P-182: Novel Liquid Crystal Switch Array Based on Total Internal Reflection

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Abstract

A novel liquid crystal switch array based on TIR effect has been presented, which can be applied to not only the display area but also the communication area. Analysis and optimization for all the related parameters for the TIR-based LC switch have been conducted. The prototype has been fabricated according to the obtained optimal configuration. High contrast and fast response can be observed in both simulation and experiment.

1. Introduction

Liquid crystal (LC) has been widely investigated in the display and optical communication areas due to its birefringence and electro-optical characteristics [1]. Numerous applications using LC have been found in displays, optical switches, variable optical attenuators and polarization controllers [2-5]. In recent years, based on the concept of total internal reflection (TIR), LC has been combined in integrated optical devices e.g. optical switches to achieve large matrix optical components [6]. Except for optical switches used in optical communication system, TIR-based switch could also be applied to display area. In recent years, researchers have investigated the displays based on the concept of TIR using electrophoresis material and polymer dispersed liquid crystal (PDLC) [7, 8]. The problems are poor contrast ratio, slow response time and additionally driving voltage of PDLC is much higher than the capacity of standard super twist nematic (STN) driver.

In this paper, we present a novel liquid crystal switch array based on TIR effect, which can be applied to not only the display area but also the communication area. Figure 1 shows the scheme of our TIR-based LC switch array [9]. In the design, the backlight comes from (Light Emitting Diode) LED array through collimating lens, enters the high index glass substrate via a coupling diffraction grating, transmits through the LC switch, and be focused after a decoupling diffraction grating and focus system attached on the exit glass substrate. The LC switch works under the electric field between the patterned electrode on exit waveguide and the common electrode on entrance waveguide.

2. Methodology

To calculate the optical performance of the TIR-based LC switch, scattering matrix method is used in the simulation to avoid

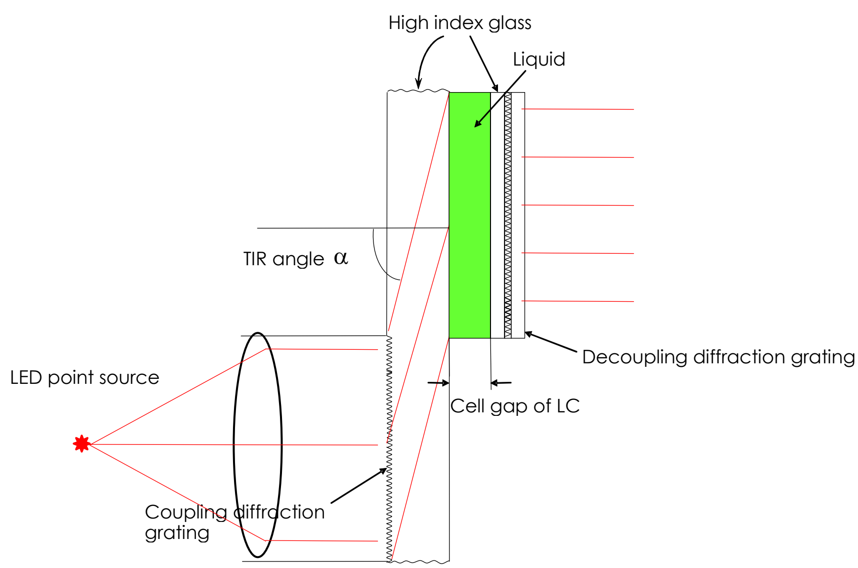

Figure 1 Scheme of our TIR-based LC switch array

instability occurred in ordinary 4 X 4 matrix method [10] in context of TIR. For feasibility of the coupling diffraction grating, the critical angle between entrance waveguide and LC layer cannot be too large. Thus, the optimal refractive index of glass substrate should be much larger than the ordinary refractive index of LC layer. Figure 2 shows a critical angle change due to the reorientation of LC molecules under electric field. A transmission window is formed between two states which can be seen clearly from the figure. If external electric field is off, TIR occurs when incidence angle is larger than 64 degree. Any incident light with angle larger than 64 degree will be totally reflected, which forms dark state. If external electric field is on (larger than threshold voltage, here 4V is used), the critical angle increases to around 80 degree. Any incident light with angle smaller than 80 degree will be transmitted through the LC layer, which forms bright state. Therefore, light incident at an angle between these two critical values can be switched on or off by application of external electric field.

