Resolution Doubling by Liquid Crystal Based Optical Shift

Abstract

We have developed an all-liquid-crystal-based optical shift solution that can double the resolution of a 2.6" LCD panel with 30µm pixels. The shift is realized by a large cell gap LC cell where the LC director is fixed at a tilted state by voltage. We also propose a polarization modulator with sectioned electrodes to improve the image quality over the whole display area. As a result, a prototype 2.6" optical shift display with doubled resolution is realized.

Keywords: optical shift; resolution doubling; LC cell

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Objective and Background:

Higher resolution is an ever present pursuit of display panels in order to generate a more lively and realistic image for viewers. Decreasing the pixel size is a straightforward way to achieve higher resolution, however, coupled with drawbacks such as more challenging process and lower aperture ratio and efficiency. As a workaround, it is also possible to gain higher resolution by temporal multiplexing. The working principle is illustrated in Fig.1 (a). A low PPI display with polarized light is used as the image source. It can be either a normal LCD or an OLED display with a circular polarizer, etc. The image light first passes through a polarization modulator (PM), where its polarization is switched 90° between adjacent frames. To achieve this function, the PM can be a fast liquid crystal cell operating in electrically controlled birefringence (ECB) mode or twisted nematic (TN) mode. Then, the temporally modulated image light passes through an optically anisotropic layer, where the layer's optical axis is at a tilted angle relative to its surface. The extraordinary light will travel a deflected path compared to the ordinary light, and thus being shifted by a certain distance. As a result, half the frames are displayed at the original position and half at a shifted position, together forming a new image with doubled spatial resolution and halved temporal resolution. This method is often known as optical shift [1-2] and has been commercialized in applications such as projector displays.

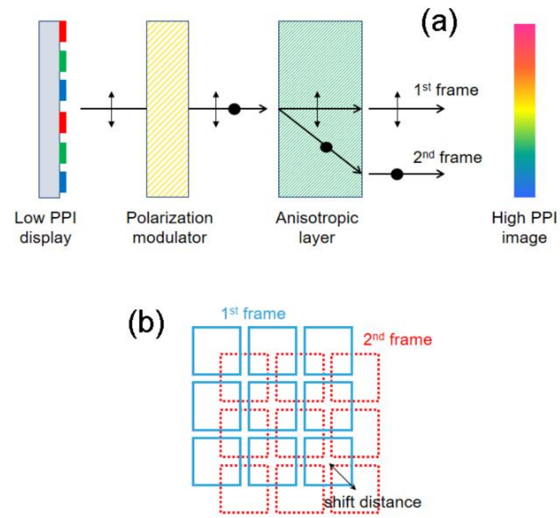

Figure 1. (a) Illustration of the working principle of optical shift. (b) Relation between shift distance and pixel pitch.

As shown in Fig.1 (b), the shift distance should be half the pixel diagonal pitch to achieve an ideal resolution-doubling effect. This means that for larger pixels, the required shift distance is also larger and the thickness of the anisotropic layer (e.g. quartz crystal) must increase proportionally. Along with the increase in size, the availability and cost of such a material become a key problem. So until now most products based on optical shift are limited to pixel pitch <10µm and size <1 inch, hindering its application to the much wider TFT LCD categories.

In light of this, we have developed an all-liquid-crystal-based optical shift solution that supports up to 30µm pixel pitch, significantly expanding its potential application. The shift is realized by a large cell gap liquid crystal cell with LC director tilted by applied voltage. We also developed a PM device with multiple electrode sections that synchronize with the scanning of the image source display correspondingly, improving the contrast between adjacent frames across the whole display area.

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Combining these components, we successfully demonstrate a 2.6” optical shift display with resolution doubled from 1920x1080 to effectively 2715x1527 and image quality enhanced.

Results:

In order for the extraordinary beam (E beam) to effectively shift compared to the ordinary beam (O beam), the LC director in the cell should possess an optimum angle α relative to the cell surface, as shown in Fig.2 (a). For normal incidence, the E beam will travel at an angle θ given by:

$$\theta = \operatorname{atan}\left(\frac{n_o^2}{n_e^2 \cdot \tan\alpha}\right) + \alpha \qquad (1)$$

, where n_e and n_o are the refractive index of the LC material. For a typical LC with n_e=1.7 and n_o=1.5, θ will have its minimum (largest deflection) when α≈41°. To verify this, we fabricated ECB mode LC cells with 100μm cell gap and controlled the LC director by applying varying voltage from 0V to 5V. The shift behavior can be tested with a simple experimental setup as shown in Fig.2 (b). A fine metal pattern on glass is used as the object, and the polarization of the illuminating light is controlled by a rotatable polarizer. The 100μm-gap LC cell is placed on top of the metal pattern and the system is observed under optical microscope. Fig.2 (c)-(e) show the image of the metal pattern when the incident polarization is perpendicular to, at 45° to, and parallel to the LC alignment direction, respectively. We can clearly see that these three cases exhibit no shift, half the light shifted, and all the light shifted, respectively. The shift distance can then be measured from Fig.2 (d). Notably, the image is clean in both Fig.2 (c) and (e) without ghosting, showing a well preserved polarization state when light passes through the thick LC cell.

