Available online at www.sciencedirect.com
SCIENCE DIRECT®

Optics Communications 238 (2004) 269–276

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Characteristics of LCoS Phase-only spatial light modulator and its applications

HaiTao Dai *, KeShu Xu YanJun Liu, Xin Wang, Jianhua Liu

State Key Lab for Advanced Photonic Materials and Devices, Department of Optical Science and Engineering, Fudan University, No. 220, Handan Road, Shanghai 20433, China

Received 3 January 2004; received in revised form 31 March 2004; accepted 28 April 2004

Abstract

The working models of LCoS (Liquid Crystal on Silicon) were optimized in parameter space by simulation. Two modes were selected, which were suitable for phase modulation. One was the RTN-52° mode, the other was parallel alignment ECB mode. Phase changes were measured when various voltages are applied to LCoS. In addition, we showed some results when the LCoS was used as a Fresnel lens.

PACS: 42.79.Kr

Keywords: LCoS; Parameter space; RTN-52° mode; Parallel alignment ECB model; Parameter space; Vari-focal Fresnel lens

1. Introduction

Liquid crystal on silicon (LCoS) [1] based displays has gained significant interest and activity over the past several years. The promise of LCoS is its capability to provide large, high quality, high-resolution displays with a very small and hence, relatively inexpensive LC device based on silicon CMOS technology. Pixel sizes less than ten microns can be fabricated with aperture ratios exceeding 90% (the pixel gap is 0.5 – 1 μm) to give smooth, apparently unpixelated images with saturated colors and rapid response times [2]. Fig. 1 shows the structure of LCoS.

Most researches of LCoS are focused on its applications in projection displays and near-eye displays [3]. However, its applications in optical information processing have been mentioned rarely. In fact, it has comprehensive applications in optical information processing field. For example the LCoS can be used as a spatial light modulator (SLM).

In this paper, we discussed the possibility of LCoS used as a phase-only SLM. There were many studies on the operated modes of LCD [4]. Here, we utilize the method of parameter space,

* Corresponding author. Tel.: +86-216-564-2156; fax: +86-216-564-1344.
E-mail address: 021021045@fundan.edu.cn (H. Dai).

0030-4018/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2004.04.047

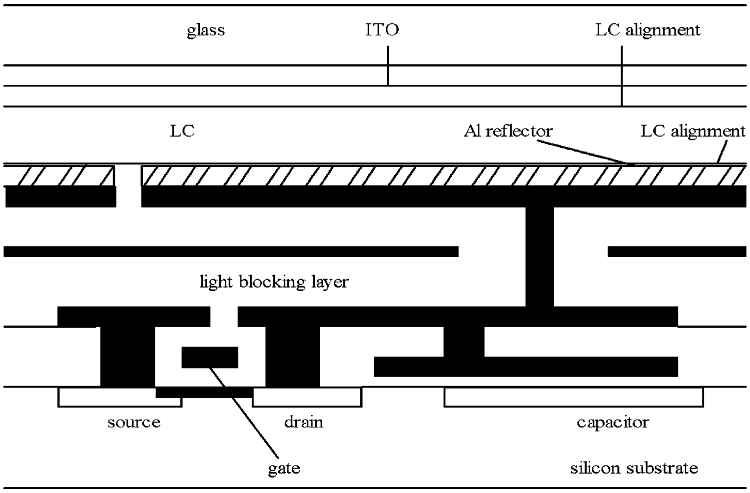

Fig. 1. The structure of LCoS.

which was introduced by Kwok et al. [5–7], to analyze the static mode of LCoS. In Section 2, two modes were analyzed in parameter space, one was RTN-52°, and the other was parallel alignment ECB. In Section 3, the phase characteristics of LCoS were measured experimentally. In Section 4, one application of LCoS (variable focus Fresnel zone plate) was studied, which showed a promising application about LCoS in optical information processing field.

