Voltage-controlled optical filter based on electrowetting

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In this letter, we propose a voltage-controlled optical filter based on electrowetting. The device is made of a transparent cubic cell filled with two immiscible liquids having three indium tin oxide electrodes fabricated on the bottom substrate of the cell. A conductive droplet carrying a color filter is placed on the ITO electrode and the surrounding liquid is density-matched silicone oil. Under zero bias, the droplet is placed in the middle of the substrate and white light passes through the filter and we can see red light on the screen. When a voltage is applied to the device, the filter moves with the liquid based on electrowetting effect, we can see the white light on the screen. Due to the movement of the liquid, our device functions as an optical switcher. The switch time of the device is ~70 ms. The proposed device has a wide application in optical communication, electronic display, and optical switch.

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Voltage-controlled optical filters have attracted the attention of many researchers because of their widespread applications in optical instruments and systems, optical switches, and optical sensors[1–5]. The most common way to switch light is by controlling the switcher mechanically, such as a color wheel, which is widely used in optical systems[6]. However, because of mechanical actuation, the fabrication of such structures is complicated and such devices tend to be relatively large. Recently, a wide variety of devices based on liquid actuation have been proposed due to advantages such as low cost, optical isotropy, broadband performance, and compact packaging. Many devices including adaptive liquid prisms[7–11], liquid lenses[12–15], and optical switches[16,17] have been successfully developed for imaging, beam steering, and other applications. Electrowetting devices, designed to switch light, often use a dyed liquid which is controlled via deformation[18,19]. By using the dyed liquid to absorb light, the device can achieve the purpose of switching light. In comparison with the previous liquid devices, the liquid of our device is transparent. We add a solid filter to the liquid that can move with the liquid − this is different from the previous devices as light is absorbed by the filter instead of the dyed liquid. When we apply a voltage to the electrodes, the droplet carries the filter moving toward the substrate based on electrowetting effect. Our experiments show that the device can switch light from white to red with a relative fast response time (~70 ms). The proposed device has potential applications in optical communications, displays, optical switches, and wave filters.

The side-view of the proposed device and the operating mechanism are depicted in Fig. 1. As shown in Fig. 1(a), the chamber is formed with four polymethy1 methacrylate (PMMA) substrates. Three ITO electrodes are fabricated on the bottom substrate and two of them are coated with dielectric layer. In the middle of the substrate is a conducting droplet that carries a red filter film. The outside space of the droplet is filled with transparent oil, which is immiscible with the droplet. A shallow channel is fabricated to make sure the droplet is moving in a specific direction. As shown in Fig. 1(b), in the voltage-off state, the droplet is placed on the middle of the substrate and surrounded by silicon oil. When a voltage is applied to the right side of the electrode, the droplet moves toward the right side of the substrate surface. When we apply a voltage to the other side of the device, it will move in the opposite direction due to electrowetting effect. The movements of the droplet are shown in Figs. 1(c) and (d). The change in the contact angle θ_1 and θ_0 between the droplet and the bottom substrate can be described by

$$\cos\theta_1 = \cos\theta_0 + \frac{U^2\varepsilon}{2d\gamma_{12}}, \tag{1}$$

where γ_{12} is the surface tension between the two liquids, θ_0 is the initial contact angle without applied voltage, θ_1 is the contact angle when applied voltage to the device, d is the thickness of the dielectric insulator, $\varepsilon = \varepsilon_0\varepsilon_r$ is the dielectric constant of the dielectric insulator, and U is the voltage applied to the electrode.

To fabricate the device shown in Fig. 1, three ITO glass strips are deposited on the bottom substrate. The left and right sides ITO (3.5×8 (mm)) are coated with a parylene-C layer (~1 μm) as an insulator, followed by

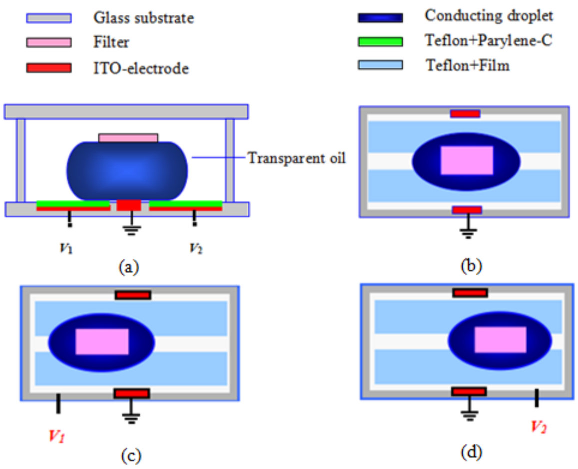

Fig. 1. Structure of the proposed device and its operation mechanism: (a) initial state, (b) top view, (c) applied voltage to the left side of the ITO electrode, and (d) applied voltage to the right side of the ITO electrode.

