Varifocal liquid lens based on microelectrofluidic technology

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This Letter presents a tunable liquid lens based on microelectrofluidic technology. In the microelectrofluidic lens (MEFL), electrowetting in the hydrophobic surface channel induces the Laplace pressure difference between two fluidic interfaces on the lens aperture and the surface channel. Then, the pressure difference makes the lens curvature tunable. In spite of the contact angle saturation, the narrow surface channel increases the Laplace pressure to have a wide range of optical power variation in the MEFL. The magnitude of the applied voltage determines the lens curvature in the analog mode MEFL. Digital operation is also possible when the control electrodes of the MEFL are patterned to have an array. The lens aperture and maximum surface channel diameter were designed to 3.2 mm and 6.4 mm, respectively, with a channel height of 0.2 mm for an optical power range between +210 and –30 D. By switching the control electrodes, the averaged transit time in steps and turnaround time were as low as 2.4 ms and 16.5 ms, respectively, in good agreement with the simulation results. It is expected that the proposed MEFL may be widely used with advantages of wide variation of the optical power with fast and precise controllability in a digital manner.

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A liquid lens is one of the best solutions for variable focal length in miniaturized imaging optics, such as mobile phone cameras, barcode readers, and medical endoscopes. Although various liquid lenses have been developed based on the shape change of elastomeric membranes by thermal [1], electrostatic [2], electromagnetic [3], piezoelectric [4], stimuli-responsive hydrogel [5], or electroactive polymer [6] actuator, direct lens curvature change induced by electrowetting [7,8] or dielectrophoresis [9] phenomena has attracted attention with its simple, fast, and effective characteristics. However, the liquid lens, with its faster and wider optical power variation, is still a challenge to extend into various application fields. Here, we proposed a tunable liquid lens based on the microelectrofluidic technology. Unlike the general electrowetting lens, which varies the lens curvature directly, the microelectrofluidic lens (MEFL) varies the lens curvature by electrowetting in surface channels.

Figure 1 shows a schematic of the basic MEFL consisting of a lens aperture, a hydrophobic surface channel, and a lens liquid. The spacer between two plates defines the surface channel height and the through-holes in the upper plate are for lens liquid in the center and for air passage on the outer side. Each side of the surface channel has dielectric-coated control electrodes for electrowetting actuation [10]. The liquid makes two fluidic interfaces with air on the lens aperture and the surface channel. The Laplace pressure difference (ΔP) between the channel (P_C) and the lens aperture (P_L) can be calculated from the Young–Laplace equation as follows:

$$P_L = -\frac{4\gamma}{D}\cos\left(\frac{\pi}{2} - \phi\right) = \frac{-16\gamma H}{D^2 + 4H^2}, \quad (1)$$

$$P_C = \gamma\left(\frac{\cos\theta_1 + \cos\theta_2}{h} - \frac{1}{r}\right) = \gamma\left(\frac{2\cos\theta_V}{h} - \frac{1}{r}\right), \quad (2)$$

$$\Delta P = P_C - P_L = \gamma\left(\frac{16H}{D^2 + 4H^2} + \frac{2\cos\theta_V}{h} - \frac{1}{r}\right), \quad (3)$$

where γ, ϕ, D, H, h, r, θ_1, θ_2, and θ_V are the surface tension of the liquid, the tangent-chord angle of the lens, the diameter of the lens aperture, the lens sag height, the surface channel height, the three-phase contact line (TCL) radius in the surface channel, the contact angles of the liquid on the bottom and upper channel surfaces, and the electrowetted contact angle, respectively.

The liquid cannot infiltrate the hydrophobic surface channel without electrowetting actuation. However, when a proper voltage is applied between the control electrodes and the liquid, the positive pressure difference caused by the reduced contact angle makes the lens curvature decrease by advancing the TCL into the surface channel. The higher the applied voltage, the smaller the curvature. On the contrary, the negative pressure difference induced by lowering the applied voltage makes the lens curvature increase with the backward motion of the TCL.

