3-D IMAGING OF MOVING DROPLETS FOR MICROFLUIDICS USING OPTICAL COHERENCE TOMOGRAPHY

Vijay Srinivasan[1], Vamsee Pamula[1], K. Divakar Rao[2], Michael Pollack[1], Joseph A. Izatt[2] and Richard Fair[1]

[1] Dept. of Electrical Engineering, [2] Dept. of Biomedical Engineering, Duke University, Durham, USA

ABSTRACT

We present the use of optical coherence tomography (OCT), an interferometric 3-D imaging technique, to visualize microdroplets in an electrowetting-based microfluidic device. Vertical cross-sectional images of stationary and moving microdroplets are obtained using this technique, to provide information on static and dynamic contact angle changes and flow profiles inside the microdroplet during transport. The initial results are encouraging and OCT appears to be a promising method to study fundamental, yet poorly understood electrowetting phenomena such as contact angle saturation and contact angle hysteresis. OCT can also be used in visualizing 3-D flow profiles in droplet-based microfluidics.

1. INTRODUCTION

There has been considerable interest lately in electrowetting-based microfluidic systems. Electrowetting refers to the electrical modulation of the interfacial tension between a conducting liquid phase and a solid electrode [1]. Though there have been considerable advances from a technology perspective, the science behind electrowetting is not understood completely, and several fundamental questions still remain unanswered [2], partially owing to the lack of good visualization tools.

Current visualization techniques in an electrowetting system have been limited to observation of the top and side views of droplets using CCD microscope cameras, with varying degrees of sophistication in automation and optics [3][4]. This technique, though sufficient for observation from the top, can pose severe constraints on materials and system design for imaging from the side. Another drawback is that these techniques do not provide 3-D tomographical information.

Optical coherence tomography (OCT) is an emerging real-time, *in-situ*, and non-invasive imaging technique based on low-coherence interferometry, with micrometer resolution [5]. Though most of its applications have been for cross-sectional tissue imaging in biological systems, OCT has recently been used to image flow patterns in a continuous flow microfluidic device [6]. In this paper we present the use of OCT to image microdroplets in an electrowetting-based microfluidic system. Unlike the CCD microscope-based methods, OCT obtains tomographical images by non-invasively scanning the droplet from above, circumventing the design constraints mentioned before.

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2. EXPERIMENTAL SETUP

Electrowetting Actuator - The electrowetting system consists of two parallel electrode plates - a continuous ground plate and an addressable electrode array. The droplet is sandwiched between the two plates, and is surrounded by immiscible 1cSt silicone oil. The electrode array is insulated from the liquid and both surfaces are hydrophobized. The spacing between the electrode array and the ground plane is 520μm in all experiments described in this paper. The fabrication details of the electrowetting chip can be found in [1]. The liquids used in the OCT experiments are required to scatter light; therefore droplets of skim milk or an aqueous solution of 1μm polystyrene beads are used.

Optical Coherence Tomography Imaging - The details of the OCT setup are described in detail in [5]. The high speed OCT system used in this study has an axial and lateral resolution of ~20μm. The axial scan range (vertical field-of-view) is set to 1.5mm, and the lateral scan range (horizontal field-of-view) is set to 1mm for the static experiments and to 2mm for the dynamic experiments. All images and videos are captured at the center of the droplet though in practice any cross-section of the droplet can be visualized. Video images are captured at a rate of 8 frames per second.

3. RESULTS AND DISCUSSION

Static Contact Angle - OCT is used to visualize the change in "apparent" contact angle of a 400nL polybead droplet with the bottom plate at different voltages. We use the term apparent contact angle since a thin oil film can exist underneath the droplet under certain conditions, resulting in a two-phase system for which contact angles are not defined. Figure 1 shows images of the droplet at various voltages. The contact angle increases with applied voltage and saturates beyond a certain voltage, as seen in the images. Saturation of contact angles at higher voltages is a very important contact angle phenomenon of interest in the fundamental study of electrowetting. Using OCT, this phenomenon can be visualized very clearly under different conditions.

