusion electrode structure for BP LCDs. In conventional protrusion electrode [8], the entire protrusions are covered with one type of electrode. However, in the proposed enhanced protrusion electrode, two different electrodes are coated on each side of a protrusion. The dead zones are eliminated by the in-plane switching (IPS)-like structure on the top of the protrusions. As a result, the average transmittance is increased, while the operating voltage is barely changed. In addition, we propose a single-cell-gap transflective BP LCD based on the modified enhanced protrusion structure which exhibits some attractive properties, such as high transmittance, single gamma driving, and wide viewing angle.

II. Device Configuration

Fig. 1(a) shows the conventional protrusion electrode structure [8], where the trapezoid protrusion electrode has a substantial height h. The bottom width of each electrode is w, the top width is w_2, and the gap between neighboring electrodes is l. In the gap between protrusions, electric fields with rich horizontal components are generated and penetrate deeply into the *LC* bulk, resulting in a lower operating voltage. However, on the top of the protrusion, electric fields are basically vertical and do not contribute to transmittance, resulting in dead zones. Thus, the average transmittance is low.

Fig. 1(b) shows the enhanced protrusion structure where one side-wall of a protrusion is coated with pixel electrode (red),

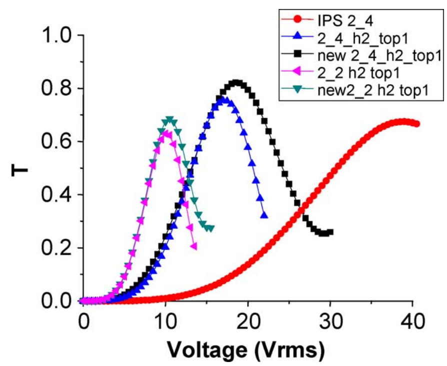


Fig. 2. Simulated VT curves of IPS electrode (red), conventional protrusion structures (blue and magenta), and new protrusion structures (black and green).

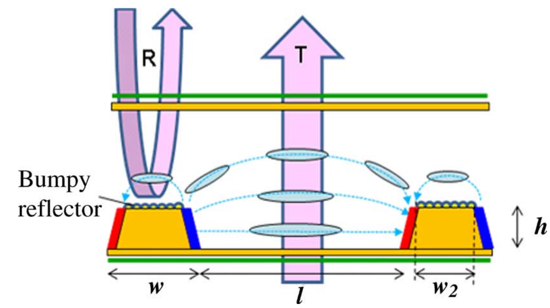


Fig. 3. Device configuration of a single-cell-gap transflective blue-phase LCD with enhanced protrusion structure.

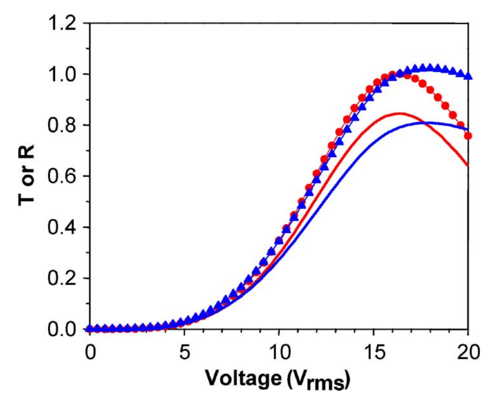


Fig. 4. Simulated VT and VR curves for the transflective blue phase LCD using enhanced protrusion structure. The red and blue lines represent simulated VT and VR curves, and the red dots and blue triangles represent normalized transmittance and reflectance.

and the other is with common electrode (blue). In the gap between protrusions, the electric field distribution is similar to that in a conventional protruded structure, so that the low operating voltage feature is still maintained. However, on the top of the protrusions, there is no longer a dead zone. Instead, it is like an IPS structure, generating horizontal fields and inducing transmittance. Therefore, the average transmittance is increased.

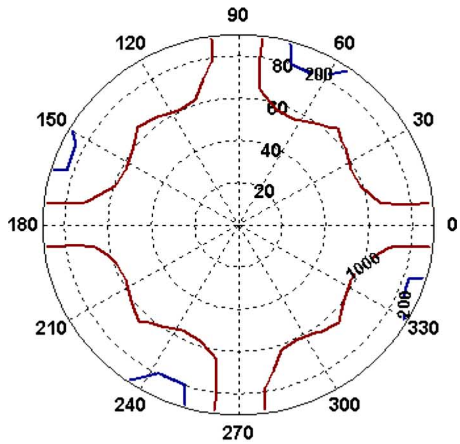
III. Results

To validate the concept, we carried out the electro-optical simulation as in [3]. First, we used commercial software Dimos (AUTRONIC-MELCHERS GmbH) to obtain the electric field potential distribution and then used a 2×2 extended Jones Matrix method [15], [16] to finish the optical calculation. The Kerr constant here used is 12.68 nm/V^2, and the saturation birefringence of the BPLC mixture is assumed to be 0.2.

