Simulation Study of an e-Beam Addressed Liquid Crystal Display for Projection

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Abstract

We have carried out a simulation study on an e-beam addressed liquid crystal projection display in which the liquid crystal is switched by the electric field of the charge, produced by an electron beam, on the surface of the display. We calculated the electric field produced by the surface charge, the liquid crystal director configuration and the profile of the transmitted light. We studied the factors affecting the resolution of the display and the effect of pretilt angle on the performance of the display. The e-beam addressed liquid crystal projection display potentially has the advantages of high resolution and high brightness.

Keywords : liquid crystal display, e-beam addressing, projection

1. Introduction

In recent years, there have been intensive research and development activities on liquid crystal projection displays because of their superior performance. The popular liquid crystal displays (LCDs) used for projection are high-temperature-poly-silicon LCD and liquid-crystal-on-silicon (Lcos). The consumer television market is, however, still dominated by the cathode-ray tube (CRT) because its low cost. A decade ago Tektronix developed the e-beam addressed LCD projection display which was a combination of a LCD and CRT [1-3]. Since that time there has been little activity on this display because of the emergence of new LCD projection technologies. Recently, however, a few companies became interested in this technology because of its potential application in high brightness and high resolution projection displays.

We have carried out a simulation study on the e-beam addressed LCD to investigate its limitations. We studied the electric field of the surface charge produced by e-beam, liquid crystal working modes and various factors affecting the resolution of the display.

2. Results

2.1 Electric field

The schematic diagram of the e-beam addressed liquid crystal projection display is shown in Fig. 1. The e-beam places electrons on the surface of the mica film. This surface charge produces an electric field inside the mica and liquid crystal films, which controls the liquid crystal director configuration.

To calculate the electric field, we use Green's function method. We first calculate the electric field produced by a point charge q. Laplace's equation of the potential $V(\vec{r})$ produced by the point charge is

$$\begin{cases} -\varepsilon_o\varepsilon_3\nabla^2 V = q\delta(\vec{r}-\vec{r}_o) & for\ z > h \\ -\varepsilon_o\varepsilon_2\nabla^2 V = q\delta(\vec{r}-\vec{r}_o) & for\ 0 < z < h \\ -\varepsilon_o\varepsilon_1\nabla^2 V = q\delta(\vec{r}-\vec{r}_o) & for\ z < 0 \end{cases} \tag{1}$$

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where $\vec{r}_o = (h+d)\hat{z}$. V and the normal component of the electric displacement $\vec{D}$ is continuous when crossing the boundaries between the media. The geometry is shown in Fig. 2. The dielectric constant ε_1 of the ITO is assumed to be ∞. For simplicity, the liquid crystal is assumed to have an isotropic dielectric constant ε_2 in the calculation of the electric field. The dielectric constant of the mica is ε_3. It can be deduced that $V(\vec{r})$ should be of the form

$$V(\vec{r}) = \frac{q}{\varepsilon_o}\int \frac{1}{(2\pi)^2} e^{i\vec{K}_\perp \cdot (\vec{r}-\vec{r}_o)_\perp} g(z,\vec{k}_\perp) d\vec{k}_\perp \qquad (2)$$

where $\vec{k}$ is the wavevector and $\perp$ indicates the $x-y$ plane. $g(z,k_\perp)$ satisfies the equation

$$\begin{cases} \varepsilon_3\left(-\dfrac{\partial^2}{\partial z^2} + k_\perp^2\right) g = q\delta(z-z_o) & for\ z > h \\ \varepsilon_2\left(-\dfrac{\partial^2}{\partial z^2} + k_\perp^2\right) g = q\delta(z-z_o) & for\ 0 < z < h \\ \varepsilon_1\left(-\dfrac{\partial^2}{\partial z^2} + k_\perp^2\right) g = q\delta(z-z_o) & for\ z < 0 \end{cases} \qquad (3)$$

The boundary conditions for g are

$$\begin{cases} g(z=h^+) = g(z=h^-) \\ g(z=0^+) = g(z=0^-) \\ \varepsilon_3 \dfrac{\partial g}{\partial z}(z=h^+) = \varepsilon_2 \dfrac{\partial g}{\partial z}(z=h^-) \\ \varepsilon_2 \dfrac{\partial g}{\partial z}(z=0^+) = \varepsilon_1 \dfrac{\partial g}{\partial z}(z=0^-) \end{cases} \qquad (4)$$