When quantifying the shift ability of an LC cell, it should be noted that the LC director within the cell is not uniformly aligned at a specific angle α. Instead, it changes gradually along the cell thickness direction, as shown by the simulated LC director profile in Fig.2 (f) under 2V voltage. In this case, the E beam angle and shift distance can still be estimated by equation (1), but for each of the infinitesimal LC layers. The total shift distance can then be expressed as an integral through the cell thickness direction. We have simulated the LC director profile from 0V to 5V, and the total shift distance is calculated and plotted as the red line in Fig.2 (g). It shows a peak value of ~10μm for voltage between 2~2.5V, and decreases for lower or higher voltages, in accordance with the dependence of θ on α. When compared to the experimentally measured shift distance (green line), the two curves show good agreement except for a small offset in voltage which may be due certain difference in LC parameters that are used in the simulation compared to the actual values. Nevertheless, the result well proves the feasibility of using an LC cell for optical shift.

For our prototype, we use a 2.6” monochromatic display with 30μm pixel pitch and 1920x1080 resolution. Referring to Fig.1 (b), the optimum shift distance should be half the pixel diagonal pitch, which is 21.2μm. So two 100μm-gap LC cells are used in series to achieve the desired shift distance in the prototype.

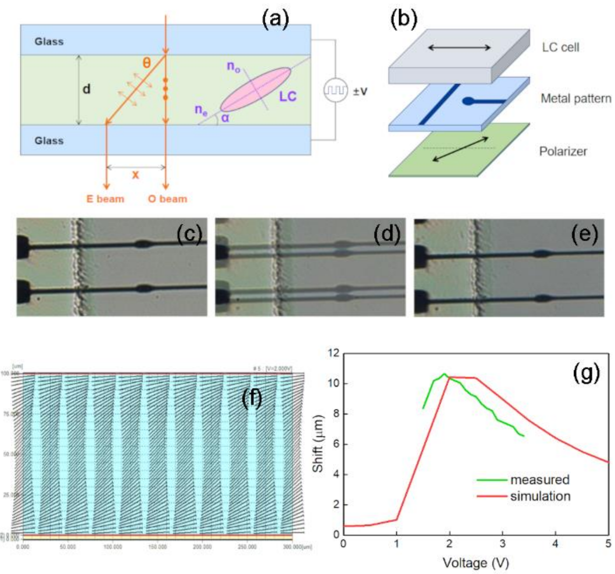

Figure 2. (a) Illustration of E beam and O beam passing through an LC cell. (b) Experiment setup for measuring shift distance. (c)-(e) Microscope images of the metal pattern when the incident polarization is perpendicular to, at 45° to, and parallel to the LC alignment direction. (f) Simulated LC director profile under 2V voltage. (g) Simulated and measured shift distance with varying voltage.

For the polarization modulator, we have fabricated ECB mode PMs with fast response and high polarization contrast. Since it is a well-studied and also commercialized device, we will not discuss the basic performance in detail. However, for its application in optical shift, it is worth discussing its electrode design and synchronization with the image source display. To effectively double the resolution, the image update on the source display and the polarization switching should be precisely matched in time. So that the content in one frame is displayed in one spatial position and the other frame in the other (shifted) position, forming an independently-addressable virtual display with doubled resolution. Deviation from this criterion will cause content mixing in the virtual display and degrades image quality.

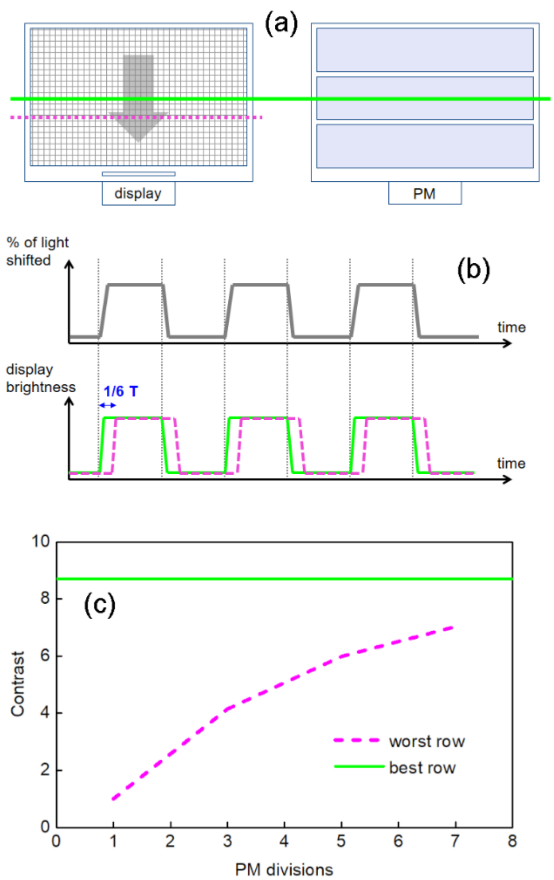

Figure 3. (a) Synchronization between image source display and PM. (b) Shift sequence of the PM and brightness change of the image source display. (c) Dependence of contrast on PM division number.