2. Theoretical modes analysis

Parameter space is generally used to design static configurations of LC cells. Here, two reflective LCD geometries are shown in Fig. 2.

The parameter space is based on the Jones matrix method. Kwok and co-workers [5–7] have described the Jones matrix and the parameter space. The most important point to be noted is that the tilt angle of the liquid crystal director is assumed to be uniform over the entire cell. It is well known that the tilt angle decreases in the middle of the liquid crystal cell due to elastic energy minimization, especially for large pre-tilt angle cases. However, as pointed out by Lien [8], even for the pre-title case, an average tilt angle can be used without producing any significant error in predicting the properties of the LCD. The Jones matrix for liquid crystal cell is given by [9]

$$\mathrm{LC} = \begin{bmatrix} a + \mathrm{i}b & -c + \mathrm{i}d \\ c + \mathrm{i}d & a - \mathrm{i}b \end{bmatrix}, \tag{2.1}$$

where

$$a = \cos\phi\cos\beta + \frac{\phi}{\beta}\sin\phi\sin\beta, \tag{2.2}$$

$$b = -\frac{\delta}{\beta}\cos\phi\sin\beta, \tag{2.3}$$

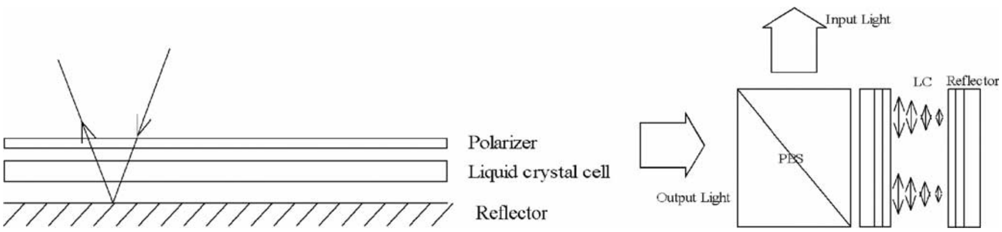

Fig. 2. Two kinds of reflective LCD schematic diagrams.

$$c = \sin\phi\cos\beta - \frac{\phi}{\beta}\cos\phi\sin\beta, \tag{2.4}$$

$$d = -\frac{\delta}{\beta}\sin\phi\sin\beta, \tag{2.5}$$

$$\beta = \sqrt{\delta^2 + \phi^2}, \tag{2.6}$$

$$\delta = \frac{\pi d \Delta n}{\lambda} \tag{2.7}$$

in which λ is the wavelength of the incident light, d is the cell thickness, Δn is the LC birefringence and ϕ is the twist angle of LC director.

$$\Delta n = n_e(\theta) - n_o, \tag{2.8}$$

where n_o is the ordinary index, $n_e(\theta)$ is the extraordinary index at an average director tilt angle of θ and is given by the following expression:

$$\frac{1}{n_e^2(\theta)} = \frac{\cos^2(\theta)}{n_e^2} + \frac{\sin^2(\theta)}{n_o^2}. \tag{2.9}$$

From Fig. 2, the Jones vector J_R of the reflective LCD can be obtained form the formula

$$J_R = \mathrm{Pol}(-\alpha)\cdot\mathrm{Rot}(\phi)\cdot\mathrm{LC}(\phi, d\Delta n)\cdot\mathrm{Rot}(-\phi) \times \mathrm{Mir}\cdot\mathrm{LC}(\phi, d\Delta n)\cdot\mathrm{Pol}(\alpha)\cdot J, \tag{2.10}$$

where $\mathrm{Pol}(\alpha)$ is the Jones matrix of the polarizer and α is polarized angle

$$\mathrm{Pol}(\alpha) = \begin{bmatrix} \cos^2(\alpha) & \cos(\alpha)\sin(\alpha) \\ \cos(\alpha)\sin(\alpha) & \sin^2(\alpha) \end{bmatrix}, \tag{2.11}$$

