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Electro-optical properties of dielectric liquid microlens

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ABSTRACT

We report the electro-optical properties of dielectric liquid droplets based on dielectrophoretic effect. Due to dielectric force, the surface of each droplet can be reshaped which in turn alters its focusing behaviors. Our experimental results show that a deformed droplet can recover to its original shape with a negligible hysteresis. Both amplitude and frequency of the applied voltage play important roles affecting the droplet's shape change. The rise time is mainly governed by the applied voltage: for a given frequency a higher voltage results in a faster rise time. On the other hand, the decay time is jointly determined by the interfacial surface tensions, droplet size, and viscosity of the employed liquids.

1. Introduction

Adaptive liquid lenses are attractive in image processing, optical communications, lab-on-a-chip technologies, and other photonic device applications [1–6]. These devices have advantages in compact structure, high efficiency, good optical performance, and low power consumption. Nowadays, electrowetting and dielectrophoretic effects are the two most commonly used principles governing the liquid's shape change induced by an external voltage [4–11]. Electrowetting lens and dielectrophoretic lens share a common ground: they all employ two immiscible liquids. One liquid forms a droplet on the bottom substrate surface and another liquid fills the surrounding space. However, for a dielectrophoretic lens both liquids are insulators with different dielectric constants. The shape of the droplet is manipulated by the generated dielectrophoretic force rather than electrostatic force [12]. Depending on the direction of the generated dielectric force, the shape of the droplet can be either contracted or expanded. A dielectric lens can safely bear a high operation voltage without breakdown. Evaporation is not a major concern if water is not employed in the lens cell.

Several approaches for the dielectric liquid lens and microlens array have been demonstrated [4–6,13,14]. Most of previous work focused on device design, electrode pattern optimization, and performance evaluation, but very little work was devoted to understanding the fundamental electro-optical properties of the liquid lens. For examples, how do the amplitude and frequency of the applied voltage affect the droplet shape change? How severe is the hysteresis of the reshaped droplet? And how does voltage affect the droplet's response time? A better understanding of these basic properties will undoubtedly improve the device performances.

In this paper, to address these questions we prepared different dielectric liquid droplets and investigated their electro-optical properties. Our results show that the surface of a droplet can be dynamically reshaped by an external voltage with a negligible hysteresis. Both amplitude and frequency of the applied voltage play important roles affecting the droplets. The response time of a droplet is dependent on the applied voltage: a higher voltage results in a faster turn-on time, but the decay time is mainly dependent on the droplet size. Detailed device fabrication process is given and the experimental results are analyzed.

2. Device structure and operation mechanism

Fig. 1 shows the side-view structure of a lens cell. Two immiscible liquids are sandwiched between indium tin oxide (ITO) electrodes. The bottom ITO surface is coated with a thin dielectric layer and the droplet is anchored on the dielectric layer surface. The surrounding space of the droplet is filled with another immiscible liquid-2. In the voltage-off state, the droplet is relaxed and has a spherical shape due to the balanced interfacial tension between droplet/dielectric layer, droplet/liquid-2, and liquid-2/dielectric layer. The adhesive force prevents the droplet from splitting. The aperture of the droplet is 2a and its contacting angle on the bottom dielectric layer is θ. When an AC voltage is applied to the cell, the droplet experiences a nonuniform electric field. The dielectric particles on the droplet surface become electrically polarized as a result of partial charge separation, which leads to an induced dipole moment. The effective dipole moment is expressed as [15]

$$P = 4\pi\varepsilon_2\left[\frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+2\varepsilon_2}\right]r^3\vec{E} \quad (1)$$

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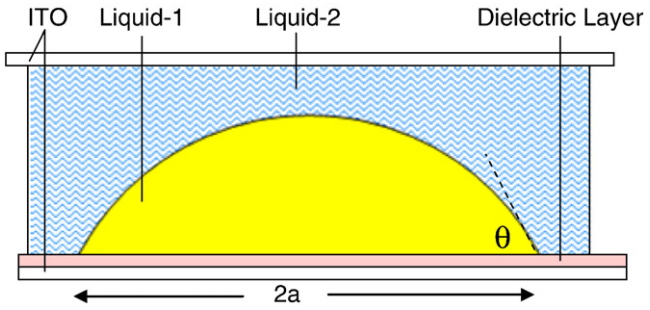