In Fig.3 (a) and (b), the mechanism is illustrated in more detail. Suppose the image source display scans from top down, and the scanning of the middle row is synchronized with the PM switching, as denoted by the green line in Fig.3 (a). Then for this row on the source display, its image update and position shift is constantly matched. For example, as illustrated in Fig.3 (b), if the green row is displaying an alternating white-black image, the white frame will always correspond to the shifted state of the PM (shown by the gray line) and the black frame to the non-shifted state. Thus this row is independently addressable. By comparison, for other rows on the source display, its content update will have an offset in time relative to the PM switching, leading to the content of each frame to be partially projected to both spatial positions, causing blurring. Specifically, for the top and bottom rows with half-frame offset, any image content will be evenly divided into the shifted and non-shifted positions. In this case there is effectively no resolution enhancement.

To overcome this limitation and achieve resolution boost for the full active area, we have designed a PM with sectioned electrodes. Each of these sections are switched independently, synchronizing with the corresponding portion of the image source display. For example referring to Fig.3 (a), if the PM is divided into 3 equal sections, then the upper, middle, lower sections can be synchronized to the 1/6, 3/6, 5/6 row of the source display, respectively. Then even the worse row would have only 1/6 frame offset instead of half frame, largely retaining the resolution enhancement.

To quantify the gain by sectioning the PM, we have calculated the contrast between two adjacent frames. The contrast is defined as the light intensity ratio between the shifted and non-shifted positions while the display is showing an alternating white-black image. The image source display runs at 120Hz and the rise curve and fall curve of both the source display and the PM are taken from experimental measurements. The results are plotted in Fig.3 (c). For the best row, where image update and shift switching is precisely matched, the contrast is over 8. This value depends on the response time of the source display and the PM, as well as the polarization crosstalk of the PM, and is independent of electrode divisions. On the other hand for the worst row, which corresponds to the edge of each section, the contrast increases with increased number of electrode divisions. In principle it will approximate the best row for a large enough number of divisions, but in practice choosing 5-7 divisions can already achieve good contrast – thus a good balance between performance and driving complexity. In our prototype we have chosen 5 divisions for the PM.

Lastly, we assemble the 2.6” display, the PM, and the 100μm-gap LC cells into an optical shift display prototype. The PM electrode switching is synchronized with the corresponding portion of the display, and the display is set to show two contents alternately, for the even and odd frames. The contents for the even and odd frames are generated by our algorithm considering the pixel distribution of the virtual display after optical shift, the detail of which is beyond the scope of this paper. Fig.4 shows an example of the resolution enhancement with optical shift. The prototype displays a test pattern, where a portion of the pattern consists of concentric fringes with decreasing pitch towards the periphery, as shown in Fig.4 (a). The prototype is observed under optical microscope, for the case of optical shift disabled (Fig.4 (b)), and optical shift enabled (Fig.4 (c)), respectively. We can clearly see an improvement in both pattern visibility and overall image quality, proving the successful enhancement in display resolution by optical shift.

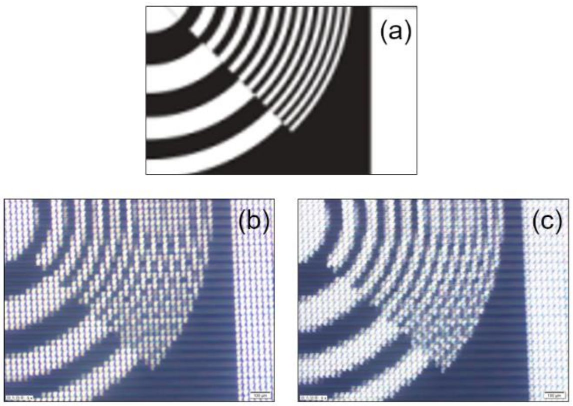

Figure 4. (a) Resolution test pattern. (b) Image without optical shift, observed under optical microscope. (c) Image with optical shift, observed under optical microscope.

Impact:

In this work we have demonstrated the feasibility of using a large cell gap LC cell as the optical anisotropic layer for optical shift of display pixels, supporting up to 30μm pixels when two cells are used in series. This method opens up new possibilities for enhancing display resolution with optical shift. We also discussed the gain in content contrast by sectioning the polarization modulator and synchronize the sections with the corresponding portions of the display. Considering the simplicity of the components used, the reported results may find application for a wide range of display products where resolution improvement is desired.

Reference:

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