Asymmetric-Polarization AC Electroosmotic Micropump

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The developments in microfluidics, micro-electro-mechanical systems (MEMS), and micro-total-analysis (μTAS) calls for a means to transport and mix fluid at microscale with reliability and control. Such microfluidic devices are instrumental to the realization or improvement of miniature bio/medical/chemical diagnostic kits, high performance liquid chromaographs (HPLC), fuel cells, ion exchange devices, chip and micro-circuit cooling, biochips for drug screening etc.

We have developed a new technique to transport or mix fluid for micro- devices. The key concept is to exploit different polarization mechanisms and strength of the double layer at the electrode/electrolyte interface, to produce a uni-directional Maxwell force on the fluid, therefore to generate through flow pumping. By adjusting the applied electric fields, the electrode polarizations are modified. Consequently, flow direction can be manipulated simply by changing energizing electrical signals.

Electroosmosis (EO) is the fluid motion induced by the movement of surface charges at the solid/liquid interface under the influence of electric fields. AC electroosmosis is implemented by applying AC electric potentials over the electrodes that are immersed in a fluid that contains ions (either an electrolyte or a dielectric liquid with ionic impurities). In AC EO, the charges in the electrical double layer are induced by the electric potentials over electrodes instead of surface charges in DC EO, and the applied potentials also provide tangential electric fields to drive the ions. Because electric fields around a symmetric electrode pair exhibit mirror symmetry, and charges in the double layer and electric fields change directions simultaneously, AC EO produces steady, counter-rotating local vortices above the electrodes [1].

To use AC EO for pumping, it is essential to break the symmetry of electric fields within an electrode pair to produce a uni-directional flow. This can be achieved by spatial asymmetry in electrode design as people typically do, or by polarization asymmetry as suggested in this proposal. Attempts with spatial asymmetry to induce a net flow include asymmetric parallel electrodes [2] and orthogonal electrodes [3]. However, the former still produce counter-rotating vortices that reduce the net flow, and the latter has a small flowing surface along the narrow orthogonal electrode. This work demonstrated for the first time

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through-flow pumping using symmetrical electrode pairs, which is based solely on asymmetric electrode polarization (A-P).

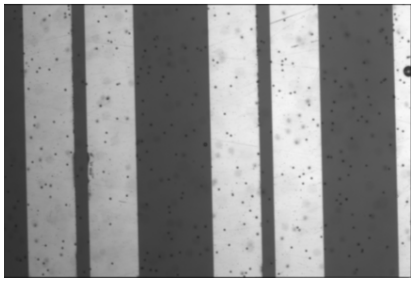
There exist several electrode processes when an electric potential is applied over the electrodes in an electrolyte. With DC fields, it is accepted that electric potentials over the electrodes *attract* counter-ions from the electrolyte to screen the electrode potential (a.k.a. *capacitive or induced charging*), or *generate* co-ions from electrochemical reactions at the electrodes following Faraday's law (a.k.a *Faradaic charging*), when the electrode is positively charged. With AC fields, electrode polarization by capacitive charging has been widely recognized [4] and has been used to generate AC EO, while the polarization by Faradaic charging and related EO phenomena were reported only recently based on our experimental results [5, 6].

Capacitive and Faradaic charging have the following distinct features that are the foundation of the concept of asymmetric polarization AC EO. With electrodes positively biased, the two charging mechanisms produce *ions of opposite signs* in an electrical field, which in turn result in *EO flows in opposite directions*. However, capacitive charging *cannot* produce a polarization exceeding the equilibrium charge density on the electrode side, while Faradaic charging *can* produce charge densities orders of magnitude beyond equilibrium values. Also, the two polarizations have different dependence on the applied voltage, and so are the slip velocities, u_t, induced by two polarizations. For capacitive charging, $u_t \sim V^2$, while for Faradaic charging, $u_t \sim \exp(V)$. Because there is a threshold voltage for Faradaic reaction to occur, capacitive charging predominates at low voltages, while Faradaic charging takes over at higher voltages with its exponential dependence on potential. A-P or biased AC EO capitalizes on the alternating dominance of capacitive and Faradaic charging to break electrode polarization symmetry and consequently realize directed flow motion.

