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NONLINEAR LOCALIZATION FOR ELECTROWETTING-BASED DIGITAL MICROFLUIDIC ACTUATION

Milad Abolhasani
University of British Columbia
Kelowna, BC, Canada

Kurt D. Devlin
University of British Columbia
Kelowna, BC, Canada

Homayoun Najjaran
University of British Columbia
Kelowna, BC, Canada

Mina Hoorfar
University of British Columbia
Kelowna, BC, Canada

Jonathan F. Holzman
University of British Columbia
Kelowna, BC, Canada

ABSTRACT

The method described in this paper introduces a new multiplexing format for cross-referencing of DMF systems through the simultaneous use of threshold-based voltage actuation (which sets a minimum voltage to initiate droplet motion) and bi-polar voltage activation on the overlying and underlying electrodes. The design makes use of bi-polar voltage activation and threshold effects to eliminate inter-droplet interference and overcome addressability limitations. In the proposed DMF multiplexer structure, these two requirements must both be satisfied for 2-D multiplexed addressability.

Experimental characterization of the threshold voltage associated with the first requirement is presented. With regard to requirement two, the bi-polar voltage activation scheme is applied to a fabricated DMF multiplexer, and independent microdroplet motion is shown. The technique can be applied in actuating isolated microdroplets or microdroplet groups (simultaneously) in large-scale/highly-parallel DMF devices.

INTRODUCTION

In recent years a new class of microfluidics, called digital microfluidics, has been demonstrated for discrete microdroplet motion on individually activated electrodes [1, 2]. Electrowetting forces are used in DMF systems to move microdroplets in the structures. Compared to continuous microfluidics, with physical micro valves and micro channels, DMF devices have greatly reduced risks of fatigue and valve clogging. Also, DMF devices can operate at higher throughputs and lower power consumption levels with reduced reagent and sample volumes [3, 4]. However, the most important feature of DMF structures is the dynamic reconfigurability that can be applied for different laboratory tasks.

Electrowetting is the desirable actuation mechanism for DMF devices, although there are still some structural challenges for this actuation method. The first generation of DMF systems [5], called open system, makes use of a catena wire inside the microdroplet. The droplet is placed on a covered electrode with hydrophobic and dielectric layers. Some of the limitations of open systems, such as high evaporation rates and electric current, can be overcome by adding a top plate to the DMF system. This bi-layered second generation DMF system is based upon a closed DMF architecture [1]. The new closed geometry has many advantages, including reduced evaporation and the ability to work with multiple microdroplets.

The most important challenge remaining for closed DMF architectures is the addressability of the inner electrodes. Addressing of underlying electrodes in a closed DMF system with individually addressed electrodes in a 2-D electrode grid has severe limitations when one considers that shorting, overlapping and crossing of address lines are not allowed. This addressing becomes extremely important for systems beyond 5×5 [6]. With this in mind, Fan et al. [6, 7] introduced a bi-layer structure, with *x* and *y* electrode arrays in the lower and upper planes placed orthogonally to each other. This cross-referenced configuration is shown in Fig. 1.

The complexity of the cross-referenced DMF structure is greatly reduced compared to the 2-D individually-addressed electrode arrays. The only limitation of this new generation of DMF systems relates to the simultaneous motion of multiple microdroplets in complex systems. Undesired motion of other microdroplets can occur when they are placed on the same activated electrode row. In fact, all microdroplets placed in the same electrode row are coupled to the applied electric field and have the potential to move to the adjacent electrode. If, for example, the row electrode m = 4 becomes activated with a high voltage to move a microdroplet placed above the n = 4 grounded electrode, other microdroplets intersecting the m = 4 electrode will have the potential to move towards the neighboring electrode. Therefore, the use of a cross-referenced system with multiple microdroplets can become difficult.

To enhance the addressability of the afore-mentioned cross-referenced DMF structure, a new multiplexing format is proposed here. The DMF multiplexer system is based on two requirements: bi-polar voltage activation and threshold-based actuation. The bi-polar electrode activation creates a preferential (doubled) electric field in the intersection area of the activated electrodes, as the electric potential difference between the top and bottom electrodes is twice that of the other activated regions. Elsewhere, the magnitude of the electric potential differences between the top and bottom electrodes remains below that of the individual electrode voltages. This localized electric field can then be used together with a threshold-based actuation method to isolate a microdroplet motion in the desired region. The magnitude of the applied voltage is selected in a way that the overlapped region of the activated electrodes, with twice the applied voltage, will have an enough electric field to actuate the microdroplet. Ultimately, this configuration can overcome the afore-mentioned addressing challenges of conventional cross-referencing structures. The two requirements of the proposed DMF multiplexer system are studied experimentally and described in the following two sections.