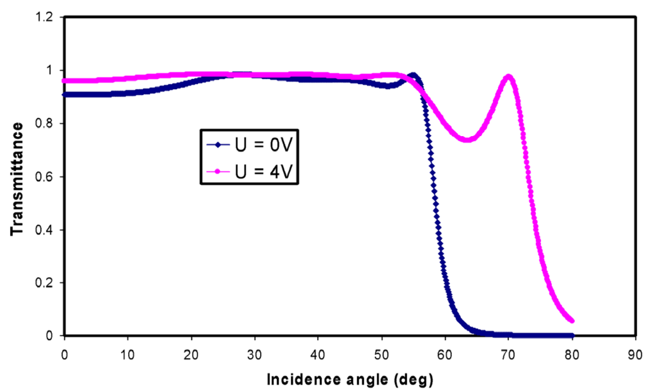

Figure 2 Critical angle change under electric field

It should be noted that the design is very sensitive to the polarization of incident light and only one polarization component can be used. This is decided by the characteristics of LC itself. Since LC is a birefringence material, incident light with different polarization sees different refractive index. Thus, only TM wave can be used when LC molecules reorient in the incident plane.

The operation mode of LC layer is also an important issue during the design. One concern is change of polarization state after light goes through the LC switch. If reorientation of LC molecules involves in-plane rotation, the polarization state of output light cannot keep unchanged. This is undesirable for output optical coupling component which is polarization-sensitive.

The other concern is about the interference peaks appear in the curve of dependence of transmission on incident angle. Interference pattern that occurs in the reflection or transmission curve when incidence angle is close to critical angle deteriorates contrast ratio, which is not desirable for the display application. The interference comes from the optical path difference (OPD) between the light beam reflected at top interface and the one reflected at bottom interface. Except direct influence from cell gap of LC layer, the operation mode of LC also affects the effective OPD. The interference pattern in VAN is less significant than that in ECB mode due to smaller effective OPD between glass and LC layer.

3. Results and discussion

To obtain a wide transmission window, large optical anisotropy Δn is preferable for LC material. LC mixture with the largest Δn we can find for VAN mode is MLC-7029 from Merck KGaA. The properties of MLC-7029 are the following (at 589.3nm): optical anisotropy $\Delta n = 0.1265$, extraordinary refractive index ne = 1.6157, dielectric anisotropy $\Delta\varepsilon = -3.6$, dielectric constant $\varepsilon_{//} = 3.6$, rotational viscosity $\gamma_1 = 175$ mPas. Preparation of LC cell includes no twist, and pretilt angle is 88° for both top and bottom substrates. To diminish the interference pattern and minimize response time for high resolution driving, cell gap is 1 micron. The glass used in calculation is S-TIH1, whose refractive index n = 1.7118 at 650nm. Since wavelength of red color LED ranges from 600 nm – 650 nm, for brevity, the light source used in the simulation is He-Ne laser whose wavelength is 632.8 nm. Incident light is TM wave (p wave) which is parallel to the incident plane (Stokes vector: (1, 1, 0, 0)). Incident angle ranges from 0 ~ 80 deg. Voltage applied for on state is Von = 0V, and Voff = 4V for off state.

Figure 3 shows the dependence of transmittance on incident angle, where cell gap is 1 m. The interference pattern is more obvious and the skewness of the transmission window meliorates comparing to thinner cell. Strong interference results in significant vibration of transmission curve in the vicinity of critical angle, which impairs the width of transmission window.

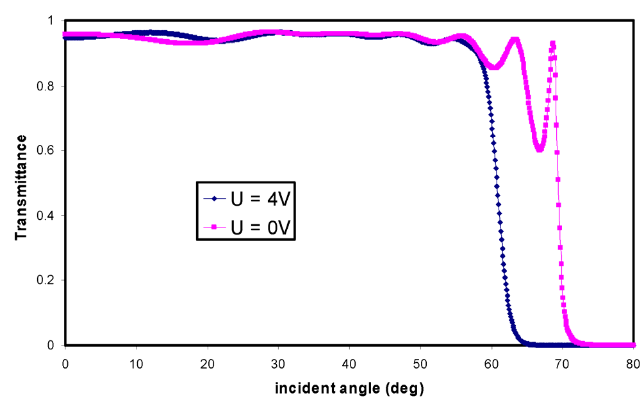

Figure 3 Dependence of Transmittance on incident angle for cell gap d = 1 μm

In order to passively drive more information, response time is an important issue of our concern. Figure 4 shows the response time of LC switch for cell gap equals to 1 m. It should be noted that the behavior of dynamic response of LC switch is related to the chosen incident angle. For instance, in fig. 5(a), since the transmission window is skew, an incident angle larger than critical angle has to be chosen to achieve a good dark state. In the calculation, the switch is sufficiently dark when incident angle is

69o. However, at this incident angle, the transmission for bright state is less than half of the maximum value. Due to the advantage of small cell gap, total response time around 1 ms (10% - 90%, 3.95 ms for full dark – full bright) can be achieved for 1 □m LC switch, which is very fast in application of nematic LC. Contrast ratio around 300:1 can be obtained in simulation, which closely depends on the incident angle.

