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Polymer dispersed liquid crystal (PDLC) is used as a dielectric layer in electrowetting. By applying voltage between a liquid droplet and the electrode underlying PDLC, electrowetting occurs at the liquid/PDLC interface accompanied with electro-optic responses of the reoriented LC droplets embedded in PDLC. Two basic experiments investigating the electrowetting by sessile water droplets and the electro-optic effects through squeezed water droplets were design and performed. The basic functions of a liquid lens and droplet manipulations, including transporting, splitting, and merging, were demonstrated. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3125253]

The dielectric layer between the solid electrode and liquid is essential to repeatable and reversible electrowetting,[1,2] known as electrowetting-on-dielectric.[3] Because the change in the cosine of contact angle is proportional to the square of the voltage applied across the dielectric layer and the specific capacitance of the dielectric layer described by the Lippmann–Young equation,[1–6] finding a dielectric material with excellent dielectric properties is one of the important tasks to decrease the driving voltage and enhance the performance of electrowetting. Numerous dielectrics, for example $SiO_2$, $Si_3N_4$, PTFE,[4] and Parylene,[5] have been investigated in electrowetting for their insulating capabilities. However, using dielectric materials possessing additional optical, thermal, or mechanical properties in electrowetting has rarely been reported. When using such materials as the dielectric layer in electrowetting, coupled effects are expected. Here we study electrowetting on a polymer dispersed liquid crystal (PDLC) thin film in order to simultaneously generate both electrowetting and electro-optic effects by applying a proper voltage across PDLC.

PDLC thin films consist of micrometer-sized LC droplets dispersed in solidified polymer matrices.[7–9] Due to its promising electro-optic properties, PDLC have been developed for light valves, light switches, tunable-focus lenses, and displays.[7–10] Inside a LC droplet in the nematic phase, the configuration of the directors (long axes) of the LC molecules is determined by the LC droplet shape and size, the anchoring condition to the polymer matrix at the LC droplet surfaces, the applied electric field, and the elastic constant of the LC.[9,11] The solid lines within LC droplets in Figs. 1(a) and 1(b) represent the orientation of the directors in the bipolar configuration.[9,11] Before voltage application, the directors between individual LC droplets are random. For a LC with a large birefringence ($n_e - n_0$, $n_e$ and $n_0$ are the extraordinary and ordinary refractive indices, respectively), the difference of the refractive indices between the random LC droplets and the polymer ($n_p$) would be significant, which strongly scatters the incident light and reduces the transmittance of the PDLC. When sufficient voltage is applied between the top probe and the PDLC-covered bottom electrode, the directors of the LC droplets covered by the water droplet are reoriented parallel to the direction of the electric

field and the incident light. If $n_0 \sim n_p$, the PDLC becomes isotropic and highly transparent.

The water droplet in the experiment serves as a liquid electrode whose contact angle is changed from $\theta_0$ to $\theta(V)$ by the voltage application, as shown in Figs. 1(a) and 1(b). In general, the contact angle change by applying voltage $V$ across a homogeneous dielectric layer can be described by the Lippmann–Young equation

$$\cos \theta(V) = \cos \theta_0 + \frac{\varepsilon_0 \varepsilon}{2 \gamma_{LG} t} V^2, \tag{1}$$

where $\varepsilon_0$ is the permittivity of vacuum, $\varepsilon$ and $t$ are the relative permittivity and the thickness of the dielectric layer, respectively, and $\gamma_{LG}$ is the surface tension between the liquid and gas surrounding.

