New Trends on Optical Fiber Tweezers

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(Invited Paper)

***Abstract*—In the last few decades, optical trapping has played an unique role concerning contactless trapping and manipulation of biological specimens. More recently, optical fiber tweezers (OFTs) are emerging as a desirable alternative to bulk optical systems. In this paper, an overview of the state of the art of OFTs is presented, focusing on the main fabrication methods, their features and main achievements. In addition, new OFTs fabricated by guided wave photo polymerization are reported. Their theoretical and experimental characterization is given and results demonstrating its application in the manipulation of yeast cells and the organelles of plant cells are presented.**

***Index Terms*—Chemical etch, focused ion beam, heating and drawing, optical fiber tweezers, optical trapping, polishing, two photon lithography.**

I. Introduction

OPTICAL trapping was reported by A. Ashkin in 1970 [1] when, for the first time, micron-sized particles were stably trapped between two counter propagating beams due to the radiation pressure effects. Later, in 1986, A. Ashkin demonstrated the same effect using a single tightly focused optical beam, also named as optical tweezers, to successfully trap particles, in the nano to micrometer size range [2].

The optical force acting on a dielectric particle originates in the momentum transference from the beam to the particle during the reflection and refraction of the photons in its surface. Conventionally, the total force can be decomposed in two components: the scattering force and the gradient force [3]. The scattering force is proportional to the intensity of the electric field, therefore, it is responsible for pushing the particles away from the beam. The gradient force is proportional to the gradient of the intensity of the electric field, resulting in the redirection of the particles into the highest intensity region. In the case of the two counter propagating beams, the balance of the axial scattering forces from the two beams is crucial for the attainment of a stable trap. However, in the case of the single beam trapping, the gradient force plays the major role. Whenever the gradient of the light intensity is steep enough, the axial component of the gradient force can exceed the scattering force, establishing the conditions for attractive forces and zones of zero net force to arise, enabling trapping effects.

To achieve 3-dimensional (3-D) stable trapping conditions, traditionally the laser beam is focused by a high numerical aperture (NA) objective into a tightly focused spot. The implementation of an optical trap apparatus depends on the following elements: a laser, a number of optical components to expand and steer the beam, a high NA objective, an observation system and the sample holder. These systems are usually gathered and adapted to conventional inverted optical microscopes, by externally coupling the laser beam to the objective [4]. In alternative to conventional optical tweezers (COT), complex structured light fields have demonstrated to be of great importance in achieving higher degrees of manipulation and control. This can be attained using the so-called holographic optical tweezers (HOT) by means of computer generated holograms, which are typically achieved via spatial light modulators. In this context, standard Gaussian beams were overcome by special tailored optical beams such as Hermite–Gaussian, Laguerre–Gauss, non-diffracting beams (e.g., Bessel Beams), to name a few. As a consequence, the building up of HOT systems promoted the versatility of more advanced optical trapping devices, including for instance, multi point optical traps or the use of beams carrying optical angular momentum. Such developments were addressed by other authors with abundant details [5], [6].

Historically, the applicability of optical tweezers extends from fundamental disciplines such as atomic physics to broadband areas such as biomedicine. The current literature on cooling and manipulation of atoms, supported by optical trapping tools, reports huge advances in this area [7]–[9]. For instance, a device based on nanostructured optical gratings for magneto-optical trapping of atoms was recently demonstrated [10], opening new opportunities to introduce this technology into more complex environments, such as atomic clocks. In the case of biomedicine there is an overwhelming number of evidences corroborating how advantageous optical trapping can be as an advanced manipulation tool. The use of optical tweezers can be applied for precision measurements ranging from the molecular to the cellular level. In the first case, for example, optical trapping can be used to measure the mobility of enzymes or molecular motors in the dynamics of DNA. In the second, optical trapping at the cellular level (red blood cells, yeast cells, vegetal cells) has provided ample support in a variety of applications on single cell manipulation, stretching, sorting, among others [11]–[13]. Further improvements include the integration of imaging and spectroscopic setups into trapping platforms. The progress and new applications of optical tweezers have been extensively reviewed by several authors [4], [14], [15]. Lately, cutting edge

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improvements were reported by Zhong *et al.* where evidences of trapping and manipulation of *in vivo* red blood cells in a living mice ear capillary [16] were shown. On the basis of the evidences currently available, it seems fair to suggest that optical tweezers are one of the most promising tools for micro and nano manipulation.

Although significant results have been achieved using the COT setups, their utilization is still limited in quite a few environments. For instance, the use of COT systems, which normally have small working distances difficult the focusing of the optical beams in thick samples or turbid media. In addition, cost and portability issues are also obstructions for their widespread use. Conversely, the implementation of optical trapping setups using optical fibers enables miniaturization and low cost systems. Optical fiber tweezers (OFTs) can be integrated in small devices such as optofluidic platforms or catheters introducing the extra versatility needed for more challenging applications in medical and biological environments [17].

