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Tunable dielectric liquid lens on flexible substrate

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We demonstrate the fabrication of a tunable-focus dielectric liquid lens (DLL) on a flexible substrate made of polydimethylsiloxane, which was wrapped onto a goggle surface to show its functionality. As a positive meniscus converging lens, the DLL has the focal length variable from 14.2 to 6.3 mm in 1.3 s when the driving voltage increases to 125 V_{rms}. The resolving power of the DLL is 17.95 line pairs per mm. The DLL on a flexible, curvilinear surface is promising for expanded field of view covered as well as in reconfigurable optical systems. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4858616]

Tunable-focus liquid lens plays an important role in modern miniaturized optical systems, optical communication systems, and biomedical systems.[1–4] The liquid lens varies its focal length by changing either the refractive index or the droplet curvature, which has several advantages, such as non-necessity of mechanical actuators, small size in volume, simplicity in structure, and low power consumption, over conventional solid lens modules, and is widely adopted in photonic and optical applications, e.g., optical valves,[2] optical switches,[3] and endoscopes.[4] A liquid lens fabricated on a flexible substrate can be wrapped onto any curvilinear surface, providing further benefits of expanded field of view (FOV) covered and reconfigurability.

There are several methods used for adjusting the focal length of a liquid lens, including thermal effect,[5] hydrogel actuators,[6–10] birefringence effect in liquid crystal,[11,12] fluidic pressure,[13] acoustic waves,[14] electrowetting,[15–17] and dielectrophoretic (DEP) effect.[18–22] Each method has its own advantages. Previously, two of these methods (i.e., hydrogel actuators and electrowetting) were employed to further realize single liquid lenses and lens arrays on flexible substrates.[8–10,17] However, some drawbacks exist for many of these approaches. Long response time (>seconds) are usually associated with hydrogel actuators and thermal effect. Electrowetting using conductive liquids could lead to Joule heating and microbubbles resulting from liquid electrolysis. Liquid crystal could cause blurred images below its transition temperature. As for acoustic wave, maintaining a specific focal length would be difficult. Finally, external pressure sources are required for the focus-tuning mechanism utilizing fluidic pressure. Compared to these methods, dielectrophoretic effect adopts two non-conductive liquids, operates in small volume, boasts fast response time and low power consumption, and avoids electrolysis owing to the negligible current in the liquids.[18–22] A conventional dielectric liquid lens (DLL) is built on a flat and rigid substrate, such as glass, silicon, or polyethylene terephthalate,[15,18–20] and is not suitable to be fabricated on a flexible, curved substrate. Here, we introduced flexible materials and developed a technique suitable for realizing DLL on a flexible substrate. Our DLL is made on a flexible and transparent polymer substrate, polydimethylsiloxane (PDMS), which can be easily wrapped onto the bulged-up surface of a goggle. As a positive meniscus converging lens, the DLL has a variable focal length ranging from 14.2 mm to 6.3 mm in 1.3 s, when the actuation voltage changes from 0 to 125 V_{rms}. The resolving power of the DLL on the curvilinear goggle is 17.95 line pairs per mm (lp/mm) according to a 1951 United States Air Force (USAF) resolution chart.

In pursuit of the DLL on a curvilinear surface, we developed a type of deformable and transparent electrode. Two issues, namely, the mechanical flexibility of the DLL platform and the improvement of adhesion of metal films onto the flexible substrate, were considered and addressed. A flexible platform that could conform to a desired shape or flex during its use was developed for the DLL. Such platform consists of a pair of concentric electrodes fabricated on a flexible and transparent PDMS substrate covered with a parylene C layer, an SU-8 insulation layer, and a defined hydrophobic Teflon thin film on the topmost surface (Fig. 1). The layer of parylene C was employed as an intermediate layer to improve the metal adhesion onto PDMS, while preventing cracking in the electrodes to avoid failure under mechanical bending.[23,24] The developed DLL platform is capable of being easily wrapped onto a curvilinear surface to provide the deformable electrodes for the actuation of the DLL.

