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Brief Communication

Optimized Pixel Design to Remove Disclination Lines in a Homogeneously Aligned Liquid Crystal Microdisplay Driven by a Fringe-Electric Field

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A fringe-field-driven homogeneously aligned liquid crystal (LC) [named fringe-field switching (FFS) mode] microdisplay which is free of disclination lines has been designed. With a pixel structure newly proposed in which the LCs with negative dielectric anisotropy aligns perpendicular to the horizontal field existing between pixels and the equipotential area is optimized, the LC director is not deformed at all by this disturbing field between pixels. Consequently, the disclination lines can be suppressed even with a distance of 1 μm for a pixel size of about 15 μm so that a high resolution and high contrast microdisplay can be realized. [DOI: 10.1143/JJAP.45.1686]

KEYWORDS: liquid crystal on silicon, disclination, fringe-field switching

One of electronic information displays, liquid crystal display (LCD) has a great impact on modern electronic society as an interface between human beings and machines. At present, the sizes of LCDs range from very small sizes, less than 1 inch to larger than 50 inches with major application areas such as mobile phones, notebooks, monitors and LC televisions. However, the manufacturing cost of large size LCDs is still too expensive so that making them popular is difficult. Another alternative to realize large size LCDs is a projection display that magnifies an image in a microdisplay.[1)] Recently, two types of LC light valves for the projection displays: transmissive associated with high-temperature-poly-silicon (HTPS)[2)] and reflective associated with liquid-crystal-on-silicon (LCoS)[3)] are reported. Irrespective of either the microdisplay is transmissive or reflective types, the key technologies are to achieve a high resolution, a high contrast and a high brightness. To realize a high resolution display, the pixel size should be very small as much as about 15 μm. However, shrinking pixel size with a inter-pixel distance comparable to the LC cell gap causes unwanted disclination lines due to a strong fringe electric field, which deteriorates the contrast ratio (CR) of the device.[4)] In order to reduce such disclination lines, various LC modes such as mixed-twisted nematic (MTN) cell,[5)] vertical aligned nematic (VAN) cell,[6)] and fringe-field switching (FFS) cell[7–9)] with changes of rubbing direction, pretilt angle, and electrode slope[4,10)] were studied. Nonetheless, complete suppression of the disclination lines in vertical and horizontal inter-pixels irrespective of any driving methods was not realized.

The FFS mode utilizes a fringe-electric field to rotate the LC directors, while the MTN and VAN cells use a vertical electric field. Studies on applications of the FFS mode to the LCoS device were previously reported, in which the slit form of electrodes exists in vertical direction. One of the previous works considers each pixel electrode as a one pixel and thus the pixel pitch becomes about 5 μm, resulting in a poor performance of the FFS mode on the SXGA LCoS panel.[4)] However, the other report claimed that the use of appropriate electrode geometry allows the FFS mode to have a high CR value compared to that of the VA mode.[11)] Even in the reported electrode geometry, the generation of disclination line in inter-pixel in vertical direction is inevitable. In this paper, we study various electrode geometry related to the generation of the disclination lines and suggest the electrode geometry that eliminates them completely in vertical as well as horizontal directions of inter-pixels.

In the FFS mode, the LCs are homogeneously aligned with an optic axis coincident with one of the crossed polarizers. Therefore, the normalized light transmission of the cell can be described by:

$$T/T_0 = \sin^2(2\psi(V))\sin^2(\pi d\Delta n/\lambda)$$

where ψ is an angle between one of the transmission axes of the crossed polarizers and the LC director, d is a cell gap, Δn is the birefringence of the LC medium, and λ is the wavelength of an incident light. From the equation, one can understand that ψ is a voltage dependent value, that is, with no bias voltage (off state), ψ is zero and the cell shows a dark state. With bias voltage (on state), the ψ starts to deviate from the polarizer axis, showing light transmittance. In the FFS mode for microdisplay,[12)] the bottom electrode plays a role of a pixel electrode and the top electrode as a common electrode exists above the pixel electrode, in which the electrode width (w) 3 μm and the distance (l) 4.5 μm between them exists, as shown in Fig. 1. With this electrode structure, the fringe-electric field in which the horizontal field intensity is alternating along a horizontal electrode position is generated with a bias voltage. Therefore, the dielectric torque to rotate the LCs is different depending on electrode positions, resulting in an alternating transmittance. For simulations, we assume that the passivation layer is 4000 Å, the LC has physical properties ($\Delta n = 0.08$, $\Delta\varepsilon =$

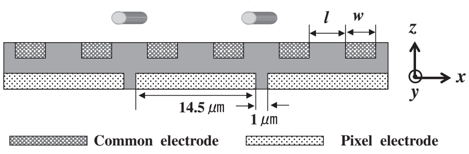

Fig. 1. Cross-sectional view of the FFS device with slit form of electrodes in vertical direction.

