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An in-situ filtering pump for particle-sample filtration based on low-voltage electrokinetic mechanism

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ABSTRACT

Microfluidic preparation is one of important functions in miniaturized diagnosis systems. However, most of existing microfluidic devices require external driving sources which occupies the majority of system size and weight. To address the insufficiency, this work provides an active fluidic pumping and filtration mechanism by travelling-wave electroosmosis (TWEO). Based on superposition of TWEO and induced-chard electroosmosis (ICEO), our numerical simulations show particles are tend to be trapped within surface microelectrodes. As driven by TWEO, thus, particle pumping and particle trapping effect are controllable by the particle size and applied electrical potential. Experimentally, in our implemented devices, 6 μm and 10 μm beads are fully trapped with the applied potential larger than 0.75 V. In addition, 91.9% 1 μm beads flowed thorough as device driven at 0.75 V and 82.3% 1 μm beads trapped on surface electrodes as device drive at 1.50 V. Finally, the HL-60 cancer cells are conducted to demonstrate the potential to handle a real-cell sample for a particle-filtration function in the developed device. The developed device provides a promising on-chip method to achieve the active filtering and pumping function with low-power characteristics for future miniaturized healthcare systems.

1. Introduction

Miniaturized healthcare technologies have become emerging research fields because of unmet needs in personalized healthcare systems [1,2]. To develop these technologies, portable electronic devices, such as smart phones or tablets, provide excellent platforms. For instance, a number of portable health accessories integrate with smart phones to monitor the user's physiological signals, such as heart rate and calorie consumption [3]. In addition to monitor the physiological signals, at the same time, researchers have also developed the image processing technique for the diagnosis of paper-based immunoassays based on a smart phone platform [4,5]. P. B. Lillehoj et al. also demonstrated a compact mobile phone platform for quantitative biomolecular detection utilizing an electrochemical method [6]. These researches show the concepts of next-generation personalized healthcare systems.

Since miniaturized sensing capabilities are essential in previously mentioned personalized healthcare systems, most of them lack for sample preparation functions, such as filtering cells from samples, which is an important process for medical diagnosis [7,8]. To fulfill requirements of these miniaturized healthcare systems, sample preparation devices should feature portability and low-power consumption. Moreover, microfluidic devices with low driving voltage is preferred because of the power constrain and electrical connection to portable platforms. It also possesses potential advantages to be accommodated into present CMOS fabrication processes to reduce manufacturing costs.

In various processes of sample preparation, the particle filtration is a fundamental function to reduce non-relevant interferences of biomolecular diagnosis. To accomplish the filtration function, electrokinetic mechanism, such as dielectrophoresis is a promising method for a portable healthcare system [9–11]. However, most electrokinetic particle filtration devices rely on a front-end fluidic pumping device, normally a mechanical syringe pump. Because of size and power constrains, these mechanically actuated pumps are obstructively integrated to be integrated with portable health-

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care platforms. On the other hand, there exists fluidic pumping techniques based on the electrokinetic mechanisms, such as electrophoresis [12,13] and electroosmosis [14,15]. These researches demonstrate promising methods to actuate microfluidics. And it is intriguing to implement a fully electro-control microfluidic system based on the requirements of the portable healthcare system.

In this work, we developed a fully electro-control microfluidic device embedded with dual functions, i.e. fluid pumping and particle trapping, simultaneously. This electrokinetic technique is able to achieve basic requirements of portable healthcare systems and be integrated with CMOS fabrication processes. In brief, while applying a travelling wave electric fields on a linear electrode array, the formation of TWEO plays a role to pump liquids in a forward direction. In addition, the electric field also generates an induced-charge electroosmosis (ICEO) on surfaces of dielectric particles. ICEO causes a counteracting flow to impair the forward TWEO. As a result, the superposition of the TWEO and ICEO results in a stabilized region to trap the dielectric particles. This in-situ filtering pump is proposed, simulated, and experimentally verified. We successfully demonstrated the pumping and filtering effect of polystyrene particles with diameter of 1 μm, 6 μm and 10 μm. Furthermore, human promyelocytic leukaemia cells (HL-60) cancer cells are also used to demonstrate a cell-filtration function required for future biomolecular diagnosis applications.

2. Principle of device concept

To employ TWEO, the design of the proposed device is composed of an array of straight electrodes as shown in Fig. 1(a). In the proposed device, the electrode array consists of 8 units and each unit has 4 consecutive electrodes to form a travelling-wave period. The applied travelling-wave electric field induces the electrolytes flowing continuously in designed direction on the device surface. The flowing electrolytes drag the liquid to form a couette flow to give a liquid pumping effect [16]. Through the TWEO mechanism, fluids from an open-end inlet is able to be pumped into the fabricated micro-channel. It should be noted that the boundary near the open-end inlet generates a downward flow field pulling the particles towards the electrode array as shown in Fig. 1(b). When the particles approach closely to the electrode, the induced electroosmosis near the surface particle should be taken account due to the strong electric field. As a result, the ICEO counteracts the TWEO pumping effect, and the particles experiences a static region near the electrode. Based on these two electrohydrodynamic mechanisms, the developed device conduct fluid pumping and particle trapping at the same time using a simple linear electrode array with a 4-phase travelling wave signal.

