Microfluidic Device for Conventional and Traveling-Wave Dielectrophoresis

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ABSTRACT

We present the design of a microfluidic device and an electric circuit capable of combining both conventional and traveling-wave dielectrophoresis in a single microchip for the consecutive manipulation and separation of suspended particles according to their electrical properties. The high-gradient ac electric field is generated using an electrical power supply producing a phase-quadrature sinusoidal signal with the amplitude of up to 200 V (peak-to-peak) at the frequency of up to 250 kHz. We describe the operating principle of the device along with results of our preliminary experiments on suspensions of $4-\mu m$ diameter polystyrene particles dispersed in deionized water.

Keywords: Microfluidics, Dielectrophoresis, Traveling-Wave dielectrophoresis, Electric-field-induced phenomena, Particle Manipulation and Separation.

1 INTRODUCTION

The term dielectrophoresis (DEP) coined by Pohl [1] is used to describe the polarization and the associated migration of a particle subjected to a spatially non-uniform electric field. It arises from the difference in the magnitudes of the force experienced by the electrical charges of a dipole, induced in the particle, when subjected to a non-uniform field. The heart of DEP techniques is an electrode array designed to generate a high gradient electric field for the manipulation of tiny particles suspended in a host fluid. DEP is a proven technique for the separation, characterization, and identification of suspended particles with potential applications ranging from the biological warfare agent detection to healthcare industry. The development of a new generation of electro-technologies is associated with the advent of modern electronics making feasible to use ac fields over a broad range of amplitudes and frequencies.

2 DIELECTROPHORESIS

The force $\mathbf{F}$ exerted by an electric field $\mathbf{E}$ on a particle immersed in a fluid includes two terms:

$$\mathbf{F} = Q\mathbf{E} + (\mathbf{P}\cdot\nabla)\mathbf{E}, \qquad (1)$$

where Q is the net particle charge and $\mathbf{P}$ is the particle dipole moment. The first term in this equation is the electrophoretic force, which causes a charged particle subjected to an electric field to travel along the electric lines, whereas the other term, often referred to as the DEP force [1-3], appears only within a spatially non-uniform field.

Under the action of an ac field:

$$\mathbf{E} = \mathbf{E}_1(\mathbf{r})\cos\omega t + \mathbf{E}_2(\mathbf{r})\sin\omega t, \qquad (2)$$

where ω is the field frequency and E_1 and E_2 are the amplitudes, the time average electrophoretic force in Eq. (1) vanishes. The oscillating velocities of the fluid and the particle can be estimated using the classical Helmholtz - Smoluchowski relations for the electroosmotic mobility of the fluid and the electrophoretic mobility of the particle [4] and the Basset-Boussinesq-Oseen equation to account for deviations of the fluid and particle motions from the steady state [5]. Taking typical values -60 mV and -40 mV for the zeta-potentials at the water/channel wall and at the water/particle interfaces, respectively, the amplitudes of the fluid and particle oscillations for ac fields of several kV/mm in the 100 kHz-frequency range are estimated to be ~ 10 nm. Their contribution to the net particle migration is therefore negligible under most conditions of dielectrophoresis.

In contrast, the DEP force in Eq. (1) averaged over the period of the ac field oscillation attains a nonzero value. It comes from the fact that the field induced dipole moment of the particle is proportional to the field strength. Specifically, the polarization of a particle depends on the time variation of the applied electric field over some characteristic time interval in the recent past. For a simple case of a sphere, we have [6]

$$\mathbf{P} = 3v_p\varepsilon_0\varepsilon_f\int_{-\infty}^{t}\beta(t-t')\mathbf{E}(t')dt',$$

where v_p is the particle volume, ε_0 is the vacuum permittivity, ε_f is the dielectric constant of the fluid, and $\beta(t)$ describes the dielectric relaxation. The real, $\mathrm{Re}(\beta)$, and imaginary, $\mathrm{Im}(\beta)$, parts of the Fourier transform

$$\mathrm{Re}(\beta) + i\,\mathrm{Im}(\beta) = \int_0^\infty \beta(t) e^{-i\omega t} dt$$

