Microelectrofluidic Lens for Variable Curvature

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ABSTRACT

This paper presents a tunable liquid lens based on microelectrofluidic technology which integrates electrowetting and microfluidics. In the novel 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. The previous electrowetting lens in which the contact angle changes at the side wall has a certain limitation of the curvature variation because of the contact angle saturation. Although the contact angle saturation also appears in the surface channel of the MEFL, the low surface channel increases the Laplace pressure and it makes the MEFL to have full variation of the optical power possible. The magnitude of the applied voltage determines the lens curvature in the analog mode MEFL as well as the electrowetting lens. Digital operation is also possible when the control electrodes of the MEFL are patterned to have an array. It is expected that the proposed MEFL is able to be widely used because of its full variation of the optical power without the use of oil and digital operation with fast response.

Keywords: Microelectrofluidic lens, variable curvature, surface channel, electrowetting, contact angle, Laplace pressure

1. INTRODUCTION

In optics, a lens is the most important element that converges or diverges a transmitted and refracted beam of light. Recently, liquid lenses have received considerable attention because they allow miniaturization of imaging optics with variable focus [1]. Figure 1a shows a liquid lens using the hydraulic pressure controlled by electroactive polymer (EAP) actuators and the pressure varies the lens curvature with a transparent elastomeric membrane [2]. Figure 1b shows a liquid lens actuated by dielectric force using two different dielectric liquid [3]. Electrowetting, which induces the contact angle change by an applied electric field, is very attractive to drive a liquid lens with low power consumption (Figure 1c) [4]. However, the optical power of the previous liquid lenses is quite limited by the material, physical and structural conditions.

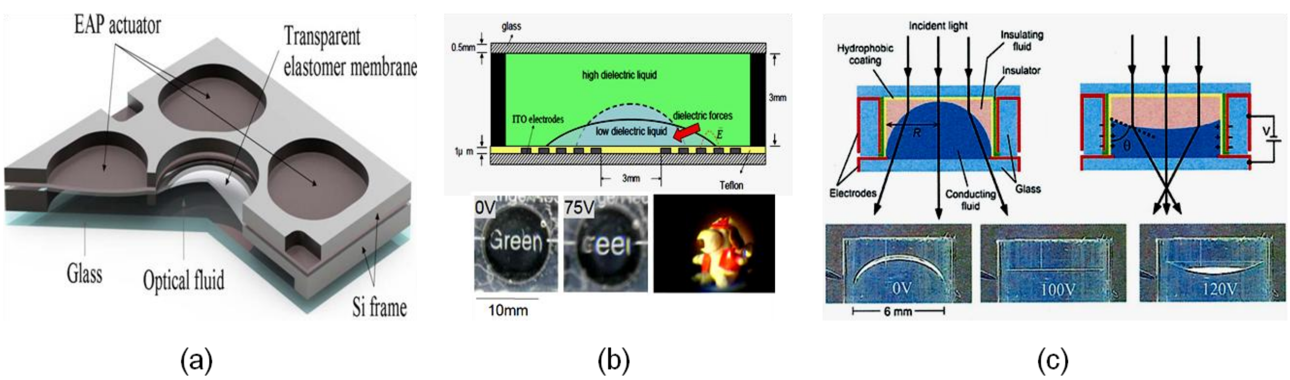

Figure 1. The previous tunable liquid lenses controlled by (a) electroactive polymer actuators [2], (b) dielectric force [3], and (c) electrowetting [4].

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This paper presents the characteristics of a tunable liquid lens based on microelectrofluidic technology which integrates electrowetting and microfluidics [5]. The novel microelectrofluidic lens (MEFL) varies the lens curvature by changing the surface channel curvature unlike the previous electrowetting lens which varies the lens curvature directly. Therefore, it allows the liquid lens to have wide variation of the optical power.

2. DESIGN AND PRINCIPLE

The basic MEFL consists of two immiscible fluids and three parallel plates with two spacers (Fig. 2). The middle plate has a throughhole lens aperture right in the center for the 1st fluid of transparent conducting liquid and throughholes at the edge for the 2nd fluid of insulating fluid such as air or oil. Each side of the surface channel has one or multiple control electrode covered by an insulating dielectric for electrowetting actuation [6] and the bottom plate has a reference electrode for grounding the liquid. The inner surface is recommended to be treated to be hydrophobic.