Optical fiber trapping was presented for the first time in 1993 by Constable *et al.* [18]. The manipulation of two counter propagating beams using two pigtailed optical sources was the base for the development of optical trapping without external bulk optical elements. In 1995 two pioneering systems were described by Lyons and Sonek [19] and by Ikeda *et al.* [20]. Both configurations were based on lensed OFTs. The first consisted in two counter propagating beams originated from two fibers with spherical tips, which reinforced the tweezing effect, and the second involved just a single lensed OFT. Since then, increasingly sophisticated optical fiber based configurations have been reported exploring a range of fabrication techniques. Presently, in spite of great progress, challenges remain in fulfilling the combination of fiber optics versatility with more advanced trapping and manipulation functions in the context of biological applications.

This paper presents an overview of the state of the art of OFTs, focusing on the main fabrication methods, their features and main achievements in optical trapping. Most recent progresses, main challenges and current trends will be briefly discussed. In addition, this paper also reports on new OFTs fabricated by a rapid and low cost method involving guided wave photo polymerization, as well as their experimental characterization and application in the manipulation of yeast cells and organelles of plant cells.

II. Fabrication Methodologies

The trapping and manipulating capabilities that can be attained with a given OFT are tightly linked with the optical and geometrical features of the fiber tip. In this regard, it is the reliability and versatility of the fabrication technique that determines what can be achieved. While reproducibility and processing simplicity are highly desirable features, the ability to obtain complex shapes is mandatory for some applications. Ideally, both would be available with low cost and rapid processing times, however, most often compromises must be made. Presently, a diversity of well-established fabrication techniques are being explored in the fabrication of different OFT configurations. Polishing, chemical etching, thermal pulling, focused ion beam (FIB) milling and femtosecond laser machining are surely the most important ones. Whereas polishing, chemical etching and thermal processes are essentially low cost techniques, they are often limited to conical and/or spherical tip designs. In contrast, micro fabrication techniques that use FIB milling or two photon polymerization processes allow fabrication of more complex structures, but have the drawback of being expensive and time consuming. Ultimately the goal is to have strong focusing effects at the fiber tip, thus enabling stronger optical forces. This allows to operate tweezers with lower optical power, a critical aspect in many biological applications. In this section a description of these key fabrication techniques will be presented, highlighting their main features and drawbacks together with some relevant progresses reported in the literature.

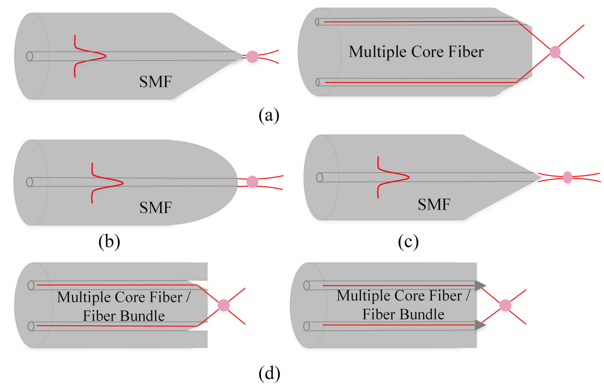

Fig. 1. Schemes of the OFT profiles that can be achieved using distinct fabrication methods (a) Polishing (b) Heating and Pulling (c) Chemical Etching (d) High Resolution Techniques.

A. Polishing

Grinding and polishing is an economical and simple method to micro machine optical fibers. It has been extensively used in the fabrication of optical fiber connectors and is also an important manufacture process of optical fiber sensors. In the context of OFTs applications, it is a suitable process for micromachining optical fibers to obtain lensed profiles. See Fig. 1 for the general OFTs designs. Indeed, the first OFTs reported in the literature by Ikeda *et al.* in 1995 were fabricated using this method [20]. The hemispherical profile used by the authors is the most commonly reported with this fabrication method [21]. One of its main advantages is keeping the guiding characteristics of the waveguides. The focusing of the output light is obtained by reshaping the fiber tip profile. First studies in this area reported on polishing tips of standard single mode optical fibers into spherical-like profiles enabling the 2-D and 3-D trapping of dielectric particles and yeast cells.

With this method curvature radius of some micrometers can be attained. The data gathered by some authors indicates that, with a curvature radius of 2 μm, a minimum of 1.3 mW is necessary to trap a 10 μm polystyrene particle [21]. However, if the curvature radius increases to 6 μm, reducing the focusing power, a minimum of 2.5 mW is required to trap the same particle. Nevertheless, in spite of the small curvature radius, the typical fiber modal profile and refractive index characteristics often result in weakly focused beams, producing relatively small optical forces. For this reason, the spatial arrangement of the polished OFTs, namely the angle and trapping distance, are critical and determine the ability to stably trap the particles. Furthermore, it has been reported that a single OFT is able to trap particles only in the *xy* plane, and dual or multiple fiber configurations are required to levitate the particles against the force of gravity, enabling 3-D trapping [22], [23]. These studies demonstrated that dual OFTs inserted at 35° are able to trap particles located on the bottom of a sample container, and to levitate and move them around. This demonstrates that an equilibrium point can be reached, where the force of gravity and buoyancy, the gradient and scattering forces, all balance.