Fig. 1. Side-view structure of the lens cell.

where r is the radius of the droplet curvature, ε_1 and ε_2 are the dielectric constants of the droplet and liquid-2, respectively, and E denotes the electric field. Usually electric polarization responds to an electric field by shifting charge particles (electrons) around. This means the charge particles will always take some time to be accelerated and de-accelerated. Therefore, the response to the field is dependent on the frequency of electric field. If the frequency is very high, the dielectric constants of ε_1 and ε_2 will approach to 1. In such a case, P ~0 or very small.

Due to the dipole moment, the droplet surface bears a dielectrophoretic force:

$$F_{DEP} = \frac{1}{2}\mathrm{Re}(P\cdot\nabla)E. \tag{2}$$

From Eqs. (1) and (2), one can get

$$F_{DEP} = 2\pi R^3 \varepsilon_1 \mathrm{Re}\left(\frac{\varepsilon_2-\varepsilon_1}{\varepsilon_1+2\varepsilon_2}\right)\nabla E^2. \tag{3}$$

Because of the curved droplet surface, the electric field exerting on the droplet has a gradient. According to our previous analysis [6], F_{DEP} is the strongest at the border of droplet aperture. When the dielectrophoretic force is sufficiently strong, the liquid particles inside the droplet are forced to shift and the droplet surface is reshaped in order to reach a new force balance. If $\varepsilon_1<\varepsilon_2$, the droplet will contract, and reversely the droplet will expand.

According to Knollman's theory [16], if the interfacial surface tension of the droplet is considered as that of the elastic membrane in a membrane lens, then the surface configuration of the droplet can be deduced in a cylindrical coordinate system (z, r) to:

$$z = \frac{P}{4T}\left(a^2-r^2\right), \tag{4}$$

where P is the Laplace pressure of the droplet interface, T the interfacial tension of the droplet, and a the aperture of the droplet. One can see that the surface configuration of the droplet exhibits a parabolic shape. However, if the tension T is large and the aperture a is small, then its parabolic shape can be approximated by a spherical shape. The error for such an approximation is negligible. From Eq. (4), the shape of the droplet is dependent on the surface tension and the pressure P. Usually T is constant, so the droplet shape is mainly governed by the change of P. From Eq. (3), F_{DEP} can change the contact angle of the droplet, thus the pressure P is varied accordingly. Since the droplet exhibits a lens character, the focal length of the droplet will be changed accordingly. If the refractive index of the droplet is larger than that of the surrounding liquid, the droplet behaves like a converging lens.

3. Experiment

To demonstrate a liquid droplet with the structure sketched in Fig. 1, we prepared a lens cell using following materials and procedures. Two ITO glass plates were chosen as the cell substrates. We coated a very thin polyimide layers (PI2556, from HD Microsystems, surface tension γ_P~40 dynes/cm) on the bottom ITO electrode surface as the dielectric layer. Such a dielectric layer helps the droplet to form a suitable contact angle and also lubricate the ITO surface so that the formed droplet exhibits a circular aperture. A clear liquid oil (SL-5267, refractive index $n_o=1.67$, dielectric constant ε_o~5) was used as the droplet material, and glycerol ($n_g=1.47$ and ε_g~47) as liquid-2. At room temperature (~23 °C), the two materials were immiscible. We first formed oil droplets on the dielectric layer surface and then used glycerol to cover the oil droplets. The two liquids were sealed by a top glass plate. The cell gap was controlled using a 100-μm Mylar film.