Our DLL is formed by a droplet containing two immiscible media in a chamber situated on top of the flexible platform as shown in Fig. 1. The droplet composed of silicone oil is surrounded by polyalcohol liquid. Both liquids are non-conductive and have iso-density. In the flexible platform, the top surface was covered by a thin Teflon layer to define wettability (hydrophilic/hydrophobic properties) on the surface, which confines the oil droplet at its rest state and reduces the friction force during its movement. Below the insulation SU-8 layer, a pair of concentric electrodes with a width of 50 μm and a gap of 25 μm was used to induce non-uniform electric

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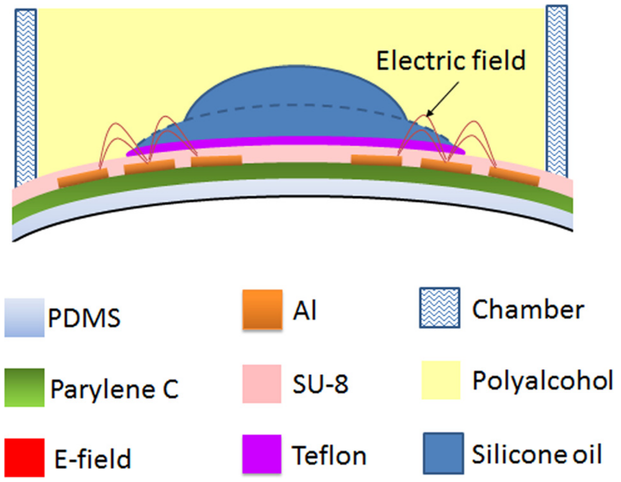

FIG. 1. Schematic diagram of a cross sectional view of the DLL on a flexible platform. The flexible DLL platform consisting of a PDMS substrate covered with parylene C, Al electrodes, an SU-8 insulator, and a defined Teflon layer can be wrapped onto any curvilinear surface. The DLL contains a silicone oil droplet surrounded by a polyalcohol liquid. When a voltage is applied across the electrodes, the resultant dielectric force squeezes the droplet and increases its contact angle to the bottom surface.

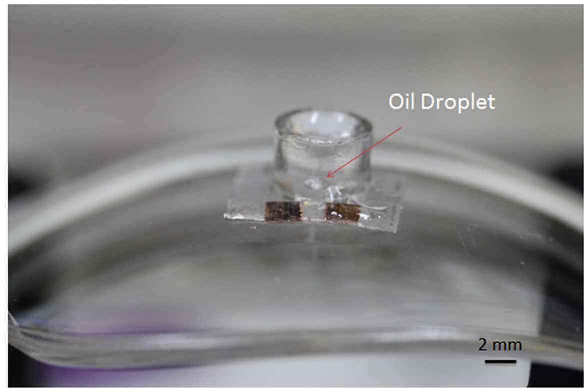

FIG. 2. The flexible DLL platform is wrapped onto a transparent curvilinear goggle after corona plasma treatment. The oil droplet is confined within the defined Teflon layer. The optical performance of the DLL is characterized based on this setup and compared with the DLL on a flat glass substrate.

field that generates dielectric force (F), as described in Eq. (1),[18] at the phase boundary between the two liquids

$$\vec{F} = -\frac{\varepsilon_0}{2}\nabla[(\varepsilon_1 - \varepsilon_2)|\vec{E}|^2], \tag{1}$$

where ε_0 stands for the permittivity of free space, ε_1 and ε_2 represent the dielectric constants of the surrounding liquid and the silicone oil droplet, respectively, and E denotes the electric field intensity across the interface of the two liquids. In our case, the central oil droplet has a lower dielectric constant than the surrounding polyalcohol, leading to a DEP force that squeezes the droplet inward and increases the contact angle to the bottom surface. The magnitude of the force depends on the voltage applied to the concentric electrodes.

