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Optoelectronic tweezers based on photorefractive space charge fields: recent achievements and challenges

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Abstract: We present an overview of the operation of optoelectronic tweezers based on the photorefractive effect, paying special attention to the more recent results achieved by our group. The main challenges faced by the technique to enhance its technological potential are also discussed.

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1. Introduction

In the last decade a new kind of applications for photorefractive (PR) crystals, and particularly for those with high bulk photovoltaic effect, has emerged in the field of nano- and bio-photonics. It consists in using them as substrates to generate light-induced electric fields able to manipulate, trap and pattern micro- and nano-objects. The technique is usually called photovoltaic or photorefractive tweezers (PVT or PRT). First developments typically used LiNbO₃:Fe crystals with the usual orientation, having the polar axis parallel to the surface substrate (*x*- or *y*-cut), to get 1D particle patterns [1]. Initially, the structures had periods in the range of 50-500 μm that later became smaller, up to a few microns. 2D patterns were also attempted, but serious patterning limitations were found due to crystal anisotropy.

In this work, we present very recent achievements that remarkably contribute to develop the technique and its potential applications. We will also briefly discuss several challenges to further enhance the potential of the technique that is expected to become a leading kind of optoelectronic tweezers.

2. Recent results and discussion

2.1 Optimization of 2D patterns

First reported 2D particle patterns using *x*- or *y*-cuts presented the limitation that patterning along directions parallel to the *c*-axis were not possible because charge transport is parallel to the polar axis. An outstanding progress has been to use *z*-cut substrates, an unusual configuration for other PR applications. First work using *z*-cut was reported by Esseling et al. [2]. They used charged particles because they assumed that dielectrophoretic (DEP) forces acting on neutral particles are very weak in this configuration [3]. Nevertheless, using highly doped crystals our group has demonstrated excellent performance for 2D trapping with neutral inorganic micro- and nanoparticles (NP) [3] and biological objects [4]. The experimental results have been accompanied with the development of an appropriate theoretical framework for this configuration [5] that satisfactorily explain the experimental patterns.



2.2 Action on charged and comparison with neutral particle operation

Although PVT are, in principle, able to manipulate both charged and neutral objects via electrophoretic (EP) or DEP forces, respectively, most initial experiments and theoretical calculations dealt only with neutral 1D particle patterning. To expand the possibilities of the technique we have recently investigated charged particle organization in z -cut and compared the differences between EP and DEP trapping by theory and experiments. A series of 2D nanoparticle patterns with charged and neutral aluminum NP on top of LiNbO₃:Fe crystals have been carried out. From these results we have obtained a further confirmation of three key aspects in this field: *i*) The possibility of successful trapping of charged particles, *ii*) the achievement of good quality 2D patterns, and *iii*) the ability of the developed theory to explain the main EP and DEP observed phenomenology.

2.3 Applications

Development of specific applications such as fabrication of metal NP platforms for plasmonic fluorescence (FL) enhancement from organic/biological molecules [6], patterning of micro- or nanometric biological species [4,7] or fabrication of photonic devices (fresnel lens and diffraction gratings) [8] have been recently reported. Another interesting kind of applications of the PV fields is the effective manipulation of micro and nano-droplets recently reported in several papers [9-12]. Let us describe two illustrative examples of PVT applications. First, PVT allow flexible patterning of metal NPs. In Figures 1a and 1b two patterns of Ag NP (25 nm diameter) are shown. After fabrication, and once the PR field has been erased, the samples are covered with a luminescent dye (DR1). Micro-luminescence measurements display in Figures 1c and 1d show a clear plasmonic enhancement (about a factor 10) of the dye FL just in the regions where the NP are located. Similar results have been obtained for fluorescein labeled DNA molecules on the metallic structures. In turn, in Figure 2, some examples of nanometric bio-objects patterning are shown.

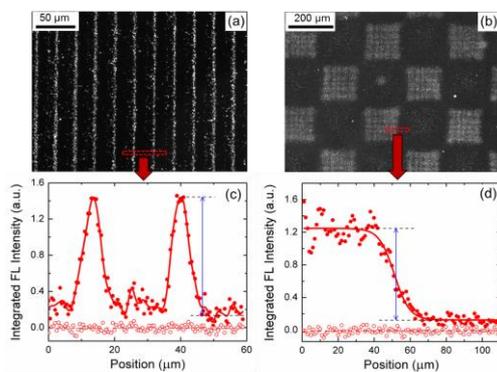


Figure 1: Fluorescence microscope photographs of (a) a 1D fringe patterns and (b) 2D square pattern. (c) and (d) show the corresponding micro-luminescence profiles of a region of the patterns.

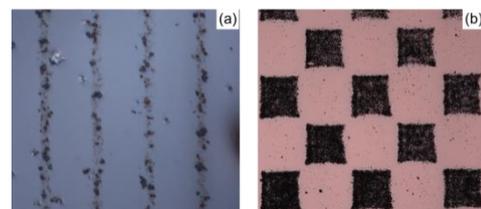


Figure 2: Optical microscope images of 1D fringes ($\lambda=14 \mu\text{m}$) (a) and 2D square (side $200 \mu\text{m}$) (b) patterns of nanometric spore and pollen fragments on x -cut and z -cut LiNbO₃:Fe crystals, respectively.

3. Overview and remaining challenges

The progress of the PVT technique, that we have briefly summarized, is remarkable indicating that it is becoming a very promising and simple method for particle manipulation and massive trapping. However, there are a number of challenges to enhance even more its technological potential. Main challenges, that in principle should be achievable, are: *a*) to enhance the pattern resolution to the nanometer scale, *b*) to increase the reproducibility and control of the deposition process, and *c*) to satisfactorily manipulate and deposit the particles from aqueous solutions favoring biotechnological applications. Further work in those directions should provide key advances in the near future.

Acknowledgments

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