To circumvent the limitations arising from low focusing power, studies on plural arrangements (two or more fibers) of hemispherical lensed fibers have been performed. Multiple fibers allow not only a more effective trapping, with lower optical powers, but also introduce extra manipulation capabilities like the possibility to rotate non-spherical micro-objects [24]. This rotation effect is caused by the momentum of the force (torque) and is mainly controlled by switching on and off the different OFTs.

More recent trends include the use of special optical fibers introducing the possibility to obtain more advanced configurations by polishing. A multiple core fiber in an annular-distribution (e.g., two, three, or four cores), or even annular-core optical fibers, when polished at certain angles can be restructured to obtain stable trapping devices. The requirement for trapping using multiple beams of light from multiple cores is that the propagation direction of the multiple beams must intersect with an exact angle. To do so, the optical fibers are polished at specific grinding angles, yielding outputs with fixed convergence angles, as depicted in the scheme of Fig. 1(a). The optical beams that are guided through the individual cores are reflected by the edge of the fiber [25]. This causes their intersection at a certain distance from the extremity of the fiber, where the trapping is bound to occur. It was shown that there is a dependence of the working distances of these OFTs with the grinding angle that can be explored in the optimization of the tweezer operational characteristics [26]. With such designs was demonstrated the 2-D trap of single yeast cells, in the *xy* plane. Further experiments using an annular core fiber with a grinding angle of 18° enabled the trapping of a large sphere with 45 μm diameter. Also, the efficiency of the optical trap can be further optimized by increasing the reflectivity of the fiber polished surfaces with adequate coating materials [27].

To summarize, polishing is a reproducible process but somewhat delicate due to the small size of the tips. It allows to obtain micro lenses with good optical quality and small curvature radius and is compatible with batch processing. However, due to intrinsic characteristics of standard fibers the resulting OFTs have low focusing power requiring the use of higher optical power to enable effective trapping effects. Nevertheless, it has been shown that using multiple tweezers can improve trapping abilities. In addition, more recent trends are establishing polishing of special multi core fibers as a method to obtain more versatile optical trapping devices.

B. Thermal Pulling

The heating and drawing process is frequently employed in the fabrication of tapered optical fibers. These structures are normally used as evanescent optical sensing probes, since the core of the fibers is also tapered exposing the optical field to the surrounding medium [28]. In the context of OFT, the heating process can be used to fabricate micro lenses on the extremity of optical fibers (see Fig 1(b)). Like the polishing and etching processes, this is also a relatively simple and inexpensive fabrication method, widely explored in the context of OFT applications. The heating process, which can be carried out by a flame, a CO_2 laser or an electric arc is applied to soften the fiber near the melting point. Simultaneous pulling, in a controlled fashion, allows to obtain distinct adiabatic or abrupt taper profiles. Adiabatic tapers usually result in very small focusing distances. To obtain devices with higher working distances, usually multistep drawing stages are required. The control of the final tip shape is very delicate as it depends on the fiber breaking. The technique is not amenable to batch processing. Nevertheless, several authors have reported distinct applications using different types of thermal tapers.

In 2006, Liu *et al.* explored the use of an abruptly single mode tapered optical fiber, for 3-D trapping of yeast cells in water, manufactured by heating and drawing technology [29]. The fiber was primarily heated and right away drawn. By changing the drawing speed from 0.03 to 0.32 mm/s the diameter of the fiber was reduced from 125 μm to about 10 μm with a length of 600 μm. This tapered section of the fiber was subsequently drawn at 1.6 mm/s until the fiber broke in the waist position. Consequently, a parabola-like profile, with a curvature radius of approximately 5 μm (estimated from the picture in reference [29]) was formed at the fiber tip due to the surface tension of the fused silica. With this probe the trapping of yeast cells was achieved. After this paper several others reported similar OFTs fabrication procedures [30], [31]. The main difference among the fiber probes reported rely on the final optical fiber taper profiles and their focusing capabilities. Wright *et al.* demonstrated that laser beams with a beam waist superior to 0.7 μm cannot 3-D trap dielectric particles [32]. Therefore, this is a crucial parameter that will define if the 3-D trapping can or not be achieved by a given OFTs.

Later on, Xin *et al.* demonstrated the manipulation capabilities of a tapered OFT [33] with a hemispherical tip of 1.6 μm in diameter. Exploring the effects of push, pulling and trapping at different distance of the focal point, the OFTs were used to perform trapping and arrangement (linear chains) of multiple particles [34]. Also, a sharper probe (380 nm diameter) was used in a microfluidic platform to study *E. coli* bacteria dynamics [30]. Rather than a standard taper a more abrupt profile yielding larger focusing distances and enabling truly contactless trapping of *E. coli* bacteria [31] was tested. In this particular case, the fiber tip, submitted to a multi-step drawing process, had a protruding tip, which caused a tighter focusing and the extension of the trapping region. Thus, *E. coli* bacteria (1.7 μm length and 500 nm diameter) were trapped without physical contact and a detailed study on the bacteria dynamics was performed: the motility of the bacteria and the conditions for a stable trap were evaluated.