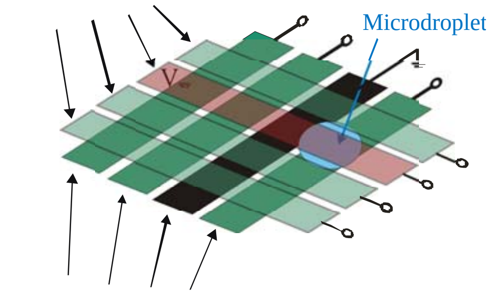


Figure 1. Schematic of a cross-referenced DMF structure.

THRESHOLD VOLTAGE PHENOMENON

Before applying voltage to an electrode under the microdroplet and hydrophobic layer in a closed DMF system, the water microdroplet is symmetric (i.e. all contact angles are approximately 114º). After applying a voltage, there exists a possibility for microdroplet asymmetry, deflection and motion.

As shown in Fig. 2, at voltages below the threshold voltage on the right electrode, the contact angle change of the microdroplet edge over the activated electrode is negligible. In this case, the electrowetting on a dielectric (EWOD) forces are smaller than the static friction forces between the microdroplet and the hydrophobic layer, so the microdroplet does not move towards the activated electrode.

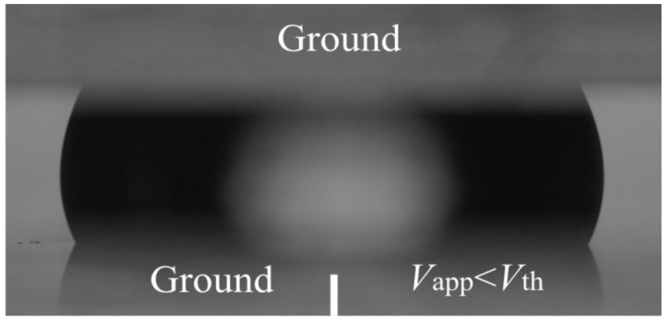


Figure 2. A cross-sectional image of a closed DMF system acquired by the high-resolution camera at a voltage below the threshold voltage is shown in this figure.

By increasing the applied voltage, the contact angle of the microdroplet can be made to decrease as the hydrophobic surface becomes hydrophilic. However, this does not occur until the applied voltage reaches the threshold voltage V_{th}. Fig. 3 shows this point. At the threshold voltage, the EWOD forces are large enough to overcome the friction forces between the microdroplet and the hydrophobic layer, and the microdroplet starts to move. The contact angle change of the microdroplet becomes noticeable at this point.

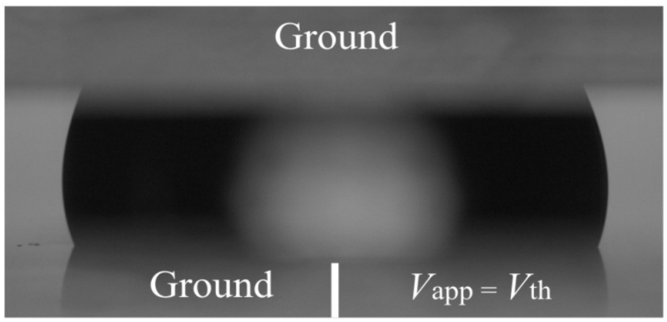


Figure 3. Cross-sectional image of a closed DMF system acquired by the high-resolution camera at the threshold voltage is shown in this figure. The contact angle change of the right bottom edge of the microdroplet is visible, and the microdroplet has started to move.

At voltages beyond the threshold voltage, the microdroplet moves faster, and the contact angle change is greater than the contact angle change at the threshold voltage. The change of contact angle for a voltage beyond the threshold voltage is shown in Fig. 4.

The complete characterization for the contact angle θ versus V_{app} relationship is presented in Fig. 5. The presence of a threshold condition in the experimental data at V_{th} = 160 V is readily apparent. This meets the first requirement for 2-D localization in the proposed DMF multiplexer. For voltages V_{app} in the range 160 V to 220 V, the contact angle θ changes from its nominal value θ_0, defined at V_{app} = 0, according to the Lippmann-Young equation [8, 9]:

$$\cos\theta = \cos\theta_0 + \frac{C}{2\gamma_{lv}} V_{app}{}^2 , \quad (1)$$

where C is the capacitance per unit area, and γ_{lv} is the liquid-vapor surface tension.