To characterize the electro-optical properties of the droplets, we used a simple setup as Fig. 2 depicts. A collimated He-Ne laser beam was used to probe the cell at normal incidence. The transmitted beam was expanded by an imaging lens and received by a photodiode detector. A diaphragm was placed right before the detector. At V=0, we adjusted the diaphragm aperture so that part of the beam was received by the detector. When a sufficiently high voltage was applied to the sample, the focal length of the droplet became shorter resulting in a decreased effective focal length of the system. Thus, the laser beam was expanded and the intensity received by the detector decreased.

4. Results and discussion

In experiment, we prepared several oil droplets with different aperture sizes and observed their surface profiles using an optical microscope. To study the electro-optical properties of the droplets, we selected a droplet with 210-μm aperture (diameter) for investigation. Fig. 3(a) shows the surface profile of the droplet. Its aperture is indeed quite circular. To evaluate its imaging performance, we placed a resolution target bar behind the lens cell as object. By adjusting the distance between the object and the droplet we observed a clear image through the droplet, as Fig. 3(b) shows. The reversed image implies the droplet functions as a converging lens. This is because the refractive index of the employed oil is larger than that of the liquid glycerol. To analyze the focusing performance of the droplet, we used a CCD camera to capture the transmitted light profile at V=0 and 60 V_{rms}, and results are shown in Fig. 3(c) and (d), respectively. When a 60 V of voltage was applied to the droplet, the transmitted light was tightly focused and a small spot was obtained, as Fig. 3(d) shows. This is because the droplet surface was reshaped and the focal length of the droplet was changed accordingly.

Fig. 4 is a plot of the voltage-dependent light intensity change through the droplet. As the applied voltage increases from zero to 80 V_{rms} (f=300 Hz), the intensity decreases gradually. The decreased intensity implies the droplet shape has the tendency to contract. From Fig. 4, there is no clear threshold voltage for the droplet shape change.

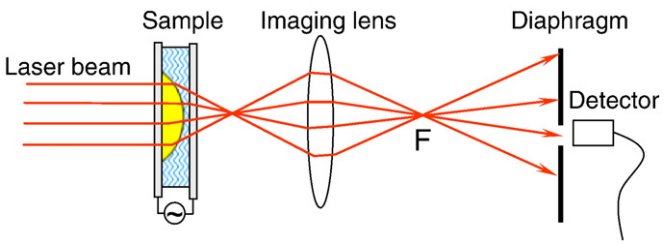

Fig. 2. Experimental setup for measuring the electro-optical properties of liquid droplets.

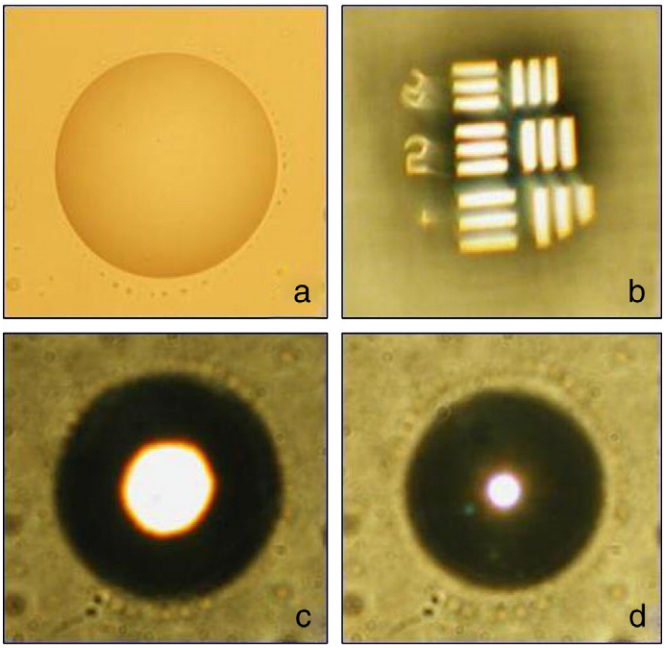

Fig. 3. Images observed using an optical microscope by focusing on (a) droplet surface, (b) object target bar, (c) large defocus at V = 0, and (d) focus at V = 60 V_{rms}.

