Optical switch using a deformable liquid droplet

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An optical switch based on a deformable liquid droplet is demonstrated. The device consists of a clear liquid droplet surrounded by a black liquid. In the voltage-off state, the incident light is absorbed by the black liquid. As the voltage increases, the dielectric force reshapes the droplet by uplifting its dome. As the dome touches the top substrate, a clear channel is opened, allowing the incident light to pass through. Once the voltage is removed, the deformed droplet relaxes back to its original shape and the channel is closed. Devices based on such an operation mechanism have potential applications in light shutters, variable optical attenuators, adaptive irises, and displays. © 2010 Optical Society of America

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Polarization-independent optical switches can be used as spatial light modulators, optical attenuators, and display devices. A polymer-dispersed liquid crystal (PDLC) [1–3] and electrowetting [4–6] are two common approaches for such an optical switch. A major advantage of a PDLC is its simple fabrication process. However, a PDLC is a forward scattering device; thus its optical attenuation is sensitive to the distance between the device and the detector. On the other hand, an electrowetting device employs two immiscible liquids: one liquid (oil) forms a thin film, and conductive water covers the oil. When a sufficiently high voltage (V) is applied, the oil film shrinks to a droplet. Because the light transmittance is controlled by shrinking the oil, the device response time increases significantly as the active area increases. Moreover, the transmitted light intensity is not uniform in a pixilated droplet because only the areas covered by the oil could attenuate the incident light. Such a device is better suited for display applications, because the human eye integrates the transmitted intensity even if some local nonuniformity exists.

Similar to electrowetting, the dielectrophoretic effect can also be used for light modulation through voltage-induced reshaping upon a liquid surface [7–9]. Various adaptive lenses have been demonstrated based on the dielectrophoretic effect. Recently, we developed a dielectric liquid droplet whose dome can be deformed from a spherical shape to flat by the generated dielectric force [10]. Such a droplet is useful for optical beam control, e.g., as a beam expander or light diffuser, but is not suitable for an optical switch.

In this Letter, we demonstrate an optical switch using a clear liquid droplet surrounded by a black liquid. In the voltage-off state, the incident light is absorbed by the black liquid after passing through the clear droplet. As the voltage increases, the dielectric force uplifts the droplet. As soon as the dome touches the top substrate, a clear channel is opened up, allowing the incident light to pass through. By removing the voltage, the deformed droplet relaxes back to its original spherical shape.

Figure 1 depicts the side-view structure of the droplet cell. Two immiscible liquids are sandwiched between two indium–tin–oxide (ITO) glass substrates. The clear liquid forms a droplet on the bottom substrate, and the black liquid fills the surrounding space. At $V = 0$, the dome of the droplet is close to the top substrate. Such a structure is stable when the interfacial tension satisfies the following relation [10,11]:

$$\gamma_{D,B} \cos\theta = \gamma_{D,S} - \gamma_{B,S}, \quad (1)$$

where γ is the interfacial tension and subscripts D, B, and S represent droplet, black liquid, and bottom solid surface, respectively, and θ is the contact angle of the droplet. Here we assume the interfacial tension satisfies that $\gamma_{D,B} \gg \gamma_{D,S}$. When a voltage is applied to the cell, the droplet surface bears a dielectric force (F_{DEP}) [12], which reshapes the surface of the droplet. If the dome of the droplet touches the top substrate, then the droplet should be elongated in the vertical direction. Therefore, the contact angle increases, as shown in Fig. 1(b). From Eq. (1), a new balance is expressed as

$$\gamma_{D,B} \cos\theta' + F_{DEP} = \gamma_{D,S} - \gamma_{B,S}. \quad (2)$$

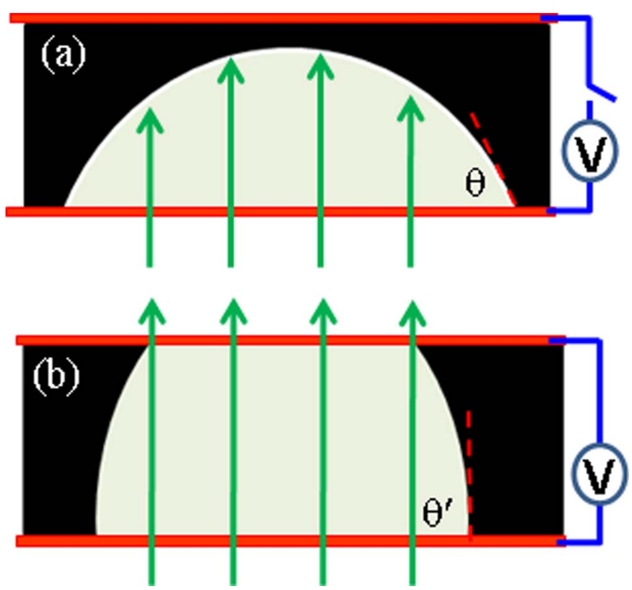

Fig. 1. (Color online) Schematic cross section of a liquid droplet cell in (a) voltage-off state and (b) voltage-on state.

