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Integrated Digital and Analog Microfluidics by EWOD and LDEP

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Abstract*—EWOD (electrowetting-on-dielectric) and LDEP (liquid dielectrophoresis) are investigated to provide digital and analog microfluidic functions on an integrated chip respectively. By altering the frequency of the applied voltage and the surrounding medium of a EWOD device, we found that when using oil as surrounding medium and applying an AC signal ~100 kHz, liquid column would be drawn and follow the thin connecting lines of the EWOD driving electrodes instead of remaining on top of the center of the EWOD driving electrodes. This new phenomenon is described in this paper and is regarded as a LDEP effect. Three fundamental tools for integrated digital and analog microfluidics are developed, including a digital-to-analog converter, an analog-to-digital converter, and a valve. Combining EWOD and LDEP effects, liquids can be pumped on a virtual channel (analog microfluidics), defined by energized thin LDEP electrode lines, continuously from liquid reservoir or from a digitized droplet (digital microfluidics). On the contrary, liquids on LDEP electrodes (analog microfluidics) can also be pumped on a EWOD electrode and be digitized in droplet forms with precise volumes (digital microfluidics). EWOD and LDEP can be selectively programmed on a single chip, making integrated digital and analog microfluidics a reality.

Keywords-EWOD; LDEP; Digital Microfluidics; Analog Microfluidics

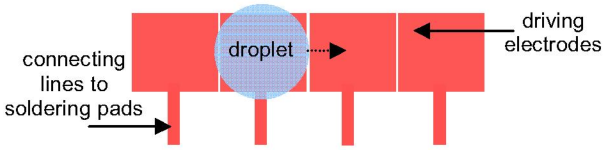
I. INTRODUCTION

Microfluidics is a technique to handle fluids on the microscale. It can be classified into "analog" and "digital" microfluidics by the form in that microfluids are manipulated. In analog or continuous flow microfluidic devices, fluids are conduited in microchannels made of silicon, glass, or plastics and pumped continuously along the microchannels by mechanical or non-mechanical micropumps. Various analog microfluidic devices have been demonstrated for different applications, including capillary electrophoresis (CE), liquids mixing, PCR, and other bioassays [1]. On the other hand, digital microfluidics processes fluids in discrete droplet forms. Droplets are usually transported on an open surface [2, 3] or between two parallel plates [4-6] instead of in closed microchannels. The path of a droplet is not predefined and can be programmed flexibly for different applications. Moreover, since microchannels are not required, the fabrication is simple. Both analog and digital microfluidics have their own advantages. For example, analog microfluidics is suitable for routine fluids handling, while digital microfluidics is desirable in preparing numerous samples on a limited chip area. However, for their different pumping mechanisms, it is difficult to integrate analog and digital microfluidics. In this research, we utilized electric fields to perform both digital and analog microfluidics on a chip.

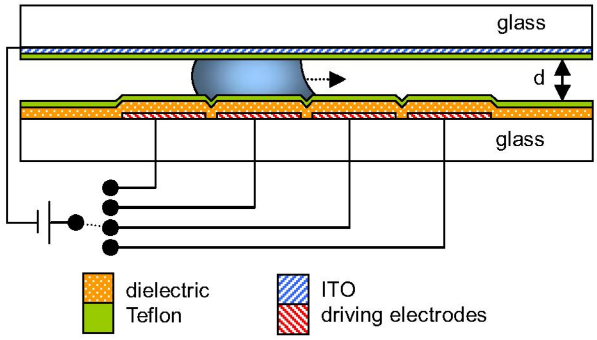
II. PRINCIPLE

A. EWOD

EWOD (Electrowetting-on-dielectric), an electric means to change the surface wettability (i.e., contact angle change) on a dielectric coated electrode, is one of the mechanisms to actuate droplets in digital microfluidics. As shown in Fig. 1, a droplet is placed between two parallel plates. The top plate contains a Teflon-coated blank ITO (Indium-Tin-Oxide) electrode; while the driving electrodes are patterned on the bottom plate and covered by a dielectric and a Teflon layer. When applying an electric signal between the top ITO and one of the driving electrodes, the surface on top of the activated driving electrode is electrically changed from hydrophobic to hydrophilic. Pumping of the droplet onto the activated driving electrode can be achieved. Through proper electrode design and pre-programmed electric signals, multiple droplets can be manipulated individually and various digital microfluidic functions (e.g., transporting, creating, cutting, and merging) can be performed on a single EWOD device [6].