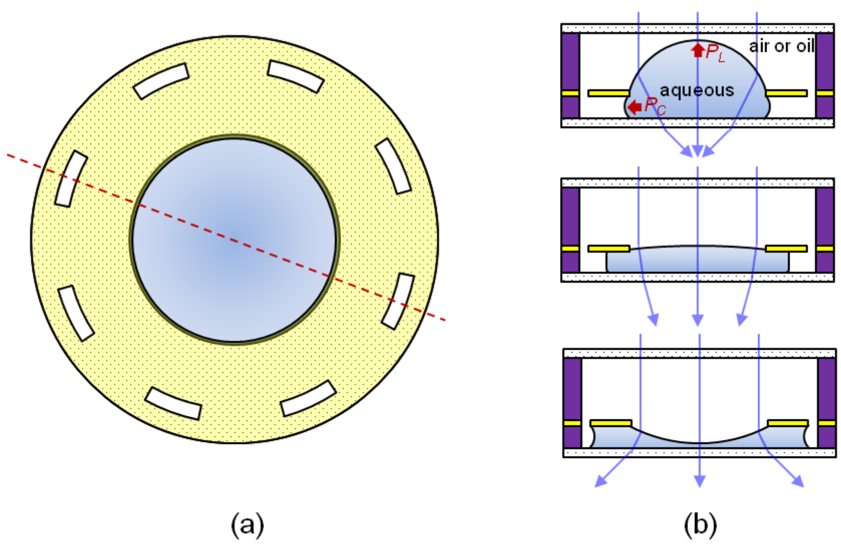

Figure 2. Schematics of the MEFL; (a) top and (b) cross-sectional views.

In the MEFL, the aqueous makes two fluidic interfaces on the lens aperture and the surface channel without difference of Laplace pressure. The pressure difference between the channel and the lens parts (ΔP) can be calculated from the Young-Laplace equation as follows;

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

$$P_C = \gamma\left(\frac{\cos\theta_t + \cos\theta_b}{h} - \frac{1}{r}\right) = \gamma\left(\frac{2\cos\theta_V}{h} - \frac{1}{r}\right) \tag{2}$$

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

where, γ, D, H, h, r, and θ_V are the fluids' interfacial tension, the diameter and thickness of the lens, the height, the radius, and the electrowetted contact angle of the 1st fluid in the surface channel, respectively.

In the initial state, the liquid does not infiltrate to the hydrophobic surface channel. However, when a proper voltage is applied between the control electrodes and the reference electrode, the pressure difference becomes positive and the lens volume decreases by infiltrating the liquid to the channel, and hence the lens curvature decreases. In electrowetting, the contact angle changes as the following Lippmann-Young equation;

$$\cos\theta_V = \cos\theta_0 + \frac{c}{2\gamma}V^2 \tag{4}$$

where, θ_0, c, and V are the initial contact angle, the capacitance per unit area of the dielectric layer, and the applied voltage. The higher the applied voltage is, the smaller the curvature is.

3. SIMULATION & RESULTS

Figure 3 shows the computational fluidic simulation results with the lens diameter of 3.2 mm and the channel height of 0.5 mm using Flow-3D (Flow Science, Inc., USA). When the contact angle of the channel surface decreases, the liquid infiltrates to the channel and hence the lens curvature decreases until the pressure difference is zero. However, contrary to the simulation results, there is a limitation of curvature variation due to the contact angle saturation in electrowetting. The contact angle cannot decrease a saturation angle which is known to be about 80° for Teflon-water-air system [7].