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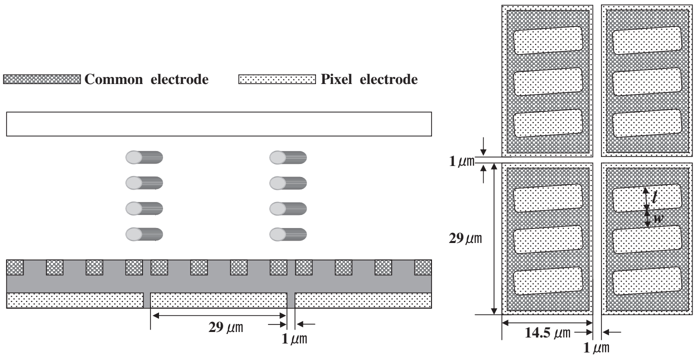


(a) (b)

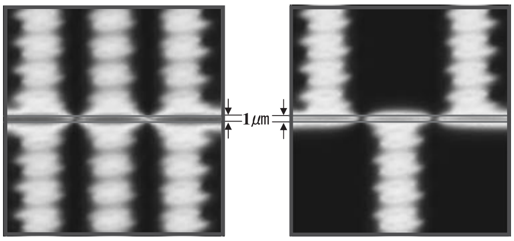
Fig. 2. Cross-sectional view (a) and top view (b) of the FFS device with slit form of electrodes in horizontal direction.

-4.0, $K_1 = 13.5\,\text{pN}$, $K_2 = 6.5\,\text{pN}$, $K_3 = 15.1\,\text{pN}$), the surface tilt angle is 2°, and the cell gap is $4\,\mu\text{m}$. We have used a commercially available two-dimensional (LCD Master from Shintech, Japan) and three-dimensional LC simulator (TechWiz LCD from Sanayi System, Korea), in which both systems are based on the Ericksen–Leslie theory and use the finite element method to calculate the motion of the LC director and then 2×2 Jones Matrix is applied to make the optical transmittance calculation.

In the electrode geometries for the application of the FFS mode to microdisplay, three different cases are considered and the transmittance in an off (dark) and on (white) state is investigated in each case. Here, the size of the pixel electrode is $15.5\,\mu\text{m}$ corresponding to about the SXGA (1280×1024) resolution in a $0.95''$ panel. For driving methods, we apply a dot inversion which is the most severe condition to cause the disturbing fields between pixels.

The first case of the pixel electrode structure is shown in Fig. 1, where the common electrodes in a slit form exists in y direction. With this electrode structure,[12] when the inter-pixel distance is $1\,\mu\text{m}$, the transmittance occurs strongly even at the neighboring pixels although the pixel is in off state. With increasing the inter-pixel distance to $6\,\mu\text{m}$, the transmittance does not occur in the off-pixel. This indicates that the rotated LCs in on-state pixel forces to rotate nearby LCs, resulting in an occurrence of ψ in off-state pixels. From the results, one can know that the twist elastic coherence length is more than a few micrometers. The light leakage on neighboring pixels although they are off state causes a severe decrease of the CR. The light leakage is well suppressed with the inter-pixel distance of $6\,\mu\text{m}$, however, this will lower pixel density in the microdisplay (this distance reduces to $4\,\mu\text{m}$ when the cell gap is $2\,\mu\text{m}$[12]). Therefore, we conclude that an application of the FFS mode with slit electrodes in a vertical direction to the microdisplay is not suitable enough.