An emulsionlike process based on spin coating and curing was developed. Polydimethylsiloxane (PDMS) (Ref. 12) (Sylgard 184, Dow Corning) was chosen as the polymer matrix because it is mechanically elastic and stable, optically transparent down to $\sim$230 nm,[13] chemically inert, and of low interfacial energy.[14] The broad range of curing tempera-
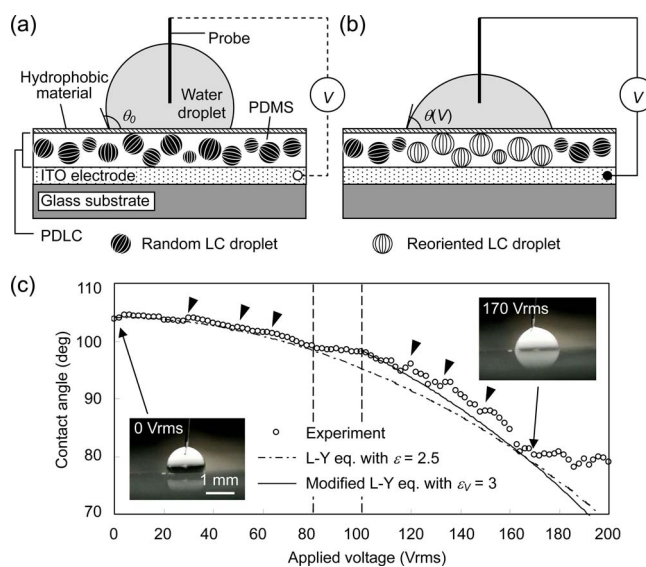


FIG. 1. (Color online) Electrowetting on PDLC studied by the sessile drop method. (a) No voltage applied. (b) Voltage applied. (c) Measured contact angles (circles) plotted against the applied voltage with two theoretical curves based on Eqs. (1) and (2).

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ture of PDMS, from room temperature to 200 °C,[15] makes the PDLC fabrication process flexible. In our experiment, the mixture of E7 LC (8.3 wt %) and PDMS was first spun on indium tin oxide (ITO) glass substrates (100-nm-thick ITO and 0.7-mm-thick glass). E7 (Merck) LC molecules were chosen for the large birefringence ($n_e=1.7462$ and $n_0=1.5216$).[16] The PDLC was cured at 60 °C to obtain a 10-$\mu$m-thick PDLC. The average diameter of the LC droplet was around 3 $\mu$m inspected by polarized light microscopy. Teflon was then spun on the PDLC to deliver a 50-nm-thick hydrophobic layer.

Figure 1(c) shows the measured contact angle of a 2 $\mu$l de-ionized water sessile droplet placed on a Teflon-coated PDLC. The initial contact angle $\theta_0$ was ~104°. The applied signal was a 1 kHz sine wave with the amplitude increased continuously from 0 to 200 $V_{rms}$. Contact angle saturated at ~80° when the voltage was applied above 170 $V_{rms}$. A deviation from the theoretical quadratic curve [broken line, Eq. (1)] was obvious at ~80 $V_{rms}$. We attribute the deviation to the reorientation energy and dielectric anisotropy of the LC. Different from ordinary dielectric layers, part of the applied electrostatic energy contributes to reorient the LC, reducing the electrowetting effect. The reorientation energy consists of mainly the elastic and anchoring energy of the LC which is related to the viscosity, elastic constant, anchoring condition, and the LC droplet size.[9,11] Because of the positive dielectric anisotropy of the E7 LC ($\varepsilon_\perp=5.2$ and $\varepsilon_\parallel=19$),[16] the permittivity of the tested PDMS increases as the LC is reoriented. Therefore, we propose a modified Lippmann–Young equation considering the reorientation energy per unit area $W_{LC}$ and the voltage-dependent relative permittivity $\varepsilon_V$ of PDLC

$$\cos\,\theta(V) = \cos\,\theta_0 + \frac{\varepsilon_0\varepsilon_V}{2\gamma_{LG}t}V^2 - \frac{W_{LC}}{\gamma_{LG}}.\quad(2)$$

Above 100 $V_{rms}$, the experimental data was fitted by the solid curve based on Eq. (2) when substituting 3 and 6.2 mJ m$^{-2}$ for $\varepsilon_V$ and $W_{LC}$, respectively. $W_{LC}$ was considered equal to the increased electrostatic energy per unit area of the PDLC between 80 and 100 $V_{rms}$ [i.e., $\varepsilon_0(\varepsilon_V 100^2 - \varepsilon_V 80^2)/2t$ J m$^{-2}$] with the unchanged surface energy. In addition to the major deviation at 80 $V_{rms}$, some minor deviations indicated by arrows in Fig. 1(c) were found for the various reorientation energy caused by the widely distributed LC droplet sizes. Moreover, the different size distributions among tested PDLC thin films made the deviations occurring differently among experiments. Nevertheless, electrowetting on PDLC exhibited reversibility and the tendency for $\theta$ to decrease with the increased $V$.

