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Fringing field stretching of a pillared liquid crystal droplet

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Abstract
We demonstrate a liquid crystal (LC) droplet whose surface profile could be deformed by a fringing field. In the voltage-off state, the LC droplet exhibits a pillared shape by touching both substrates. As the voltage increases, such a droplet could be stretched to a cone-like shape or thin film. For a 1.5 mm aperture LC droplet, its occupied area could be expanded by ~4.3× at 6.5 V_{rms} μm^{-1}. Upon removing the voltage, the droplet could fully recover to its original shape. The shape stretching and recovering time are dependent on the expanded area. With the support of silicon oil around the droplet, the device is stable and the gravity effect is negligible.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A voltage-induced surface-deformable liquid has found useful applications in adaptive lens [1–5], beam steering [6, 7], adaptive diaphragm [8] and display [9]. To reshape the liquid surface, various approaches have been developed [1, 4, 10–12]. Among them, dielectrophoretic force (DEP) is particularly attractive because of its low power consumption, high voltage bearing, and little heat generation. In addition to liquid lenses [4, 5], DEP has also been used to manipulate dielectric particles [13], move water droplets in microfluidic channels [14], and wave the surface of a liquid for grating use [15]. However, using DEP to expand and contract the shape of a large liquid droplet has not been explored.

In our previous work [16], a liquid cell based on DEP was demonstrated. In the cell, a liquid droplet was pinned on one substrate surface. The dome of the droplet was controlled to be fairly close to the top substrate surface. In a voltage-on state, the dome of the droplet could be uplifted to touch the top substrate. Optical beam control is achieved due to the shape of the droplet changing from spherical to cylindrical. Devices with such a structure face two problems: (1) the cell gap is not easy to control and (2) a large-sized droplet requires a large cell gap, resulting in a high operating voltage.

In this paper, we propose to use fringing field to stretch a liquid droplet. In the voltage-off state, the droplet presents a pillared shape by touching both substrates. In a voltage-on state, the droplet is stretched to a cone-like shape or thin-striped film depending on the amplitude of the voltage. The proposed droplet shape changing from flat ($V = 0$) to curved ($V > 0$) is opposite to that changing from curved ($V = 0$) to flat ($V > 0$) [16, 17]. However, the cell with former structure can be fabricated easily without worrying the precise control of the cell gap. Moreover, the voltage is independent of the cell gap, so the size of the droplet is scalable.

2. Operation principle

A pillared liquid droplet (yellow) is sandwiched between two glass substrates by touching their inner surfaces directly, as shown in figure 1(*a*). The outside space of the droplet is filled with another dielectric liquid (pink). The surface of the bottom substrate has an interdigitated indium-tin-oxide (ITO) electrode. On the top of ITO surface there is a thin Teflon layer. The Teflon is patterned with a hole, as figure 1(*b*) shows. The hole is the place for pinning the pillared droplet. A thin Teflon layer is also uniformly coated on the top glass surface (not shown in figure 1(*a*)). The dielectric liquid around the droplet is used to balance the gravity effect of the droplet.

When a voltage is applied to the electrode, a fringing field is generated across the ITO strips. It is well known that the droplet bears a dielectric force if the dielectric constant of the droplet (ε_1) is different from that of the surrounding liquid (ε_2). The dielectric force is expressed as [18]

$$F_{DEP} = \tfrac{1}{2}\varepsilon_0(\varepsilon_1 - \varepsilon_2)\nabla E^2 \quad (1)$$

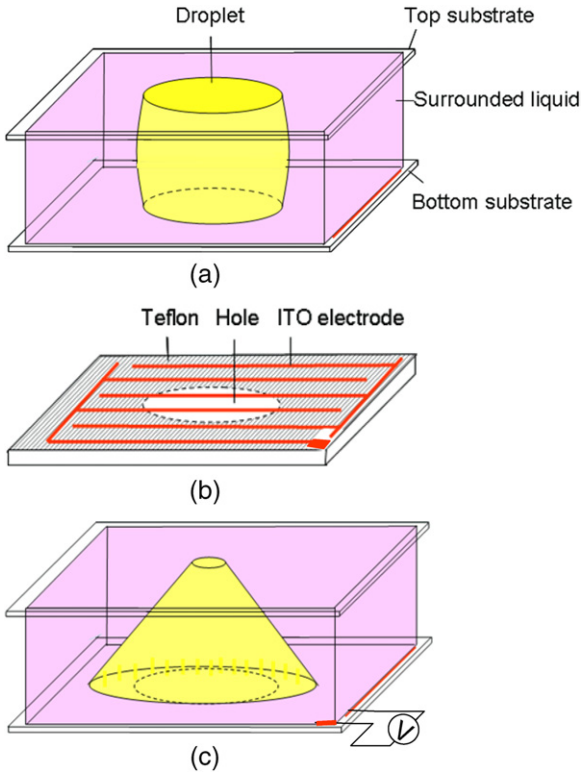

Figure 1. Structure of the device and the working principle: (*a*) the device structure, (*b*) arrangements of ITO electrode and over-coated Teflon layer. The Teflon hole is used to locate the droplet. The droplet size and the width of ITO strip are not scaled, and (*c*) a voltage attracting the droplet to lean to the bottom substrate surface and causing the contacting area on the top substrate to shrink.