(a) Top view of a EWOD device. Droplet can be pumped by applying voltage on driving electrodes.



(b) Cross-sectional view of a EWOD device.

Figure 1. Digital microfluidics manipulated by EWOD.

Digital microfluidic functions were successfully performed in EWOD devices with two plates spaced 100 µm apart (i.e., d is 100 µm in Fig. 1). The width of the connecting lines is 100 µm, and the dimension of driving electrodes is 1 mm x 1mm. Besides EWOD manipulated digital microfluidics, analog microfluidics was also demonstrated by LDEP (liquid dielectrophoresis) in such a device.

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B. LDEP

Dielectrophoresis (DEP) is a translational movement of polarizable objects toward the direction of the electric field gradient. This phenomenon has been widely used in manipulating suspended polarized biological objects, including nucleic acids, proteins, cells, and virus, in aqueous solutions [7]. Pellat investigated the rise of dielectric liquid by DEP between two activated parallel electrodes more than one hundred years ago [8]. Recently, Jones modified Pellat's experiment and successfully raised conductive liquid by energizing two parallel dielectric-coated electrodes [9]. This movement of liquid toward a higher electric field region was considered a liquid dielectrophoresis (LDEP) phenomenon. Furthermore, Jones demonstrated the use of a pair of coplanar electrodes to project liquid finger from a water droplet dispensed on an open surface.

III. DESIGN AND EXPERIMENTS

A. Digital Microfluidics: Frequency and Medium Effect

As mentioned above, when applying an electric signal between the ITO and one of the driving electrodes, droplet can be moved onto the energized electrode by EWOD between two glass plates (Fig. 1). Lippmann and Young's equation expresses the relationship between the contact angle change of a droplet (from θ_0 to $\theta(V)$) and the voltage V across a dielectric layer:

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

where ε_0 is the permittivity of vacuum, ε and t are the permittivity and thickness of the dielectric layer, γ_{LG} is the liquid-gas interfacial tension.

From (1), DC or AC voltage can generate contact angle change, causing droplet movements. However, since V is the voltage across the dielectric layer instead of the applied voltage (V_{app}), DC or AC signal does make differences in contact angle change. For instance, when applying a DC voltage between ITO and driving electrodes, most of the applied voltage is exerted across the dielectric layer. In such a case, one can assume that the voltage across the dielectric, V, is equal to V_{app}. As the frequency of the applied voltage increases, the voltage across the dielectric V decreases, while the voltage across the liquid increases. In other words, the contact angle change is dependent on the frequency of the applied voltage, which is not shown in (1). It was reported that the moving speed of the droplet is dependent on the frequency of the applied voltage [5].

To investigate EWOD-actuated digital microfluidics, EWOD devices were fabricated. An ITO-coated glass substrate was first cleaned and wet etched to pattern driving electrodes on the bottom plate. Positive (AZ 5214, or AZ 4620) and negative (SU8) photoresist was then spun on as a dielectric layer. Teflon (500 Å thick) was subsequently spin-coated on the PR to make a hydrophobic surface. The top plate was simply prepared by spinning Teflon (500 Å thick) on a cleaned ITO glass. DI water was dispensed on the bottom plate. Finally, the top plate was bonded on top of the bottom plate with a 100 µm-thick spacer.

Water droplets were successfully transported, cut, and merged when applying a 1 kHz AC signal in an air medium. For lower frequencies (e.g., DC), electrolysis was sometimes observed. Slower pumping of droplet was obtained at higher frequencies (e.g., 100 kHz). Besides, satellite droplet was expelled at frequency higher than 60 kHz. Fig. 2 shows the satellite droplets when applying a 100 kHz signal. Therefore, to manipulate droplets by EWOD, a 1 kHz AC signal is preferentially applied in our experiments.

