Combination Ultrasonic- Dielectrophoretic Particle Traps for Particle Trapping and Sample Purification in a Microfluidic Channel

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ABSTRACT

Ultrasonic and dielectrophoretic particle manipulation have been studied for particle trajectory modification and particle trapping in microfluidic channels. We report an approach that combines dielectrophoresis (DEP) and ultrasonic fields to trap and concentrate particles and cells in an aqueous suspension. By simultaneously applying electric and ultrasonic fields to the sample, the favorable attributes of each field-based manipulation technique can be utilized. Additionally, the parameter space for sorting particles by intrinsic properties spans both acoustic (density and compressibility) and dielectric properties. Particle sorting and trapping efficiency against on-chip flow are evaluated. Two different experimental situations are presented

(i) non-resonant ultrasonic excitation, and

(ii) resonant ultrasonic excitation.

Keywords: particle manipulation, ultrasonic, dielectrophoresis

1 INTRODUCTION

Particle handling and trapping are becoming very important tools in biology, chemistry, environmental monitoring and clinical research. Capture of particles at predetermined locations within flow channels or modification of their trajectories has found increasing utility in many applications including: flow cytometry[1], hybridization assays[2], and different immunoassays[3].

The present research investigates the development of a particle handling and trapping device that is designed to excite both ultrasonic and dielectrophoretic manipulation forces within a microfluidic channel. The device is constructed from a planar quasi-one-dimensional piezoelectric array. By creating piezoelectric elements with dimensions of order several hundred microns, the electrodes that energize the piezoelectric elements also create a non-uniform electric field within the microfluidic chamber. Proper electrode design can allow for simultaneous excitation of DEP and ultrasonic manipulation forces within the microfluidic chamber. Experimental results and a description of operation of the device are given.

2 BACKGROUND

Ultrasonic radiation pressure has been demonstrated as a viable means to manipulate and locally trap particles in microfluidic environments. The associated force depends upon frequency of excitation, pressure amplitude within the medium, and the density/compressibility contrast between the particle of interest and the host medium. Within an ultrasonic standing wave, particles experience a drift force, resulting from acoustic radiation pressure, that transports them to a nodal or an anti-nodal plane of the applied standing wave. The technique has been successfully demonstrated in particle conditioning experiments involving trajectory steering, agglomeration[4], retainment[5], mixing[6], selective retainment[7] and deposition of cells on a surface[8].

The acoustic radiation force $F_U(x)$ on a spherical particle is given by the well known formula[9]:

$$F_U = -\nabla\left\{2\pi a^3 \rho\left[\frac{\left\langle p'^{\,2}_{in}\right\rangle}{3\rho^2 c^2} f_1 - \frac{\left\langle v'^{\,2}_{in}\right\rangle}{2} f_2\right]\right\} \qquad (1)$$

where $p'^{\,2}_{in}$ and $v'^{\,2}_{in}$ are the mean square fluctuations of the pressure and velocity at the location of the particle,

$$f_1 = 1 - \frac{c^2 \rho}{c_0^2 \rho_0}$$

$$f_2 = 2\frac{\rho_0 - \rho}{2\rho_0 + \rho} \quad ,$$

and

ρ = mass density of the fluid
ρ_0 = mass density of the particle
a = radius of the particle
c = speed of sound in the fluid
c_0 = speed of sound in the particle.

The brackets correspond to a time-averaged quantity.

In most ultrasonic particle manipulation applications, a standing wave is created in a chamber, thus mandating a resonance condition to exist. Historically, for particles in a host fluid medium, the resonance condition has required a $\lambda/2$ spacing between a drive transducer and a semi-rigid reflector based upon simple boundary conditions. In this

arrangement, most particles of interest (cells, bacteria, microspheres) are transported to locations that coincide with pressure nodes. As a result of the boundary conditions, their locations are spatially situated away from the transducer and reflector surfaces. Recent work has shown that by proper selection of layered materials, λ/4 resonators can be used to transport these particles to pre-selected boundaries (e.g. reflector surface) within a microfluidic chamber. Such an effect can be used to significantly increase reaction kinetics of particles at a functionalized surface[8]. It should be noted that due to the requirement of resonance conditions, the bandwidth of excitation is controlled by the quality factor (Q) of the chamber.

Another manipulation field of interest for this study is DEP. In a spatially non-uniform electric field, a particle experiences a dielectrophoretic force (the product of the particle dipole moment and the gradient of the field strength). The particle can experience positive DEP (particle driven towards the electrode) or negative DEP (particle driven away from the electrode). The DEP force can be used to separate[10], concentrate[11], or trap particles in a non-uniform electric field [12].

The DEP force acting on a particle due to an existing electric field is given by:

$$F_{DEP} = 2\pi\varepsilon_0\,\varepsilon_m a^3\,\mathrm{Re}(f_{CM}(\omega))\,\nabla\left\langle E_{RMS}\right\rangle^2 \qquad (2)$$

where

f_{CM} = Clausius- Mossotti factor,
a = particle radius,
ω = angular frequency and
E_{RMS} = root-mean-square of electric field.