Rot is the rotation matrix

$$\mathrm{Rot}(\phi) = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{bmatrix}, \tag{2.12}$$

Mir is the mirror matrix

$$\mathrm{Mir} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \tag{2.13}$$

J and J_R is the Jones vector of incident light and output light, respectively. The reflectivity can be derived

$$R = |J_R(e)|^2 + |J_R(o)|^2, \tag{2.14}$$

so

$$R = \frac{1}{4\beta^4}\Big\{[\beta^2 - \delta^2 + \phi^2 + (\beta^2 + \delta^2 - \phi^2)\cos 2\beta]^2 + 4(2\phi\delta\sin 2\alpha\sin^2\beta + \beta\delta\cos 2\alpha\sin 2\beta)^2\Big\} \tag{2.15}$$

and the phase shift is

$$\Delta\delta = \tan^{-1}\frac{\mathrm{Im}(J_R(e))}{\mathrm{Re}(J_R(e))} = \tan^{-1}\frac{\mathrm{Im}(J_R(o))}{\mathrm{Re}(J_R(o))} = 2\delta - \tan^{-1}\frac{\beta^2 - \delta^2 + \phi^2 + (\beta^2 + \delta^2 - \phi^2)\cos 2\beta}{4\delta\phi\sin 2\alpha\sin^2\beta + 2\delta\beta\cos 2\alpha\sin 2\beta}, \tag{2.16}$$

where $J_R(e), J_R(o)$ are orthogonal components of J_R. From (2.16), the phase shift is an arctan function, so a phase jumping about π would be induced during the phase changing.

By varying the $d\Delta n$ and the twist angle ϕ in Eq. (2.15), a parameter space contour plot is generated. From the contour plot, some suitable modes can be verified. Here because our attention concentrates on the application of LCoS in phase modulating, our purpose is to find a mode, whose phase changing is large enough but amplitude changing is small at the same time. Meanwhile, the profile of phase should be linear-like. For display, the chromatic dispersion should be considered. However, we only care the reflectivity, phase changing and its voltage characters because of the use of monochromatic light. Generally, there are two kinds of configurations of RLCD. One is normally black (NB), the other is normally white (NW). NB and NW conditions are related to each other by a proper rotation of the polarizer. Many display modes have been studied, several were shown in Fig. 3. From Fig. 3, there are some positions where the values of reflectivity are minimum and it is obvious that these wells are symmetrically placed at where ϕ is about 0°. Those minima are so-called the TN-ECB modes. In these wells, because the rate of reflectivity changing is very large, these positions are not suitable for phase modulating. Fig. 4 shows the reflectivity changing near the minima, if we choose A point as a working mode, the amplitude will change severely with the phase changing. So this is not suitable for the phase-only modulation. With the polarized angle α varied, more modes will be found (as shown in Fig. 5).

From Fig. 5, only when $\alpha = 0$ or 180°, the TN-ECB well is symmetrically placed at about $\phi = 0°$. Especially, when $\phi = 0°$, the amplitude is constant along with vertical axis. So these positions are very

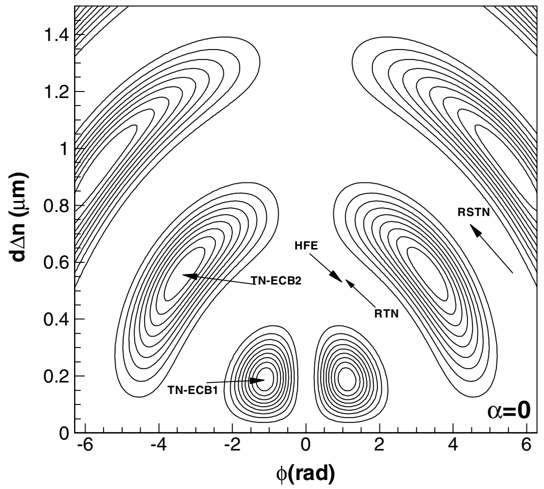

Fig. 3. The $\phi - d\Delta n$ parameter space for RLCD. $\lambda = 0.532$ μm, $\alpha = 0°$.

