AN INTEGRATED PLATFORM FOR LIGHT-INDUCED DIELECTROPHORESIS AND ELECTROWETTING

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ABSTRACT

We demonstrate a technique that seamlessly integrates both light-induced dielectrophoresis and electrowetting on the same chip. This allows for the parallel manipulation of not only individual droplets, but for particles within the droplet as well. The device requires no photolithography and dielectrophoresis/electrowetting functionality is selected through a simple change of device bias. 12.5 nL droplet and 10 μm polystyrene bead speeds of 0.8 cm/s (40 Vppk, 10 kHz) and 60 μm/s (10 Vppk, 200 kHz) are demonstrated. Additionally, by applying this technique to concentrate a sample within an individual droplet and subsequently split the droplet, consistent sample concentration enhancements of 3-4x are achieved.

KEYWORDS: electrowetting, dielectrophoresis, optoelectronic tweezers, digital microfluidics, EWOD

INTRODUCTION

Digital microfluidics (DM) has received much attention over the past decade for its promise to improve both cost and performance of many fields ranging from pharmaceutical development to biodefense. Traditional DM devices use electrically-addressable arrays of electrodes to transport droplets [1]. Recently, we have reported the use of a technology, Light Actuated Digital Microfluidics (LADM), which replaces the lithographically defined electrodes with a continuous film of photoconductor [2]. By translating optical patterns over the surface of the device, ‘virtual’ electrodes are created which enable droplet manipulation. With this methodology, real-time, parallel droplet control can occur without the need for complex addressing schemes. While DM (and LADM) provides the ability to manipulate individual droplets, it does not provide a means to manipulate objects within the droplet itself. This ability would be useful for applications including selective sample concentration and sorting. While our group has demonstrated the integration of traditional DM with a light-induced dielectrophoresis (DEP) manipulation technique, the device fabrication and operation is quite complicated [3]. Here we present the ability to use the LADM device to perform the light-induced manipulation of both individual droplets and particles within the droplet, in parallel, by simply changing the device bias.

THEORY

Traditional DM devices operate by selectively applying voltages to microelectrodes which are encapsulated by a dielectric layer. If one edge of an electrically grounded aqueous droplet is located over the activated electrode, the droplet will experience a net electromechanical force which enables droplet movement (often referred to as electrowetting (EW)). In LADM, we eliminate the need for individually addressable microelectrodes by using optical energy interacting with a photoconductive film to create ‘virtual’ electrodes. Specifically, incident light patterns cause the conductivity of the illuminated photoconductive film (e.g. a-Si:H) to increase by orders of magnitude. Below a critical electrical frequency, this causes aqueous droplets in the vicinity to move towards the light pattern. Particles within the droplet are transported along with the droplet. In this modality, the electrically insulating Al2O3 and Teflon layers are shorted out and field is now concentrated in the liquid/droplet layer. Therefore, particles within the droplet experience a DEP force when in the vicinity of incident optical energy. In this regime, the LADM device electrically looks identical to Optoelectronic Tweezers.
Figure 2: Frequency response. (a) Theoretical frequency response of the normalized electrowetting force (blue) acting on a droplet and the DEP force (red) acting on an insulating bead within the droplet. EW force is maximized at around 10 kHz and DEP actuation is maximized at around 200 kHz. (b) Experimental data showing speed (which is proportional to force) of a 12.5 nL droplet (blue, 40 Vppk) and speed of a 10 μm polystyrene bead (red, 10 Vppk). The droplet movement is maximized at 10 kHz due to electrowetting, though a secondary hump is present at 200 kHz due to DEP enhancement of droplet movement. Bead speed is maximized at 200 kHz due to DEP. Results agree well with theory.

However, for frequencies above a critical frequency, the insulating layers act as electrical short circuits and the bias now drops primarily across the liquid/droplet layer. Due to the spatial localization of the light pattern, electric field gradients are created near the edges of the light pattern. This results in a dielectrophoretic (DEP) force on particles within the droplet (Fig. 1(b)). At these frequencies, the device looks electrically identical to our previously reported Optoelectronic Tweezers device [4]. So, by operating in this regime, particles within the droplet can be manipulated by simply altering the location of the incident optical patterns. It should be noted that there will also be a DEP force on the droplet itself. However, this force is typically much weaker than the electrowetting force experienced at lower frequencies.