where ε_0 represents the permittivity of free space and E denotes the electric field on the curved droplet. Excepting F_{DEP}, there are two more forces taking effect on the shape of the droplet. The substrate surface attracting the droplet due to the adhesive force and the adjacent molecules in the droplet bonding together to prevent the droplet from breaking due to the cohesive force. According to equation (1), if we choose $\varepsilon_1 > \varepsilon_2$, the generated F_{DEP} grabs the droplet to move towards the strong electric field region, i.e. along the ITO strip. Meanwhile, the adhesive force attracts the droplet. As a result, the droplet is stretched in one direction. With the help of cohesive force, the droplet keeps the unity state without breaking. Because the droplet volume is fixed, the top touching area of the droplet would shrink while the bottom touching area increases, as shown in figure 1(*c*). In comparison with its original occupied area (the inner dashed circle), the touching area of the bottom droplet is much bigger and the droplet presents a cone-like shape. When the applied voltage is high enough, the droplet could be deformed extensively and it would completely escape from top substrate.

3. Experiment

Figure 2 depicts the beam modulation in the $V = 0$ and $V > 0$ states. Suppose the droplet has a higher refractive index than the surrounded liquid and the incident beam is collimated, the light beam can pass through either the droplet (probing beam-1, solid-line) or the surrounded liquid (probing beam-2, dashed lines) with the highest intensity at $V = 0$, as figure 2(*a*) shows. After passing through the cell, each beam is received by a photodiode detector. In such a case, each detector receives the highest light intensity. By applying a voltage to the cell, the droplet's contacting area on the right (top) substrate decreases, as shown in figure 2(*b*). The light rays of beam-1 meeting the tilted liquid surface will be deflected (or scattered) and cannot be detected by the detector. Therefore, the transmitted light intensity will decrease accordingly. As for beam-2, it is very close to the droplet at $V = 0$, so that any droplet stretching outwards could be instantly detected by the beam even in the low voltage region. Depending on the voltage, beam-2 can be either partially or totally deflected by the curved droplet surface.

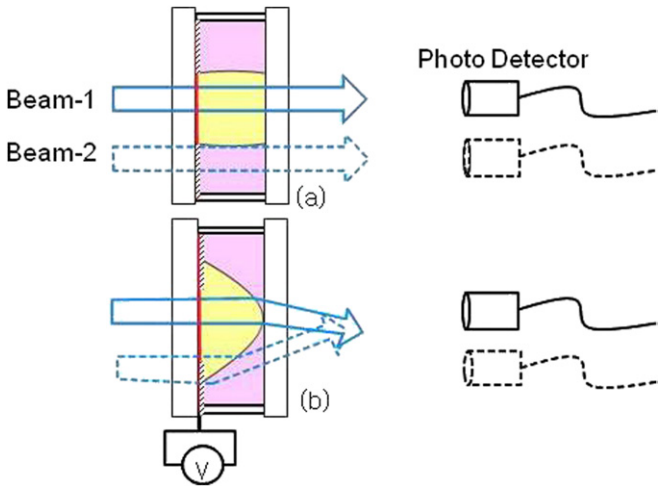

Figure 2. Experimental setup for measuring the dynamic response of the deformed droplet. Beam-1 is for passing through droplet and beam-2 is for passing through the surrounded liquid but close to the droplet.

4. Cell fabrication

To prepare a cell in figure 1(*a*), we first etched the ITO electrode on one substrate surface with interdigitated strips. The width and gap of the adjacent strips are 10 μm and 10 μm, respectively. To form a hole-patterned Teflon layer, we dripped a small UV glue droplet on the electrode surface. After UV exposure, it is solidified and fixed to the substrate. The aperture of the droplet was measured to be ~1.5 mm. We then spin-coated the substrate with Teflon solution (400S1-100-1, from DuPont) at 4000 rpm for 20 s, and prebaked it at 120 °C for 5 min. By removing the NOA65 droplet using a solvent, a hole-patterned Teflon layer is formed on the substrate surface, as shown in figure 1(*b*). This Teflon layer was post-baked at 330 °C for 15 min again, so that it is fully polymerized. This substrate is used as the bottom substrate of the cell.

