Submillisecond-response Polymer Network Liquid Crystal Cylindrical Microlens Array for 3D Displays

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Abstract

We demonstrate a submillisecond-response tunable-focus cylindrical microlens array based on polymer network liquid crystal. The focal length can be tuned from 1.9 cm to 5 cm by increasing the voltage from 0 to 80V. This microlens array has potential applications in autostereoscopic 3D displays.

Author Keywords

polymer network liquid crystal, lenticular lens, 3D display

1. Introduction

Adaptive liquid crystal (LC) cylindrical lens array [1-3] is attractive for 3D display applications because of its electrically tunable focal length. Traditional method for fabricating LC microlens array involves patterned or curved electrodes, which usually requires delicate and expensive instruments and procedures. Furthermore, to get a short focal length, large optical path difference between lens center and edge is needed. With a given birefringence, increasing LC layer thickness (*d*) is a straightforward approach to improve the dynamic range of the LC lens. Since the response time of a LC device is proportional to d^2, a large cell gap will significantly slow down the response time especially for the relaxation process. A typical response time of a nematic LC lens with d~15 µm is around 200 ms. For a 2D/3D switchable display, such response time is barely acceptable. But for the time-multiplexing autostereoscopic displays, it is far from sufficiency.

In order to shorten response time, several approaches have been developed, such as using a high birefringence LC material to enable a thinner cell gap while keeping the same phase change [4,5], overdrive and undershoot voltage method [6-8], dual frequency liquid crystals [9,10] and polymer network liquid crystals (PNLCs) [11-17], just to name a few.

In this paper, we demonstrate a PNLC-based tunable focus cylindrical microlens array with a pitch length of ~630 µm. With the assistance of a moving photomask, the effective extraordinary refractive index (n_e) of the PNLC can be locally controlled by curing the precursor at different biased voltages [16]. Due to the strong anchoring effect of polymer network, our PNLC microlens array shows submillisecond response time, which is much faster than nematic device. The focusing properties of our microlens array were also investigated.

2. Experiment

To fabricate a cylindrical lens array, we first prepared a photopolymerizable mixture with 89.99% liquid crystal host (HCCH HTG-135200), 10% Reactive Mesogen (Merck RM257) and 0.01% photoinitiator (GENOCURE BAPO). To suppress scattering without increasing operating voltage too much, we carefully controlled the monomer ratio and LC host [13-15]. Next, we filled this precursor into an LC cell with homogeneous alignment and 15-µm cell gap. After that, we cured the sample cell with a UV lamp. The mechanism of the UV curing process is illustrated in Fig. 1. By using a moving photomask, we are able to locally control the extraordinary refractive index of the PNLC by curing the precursor at different locations with different biased voltages. Here, the travelling speed of the photomask was controlled at ~0.63 mm/min. For a moving distance of 0.63 cm, it took about 10 minutes.

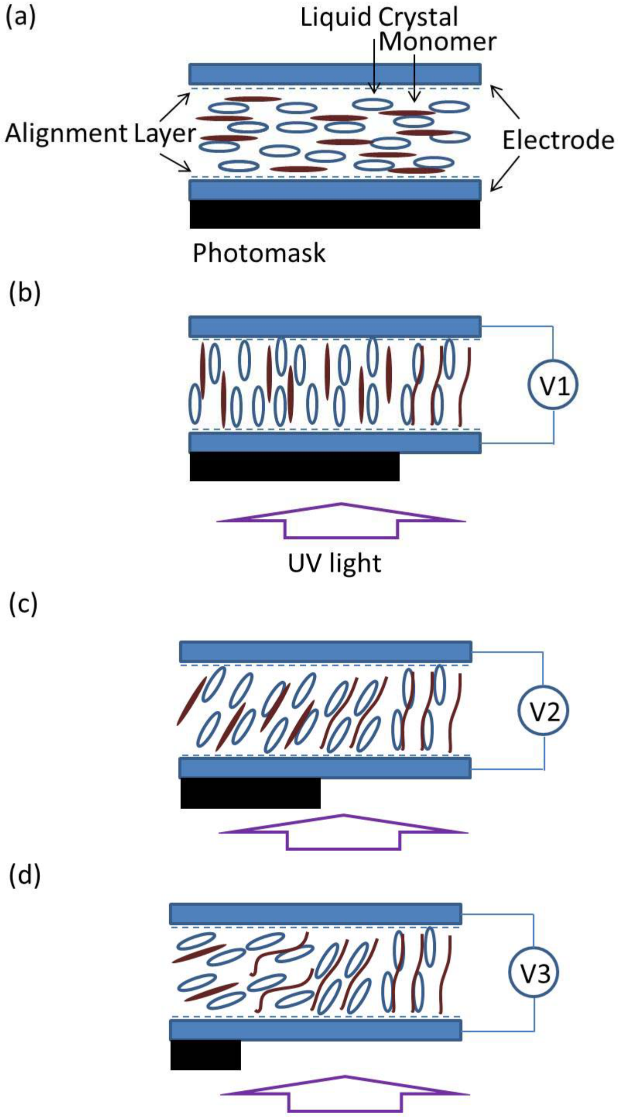

Figure 1. Fabrication procedures of our PNLC cell. Here, V1>V2>V3.