In order to reduce the necessary optical power to trap a single particle, OFTs fabricated by the heating and drawing method based on the use of multiple core fibers, can be used. In this method the multiple core fibers are tapered, resulting in multiple beam interference at the hemispherical tip. In such cases, besides reducing the optical power required for trapping, the interference features may be used to attain a higher degree of control. For instance, Yuan *et al.* reported the use of a dual core OFT for single particle manipulation, where the lensed fiber is linked to a Mack–Zehnder interferometer [35]. By bending the interferometer, the phase of the beams is modified and the orientation of the particle is changed, due to changes on the output field distribution. In this case the optical power threshold was 1 mW and the experiments were carried out using a maximum of 5 mW that produced a 5 pN force. More recently, Barron *et al.* reported a lensed four core OFT for manipulation of multiple particles at the same time. In this case the interference of the four beams formed a square lattice profile, located at approximately 250 μm from the fiber tip, having intensity maxima separated from each other by 2.75 μm. In this case the particles were trapped in the high intensity points of the lattice, enabling simultaneous multiple traps.

Thermal pulling methods allow obtaining a diversity of tapered profiles. However, to attain versatile OFTs, somewhat delicate multi-step fabrication processes are often required that preclude batch processing. Nevertheless, the use of multicore fiber can is now enabling trapping probes with higher degrees of control.

C. Chemical Etching

Chemical etching methods have been extensively employed in the fabrication of tapered fiber probes for Scanning Near-Field Optical Microscopy (SNOM). Etched fiber tips also play an important role in a diversity of sensor applications [36]. It is a well-established method, compatible with batch processing and relatively simple to implement at a low cost. Nevertheless, it can be time consuming and requires the use of very dangerous chemicals, such as hydrofluoric acid (HF). Reproducibility and low surface roughness can be obtained only at the expense of a tight control of processing and environmental parameters such as temperature, concentration and vibration. Also, the accumulation or diffusion of reaction products can play a critical role in the outcome and should be carefully considered. Often improved control requires the use of extra chemicals or alternative techniques such as gas phase etching [37]. In spite of these challenges, etching methods are very attractive in the context of OFT as they allow obtaining conical surfaces at the fiber tip (see Fig. 1(c)). Conical tips with adequate parameters are the precursors of axicon lenses, which enable to have Bessel beams. These are highly attractive for trapping applications as they can maintain their tight focus characteristics for extended ranges, even after interacting with target particle. Such features enable, for instance, to simultaneously trap several particles.

In the context of OFT two main techniques are used for fabrication of conical axicon tips: the liquid protection layer, or "Turner method" [38], [39], and a variation called the tube etching method [40]. In the first method the optical fiber is immersed in a HF solution having a protection overlay of a lower density organic liquid, typically Silica oil. In this case, the fiber tip is formed at the interface between the etchant solution and the protection layer. The taper is formed due to the gradually reducing height of the meniscus as the fiber diameter is reduced by the etchant solution. This is a self-terminating process where the relative surface tensions determine the meniscus features and the resulting tip angle. Modifications of this process, such as use of different overlay materials, or multi step etching, allow to obtain different tip profiles. In the second process, the fiber is immersed in the etchant solution without removing the polymer coating. Therefore, the etching occurs inside the fiber buffer layer, where micro convection and transient capillary effects concur for a more stable etching process. Indeed, tube etching was shown to be more insensitive to environmental parameters resulting in tips with lower surface roughness. The large cone angles obtained were mostly dependent on the type of fiber used.

In 2008, Mohanty *et al.* described the use of an axicon optical fiber, produced using the tube etched method, for the trapping of low refractive index particles [41]. The apex angle of the fiber tip was approximately 17°, producing an output beam with a donut profile (minimum at the center surrounded by a symmetric maximum). This allowed the 3-D trapping of the water droplets in an acetophenone solution (5 to 9 μm in diameter), at large distances from the fiber (tens of micrometers), and using optical powers in the range of 17 mW to 30 mW. The authors concluded that placing the fiber horizontally would cause only an axial trapping of the droplets, but if the probe was fixed at angle (45°) or vertically, both axial and transverse trapping could be achieved. This demonstrated that at an angle, the scattering force can be balanced with the buoyancy force, contributing for stable trapping in the transverse direction.

Studies of the influence of the apex angle on the working distance (near filed or far field) of the OFT have also been reported [42]. An axicon with an apex angle of 60° produced an output Bessel beam profile demonstrating stable trapping of multiple particles arranged in a linear chain, at 5 μm from the fiber tip, at 146 mW (far field trapping). For smaller apex angles, $\leq 30^\circ$, there is a total internal reflection effect on the conical tip. This way, the amount of light transmitted through the fiber is decreased and the trapping of particles can only be attained very close to the fiber surface (near field trapping).