The solution in the region $0 < z < h$ is

$$V = \frac{q}{2\pi\varepsilon_o(\varepsilon_2+\varepsilon_3)}\sum_{n=0}^{\infty}(-\lambda)^n\left\{r_\perp^2 + \left[(2n+1)h + d - z\right]^2\right\}^{-1/2} - \frac{q}{2\pi\varepsilon_o(\varepsilon_2+\varepsilon_3)}\sum_{n=0}^{\infty}(-\lambda)^n\left\{r_\perp^2 + \left[(2n+1)h + d + z\right]^2\right\}^{-1/2} \qquad (5)$$

where $\lambda = (\varepsilon_2 - \varepsilon_3)/(\varepsilon_2 + \varepsilon_3)$. The solution in the region $h < z < (h+d)$ is

$$V = \frac{q}{4\pi\varepsilon_o\varepsilon_3}\left\{\left[(r_\perp^2 + (h+d-z)^2\right]^{-1/2} - \lambda\left[(r_\perp^2 + (h-d-z)^2\right]^{-1/2}\right\} + \frac{q}{4\pi\varepsilon_o\varepsilon_3}(\lambda^2-1)\sum_{n=0}^{\infty}(-\lambda)^n\left\{\left[(r_\perp^2 + ((2n+1)h+d+z)^2\right]^{-1/2}\right\} \qquad (6)$$

In the numerical calculation the highest order term used in n=30.

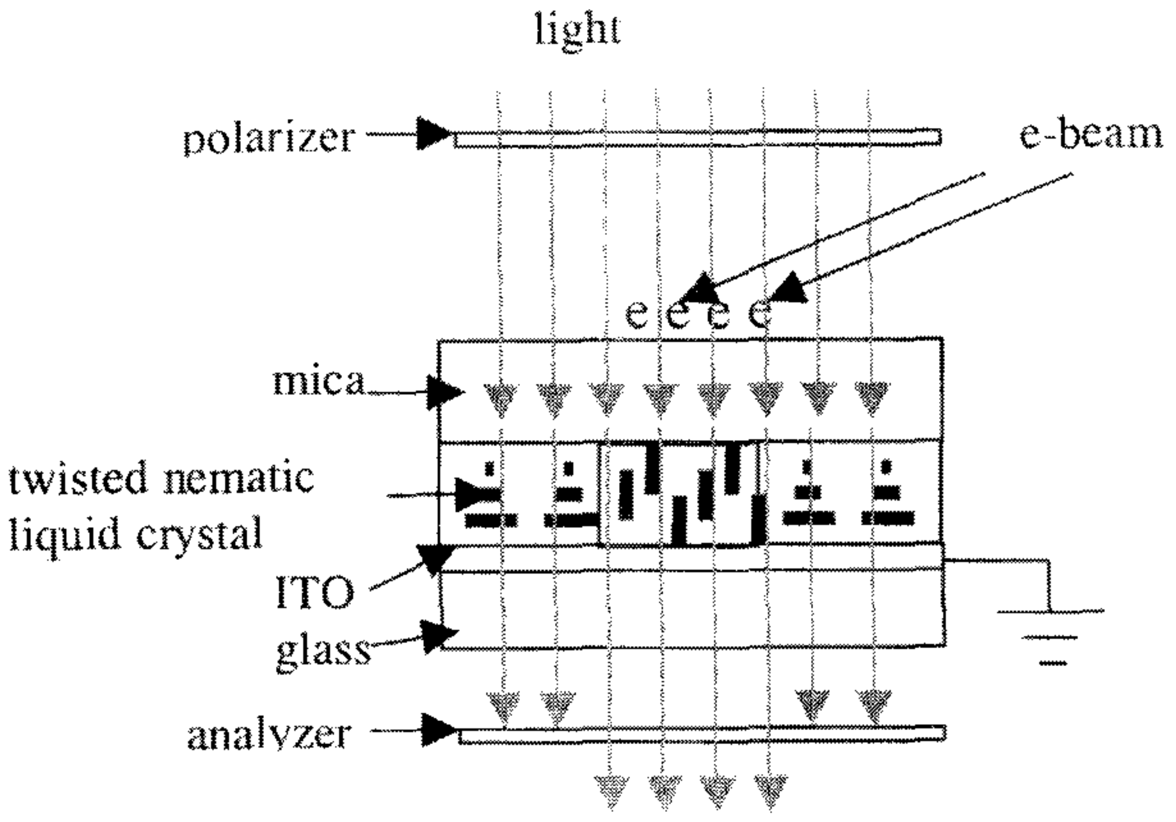

Fig. 1. Schematic diagram of the e-beam addressed liquid crystal projection display.