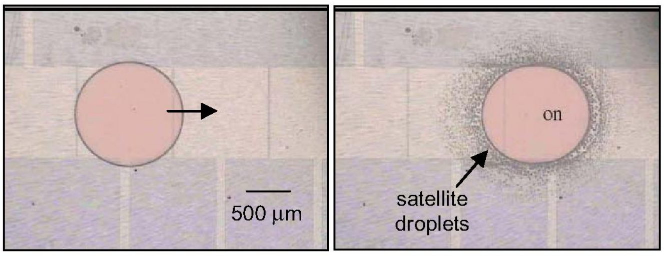


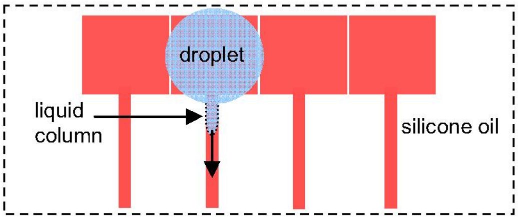
Figure 2. Satellite droplets expelled when driving water droplet in air with a 100 kHz voltage.

This satellite droplet expelling phenomenon was observed and reported by researchers investigating EWOD on a sessile drop with an AC voltage [10, 11]. They found the contour line instability is suppressed when a sufficient amount of salt is dissolved in water. In stead of increasing the ionic concentration of the droplet, in this experiment, we successfully prevent the expelling of satellite droplets by immersing the droplet in a silicone oil medium. By filling silicone or olive oil between the plates around the liquid droplet, the droplet was pumped slower than that in air under the same applying voltage. It is because the silicone oil has a higher viscosity than air.

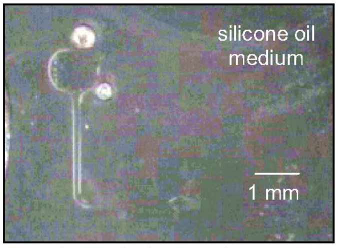
B. Digital- to-Analog Microfluidics Converter

Since the droplet pumping speed is slow in air when using a 100 kHz signal, the pumping speed is even slower when the droplet is immersed in an oil medium. To overcome this difficulty, a higher voltage was applied. Surprisingly, besides increasing the droplet moving speed, we found that the higher voltage caused the liquid column to be projected along the connecting lines from the droplet, as shown in Fig. 3(a). Fig 3(b) shows a 100-µm-wide DI water liquid column was drawn from a droplet sitting on a square (1 mm × 1 mm) EWOD driving electrode in the olive oil medium with the viscosity of 92 cSt. The width of the liquid column was determined by the width of the connecting lines, which were designed for electric connections from the soldering pads to the EWOD driving electrodes. The applied voltage was 100 kHz and 120 Vrms. The dielectric layer was a 1.6-µm-thick AZ 5214.

From contact angle and pressure differences analyses (will be discussed elsewhere), EWOD can not provide sufficient force or pressure difference to draw a 100-µm-wide liquid column from a droplet with a 1 mm diameter before contact angle saturation. Besides, at 100 kHz, most of the voltage drops across the liquid and the surrounding medium instead of across the dielectric layer. EWOD force is much decreased for the effective voltage across dielectric is reduced. We consider this liquid column is drawn by LDEP. For water and oil has different electrical properties, the non-uniform electric fields make water column moved by DEP. Since LDEP can be generated on a EWOD device, it serves as a digital-to-analog microfluidic converter. By changing the applied frequency from 1 kHz to 100 kHz, liquid can be transported from a digital form (droplet) to the analog form (liquid column).



(a) Satellite droplets are eliminated by immersing water droplet in oil when applying a 100 kHz voltage; at higher voltages, liquid starts to follow the connecting lines to the soldering pads and forms a liquid column.



(b) Liquid column was observed when 100 kHz, 120 Vrms was applied on a EWOD device with 1.6 µm AZ5214 as dielectric. The driving electrode is 1-mm-wide and the connecting line is 100-µm-wide.

Figure 3. Analog microfluidics manipulated by LDEP.

C. *Analog Microfluidics*

Analog microfluidics can be performed by generating merely LDEP on chip to pump liquids. As discussed above, the liquid column would follow the thin connecting lines of the EWOD driving electrodes when applying a 100 kHz signal with sufficient voltage. With appropriate design of electrodes, a liquid column can be projected from a liquid reservoir and proceed on the electrode. In such a case, the electrode acts as a virtual microchannel to conduit liquids electrically. Therefore, a novel analog microfluidic technique is proposed. Continuous flow microfluids can be pumped non-mechanically in virtual microchannels without channel walls.