While it is relatively easy to obtain axicon lenses with a broad range of apex angles using the methods just described, the diversity of shapes obtained with standard fibers is relatively limited. Nevertheless, more recently, new studies using chemical etching of different fibers promise more sophisticated configurations for the fabrication of axicon like profiles. A segment of graded index fiber (GIF) spliced to the end of a standard single mode fiber (SMF) and subsequently etched [43] allows to obtain different tip profiles. The authors pointed out that the use of a GIF, which produces a periodically self-focusing effect may increase the trapping efficiency when compared with conventional optical fibers. Also, since the etching rate depends of the fiber doping profile, using special fibers with pre-optimized refractive index profiles can be a route to easily obtain exotic tip shapes using etching methods. Such approach has been explored in the design of some sensing devices and is bound to be a new trend to explore in the context of OFT [44].

In a nutshell, chemical etching is a well-established low cost technique, requiring a tight control of processing parameters. It is a straightforward method to obtain axicon tips and Bessel beam OFT using standard fibers, and it holds great promise for more sophisticated shapes if fibers with special doping profiles are made available.

D. High Resolution Micromachining

High resolution micromachining techniques that are available allow to directly write complex patterned structures in a diversity of substrates. While such methods are usually associated with very expensive instrumentation, and are often time consuming, they are unique choices for advanced prototyping and test of new devices. In the context of OFT, micromachining techniques are still little explored. Nevertheless, representative examples are reported using FIB and two photon lithography (TFL).

The FIB is a method that enables simultaneous micro/nano imaging, deposition and controlled milling. It is usually inserted in a double system composed by an ion Ga^+ ion source and an electron source, the so-called scanning electron microscope (SEM) [45], [46]. The SEM enables image acquisition through the scanning of the sample using a focused electron beam. Whereas, in the FIB system the Ga^+ ions are accelerated to and focused in the sample surface. The ions are accelerated by means of a differential voltage and are focused using special electrostatic lenses. The accelerated ions allow milling away the substrate material with resolutions of the order of a few nanometer.

FIB micromachining tools have been used to accurately fabricate special structures on the top of optical fibers, allowing to improve some of the features achieved so far using lenses fabricated by more conventional methods. In a pioneer work, FIB milling technique was used in the fabrication of very precise axicon lenses to produce high quality Bessel beams. The tweezers fabricated in this way were used for successfully trapping 2 μm polystyrene beads, and water bubble of different sizes, at different distances from the fiber tip [47]. The authors were able to solve some issues regarding the linearity of the milling process by carefully adjusting the ion dose along the designed pattern. While focusing on a model structure such as an axicon, the quality of the results clearly demonstrated the potential of FIB tools for prototyping more complex tweezers.

In 2007, a new ground-breaking OFT configuration was reported by Liberale *et al.* [48], [49]. In this paper, a high NA OFT bundle was described and demonstrated with 3-D trapping of polystyrene spheres. The authors studied the effect of total internal reflection on the interface of the fiber to the surrounding medium, and its influence on the focusing of the beam. To do so, they considered an annular core fiber with a reshaped surface as a model. The calculations indicated that the trapping position should be located at approximately 35 μm from the fiber and that the NA for this structure would be around 1.06 (akin to standard COFs). Experimentally, the design was achieved using a four fiber bundle structure, as described in Fig. 1(d). The fibers were placed in a capillary, with 200 μm of inner diameter, 360 μm of outer diameter and fixed with an epoxy resin. Optical fibers with 80 μm cladding diameter and SM at 1060 nm were used. Then the fiber-end surfaces were polished and covered by a metallic film (to decrease charging effects during the FIB milling). Finally, the structures were drilled to obtain micro indentations at specific locations and with very precise angle on the top of the fibers, using a beam current of 20 nA. This way, both the location of the interference spot and the crossing angle of the multiple beams could be controlled with very high precision. To validate this new approach, the probes were tested for trapping of 10 μm fluorescent polystyrene particles where 3-D trapping was demonstrated. This way, the fibers were tested for trapping and simultaneous collection of the fluorescent signal resulting from the excitation of the beads. Both trapping and sensing capabilities of the fiber bundle were accessed, and validated. The authors choose to use a multiple fiber bundle instead of an annular fiber to enable specialization of each fiber.

More recently, a very similar configuration was demonstrated, this time using another alternative for the fiber micromachining, namely, high resolution TPL [50]. This is a modern technique used to fabricate 3-D nano and micro structures. This method is based on the two-photon absorption effect, which is accomplished when a high intensity very short laser pulse is focused into a very small spot of light inside the polymer. Because this is a non-linear process polymerization occurs only above a certain intensity threshold level. This way, the laser can be scanned through the sample and a 3-D isolated structured can be formed within the polymer. The remaining non polymerized material can be dissolved and the structure is revealed. The main advantages presented by this technique are: 3-D resolution, sub-diffraction spatial resolution ($\sim$100 nm), high penetration depth, and ability to be applied in a diversity of materials [51]. While the fabrication process can be very fast, the associated instrumentation is relatively expensive. Nevertheless TPL is also a fast prototyping technique.