The Clausius-Mossotti factor, f_{CM}, is given by:

$$f_{CM} = \frac{\varepsilon_p^*(\omega) - \varepsilon_m^*(\omega)}{\varepsilon_p^*(\omega) + 2\varepsilon_m^*(\omega)} \qquad (3)$$

where $\varepsilon_p^*(\omega)$ and $\varepsilon_m^*(\omega)$ are the frequency-dependent complex permittivities of the particle and its surrounding medium, respectively. The direction of the force (negative or positive DEP) is dictated by the value of f_{CM}. In contrast to the ultrasonic particle manipulation force, the DEP force does not require a spatial resonance to exist within a cavity. This restriction allows the DEP force to act over a very broad range of frequencies of excitation.

3 CELL CONSTRUCTION

The microfluidic channel design is a planar structure with a double-sided, copper-clad circuit board serving as the mounting substrate. A Lead Zirconate Titanate (PZT) plate with gold electrodes (Piezo Systems Inc., Cambridge, MA) is adhered to the circuit board with silver epoxy to serve as the transduction mechanism for the ultrasonic manipulation field. The piezoceramic crystal has the following dimensions: 15.78mm long, 10.12mm wide and 1.04mm thick. Linear channels are created with a diamond saw with an abrasive blade of width 100μm. Cuts were made to a depth of 750μm. Ten channels of different widths were created. The widths of channels are: 412.5μm, 412.4μm, 435.9μm, 389.1μm, 325.2μm, 617.7μm, 266.1μm, 226.9μm, 136.6μm, and 106.5μm.

The chamber is constructed by placing a mylar spacer of thickness 120μm between the a poly(methyl methacrylate) (PMMA) cover of thickness 1.04mm and the PZT. The components are sandwiched together using a thin layer of silicone vacuum grease between each layer. The saw kerf between the PZT channels is filled with a layer of epoxy (PMC-780, Smooth-On Corporation, Easton PA).

In typical ultrasonic array construction methods, a ground plane is placed at the boundary between the PZT and the fluid. The array elements are driven from the electrode surface opposite the fluid interface. For the present research, we wish to excite electric fields within the fluid to drive DEP. Therefore, the ground plane in our cell is placed at the boundary between the circuit board and the PZT. The array elements are driven at the electrode interface positioned at the fluid boundary.

To approximate the behavior of the electric field within the fluid channel, a simulation of the electric field magnitude

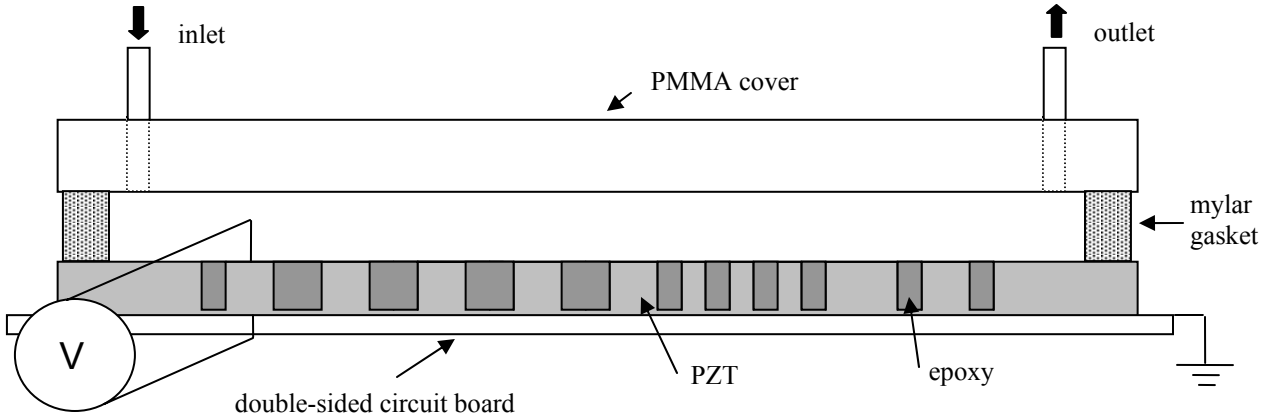

Figure 1: Construction of combination DEP / ultrasonic particle manipulation device.

within the structure is shown in Fig. 2. It was generated using FEMLAB finite element software in an electrostatics approximation. Array elements comprised of PZT are shown as the large, periodic blocks on the bottom of the figure. The small spaces between them are modeled with a dielectric of low permittivity and conductivity. The array structure is covered by a water layer followed by a PMMA top. A continuous electrode surface at the bottom of the array is set to ground. To create a nonuniform electric field distribution, the center channel is driven at a constant voltage while the other channels are set to ground. Large electric field gradients are shown at the electrode edges at the fluid-PZT boundary and a localized electric field minimum is shown centered directly above the channel at the fluid-PMMA boundary.