describe the interaction of a particle with an ac field. A model of a perfect dielectric assumes the immediate response of polarization to an applied field so that $\beta = C_1 \delta(t)$ with some constant C_1 and $\delta(t)$ being the delta-function, $\mathrm{Re}(\beta) = C_1$, and $\mathrm{Im}(\beta) = 0$. The opposite extreme of a perfectly conducting material corresponds to the polarization proportional to the rate of the time variation of an applied field so that $\beta = C_2 \delta'(t)$ with some constant C_2 and $\delta'(t)$ being the derivative of the delta-function, $\mathrm{Re}(\beta) = 0$, and $\mathrm{Im}(\beta) = \omega C_2$. For a simple case when the so-called model of a leaky dielectric [4] represents the electric properties of the particle and that of the fluid, i.e., when their dielectric constants, ε_p and ε_f, and conductivities, σ_p and σ_f, are frequency independent, we obtain

$$\mathrm{Re}(\beta) = \frac{\varepsilon_p - \varepsilon_f}{\varepsilon_p + 2\varepsilon_f} + \frac{3(\varepsilon_f \sigma_p - \varepsilon_p \sigma_f)(\sigma_p + 2\sigma_f)}{\left[(\sigma_p + 2\sigma_f)^2 + \omega^2(\varepsilon_p + 2\varepsilon_f)^2\right](\varepsilon_p + 2\varepsilon_f)}, \qquad (3)$$

$$\mathrm{Im}(\beta) = -\frac{3\omega(\varepsilon_f \sigma_p - \varepsilon_p \sigma_f)}{(\sigma_p + 2\sigma_f)^2 + \omega^2(\varepsilon_p + 2\varepsilon_f)^2} \qquad (4)$$

In *conventional* DEP, electrodes are energized with a single-phase ac voltage, so that only the one component appears in Eq. (2) and the time-average DEP force is [1-3]

$$\mathbf{F}_{\mathrm{DEP}} = (3/2)\varepsilon_0 \varepsilon_f v_p \,\mathrm{Re}(\beta) \nabla \mathbf{E}_{\mathrm{rms}}^2 .$$

This force drives a particle toward the regions of high field (*positive* dielectrophoresis) or low field (*negative* dielectrophoresis), depending on the sign of $\mathrm{Re}(\beta)$. In particular, the use of a sufficiently high frequency [$\omega \to \infty$ in Eq. (3)] enables the separation of particles according to the ratio of their dielectric constant, $\varepsilon_f/\varepsilon_p$, whereas the use of a sufficiently low frequency [$\omega \to 0$ in Eq. (3)] enables the separation of particles according to the ratio of their conductivities, σ_f/σ_p.

In *traveling-wave* dielectrophoresis (twDEP), the electrode array is energized with a series of sequentially phase-shifted ac voltages. The wave contains both components in Eq. (2) so that $\mathbf{E}_1 = \mathbf{E}_0 \cos\varphi$ and $\mathbf{E}_2 = \mathbf{E}_0 \sin\varphi$ where the spatial variation of the phase φ is significantly larger than that of the amplitude $\mathbf{E}_0$. In this case, the time-average twDEP force is [7, 8]

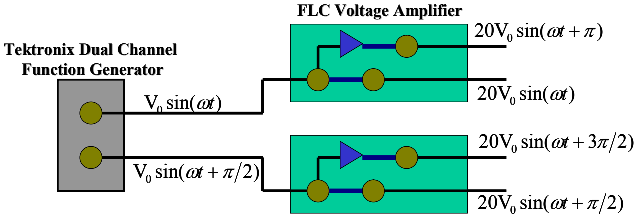

Figure 1. The electric circuit diagram.

$$\mathbf{F}_{\mathrm{twDEP}} \approx -(3/2)\varepsilon_0 \varepsilon_f v_p \,\mathrm{Im}(\beta) \mathbf{E}_0^2 \nabla \varphi .$$

Depending on the sign of $\mathrm{Im}(\beta)$, this force directs a particle toward the regions where the phase is larger or smaller. In particular, when the value of $\mathrm{Im}(\beta)$ is given by Eq. (4), the use of twDEP enables one to separate particles with different ratio $\varepsilon_f \sigma_p / \varepsilon_p \sigma_f$.

In contrast to previous investigations, we focus on the field driven aggregation of suspended particles in strong AC electric fields and the consecutive manipulation and separation of suspended particles utilizing both DEP and twDEP. Here, we present the design of a microfluidic device and an electric circuit for studying DEP and twDEP in strong fields.