To largely deform the liquid droplet with a reasonable voltage, it is desirable to choose a liquid with relatively low surface tension and large dielectric constant. Nematic liquid crystal (NLC) Merck ZLI-4389 has such properties.

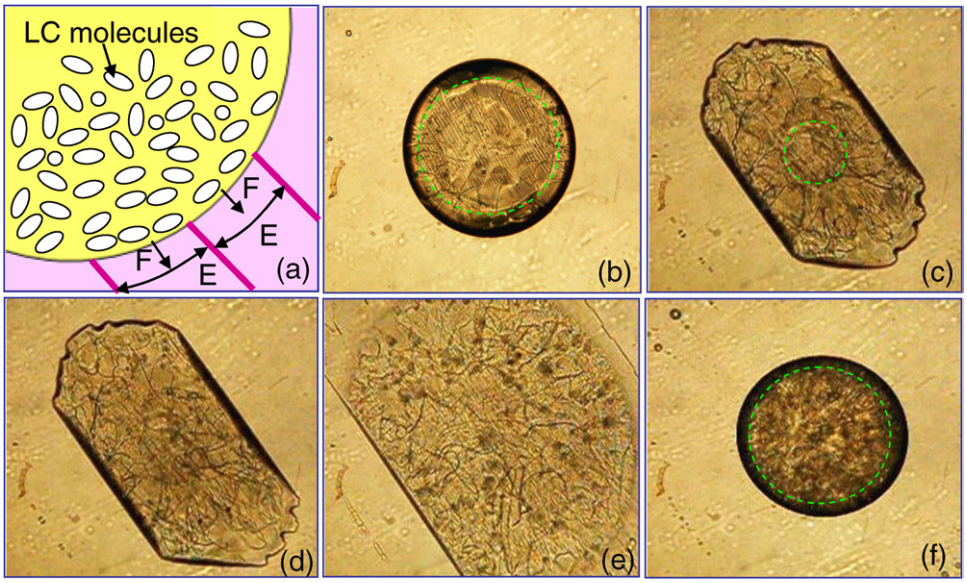

Figure 3. (*a*) The impact of electric field on the orientation LC molecules in a LC droplet. The surface of a 1.58 mm-aperture LC droplet deformed with different voltages from (*b*) to (*f*).

The physical properties of ZLI-4389 are listed as follows: $\varepsilon_{\parallel} = 56$, $\Delta\varepsilon = 45.6$, $\gamma \sim 38\,\mathrm{mN\,m^{-1}}$, $\langle n \rangle \sim 1.58$ and $\rho \sim 0.98\,\mathrm{g\,m^{-3}}$. When we dripped a small amount of ZLI-4389 to the Teflon hole, a droplet with nearly spherical shape and minimal surface-to-volume ratio was formed. This results from the low surface tension of Teflon ($\gamma \sim 18\,\mathrm{mN\,m^{-1}}$) at room temperature [19]. Another Teflon-coated glass plate was used as the top substrate to sandwich the LC droplet. The gap of the cell was controlled using 0.5 mm thick spacers. Silicon oil ($\varepsilon_{\mathrm{oil}} \sim 2.9$, $\gamma \sim 21\,\mathrm{mN\,m^{-1}}$, $n \sim 1.4$, and $\rho \sim 0.97\,\mathrm{g\,cm^{-3}}$) was chosen as the liquid to fill the outside space of the droplet. Silicon oil and LC are immiscible and their densities match well. The periphery of the cell was sealed by glue in order to prevent the liquids from leaking.

5. Results and discussion

By applying a voltage to the electrodes, a fringing field (E) is generated across the ITO strips, as figure 3(*a*) shows. If the electric field is high enough, LC molecules at the droplet border can conquer the weak interfacial tension force of the silicon oil and reorient along the electric field direction. According to equation (1), the dielectric constant of the LC droplet (ε_1) should be replaced by $\varepsilon_{\parallel}$(~56). Because $\varepsilon_{\parallel} \gg \varepsilon_{\mathrm{oil}}$, the droplet suffers a pulling dielectric force along the ITO strip direction. As the voltage increases, LC moves to the higher electric field region while keeping the orientation along the electric field. At the droplet border, LC molecules experience the highest dielectric force. Thus, the droplet deformation should start from the border. When the LC molecules are dragged to move along the strips, the droplet expands.