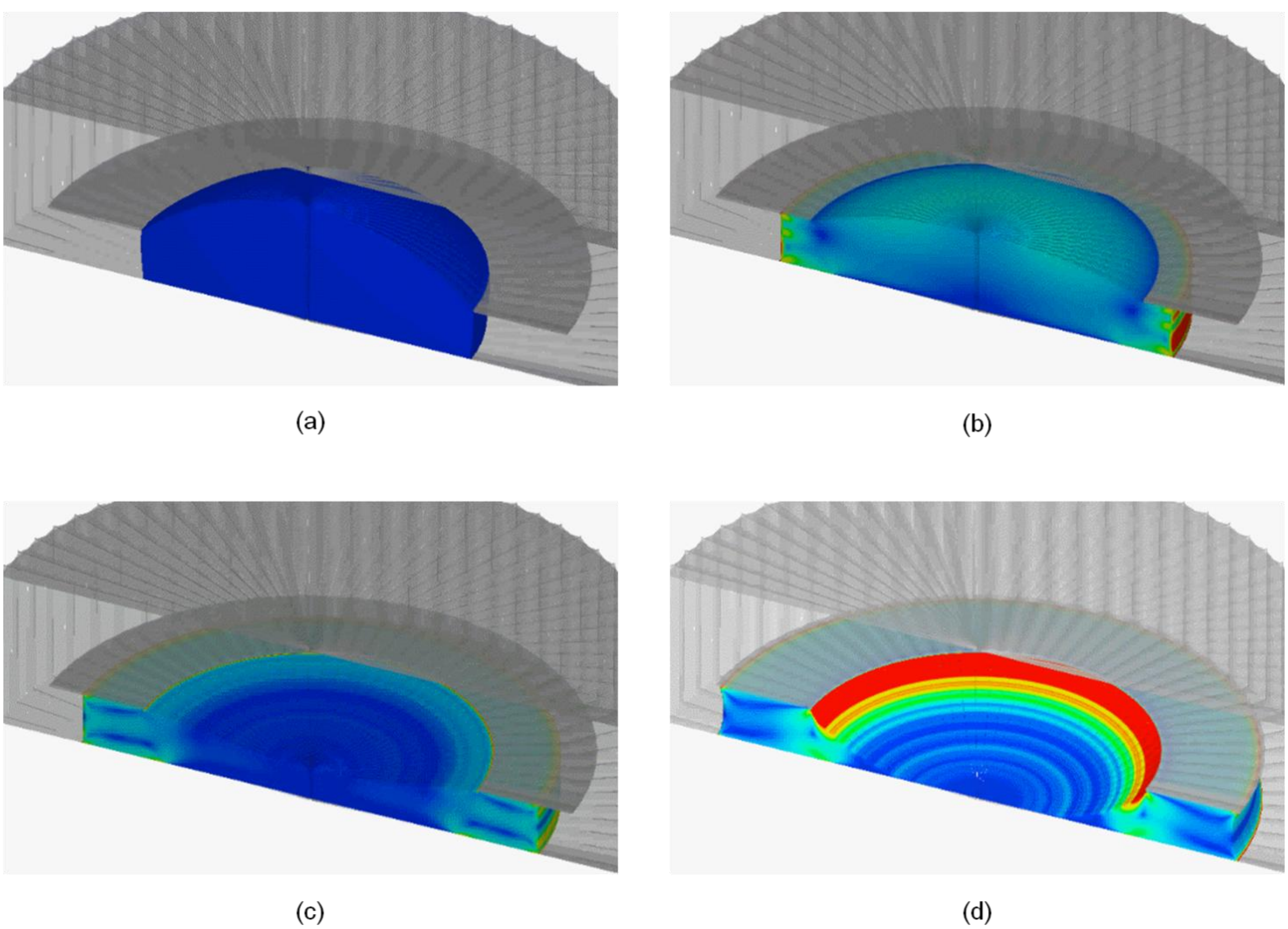

Figure 3. Flow-3D simulation results of the relationship between the channel radius and the lens height for the MEFL.

The channel height and the initial lens thickness of the MEFL depending on the volume of lens liquid affect the required contact angle and the channel radius for obtaining a certain optical power as shown in Eq. (3). Figure 4a shows the Laplace pressure and the optics power of the MEFL having the lens diameter of 3.2 mm. Figure 4b and c show the required channel radius and the required contact angle according to the channel height to vary the lens thickness from 0.45 mm to -0.4 mm. As mentioned above, the saturation angle of 80° with the channel height of 0.5 mm restricts the variation of the lens thickness down to below -0.12 mm unlike the simulation result in Figure 3d.

