Tunable Aperture controlled by Liquid Crystal Optical Switch

Yumee Kim[1] and Kukjin Chun[2]
[1,2] Department of Electrical and Computer Engineering, Seoul National University, South Korea
Inter-university Semiconductor Research Center
E-mail: [1]yumeekim@snu.ac.kr, [2]kchun@snu.ac.kr

Abstract: We propose the tunable aperture using liquid crystal (LC). The device size is 9 × 9 × 1.8mm^3 and the aperture diameters are 1.35mm and 0.63mm for F3.0 and F6.3 respectively. This device has not only electrical benefits from 3V low driving voltage and 16ms fast response time for the proper mobile application, but also mechanical benefits from absence of movable parts for high reliability and low spherical aberration of circular pattern.

1. Introduction

Micro camera inserted in smart cars, mobile devices, gesture recognition sensor or wearable devices needs tunable aperture providing high functionality of adjusting the amount of light, field of view, and depth of field (DOF). The tunable aperture can also measure a distance and obtain the image at the same time. By the DFD (Depth of Defocus) method [1], the depth map can be extracted from the two obtained images that have different DOF each other, and we are able to find the distance between the object and camera, as well as image. Dual aperture [2] in mobile camera is composed of two apertures respectively, so it is difficult to align the two apertures and needs new color filter pattern on the image sensor to obtain further IR information. To overcome these major problems, the aim of the present study is to develop the tunable aperture inserted in a conventional camera module. The tunable aperture requires low driving voltage and fast response time to apply mobile applications and real-time range measuring. Yu et al. [3] presented miniaturized tunable aperture using comb-drive actuator that is able to rotate blades and control the aperture size, and Li et al. [5] reported the tunable aperture using electrowetting of opaque liquid. These apertures and others had high driving voltage and slow response time to apply diverse application and detect the distance in real-time as shown in Table 1.

Table 1. Comparison of Tunable micro apertures

Control Mechanism	Driving voltage [V]	Driving Current [A]	Response Time [ms]	Reference
Mechanical	0~100	-	1.6	[3]
Ferrofluidic	-	2.6	-	[4]
Electrowetting	60~70	-	42	[5]
Dielectrophoretic	40~160	-	1330	[6]
Pneumatic	0~80	-	-	[7]
LCD	3	-	16	This work

We demonstrate the tunable aperture using light modulation characteristic of LC with dielectric anisotropy. Due to the characteristic of LC, this tunable aperture can have lower voltage and faster response time with no assembly process and no movable parts than other conventional approaches

2. Design and Fabrication

The tunable aperture of this study used LC optical switch with twisted nematic LC in normally white mode. This tunable aperture structure is formed between two transparent electrode/glass/polarizer substrates, which are coated with alignment layer and filled in liquid crystal.

In Fig. 1, when no electric field is applied, the external light pass through the first polarizer, liquid crystal rotated by the helical structure and second polarizer set at 90° to the first polarizer due to twisted configuration of nematic liquid crystal molecules by 90°. On the contrary, when an electric field is applied between the two electrodes, the liquid crystals align parallel to the electric field itself which result in blocking the light by the second polarizer.

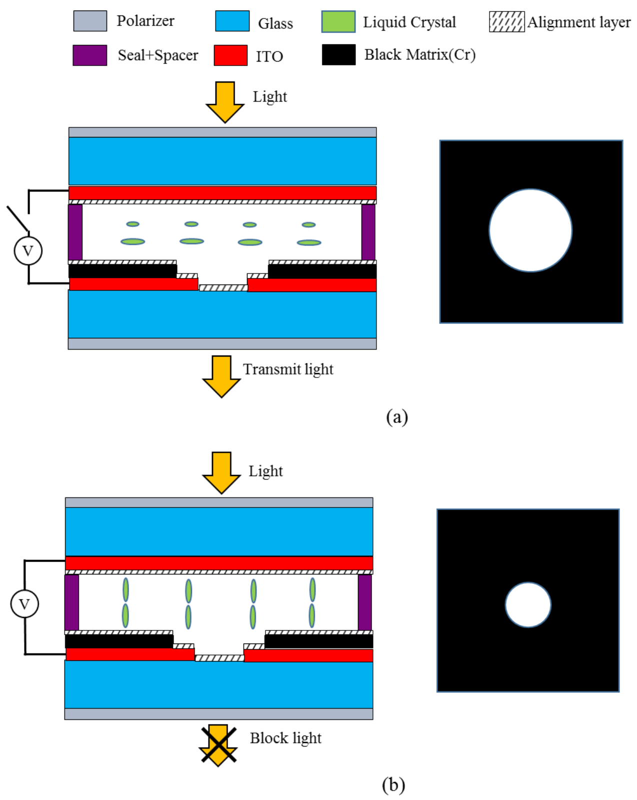
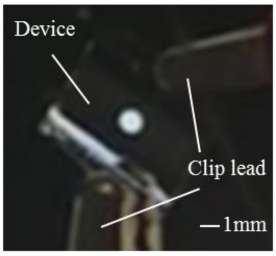
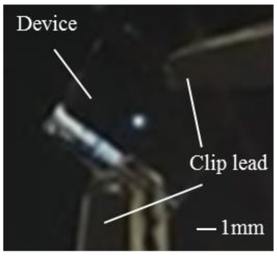