Figures 3(*b*) to (*f*) show the deformed droplet at different voltages. At $V = 0$, the LC droplet touched both substrates due to its large size. Through an optical microscope, the droplet diameter (~1.58 mm) was found to be slightly larger than that of the Teflon hole. Because of the large size, most LCs in the bulk will not be affected by the fringing field before the droplet is stretched to a film. In this circumstance, the LC molecules exhibit random orientations so that the LC droplet is polarization insensitive but with a fairly large scattering. Using the microscope, we could also clearly observe the contacting borders of the droplet on both substrate surfaces. Since both substrate surfaces were coated with Teflon, the contacting areas of the droplet on the two surfaces should be symmetric, e.g. it presents a pillared shape. When a voltage with $V = 3\,\mathrm{V_{rms}}$ is applied to the cell, only the LCs on the Teflon-hole surface are reoriented, as the circled area shows in figure 3(*b*). A clear striped pattern is observable. The shape of the droplet is not impacted by the voltage. When the voltage is gradually increased to $15\,\mathrm{V_{rms}}$, the droplet begins to stretch along the strip electrodes. At $V = 25\,\mathrm{V_{rms}}$, the deformation becomes more noticeable (figure 3(*c*)). The contacting area of the droplet on the opposite substrate (shown by the dashed circle) shrinks considerably. At $V = 50\,\mathrm{V_{rms}}$, the droplet escapes from the opposite substrate and is stretched significantly, as shown in figure 3(*d*). At $V = 70\,\mathrm{V_{rms}}$, the droplet is deformed to a thin layer, as figure 3(*e*) shows. Removing the voltage, the droplet returns to its original position and shape (figure 3(*f*)).

From figure 3, the LC droplet extends along the ITO strip direction in a voltage-on state, while the width of the elongated droplet does not decrease. Therefore, the extended area of the droplet increases as the voltage increases. Figure 4 shows the relationship of the expanded area versus voltage. At $V \sim 15\,\mathrm{V_{rms}}$, the droplet is about to expand. At $V \sim 65\,\mathrm{V_{rms}}$, the covered area of the droplet increases to ~4.5× in comparison with its original occupied area. Further increasing the voltage will stretch the pillared droplet to a thin film.

To measure the switching speed, we sent a collimated He–Ne laser beam ($\lambda = 633$ nm; beam-1 as shown in figure 2) to probe the dynamics of the droplet. At $V = 0$, the beam goes through the droplet with the highest transmittance. We then applied a $70\,\mathrm{V_{rms}}$ square-wave voltage to the droplet

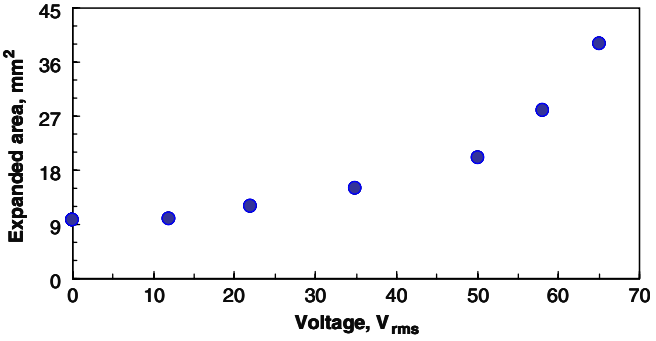

Figure 4. The expanded area of the droplet versus applied voltage.

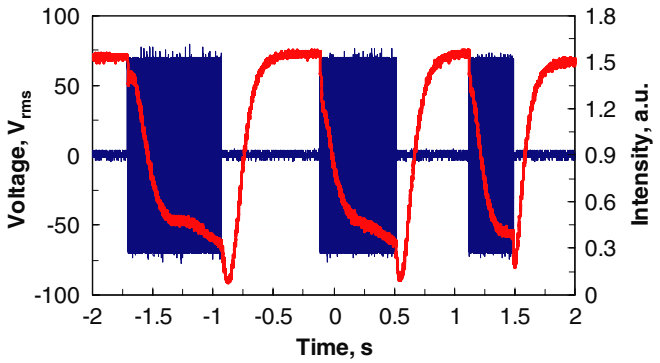

Figure 5. Measured intensity change of the beam passing through the droplet in three different cycles. $V = 70\,\mathrm{V_{rms}}$.

and recorded the intensity change by an oscilloscope. The photodiode detector was placed at ∼15 cm behind the droplet cell. Results are displayed in figure 5.