The critical frequency at which one is able to transition from droplet manipulation to the manipulation of particles within the droplet is governed by the dimensions of the device itself (namely the impedances of the liquid, photoconductor, and dielectric). In the case of the device presented here, that frequency is around 100 kHz as indicated by Fig. 2a. In this figure, the normalized electrowetting and DEP forces are calculated for typical device, droplet, and particle dimensions. One can see that the electrowetting effect peaks around 10 kHz whereas DEP peaks at around 100 kHz, indicating two distinct operating regimes. Therefore, by switching above and below this critical frequency either droplet or particle manipulation can occur.

EXPERIMENTAL

The LADM device is depicted in Fig. 1a. The device consists of an indium-tin-oxide (ITO) (300 nm) coated glass substrate, a 1 μm thick photoconductive a-Si:H layer deposited via PECVD (Oxford Plasmalab 80plus), a 100 nm film of Al₂O₃ deposited by ALD (Picosun Sunale R150) and a 25 nm film of spin coated 0.2% Teflon (3000 rpm, 30 s). The top substrate is formed from another Teflon-coated ITO glass wafer. The entire fabrication process does not require any photolithographic steps. The two substrates are then placed on top of one another separated by a spacer layer of double-sided tape (100-300 μm) forming the microfluidic manipulation chamber. Device bias is applied between the two ITO layers (10-40 Vppk, 1-500 kHz).

Optical patterns are generated by a commercial data projector (Dell 4210X) controlled by an external computer and focused onto the LADM device using a 1:1 telescope. Viewing occurs through a 5x objective connected to a CCD camera (Sony XCD-X710CR). Speed measurements for the polystyrene beads are extracted using a motorized stage controller (Newport ESP300).

Samples are prepared by suspending 10 μm polystyrene beads (Polysciences Inc.) in a 10 mS/m aqueous solution along with 0.2% Pluronic F-68 surfactant (Sigma Aldrich). Droplets of the polystyrene mixture are then deposited in the LADM device and surrounded by a silicone oil (1.0 cSt Trimethylsiloxy-terminated Polydimethylsiloxane, Gelest Inc).

RESULTS AND DISCUSSION

While Fig. 2a shows the theoretical frequency response of both the EW and DEP modalities, Fig. 2b shows the corresponding experimental frequency response. The agreement is quite good between the two with EW dominating at 10 kHz and DEP at 200 kHz. An interesting aspect of Fig. 2b is the secondary peak seen in the EW response at higher frequencies. The peak occurs at the same frequency as the DEP peak (200 kHz) indicating a DEP enhancement (in addition to electrowetting) of droplet movement. This indicates that both electrowetting and DEP are simultaneously occurring to enact droplet movement. Therefore, when manipulating particles with DEP within the droplet care must be taken not to move the droplet itself. This is easily achieved by operating at low actuation voltages and using light patterns which are small relative to the overall size of the droplet.

The utility of this seamless transition between EW and DEP is well suited for on-demand sample concentration. In order to demonstrate this, a 300 nL, 10 mS/m droplet containing 10 μm polystyrene beads is placed in the LADM device. Using the DEP modality, the beads are concentrated at one end of the droplet. Then, using the EW modality, the droplet is split into two 150 nL droplets with a higher concentration of beads than the other. This process is depicted in
Fig. 3. The process is easily repeated to achieve serial dilution/enhancement until a minimum droplet volume is achieved in which further droplet splitting is no longer achievable (i.e. when the droplet diameter approaches the chamber height). During the splitting process, fluidic flows within the droplet are generated which will tend to move a fraction of the concentrated beads to the diluted side. Additionally, beads which come in contact with the oil/water interface are difficult to move with DEP and are often left behind during DEP concentration. As a result, a small number of beads are left in the diluted droplet. Despite these issues, a concentration enhancement of 3-4x is consistently achieved (number of beads in concentrated droplet divided by number of beads in diluted droplet) and is in agreement with prior work [5]. This enhancement can likely be improved by optimizing the location of the concentrated beads within the droplet in order to minimize bead relocation during droplet splitting (e.g. away from the edges of the droplet where strong internal fluidic flows are generated during droplet splitting).

CONCLUSION

We have presented a technique that seamlessly integrates the parallel manipulation of both droplets and the particles within those droplets using light-induced dielectrophoresis and electrowetting. The manipulation modality is switched by altering the frequency of the applied electrical bias. The operation frequencies are governed by the device structure. Concentration enhancements of 3-4x of suspended polystyrene beads are demonstrated. This technology provides a platform for the massively parallel manipulation of individual droplets and particles for use in applications ranging from biological assays to on-chip chemistry.

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