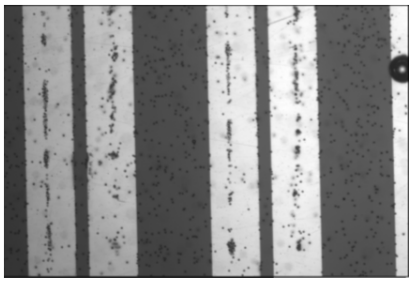
Biased AC EO is realized by applying biased AC signals over electrode pairs, leaving the electrolyte floating; therefore, two electrodes have different electrical potentials relative to the electrolyte. With a biased AC signal, $V_{appl} = V_O(1+\cos\omega t)$ in the report, impressed over the electrodes, the left electrode is always positive and more prone to Faradaic charging, while the other is always negative and subject to capacitive charging. The flow motions generated by A-P AC EO are examined using microfabricated arrays of electrode pairs on silicon substrate. Au/Ti (100nm/5nm) electrodes were fabricated by lift-off procedure in IC processing. Ti is the adhesion layer between the substrate and Au, and Au is in contact with electrolytes. The electrodes are 160 μm wide and 40 μm apart. De-Ionized (DI) water was used as testing solution with suspended polystyrene spheres at a diameter of 5 μm (Fluka Chemica 79633) and at a concentration of 10^6 particles/ml (average particle spacing is 100 microns). Sinusoidal signals at 25 Hz were applied across the electrode pairs.

Figures 1 (a) and (b) show the particle movement when *Vo* is at 1.2 V over the 20 second interval after the field is turned on. This voltage is not sufficient to induce electrochemical reactions at the left electrode. Therefore, the four capacitive vortices are developed in Fig. 1 (b) as with unbiased AC forcing. Two lines of particles assemble at the predicted stagnation lines on the electrodes. Our analysis of the surface E-fields [7] for symmetric capacitive and Faradaic charging reveals that, for wide electrodes, the tangential electric fields switch directions at $1/\sqrt{2}$ of electrode-width away from its inner edge, as shown

in Fig. 2 (a). Because flow directions depend on the tangential fields, four counter-rotating vortices were formed at the electrode surface, and the stagnation lines take place where tangential fields become zero, as shown in Fig. 2 (b).

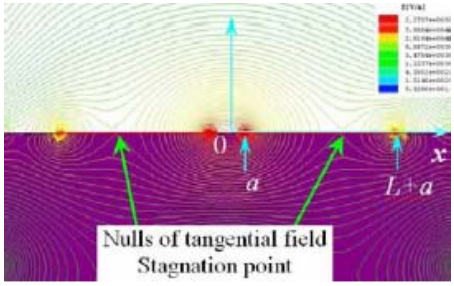


(a) Initial latex particles distribution.

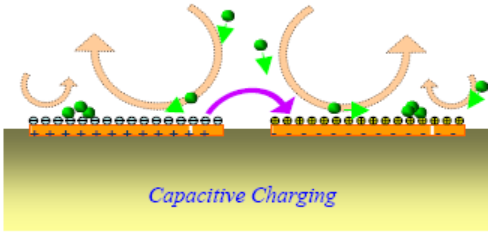


(b) Lines of concentrated particles.

Fig. 1 Distribution of latex particles over the electrodes (a) before and (b) after applying electric potentials ($|V_O|$=1.2 V).



(a)

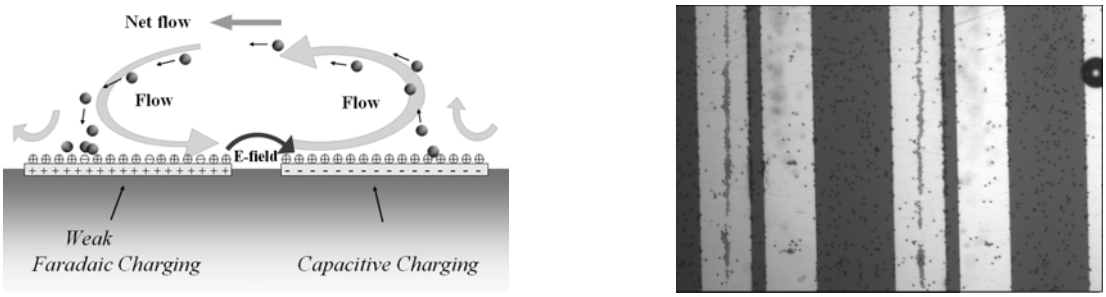


(b)

Fig. 2 (a) Electric fields around a planar electrode pair. The tangential component changes sign at $1/\sqrt{2}$ of electrode-width. (Axes: relative dimensions.) (b) Four counter-rotating vortices are formed above the electrodes due to changes in tangential electric fields, which