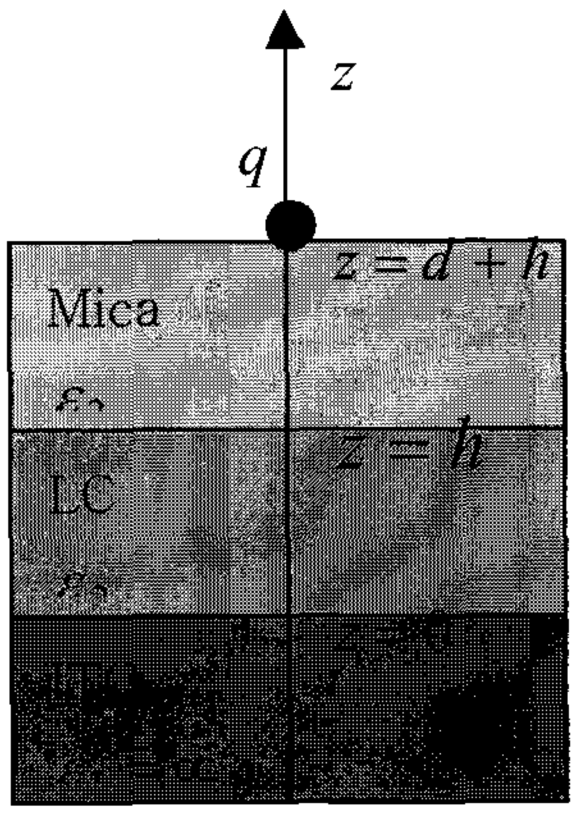

Fig. 2. Schematic diagram showing how the field produced by a point charge is calculated.

In the real display, the charge on the surface of the mica film is not a point charge but is approximately uniformly distributed over a disk of diameter D. The field produced by the charge disk is numerically calculated by adding the fields produced by the point charges located all over the disk. Fig. 3 shows the electric field produced by a charge disk with $D = 10\,\mu m$. The dielectric constant of the mica is $\varepsilon_3 = 5.8$. In the calculation an isotropic dielectric constant $\varepsilon_2 = 10$ is used. It should be noted that the electric field has components perpendicular and parallel to the liquid crystal film. It should also be noted that the field has significant strength outside the charge disk region because of the finite thickness of the mica and liquid crystal films. In this study, the thickness of the mica film and liquid crystal layer are 6 μm unless otherwise specified.

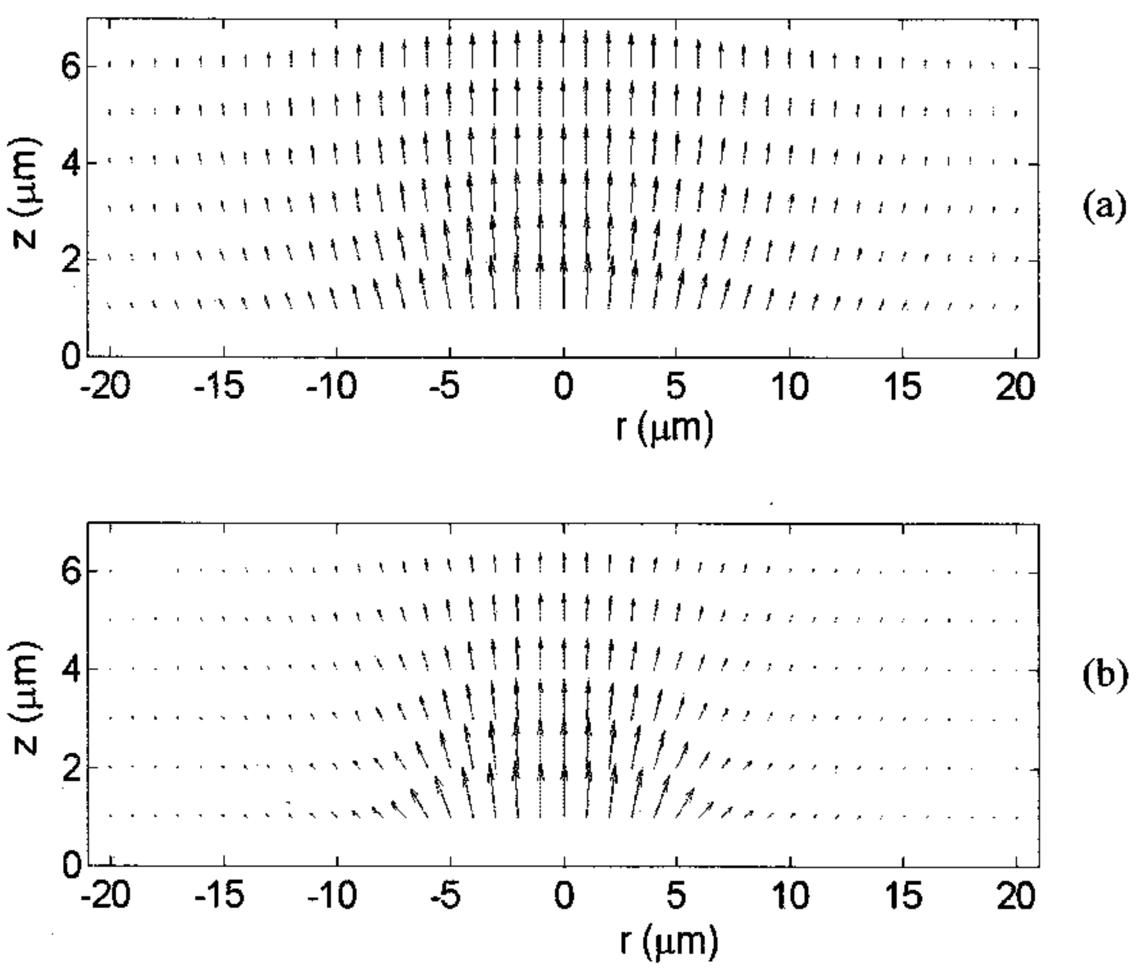

Fig. 3. Electric field inside (a) liquid crystal film and (b) mica film. The unit of the field in (b) is 3 times larger than that in (a).