The variable focal length of the MEFL can be realized with the magnitude of the applied voltage as mentioned

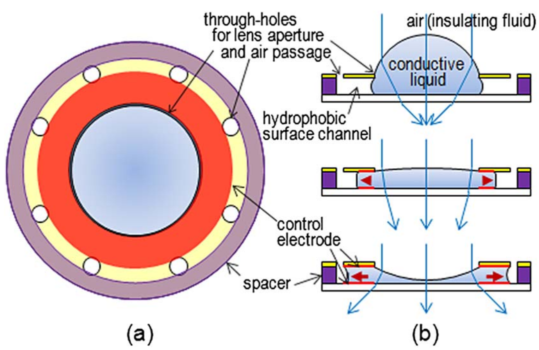

Fig. 1. (Color online) Schematic of the MEFL; (a) top and (b) cross-sectional views.

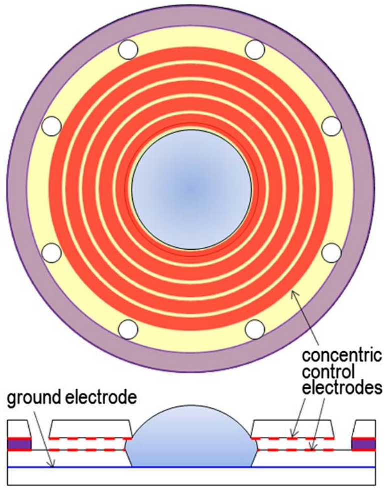

Fig. 2. (Color online) Schematic of the digital MEFL having concentric control electrodes.

above. However, since the electrowetting transit time depends on the applied voltage [11], a digital control with relatively high voltage and concentric control electrodes is required for the fast and precise operation of the MEFL. Figure 2 shows a schematic of the digital MEFL having concentric control electrodes.

The digital MEFL was fabricated and characterized with the simulation and experimental results in this work. The lens aperture and the surface channel were designed to be 3.2 and 6.4 mm in diameter, respectively, with a channel height of 0.2 mm for the variation of the sag height from +0.9 to −0.1 mm. The concentric control electrodes in the upper and bottom channel surface were patterned by indium tin oxide (ITO) and Cr to visualize the liquid motion in the channel. Through-holes for the lens aperture, air passage, and electric interconnection were formed in the upper and bottom plates by a sanding machine. The aligned upper and bottom plates with

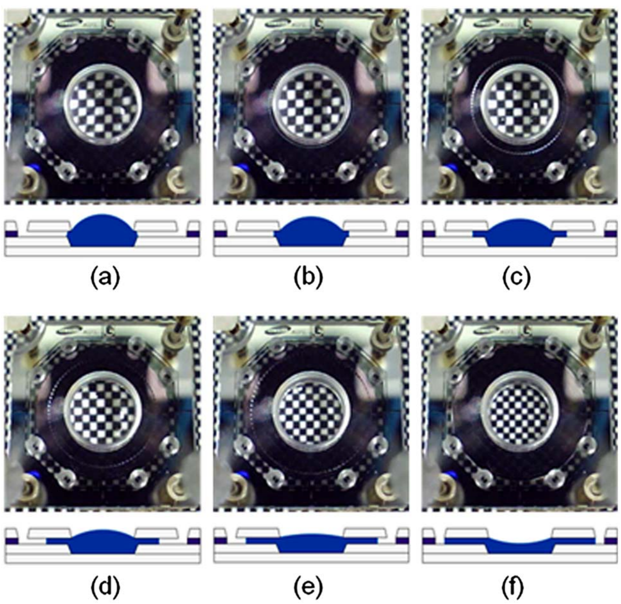

Fig. 3. (Color online) Experimental results of the fabricated MEFL and the schematic cross-sections; TCL radii of (a) 1.8 mm, (b) 2.0 mm, (c) 2.3 mm, (d) 2.6 mm, (e) 2.9 mm, and (f) 3.2 mm.

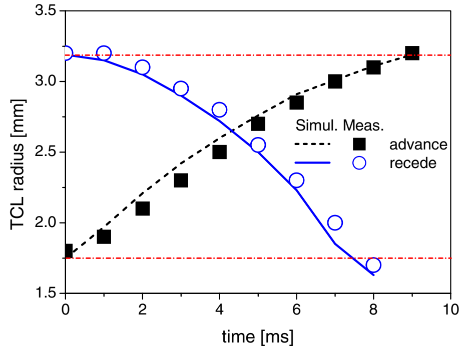

Fig. 4. (Color online) Experimental and simulation results of time-dependent TCL position in the MEFL.