In 2010 Liberale *et al.* presented the fabrication of several optical lenses on the top of optical fibers by TPL [52], including spherical and conical profiles, and also a ring phase mask. After this pioneer work, a second OFT configuration, also based on the TIR of light, using micro prisms instead of the milled structures on the top of the optical fibers was reported by the same group. [53] (see Fig. 1(d)). In this case the optical output beams are deflected by the surface of the prisms, to obtain the high NA. Both the working principle and the outcomes achieved with this fiber are quite similar to the ones presented before with the FIB milled fiber bundle. These works were extensively reviewed in chapter 8 of reference [54].

While more recently other structures fabricated by TPL were reported, including micro axicon lenses [55], this technique is still little explored in the context of FOT. Indeed, high resolution micromachining technologies such a FIB and TPL are very convenient for the prototyping of new complex structures. However, the associated instrumentation is expensive and is not readily available for the average user. Nevertheless, the potential for innovation is very high and will surely be explored as the technology becomes more widespread. Such could be the case with the TPL, and other 3-D printing systems which are being the subject of rapid evolution.

E. Other Fabrication Methods and OFTs Configurations

A diversity of other works has been reported using techniques that do not fall into the previous categories or use combination of different approaches that are worth mentioning. In 2013 Kim *et al.* reported an OFT configuration for the generation of Bessel beams to be integrated in microfluidic environments [56]. In this work the authors presented a hybrid optical probe composed by three segments of optical fiber (SMF, hollow optical fiber (HCF) and coreless silica fiber (CSF)) and a polymeric lens at the tip. With such arrangement the Gaussian mode guided by the SMF is transformed in an annular mode in the HCF, then it is expanded in the CSF and focused by the converging polymeric lens. The output beam at 1064 nm is non-diffractive over a distance of ~1 mm. The validation of this working principle demonstrates that bulk optical elements can be replaced by common optical fibers, enabling to have miniaturized devices. In this particular case, three optical probes were integrated in a microfluidic chip allowing to guide dielectric particles through a specific path.

Later, Chen *et al.* presented an OFT configuration both for trapping, rotation and translation of yeast cells [57]. In their work, a 650 nm laser was coupled into a graded index fiber with a conical tip. Then, the LP_{21} mode was pre-selected by adjusting the coupling angle, and was converted into a Bessel-like beam by the axicon lens. Using this probe they accomplished trapping of a single cells and of a two-cell dimers. Using a fiber rotator, the fiber could be twisted and bended, causing the rotation of the primary LP_{21} mode, and consequently a rotational torque, enabling to control the rotation of the dimer.

These two examples do not follow any specific fabrication methodology, on the contrary these works focus on the intrinsic guiding characteristics of the fibers, and the ability to change them using either combinations of distinct optical fibers or coupling light methods. This kind of approach establishes what will probably be the paradigm in the next years where the different fabrication techniques described will be used with special fibers and combined with modulation of its modal features to obtain more advanced OFT devices, with a higher degree of control of its trapping ability, suitable to perform more complex operations with biological samples.

III. New Polymeric OFT

Historically, the development of micro structures on the top of optical fibers extends far beyond optical trapping applications. In fact, over the years, efforts have been made to optimize the coupling of lasers to optical fibers, using these type of structures. In 1974 Cohen and Schneider presented a method for the fabrication of micro lenses on the top of optical fibers through photolithography [58]. However, despite the merit of this fabrication process, no more advances on this technique were reported. After a couple of decades, in 2001, Bachelot *et al.* presented a new low cost and fast method for the fabrication of polymeric micro structures on the top of optical fibers by free radical photopolymerization [59]. Essentially, the fabrication of the structures is achieved by depositing a photo sensitive liquid on the top of a cleaved fiber, and by coupling polymerizing light to the fiber. As the polymerization occurs, a guiding effect takes place that results in the formation of a self-assembled structure at the fiber tip, that is auto aligned with the fiber core. Research on this area has provided ample support for the use of the polymeric structures in several applications: as diode lasers to waveguide couplers [60], as refractometric sensors [61], and as luminescent optrodes for chemical sensing [62]. Nevertheless, in spite of great potential, so far the method was not explored for OFTs. From the authors knowledge there is only one case where two polymeric flat tips are used as counter propagating waveguides [63]. In this regard, the remaining content of this paper is devoted to explore the potential of the micro structures as single OFTs. In the following sections, the fabrication of new OFT by guided wave photo polymerization is reported, and its use in 2-D cell trapping and cell organelle manipulation is demonstrated for the first time.

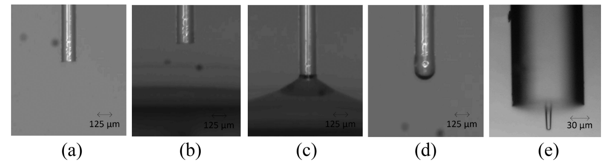

Fig. 2. Images illustrating the different fabrication steps of polymeric structures at the extremity of an optical fiber.

A. Fabrication Technique

The formulation used for the fabrication of the polymeric structures is composed by pentaerythritol triacrylate (PETIA) and Irgacure 819, which are the monomer and the initiator, respectively. The initiator is sensitive to a wavelength range between 375 and 450 nm. Therefore, a violet 405 nm diode laser was used in the photo-polymerization process. The procedure to fabricate the micro structures is illustrated in Fig. 2.

