Novel optical switch with a reconfigurable dielectric liquid droplet

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Abstract: We demonstrated a novel optical switch with a reconfigurable dielectric liquid droplet. The device consists of a clear liquid droplet (glycerol) surrounded by a black liquid (dye-doped liquid crystal). In the voltage-off state, the incident light passing through the clear liquid droplet is absorbed by the black liquid, resulting in a dark state. In the voltage-on state, the dome of the clear liquid droplet is uplifted by the dielectric force to form a light pipe which in turn transmits the incident light. Upon removing the voltage, the droplet recovers to its original shape and the switch is closed. We also demonstrated a red color light switch with ~10:1 contrast ratio and ~300 ms response time. Devices based on such an operation mechanism will find attractive applications in light shutter, tunable iris, variable optical attenuators, and displays

OCIS codes: (010.1080) Adaptive optics; (230.2090) Electro-optical devices.

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1. Introduction

Liquids have found widespread applications in tunable focus lenses [1–7], beam steering [8–10], and displays [11,12] because of their optical isotropy and high transmittance. Several mechanisms have been proposed to operate a liquid device, such as electro-wetting [1,2,11], elastic membrane [3,4], stimuli-responsive hydrogel [5], and dielectrophoretic (or dielectric) effect [6,7]. Among them, electro-wetting is also promising for display applications. In an electro-wetting display, the transmitted light through each pixel is modulated by spreading and shrinking the employed black liquid droplet on a substrate surface. Such a display device does not require any polarizer so that its optical efficiency is high. However, the black droplet always occupies a certain area within the pixel even in its aggregated state. As a result, the effective aperture ratio is reduced due to the absorption of black droplet. Unlike electro-wetting, in a dielectric liquid device the shape of a liquid droplet is reconfigurable by the generated dielectric force. By optimizing the device structure [13,14], the droplet's surface can be deformed to a large degree for beam control. Using a black liquid as the surrounding liquid, the device can be used to switch a beam [15].

In this paper, we demonstrated a white light switch and a red light switch using two different droplet cells. The first cell is used for elucidating the device operation principle while the second cell is intended for a high performance color switch. In the second cell, the incident light is absorbed in the voltage-off state, resulting in a black state. As the voltage increases, the liquid droplet is reconfigured to form a light pipe. Such a voltage-controlled reconfigurable light pipe is promising for new applications like tunable iris, light shutter, and polarization independent displays.

2. Device configuration

Figures 1(a)–1(d) illustrate the fabrication procedures of the dielectric liquid device. A glass plate with indium tin oxide (ITO) electrode is chosen as a bottom substrate. The ITO is overcoated with a thin dielectric layer. A small amount of liquid is dripped on the dielectric layer surface to form a droplet (Fig. 1(a)). The liquid droplet has a fairly large surface tension. Another ITO glass plate coated with the same dielectric layer is used as the top substrate. The gap of the two substrates is controlled using spacers (Fig. 1(b)). The cell gap is larger than the apex distance of the droplet (d>s), so that the dome of the droplet does not touch the top substrate. The area that the droplet contacts on the bottom surface is defined as the droplet aperture (A). Another liquid with a relatively small surface tension is chosen to fill the surrounding space of the droplet (Fig. 1(c)). These two liquids are immiscible and they have a different dielectric constant.

With no voltage, the droplet is in its maximal relaxation state. As voltage increases, the surface of the droplet is reconfigured by the generated dielectric force [7,16]. Because the dielectric constant of the droplet is larger than that of the surrounding liquid, the droplet is strained and has a tendency to expand in vertical direction, causing the dome to uplift. Keep increasing voltage will push the dome to touch the top surface and finally become flat (Fig. 1(d)). Meanwhile, the surrounding liquid has to yield the space and is pushed aside. Since the top and bottom terminals of the droplet are flat, the incident light will pass through the liquid pipe. The diameter of the top terminal is defined as top aperture (D). Due to the balanced surface tension and dielectric force, aperture D is smaller than the bottom aperture b; i.e., $D<b$. This makes the liquid channel asymmetric. Suppose the droplet has a volume of V and its shape is right circular cone, then the volume is expressed as:

$$V = \frac{1}{12}\pi d(D^2 + Db + b^2) \tag{1}$$

Depending on the surface tension of the top substrate and the applied voltage, D can be varied. To keep the same volume, b is changed accordingly. If a cylindrical-shaped droplet is considered as an ideal case, then we have D~d. Under such a circumstance, we have

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$$D = \sqrt{\frac{4\pi V}{d}} \tag{2}$$

From Eq. (2), for the droplet with a fixed volume (V), increasing the cell gap (*d*) will decrease the touching area of the dome. As the voltage is removed, the droplet will return to its original shape because the surface tension of the top substrate is fairly small and it cannot sustain the deformed droplet which has a large surface tension.

