Real-time manipulation of microparticles in aqueous media by photovoltaic optoelectronic tweezers operating at high light intensities

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Photovoltaic optoelectronic tweezers (PVOT) have emerged as a powerful tool for the manipulation of a wide variety of micro/nano-objects (particles, liquid droplets, bubbles or biological material) based on the electric fields induced by the bulk photovoltaic (PV) effect, often using $LiNbO_3$:Fe crystals [1, 2]. Nevertheless, the manipulation of such objects in aqueous media has remained mostly elusive so far, due to the fast screening of electrostatic fields in water. The time constant that governs the screening speed is given by $\tau_s = \varepsilon\varepsilon_0\rho$, where ε is the relative permittivity of the medium, ρ its resitivity and ε_0 the vacuum permittivity. Even in the case of ultrapure Milli-Q water, with a resistivity of 18.2 MΩ · cm at room temperature, the PV electric fields are screened in around ~100 μs, thus hindering the proper functioning of PVOT. To the best of our knowledge, only two experiments have revealed some effects in water [3, 4]. However, water is ubiquitous in biological environments, where it plays a vital role. Therefore, the successful operation of PVOT in water is of remarkable interest for potential applications in biotechnology or biomedicine, among others. An interesting approach to circumvent this constraint consists of manipulating aqueous droplets in a nonpolar medium [5-9], which may serve as carriers of particles or biological material [7]. This scheme is currently a very active field of research.

In this work, we show experimentally that it is feasible to employ PVOT in deionized Milli-Q water by using simultaneous light excitation with high intensities. A few years ago, M. Esseling developed a simple theoretical model to describe the time evolution of the PV electric field when the crystal is surrounded by a leaky medium with a non-negligible electrical conductivity [10]. In that model, the buildup of the PV electric field is given by:

$$E_{PV}(t) = \frac{E_{sat}\tau_s}{\tau_{PV}+\tau_s}\left(1 - e^{-t/\tau_0}\right) \quad (1)$$

where τ_s the screening time of the surrounding medium, τ_{PV} the PV response time (inversely proportional to the light intensity), $\tau_0 = \tau_s\tau_{PV}/(\tau_s + \tau_{PV})$ is the effective time constant and E_{sat} is the saturation PV field when the surrounding medium is not leaky (i.e. $\tau_s \to \infty$). Thus, both the saturation PV field and the effective time constant τ_0 depend on the light intensity. Namely, the higher the intensity, the higher the saturation PV field and the faster the time evolution.

Herein, we show the successful operation of PVOT using high intensities of around ~1 kW/cm². At such intensities, the screening time of water is not negligible compared with the PV buildup time,

allowing for the generation of an evanescent electric field (which persists as long as light excitation is maintained). A representative result on a z-cut substrate, using micro-clusters of silver nanoparticles with diameters of ~100 nm, is shown in Figure 1 for two light intensities. For the lower intensity a disk-like trapping pattern can be observed at the center of the light spot, whereas a ring-like shape occurs for the higher intensity. These results could be explained by recently reported numerical simulations of the dielectrophoretic forces exerted by PVOT when operating with z-cut substrates [11]. Nevertheless, the additional interplay of optical or thermal effects cannot be disregarded at such high intensities, and further investigation is required.

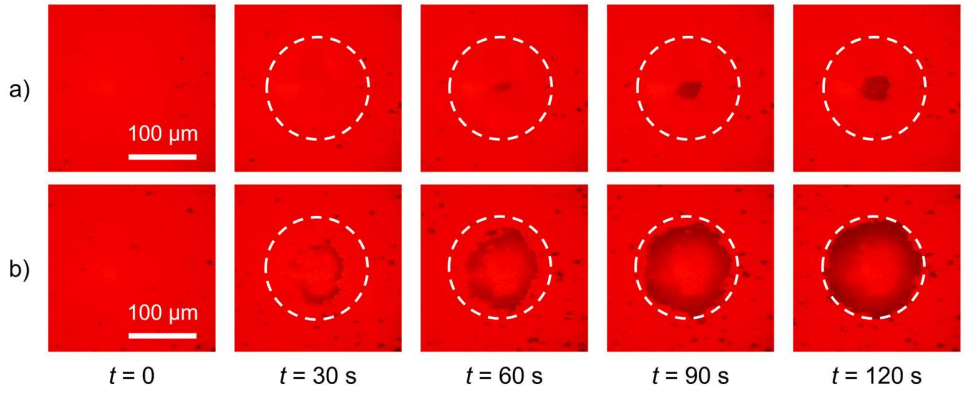

Figure 1: Time sequence of silver particle trapping suspended in Milli-Q water on a z-cut $LiNbO_3$:Fe substrate. At $t = 0$ the substrate is illuminated with a Gaussian light beam ($\lambda = 532$ nm, $1/e^2$ diameter of 150 µm indicated by a white dashed circle), with an intensity of a) 0.97 kW/cm^2, and b) 2.0 kW/cm^2.

Furthermore, when light is switched off, the evanescent field rapidly fades away, allowing us to carry out dynamic real-time manipulation, very constrained in nonpolar liquids due to the long lifetime of the electric fields in the dark. Fruitful results with both z-cut and x-cut $LiNbO_3$:Fe crystals have been accomplished, achieving a long-sought milestone for PVOT.

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