Figure 2(a) shows a photo of our sample cell. The cell is placed on a light table, sandwiched between two crossed polarizers. The rubbing direction of the LC cell forms a 45° angle with the polarization direction. The periodic structure corresponds to our lenticular lens. This lenticular lens has a pitch length of 630 μm. The effective area (lens area) is 1.8 cm x 0.63 cm (10 pitches). It is easy to add more pitches by increasing the travelling distance of photomask while repeating the curing voltage cycles. Figure 2(b) is a sketch of the intended lens profile n_e.

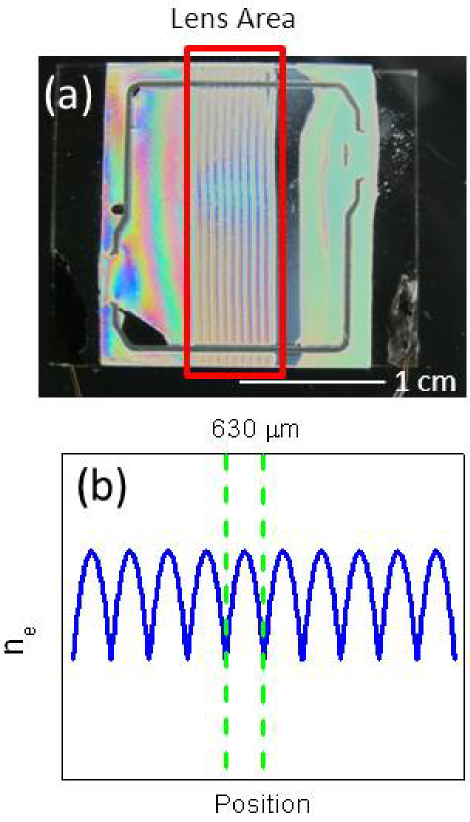

Figure 2. (a) Sample cell is sandwiched between two crossed polarizers on a light table, and (b) Sketch of the intended lens profile (n_e).

To characterize the optical phase difference of the lenticular lens, we observed the sample under a polarizing microscope in transmission mode. In Fig. 3, sample is sandwiched between two crossed polarizers with rubbing direction oriented at 45° with respect to the polarizer's transmission axis. A white light lamp with a 633-nm color filter was used as the light source. The observed spatially variation in intensity is caused by the local birefringence difference [18]. As the operating voltage increases, the observed fringes move towards the lens center, indicating the phase contrast of the lens is decreasing.

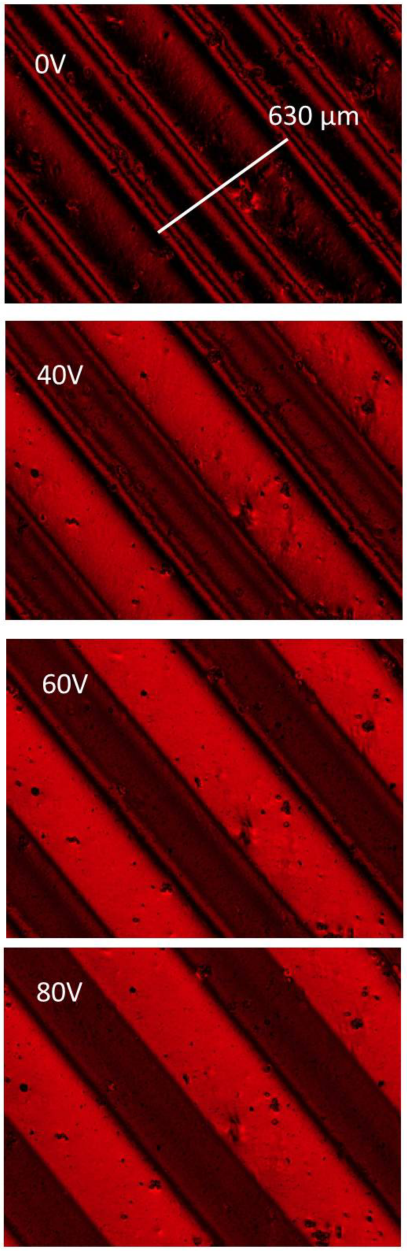

Figure 3. Microscope images: Sample is sandwiched between two crossed polarizers.

The extracted phase difference between lens center and edge is plotted versus the operating voltages in Fig. 4. The focal length can be calculated through following equation [2,17]:

$$f = \frac{\pi p^2}{4\lambda\delta}, \quad (1)$$

where p is the lens aperture and δ is the phase difference between lens center and edge. As the operating voltage increases from 0 V to 80V, the focal length of lenticular lens can be tuned from 1.9 cm to 5 cm (Fig. 5).