At voltages beyond 220 V, saturation effects begin to affect the contact angles, and the validity of the Lippmann-Young equation is reduced. The threshold voltage of V_{th} = 160 V seen here is a characteristic of the tested device geometry, which incorporates polydimethylsiloxane, PDMS, (Dow Corning corporation, Midland, MI) as both the hydrophobic and hydrophilic layers and a vertical plate separation of 250 μm. The threshold voltage can be reduced, as needed, by application-specific selection of dielectric and hydrophobic layer materials (Teflon AF and Parylene C) and reduced layer thicknesses.

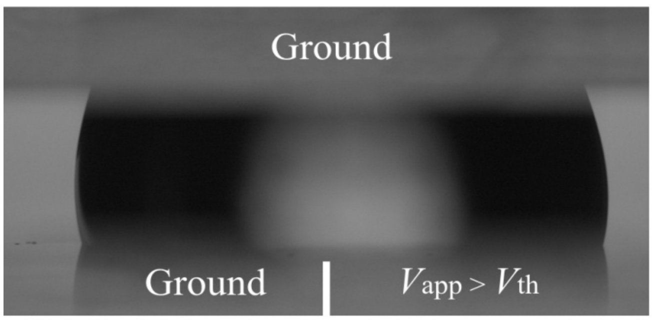


Figure 4. Contact angle change of the right bottom edge of the microdroplet at a voltage greater than the threshold voltage is shown in this figure.

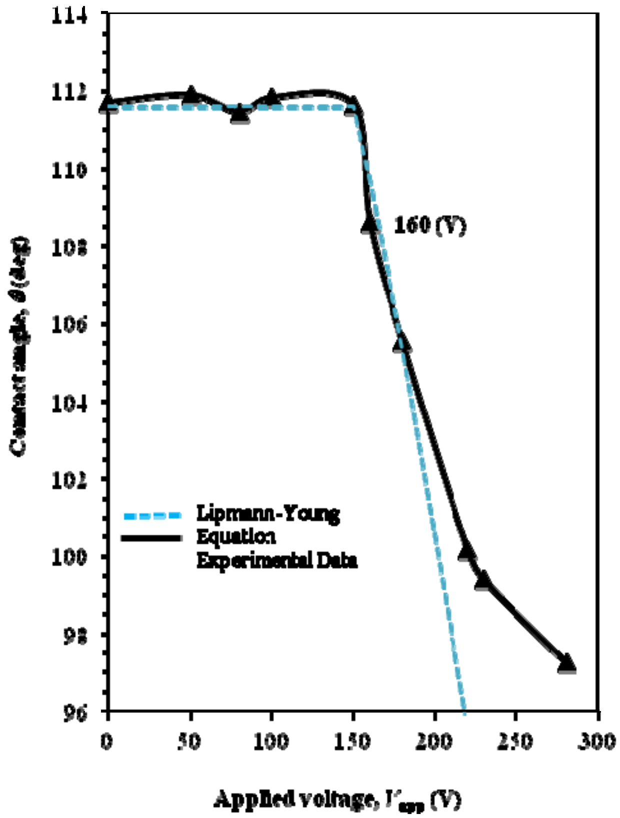


Figure 5. Experimental results of the contact angle change versus the applied voltage are shown for the closed DMF system.

BI-POLAR VOLTAGE ACTIVATION SCHEME

The fundamental operation of the proposed DMF multiplexer system makes use of a cross-referencing architecture and bi-polar voltage activation. This is shown in Fig. 6. This new form of bi-polar electrode activation can be used to accentuate threshold-voltage effects of the fluid motion. The DMF multiplexers are designed such that motion is induced only in regions where the overlying top electrodes (with $+V_{app}$) overlap the underlying bottom electrodes (with $-V_{app}$). A threshold condition is used to ensure that only the $2V_{app}$ voltage difference in this location can cause the microdroplet motion. Regions experiencing only $\pm V_{app}$ voltage differences will not overcome the threshold voltage condition and will not induce motion. This technique is, to our knowledge, the first of its kind and is expected to allow for $m \times n$ addressability with multiple microdroplets and only $m+n$ electrodes.