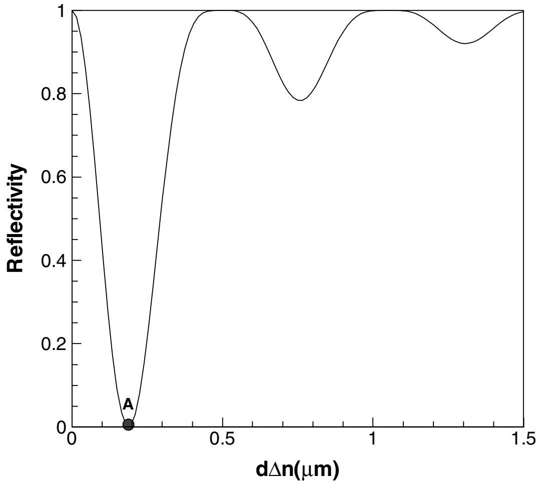

Fig. 4. The reflectivity changing near the minimum $\lambda = 0.532$ μm, $\alpha = 0°$, $\phi = 63.6°$.

suitable for phase modulating. However, some factors should be practically considered, for instance, the cell thickness should be reasonable for process conditions.

In our experiments, the twist angle of LCoS is 52° and its characteristics were studied in parameter space. From Fig. 6(b), only when $\alpha = 0°$ and $d\Delta n > 0.8$, the amplitude changing is less than 20%, under the other conditions, such as $\alpha = \pi/6$ or $\pi/4$, the rate of amplitude changing is very large. According to Fig. 6(b), the reflectivity tends to even as the polarized angle tends to 0°. So $\alpha = 0°$ and $d\Delta n > 0.8$ is feasible for phase modulation when the twist angle is 52°.

As discussed above we analyzed the two working modes of LCoS, which was applied to phase modulation, parallel alignment ECB mode and RTN 52° mode. We concluded that $\alpha = 0°$ was the best choice.

3. Experimental result

3.1. RTN-52°

The experimental setup was shown in Fig. 7 to measure the phase changes of LcoS at different applied voltages. The LCoS was driven by a computer. And different gray levels on the computer screen meant different voltage outputs at XVGA port. A CCD was used to detect the reflected light from LCoS. The driven pattern and detected fringes were shown in Fig. 8. It showed an obvious fringe shift, which was induced by phase changes. However, in the gap between the upper and the lower, the fringe shift was somewhat obscure. Two main reasons contribute to this phenomenon. One is that the applied voltage changed abruptly at the midline in the driven pattern, but the phase changing is not keen because of the force among liquid crystal molecules. The other is that the voltage change of the midline in the driven pattern will induce to a cutting edge in the middle of LCoS, which gives rise to a cutting edge diffraction. The center black gap is the diffraction main lobe, and the other black lines are side lobes, which distribute symmetrically both sides of the center black gap in our image.

The gray level varied from 0 to 255 every 10 gray levels. The wavelength of light source was 0.532 μm. As observed experimentally, there was no clear fringe displacement when the gray level varied from 0 to 30. However, the largest fringe displacement is less than one fringe spacing even the gray level reached the biggest level 255. This meant the phase changes could not reach 2π. The measured phase changes were 1.9π. The phase changes were shown

