

Particle Transportation using Programmable Electrode Arrays

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Abstract — This study presents a technique to manipulate particles in microchannels using arrays of individually excitable electrodes. These electrodes were energized sequentially to form a non-uniform electric field that moved along the microchannel. The non-uniform electric field caused dielectrophoresis to make polarized particles move. This technique was demonstrated using viable yeast cells in a suspending medium with different conductivities. The viable yeast cells experienced positive dielectrophoresis and negative dielectrophoresis in medium conductivity of 21.5 $\mu\text{S}/\text{cm}$ and 966 $\mu\text{S}/\text{cm}$ respectively. The experimental results indicate that the cells can be transported in either condition using the proposed technique.

Index Terms — dielectrophoresis, particle manipulations, moving electric field.

I. INTRODUCTION

The processing of bio-particles in microdevices generally involves moving these particles around the microchannel for different stages of operations. For example, a microfluidic device for malaria detection requires that cells be transported across isolation, lysis, and

PCR modules [1]. Typically, particle transportation is achieved using fluid flow, where the moving fluid carries the particles along. There have been substantial efforts devoted to design miniaturized pumps, in an effort to replace the external syringe pumps. These micropumps utilize various techniques. For instance, chemical reaction can be used to generate gas to propel the liquid [2]. Some other techniques use electrically induced fluid flow like electroosmosis, AC electroosmosis [3-5], and electrowetting [6]. Mechanical techniques have also been reported, such as the optical tweezer driven counter-rotating particles pump [7], mechanical disc pump [8], and gravitational gradient fluid flow [9].

In contrast, dielectrophoresis [10] has been used to transport particles without the need of flowing fluid. It is based on the concept that a non-uniform electric field induces a dipole on the particle, which in turn interacts with the applied electric field to make the particle move towards or away from the high electric field gradient regions depending on the induced dipole properties [11]. Traveling wave dielectrophoresis is one of the dielectrophoretic methods reported to move and separate cells [12]. Cells transportation has also been demonstrated using a variant of the traveling wave dielectrophoresis utilizing electric field cages [13]. The programmable electrode arrays could be employed to form electric field cages to move the particles. For instance, matrix-based electrodes have been built on CMOS chip to position cells [14]. Elongated electrode arrays have been used to move particles in cage-speed technique [15].

In this investigation, moving dielectrophoresis (mDEP) is proposed and implemented as an alternative method to transport particles. This method works on a programmable electrode array, where individual electrodes are energized sequentially to generate an electric field that move along the microchannel. The particle is carried along with the moving electric field due to the dielectrophoretic force. Viable yeast cells were used to demonstrate the technique.

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II. MATERIALS AND METHODS

A. Microelectrodes fabrication

Microelectrodes were fabricated on glass wafers (Pyrex 7740) using a lift-off process, see Fig. 1. First, the glass wafers were cleaned and blown dry. Subsequently, a thin film of chromium was sputtered onto the glass wafers. A layer of photoresist (AZ 7220, Clariant) was spin coated onto the glass wafers. After soft baking, the photoresist was exposed and developed using AZ developer solution. After chromium and gold were sputtered onto the prepared glass, the lift-off process was performed by soaking the glass wafers in acetone and ultrasonic bathed for approximately 30 min until the electrodes were fully developed. The glass wafers were again cleaned and blown dry. The electrodes were measured using a surface profiler (P-10, KLA Tencor) and they had an average thickness of 330 Å. The glass wafers were diced to produce individual microelectrodes chips.

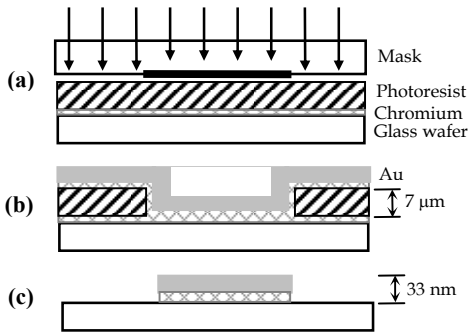


Fig. 1 Lift-off process to fabricate microelectrodes.

The microelectrodes chip was assembled, with a piece of ITO glass forming the other continuous electrode. A 25 μm thick acrylic polymer (ARclear™ 8154, Adhesives Research) was employed as a spacer between the ITO and micro-electrodes, with a micro-cavity (which acted as microchannel) laser machining onto the spacer. There were two $\varnothing 1$ mm holes on the ITO glass to act as fluid inlet and outlet.