To investigate the pumping ability of LDEP, a long 100-µm-wide electrode pattern was designed, shown “NCTU” in Fig. 4(a). Fig. 4(b)-(f) are the sequential frames captured from a recorded video, showing the liquid pumped in an electrically-defined virtual microchannel from a reservoir by LDEP when applying 100 kHz and 120 Vrms on the electrode. The dielectric layer used in Fig. 4 is AZ 5214 with thickness of 1.6 µm. DI water was pumped in olive oil with viscosity of 92 cSt. As can be seen form Fig. 4 (b)-(f), after a 100 kHz signal was applied, water was drawn along the electrode. The front line of water would keep proceeding until the water in the reservoir is depleted. To stop the front line, we designed a notch-shaped valve, which will be discussed in the next paragraph. Fig. 4(g) shows water driven by LDEP using a 0.65 cSt silicon oil as medium. Liquid column is wider than the electrode in less viscous oil. A more systematic study needs to be done to realize the effect of the oil to the geometry of the liquid column. This new analog microfluidics is more flexible than the traditional one since the flow of fluids can be programmed by electrical signals without physical microchannels.

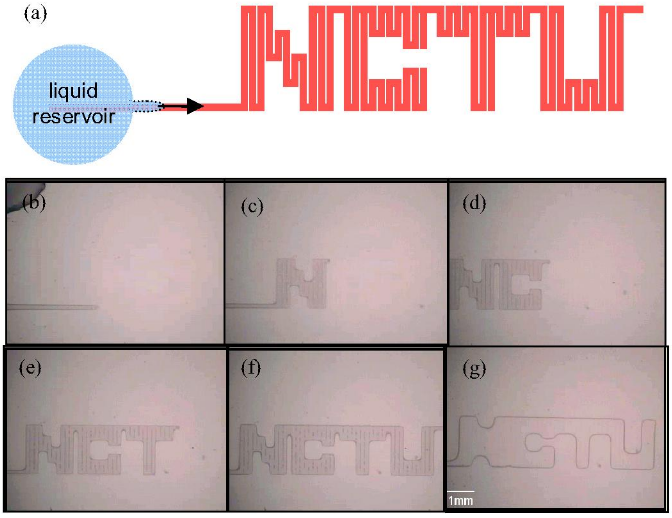
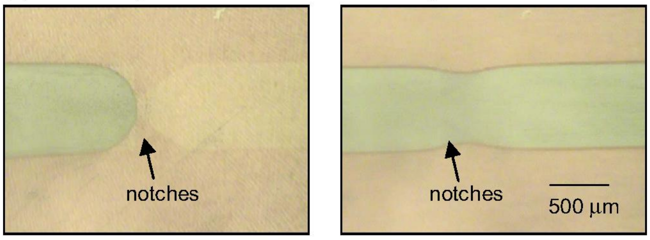


Figure 4. Virtual liquid channel was formed by LDEP when 100 kHz, 120 Vrms were applied on an electrode covered by 1.6 µm AZ5214. (a) Electrode design. Water pumped in oil with a viscosity of 92 cSt (b)-(f) and 0.65cSt (g).

To be able to control the liquid column position, a virtual voltage controlled LDEP valve was also developed. As shown in Fig. 5(a), two notches were patterned on a LDEP electrode to make a liquid valve. Liquid was designed to be stopped at the notched area. The tested electrode was 500 µm in width, and its narrowest width at the notch tip is 100 µm. Fig. 5(b) and (c) shows the valve function tested on device with a 6.2-µm-thick AZ 4620 dielectric layer. When applying 84 Vrms, the liquid was stopped at the edge of the notches. As the voltage was increased, the liquid started to pass through the valve at 112 Vrms.

(a) A notch-shaped LDEP electrode as a virtual liquid valve.



(b) 100 kHz, 84 Vrms was applied; liquid could not pass through the notched area.

(c) 100 kHz, 112Vrms was applied; liquid passed the notched area.

Figure 5. A virtual LDEP valve controlled by applied voltage.