The second case of the pixel electrode structure is shown in Fig. 2, where the common electrodes in a slit form exists with a slope angle of 10° to the x direction anticlockwise and the distance between pixel electrodes is $1\,\mu\text{m}$. In this case, the rubbing direction is in the y direction so that the LC director rotates clockwise with a bias voltage. One noticeable thing is the electric field response behavior of the LC in the area of two inter-pixels in horizontal and vertical directions. The horizontal field exists as a disturbing field between pixels in a horizontal direction and the LC director n is perpendicular to this field, so that the dielectric torque orients the LC to remain at an original state. Therefore, in this area the disturbing field does not affect the LC director at all and thus the light leakage is not generated by signals of neighboring pixels. However, considering the area of inter-pixels in vertical direction, the disturbing field direction exists so that the LC director can rotate either clockwise or anticlockwise, resulting in a transmittance. Figure 3(a) shows the transmittance when all 6 pixels are on state, in which the 6 V is applied to the common electrodes and the 12 or 0 V depending on the polarity of the pixel is applied to the pixel electrode. The transmittance does not occur at all in the horizontal direction of the inter-pixel but it does in the vertical direction of the inter-pixel. Next, the transmittance is investigated when one of the neighboring pixels is on state, as shown in Fig. 3(b). As expected, the light leakage does not occur in the horizontal sides of the off pixels; however, strong light leakage does occur in the off pixels from the vertical side of the pixels. This indicates that with this pixel geometry the decrease of the CR is inevitable and thus it is not a suitable device for the high CR microdisplay.



(a) (b)

Fig. 3. Transmittance in pixels when all the pixels are on-state (a) and one of the neighboring pixels is on-state (b) with a pixel distance of $1\,\mu\text{m}$.

Now, we know that with slant slit-electrodes the decrease of the CR is inevitable due to the existence of the disclination lines in the vertical side of the inter-pixels. In order to remove it, the third case of the pixel electrode structure is evaluated. There are two ways of holding the LCs in their original position: the disturbing field direction with mainly horizontal field should be perpendicular to the LC director or the dielectric torque should be minimized by enlarging the equi-potential region. The former is very difficult to achieve due to the rectangular shape of electrodes so that we must approach with the latter method. Figure 4 shows a new proposed pixel structure, where the common

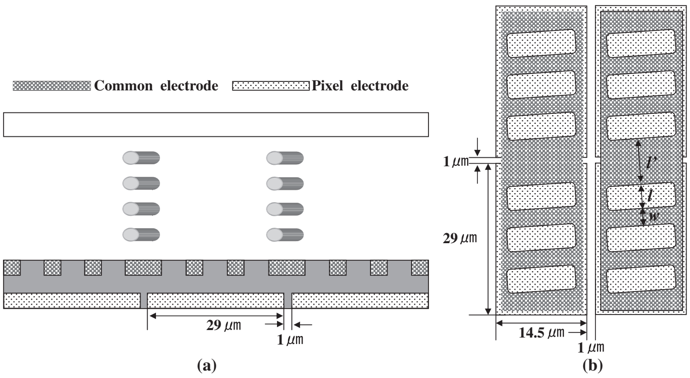


Fig. 4. Top view of the FFS device with slit form of electrodes in horizontal direction, where the common electrode covers the area of gap between pixels in vertical direction.

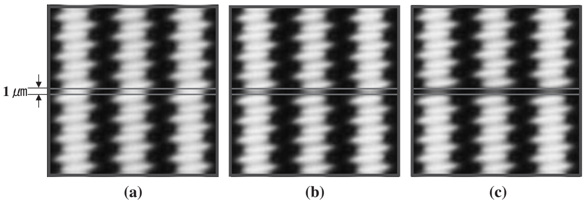


Fig. 5. Transmittance in pixels as a function of the l' for a pixel distance of 1 μm when all the pixels are on-state: (a) 3, (b) 4, and (c) 5 μm.