B. Experimental setup

The microfluidic chip was assembled to a printed circuit board (PCB), and wire bonded. The PCB was connected to edge connectors, which were in turn connected to series of relays (HE3621A0510, Breed Electronics) through IDC ribbon cables. The power lines of the relays were electrically connected to a function generator (33250A, Agilent). The control lines of the relays were electrically connected to a digital I/O card (PCI-6509, National Instruments) installed on the PCI slot of a personal computer. The switching of the relays was controlled by a program written in LabView (National Instruments). The program generated sequential TTL signal to trigger the

switching of relays, which resulted in the generation of a moving electric field on the microelectrodes. The whole switching process was automatically repeated at the end of the cycle. A commercial video tape recorder was used to record real time images. The experimental setup is illustrated in Fig. 2.

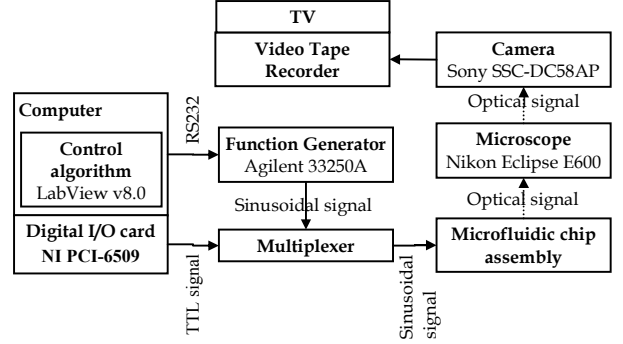


Fig. 2 Experimental setup and information flow.

Viable yeast cells, *Saccharomyces cerevisiae*, were suspended in 250 mM mannitol in two different medium conductivities of 21.5 $\mu\text{S}/\text{cm}$ and 966 $\mu\text{S}/\text{cm}$, respectively. The mannitol solutions with the desired conductivities were prepared by adding sodium chloride before the introduction of the yeast cell.

III. RESULTS AND DISCUSSIONS

A. Transportation under positive dielectrophoresis

At an applied electrical frequency of 100 kHz, the viable yeast cells suspended in medium conductivity of 21.5 $\mu\text{S}/\text{cm}$ were observed to be attracted to the electrode edges. As shown in Fig. 3, when the electrodes were sequentially energized, the viable yeast cells were observed to follow the energized electrode, moving from one electrode to another. The inter-electrode activation time was 2 s. The applied electrical voltage was 10 V_{pp} .

The cells were observed to move with a lower velocity initially. Their velocity increased as they were attracted by the electrode and approached the energized electrode. The cells stopped at the energized electrodes at each step. Thus, the cells were observed to be aligned along the energized electrodes in the images shown in Fig. 3.

Using the two-shell sphere model [16] to represent the yeast cells, the polarization factor f_{cm} for yeast cells suspended in a medium conductivity of 21.5 $\mu\text{S}/\text{cm}$ was estimated to be ~ 0.14 at 100 kHz. The polarization factor was calculated using values from literature [12, 16]. Therefore, the viable yeast cells experienced a positive dielectrophoresis at an applied electrical frequency of 100 kHz. This analytical prediction is consistent with the experimental results, where viable yeast cells experiencing positive dielectrophoresis were attracted to the electrode edge.