2.2 Liquid crystal director

The liquid crystal configuration used is a normally black (2^{nd} minimum) 90° twisted nematic. Because the electric field not only has a z component (which is perpendicular to the cell surface) but also a radial component (parallel to the cell surface), the liquid crystal director $\vec{n}$ is a function of x, y and z, that is, $\vec{n}=\vec{n}(x,y,z)$. We used the tensor relaxation method in calculating the liquid crystal director configuration [4,5]. The tensor is defined by

$$Q_{ij}=n_i n_j-\frac{1}{3}\delta_{ij} \quad i,j=x,y,z \tag{7}$$

Because the tensor relaxation method requires long computation time, the lattice size used in the calculation is $20\times 20\times 20$. The electric energy is given by

$$f_{electric}=-\frac{1}{2}\varepsilon_o\Delta\varepsilon\left(\vec{E}\cdot\vec{n}\right)^2 \tag{8}$$

The dielectric anisotropy of the liquid crystal used in the calculation is $\Delta\varepsilon=\varepsilon_{//}-\varepsilon_{\perp}=13.5-8.2=5.3$. The liquid crystal tends to align parallel to the electric field. The elastic constants of the liquid crystal used in the calculation are $K_{11}=6.4\times 10^{-12}N$, $K_{22}=3.0\times 10^{-12}N$ and $K_{33}=10.0\times 10^{-12}N$.

Consider a charge disk with a diameter of 2 μm. At zero field, the liquid crystal director is parallel to the cell surface and has a 90° twisted structure. We first consider a TN cell with the pretilt angle of 0^o. When the total charge is $1\times 10^5 e$, which is slightly above the threshold, the liquid crystal director is shown in Fig. 4(a). The liquid crystal director is tilted away from the cell surface. Because the component of the electric field parallel to the cell surface, the liquid crystal director is tilted in opposite directions on the two sides, and tilted less in the middle. When the total charge on the disk is $2\times 10^5 e$, the liquid crystal director is aligned perpendicular to the cell surface except in the region very close to the cell surface, as shown in Fig. 4(b)