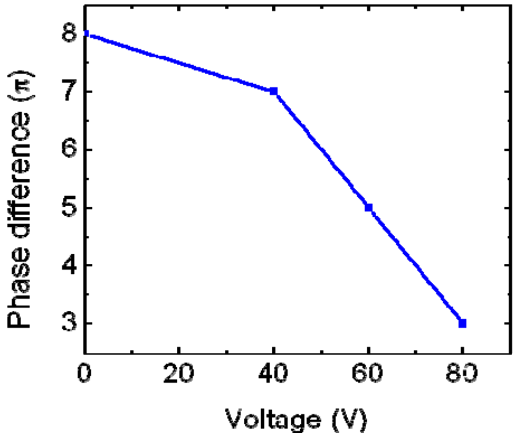

Figure 4. Voltage dependent phase difference between lens edge and center.

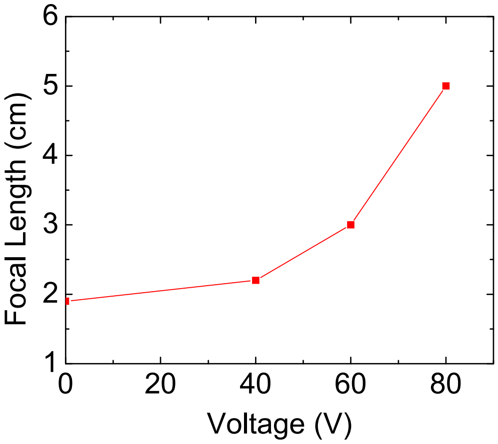

Figure 5. Voltage dependent focal length.

3. Results and Discussion

To characterize the focusing properties of this lenticular lens, we used an expanded linearly polarized He–Ne laser beam (λ=633 nm) to probe the sample. Polarization direction was parallel to the rubbing direction. The intensity distribution pattern is shown in Fig. 6. Since the image is taken at the lens focal plane at 80V, the light strips are broadened when the voltage is removed. To measure the response time of our lens array, we put an iris on the focal plane of the lens (80V) and just allowed one light strip passing through the iris. A photodiode detector was used to measure the light intensity. When the voltage was removed, the broadened light strip was partially blocked by the iris, so the detected light intensity decreased. We used an oscilloscope to record the relaxation curve (Fig. 7). The rise time was measured to be 63 μs and relaxation time 935 μs (90% to 10% transmittance change).

From Eq. (1), to increase the optical power we need to increase the phase change. To do so, we could either choose a higher birefringence LC material or increasing the cell gap. The former is preferred because the latter will increase the operating voltage and light scattering loss. To lower the operating voltage, we could select a large Δε LC material. However, the tradeoff in increased viscosity or slightly slower response time is inevitable.

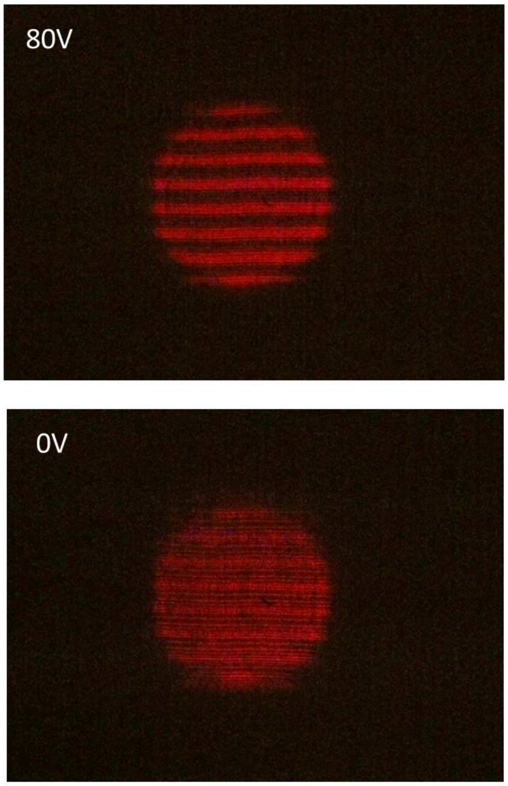

Figure 6. The focusing properties and intensity distribution of the PNLC lenticular lens at 80V and 0V.

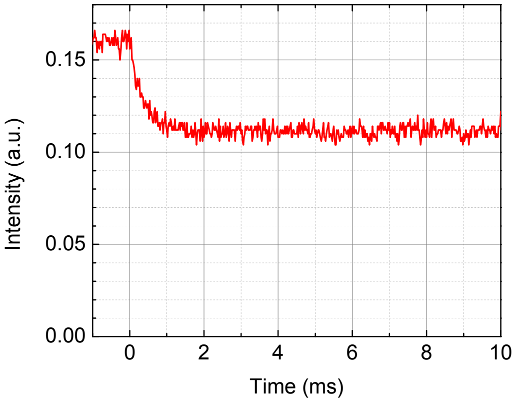

Figure 7. Measured relaxation time of our PNLC microlens. λ=633 nm.

4. Impact

We have demonstrated a submillisecond-response tunable focus cylindrical lens array based on PNLC. The fabrication process is fairly easy and fast. The focal length is tunable between 1.9 cm and 5 cm with operating voltage lower than 80V. Response time is fast (rise: 63 μs, decay: 935 μs) at room temperature. In comparison, the relaxation time of a similar E7 homogeneous cell will be slower than 200 ms. This lenticular lens has potential applications in autostereoscopic 3D displays.

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