In figure 5, after three cycles of driving with different pulse widths the droplet returns to its original state. The expanding time is defined as the time needed from the original shape to a stretched shape, while the recovering time is that from a stretched shape to its original shape. For the 770 ms pulse, the expanding and recovering times are measured to be ∼770 ms and ∼300 ms, respectively. The relatively slow response time is because the droplet travels a long distance. For the 600 ms and 320 ms driving pulses, the recovery time is reduced to ∼260 ms and ∼250 ms, respectively. As a comparison, a wider pulse gives a longer expanding time. This is because a wider pulse can cause a larger deformation. As for the recovering time, each returning speed is fairly fast. From figure 5, there is a sharp intensity decrease just after removing the voltage. Because after removing the voltage, the droplet immediately has a tendency to adjust its shape from asymmetric to symmetric shape. This will deflect more light within a short time. The light switching ratio is over ∼10 : 1 impacted by the 770 ms pulse width. This ratio is dependent on the tilted surface of the droplet, the difference of the refractive indices ($n_{\mathrm{LC}} - n_{\mathrm{oil}}$), and the distance between the liquid cell and the detector.

Since LC molecules exhibit random orientations in the droplet, a fairly large light scattering exists in the voltage-off state. To avoid such a concern, we let the laser beam pass through the silicon oil but close to the droplet, as referred to the probing beam-2 in figure 2. To do so, we just move the

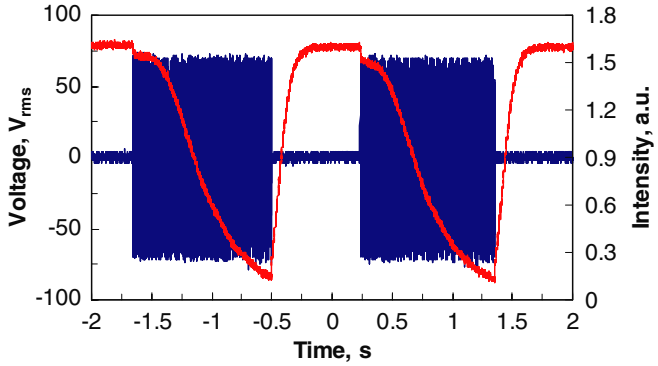

Figure 6. Measured intensity change of the beam passing through the surrounded liquid in two cycles. $V = 70\,\mathrm{V_{rms}}$.

cell upwards without changing the other conditions. Figure 6 shows the measured dynamic response. Two cycles driving with the same pulse widths are given. The measured stretching time is identical to the results shown in figure 5. However, the recovering time was measured to be ∼200 ms, which is decreased noticeably although the width of the voltage pulse is much wider. The reason for the faster recovering speed is that only part of the LC droplet blocking this beam. This part of LC is highly stretched by the dielectric force. Once the force is removed, this part of LC can quickly escape from the beam occupied area. However, for the LC droplet itself, it still needs some time to accept this part of LC to readjust its shape. In comparison with figure 5, the transmitted intensity in figure 6 is relatively higher at null voltage. This is because silicon oil does not scatter light. From figure 2, an optical beam can be controlled by either passing through the pillared droplet itself or passing through the surrounded liquid of the droplet. Each approach has its own merit. The former can control a wide optical beam whose diameter can match the aperture of the droplet; the latter can exhibit a faster dynamic response.

Selecting a proper isotropic liquid plays a key role in this experiment. For example, if we chose water or glycerol, the droplet shape cannot be deformed noticeably due to their large surface tension. Similarly, an oil droplet does not exhibit expandable property because of its low dielectric constant (∼5). In comparison with the above mentioned isotropic liquids, the LC we employed has the following advantages: medium surface tension, high dielectric constant, and high resistivity. Therefore, a relatively low voltage can extremely stretch its shape. Moreover, its power consumption is fairly low, similar to a conventional LC device. Due to the pinning effect of both substrate surfaces, the droplet can be firmly fixed in the Teflon hole area without the concern of shaking or vibrating. With the support of the surrounded liquid, the gravity effect on distorting the droplet shape is negligible. In our experiment, we found that when the top substrate of the cell was removed, the LC droplet could still be pinned on the Teflon-hole place without damage. Liquid devices based on this cell structure have merits in easy fabrication, good stability and scalable droplet size.

6. Conclusion

We have demonstrated an approach to expand the surface of a liquid droplet using fringing electric fields. In our cell, spatially inhomogeneous electric field is generated by applying a voltage to the interdigitated ITO electrode. Therefore, the voltage is independent on the cell gap and the droplet size. Thanks to the fringing field, a pillared LC droplet can be converted to an asymmetric shape. Once the voltage is removed, the stretched droplet can fully return to its original shape due to surface tension. Potential applications of such a device are foreseeable in variable optical attenuators, adaptive iris, beam diffuser and other photonic devices.

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