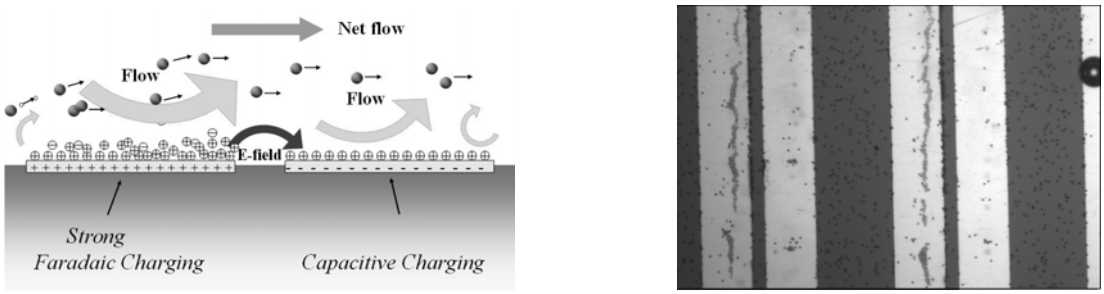
When the voltage exceeds the threshold for reaction, asymmetric vortices are formed above two electrodes as Faradaic reactions take place at the positively biased electrodes. At an appropriately biased AC potential, streamlines from capacitive charging and Faradaic charging become connected, forming a large vortex over the electrode pair, as schematically shown in Fig. 3 (a). Particles can be moved from the right to the left electrode, as shown in Fig. 3 (b), with $|V_O|$=2.2 V.

At higher voltages, the Faradaic polarization becomes sufficiently strong that the stagnation point on the left electrode disappears. The flow motion by Faradaic charging on the left electrode predominates, and a net flow to the right is produced, as schematically shown in Fig. 4 (a). Within 5 seconds after the potential was increased to $|V_O|$=3.4 V, the particle lines on the electrode surface shift from the left to the right, as shown in Fig. 4 (b), indicating a directional surface flow. Through-flow pumping is realized towards the direction of the negatively biased electrode, which is suitable for pumping implementation.



(a) (b)

Fig. 3 (a) Schematics and (b) photograph of particle transport from the right to the left at $|V_O|$=2.2 V by A-P AC electroosmosis.



(a) (b)

Fig. 4 (a) Schematics and (b) photograph of flow motion from the left to the right at $|V_O|$=3.4 V by A-P AC electroosmosis.

By reversing the polarity of the bias and AC frequency, two-way fluid delivery can also be achieved. Pumping and mixing of fluids can hence be realized by adjusting the magnitude of bias and AC signals.

The AC frequency for the above manipulations to happen should be between 10 and 1000 Hz. At too high a frequency, the field has no time to polarize the double layer on the right electrode by capacitive charging and the period is too short for appreciable Faradaic charging on the left electrode. Because of the zero-mean current, bubble generation is not observed on the left electrode until V_O=6.0 V, which is roughly ten times the threshold voltage for DC bubble generation. The wide electrode produces a large net flow with small power consumption. Preliminary experiments in closed channels with fabricated arrays indicate a flow rate of several ml per hour over a length of several cm can be driven by this pump with only 3.5 mW.

We have successfully demonstrated the pumping action with only a few volts of applied voltage and a power consumption in the range of milliwatts. It is fortuitous that this net flow is also sufficiently precise to be able to concentrate and sweep particles into a specific location on the electrode to allow detection. Such a versatile pump and trap combination with an easily fabricated array should prove useful in diagnostic technology.

Reference:

1 N. G. Green, A. Ramos, A. Gonza´lez, H. Morgan, and A. Castellanos, “Fluid flow induced by nonuniform ac electric fields in electrolytes on microelectrodes. III. Observation of streamlines and numerical simulation,” Phys. Rev. E **66**, 026305, 2002.

2 A. Ramos, A. Gonzalez, A. Castellanos, N.G. Green, and H. Morgan, “Pumping of Liquids with AC Voltages Applied to Asymmetric Pairs of Microelectrodes,” *Phys. Rev. E*, 67, 056302, 2003

3 Lastochkin, D., Zhou, R., Wang, P., Ben, Y. and H.-C. Chang. “Electrokinetic micro-pump and micro-mixer design based on AC Faradaic polarization”, J. Appl. Phys., in press.

4 T.M. Squires and M.Z. Bazant, “Induced-charge electro-osmosis,” J. Fluid Mech.,

5 J. Wu, Y. Ben and H.-C. Chang, “Particle Detection by Micro- Electrical Impedance Spectroscopy with Asymmetric-Polarization AC Electroosmotic Trapping,” submitted to Microfluidics & Nanofluidics.

6 J. Wu, Y. Ben, D. Battigelli and H.-C. Chang, “Long-range AC Electrokinetic Trapping and Detection of Bioparticles,” submitted to Industr. Eng. Chem. Research.

7 Y. Ben, J. Wu and H.-C. Chang, “Linear Particle Assembly and Erasure by AC Electro-Osmotic Flow: Effects of Faradaic and Capacitive Charging,” submitted to *Phys. Rev. E*.