Fig. 2 compares the voltage-dependent transmittance (VT) curves of the conventional and enhanced protrusion structures. The red curve denotes the VT for a traditional IPS structure. The IPS structure with an electrode width $w = 2\ \mu$m, gap $l = 4\ \mu$m and cell gap 10 μm, has a 67% transmittance at $\sim 40V_{rms}$. The blue curve is for a conventional protrusion structure with $w = 2\ \mu$m, $w_2 = 1\ \mu$m, $l = 4\ \mu$m, and height $h = 2\ \mu$m. The on-state voltage is reduced to $\sim 17V_{\rm rms}$, while the peak transmittance is boosted to ~77%. The black curve is for the corresponding enhanced protrusion structure with the same parameters. The peak transmittance is increased to ~85%, although the peak-transmittance voltage is slightly higher. The magenta curve is for a conventional protrusion with $w = 2\ \mu$m, $w_2 = 1\ \mu$m, $l = 2\ \mu$m, and height $h = 2\ \mu$m. With a smaller gap l, the operating voltage is further reduced to 10 $V_{\rm rms}$, but the transmittance is somewhat lower (~63%). On the other hand, the corresponding enhanced protrusion structure (green curve) has a higher transmittance (~69%) with almost the same operating voltage.

Transflective LCD is highly desirable for its good sunlight readability [17], [18]. Recently, blue phase has been considered for single-cell-gap color sequential transflective LCDs [19], [20]. With some modification, the enhanced protrusion design could also be used in transflective BP LCDs, as shown in Fig. 3. The BPLC cell is sandwiched between two crossed circular polarizers. A nonmetal bumpy reflector is formed on the top of each protrusion; these regions work as reflective (R) mode, and the rest of the pixel works as transmissive (T) mode. In the T region, the substantial height of the protrusion enables electric fields to penetrate deeply into the BPLC layer, resulting in large phase retardation. In the R region, the IPS-like electric field distribution has a shallow penetration so that the accumulated phase retardation is relatively small. However, the ambient light traverses the R region twice and the phase retardation is doubled. As a result, the transmittance and reflectance could be matched by properly designing the structure. Moreover, the electric fields generated by IPS electrodes in the T and R regions have a limited penetration depth. As long as the cell gap exceeds the electric field penetration depth, the VT and VR curves are insensitive to the cell gap. That means, both T and R regions could have the same cell gap, which makes the fabrication much easier.

For an optimized structure, where $w = 3\ \mu$m, $w_2 = 2\ \mu$m, $h = 2\ \mu$m, $l = 3.3\ \mu$m. and cell gap $= 10\ \mu$m, we plot the VT and VR curves at $\lambda = 550$ nm in Fig. 4. The red and blue solid lines represent the VT and VR curves for the T and R regions, respectively; both are normalized to the transmittance of two parallel polarizers. At $16.4V_{\rm rms}$, the transmittance reaches 84.4% while reflectance reaches ~80%. The dotted curves denote the normalized VT and VR curves to their individual transmittance and reflectance at $16.4V_{\rm rms}$ respectively. We obtain well-matched VT (red dots) and VR (blue dots) curves to enable single gamma driving.



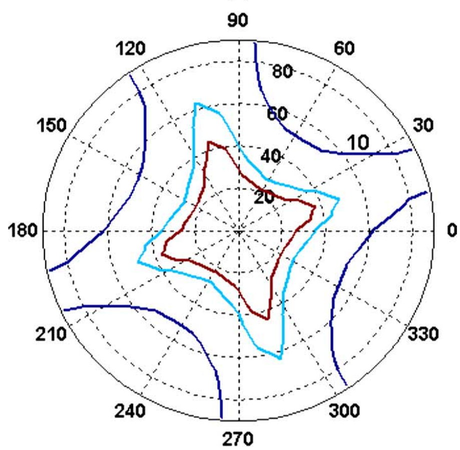


Fig. 5. Isocontrast plots of the proposed TR-LCD: (a) T region and (b) R region.

By using the broadband wide-view circular polarizers in [18] and [19], we obtain a very wide view in the T region and reasonably wide view in the R region. The isocontrast plots are shown in Fig. 5. BP LCDs have inherently wide view due to its optically isotropic dark state.

IV. Conclusion

We propose a new enhanced protrusion design for BP LCDs. In the transmissive LCD, the new structure improves the transmittance by 10% compared to conventional protrusion structure, while maintaining a low operating voltage. In the single-cell-gap transflective BP-LCD based on this enhanced protrusion design, both T and R regions could achieve a reasonably high transmittance (∼84.4%) and reflectance (80%). Moreover, the well-matched normalized VT and VR curves enable a single gamma driving.

