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A microfluidics device for 3D switching of microparticles using dielectrophoresis

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ABSTRACT

Here we describe the design, modeling, fabrication, and successful utilization of a microfluidic switching device that employs dielectrophoresis to effectively manipulate micro-scale entities in a microchannel. Two sets of opposing interdigitated transducer electrodes are micropatterned at the bottom of the device. The electrodes enter slightly from each side-wall into the channel. Finite Element Analysis and experimental results demonstrate that this design enables 3D switching of micro-objects at any location in the microchannel. Living cells are switched to one of the three downstream branches by varying the actuation voltages on the electrodes.

1. Introduction

The advancements in microfluidics offer exciting opportunities in developing miniaturized lab-on-a-chip platforms capable of performing a multitude of parallel in-vitro analyses at considerably high throughput rates [1,2]. These miniaturized sensors – employing low Reynolds number flows - have proven to be beneficial in application areas such as biotechnology [3], environment monitoring [4,5], food processing [5], medicine, and diagnostics [6]. The success of these platforms and their inclusion in the respective markets rely on their accuracy, swiftness, cost-effectiveness, and their ability to operate with great autonomy and repeatability [7]. While significant progress has been witnessed in the emergence of novel analysis techniques, there still remains a gap in automating and integrating multiple operational steps on a single platform during the analysis. For example, the sample preparation/processing steps still require a skilled operator's involvement and are mostly performed off-device in the laboratory, thus negating the full potential of these point-of-care devices. Microfluidic switching is a technique that can greatly help in the development of a high-throughput and integrated point-of-care device capable of performing multiple operations in parallel. Switching refers to the path diversion of micro-objects towards a desired downstream branch of a microchannel [8]. It accomplishes a continuous and effective steering of precise amounts of sample volume towards the regions of interest. Furthermore, switching can be easily integrated with other microfluidic operations like Polymerase Chain Reaction (PCR) and flow Cytometry.

A variety of techniques–e.g., surface acoustic waves (SAW), Hydrophoresis, Magneto-hydrodynamics (MHD), and Dielectrophoresis (DEP)–have been introduced to perform switching of micro-objects in a microfluidic platform [8–10]. Among these techniques, DEP is a label-free method that has attracted considerable attention over the past few years because of its simplicity, accuracy, selectivity, and sensitivity. DEP refers to the migration of neutral (but polarizable) micro-entities, suspended in a conductive medium, in the presence of an inhomogeneous electrical field [11]. The micro-entities have the tendency to either translate towards the maxima or towards the minima of the gradient of that inhomogeneous electric field [12–14]. The phenomena are termed 'positive-DEP (pDEP)' and 'negative-DEP (nDEP)' respectively. Mathematically, the time-averaged magnitude of the DEP force on a spherical object having radius 'r' in the non-uniform electric field with $\boldsymbol{E}_{rms}$ as its root-mean-squared value as:

$$\boldsymbol{F}_{DEP} = 2\pi\varepsilon_m r_o^3 Re[f_{CM}]\nabla|\boldsymbol{E}_{rms}|^2 \quad (1)$$

where ε_m is the medium permittivity. The term $Re[f_{CM}]$ represents the real component of the Clausius-Mossotti (CM) factor and is given by equation

$$f_{CM} = \frac{\varepsilon_o^* - \varepsilon_m^*}{\varepsilon_o^* + 2\varepsilon_m^*} \quad (2)$$

The complex permittivity for the micro-object/medium is defined as:

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$$\varepsilon^*_{o/m} = \varepsilon_{o/m} + \frac{\sigma_{o/m}}{\omega} j \tag{3}$$

The complex permittivity of micro-object/medium ($\varepsilon^*_{o/m}$) depends on the permittivity value of the object/medium ($\varepsilon_{o/m}$), their conductivities ($\sigma_{o/m}$), and the angular frequency ($\omega = 2\pi f$) where f is the operating frequency.

DEP has been a popular choice among researchers for successful manipulation of the target objects (cells, beads, DNA, proteins etc.). A variety of DEP devices accomplishing the same purpose have been introduced. A microfluidic device [15] employing nDEP in a microchannel sandwiched between two glass wafers successfully focused, trapped, and switched latex particles and living mammalian cells to one of the two outlets. Platinum/titanium and indium tin oxide (ITO) electrodes were deposited respectively on each glass wafer. The focusing and switching of polystyrene beads was also demonstrated in a DEP-based three-layered microfluidic device [16]. A polyimide microchannel was sandwiched between two glass layers, each containing planar electrodes. The electrode pairs at the junction of two downstream branches were utilized for effective switching of the focused stream of polystyrene beads to either of the outlet. An array of three-dimensional vertical electrodes has been made on sidewalls to successfully perform switching of cells and beads [17]. Selective manipulation of the actuation voltage subjected the micro-objects (cells and beads) to unequal nDEP forces from opposing sides resulting in their path diversion towards the desired branch. Metal inkjet printing was also used to fabricate DEP-based device for switching of Polystyrene beads [18]. Gold (Au) electrodes were deposited on the bottom of the channel and 3D silver (Ag) electrodes were fabricated on top of the Au electrodes using metal inkjet printing. The efficacy of the device was demonstrated by trapping 4 μm Polystyrene beads on the electrodes by applying 20 Vp-p AC signal at 500 kHz. Recently, a micro-device employing planar electrode on the top face and interdigitated electrode sets at the bottom of the microchannel was introduced [19]. The configuration generated both pDEP and nDEP forces by creating non-uniform AC electric field in the complete volume of the microchannel. The device performed successful separation of viable and nonviable human epithermal breast (MCF10A) cells. The viable cells, under the influence of nDEP, traversed towards the middle of the channel while the non-viable cells, experiencing pDEP, were attracted towards the bottom interdigitated electrodes where the electric field gradient was maximum. Furthermore, a nDEP-based microfluidic platform was also developed to separate multiple particles in the microchannel in a continuous manner. The microdevice employed an array of electrodes at the bottom of the channel while a top conductive indium tin oxide (ITO) transparent glass layer served as a counter electrode. The particles were focused initially into a single stream by the focusing unit and were later sorted by a movable DEP trap by manipulating the applied voltage on the bottom electrodes. The device performed successful separation of two types of polystyrene particles based on the difference between their sizes [20].