3 EXPERIMENTAL TECHNIQUES

3.1 Electrical AC Power Supply

The electric circuit for generating a phase-quadrature sinusoidal signal is shown schematically in Fig. 1. A dual channel function generator (Tektronix) is used to produce two signals [up to 10 V (peak-to-peak) and up to 250 kHz] having a 90-degree phase shift. Each of two voltage amplifiers (FLC) is then fed with the input signal from the function generator to provide dual signals amplified 20 times with a phase shift of 180 degrees. The final output of the amplifiers consists of four signals having the same voltage and frequencies with phase shifts of 0, 90, 180, and 270 degrees. The system is capable of generating the voltage amplitude of up to 200V (peak-to-peak) at frequencies as high as 250 kHz. For conventional DEP, only one of the four output signals is used to energize the electrodes.

3.2 Device and Materials

A standard photolithographic process was used to fabricate a comb structure with 24 independently addressable microelectrodes (Fig. 2a). Four inch silicon

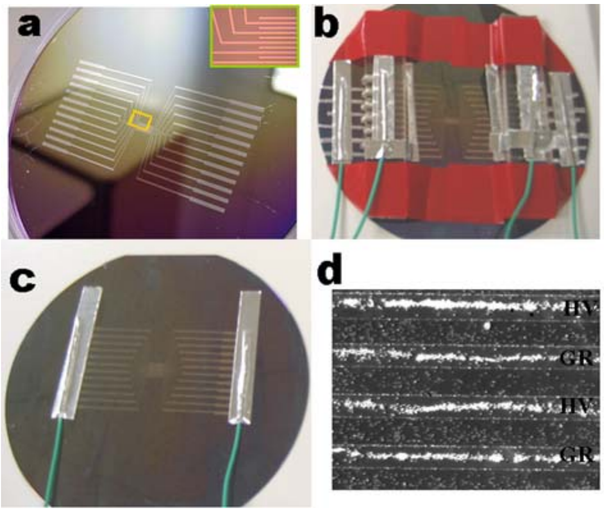

Figure 2. Microdevice for generating twDEP and DEP.

wafers with a 150 nm thick thermal oxide were patterned with microelectrodes (10 nm Ti, 200 nm Au). The inset in Fig. 2a shows the arrangement of electrodes in the central region of the microfabricated chip. The electrode width and spacing are $50\mu m$. Figure 2b demonstrates the connections to the electrodes for generating twDEP: wires 1-4 are connected to the power supply with phase shifts of 0, 90, 180, and 270 degrees, respectively. Figure 2c shows the connection to the electrodes for conventional DEP: wires 1 and 2 are connected to high voltage and ground, respectively.

Experiments were conducted on a dilute suspension of 4-micrometer polystyrene particles (Bang Laboratories) dispersed in deionized water (conductivity=0.55 $\mu S/cm$, pH=5.5-6). The microfluidic chamber was prepared by making a square cavity of thickness $\sim 400\mu m$ above the electrodes. The cavity was filled with the suspension using a syringe carefully enough to avoid any bubble formation prior to the field application. Once the cavity was filled, it was then covered with a transparent glass slide tightly pressing from the top. Once chamber was filled and closed from top, the electrodes were energized and the particle motion was observed from the top using a microscope (Nikon SMZ-2T).

4 PRELIMINARY RESULTS

We tested the microfluidic device first for conventional DEP at the field frequency 100 kHz (Fig. 2c) by connecting alternate electrodes to high-voltage and ground. Photograph presented in Fig. 2d shows the aggregation pattern formed in a dilute ~0.0025%(v/v) suspension exposed to an ac electric field of ~1 kV/mm. As can be seen from the photo, the polystyrene particles exhibiting negative DEP accumulate in the regions of low-field strength which, due to symmetry, are located above the centerline of both energized and ground electrodes.

5 CONCLUSIONS

We presented the design of a microfluidic device and an electric circuit capable of utilizing both conventional DEP and twDEP in a single microchip for the consecutive manipulation and separation of suspended particles according to their electrical properties. We are in the progress of investigating the effects of the field strength, frequency, and phase shift on the particle aggregation and separation.

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