Microelectrofluidic Iris for Variable Aperture

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ABSTRACT

This paper presents a variable aperture design based on the microelectrofluidic technology which integrates electrowetting and microfluidics. The proposed microelectrofluidic iris (MEFI) consists of two immiscible fluids in two connected surface channels formed by three transparent plates and two spacers between them. In the initial state, the confined aqueous ring makes two fluidic interfaces, on which the Laplace pressure is same, in the hydrophobic surface channels. When a certain voltage is applied between the dielectric-coated control electrode beneath the three-phase contact line (TCL) and the reference electrode for grounding the aqueous, the contact angle changes on the activated control electrode. At high voltage over the threshold, the induced positive pressure difference makes the TCLs on the 1st channel advance to the center and the aperture narrow. If there is no potential difference between the control and reference electrodes, the pressure difference becomes negative. It makes the TCLs on the 1st channel recede and the aperture widen to the initial state. It is expected that the proposed MEFI is able to be widely used because of its fast response, circular aperture, digital operation, high aperture ratio, and possibility to be miniaturized for variable aperture.

Keywords: Microelectrofluidic iris, variable aperture, surface channel, electrowetting, contact angle, Laplace pressure

1. INTRODUCTION

An iris, an aperture stop, is a basic optical element that controls aperture size, brightness of light reaching the focal plane, and field of view to prevent light scattering and improve image quality by limiting spherical aberration [1, 2]. In macroscopic optics, the iris diaphragm has been made up of sliding blades which form variable polygon apertures. Although this type of iris has been widely used in photography, its complicated structure containing the mechanical moving parts is not appropriate to be miniaturized. Recently, fluidic iris diaphragms have attracted much attention to realize miniaturized tunable iris with advantage of simple fabrication without any mechanical element (Fig. 1) [1-4]. However, each previous fluidic iris has some of disadvantages of low driving speed, small tunable range, and blurred aperture boundary.

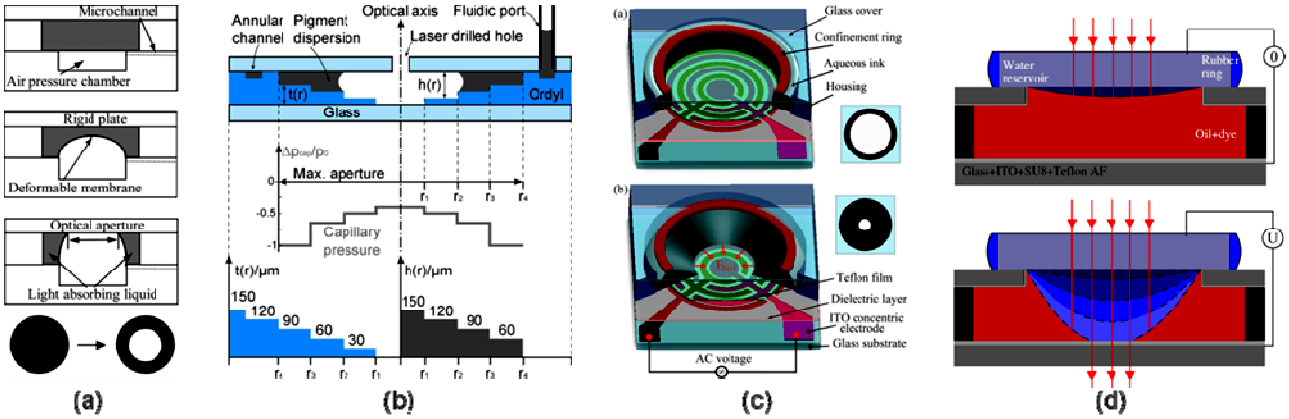

Figure 1. The previous fluidic tunable irises controlled by (a) membrane tension [1], (b) capillary force [2], (c) dielectric force [3], and (d) electrowetting [4].

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This paper presents a variable aperture design based on the microelectrofluidic technology which integrates electrowetting (EW) and microfluidics. EW induces the contact angle change by an applied electric field and it has advantages of simple structure, fast response, and low power consumption, so it has wide applications in digital microfluidics [5, 6], liquid lenses [7, 8], and displays [9, 10]. The microelectrifluidic iris (MEFI) takes an interest in gradual filling a surface channel with an aqueous by capillary action and it is controlled with the contact angle change by EW. The MEFI allows nearly perfect circular apertures to be controlled with high driving speed, high aperture ratio, and clear aperture boundary without any external actuator.