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The direction of effective F_{DEP} is along the droplet's axis in the horizontal direction. Because the volume of the droplet does not change, the black liquid has to yield the space and is pushed aside when the dome of the droplet touches the top substrate. The contact area of the dome depends on the size of the droplet. If the droplet is big, then the contact area will be large. From Eq. (2), if the dielectric force is removed, then the top surface will not be strong enough to maintain the deformed shape of the droplet because $\gamma_{D,B} \gg \gamma_{D,S}$. Thus, the droplet has to return to its original shape.

To fabricate a droplet cell, a clear liquid with large surface tension is chosen. First, the liquid is sprayed on a glass substrate (called the bottom substrate) so that it forms various droplets. Each droplet exhibits a ball shape owing to its surface tension force balance. The area of the droplet contacting the substrate surface is the aperture of a droplet. A large droplet always owns a large aperture. Next, a top flat substrate is used to sandwich the droplets. The cell gap is controlled by spacers. If the apex distance of the droplet is shorter than the cell gap, the dome of the droplet will not touch the top substrate. For the bigger droplet, its dome may touch the top substrate naturally owing to its large volume and high apex distance. Finally, we filled the outside empty space with a black liquid through capillarity.

According to the above-mentioned procedures, we chose a transparent glycerol as the droplet material. The glycerol (surface tension $\gamma \sim 63$ dynes/cm) was dispersed on an ITO glass plate with various droplets. The ITO surface was overcoated with a thin ($\sim$0.8 μm) dielectric polymer layer in order to lubricate the surface and also to prevent electron injection from the electrode. The cell gap was controlled using two mylar stripes (100 μm thick). For the droplet whose aperture is smaller than 200 μm, its dome will not touch the top substrate. To prepare black liquid, we doped 1.5 wt. % black dye (S-428, Mitsui) in a negative liquid-crystal (LC) mixture (ZLI-2585, $\varepsilon_{//} = 3.6$, $\Delta\varepsilon = -4.5$, and $\Delta n = 0.038$, Merck). The dye-doped LC is immiscible with the glycerol. The LC was injected into the cell. The absorption of dyes is isotropic due to random LC orientation.

To evaluate the impact of dielectric force on liquid droplets, we observed the light switching of two droplets at $V = 0$ and $V = 35$ V_{rms} with an optical microscope and recorded the images by a mounted CCD camera. Results are shown in Fig. 2. The aperture of the smaller droplet is $\sim$175 μm, and its apex distance is estimated to be $\sim$80 μm before filling the black LC fluid.

At $V = 0$, the dome of the smaller droplet is covered by the black LC, and the dome of the bigger droplet (partly shown) touches the top substrate. Because the dome of the smaller droplet is fairly close ($\sim$20 μm) to the top substrate, the area above the dome is observable. But the other area still presents a dark state. As for the larger droplet, the incident light could pass through the flattened dome without absorption. At $V = 35$ V_{rms}, the dome of the smaller droplet touched the top substrate with a large flattened area, and the black LC was pushed aside. Therefore, light passed through this area without absorption. For the larger droplet, its dome touching area was not affected by the voltage. In a comparison of these two areas, they have almost the same light transmission.

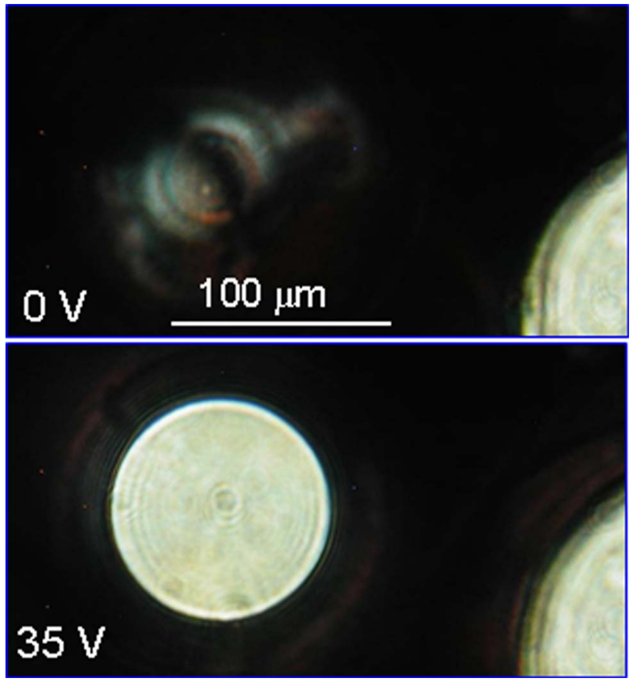

Fig. 2. (Color online) Observed images of two droplets at $V =$ 0 and 35 V_{rms} under an optical microscope with white light.

By removing the voltage, the smaller droplet quickly relaxed to its initial shape.

