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Continuous Separation of Submicron Particles Using Angled Electrodes

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Abstract. Dielectrophoretic separation of particles is achieved by the generation of electric forces on the particles by non-uniform electric fields. This paper presents a technique based on negative dielectrophoresis in a novel design of electrode array for the non-contact separation of polarisable particles. Angled electrodes are used to generate a lateral force in a microfluidic channel separating a mixed stream of particles into distinct streams of constituent components and achieving a high degree of spatial separation.

1. Introduction and Background
Dielectrophoresis is the movement of polarisable particles in non-uniform electric fields [1,2]. The induced dipole moment of the particle experiences a net force in an AC electric field, resulting in motion. The DEP force is given by the following equation [1, 2].

\[ \langle F_{DEP} \rangle = \frac{1}{4} \nu \text{Re}[\alpha] V |E|^2 \]  

(1)

where \( \nu \) is the volume of the particle, \( \alpha \) the effective polarisability of the particle and \( E \) is the electric field. The effective polarisability depends on the conductivity and permittivity of both the particle and the fluid medium it is suspended in, as well as the frequency of the applied electric field. As a result of this term and the volume, the dielectrophoretic force is unique for a given particle type, resulting in a high degree of discrimination for separation. DEP separation has been demonstrated for a wide range of different particle types, from cells down to nanoparticles [2,3].

The separation of particles and nanoparticles has a wide range of applications, such as environmental monitoring, medical diagnosis, food technology and water monitoring systems. Studying the DEP behaviour in AC fields also allows the measurement and determination of particle internal dielectric properties, a separate area of research with practical application in the areas of detection, diagnosis and biophysics. However, there are fundamental physical limitations on the separation of submicrometre and nanoparticles, due to the randomising influence of Brownian motion [3]. These particles are also not significantly affected by gravity and, as a result can easily be carried away by viscous drag from a moving fluid stream.

However, in designing devices for DEP separation, there are a number of different parameters that can be altered to achieve stronger forces and therefore produce deterministic movement of smaller particles. The medium conductivity can be varied to change the magnitude of the DEP force and its direction. Increasing the applied voltage has a stronger effect since the force is proportional to the...
square of the electric field magnitude. More significantly, however, the DEP force is inversely
proportional to distance cubed. This means that decreasing the characteristic dimension of an
electrode array, typically the separation between the electrodes, has a substantial effect on the force
generated. In this paper, the use of a pair of arrays of interdigitated electrodes on the top and bottom
of a microfluidic channel for the flow-through dielectrophoretic separation of micrometre sized
particles is presented. Details of the devices design and the results of preliminary tests are discussed.

2. Experimental Methodology

2.1. Device design
The DEP separation of particles using arrays of interdigitated electrodes has been demonstrated in the
literature, for example Nieuwenhuis J.H. et al [4] and Durr, M., et al [5]. The device design
presented here is different: it consists of two arrays of chevron shaped electrodes fabricated on top and
bottom of a microfluidic channel as shown schematically in figure 1.

![Figure 1](image_url)

Figure 1. Schematic design of the DEP device design. Two chevron shaped interdigitated electrode arrays are aligned on top and bottom of a channel. A stream of different particles is injected to one side of the channel and separate as each different particle type experiences a different net displacement due to dielectrophoresis as it travels through the array.

The two arrays are aligned and powered using the same frequency of applied signal. The principle of
operation as a separator is also shown in the figure. A set of experimental conditions is selected so
that negative DEP is experienced by the particles in the mixture. This is preferable since in many
useful cases, positive DEP cannot occur due to, for example, high medium conductivity. The particle
mixture is focussed to one side of the array, by means of hydrodynamic focussing or a preceding
electrode array. The combined action of each subsequent pair of electrodes (top and bottom) is to
produce a gradual sideways motion of the particles across the array until they exit at the far end. The
integral effect of the array is to produce a lateral displacement of the particles, proportional to the net
effect of the DEP force down the entire length of the array.

There are several advantages to this design. First, the DEP force does not have to be sufficient
such that the electrode pairs act as a barrier to the particle as in previous designs, allowing lower
voltages and smaller particles to be separated. The length of the array can also be increased to achieve
separation of smaller particles in a predictable manner. In addition, mixtures of multiple particle types
can be separated in the same array into separate streams in a continuous flow through manner.
2.1.2. Fabrication

The microelectrodes were fabricated in layers of titanium and platinum using photolithography [1,3]. In these initial experiments, the electrode width and the separation between adjacent electrodes was 21 micrometres. The total length of the array of microelectrodes in the channel was 3mm. A fluidic channel, 500 micrometres in width and 37 micrometres in height, was fabricated using a dry film epoxy laminate. The laminate is photopatternable and has the advantages of simple, rapid processing; low cost; good compatibility with the sample fluids; and strong adhesion to different materials and low cost. The fabrication process is outlined in Figure 2.

2.1.3. Experimental

The separation array was tested using latex spheres loaded with a fluorescent dye (Molecular Probe, Oregon, USA). This type of particle is an ideal test particle as it has a simple dielectrophoretic response and small sizes can be readily visualised using a fluorescent microscope. The spheres are carboxylate-modified, with a yellow-green fluorescent dye and have a high surface charge density, partly to ensure that they remain in suspension. For the preliminary demonstration of the electrode array, we used a mixture of 1 and 2 micrometre diameter particles, suspended in an aqueous solution of potassium chloride with a conductivity of 14 mS/m. A custom built fluorescent microscope was used to visualise the particles in the channel. A x10 microscope objective and a Panasonic AW-E600 CCD camera was used, which contains 3 separate 2/3 inch CCD arrays for the RGB channels. This setup gave a clear image of the fluorescent spheres in the green with a low background level.

3. Results and Discussion

The flow rate of the sample stream was 0.1µl/min and the sheath flow was 0.2µl/min, resulting in an average particle velocity of 0.1mm/sec as the sample entered the array. The applied signal in this experiment was 20MHz and 20 Volts peak to peak. Figure 3 (a) – (d) show video frames from different regions of the electrode array, demonstrating the operation of the system. The mixture of the two particles flows from left to right, entering the electrode array at the bottom of the channel: (a). As the mixture travels through the array, the 2µm particles experience a stronger negative DEP force which pushes them across the channel: (b) and (c). Figure 3(d) shows the channel at the output end of the array, with the 2µm spheres, distinguishable by their greater fluorescent intensity, displaced across the channel from the 1µm spheres. Figure 4 shows a plot of intensity integrated in the horizontal direction across figure 3(d), showing two peaks representing the two populations of particles. These two populations can then be recovered in a separated form by splitting the channel downstream from the array with the junction point between the two streams of particles.
Figure 3. Video frames showing the different sections of the separator during operation. (a) the start of the array with the mixture of particles entering at the bottom of the channel. (b) and (c) sections of the array, where the 2mm spheres can be seen being pushed by the electrodes and travelling across the channel. (d) at the exit of the array, the two different sizes of particles can be seen travelling from left to right at different positions across the channel.

4. Conclusion
A method of separating micrometre sized particles using dielectrophoresis has been demonstrated using a novel design of electrode array. The design consists of two arrays of aligned interdigitated and angled electrodes on top and bottom of a microfluidic channel. Separation was demonstrated using a mixture of latex spheres at high frequency using negative dielectrophoresis, an advantage in that it completely non-contact and no contamination of the electrodes occurs. The separation efficiency was 100% and was achieved at high frequencies, avoiding unwanted electrochemical or fluidic effects. The design is also a flow through system which could be used in a continuous manner for which the lack of electrode contamination is a further benefit.

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