The electro-optic property, i.e., transmittance, of the PDLC was measured through a squeezed water droplet 300-$\mu$m-high between a pair of unpatterned parallel electrodes [Figs. 2(a) and 2(b)] to eliminate the refraction at the liquid surface. An integrating sphere or a charge coupled device (CCD) was placed above the device to detect the bottom incident light from a halogen lamp. When no voltage was applied, the incident light was scattered, showing a dark CCD image in the bottom right inset of Fig. 2(c). The transmittance between 400 to 800 nm was measured by the integrating sphere and plotted as hollow circles. When voltage was applied between the plates, the directors of the LC droplets overlapping the water droplet were reoriented to transmit the bottom incident light, showing a bright circle in the top
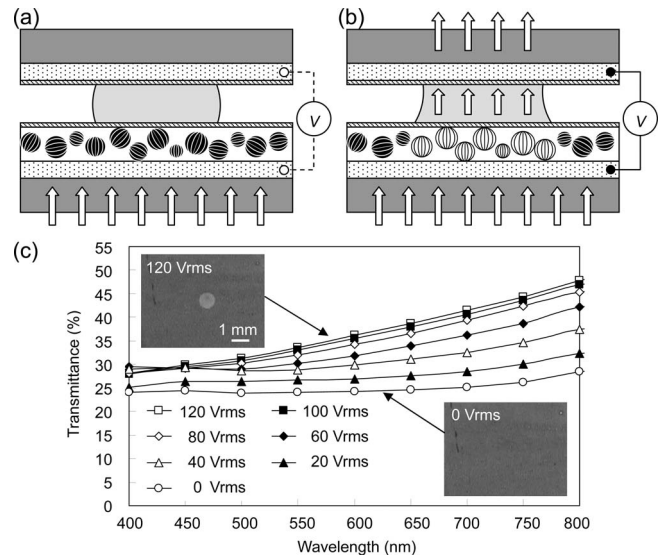


FIG. 2. Transmittance measurement of PDLC through a squeezed water droplet between parallel ITO electrodes. (a) No voltage applied. (b) Voltage applied. (c) The transmittance of a 1 kHz signal with difference amplitudes.

left inset of Fig. 2(c). The transmittance increased as the voltage of the applied 1 kHz signal increased, and started to saturate at high voltages. The transmittance can be further improved by using other polymer-LC combinations of matched indices, for example, NOA 65 and E7.[9]

The coupled electrowetting and electro-optic effects on PDLC can be applied to most reported electrowetting-based devices, including optical components, i.e., lenses and displays, and lab-on-a-chip (LOC) to enhance their electro-optic performance. For example, by replacing the regular dielectric with PDLC in electrowetting-actuated tunable liquid lenses,[17,18] not only the focal length but also the light intensity would be controllable. Figures 3(a) and 3(b) show the top views of a sessile drop liquid lens placed on PDLC (NOA 65 and E7) without and with voltage applications, respectively. Before voltage applied, the background image through the droplet was scattered and reflected by the random LC droplets, showing a blurred and dim image [Fig. 3(a)]. When voltage was applied, the image passing through the reoriented LC droplets became clear [Fig. 3(b)]. Additionally, the magnification of the background letters was changed by the voltage-modulated focal length of the liquid lens.