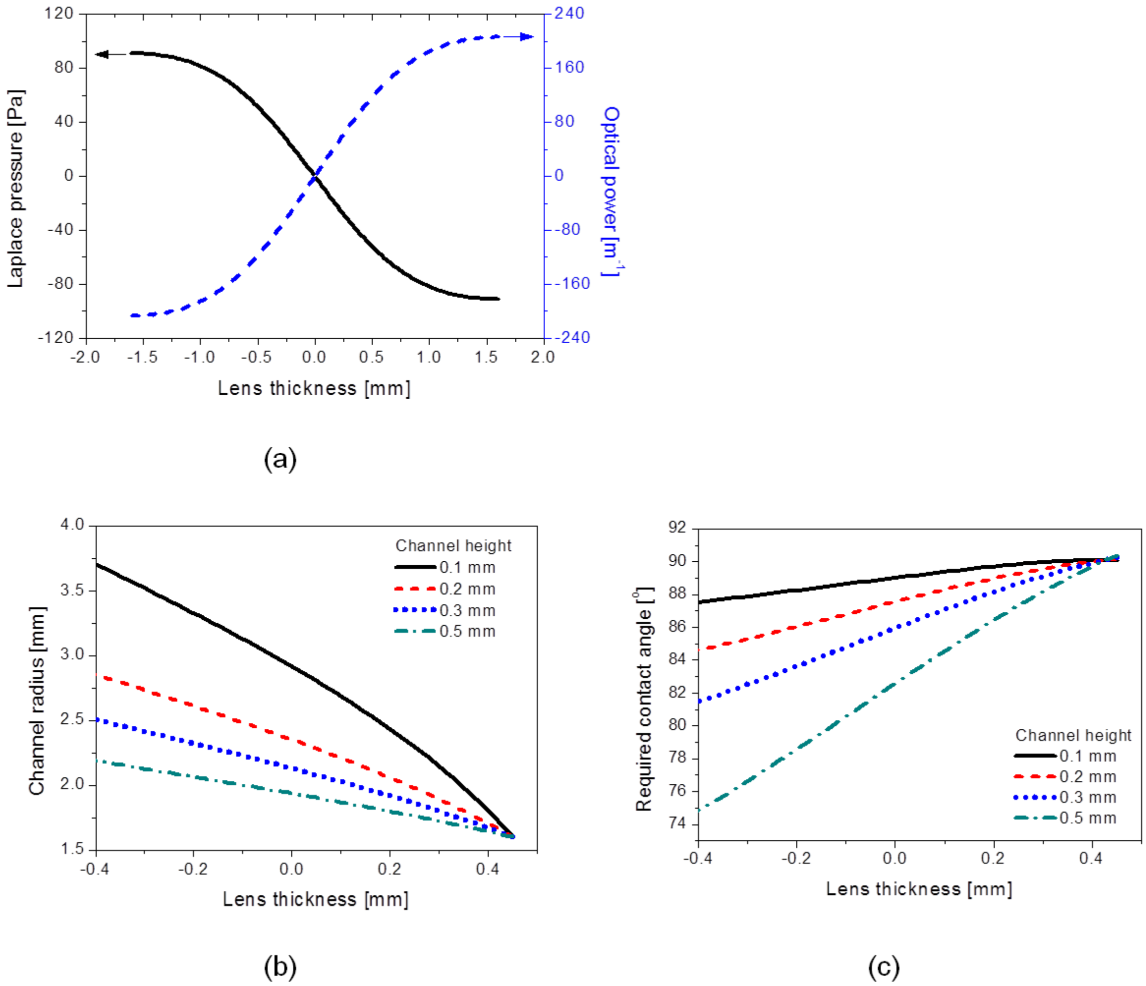

Figure 4. (a) Laplace pressure and optical power, (b) required channel radius, and (c) required contact angle according to the channel height depending on the lens thickness for the MEFL.

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. The typical electrowetting lens in which the contact angle changes at the side wall has a certain limitation of the curvature variation because of unwanted phenomenon called the contact angle saturation [4, 8]. Although the use of oil as the insulating fluid enlarges the contact angle variation in the electrowetting lens, it may decrease the difference of refractive indices. The contact angle saturation also appears in the surface channel of the MEFL. However, the Laplace pressure can increase by lowering the surface channel height and it makes the MEFL to have full variation of the optical power possible without regard for the use of oil. At this time, a larger surface channel area and an additional space for concaving the lens are required (Fig. 5a), and multiple surface channels can be an appropriate solution for addressing these concerns (Fig. 5b). When the lens diameter is 3 mm, the optical power variation in the MEFL is calculated to be nearly three-fold higher than that in the electrowetting lens of 150 diopter [4].