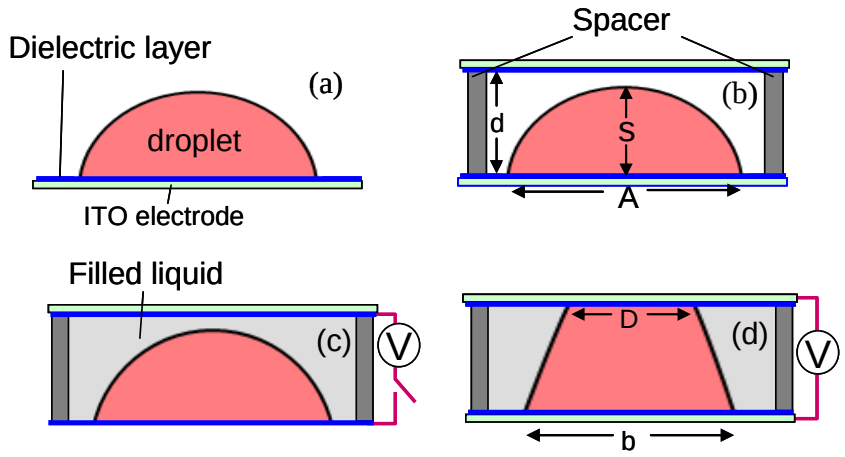

Fig. 1. Droplet cell fabrication procedure and the droplet operation mechanism.

3. Experiment

According to the abovementioned procedures, we prepared a droplet cell as Fig. 1(c) shows. An ITO glass surface was coated with a thin polyimide layer (surface tension ~40 mN/m). This dielectric layer helps to lubricate the substrate surface and prevent the injection of electrons from the electrode. Liquid glycerol was chosen as the droplet material; its surface tension and dielectric constant is ~63 mN/m and ~47, respectively. Due to large surface tension, when a small amount of glycerol was dripped on the substrate surface, it presented a spherical shape. To realize intensity modulation, we filled the surrounding space of the droplet with a black liquid. The black liquid consisted of 1.5 wt% black dye doped in a negative (dielectric anisotropy $\Delta\varepsilon<0$) liquid crystal (LC) mixture. The dye-doped LC was immiscible with the glycerol. The black liquid was injected into the cell through capillarity. The absorption of dyes is isotropic due to random LC orientation. The surface tension of the LC is estimated to be ~20 mN/m. The cell gap was controlled using two striped 200-μm-thick Mylar films. Such a cell can, in principle, restore a droplet with 400 μm maximum aperture without touching the top substrate. But to keep a safe distance from the droplet dome to the top surface, a smaller droplet size is preferred.

To demonstrate a droplet which can be operated between Figs. 1(c) and 1(d), we firstly prepared a special droplet cell. The aperture of the droplet is ~340 μm measured using an optical microscope. The dye doped in the LC was not stirred so that some dye clusters could float in the LC bulk. We did this for two purposes: to clearly observe the motion of the LC fluid during droplet deforming, and to track the aperture change of the top terminal.

4. Results and discussion

Figure 2(a) shows the observed droplet covered by the dye-doped LC. At V = 0, the black dye clusters are randomly dispersed in the LC host. The dye clusters covering the top of droplet reveals that the droplet's dome does not touch the top substrate in the relaxed state. The dome area gives a high brightness and only few dye clusters are dispersed in that area, indicating the

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dome is relatively close to the top substrate. It appears darker in the droplet periphery due to the absorption of randomly dispersed dye molecules. As the voltage (f = 300 Hz) increases, the dye clusters over the dome center begin to move away. At V = 25 V_{rms}, the dye clusters are pushed aside because the dome has just touched the top surface (Fig. 2(b)). At V = 40 V_{rms}, the contact area continues to grow and become flat (Fig. 2(c)). Under such a circumstance, the incident light would pass through the liquid pipe with very little loss, except for the refraction of the off-axis light. Keep on increasing voltage does not alter the top aperture too noticeably. When the voltage is decreased to ~30 V_{rms}, the dye clusters begin to shift from periphery to dome. It means the dome of the droplet is separated from the top substrate. As the voltage is removed (V = 0), the droplet returns to its original shape (Fig. 2(a)) due to the large surface tension of glycerol.