3. Theory

In the developed device, the travelling wave signal is applied on the linear electrode array. The travelling-wave potential induces two electrohydrodynamic (EHD) flows, TWEO and ICEO: TWEO is utilized to achieve fluid pumping and ICEO is used to conduct particle trapping. To estimate these two EHD flows, at first, the electrical potential distribution induced by the travelling wave signal is calculated. This numerical simulation is performed by COMSOL Multiphysics (v4.3a, COMSOL, Stockholm, Sweden) with the AC/DC current model. The geometry of the simulated model is shown as Fig. 2(a) which includes a finite sized particle near the electrode edge. The electrical potential is modeled by introducing phasor term as $\tilde{\psi} = \psi_R + i\psi_I$, where ψ_R and ψ_I are real and imaginary part of the potential, respectively. Above the surface of microelectrode, in microfluidic model, an open-ended microchannel is filled with 100 μM KCl electrolyte. There is an electrical double layer between the interface of the electrode and electrolyte. As a consequence, the low frequency electric field creates a quasi-equilibrium for the electrical double layer [17]. It should be noted that the electrical potential in the bulk electrolyte satisfies Laplace's equation, $\nabla^2\Psi = 0$.

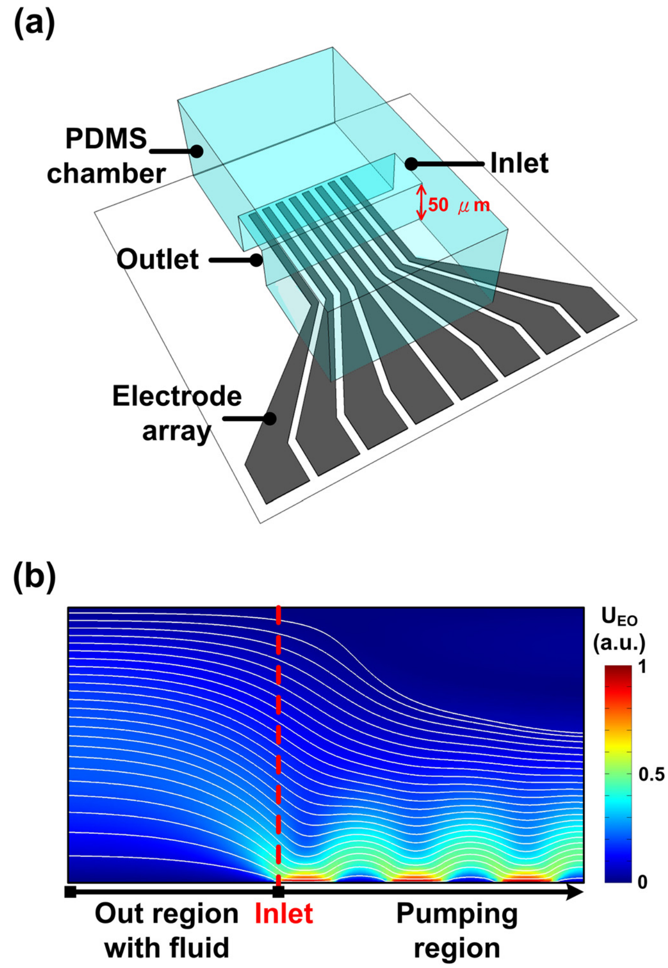

Fig. 1. (a) The schematic of filter-pump microfluidic device composed of a linear electrode array and a microfluidic channel. (b) The numerical simulation of normalized flow velocity and streamline around the inlet boundary.

On the boundary of the electrode surface, the surface charge conservation equation describes the charging of the double layer due to the current in the bulk shown in Eq. (1) [18].

$$\sigma \frac{\partial \tilde{\psi}}{\partial z} = i\omega C_{DL}(\tilde{\psi} - \tilde{V}) \tag{1}$$

where σ is the conductivity of the liquid, ω is the signal frequency, and C_{DL} is the capacitance of the electrical double layer. At the interface between the substrate surface and electrode, on the other hand, the normal current is zero.

Regarding to the effect of electroosmosis near the particle surface, the diffusion layer induces a higher ionic conductivity and electroosmosis flow. By introducing the concept of surface conductivity, the boundary condition of normal current conservation is applied on the particle surface shown as Eq. (2) [19].

$$\sigma_l \nabla\tilde{\psi}\cdot\mathbf{n} - \sigma_p \nabla\tilde{\psi}\cdot\mathbf{n} = -\sigma_s \nabla_s^2 \tilde{\psi}\cdot\mathbf{n} \tag{2}$$

Where σ_l and σ_p are the ionic conductivity respectively, the σ_s is the particle surface conductivity, and ∇_s^2 denotes the surface gradient. The term on the right-hand side of the equation means the tangential current flux along the particle surface, which equals to the normal current flux into the particle.