Also included in Fig. 4 is the backward scan from V = 80 V_{rms} to V = 0. As the voltage decreases, the light intensity increases. These two curves overlap reasonably well, i.e., the hysteresis is small at high voltage. The hysteresis is mainly due to the interfacial tension of the oil droplet and the dielectric layer. However, our results show that the droplet can recover to its initial state when the voltage is removed [17].

To study how the frequency of the applied voltage affects the droplet shape, we have conducted experiments under different frequencies. Fig. 5 shows a curve with 300 Hz frequency. Two curves at frequencies of 60 Hz and 500 Hz were also measured (not shown). In the low voltage region, three curves overlap quite well. As voltage increases, these three curves still have similar tendency without noticeable deviation. However, as the frequency continues to increases, the impact of frequency on the droplet shape change will take place. A curve measured at 10 kHz is shown in Fig. 5. As the voltage exceeds 20 V_{rms}, frequency makes a clear impact to the intensity change. The 10 kHz voltage leads to a smaller intensity change than that of 300 Hz, i.e., a lower frequency voltage causes a larger shape change. Such a result is mainly due to the induced dipole moment responding to the frequency as we analyzed above. As the operating frequency increases, the ability of the voltage deforming the shape of the droplet decreases.

When such a liquid droplet cell is operated by a high frequency voltage, the power dissipation becomes a concern. Because the

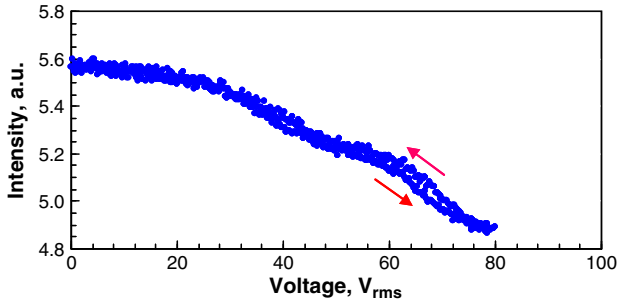

Fig. 4. Voltage-dependent intensity change of a 210-μm-aperture droplet.

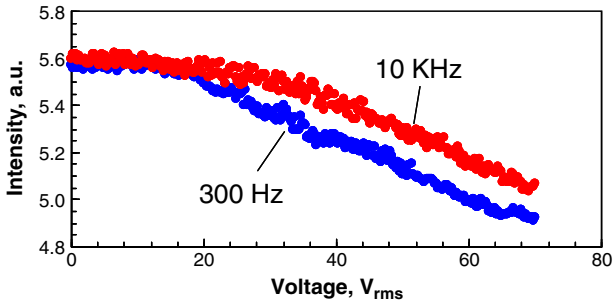

Fig. 5. Voltage-dependent intensity change with $f = 300$ Hz and 10 kHz frequencies.

droplet cell behaves likes a capacitor, the liquid will bear a large current-carrying at a high frequency. As a result, the droplet will be heated and the device performance deteriorated. Ideally, the dielectric liquid droplet should be operated with a low frequency or DC voltage. For the device operating at 80 V_{rms} and 300 Hz, the power consumption is estimated to be less than 0.5 mW.

Dynamic response is another important factor for the adaptive liquid lenses. To measure the response time, we used a digital oscilloscope to record the transient intensity change. Fig. 6 shows the measured response time of the droplet impacted by different square-wave voltage bursts ($f = 300$ Hz and 200-ms width). Both rise and decay times of the 210-μm droplet were measured. The rise time is the time that the droplet reshapes from relaxed to contracted states, while the decay time is from contracted to relaxed states. From Fig. 6, the rise time (filled circles) is ~20 ms at V = 50 V_{rms}. As the voltage increases, the rise time gradually decreases because of the increased dielectric force. However, the decay time (open circles) is not sensitive to the applied voltage (or shape change). It fluctuates a little bit as the voltage changes, but on average the decay time is ~24 ms.