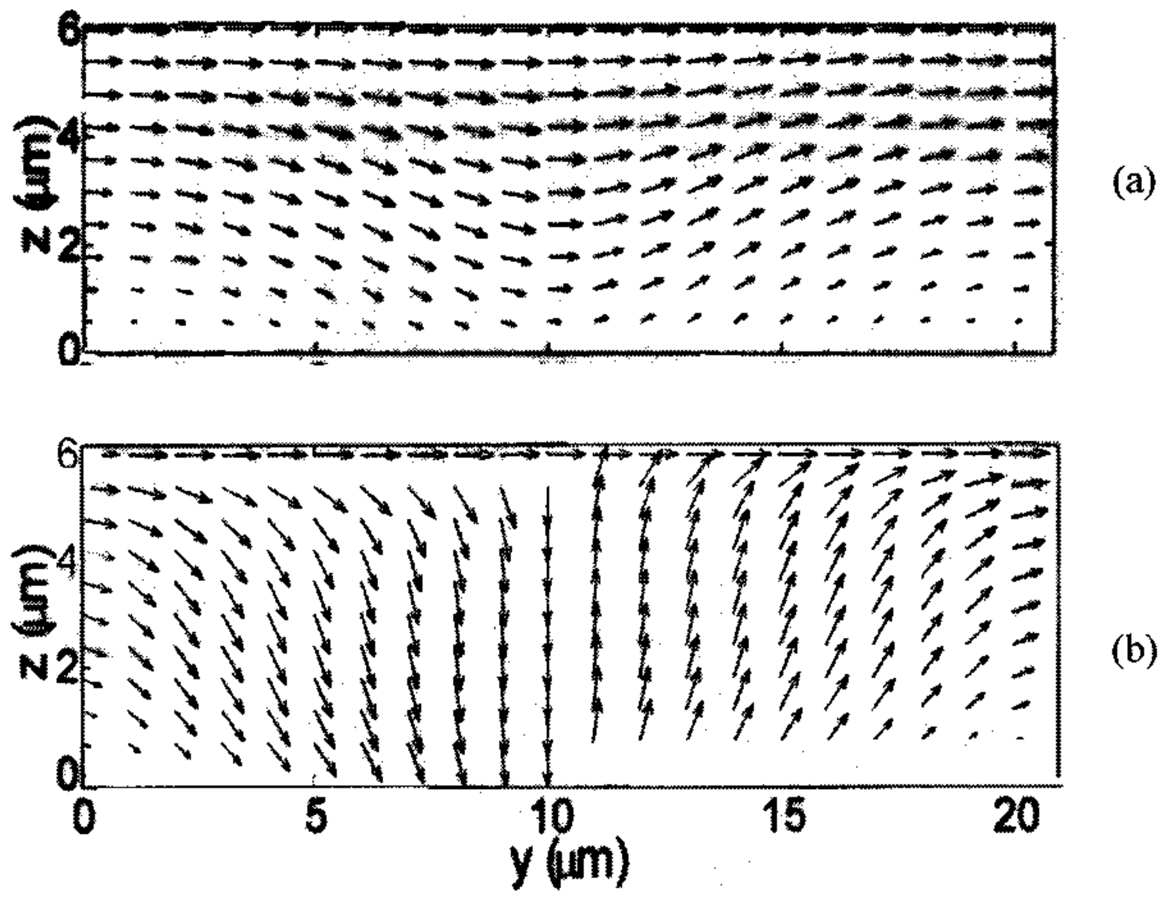

Fig. 4. The liquid crystal director configurations. The pretilt angle is 0°. The total charges are (a): 1×10^5e and (b): 2×10^5e.

2.3 Optical properties

We use Jones matrix method to study the optical properties of the display. In the calculation the refractive indices are $n_{//}=1.678$ and $n_{\perp}=1.501$. The wavelength of the light used is 550 nm. The simulated transmittances as function of position for the director configurations shown in Fig. 4 is shown in Fig. 5(a) and (b), respectively. When the total charge on the disk is $1\times 10^5 e$, the director is tilted less in the middle, resulting in a minimum, as shown in Fig. 5(a). The transmittance is normalized to the light before the polarizer. This minimum in the middle is an undesirable property which tends to decrease the image quality. When the total charge on the disk is 2×10^{-5}e, the electric field is sufficiently strong to align the director perpendicular to the cell surface, and the transmittance under the charge disk reaches the maximum, as shown in Fig. 5(b). The diameter of the transmittance peak is approximately 15 μm.