2. DESIGN AND PRINCIPLE

The proposed MEFI has an aqueous diaphragm in two connected circular surface microchannels formed by three transparent plates and two spacers (Figs. 2 and 3). The middle plate has a center hole and edge holes for transparent air or oil and opaque aqueous passage, respectively. The surfaces of each plate are allowed to have conducting electrodes and an insulating dielectric for EW actuation. Especially, concentric control electrodes are recommended for digital control of circular aperture in the 1st channel, and a reference electrode for grounding the aqueous and hence improving the EW efficiency. It is desirable that the 2nd channel is higher than the 1st channel for high aperture ratio, however, the heights affect the Laplace pressure at the fluidic interfaces and driving performance significantly. The hydrophobicity of the channel surface is very important and high inherent contact angle and low contact angle hysteresis makes the EW actuation more effective.

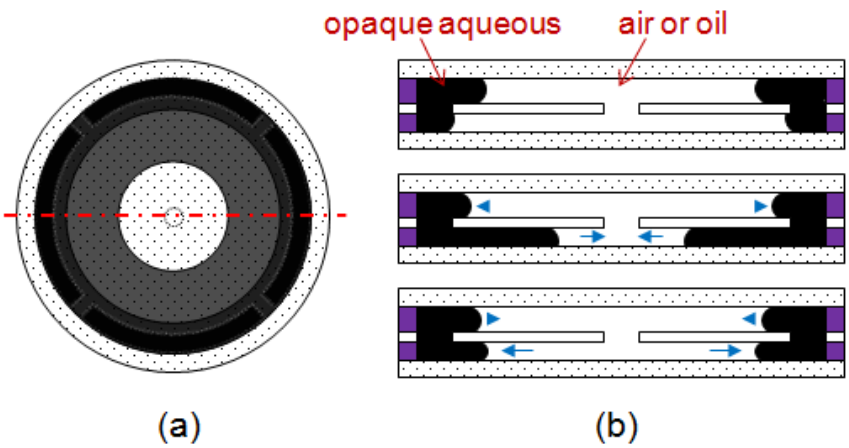


Figure 2. Schematics of the MEFI; (a) top and (b) cross-sectional views.

The fundamental operating principle of the MEFI is based on the Laplace pressure. In the initial state, the confined aqueous ring makes two fluidic interfaces on the hydrophobic surface channels on which the Laplace pressure is same. The Laplace pressure (P_1 and P_2 for the 1st and the 2nd channels) and the pressure difference (ΔP) at the fluidic interfaces can be calculated from the Young-Laplace equation as follows;

$$P_1 = \gamma\left(\frac{\cos\theta_{11} + \cos\theta_{12}}{h_1} + \frac{1}{r_1}\right) \tag{1}$$

$$P_2 = \gamma\left(\frac{\cos\theta_{21} + \cos\theta_{22}}{h_2} + \frac{1}{r_2}\right) \tag{2}$$

$$\Delta P = P_1 - P_2 = \gamma\left[\frac{\cos\theta_{11} + \cos\theta_{12}}{h_1} - \frac{\cos\theta_{21} + \cos\theta_{22}}{h_2} + \frac{1}{r_1} - \frac{1}{r_2}\right] \tag{3}$$

where, γ, h_1, h_2, r_1, r_2, θ_{11}, θ_{12}, θ_{21}, and θ_{22} are the fluids' interfacial tension, heights and lateral radii of the 1st and the 2nd channels, and contact angles at the three-phase contact lines (TCLs) on the channels, respectively.

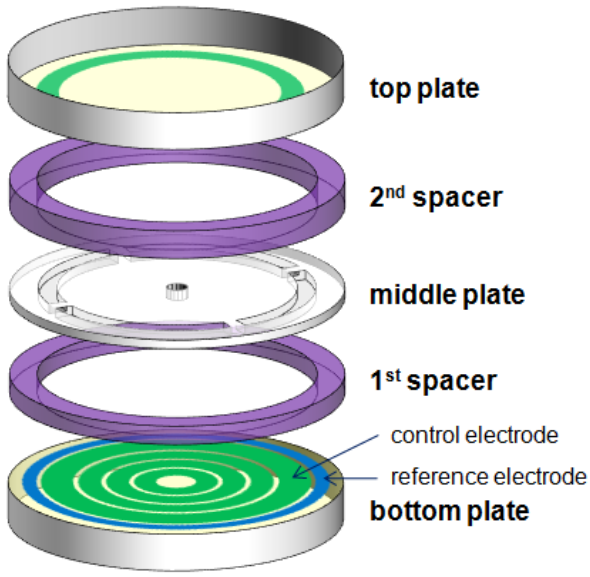


Figure 3. Schematic exploded oblique view of the MEFI.