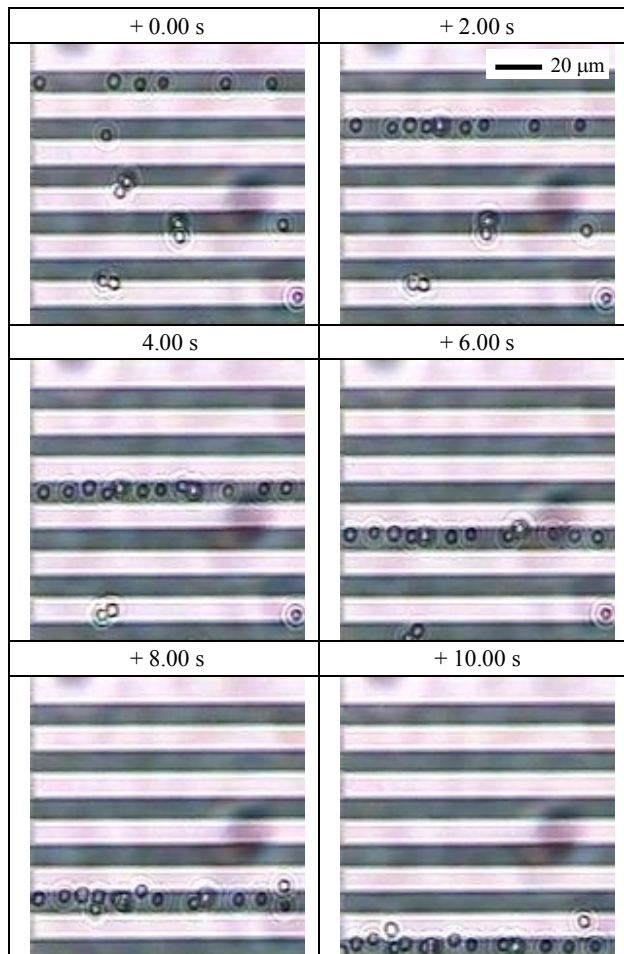


Fig. 3 Experimental results showing viable yeast cells experiencing positive dielectrophoresis transported using a moving electric field. The viable yeast cells were suspended in 250 mM mannitol with medium conductivity of 21.5 $\mu\text{S}/\text{cm}$, applied electrical voltage of 10 Vpp, frequency of 100 kHz, and inter-electrode switching time of 2 s. This mode of transportation was characterized by cells attracted to the energized electrodes. The cells were seen to align to the electrodes.

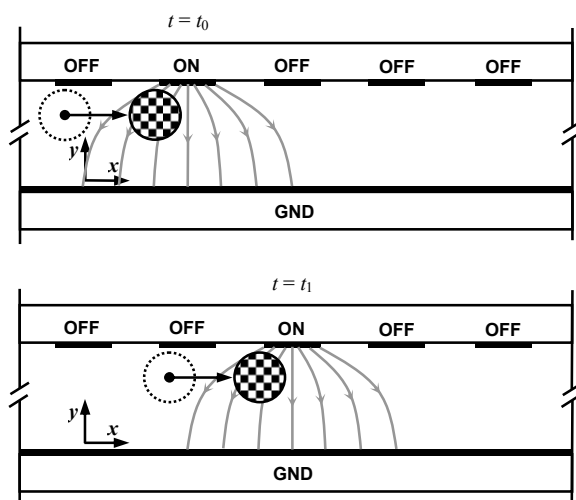


Fig. 4 Illustration of particle transportation using positive dielectrophoresis. A particle is attracted to the energized electrode edge on each successive step. The particle moves by trailing the electric field.