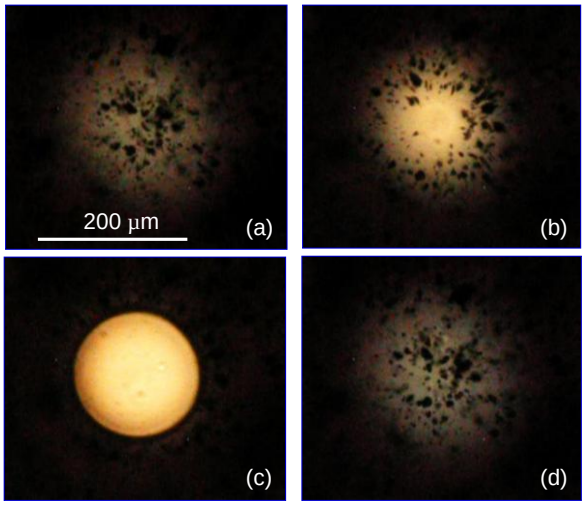

Fig. 2. A droplet cell for proving the proposed operation mechanism at (a) V = 0, (b) V = 25 Volts, and (c) V = 40 Volts. (d) (Media 1) The dynamic response of the droplet with a pulsed voltage (40 Volts) applied to the cell. The droplet aperture is ~340 μm and cell gap is ~200 μm.

To visually observe the droplet deformation as well as the dynamic movement of the dye clusters, a movie was recorded in Fig. 2(d) (Media 1). Here, the voltage was increased from 0 and ~40 V_{rms} and back. From the video, we can observe that the dome of the droplet touches the top substrate at a reasonable speed. The response time was measured to be ~500 ms. In each driving period the droplet returns to its original state. From Fig. 2(a), if the black liquid exhibits a high optical density, the reconfigurable droplet would act as a high performance white light switch and the required operating voltage would be fairly low.

In addition to white light switch, another fascinating application of the reconfigurable droplet is color displays. In a normal transmissive color liquid crystal display, e.g., TV, the displayed color is governed by the embedded color filters [17,18]. Each color filter transmits one designated color. Thus, the optical efficiency is only ~30%. In our approach, to demonstrate a color display we dyed the droplet with red color. To obtain a red liquid droplet, we mixed 4 wt% Rose Bengal in glycerol at room temperature and the mixture exhibited a brilliant red color. More importantly, Rose Bengal is immiscible with the black LC.

To prepare a red light switch, we dispersed a red droplet on a glass substrate. The aperture of the droplet was measured to be ~260 μm. The cell gap was controlled using two 200-μm-thick Mylar films. To prepare black LC, we thoroughly mixed 1.5 wt% black dye in a LC host. Next, we injected the black LC into the empty space of the cell. We then observed the device under an optical microscope. At V = 0, the cell presented a very good dark state and the contour of the droplet was hardly resolved (Fig. 3(a)). This is because the gap between the dome and top substrate is relatively large, and the gap is filled with the black LC. This layer of black LC highly absorbs the incident light, leading to a good dark state. As the

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voltage was increased to ~37 V_{rms}, a clear red circular area suddenly appeared. The red area represents the top terminal aperture. Keep increasing voltage to 60 V_{rms} (Fig. 3(b)), the aperture did not grow too noticeably. At V~60 V_{rms}, the aperture was measured to be ~95 μm.

In the voltage descending cycle, we found the top aperture experienced a significant change. When the voltage was decreased from 60 V_{rms} to ~38 V_{rms}, the aperture increased slightly (Fig. 3(c)), and at V = 33 V_{rms} the aperture was expanded noticeably (Fig. 3(d)). At V~22 V_{rms} (Fig. 3(e)), the aperture reached a maximum value of ~160 μm, which is ~1.7X larger than that at V = 60 V_{rms} (Fig. 3(b)). When the voltage was decreased to zero, the droplet returned to its original dark state (Fig. 3(a)).

To visually observe the dynamic response of the red droplet, we applied a pulse voltage from 0 to ~55 V_{rms} to the cell. Figure 3(f) (Media 2) is a video showing the dynamic response of the droplet. From the video, we found that the droplet's aperture changed very rapidly and it experienced a significant change as the voltage decreased. Also noticed, in each driving period the droplet returned to its original state. The dome touching response was measured to be ~5 ms and the relaxation time (from bright to black) was ~300 ms.

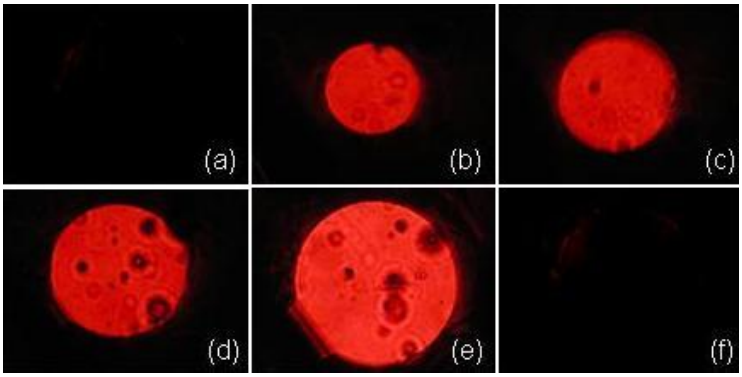

Fig. 3. A droplet cell for red color light switch at voltages of (a) V = 0, (b) V = 60, (c) 38, (d) 33, and (e) V = 22 Volts. (f) (Media 2) Shows the dynamic response of the red droplet with a pulsed voltage (55 Volts) applied to the cell. The red droplet aperture ~260 μm and cell gap ~200 μm.