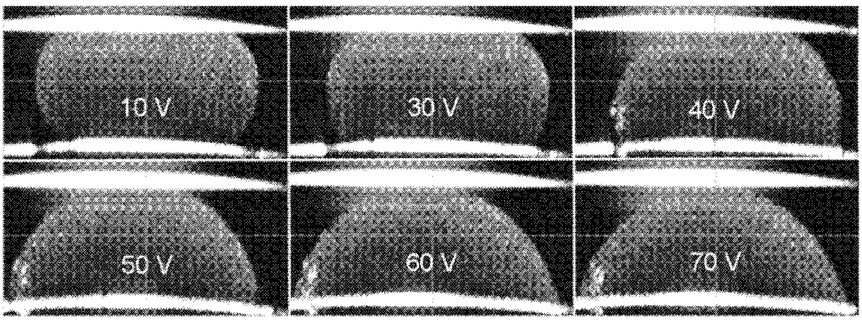

Figure 1 – Change in static contact angle as a function of voltage

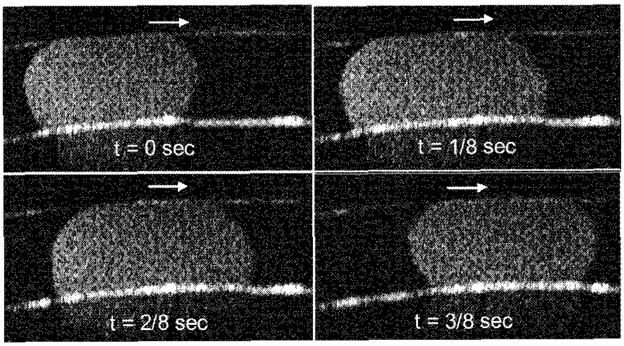

Figure 2 - OCT cross-section image of a moving droplet

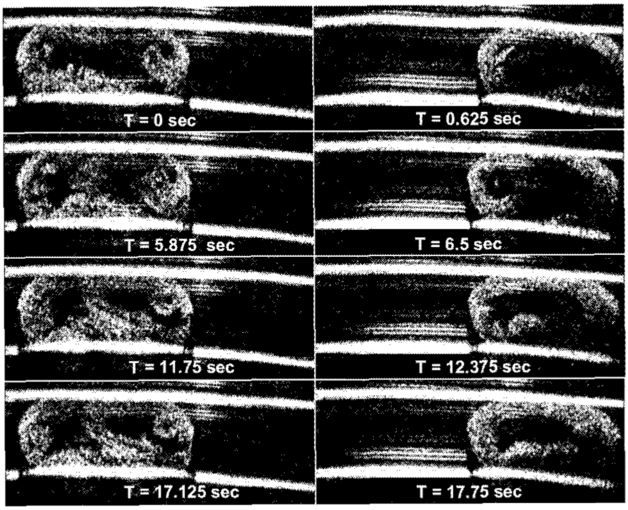

Figure 3 - Flows patterns inside a moving droplet

Dynamic Contact Angle - Dynamic contact angle changes are visualized using OCT while the droplet is in motion. Figure 2 shows snapshots of a 500nL skim milk droplet as it moves across two 1mm electrodes. The arrow indicates the direction of droplet motion. The dynamic contact angle information can be used to study the effect of contact angle hysteresis on the droplet transport.

Flow Patterns during Transport - Flow profiles inside the droplet can be obtained by imaging a moving droplet loaded with beads. A 500nL KCl droplet (0.1M) is loaded with a small volume (<50nL) of the polybeads. The droplet is then shuttled across two 1mm electrodes. Figure 3 shows snapshots of the droplet as it moves across the two electrodes. Complete flow reversibility is evident from the images, corroborating the observations in [3].

Comparing the results from the static and dynamic experiments, we can see that that the non-linearities at the edges of the image are more pronounced while using a 2mm lateral scan. The lateral scan should be limited to 1mm to obtain good linearity, which means that smaller electrodes need to be used.

Quantitative Contact Angle Data - The most accurate method of determining the contact angle from the OCT images is by fitting the outline of the droplet to the Laplace-Young equation; $\Delta P = \gamma (1/R_1 + 1/R_2)$, where ΔP is the pressure difference across the drop-let–oil interface, γ is the surface tension, and R_1 and R_2 are the principal radii of curvature of the droplet-oil interface. This is because the contact angle measured from the OCT images is very sensitive to the location of the (apparent) 3-phase contact point, which is difficult to determine accurately. The images also need to be compensated to account for changes in effective path length that arise due to differences in refractive indices between the droplet and the oil. Therefore, significant post-processing of these images is required to obtain useful quantitative data.

4. CONCLUSIONS AND FUTURE WORK

We have demonstrated the use of OCT to image microdroplets in an electrowetting-based microfluidic system. OCT was used to obtain static and dynamic contact angle information, which is of use in studying important electrowetting phenomena such as contact angle hysteresis and saturation. Flow profiles were visualized inside a droplet with beads. The flow visualization can be further extended to study droplet mixing. The initial results yielded qualitative information on the utility of OCT to image droplets. Further analysis is needed to obtain quantitative results.

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