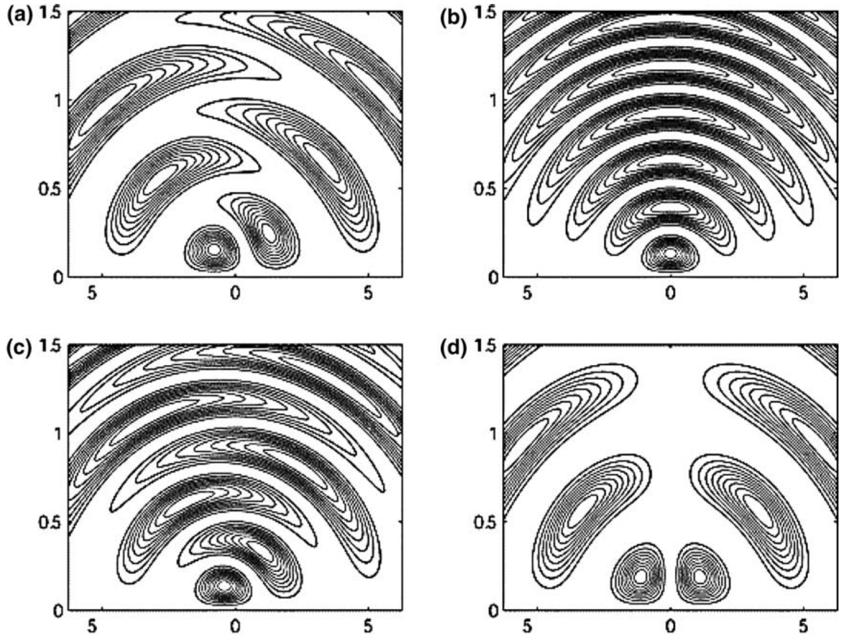

Fig. 5. The contour plot of various polarized angle: (a) $\alpha = 15°$; (b) $\alpha = 45°$; (c) $\alpha = 120°$; (d) $\alpha = 180°$. Horizontal axis is twist angle ϕ (rad) and vertical axis is $d\Delta n$ (μm). All cases were used $\lambda = 0.532$ μm.

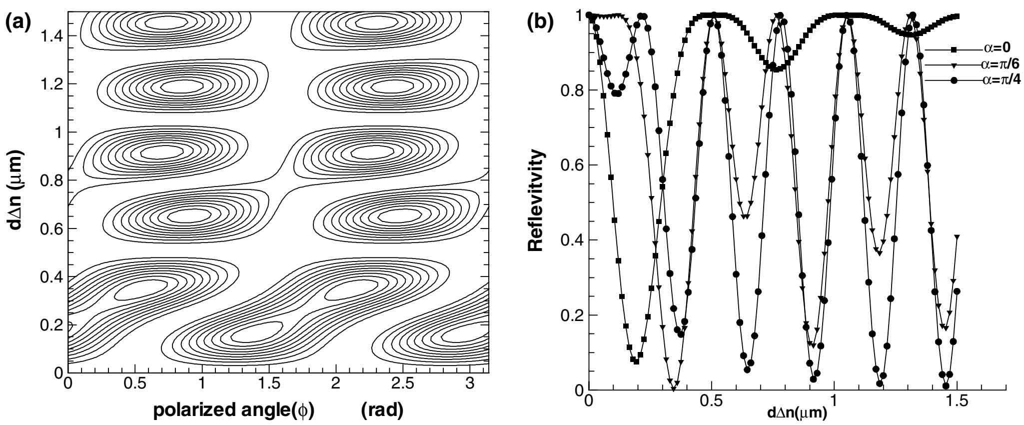

Fig. 6. Reflectivity of RTN 52° mode at different polarized angle: (a) the contour plot of reflectivity; (b) the reflectivity curves at $\alpha = 0$, $\alpha = \pi/6$ and $\alpha = \pi/4$. $\lambda = 0.532$ μm.

in Fig. 9. We can see that the changes were nonlinear. The reason is that the phase changes are an arc tangent function. Certainly this could be corrected by the formula of phase shift. For the measurement of the phase changes, because the surface of LCoS is not very plain, this makes the measurement of the whole phase changes very difficult. But the sampling area is very small, the phase shift could be view as uniform.