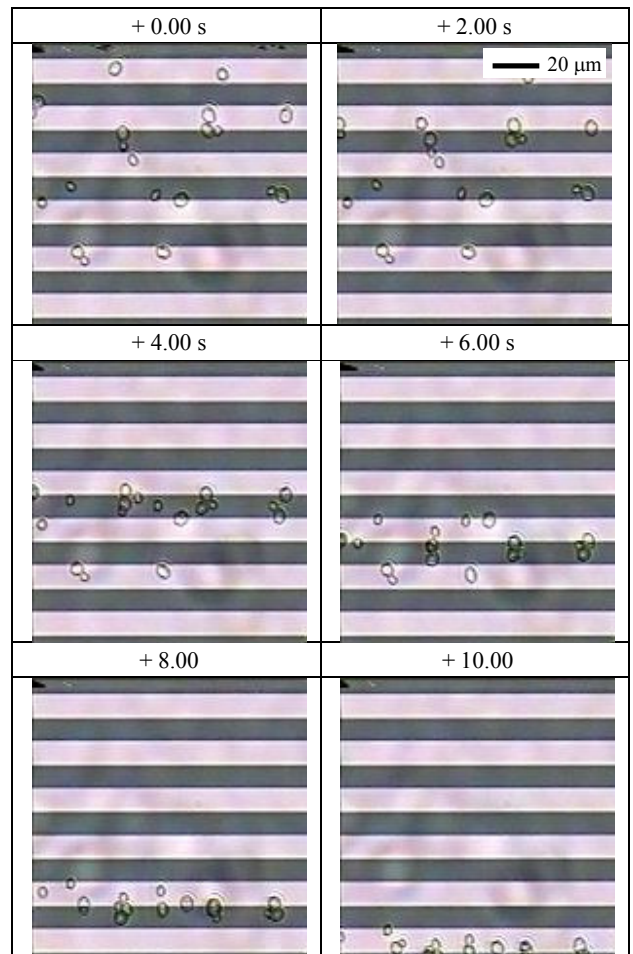


Fig. 5 Viable yeast cells experiencing negative dielectrophoresis were transported. The viable yeast cells were suspended in 250 mM mannitol with medium conductivity of 966 $\mu\text{S}/\text{cm}$. The applied electrical voltage was 10 Vpp and electrical frequency was 100 kHz. The inter-electrode switching time was two seconds. The cells did not align as in the case of positive dielectrophoresis.

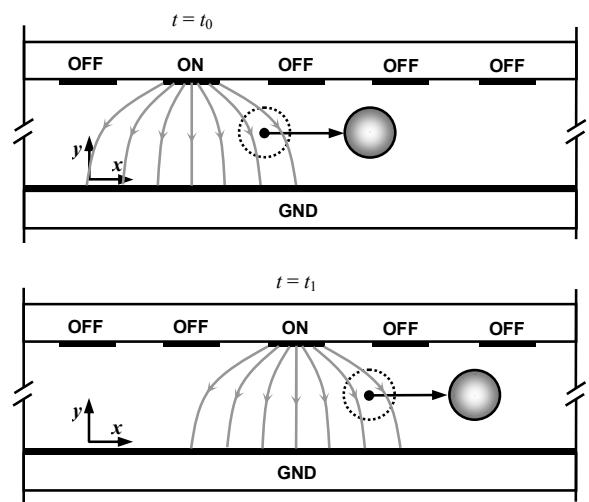


Fig. 6 Illustration of particle transportation using negative dielectrophoresis. The particle is repelled from the energized electrode edge on each successive step. The particle moves by leading the electric field.

Fig. 4 illustrates the transportation of a particle experiencing positive dielectrophoresis. The particle attracted to the energized electrode would continue to follow the moving electric field when one electrode is turned off, but with its neighboring electrode turns on. By sequentially switching on the subsequent electrodes, the particle experiencing positive dielectrophoresis would be transported along the microchannel. This mode of transportation is characterized by the particle trailing the electric field.

B. Transportation under negative dielectrophoresis

At 100 kHz, the viable yeast cells suspended in medium conductivity of 966 $\mu\text{S}/\text{cm}$ were observed to be repelled from the electrode edges. When the electrodes were sequentially energized, the viable yeast cells moved in front of the energized electrode. The images of viable yeast cells transported under the moving electric field are shown in Fig. 5. A two-second inter-electrode activation time was used. Thus, the cells were observed to move to the next electrode at every 2 s interval in the images.

The cells were observed to move gradually along the microchannel. Since the cells were repelled from the electrode edge, they did not line up on the electrode edge as in the case of the positive dielectrophoresis. Therefore, it is not straightforward to identify the energized electrode in the case of negative dielectrophoresis.

In a medium of conductivity 966 $\mu\text{S}/\text{cm}$ and electrical frequency of 100 kHz, the viable yeast cells were predicted to experience a negative dielectrophoresis. Using the two-shell sphere model [12, 16], the polarization factor was estimated to be -0.48. The experimental results shown in Fig. 5 supported this prediction, since the viable yeast cells were observed to repel from the electrode edge.

As illustrated in Fig. 6, a particle experiencing negative dielectrophoresis would be repelled from the energized electrode. The particle would continue to lead the electric field when the electric field moves to another electrode. Cells under negative dielectrophoresis would be transported by leading the moving electric field. The cells are expected to move with a higher initial velocity, but with the velocity decreases away from the energized electrode. These phenomena are due to the fact that the dielectrophoretic force acting on the cells is larger at the electrode edge region.

IV. CONCLUSION

A particle transportation method using programmable electrode arrays was presented. The device generated a moving electric field to move the particle along the microchannel. A particle under positive dielectrophoresis was transported by trailing the moving electric field, whereas a particle under negative dielectrophoresis was transported by leading the moving electric field.

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