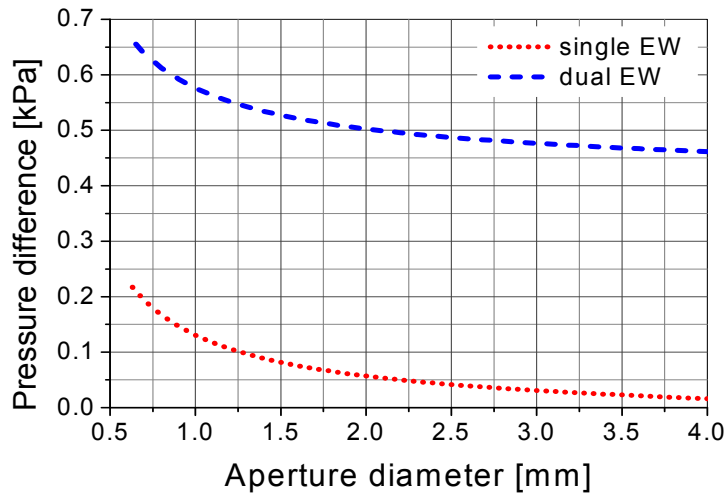
When a certain voltage is applied between the control electrode beneath the TCL and the reference electrode, the contact angle changes on the activated control electrode as the following Lippmann-Young equation;

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

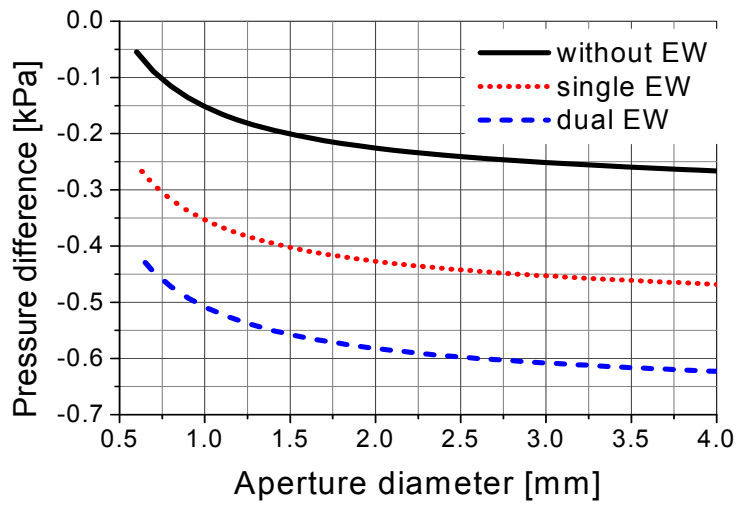
where, θ_0, θ_V, c, and V are initial advancing angle, electrowetted contact angle, capacitance per unit area of the dielectric layer, and the applied voltage. At high voltage over the threshold, the induced positive pressure difference makes the TCLs on the 1st channel advance to the center and the aperture narrow. At this time, θ_{11} and θ_{12} are same as θ_V and θ_0, respectively, and θ_{21} and θ_{22} are receding angle of θ_0-α, where α is the contact angle hysteresis. If there is no potential difference between the control and reference electrodes, the pressure difference becomes negative and it makes the TCLs on the 1st channel recede and the aperture widen to the initial state. At this time, θ_{11} and θ_{12} are receding angle of θ_0-α and θ_{21} and θ_{22} are advancing angle of θ_0.

3. SIMULATION & RESULTS

Figures 4 shows the calculated pressure difference, from Eq. (3), of the MEFI having maximum and minimum aperture of 4.0 mm and 0.6 mm diameter, respectively, when the electrowetted contact angle of water on a hydrophobic Teflon surface is ~80°, the saturated contact angle, and the 1st and the 2nd channel heights are 100 and 250 μm, respectively. For the more accurate calculation, advancing angle of 116° and receding angle of 111° were also considered [11]. A positive pressure difference makes the aperture narrow and a negative pressure difference makes the aperture widen. EW with the concentric electrodes allows digital control of the circular aperture possible. If the middle plate has the control electrodes face to face with the control electrodes on the bottom plate, the dual EW makes the driving force for narrowing the aperture double [12], and the positive pressure difference increases significantly (Fig. 4a). Although the MEFI can be reversed without EW actuation, EW on the 2nd channel makes the widening pressure difference bigger and it may results the widening speed faster than before when the control electrodes can be patterned on the 2nd channel surfaces as well as the 1st channel surfaces (Fig. 4b).



(a)



(b)

Figure 4. Calculated pressure difference of the MEFI; when (a) narrowing and (b) widening the aperture.