Finally, we also discussed the amplitude changes when LCoS used as a phase modulator. The intensity of the light outputted was recorded by the

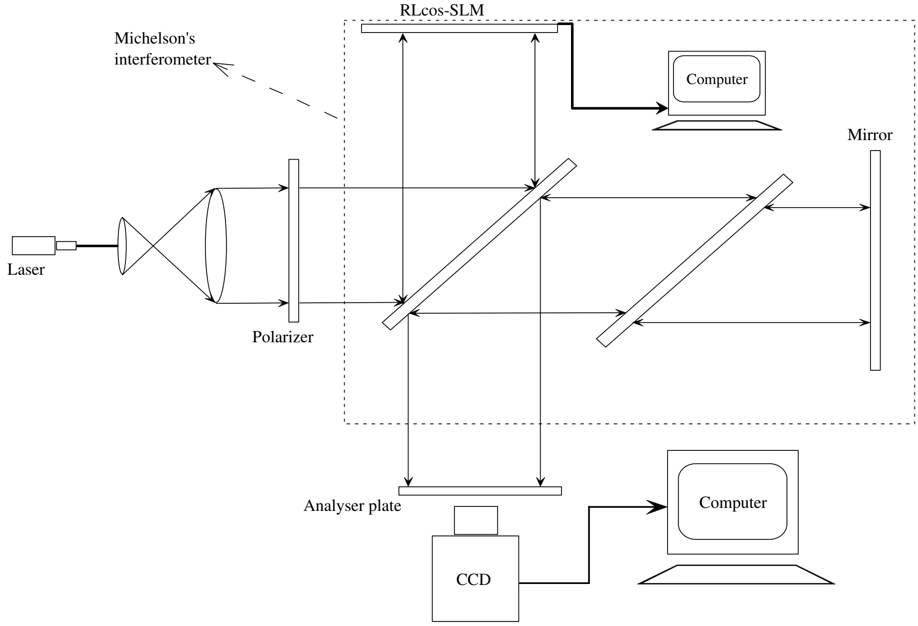

Fig. 7. The experimental setup.

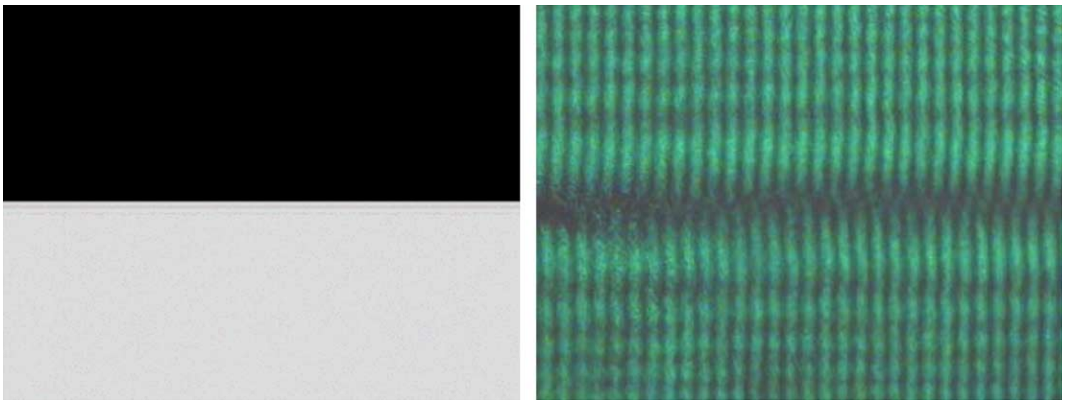

Fig. 8. The driven pattern and detected fringes.

CCD. Compared with the intensity at the gray level 0, the biggest amplitude changes were less than 5% during the phase modulation. The result was shown in Fig. 10.

3.2. Parallel alignment mode

A 6-pixel LC cell was made, which worked on parallel alignment mode. Its thickness was 5.75 μm. And the birefringence of LC was 0.2272. The measured phase shift was shown in Fig. 11.