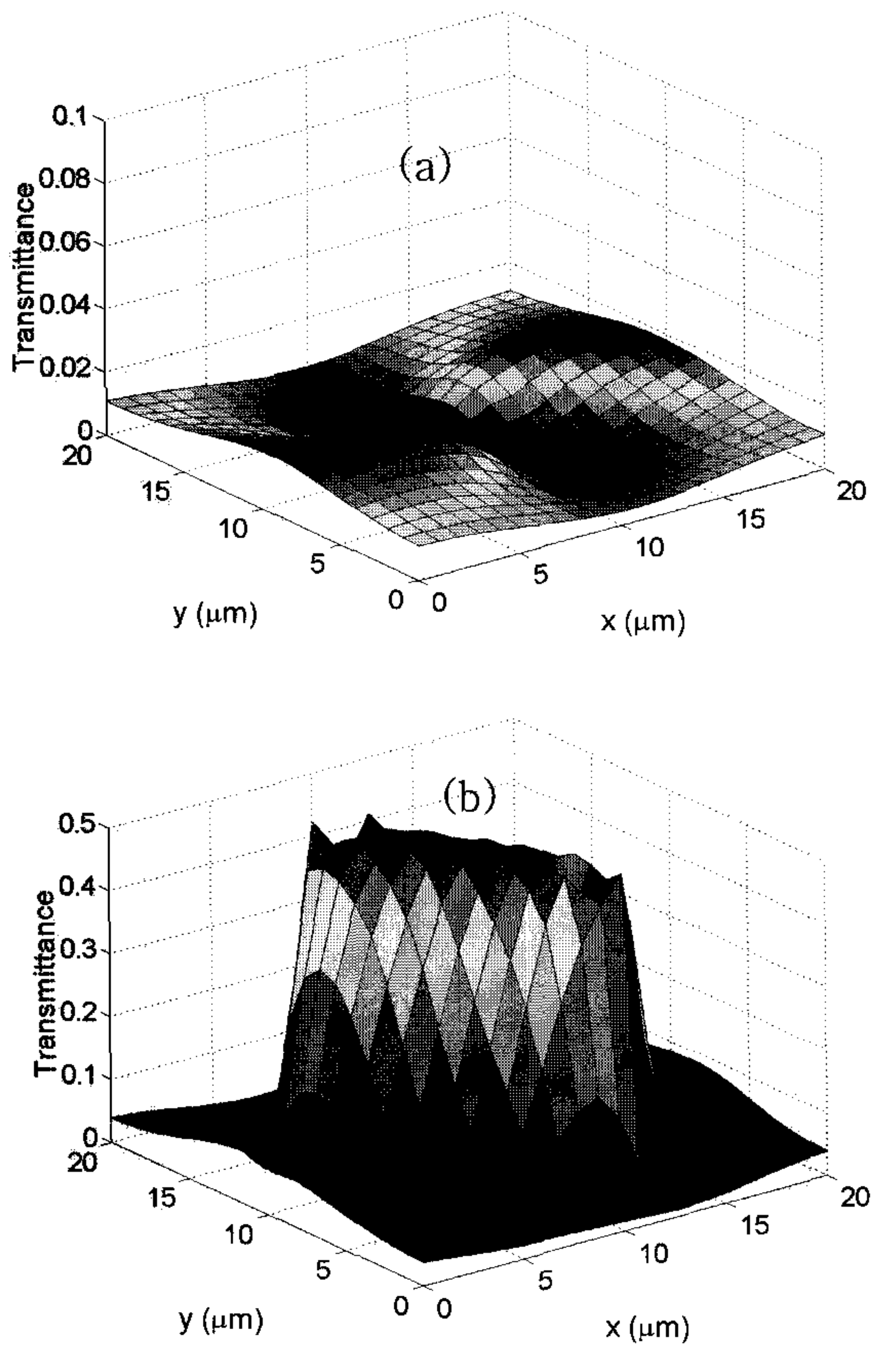

Fig. 5. Transmittance as a function of position. The pretilt angle is 0°. The total charges are (a): 1×10^5e and (b): 2×10^5e.

Fig. 6(a) shows the tilt angle, which is the angle between the liquid crystal director and the $x-y$ plane at the middle plane of the cell and the center of the charge disk, as a function of the total charge on the charge disk. When the total charge is below $1\times10^5 e$, the tilt angle remains at 0°. As the total charge is increased above $1\times10^5 e$, the 0-tilt-angle in the middle configuration becomes unstable, and the tilt angle changes discontinuously. Fig. 6(b) shows the maximum transmittance, which may not occur in the center of the charge disk, as a function of the total charge. Because the discontinuous change of the tilt angle, gray scale operation is difficult.