To improve the light switching ability, we could increase the gap between the droplet's dome and the top substrate. Here we chose another relatively small droplet for investigation. Before LC filling, the aperture of the droplet was measured to be $\sim$140 μm, and its apex distance was estimated to be $\sim$70 μm. Figure 3 shows the observed droplet using a microscope at different voltages. At $V = 0$, the droplet could not be observed, because it was covered by a thick black LC layer. At $V = 30$ V_{rms}, a weak light spot started to appear. This

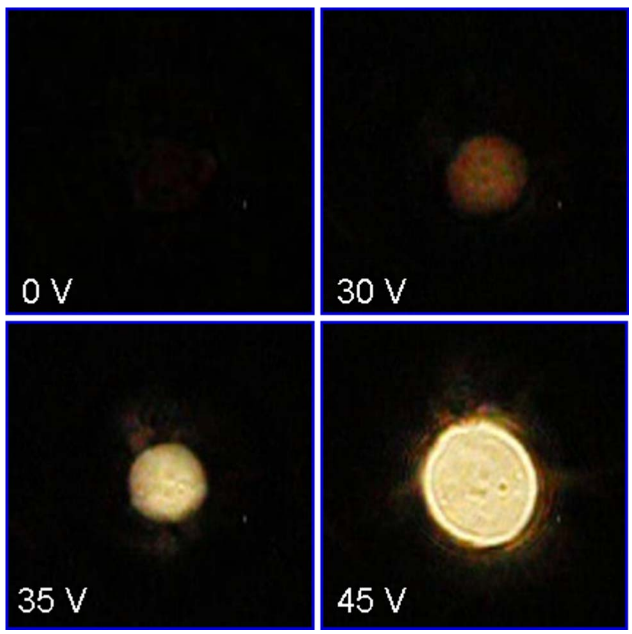

Fig. 3. (Color online) Observed images of a relatively small droplet (aperture $\sim$ 140 μm) covered by a thicker ($\sim$30 μm) black liquid layer.

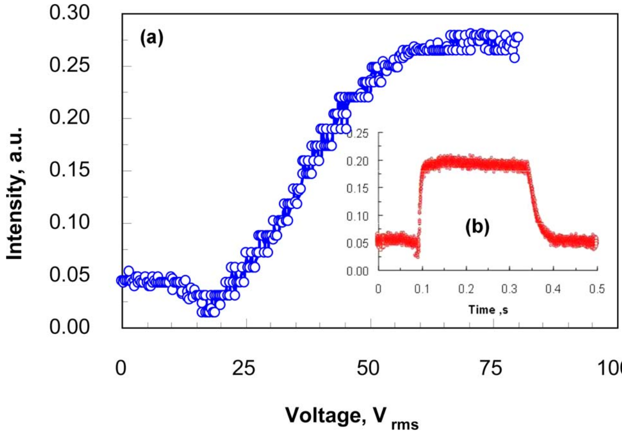

Fig. 4. (Color online) (a) Voltage-dependent transmittance and (b) the measured response time of the droplet with $V = 45\ V_{rms}$ (500 Hz) and $\lambda = 633$ nm.

is because the droplet's dome is uplifted toward the top substrate so that the black LC layer thickness is reduced. At $V = 35\ V_{rms}$, the light intensity became stronger, because the droplet dome was much closer to the top substrate. At $V = 45\ V_{rms}$, the dome largely touched the top substrate surface and the black LC was pushed aside. As a result, the incident light passed through the droplet without absorption. The contacting area of the dome is ~50% in comparison to the droplet's bottom aperture.

To evaluate the optical switch of the droplet, we measured the electro-optical properties of the droplet. The cell was placed in the vertical direction, and a collimated He–Ne laser ($\lambda = 633$ nm) was used as a probing beam at normal incidence. The beam was focused on the droplet, and a photodiode detector was placed behind the droplet. An imaging lens was placed between the droplet and the detector to expand the beam. Figure 4(a) depicts the voltage-dependent light intensity change. At 12 V_{rms}, the detected laser intensity starts to decrease and reaches a minimum at 16 V_{rms}. This is because most of the LC is forced to reorient along the substrate surface rather than displaying a random orientation, and therefore more light was absorbed by the black dye. When the voltage is further increased, the intensity begins to increase because the dome is approaching the top substrate. At $V > 54\ V_{rms}$, the intensity gradually saturates.

For practical applications, fast response is always desirable. To measure the response time of the 140 μm aperture droplet, we applied a gated square wave of 45 V_{rms} pulse (500 Hz) to the droplet. The light intensity change was recorded by a digital oscilloscope. Results are shown in Fig. 4(b). The measured rise time and decay time are ~18 and ~32 ms, respectively.

Based on the above-mentioned cell structure, the area of the dome contacting the top substrate can be increased if the aperture of the droplet becomes larger. To keep a low operating voltage, we could use a lateral electric field to deform the droplet [7]. To enhance the light switching ability, it is better to use a high-optical-density black liquid to replace the black LC. For droplets with apertures over several hundred micrometers, the densities of the two liquids should match well in order to overcome the gravity effect [13].

In conclusion, we have developed a liquid droplet for optical switching. In the voltage-off state, the droplet's dome is covered by a black LC. In a voltage-on state, the dome touches the top substrate and forms a clear channel. Such an optical switch is polarization independent, and the response speed is reasonably fast. Devices based on such an operation mechanism have potential applications in light shutters, optical attenuators, adaptive irises, and displays.

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