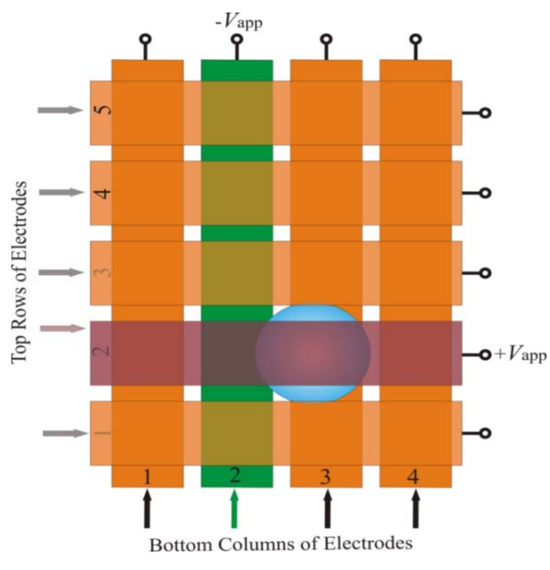


Figure 6. The top view of the DMF multiplexer system is shown for the proposed DMF multiplexer.

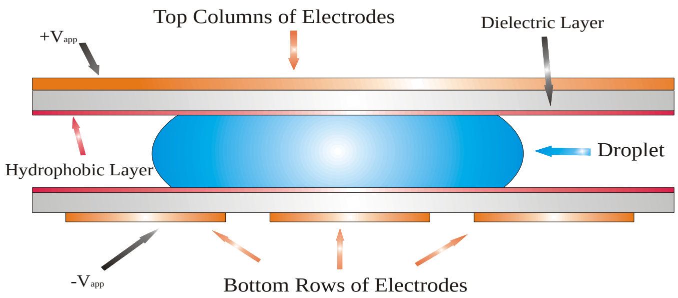


Figure 7. The cross-sectional view of the DMF multiplexer system is shown for the proposed DMF multiplexer.

EXPERIMENTAL RESULTS

To verify the proposed multiplexing format, a DMF multiplexer is fabricated and tested in UBC DMF laboratory. Pre-coated copper (45 nm thickness) microscope slides (EMF Corporation, Ithaca, NY) are used as substrates of the proposed DMF multiplexer system.

All masks for the DMF multiplexers designed in this research are fabricated onto microscope slide substrates with arrays of *X* and *Y* electrodes patterned onto separate slides. The masks are printed and subsequently patterned onto the substrates via UV lithography. PDMS is then spin-coated onto the patterned metal features, shown in Fig. 8, to act as the hydrophobic/dielectric layers. The *X* and *Y* electrode arrays are then overlapped orthogonally at a fixed 250 μm separation using spacers positioned along the outer edge of the device. The final assembled DMF multiplexer is shown in Figure 9. Voltages are applied to the *X* and *Y* electrodes, while microdroplet motion is recorded by a high-resolution camera.

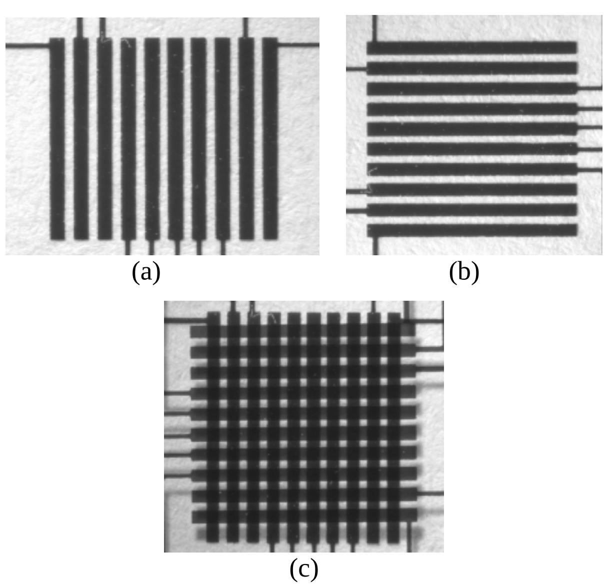


Figure 8. Fabricated *X* and *Y* electrodes are shown in this figure: (a) *X* electrodes, Number of electrodes = 10, electrode size = 1 mm, gap size = 250 µm, (b) *Y* electrodes, Number of electrodes = 10, electrode size = 1 mm, gap size = 250 µm, and (c) overlapped masks.