From the Fig. 11, phase shift did not occurred until the driven voltage reached 1.2 V_{rms}, and it kept linear change until the driven voltage reaches 2.6 V_{rms}. But when the driven voltage was more than 2.6 V_{rms}, it was no longer linear. This can be explained by the action of LC molecules under the electric field. At first, the driven voltage was small,

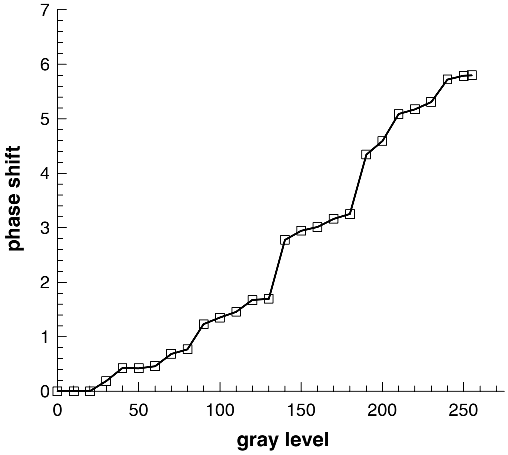

Fig. 9. The phase shift as a function of the gray level change.

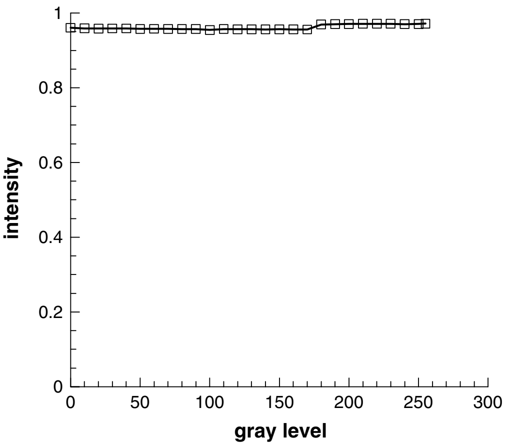

Fig. 10. The intensity changes during the phase modulation.

which could not overcome the LC molecule elastic torque, so there was no phase shift occurring. With the driven voltage increased, when the external force induced by the electric field was larger than elastic force, the LC molecules began to reorient along the electric field. And also the phase shift began to occur. As the deformation of LC molecules became larger, their elastic torque became larger too. And the deformation became more and more difficult. This was why the phase shift became nonlinear. At last, the LC molecules completely oriented along with the electric field. No phase shift would occur when the voltage was more than 8 V_{rms}.

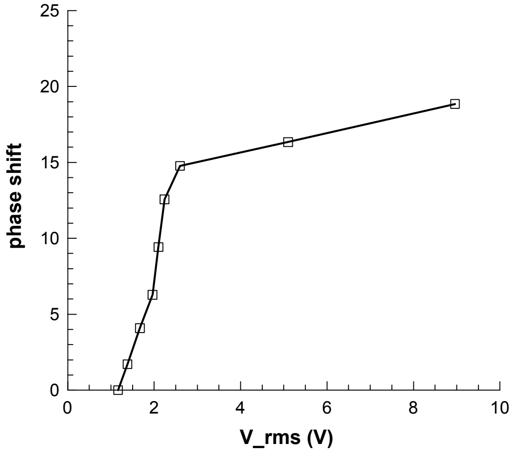

Fig. 11. The phase changing when the voltage changes.

4. The application of LCoS

As discussed above, LCoS as a phase modulator has promising applications. Here we showed one application-a variable focal Fresnel lens. As schematically depicted in Fig. 12, the phase difference of adjacent zones is π, it provides focusing properties like a conventional converging lens. The zone distance S_m is related to the primary focal length f of the Fresnel zone plate and the wavelength of light by the equation

$$S_m = \sqrt{m\lambda f} \tag{2.17}$$

in which m is an integer.