Here, we have developed a non-contact nDEP-based 3D switching microdevice with planar electrodes micropatterned at the bottom of the microchannel. The 3D switching here means that the micro-particles can be switched to any location along the height and width of the microchannel. The proposed device is schematically represented in Fig. 1. The device employs two sets of planar interdigitated transducer (IDT) electrodes on both sides of the microchannel that are independently controlled. The electrodes slightly protrude into the microchannel from both sidewalls. The advantage of the proposed electrode configuration is that the device can be fabricated using standard microfabrication techniques unlike those involved in the fabrication of three-dimensional vertical electrodes detailed in literature [17,21,22]. Moreover, the proposed microfluidic device is easier to fabricate in comparison with the available microdevices with planar electrodes embedded on top and bottom surfaces of the microchannel [16,23,24].

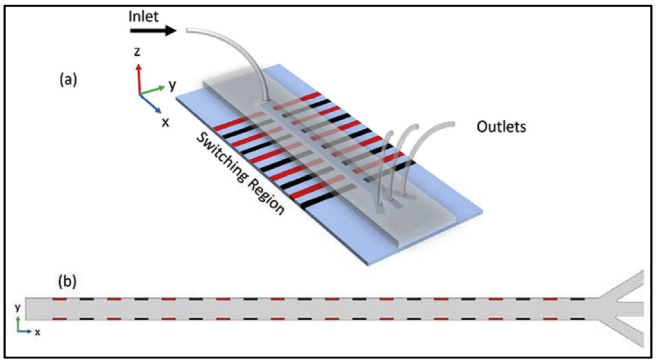

Fig. 1. Schematic representation of the proposed microfluidic device for switching of micro-objects. The x-direction represents the length of the microchannel, y-direction is channel width, and the z-direction is channel height. The in-phase electrodes for each electrode set are shown with one color (red or black). Both the electrode sets can be controlled independently. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

In other planar devices [8,20] having simpler microfabrication process, the operation of switching is dependent on the arrangement of planar electrodes. However, the novelty of the current device is that the micro-objects are influenced by the nDEP forces from the opposing arrays of electrodes simultaneously making the switching size-independent. This maximizes the region of influence of the nDEP force and provide more control as opposed to the designs in which the micro-objects are manipulated using a single set of electrodes. Consequently, a precise control of the steady-state locations of the micro-objects to any location at the outlets is possible by manipulating only the operating voltage and frequency without altering the design. The operation of switching is not dependent on the arrangement of electrodes and the device can be scaled to higher number of outlets. Another advantage of the proposed design is that it can realize 3-D switching of the target objects irrespective of their physical size. A single stream of the micro-objects – contrary to a single plane in the case of 2-D switching – can be formed at any location in the microchannel which is then directed to the desired outlet downstream. Lastly, the electrode configuration utilized in the proposed device generates a higher non-uniform electric field compared to parallel facing 3D vertical electrodes. Hence the switching of the target objects can be achieved at a greater efficiency.

2. Device operation

The operating principle of the device is based on the generation of DEP forces at a single frequency from the opposing arrays of IDT electrodes on the sides of the microchannel. The operating frequency is selected in such a way that the target objects always experience nDEP from both sets of electrodes and are repelled to the regions of electric field minima. The steady-state locations inside the channel of the target objects depend on the interaction of the nDEP forces from both arrays of electrodes. Both the horizontal and vertical positions of the micro-objects can be adjusted precisely by manipulating the operating voltages of both electrode sets. The horizontal components of nDEP force along the width of the microchannel from both electrode sets have opposite directions, and hence, tend to oppose each other. Thus, the target micro-objects settle at the steady-state location along the width of the microchannel where the horizontal force components from the two sets balance each other. Mathematically, it can be expressed in the form of Eq. (4)

$$2\pi\varepsilon_m r_o^3 Re[f_{CM,1}] \frac{\partial}{\partial y} |\boldsymbol{E}_{rms,1}|^2 = 2\pi\varepsilon_m r_o^3 Re[f_{CM,2}] \frac{\partial}{\partial y} |\boldsymbol{E}_{rms,2}|^2 \tag{4}$$

where the subscript 1 and 2 denote the first and second sets of