Figure 5 presents the computational fluidic simulation results using Flow-3D (Flow Science, Inc., USA). Though the shape and number of the aperture can be controlled easily by patterning the control electrodes in the fabrication process, the control region in the 1st channel was divided in five discrete steps by concentric ring patterns to have circular aperture in the simulation. The fluidic interface in the 1st channel advanced from the outer ring or receded from the center of the MEFI to the boundary between the hydrophobic region and the hydrophilic region. As the results, the response time for the aperture diameter from 4.0 mm to 0.6 mm is 36 msec in the case of single EW actuation and as fast as 3.8 msec in dual EW actuation. The average advancing velocity of the fluidic interface at the 1st channel is 48 mm/sec and 450 mm/sec, respectively. The response time and the average velocity for widening the aperture are 11 msec and 160 mm/sec,

respectively, without EW actuation. When the minimum aperture becomes narrow under 0.5 mm, the pressure difference becomes positive and it makes the MEFI not reversible without EW actuation at the 2nd channel. The simulation was performed only with the channel heights of 100 μm and 250 μm and the results are absolutely dependent on the simulation parameters including the channel heights and their ratio.

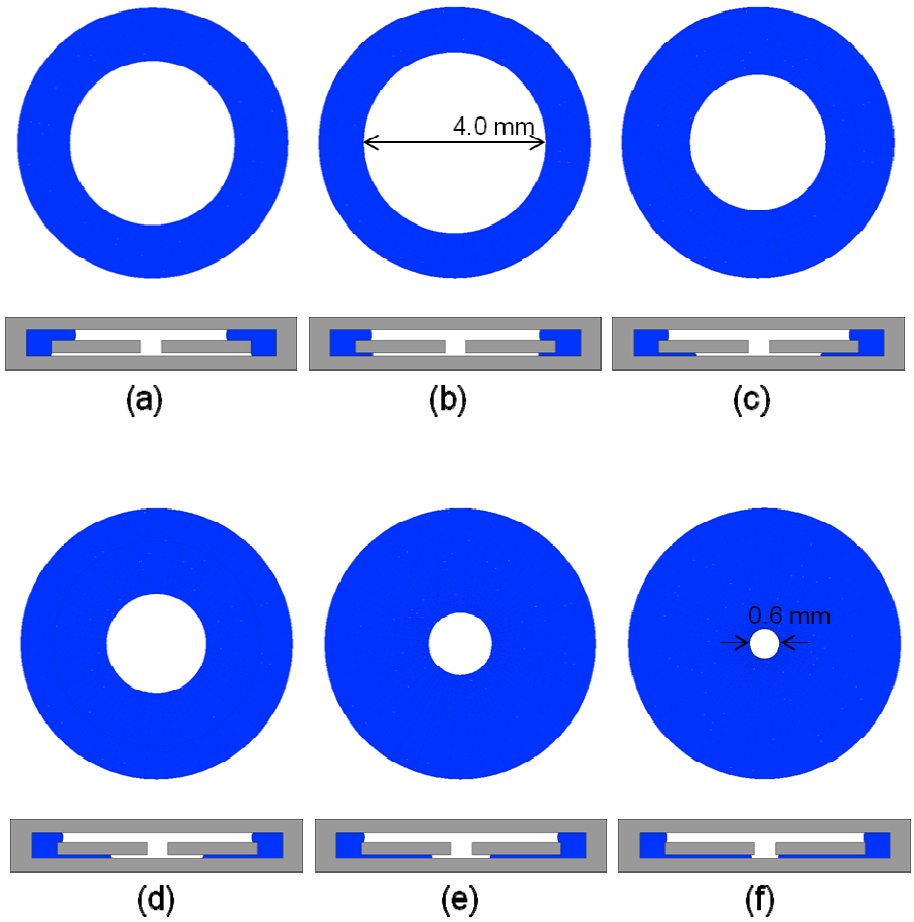


Figure 5. Flow-3D simulation results of top and cross-sectional view for the MEFI; (a) initial state, (b) maximum aperture diameter of 4.0 mm, (c) 3.0 mm (d) 2.2 mm, (e) 1.4 mm, and (e) minimum of 0.6 mm.

4. CONCLUSION

In this paper, a novel concept of a microelectrofluidic device for the variable aperture was demonstrated. The pressure difference between two fluidic interfaces of two connected surface channels can be controlled by EW and it makes the aperture widen or narrow. The fluidic simulation for the proposed MEFI was performed with the 1st and the 2nd channel heights of 100 μm and 250 μm, the aperture diameter between 0.6 mm and 4.0 mm, and EW saturation angle of water on Teflon surface and its dynamic contact angles. As the results, the circular fluidic aperture was successfully controlled in five discrete steps with separated active region and full narrowing and widening was performed within several tens of msec. The proposed MEFI is expected to be scaled up and down well for variable aperture size from several centimeters into microdomain with advantages of high driving speed, high aperture ratio, clear circular boundary, low power consumption, simple fabrication without any external actuator.

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