To fabricate the flexible DLL platform, we started by spinning PDMS mixture onto a photoresist coated glass slide and cured it at 70 °C for 4 h. 2-μm thick parylene C was subsequently deposited onto the PDMS (SCS Labcoter, Special Coating Systems, Indianapolis, Indiana, USA). A 500-nm-thick aluminum (Al) layer was sputtered onto the flexible substrate and patterned in a photolithography step, followed by wet etching (H_3PO_4:HNO_3:CH_3COOH:H_2O = 3:3:1:1 at 40 °C for 100 s) to define the concentric electrodes. After the fabrication of the concentric electrodes, 2-μm-thick SU-8 resin was patterned as an insulating layer. Finally, a hydrophobic Teflon (AF-1600, DuPont, Wilmington, DE, USA) layer of 100 nm was spin-coated on the SU-8 resin and photopatterned using O_2 plasma to define the region for trapping/confining the oil droplet. The DLL platform could be easily peeled off by immersing the sample into acetone for 5 min and wrapped onto a transparent goggle after corona plasma treatment (Fig. 2). The DLL platform can sustain at least 10 times of bending cycle with the bending radius of 1 cm. The droplet made of silicone oil (Dow Corning 550, Dow Corning Corp., Midland, MI, USA) was confined by the Teflon layer via surface tension and surrounded by the polyalcohol inside a chamber. The silicone oil and polyalcohol liquid have refractive indices of 1.49 and 1.39, respectively. The extended pads from the concentric electrodes were connected to a copper tape using conductive silver paste. Before measuring the optical performance, a piece of thin cover glass was placed on top of the chamber to temporarily seal the DLL. The applied voltage was output from a universal source meter (HP 3245A) and amplified via a transformer (Spitznagel D78609). The voltage signal was measured using a 6-1/2 digit multimeter (Agilent 34411A). The variation in the contact angle of the liquid lens was captured and analyzed using a contact angle goniometer (Dataphysics OCAs 15).

The deformation of the liquid lens in response to the driving voltage operating at a frequency of 1 kHz was observed via both the cross-sectional and the top views. Figs. 3(a)–3(d) show the surface profile of the liquid lens at 0, 50, 100, and 125 V_{rms}, respectively. Initially, the oil droplet confined by the hydrophobic Teflon layer had a small contact angle of 30.3°. When a voltage was applied across the concentric electrodes, the non-uniform electric field across the gap between two adjacent electrodes generated dielectric force at the phase boundary, squeezing the droplet towards the center and leading to an increase in the contact angle.[18–20] The droplet reached its maximum deformation with a contact angle of 66.4° at 125 V_{rms} [Fig. 3(d)]. The response time of the DLL was measured to be 1.3 s according to the angle variation from 10% to 90% from the recorded video of the contact angle measured through a goniometer. The sequential deformation of the liquid lens can be seen in the top view shown in Figs. 3(e)–3(h). When the voltage was increased, the phase boundary of the droplet started shrinking and moving inward until 125 V_{rms}. Some tiny particles or air bubbles trapped between the DLL platform and the goggle might have caused locally non-uniform (non-smooth) surface that might deteriorate the lens performance. As comparison, we also characterized the DLL lens before being peeled from the glass slide. The lens passed through the innermost electrode and shrank to the aperture at a voltage of 100 V_{rms} with a larger contact angle of 85 °.

The measurement of the focal length of the DLL was conducted using a microscope (Nikon SMZ1500) and a CCD camera to capture the focused image from the Mylar film