Similarly, the contrast ratio of the electrowetting-based reflective displays[19] would increase by modulating both the conformation of the dye oil droplet and the transmittance the
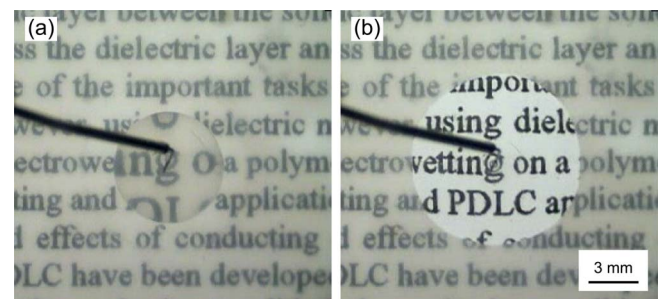


FIG. 3. (Color online) An electrowetting-driven liquid lens using PDLC as the dielectric layer. (a) No voltage applied. (b) Voltage applied.
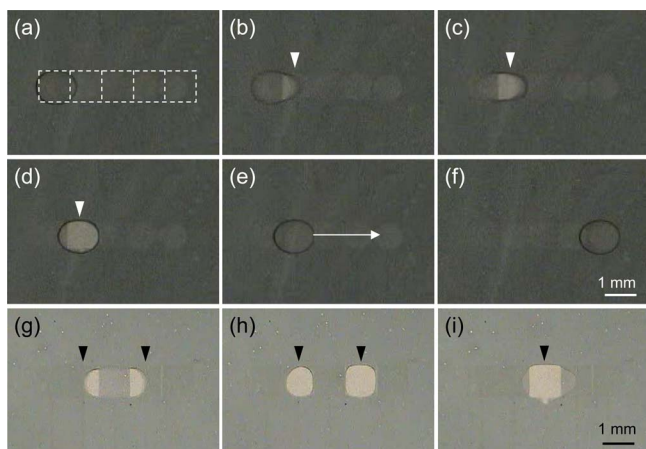
FIG. 4. (Color online) Droplet transporting in a parallel-plate electrowetting device using PDLC as the dielectric layer. [(a)–(f)] Droplet transported from left to right. [(g)–(i)] Droplet splitting and merging.

PDLC dielectric layer. When no voltage is applied, the homogeneous oil film and the translucent dielectric decreases the reflectivity of the pixel, while light can be reflected from the white substrate by the contracted oil droplet and the transparent dielectric layer when voltage is applied. On the other hand, light would be regulated for programmable optical excitations or sample detections on electrowetting-based LOC.[20,21] For instance, in the application of a colorimetric glucose assay,[20] the absorbance of individual droplet can be distinguishable even on a compact droplet array by managing the local transmittance.

Droplet manipulation by electrowetting on PDLC consisting of PDMS and E7 was performed on a parallel-plate device with a configuration similar to other droplet-based LOC.[2,20,21] The bottom glass plate contained patterned ITO driving electrodes covered by PDLC and Teflon layers. The top plate was a Teflon-coated ITO glass. A 750 nl water droplet was placed in a 300-$\mu$m-high gap between the parallel plates. Figures 4(a)–4(f) show the transportation of water droplet from left to right by sequentially applying a 1 kHz and 100 $V_{rms}$ signal on the arrow-indicated driving electrodes. When voltage was not applied, electrowetting did not occur and the transmittance of the PDLC was low, as shown in Fig. 4(a). In Figs. 4(b)–4(d), the bright area increased because of the increasing overlapping area caused by

the proceeded water droplet, until it moved entirely on the powered electrode. The droplet became dim after removing the voltage [Fig. 4(e)]. The droplet was pumped to the right by electrowetting, as shown in Fig. 4(f). Other basic droplet functions including splitting and merging droplet were also achieved, as shown in Figs. 4(g)–4(i).

In summary, PDLC thin films have been fabricated to serve as a dielectric layer in electrowetting devices. When applying a voltage across the PDLC thin film, its surface wettability and transmittance were simultaneously changed. Basic liquid lens functions and droplet manipulations were demonstrated.

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