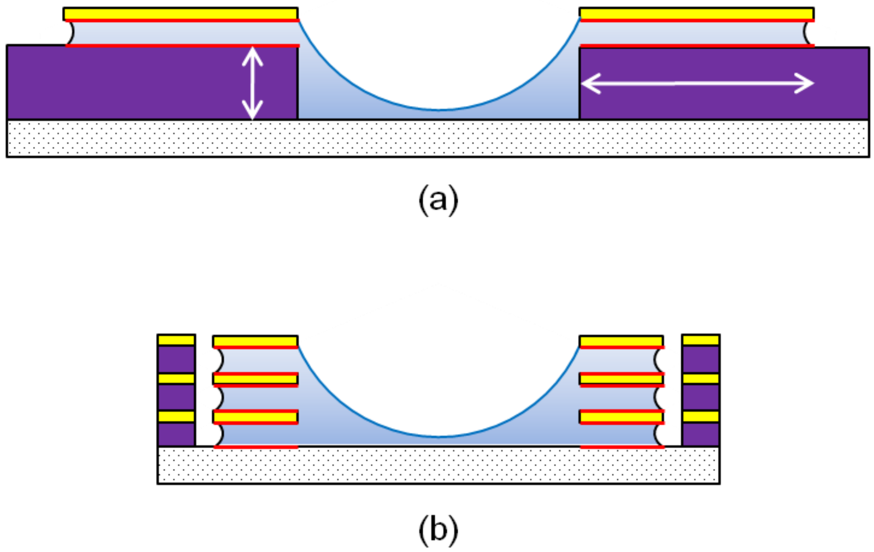

Figure 5. Schematic cross-sections of the MEFL for enlarging the optical power by lowering the channel height; (a) a larger surface channel and (b) multiple surface channels.

The above mentioned MEFL operates in analog mode in which the curvature variation depends on the applied voltage. However, the transit time for the electrowetted contact angle also depends on the applied voltage [9]. Therefore, high voltage is recommended for the fast response for the curvature control of the MEFL. If the control electrodes of the MEFL are patterned as shown in Fig. 6, digital operation is possible with fast response.

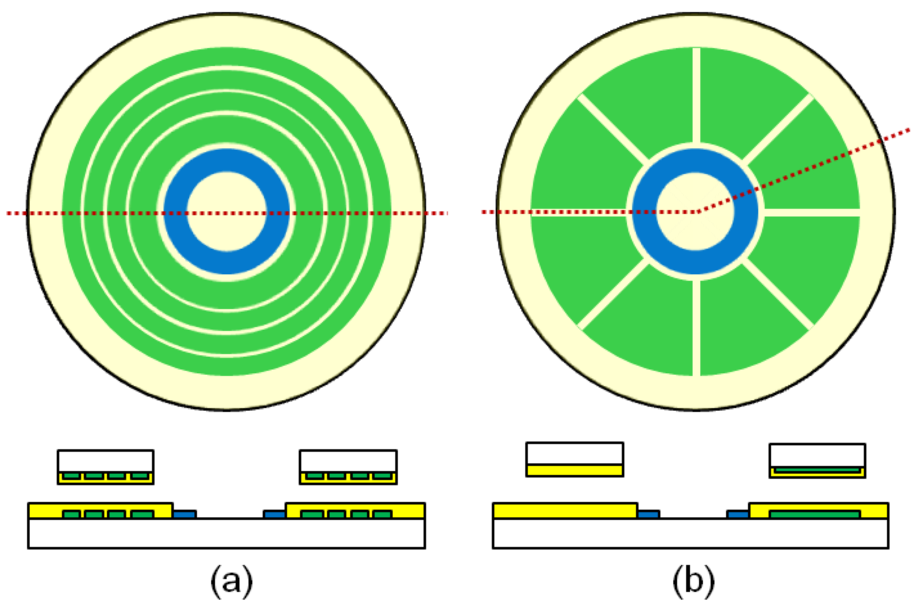

Figure 6. Schematic cross-sections of the MEFL for enlarging the optical power by lowering the channel height; (a) a larger surface channel and (b) multiple surface channels.

4. CONCLUSION

In this paper, a novel concept of MEFL for the variable curvature was demonstrated with simulation results. The pressure difference between two fluidic interfaces of the lens and the surface channel parts can be controlled by electrowetting and it makes the curvature tunable. In the MEFL, the size and the optical power are quite dependent on the channel height and low 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 low surface channel can reduce by using multiple surface channels and the patterned control electrodes allow digital operation with fast response possible. It is expected that the proposed MEFL is able to be widely used because of its full variation of the optical power without the use of oil and digital operation with fast response.

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