During the entire process a camera is used to verify both the fiber conditions and the fabrication development. First, an optical fiber is cleaved and placed vertically in a moving stage (see Fig. 2(a)). At that point, it is slowly dipped (see Fig. 2(b)) into the solution (see Fig. 2(c)). Then, the fiber is removed from the polymer allowing a drop of the solution to form in its extremity (see Fig. 2(d)). Next, the polymer is illuminated and consequently cured. To finish, the remaining liquid solution is washed out with ethanol, revealing the polymerized micro structure at the fiber tip. The visual aspect of the resulting polymeric tip is shown in Fig 2(e).

The polymeric structure is formed by means of a self-assemble photo-polymerization effect [60], [64]. This means that during the solidification of the polymer, its refractive index increases, creating a guiding effect that prevents the radiation from scattering in the remaining of the drop. Therefore, the resulting structure generally has a diameter close to the fiber modal diameter and the length determined by the initial polymer drop thickness. Particularly, the geometry of the structure can be finely adjusted by selecting the appropriate fabrication conditions, such as, laser intensity, irradiation time and pre-excited mode profile of the optical fiber.

For these particular tests, typical power values at the tip extremity and exposure times used were approximately 6 μW and 10 s, respectively. The optical fibers used in this experiment are single mode at 980 nm (Thorlabs SMF980, 5.8 μm modal diameter), which means that they will behave as a multimode fiber at the polymerization wavelength, 405 nm. In this sense, the structure of the tips will depend on the specific mode that is excited by the laser in the multimode waveguide, because during the polymerization the mode profile is imprinted on the shape of the polymeric structure. Therefore the way light is injected into the fiber will have an important role in the final result. A scheme of the setup used to couple the free space laser to the optical fiber is depicted in Fig. 3(a). The laser is coupled to the optical fiber using two mirrors, and a fiber coupling system. Both the mirrors and the fiber coupling system can be tilted and

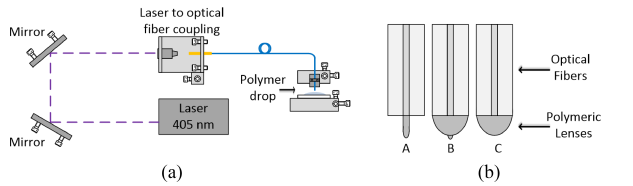

Fig. 3 (a) Experimental setup used to fabricate the polymeric tips. (b) Scheme of the different polymeric lenses that can be achieved using the photo-polymerization process.

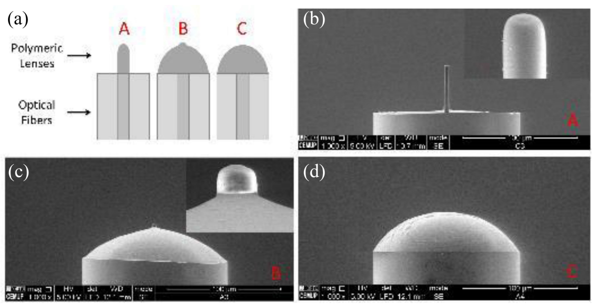

Fig. 4. SEM images of the polymeric lenses: (a) Tip A, (b) Tip B, (c) Tip C.

translated with micrometer precision. In this regard, it is possible to adjust the input angle of the laser to the optical fiber, and specifically, pre-select which guided mode is excited, and applied in the polymerization process. With this method, it is possible to have structures with various designs, which can be tailored for specific applications. Additional details on this special feature of the fabrication method and their outcomes are described in reference [65].

In the first scheme of Fig. 3(b) one can see the typical aspect of the long and thin polymeric structure on the top of an optical fiber attained with the process described above. Due to its aspect ratio, such structure can present some fragility. However, if the drop of polymer located at the top of the optical fiber is illuminated externally (sideways), the entire drop can be polymerized. Therefore, a lens/structure covering the entire optical fiber cleaved top can be formed. Such type of structure can be visualized in the scheme of Fig. 3(b). In this case, the final characteristics of the outer layer obtained are governed only by the polymer drop features such as viscosity and thickness. In practice, the two approaches can be used in combination to obtain different types of structures, having tips with different curvatures and also a mechanical reinforcement effect. Some examples of structures that can be fabricated using these methods are described in the next section.

B. Structures Design

In order to verify the utility of the polymeric structures as OFTs, three distinct configurations (A, B and C) were fabricated, as represented in Fig. 4(a). The different types were then tested and compared for optical trapping of yeast cells.

The structure of type A is a single tip. It has a length of $\sim$48 μm and a curvature radius of 3 μm. It was fabricated by guided wave photo-polymerization exciting the LP_{02} mode in the 980 SM fiber. Consequently, the profile of this mode (two concentric rings) was imprinted on the end of the polymeric structure, and a nearly spherical tip was obtained, as can be seen if Fig. 4(b). The power and exposure time used were 6 μW and 10 s, respectively. The diameter of the tip is approximately 6 μm, matching the fiber mode field diameter.