We can use Fig. 1(d) to briefly explain the variable aperture of the red droplet. When the droplet touches the top surface, the top surface tries to catch the deformed droplet and balance the force with the bottom substrate through their surface tension forces. However, the dielectric force plays a main role to deform the droplet. The droplet on the bottom surface experiences a lager force. The dielectric force strains the droplet to expand outward. Therefore, the aperture of the top terminal has a tendency to decrease, but the change is rather limited. Further expanding the droplet will need a much stronger dielectric force in order to get a new force balance. However, when the voltage is decreased both substrate surfaces have influences on the droplet; the generated dielectric force is no longer the primary force although it still has impact on the droplet. Therefore, the droplet is strongly elongated in vertical direction forming a channel with maximum aperture. As the voltage is further decreased, the top substrate cannot sustain the droplet anymore because of the large surface tension of the droplet. As a result, the droplet returns to its original shape.

Such a result does not occur to the first droplet cell, presumably due to following reasons: (1) The red droplet aperture is relatively small as compared to its cell gap, thus it has enough space to shrink and expand. (2) Rose Bengal reduces the surface tension of the droplet, so that the droplet shape is much easily affected by the substrate surfaces.

To measure the electro-optical property of the droplet, we placed the droplet cell in vertical direction and used a collimated He-Ne laser beam to probe the droplet at normal incidence. The transmitted beam was received by a photodiode detector. Figure 4 depicts the measured voltage-dependent light intensity variation. As V is increased to 7 V_{rms}, the detected laser intensity starts to decrease slightly. This is because most of the LC molecules ($\Delta\varepsilon<0$) are

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reoriented by the electric field to be parallel to substrate surface rather than randomly distributed. Therefore, more light was absorbed by the dichroic black dye. As the voltage is further increased, the laser intensity gradually increases because the dome of the droplet is getting closer to the top substrate surface and the thickness of the black LC layer is reduced. However, at V>27 V_{rms}, the intensity has a tendency to decrease. The responsible mechanism is not yet clear, but it is speculated that the droplet's dome becomes sharper which in turn causes the effective area of the dome to decrease. At V~37 V_{rms}, there is a sharp intensity increase, indicating the distorted dome just making contact with the top surface. As the voltage increases further, the intensity has a tendency to decrease again. Such results have been explained using Fig. 1(d).

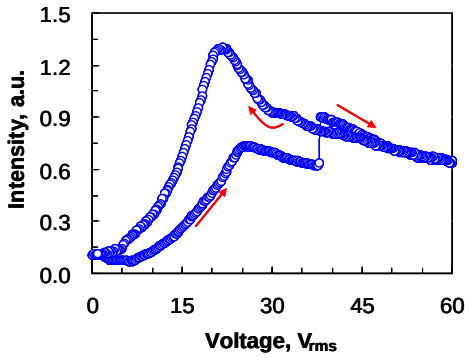

Fig. 4. Measured voltage dependent light transmittance. The red arrow indicates voltage increasing or decreasing direction. The aperture of the red droplet is ~260 μm and the cell gap is ~200 μm.

In the return loop, as the voltage is decreased to V = 40 V_{rms} the light transmission does not follow the initial route. Instead, it begins to increase and reaches a peak at V~22 V_{rms}, where the aperture of the top terminal reaches a maximum and it provides the largest opening for the probing beam to pass through. Further decreasing the voltage will cause the intensity to decrease because the droplet dome is departing the top substrate and the aperture of the top terminal is shrinking until the droplet returns to its original shape at V = 0.

From Fig. 4, the measured contrast ratio is ~10:1 using a 5-mW laser beam. To improve contrast ratio, a black isotropic liquid (rather than dye-doped liquid crystal) with a high optical density is desirable. By increasing the distance between the droplet dome and the top surface would increase the contrast ratio, but the required voltage is increased.

5. Conclusion

We prepared a liquid droplet cell and demonstrated a transmissive single-pixel red color display. Such a new display does not need any polarizer and color filter. Thus, its optical efficiency is high. For the cell with a 260-μm-aperture droplet and 200-μm gap, its contrast ratio is ~10:1. With 40 volts of operating voltage, the measured doom touching speed is ~5 ms and decay time is ~300 ms. Contrast ratio can be further improved if a high optical density isotropic liquid is employed.

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