D. *Analog-to-Digital Microfluidics Converter*

The last but not the least function to fulfill integrated digital and analog microfluidics is the analog-to-digital microfluidic converter, namely, creating droplets from LDEP pumped liquid column. Fig.6 shows the design of the electrodes and the procedure of droplet creation. The dielectric layer of the tested device is 6.2-μm-thick AZ 4620, and the medium is 50 cSt silicone oil. We first supplied 100 kHz, 110 Vrms to the LDEP electrode to perform analog microfluidics on chip. As can be seen in Fig. 6(a) and (b), the liquid column proceeded along the LDEP electrode until the trapezoid-shaped end. 1 kHz, 80 Vrms was then applied on the EWOD electrode to transport the liquid onto the electrode. When the liquid filled up the EWOD electrode, we turn off the LDEP electrode. The surface tension would draw the liquid on the LDEP electrode back to the reservoir and break the thin liquid column at the end of the trapezoid as shown in Fig.6 (c). A droplet (Fig. 6(d)) was therefore created and can be further processed by digital microfluidics. Since the LDEP electrode is thin (e.g., 100 μm), droplet generation with a consistent volume is more reliable than using only EWOD force to break droplets on wide EWOD driving electrodes (e.g., 1 mm) [5]. By integrating EWOD and LDEP, an analog-to-digital microfluidic converter was demonstrated.

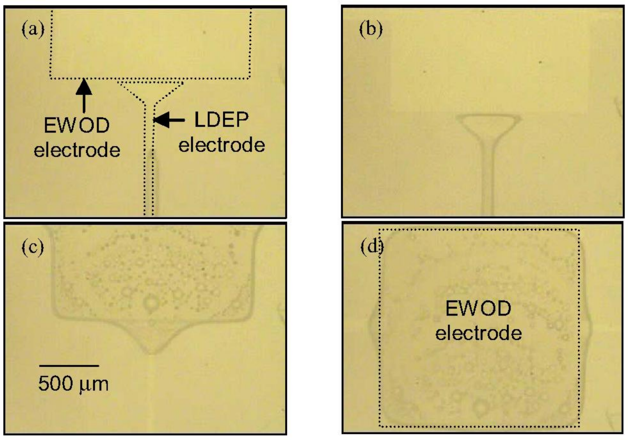


Figure 6. Droplet created by EWOD and LDEP: (a) and (b) 100 kHz, 110 Vrms voltage applied on the LDEP electrode. (c) and (d) 1 kHz, 80Vrms voltage applied on EWOD electrode and turned off the LDEP electrode.

IV. CONCLUSIONS

We succeed to integrate EWOD and LDEP on a single chip. EWOD is the driving mechanism for droplets in digital microfluidics. To provide sufficient voltage without electrolysis, 1 kHz signal was desirable for EWOD. EWOD actuation with different frequency, dielectric, and surrounding medium were tested. At 100 kHz, the EWOD actuation is less effective since the voltage across the dielectric is reduces. Moreover, at 100 kHz, the expelling of satellite droplets was found. By changing the surrounding medium from air to oil, the expelling phenomenon was eliminated. LDEP was found when manipulate liquid droplets in oil by applying 100 kHz. Thin liquid column was drawn by the gradient of the electric field causing by the top ITO and the thin connecting lines on the bottom plate. The liquid column would proceed along a thin electrode (virtual microchannel) until liquid was depleted from the reservoir. Three fundamental tools of integrated digital and analog microfluidics were developed in this paper, including a digital-to-analog microfluidic converter, an analog-to-digital microfluidic converter, and a valve.

With the three tools, we can develop an integrated digital and analog microfluidic platform. A conceptual diagram of an envisioned platform using EWOD and LDEP is shown in Fig. 7. Droplets can be created with precise volume by the propose analog-to-digital microfluidic converter. The droplets can be manipulated for sample preparation by EWOD. Then the prepared sample can be pumped on virtual microchannels by LDEP for further sample treatment or analysis.

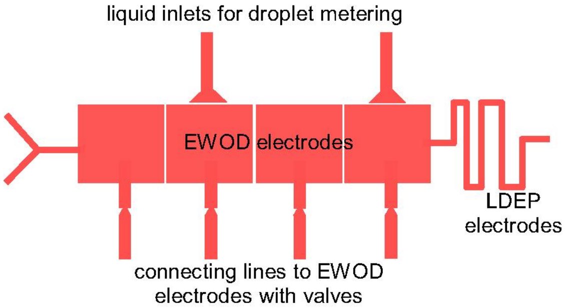


Figure 7. Conceptual diagram of achieving a integrated digital and analog microfluidics device using EWOD and LDEP.

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