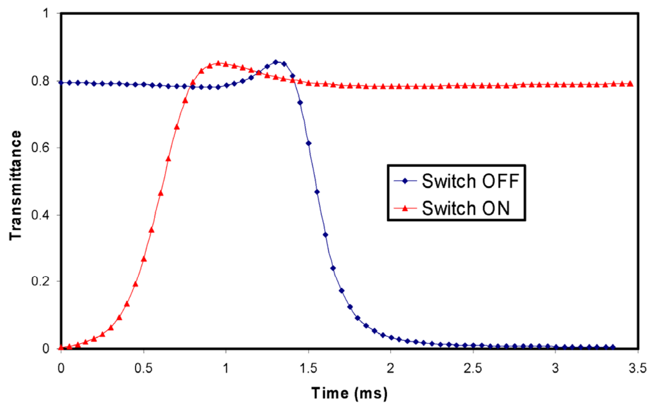

Figure 4 Response time of LC switch for cell gap d = 1 μm

The prototype has been made in experiment according to the results from simulation. The dynamic response of the prototype shown in the figure 5 proves the consistence between simulation and experiment. Response time as fast as 1.6 ms can be obtained for 10%-90% transmittance. Contrast ratio in experiment is around 200:1.

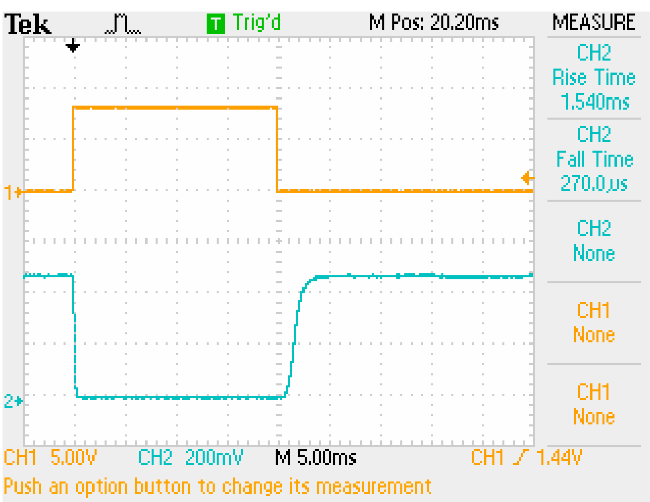

Figure 5 Dynamic response of LC switch under electric pulse in experiment

5. Conclusion

In a summary, a novel liquid crystal switch array based on TIR effect has been presented, which can be applied to not only the display area but also the communication area. Analysis and optimization for all the related parameters for the TIR-based LC switch, including the operation modes, LC mixtures, and refractive index of glass have been conducted. The prototype has been fabricated according to the obtained optimal configuration. High contrast and fast response can be observed in both simulation and experiment.

6. Acknowledgements

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7. References

[1] [1] de Gennes P. G. and Prost J. (Oxford: Clarendon Press, 1993).

[2] [2] Vladimir G. Chigrinov, (Boston: Artech House, 1999).

[3] [3] N. A. Riza and S. Yuan, J. Lightwave Technol. 17, 1575–1584 (1999).

[4] [4] K. Wu, J. Liu, and Y. Chen, U.S. patent 5,963,291 (5 October 1999).

[5] [5] K. Hirabayashi and C. Amano, IEEE Photon. Technol. Lett. 14, 504–506 (2002).

[6] [6] Ailing Zhang, Kam Tai Chan, M. S. Demokan, Victor W. C. Chan, Philip C. H. Chan, Hoi S. Kwok and Andy H. P. Chan, Appl. Phys. Lett. 86, 211108 (2005).

[7] [7] M. A. Mossman, A. Kotlicki, L. A. Whitehead, R. W. Biernath, and S. P. Rao, SID'01 Digest, 32, pp. 1054-1057, 2001.

[8] [8] Jun Qi and Gregory P. Crawford, SID'03 Digest, 34, pp. 648-651, 2003.

[9] [9] S. McGrew; D. DeVries, R. Wink, D. Foster, United States Patent 5,973,727, 1999.

[10] [10] P. Xu, V. Chigrinov and H. S. Kwok, submitted to J. Opt. Soc. Am. A, 2007.