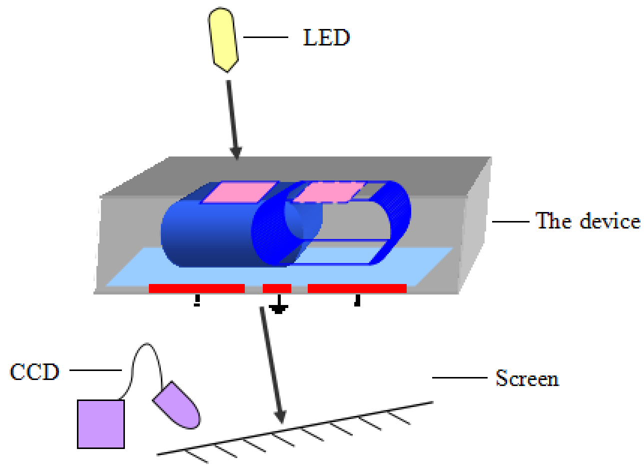

Fig. 2. Experimental setup.

a thin Teflon layer (AF-1600, from DuPont, ~2 μm). The surface energy of the Teflon layer is ~18 mN/m at room temperature[20]. The size of the middle electrode is 1×8 (mm). Among the three ITO glass stripes there are two small gaps (~200 μm) filled with glue to insulate the three ITO glass stripes with one another. Then the electrodes are inset into the polydimethylsiloxane substrate. Four PMMA substrates are stacked together using UV331 glue to form the cell chamber. Two 100 μm thick glass thin films coated with Teflon are stuck on the substrate to form the channel. The width of the channel is 3 mm. In our experiment, NaCl solution is used as the conducting droplet (the density is 1.05 g/cm^3, the molarity is 0.154 mol/L, and the volume is ~0.04 mL) and the surrounding is filled with silicone oil (the density is 0.96 g/cm^3). The filter we use is a red plastic filter film, whose size is 3×3 (mm) (the transmittance is more than 90% and absorption spectrum is ~635 nm). Its weight and thickness are 6 mg and 100 μm, respectively. The liquid wets the filter material. The filter is sufficiently rigid so that the droplet does not deform the filter. The size of the whole cell is 9×9×5 (mm).

To measure the performance of the device, we used a charge-coupled device (CCD) camera to detect the cell. Figure 2 shows the experimental setup. We used a white light-emitting diode (LED) light to illuminate the device. In the initial state, the liquid carrying the filter was placed on the middle of the substrate surface. When the white light passed through the filter, we could see the red light on the screen. When we applied voltage to the right (or left) sides of the electrodes, the filter moved with the droplet, and the white light could pass through the device. The movements of the droplet are shown in Figs. 3(a)–(c). The transmitted light arrived to the screen and we could get the white light on the screen. Figures 4(a) and (b) shows the results on the screen.

In this experiment, when the external voltage $U < 35$ V, the droplet could not move because the threshold-driven voltage of the device was 35 V. Then when we increased the voltage ($U < 45$ V), the droplet could move a little bit so that the white light cannot pass the device completely. On continually increasing the voltage $45 < U < 80$ V, the droplet could move around within the substrate and the white light could pass the device completely. When the voltage $U > 80$ V, the droplet could not move further on the substrate. We define the center of the droplet as the original point. L and R represent the distances from the center to the margin of the droplet when we apply a voltage to the left or right side of the electrodes, respectively, as shown in Fig. 5.

Response time is a key parameter to measure the performance of the light switcher. We define the rise (decay) time as the time it takes to switch light from red (white) to white (red). We measure the response

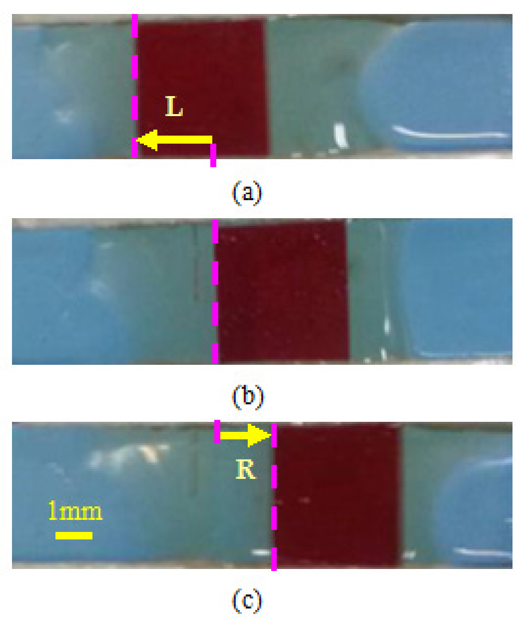

Fig. 3. Results of the droplet moving via electrowetting: (a) applied voltage to left side, (b) initial state, and (c) applied voltage to right side.