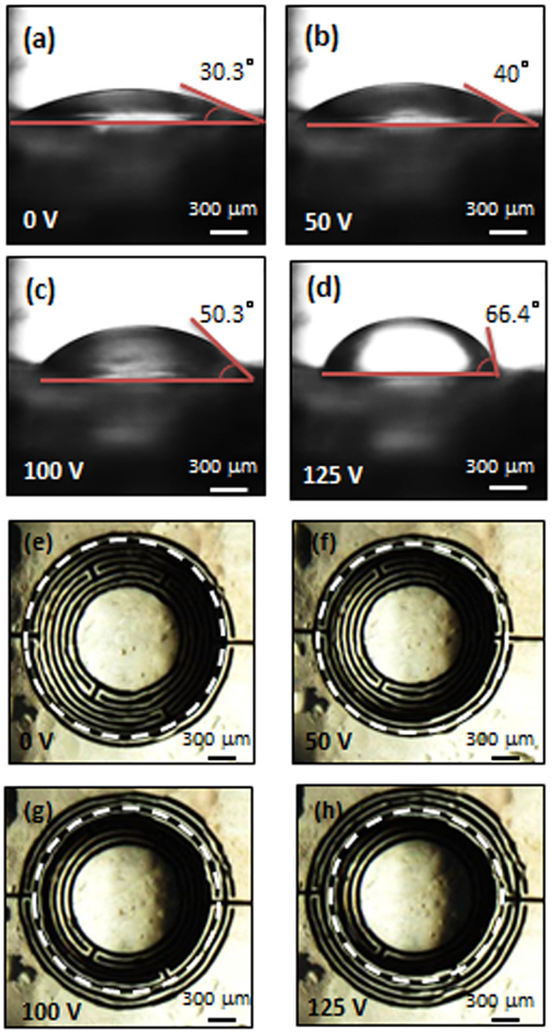

FIG. 3. The deformation of the surface profile of the DLL wrapped on the goggle with respect to applied voltage. (a)–(d) Contact angle of the oil droplet varies from 30.3° to 66.4° when the driving voltage increases from 0 to 125 V_{rms}. (e)–(h) Top view of the DLL. The droplet is initially confined by the defined hydrophobic Teflon layer at the rest state (V = 0) and subsequently squeezed towards the center with the increase in the applied voltage. At 125 V_{rms}, the droplet reaches the maximum deformation.

positioned at 6.7 cm below the DLL. By adjusting the distance between the objective lens and the DLL, we measured the focal length of the DLL where the sharp image was found. The DLL wrapped on the goggle acted as a positive meniscus converging lens with the concave-convex configuration (Fig. 1), since the refractive index of the oil droplet is larger than that of the surrounding polyalcohol. The positive meniscus DLL has a longer focal length than the DLL situated on a flat glass slide (plano-convex). Fig. 4 plots the contact angle and the focal length as functions of the applied voltage. At the rest state (contact angle = 30.3°), the focal length of the DLL was 14.2 mm. With increased applied voltage, the increase in the contact angle led to a smaller radius of curvature, or a decrease in the focal length. The liquid lens showed a minimum focal length of 6.3 mm at 125 V_{rms} (contact angle = 66.4°). Hysteresis was observed in the DLL, as evidenced by two distinct performance paths in the advancing and receding stages. The focal length finally returned to its original value (corresponding to the rest state) after one cycle of operation, with a maximum difference of

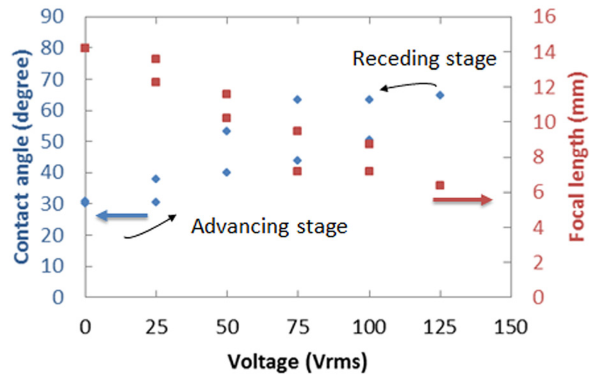

FIG. 4. The contact angle of the oil droplet and the resultant focal length of the DLL wrapped on the goggle surface, as functions of the applied voltage. As applied voltage increases, the increase in the contact angles (diamond) accompanies a decrease in the focal lengths (square). The deformation of the DLL saturates after 125 V_{rms}. The hysteresis effect causes two distinct performance paths in the advancing and receding stages.

1.6 mm in focal length due to hysteresis occurring at 75 V_{rms}. As for the DLL on flat glass slide, it has the focal length changing from 13.7 mm to 5.4 mm when the contact angle changes from 30° to 64.5°. The DLL attached onto the goggle has a longer focal length than the DLL on flat surface due to the change of the lens configuration from plano-convex to concave-convex.

The imaging capability and dynamic tunability of the DLL are shown in Fig. 5. The DLL on the goggle was inserted between a transparent Mylar film and a CCD camera. The transparent film with an array of capital letter "T" was kept 6.7 cm away from the liquid lens. The camera captured the images generated from the lens at different voltages from 0 to 125 V_{rms}. The liquid lens was a converging lens, thus inverted real images. With the increase in voltage, the shorter focal length resulted in the decrease in the size of the imaged pattern. The resolving power of the lens was measured by replacing the transparent film with a 1951 USAF resolution chart. The pattern at group 4, element 2 in the resolution chart was the finest feature that can be resolved by the lens on the goggle surface, corresponding to a resolution of 17.95 lp/mm. On the other hand, for the DLL lens on flat