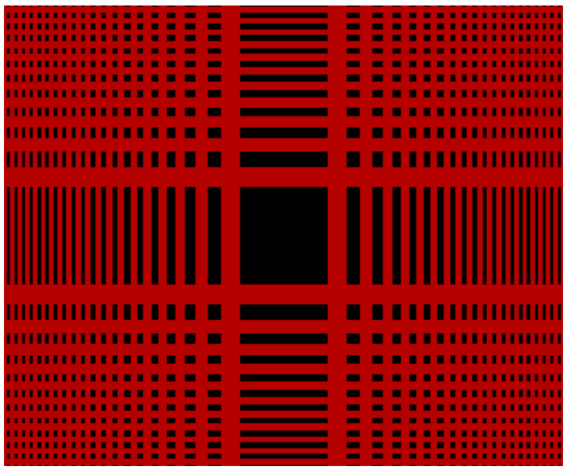

Fig. 12. The Fresnel zone plate.

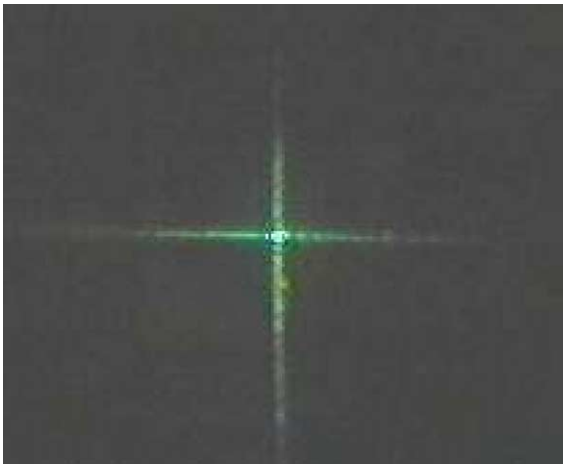

Fig. 13. The pattern of Fresnel zone plate at its focal length $f = 2$ m.

The Fresnel lens can be formed on screen by computer programming and applied to LCoS by XVGA port. This allow us to realize the variable focal Fresnel lens. The focal line measured experimentally was in good agreement with anticipated theoretically. Also, an orthogonal Fresnel zone plate will convert the incident parallel light into a cross line. This is very useful in collimator set. Four kinds of different focal lengths are fabricated, which are 1, 2, 3 and 4 m, respectively. Fig. 13 showed the case of the 2 m focal length.

5. Conclusions

In this paper, we discussed the working modes when LCoS used as phase modulators. A measuring setup of phase shift was also introduced. Both the RTN-52° modes and parallel alignment modes were studied. Theoretical analysis showed that the parallel alignment ECB was the best working modes as a phase modulator. The 0° polarized angle was the most suitable for phase modulation no matter what the twist angle was. Also a zoom Fresnel lens was fabricated by LCoS, which showed a promising application in laser collimator.

Acknowledgements

This work is supported by the State “863” project No. 2002AA84TS11, the National Natural Science Foundation and China Academy of Engineering Physics No. 10176007, the National Natural Science Foundation No. 69877004.

References

[1] Shoichi Hirota, Makoto Tsumura, Hideki Nakagawa, Toshio Miyazawa, Iwao Takemoto, SPIE 3635 (1999) 86.
[2] R.L. Mecher, Display 23 (2002) 1.
[3] Peter Janssen, Jeffrey A. Shimizu, John Dean, Remus Albu, Display 23 (2002) 99.
[4] H.S. Kwok, F.H. Yu, S.T. Tang, J. Chen, SPIE 3143 (1997) 39.
[5] H.S. Kwok, J. Appl. Phys. 80 (1996) 3687.
[6] S.T. Tang, F.H. Yu, J. Chen, M. Wong, H.C. Huang, H.S. Kwok, J. Appl. Phys. 81 (1997) 5923.
[7] F.H. Yu, J. Chen, S.T. Tang, H.S. Kwok, J. Appl. Phys. 82 (1997) 5287.
[8] A. Lien, J. Appl. Phys. 67 (1990) 2854.
[9] S.T. Tang, H.S. Hwok, SPIE 3800 (1999) 87.