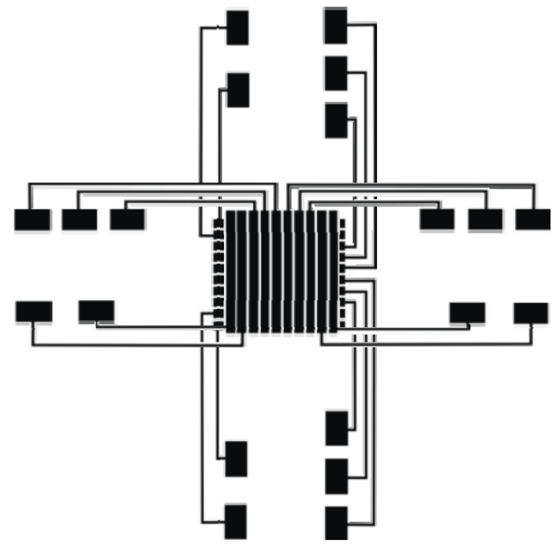


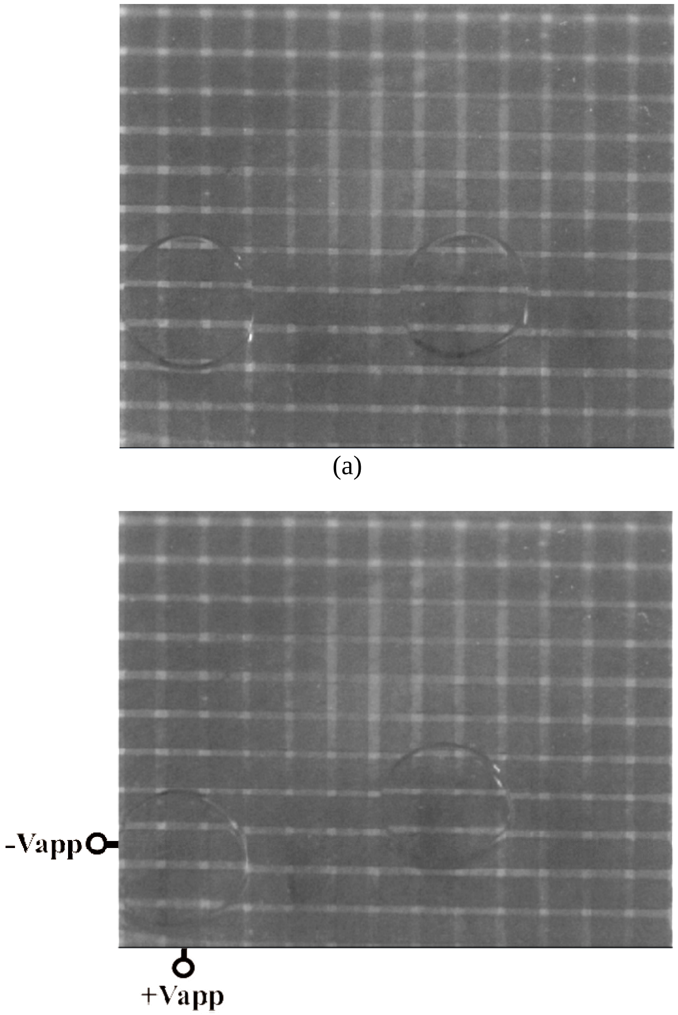
Figure 9. The final DMF multiplexer structure is shown.

Experimental results of the fabricated DMF multiplexer prototypes are shown in Fig. 10 (a, b). Fig. 10 (a) shows two microdroplets placed on the same electrode row. The desired motion in this experiment will be for downward motion of the left microdroplet. To do this, $+V_{app}$ is applied to the bottom column electrode, and $-V_{app}$ is applied to the top row electrode. These activated electrodes are identified in Fig. 10 (b). Fig. 10 (b) also shows the resulting microdroplet motion for the left microdroplet, which experiences a $2V_{app}$ electric potential. The left microdroplet, and only the left microdroplet, undergoes this motion, as the threshold-based localization is able to address this left microdroplet. The voltage applied to the right microdroplet does not overcome the motion threshold and, as desired, it remains stationary.

CONCLUSION

In this research, independent motion of microdroplets in a cross-referenced DMF structure was achieved for systems incorporating multiple microdroplets. To accomplish this motion, a multiplexing format was implemented into the conventional cross-referenced architecture to satisfy threshold-based voltage actuation and bi-polar voltage activation. These two requirements were studied experimentally.

The device met the two requirements for enhanced $m \times n$ addressability in a 2-D grid, and results were shown experimentally. Successful actuation, without disturbing neighboring microdroplets, was demonstrated through this threshold-voltage-based system. Such a technique can be applied in the actuation of isolated microdroplets or microdroplet groups (simultaneously) in large-scale and highly-parallel DMF devices.



(a)

(b)

Figure 10. Experimental results of the DMF multiplexer system are shown in this figure: (a) Two equal 0.5 µL microdroplets are dispensed between the top and bottom electrode plates; (b) the left microdroplet moves to the bottom cell, while the right microdroplet is stationary.

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