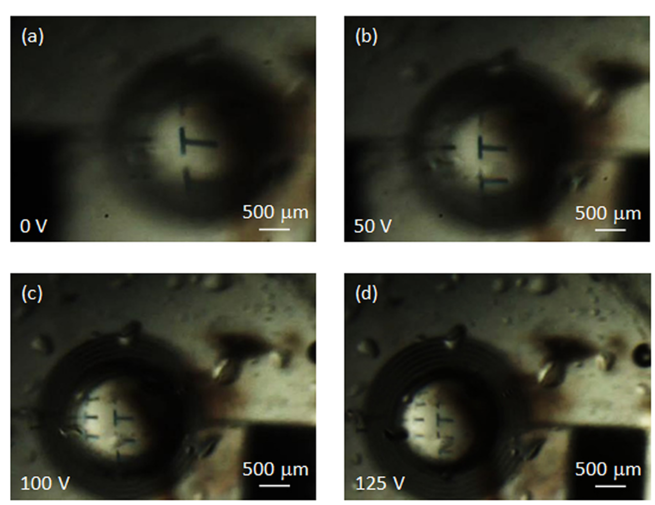

FIG. 5. Images formed by the DLL as the applied voltage increases from 0 to 125 V_{rms}.

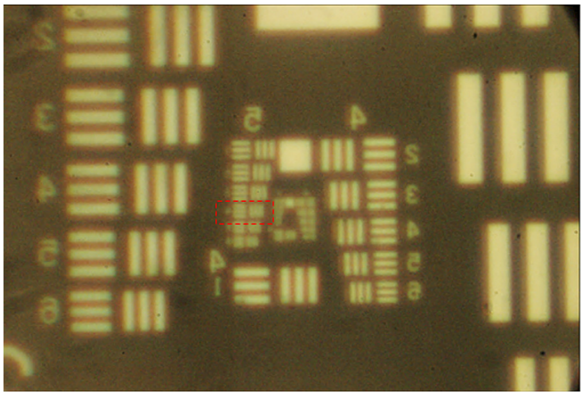

FIG. 6. Image of a 1951 USAF resolution chart captured via the DLL on a flat glass slide. The pattern at group 5, element 4 in the chart (rectangle) is the finest feature that can be distinguished by the DLL, which corresponds to a resolution of 45.3 lp/mm.

glass slide, the lens can identify smaller patterns in group 5, element 4, and has a higher resolution of 45.3 lp/mm (see Fig. 6).

DLL wrapped on the goggle surface has lower optical performance compared with the DLL on a flat surface. The larger applied voltage, the smaller contact angle and focal length variation and the lower spatial resolution might result from the locally non-smooth surface caused by trapping tiny particles and air bubbles between the flexible substrate and the goggle.

In summary, we have developed a technique to fabricate DLLs on flexible substrates. The flexible DDL platform was wrapped onto a goggle to show its functionality. With the employment of parylene C, the concentric electrode adhered well onto the PDMS, maintaining good conductivity under mechanical bending. The DLL as a positive meniscus lens, had a focal length varied from 14.2 to 6.3 mm in 1.3 s when the driving voltage increased from 0 to 125 V_{rms}. The maximum deformation of the DLL occurred at 125 V_{rms}. The resolution was 17.95 lp/mm. Such DLL on a curvilinear surface has the potential to expand its FOV covering different orientations, and could be integrated into optical and photonic systems where reconfigurability is desired. In the future, we will develop cameras formed on flexible surfaces implementing our DLL and realize flexible DLL arrays for 3-dimensional imaging, taking advantage of the expanded FOV and real-time reconfigurability due to the flexibility. One example would be an array of flexible liquid lenses attached to the distal end of a fiber endoscope in a spherical arrangement to enhance the FOV.[10] Another example would be a flexible liquid lens (converging lens) embedded in an accommodative contact lens for presbyopia correction.[17] For flexible DLL, we will further enhance the lens performance by improving the wrapping process, reducing electrode gap width and decreasing the viscosity of the oil droplet.[20] We will also explore covering the top of the chamber as a packaging step, using a transparent cap sealed by an adhesive ultra-violet glue.

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