Next, we measured the rise time and decay time of droplets with various sizes impacted by a fixed voltage (50-V_{rms} square-wave burst voltage and 200-ms width). Results are shown in Fig. 7. As the droplet aperture increases, the rise time does not change noticeably. However, the decay time increases gradually. For each droplet, the measured decay time has some fluctuations when it was measured for more than once, as given by the error bar. In general, the rise time is mainly dependent on the generated dielectric force, while the decay time is governed by several factors, such as interfacial surface tensions, droplet size, viscosity of the employed liquids, and operating temperature. Theoretical calculation of decay time is rather difficult because its interfacial tension is difficult to measure. To improve decay time, it is desirable to choose liquid with low viscosity and large surface tension. The droplet cell should work in a suitable

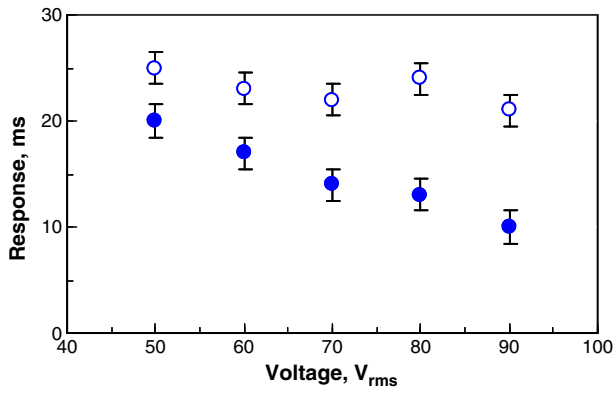

Fig. 6. Measured response time of a 210-μm droplet impacted with different voltages. Filled circles: rise time, open circles: decay time.

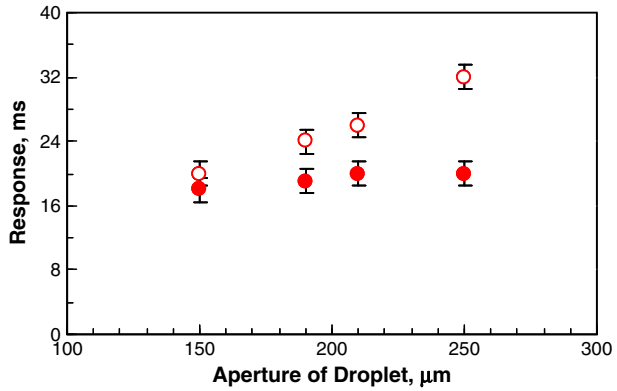

Fig. 7. Measured response time of different-sized droplets impacted by a square-wave burst voltage $V = 50\ V_{rms}$.

temperature range so that both viscosity and interfacial surface tension of the liquids can be taken into consideration.

From our experimental results, we find that the surface of a droplet can be reshaped by an external voltage with negligible hysteresis. Both amplitude and frequency of the voltage affect the droplet shape. For a given voltage, lower frequency causes a larger shape deformation. The rise time is dependent on the applied voltage, but the decay time is jointly determined by the interfacial surface tensions, droplet size, and viscosity of the employed liquids. The interfacial tensions among the droplet/liquid-2, droplet/substrate surface, and substrate/liquid-2 determine the shape of the droplet, although these quantities are difficult to measure.

5. Conclusion

Based on dielectrophoretic effect, we studied the electro-optical characteristics of different liquid droplets. For the droplet with 210-μm aperture, its surface can be reshaped by external voltage without a clear threshold value. The droplet can recover to its original shape well with a very small hysteresis. With the same amplitude of the applied voltage, a lower frequency can cause a larger shape change. Dynamic response is dependent on the amplitude of the voltage. As the voltage increases, the rise time decreases gradually. The decay time is dependent on the droplet size. A larger droplet needs a longer time to relax to its original shape. From our results, it is helpful to optimize the lens performances by considering the impact of voltage on the droplet as well as the droplet size.

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