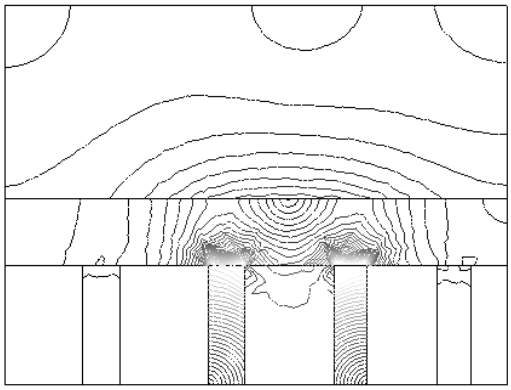

Figure 2: Electric field magnitude above PZT array. Ground plane is located at the bottom of the array. One element is excited and the rest are at ground.

4 EXPERIMENTS

Suspensions of Polybead Dyed Microspheres (Polysciences Inc., Warrington, PA) in water were diluted in distilled water to obtain suspensions of $5*10^8$ beads/mL - $6*10^8$ beads/mL. Diameters of beads used were 1μm, 2μm, 5.6μm. The suspensions were vortexed for 1 minute to allow a uniform distribution of the particles.

An Agilent 33250A Waveform Generator (Palo Alto, CA) was used to generate a sinusoidal signal to drive the system. The signal was fed into a Kalmus 121 CRM Power Amplifier. The resulting signal was monitored using a LeCroy Waverunner LT224.

The drive signal amplitudes into the PZT were typically 25-30V_{pp}. The current was measured using a 1-ohm resistor mounted in series with the piezoceramic. Pictures of the concentrated suspension pattern were taken using an Olympus BX41 Microscope (Olympus Optical Co. Ltd., Japan) and an Olympus C-3030 camera digital camera.

The bead suspensions were transported through the system using a Harvard syringe pump (Harvard Apparatus, Holliston, MA). The flow rates used in the experiment are in the range: 10 μL/min – 250 μL/min.

5 RESULTS

Figure 3: Single DEP trap collecting 5.6μm latex microspheres above a single PZT array element.

Figure 3 displays 5.6μm latex microspheres trapped directly above an array channel of width 226.9μm. The manipulation force in this instance is negative DEP. The particles are forced to the position of the minimum electric field strength that is collocated with the water-PMMA surface and is centered above the array element as shown in Fig. 2. The frequency of excitation is 20.4 MHz. To insure that this is primarily due to DEP, a similar experiment was conducted where an identical channel was constructed with array elements that did not exhibit piezoelectric behavior. Equivalent results were achieved. This ability of the device to trap particles in a single line was observed over large excitation bandwidths. This single line trap was seen at frequencies as low as 1.2 MHz and as high as 21.0 MHz.

Figure 4 displays 5.6μm latex microspheres trapped above a 389.1μm width channel. The frequency of excitation is 20.8 MHz and corresponds to a resonance of the ultrasonic field within the cavity. The sample is flowed into the chamber from the left at approximately 50 μL/min. The particles form DEP polychains as they approach the active element. The light horizontal lines in the image demonstrate this active DEP effect. To the right of the active element, the particle density is greatly reduced demonstrating a strong trapping mechanism exists.

In contrast to Fig. 3 where the particle trap is in the form of a single line along the length of the array element, the

experimental result in Fig. 4 shows a trap geometry that replaces the single line with five lines along the length of the array element. This is the result of the resonant ultrasonic field working in conjunction with the negative DEP trap. The spatial distribution of the pressure field is nonuniform as a result of the finite dimension of the transducer. This near field ultrasonic effect was observed by Lilliehorn, et. al[13], where they saw similar types of patterns in near-field ultrasonic trapping experiments in microchannels.

Figure 4: Combination DEP / ultrasonic trap collecting 5.6μm latex microspheres above a single PZT array element.

6 DISCUSSION

A microfluidic device was constructed from a planar quasi-one-dimensional PZT array. The PZT array elements were designed such that a ground plane does not exist at the PZT-fluid boundary. This allows for penetration of the electric field into the fluid. Experiments show that a negative DEP force is observed for latex particles in the frequency range 1 MHz – 21 MHz. When ultrasonic resonance is driven with the chamber, single line DEP traps are perturbed and redistributed by the presence of the ultrasonic field.

Current research is driven to understand the relationships between the two manipulation fields acting within the same chamber. One example was presented in this paper where a single DEP trap is perturbed by the presence of a resonant ultrasonic field. This is not the general case. We have also observed conditions where the ultrasonic force dominates and the DEP force is almost nonexistent. The phenomona is complicated by both the frequency dependence of the ultrasonic and DEP forces; frequency dependence is found in both the cavity geometry and the electrical impedance of the PZT.

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