References

[1] H. Kikuchi, M. Yokota, Y. Hiskado, H. Yang, and T. Kajiyama, "Polymer-stabilized liquid crystal blue phases," *Nat. Mater.*, vol. 1, pp. 64–68, 2002.

[2] S. W. Choi, S. I. Yamamoto, Y. Haseba, H. Higuchi, and H. Kikuchi, "Optically isotropic-nanostructured liquid crystal composite with high Kerr constant," *Appl. Phys. Lett.*, vol. 92, 2008, Art. ID 043119.

[3] Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S. T. Wu, "Electro-optics of polymer-stabilized blue phase liquid crystal displays," *Appl. Phys. Lett.*, vol. 94, 2009, Art. ID 101104.

[4] Z. Ge, L. Rao, S. Gauza, and S. T. Wu, "Modeling of blue phase liquid crystal displays," *J. Display Technol.*, vol. 5, no. 7, pp. 250–256, Jul. 2009.

[5] K. M. Chen, S. Gauza, H. Xianyu, and S. T. Wu, "Submillisecond gray-level response time of a polymer-stabilized blue-phase liquid crystal," *J. Display Technol.*, vol. 6, no. 2, pp. 49–51, Feb. 2010.

[6] Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," *Appl. Phys. Lett.*, vol. 96, 2010, Art. ID 113505.

[7] K. M. Chen, S. Gauza, H. Xianyu, and S. T. Wu, "Hysteresis effects in blue-phase liquid crystals," *J. Display Technol.*, vol. 6, no. 8, pp. 318–322, Aug. 2010.

[8] L. Rao, Z. Ge, S. T. Wu, and S. H. Lee, "Low voltage blue-phase liquid crystal displays," *Appl. Phys. Lett.*, vol. 95, 2009, Art. ID 231101.

[9] L. Rao, J. Yan, and S. T. Wu, "Prospects of emerging polymer-stabilized blue-phase liquid crystal displays," *J. Soc. Inf. Display*, vol. 18, pp. 954–959, 2010.

[10] L. Rao, J. Yan, S. T. Wu, S. Yamamoto, and Y. Haseba, "A large Kerr constant polymer-stabilized blue-phase liquid crystal," *Appl. Phys. Lett.*, vol. 98, 2011, Art. ID 081109.

[11] S. Yoon, M. Kim, M. S. Kim, B. G. Kang, M. K. Kim, A. K. Srivastava, S. H. Lee, Z. Ge, L. Rao, S. Gauza, and S. T. Wu, "Optimisation of electrode structure to improve the electro-optic characteristics of liquid crystal display based on the Kerr effect," *Liq. Cryst.*, vol. 37, pp. 201–208, 2010.

[12] M. Kim, M. S. Kim, B. G. Kang, M. K. Kim, S. Yoon, S. H. Lee, Z. Ge, L. Rao, S. Gauza, and S. T. Wu, "Wall-shaped electrodes for reducing the operation voltage of polymer-stabilized blue phase liquid crystal displays," *J. Phys. D: Appl. Phys.*, vol. 42, 2009, Art. ID 235502.

[13] M. Jiao, Y. Li, and S. T. Wu, "Low voltage blue-phase liquid crystal displays," *Appl. Phys. Lett.*, vol. 96, 2010, Art. ID 011102.

[14] L. Rao, H. C. Cheng, and S. T. Wu, "Low voltage blue-phase LCD with double-penetrating fringe fields," *J. Display Technol.*, vol. 6, no. 8, pp. 287–289, Aug. 2010.

[15] A. Lien, "Extended Jones matrix representation for the twisted nematic liquid-crystal display at oblique incidence," *Appl. Phys. Lett.*, vol. 57, pp. 2767–2769, 1990.

[16] Z. Ge, T. X. Wu, X. Zhu, and S. T. Wu, "Reflective liquid-crystal displays with asymmetric incident and exit angles," *J. Opt. Soc. Amer. A.*, vol. 22, pp. 966–977, 2005.

[17] X. Zhu, Z. Ge, T. X. Wu, and S. T. Wu, "Transflective liquid crystal displays," *J. Display Technol.*, vol. 1, no. 1, pp. 15–28, Sep. 2005.

[18] Z. Ge and S. T. Wu, *Transflective Liquid Crystal Displays*. Hoboken, NJ: Wiley, 2010.

[19] Y. Li, M. Jiao, and S. T. Wu, "Transflective display using a polymer-stabilized blue phase liquid crystal," *Opt. Exp.*, vol. 18, pp. 16486–16491, 2010.

[20] F. Zhou, J. P. Cui, Q. H. Wang, D. H. Li, and D. Wu, "A single-cell-gap transflective display using a blue-phase liquid crystal," *J. Display Technol.*, vol. 7, no. 4, pp. 170–173, Apr. 2011.