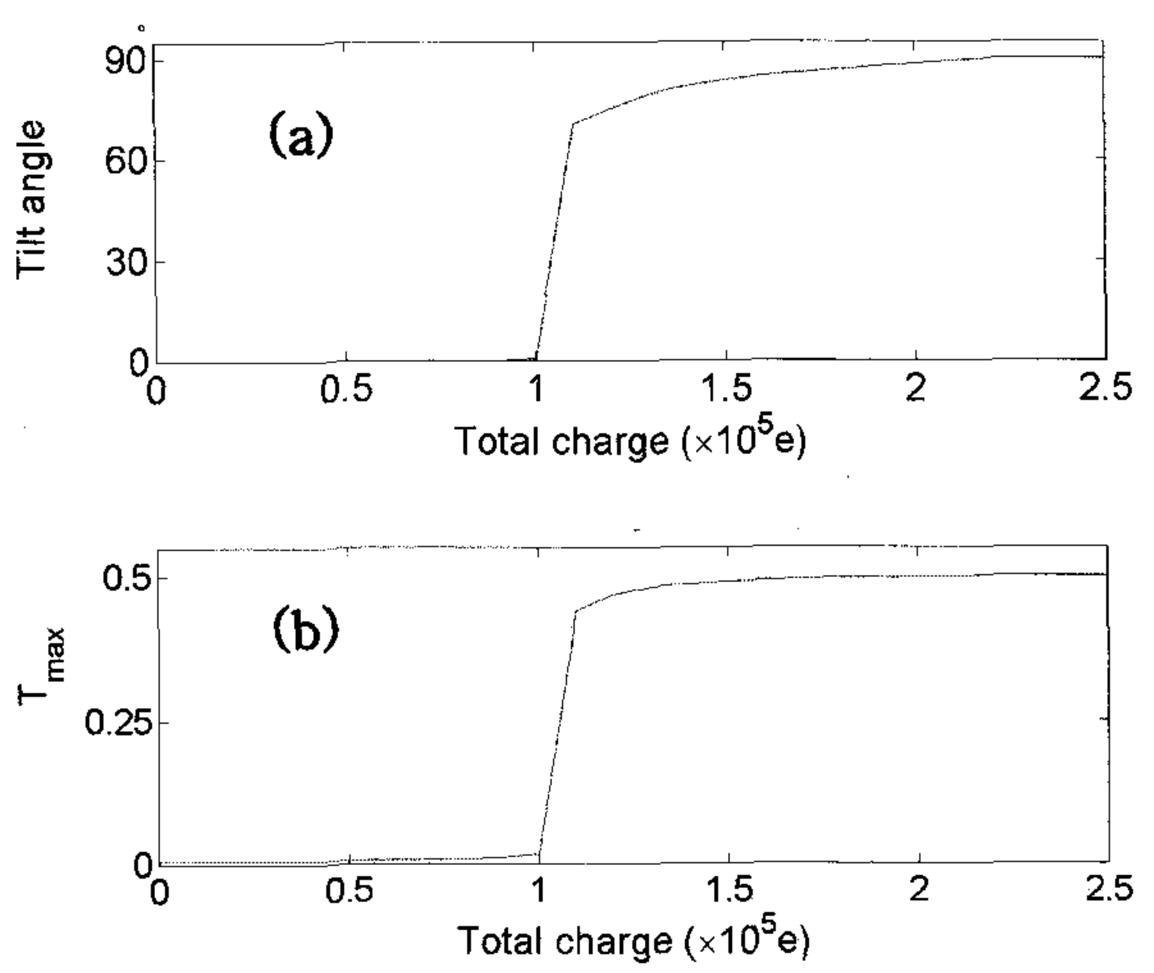

Fig. 6. (a): The tilt angle vs. the total charge, (b): The maximum transmittance vs. the total charge.

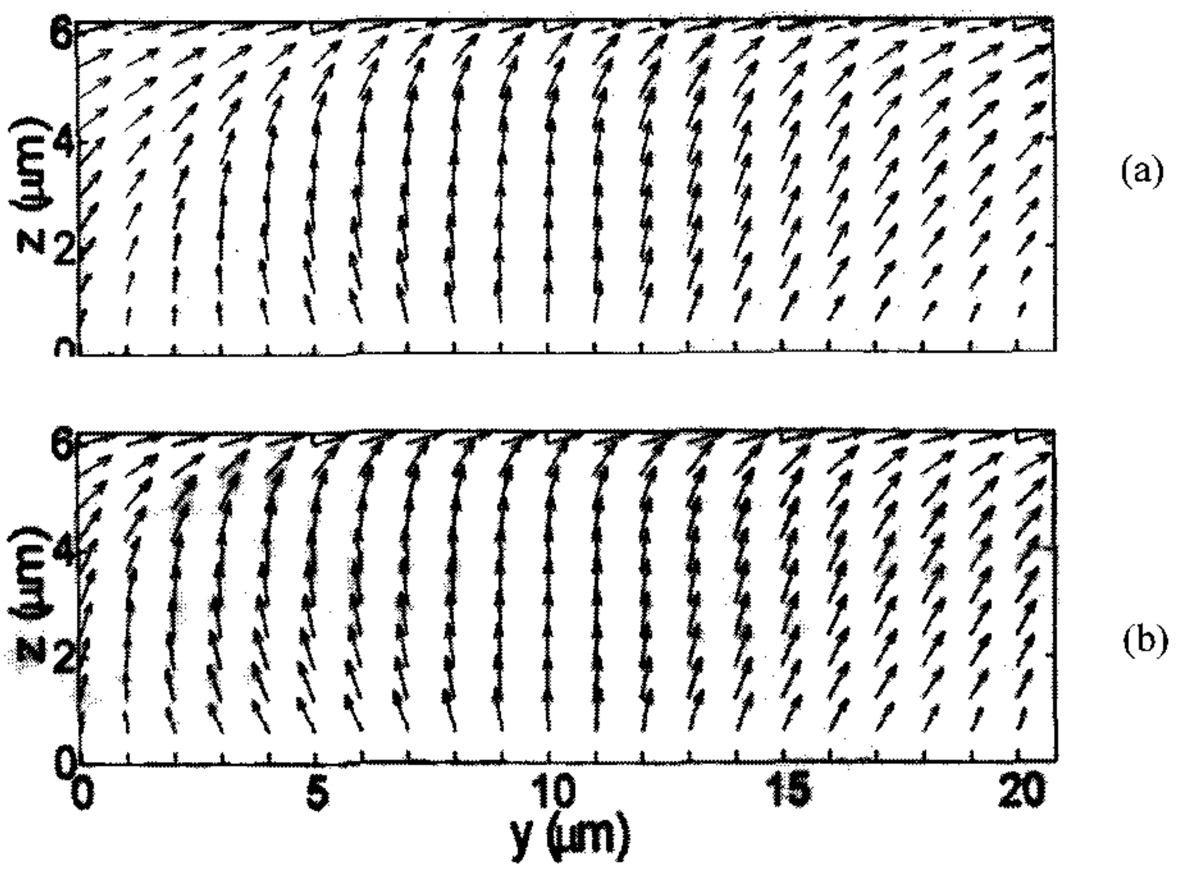

Fig. 7. Liquid crystal director configurations. The pretilt angle is 0°. The total charges are (a): 1×10^5e and (b): 2×10^5e.

We found that the problem of the transmittance minimum in the middle of the transmittance peak , as shown in Fig. 5(a), could be solved by using high pretilt angle alignment layers. For a liquid crystal cell with the pretilt angle of 15°, the liquid crystal director configurations are shown in Fig. 7. The director is approximately uniformly tilted across the region under the charge disk. The corresponding transmittance patterns are shown in Fig. 8. In this case, gray scale operation is possible.