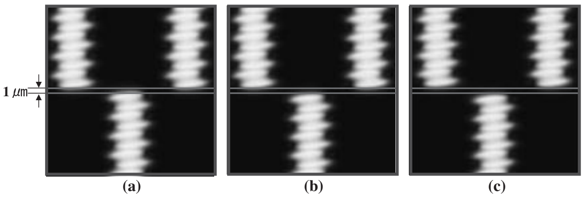


Fig. 6. Transmittance in pixels as a function of the l' for a pixel distance of 1 μm when one of the neighboring pixels is on-state: (a) 3, (b) 4, and (c) 5 μm.

electrode covers the inter-pixel region in a vertical direction and the distance between pixel electrodes still remains 1 μm. In this structure, the width (l') of pixel electrode in the inter-pixels is key parameter since the LCs at both edges of this electrode width will rotate clockwise with a bias voltage whenever one of the pixels is on state. Consequently, the rotation of the LC director in one pixel will rotate the LC director in the neighboring pixel by twisting elastic force and thus the light leakage is generated although the pixel is off state. First of all, the transmittance is evaluated as a function of l' when all the pixels are on state, as shown in Fig. 5. For $l' = 3$ μm, the transmittance in that area occurs like in the other transmitted area and as the l' increases to 5 μm, the transmittance decreases in that area. Next, the transmittance is calculated when one of the neighboring pixels is on state. When the l' is 3 μm, the light leakage occurs near neighboring pixels but as it increases to 5 μm, the light leakage due to rotation of the LC director by neighboring LCs does not occur at all, as it is clearly seen in the magnified image of Fig. 6. Consequently, with this electrode geometry, a complete suppression of the inter-pixel interference due to elastic coherence length by twist deformation on all sides of one pixel is possible, indicating that the high CR FFS microdisplay can be achieved.

We have also performed a simulation when the cell gap is 2 μm and achieved the same result. In conventional microdisplays, a low cell gap such as 2 μm is often used to achieve a fast response time. However, the lower the cell gap, the intensity of an oblique field becomes stronger, increasing the degree of unwanted disclination lines. However, in the FFS mode, there is no electrode on top substrate so that the decrease in cell gap does not cause increase in interference between pixels. This indicates that in the FFS mode the interference between pixels is not much affected by a cell gap.

In the microdisplay, the suppression of disclination lines in inter-pixels is very difficult, which makes it difficult to achieve a high contrast ratio. The conventional LC devices utilize a vertical electric field and thus the fringe electric field existing in the inter-pixels generates a problem. In our research, we evaluated the FFS device that has electrodes only on the bottom substrate and thus the fringe-electric field is utilized. The optimized electrode structure in which the common electrode has a slant shape with respect to the horizontal direction and covers the area on inter-pixel with optimal electrode width, and the pixel distance is 1 μm with a pixel size of about 15 μm, suppresses the inter-pixel interferences completely in all directions, thereby making it possible to realize a high CR FFS microdisplay.

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1) K. Allen: Microdisplay 2001, Colorado, 2001, p. 1.
2) C. Chinnock: Microdisplay 2001, Colorado, 2001, p. 71.
3) F. Sato, Y. Yagi and K. Hanihara: SID Int. Symp. Dig. Tech. Pap. **28** (1997) 997.
4) K.-H. F. Chiang, S. T. Wu and S. H. Chen: Jpn. J. Appl. Phys. **41** (2002) 4577.
5) S. T. Wu and C. S. Wu: Appl. Phys. Lett. **68** (1996) 1455.
6) K. Ohmuro, S. Kataoka, T. Sasaki and Y. Loike: SID Int. Symp. Dig. Tech. Pap. **28** (1997) 845.
7) S. H. Lee, S. L. Lee and H. Y. Kim: Appl. Phys. Lett. **73** (1998) 2881.
8) G.-D. Lee, G.-H. Kim, S.-H. Moon, J.-D. Noh, S.-C. Kim, W. S. Park, T.-H. Yoon, J. C. Kim, S. H. Hong and S. H. Lee: Jpn. J. Appl. Phys. **39** (2000) L221.
9) T. B. Jung, J. C. Kim and S. H. Lee: Jpn. J. Appl. Phys. **42** (2003) L464.
10) Y. L. Zhang, P. J. Bos and D. B. Chung: SID Int. Symp. Dig. Tech. Pap. **34** (2003) 1382.
11) W.-Y. Chou, C.-H. Hsu, S.-W. Change, H.-C. Chiang and T.-Y. Ho: Jpn. J. Appl. Phys. **41** (2002) 7386.
12) T. B. Jung, J. H. Song, S. T. Oh and S. H. Lee: J. KIEEME **17** (2004) 622 [in Korean].