DOI: 10.1478/C1V89S1P075

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 89, Suppl. No. 1, C1V89S1P075 (2011)

LOCAL ELECTRIC FIELD MEASUREMENTS BY OPTICAL TWEEZERS

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ABSTRACT. We report a new technique to measure direction and amplitude of electric fields generated by microelectrodes embedded in polar liquid environment, as often used in microfluidic devices. The method is based on optical tweezers which act as sensitive force transducer while a trapped charged microsphere behaves as a probe. When an electric field is applied the particles moves from its equilibrium position and finishes in a new equilibrium position where electric and optical forces are balanced.A trapped bead is moved to explore the electric field in a wide region around the microelectrodes. In such way maps of electric fields with high spatial resolution can be reconstructed even for complex electrode geometries where numerical simulation approaches can fail. Experimental results are compared with calculations based on finite element analysis simulation.

1. Introduction

Many lab-on-a-chip systems make use of electric fields generated by microelectrodes to handle or to sort microparticles [1, 2] as well as cells [3, 4] and also to detect macromolecules [5, 6]. Moreover, microfluidic devices use electrokinetic phenomena to pump, mix, inject and sort also fluids. In particular, more recently, is increasing the interest for miniaturized electroporation systems [7], in order to create nanopores in cell membranes by applying relatively small potentials. In all these systems it is crucial to know local distribution of the electric field which is not trivial technical problem. Strictly related to this problem, is the measurement of low charges carried by single nano- or micro-particles. Sensitive methods for charged colloids measurements have been recently proposed [8, 9, 10]. These techniques use optical tweezers to hold charged particles while they are driven by an external electric field. Charges, as low as a few elementary charges, were measured with an accuracy of about 0.25 e. It is worth to note that these experiments have been performed in non polar solutions where screening effects of free ions aere negligible. In this letter we report the measurement of both direction and amplitude of the electric fields generated by micro- electrodes in aqueous environment using trapped charged polystyrene particles as probes.

2. Experimental

The experimental setup is described in details in our previous papers [11, 12]. Briefly, it comprises a home made optical microscope with a high-numerical-aperture water immersion objective lens (NA=1.2) and a frequency and amplitude stabilized Nd-YAG laser. Negatively charged sulfate coated polystyrene micro-spheres with a diameter of $1.00\pm0.05\mu$m were diluted in distilled deionized water to a final concentration of a few particles/μl. The surface charge density, provided by the manufacturer, was 5.7 μC/cm^2 that corresponds to a total charge of $1.79 \times 10^{-13}\ C$. However due to screening effects of the polar solvent the effective charge of the particles is unknown and has to be measured before using them as probes. A droplet of such solution (100 μl) is placed inside a sample chamber made of a 150 μm-thick coverslip and a microscope slide, both coated with ITO that act as planar electrodes. The sample cell was mounted on a closed-loop piezoelectric stage, which allows movements with nanometer resolution. The 3D position was monitored through the forward scattered light imaged on a a InGaAs Quadrant Photodiode (QPD, Hamamatsu G6849) at the back focal plane of the condenser lens [13].

3. Theory

The basic idea is to use charged microspheres confined by an optical trap and placed between two electrodes. In principle, the electric field E can be measured from the equilibrium between the electric force and the elastic optical restoring force: $q \cdot E = k \cdot \Delta x$, where q is the charge (supposed known) of the particle, k the trap stiffness, and Δx the particle displacement. Nevertheless, in polar solutions like water, even for distilled deionized water (conductivity $1.0\,\mu\,S/cm$), the number of free ions is high enough to generate a double-layer around the electrodes and the charged particle that screens the electric field and reduces the particle charge to an effective value q_{eff}. Thus in polar solutions, static measurements are impossible and it is necessary to use alternating fields with oscillation frequency higher than the transit time of free ions in solution. The analysis of the trapped charged oscillatory motion gives the amplitude of the force exerted on it. Nevertheless this motion is superimposed to the thermal motion caused by collision with water molecules. To extract the oscillation amplitude the Auto Correlation Function (ACF) is used[8, 9]. For a trapped bead of diameter d and effective charge qeff, subjected to an external sinusoidal electric field with constant amplitude and frequency fe, the normalized ACF of the bead motion along one of the three axis, i = (x, y, z), reads:

$$ACF_i(\tau) = \frac{1}{1+\gamma_i^2} exp(-2\pi f_{C_i}\tau) + \frac{\gamma_i^2}{1+\gamma_i^2} cos(2\pi f_e \tau) \tag{1}$$

where f_C is the optical trap corner frequency related to the trap stiffness k by the relation: $k = 6\pi^2 \eta d f_C$, being η the medium viscosity. The adimensional parameter γ is defined as:

$$\gamma^2 = \frac{1}{1+(f_e/f_C)^2} \frac{q_{eff}^2 E^2}{2k_B T k}. \tag{2}$$

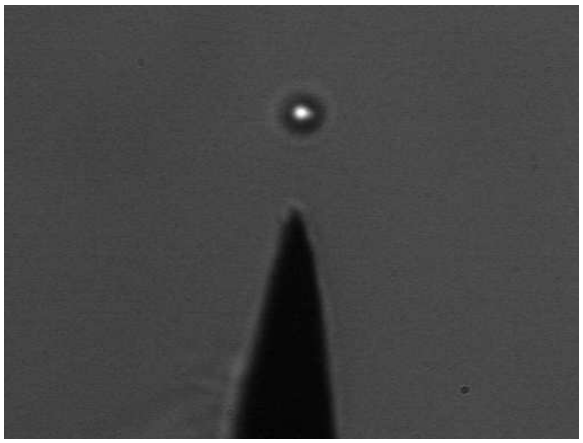

Figure 1. Optical microscopy picture of the charged trapped bead close to the electrode tip.

where k_B the Boltzmann constant and T the absolute temperature. From Eq.2, provided the charge q_{eff} is known, the components of the electric field are straightforwardly obtained:

$$E_i = \frac{\gamma_i}{q_{eff}} \sqrt{12\eta\pi^2 d k_B T \frac{(f_{C_i}^2 + f_e^2)}{f_{C_i}}}. \tag{3}$$

4. Results and Discussion

4.1. Effective charge determination. We first measured the charge of the trapped bead using the two ITO coated glasses that generated a uniform electric field whose amplitude was $E = V/h \sim 2.7\, kV/m$, $(h = 185\, \mu m)$. To check the uniformity of this field we recorded the bead motion at several positions over a wide area of about $500 \times 500\ \mu m^2$. The electric field resulted to be uniform within the experimental error both in amplitude and direction. The effective charge q_{eff} measured was $(1.03 \pm 0.07) \times 10^{-16}\ C$, that is about 2000 times smaller than the value reported by the manufacturer. This is due to the screening caused by the double-layer around the surface of the bead.

4.2. Electric field mapping. We used a gold coated tungsten wire with a diameter of $50\ \mu m$ to make a nanometric tip using electro-etching technique. The electric field was generated by the tip and another electrode made by the same wire. They were positioned perpendicularly each other separated by a distance of 800 μm and the tip height in the middle of the sample cell. For simplicity we measured the electric field only in the plane of the wires in the proximity of the tip where the highest gradient is expected (see Fig.1). The amplitude of the sinusoidal voltage at the electrodes was $V = 500\, mV$ with a frequency of 87 Hz. Starting from an initial position the sample cell was moved with a fixed step in a raster scan around the tip. In every position the bead trajectory was acquired for 20 s.

We investigated also a second geometry: the electrodes were two wires (10 μm in diameter) placed at a distance of 220 μm positioned at a height of 85 μm from the bottom

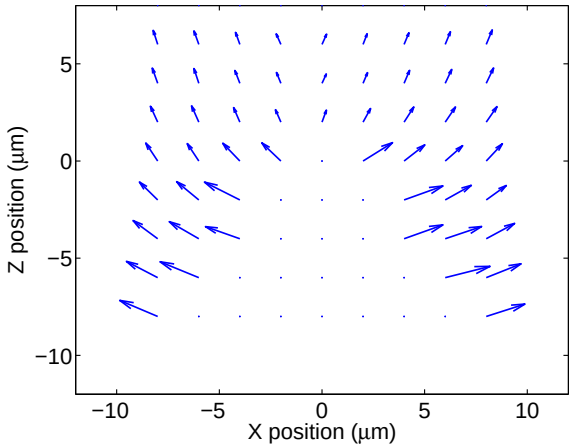

Figure 2. Electric field map around the tip shown in Fig.1. The tip is at the axis origin and the scanning step size is 2 μm.

coverslip and 90 μm from the upper microscope slide. The electric field map concerning tip electrode is shown in Fig.2. We estimated the theoretical field distribution using the finite elements method. The agreement between experiments and simulations was reasonably good for all studied geometries.

5. Conclusions

In conclusion we have developed a high sensitive and precise technique to measure the three-dimensional map of an electric field generated by microelectrodes using an optical tweezers as force transducer. As examples we applied the technique to a simple microelectrodes configurations, but it can be used in whatever complex configuration is needed. The technique provide a direct and realistic estimation of the electric field generated by microelectrodes even when numerical simulation can fail.

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Paper presented at the ELS XIII Conference (Taormina, Italy, 2011), held under the APP patronage; published online 15 September 2011.