We studied the factors affecting the resolution of the display and found that the thickness of the mica and liquid crystal films is the main factor. When the total charge on the charge disk is twice the threshold, we approximately have the relation: $D_{TP} = h + d + D$, where D_{TP} is the diameter of the transmittance peak at half maximum. With the current technology, the size of the e-beam, which is essentially the diameter of the charge disk, can be as small as 2 μm. In order to achieve high resolution, the thickness of the mica and liquid crystal films must be small.

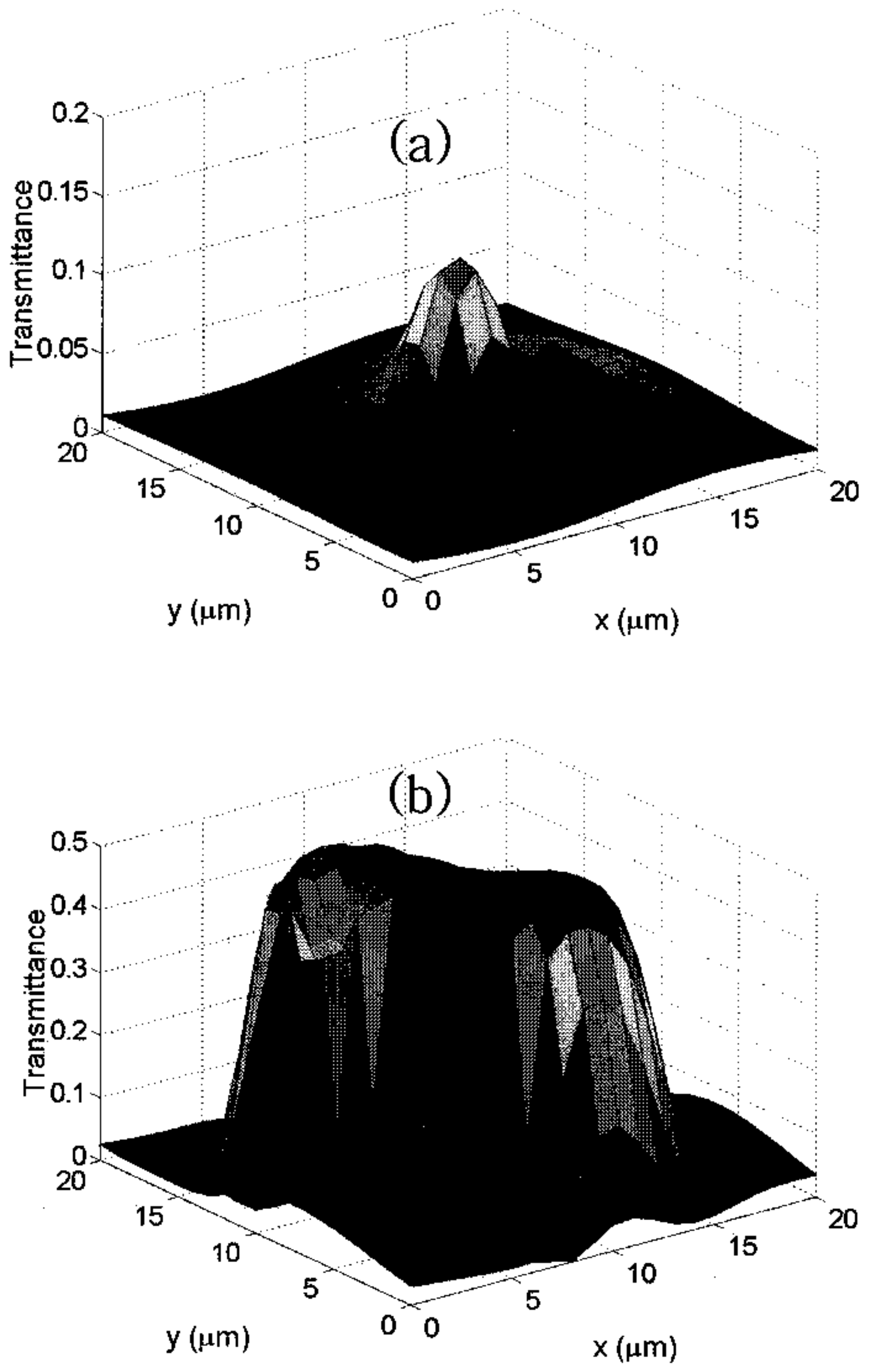

Fig. 8. Transmittance as a function of position. The pretilt angle is 0°. The total charges are (a): 1×10^5e and (b): 2×10^5e.

3. Conclusion

We have performed a simulation study of the e-beam addressed liquid crystal projection display. Our results show that the technology can be used to make high resolution displays because the pixel size on the LCD panel can be smaller than 10 μm. Our results also show that the defect in the liquid crystal director field can be eliminated by using alignment layers with high pretilt angles.

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