Fig. 1. Operating principle of the tunable aperture with LC
(a) No electric field is applied
(b) An electric field is applied



(a)



(b)

Fig. 2. The tunable aperture with operating voltage: (a) V=0; (b) V=3V

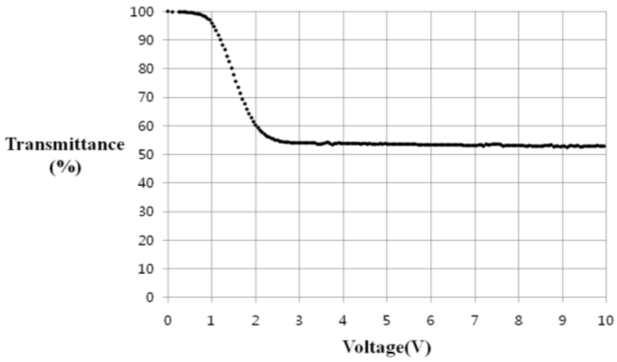


Fig. 3. Measured Voltage-Transmittance

In fabrication process, ITO layer and black material on glass bottom substrate was patterned to form a ring shape aperture by photo-lithography with 2 masks. Then, alignment layer was coated and rubbed in one direction on the top and bottom ITO glass surfaces, respectively. The sealant was then printed on the bottom substrate for sealing of liquid crystal and bonding of top and bottom substrates. The sealant contained the spacer of 4um to maintain the gap between top and bottom substrates, or the liquid crystal layer, matching with the birefringence of liquid crystal. The top substrate was assembled with the bottom substrates. After dicing process, TN-90°, normally white liquid crystal(ZKC-5097LA, JNC Korea Co.) was inserted using capillary tubes. The polarized film was attached parallel to the rubbing direction.

3. Result

The tunable aperture size is 9 × 9 × $1.8mm^3$, and the aperture diameter are 1.35mm and 0.63mm, respectively. Fig.2 is the image of actuated tunable aperture when the 3V of driving voltage was applied at 1Hz.

In experiment, the driving voltage of the tunable aperture can be seen that by increasing the driving voltage of the tunable aperture to 10V, the transmittance can be changed from bright state to dark state. For the measurement, a He-Ne laser of 632.8 nm (05 STP, Melles Griot) and a digitizing oscilloscope (TDS 420, Tektronix) were used. As a result, the driving voltage was 2.9 ± 0.4V. The transmittance was approximately 53% as shown in Fig.3. The low transmittance was not reliable because the diameter of used laser beam was 0.5mm which is smaller than the size of the outer aperture. Therefore, the required additional calculation of transmittance was done. The glass substrates have significant impact on the transmittance because refractive index of glass is 1.474: having large difference between air and glass and little difference between liquid crystal and glass. It was defined that the transmittance of glass substrates is 92.15% at 0.7mm thickness of glass as predicted by the Beer-Lambert law (1), [8].

$$I_T = I_0(1-R)^2 e^{-\beta x} \qquad (1)$$

x : Thickness of glass, β : absorption coefficient

The response time was also measured. We measured the resistor connected to photo diode (ST3811, KODENSHI AUK) under the tunable aperture. When a square wave 4V was applied to the tunable aperture and 5V DC voltage was applied to the circuit, the resistance of the photo diode changed by working of the tunable aperture under a light source and the resistance of output resistor also changed. The measured rise and fall times were 16.1ms and 4.5ms, respectively.

4. Conclusion

One advantage of the present study using LC is that this tunable aperture can operate at 3V, in any size, while the sizes of other conventional tunable apertures are difficult to control if aperture sizes were not linear to voltage or driving voltage were high. Also, the aperture sizes are fixed by only photo-lithography, so there is not limit to aperture sizes. And, this aperture has high reliability because it is operated directly by 3V with no moving mechanical parts. Also, it can reduce optical aberration that may occur in the process of arranging between each different sizes of the apertures and in the performance of moving parts. In micro fabrication process, this tunable aperture could have precision of semiconductor fabrication. And this small size aperture can be mounted in a compact camera. F3.0 and F6.3 apertures can capture the image respectively and extract the depth map which can obtain the image and distance information at the same time. When we compare two parameters which is low voltage and fast response time simultaneouly, this work has the best performance among conventional tunable apertures. That is suitable to the mobile phones, tablet PCs, game devices and smart cars.

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