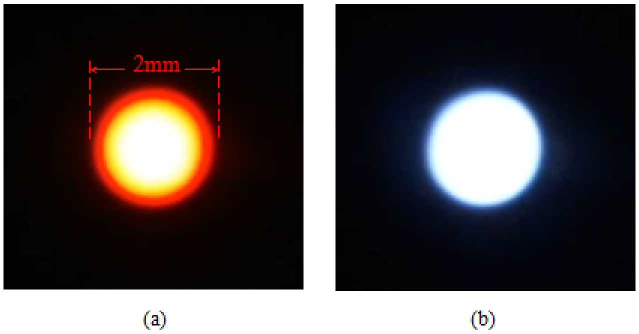

Fig. 4. Results of the light switcher: (a) initial state and (b) applied voltage to the right (left) side of the electrode (Media 1).

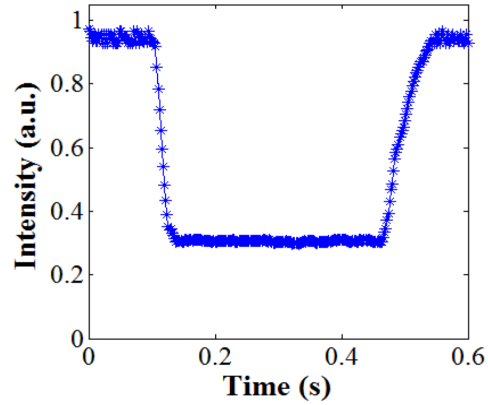

Fig. 6. Response time of the device.

time of the device and the results are shown in Fig. 6. When white light passes through the red filter, some energy is absorbed by the filter, so the intensity we detected is low, whereas when the filter moves away from the droplet, the intensity becomes high. The measured rise time and decay time are ~70 and ~90 ms, respectively.

The proposed device can also be extended to switch different color lights by using different filters, which can be applied to design an electronic display device. How to make it apply to color electronic display is our further work. Besides, the device can also be used as an optical switch. We use a green light source to irradiate the device. At first, the green light passes through the red filter, and no light can be seen due to the absorption of the filter. When a voltage is applied to one side of the ITO electrode, the filter moves with the droplet, so green light can pass through the device, and we can see the green light. With this method, it can achieve the function of a green light switch.

The proposed device still has some unsolved issues. In our experiment, the external voltage is so high that it may destroy the device via, for example, electrical breakdown. For this issue, we can decrease the thickness of the insulating layer or choose a dielectric layer with a high dielectric to decrease the driving voltage. From Fig. 6, we can see that there is a difference in rise

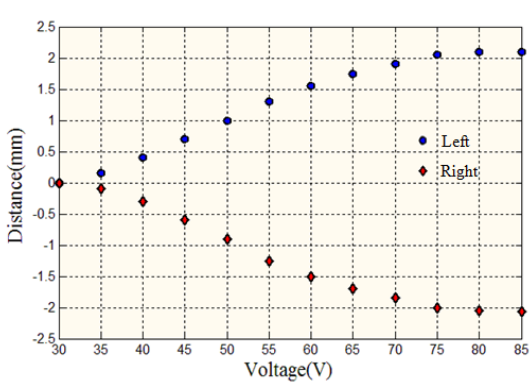

Fig. 5. Droplet displacement distance when voltages are applied to the electrodes.

time and fall time as the switch is turned on/off. This is because once the droplet moves, it cannot be restored to its original position completely, and the residual charge can also affect the response time. Besides, the response time depends on the distance that the droplet moves, so it can be improved by reducing the width of the channel space. In our previous experiment, the traveling distance was about 1.8 mm. We conducted another experiment also. When we decrease the volume of the liquid, the distance is shortened. But the liquid volume cannot be too less. Besides, by reducing the whole size of the device, the distance can be further shortened. When we employ the abovementioned method, the distance can be reduced to 2.1 mm. So the performance of the device can be further improved. At first, an asymmetric image is observed. We have considered the following reasons: when white light passes through the filter, dispersion happens because of unlevel surface of the filter; the overexposure happens while taking a photograph. So we conducted another experiment, and it can be seen that the asymmetric image disappears after the exposure adjustment. We feel that the asymmetric image was caused by the second reason. In our experiment, since the densities of the two liquids do not match well, the generated gravity force can affect the application of the device. This problem can be solved by choosing suitable clear oil whose density matches that of the conductive liquid. Besides, a suitable filter is important, its width should be narrower than channel and the size should be smaller than the conductive liquid. So a filter with small size, light weight, and good adhesion is preferred, thus it is sufficiently rigid so that the droplet does not deform the filter. With these methods we can make the device more competitive.

In conclusion, we propose a voltage-controlled optical filter based on electrowetting. When we apply voltage to the electrodes, the droplet carrying the filter shifts toward the substrate based on electrowetting effect, and the light on the screen can be switched from red to white. Thus, the device can achieve the function of colored light switcher. The response time of our device is ~70 ms.

The proposed device has wide applications in optical communications, electronic displays, and optical switches.

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