0.2 mm thick optically clear adhesive (OCA) spacers were interconnected by using conductive paste. A 3 μm thick Parylene-C was coated as the electrowetting dielectric and an additional ITO plate was bonded from the bottom for grounding the liquid. After hydrophobic surface treatment by Teflon-AF, 12 μL of aqueous LiCl solution was pipetted as the lens liquid. The reversible digital actuation of the MEFL was successfully observed by switching the control electrodes with an applied voltage of 120 V step by step and simultaneously (Fig. 3).

The reversible operation of the fabricated MEFL was recorded by using a high-speed camera, and the advancing and receding velocity was obtained by analyzing the recorded video clip from the start to the point that the TCL touches the next control electrode. As a result, the advancing and receding motion of the lens liquid in the surface channel was observed within a transit time of 2.4 ms in steps with the patterned nine pairs of concentric control electrodes. When all control electrodes were switched simultaneously, the transit time for advancing and receding motion was measured at 9.0 and 7.5 ms, respectively, in good agreement with the computational fluidic simulation results using Flow-3D (Flow Science, Inc., USA; Fig. 4). The liquid surface tension of 87.5 mN/m, dynamic viscosity of 3 mPa·s, and electrowetted and receding contact angles of 80° and 110° were used in the simulation.

The optical power, the reciprocal of the focal length, of the lens is proportional to the curvature and the difference of refractive indices between the fluids, which varied from +210 to −30 D with the TCL radius change in the fabricated MEFL (Fig. 5). The optical

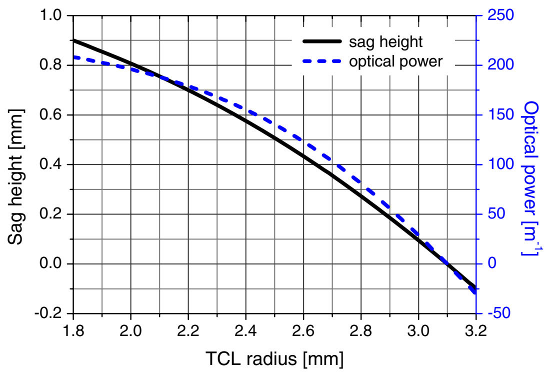

Fig. 5. (Color online) Sag height and optical power depending on the TCL radius in the MEFL.

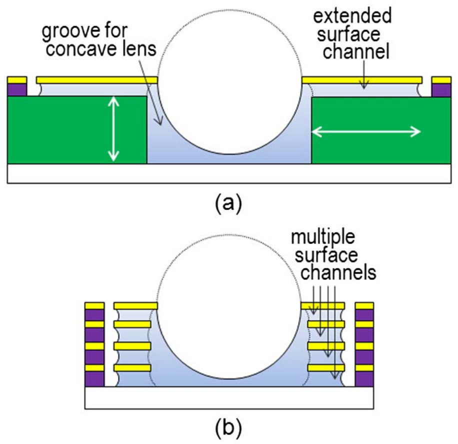

Fig. 6. (Color online) Schematic cross sections of the MEFL for enlarging the optical power by lowering the channel height; (a) a larger surface channel and (b) multiple surface channels.

power variation in the MEFL of 240 D is much higher than that in the previous electrowetting lens of 150 D [7]. The electrowetting lens, in which the contact angle changes at the side wall, has a certain limitation of the curvature variation because of the unwanted phenomenon called contact angle saturation [7,12]. The use of oil as the insulating fluid enlarges the curvature variation in the electrowetting lens, however, it may decrease the difference of refractive indices. Although the contact angle saturation also appears in the surface channel of the MEFL, the Laplace pressure can increase by lowering the surface channel height, allowing the MEFL to have full variation of the optical power possible. In order to obtain a wider optical power range with a given lens aperture diameter, a larger surface channel area and an additional space at the bottom of the aperture for concaving the lens are required [Fig. 6(a)]. At this time, multiple surface channels may be an appropriate solution for addressing these concerns [Fig. 6(b)].

In this Letter, a novel concept of MEFL for the variable curvature was demonstrated with experimental results. The pressure difference between two fluidic interfaces, in the lens and the surface channel, can be controlled by electrowetting making the curvature tunable. In the MEFL, the size and the optical power are quite dependent on the channel height and narrow surface channel allows wide variation of the optical power without the limitation caused by contact angle saturation. The size of the MEFL, according to the narrow surface channel, can be reduced by using multiple surface channels while the patterned control electrodes allow digital operation with a fast response. The proposed MEFL is expected to be applied to various imaging optics that require fast and precise control of wide optical power range.

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