In the second case, the structure B is composed by an inner tip, similar to type A, surrounded by a reinforcement structure. For this case also the LP_{02} mode was excited in the optical fiber. The inner structure was fabricated using the same process and parameters used for type A. However, after this first step, the resulting micro structure was dipped in the polymer again, and was illuminated externally. This way, the whole drop was polymerized forming a protection layer to the original micro tip, as can be seen in the SEM image in Fig. 4(c). The tip was exposed during 30 seconds to 10 mW of 405 nm radiation, directly from the laser. The final characteristics of the lenses were: a curvature radius of 3 μm, and a length of 35 μm, for the inner lens, while the protective structure has a curvature of 65 μm and a length of 30 μm. This means that the inner lens is not totally covered by the protection layer, and it stands out at the tip extremity as can be seen in Fig. 4(c).

Finally the structures of type C, were achieved making a larger protection layer totally covering the inner polymeric micro lens. The SEM Fig. 4(d) shows a lens of 40 μm length and 65 μm curvature radius. In the example shown in Fig. 4(d), the lens of type C was obtained by submitting twice a lens of type A to additional dipping and external polymerization steps, using the same power and exposure time settings. In this particular case, the same polymer was used in both instances. With no optical contrast the whole structure will behave as single spherical lens with a curvature radius of 65 μm. Nevertheless, the use of polymers with different refractive indexes can be explored to further control the light confinement in the first micro lens, and adjust the overall result of the lensed fiber tip.

To sum up, this fabrication process is a fast (some seconds) and low cost way to produce spherical like lenses, with high reproducibility, and good optical quality (as can be seen in the images of the fiber tips).

C. Computational Models

To better evaluate the potential of the new polymeric structures presented in this paper a theoretical analysis was made that is described in this section. Indeed, the performance of the new fiber tips as OFT can be investigated using computer simulations which allow to determine the intensity distribution of the optical field and how it is scattered by the particles. From this distribution it is possible to compute the optical force by calculating the Lorentz force acting on the dipoles that compose the particles, as described by Barnett and Loundon [66]. According to this, the Lorentz force density is given by

$$\vec{f} = (\vec{P} \bullet \nabla)\vec{e} + \frac{\partial \vec{P}}{\partial t} \times \vec{b} \tag{1}$$

where $\vec{P}$, $\vec{e}$ and $\vec{b}$ are the microscopic polarization, electric and magnetic field, respectively. Combining Eq. (1) with the microscopic Maxwell equations [67], and the macroscopic polarization, $\vec{P} = \frac{1}{2}\varepsilon_0(\varepsilon_p - \varepsilon_m)\vec{E}$, and knowing that for a stationary field the second term in the equation vanishes, it yields

$$\vec{f} = \frac{1}{2}\varepsilon_0(\varepsilon_p - \varepsilon_m)\nabla\vec{E}^2, \tag{2}$$

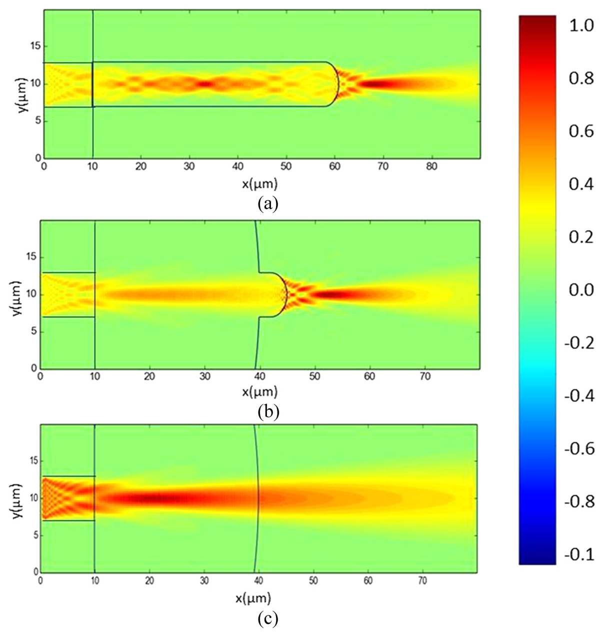

Fig. 5. Field intensity profile for tips A, B and C, respectively.

where ε_0 is the vacuum permittivity, ε_p is the particle relative permittivity and finally ε_m is the relative permittivity of the medium where the particle is immersed.

Equation (2) expresses the optical force density in terms of the optical power E^2, which can be calculated using a solver of the electromagnetic field. In the presented computer simulations the calculations of the net optical force was done in two phases, as described in [68]. First it was used the implementation of the finite differences time domain developed at the Massachusetts Institute of Technology, called MEEP. For simplicity, due to the symmetry on the structures, the simulations were performed in 2-dimensions. Using the described computational model, the solutions of the electromagnetic field propagation over the structures A, B and C, were calculated. These structures were composed by the waveguide, the tip and a dielectric particle, corresponding to the trapping target. Then, with the field distribution obtained from the MEEP solver, the total force acting on the particle could be calculated by integrating Eq. (2) over its volume.

The dimensions of the structures simulated where set according with the experimental measured values, as described for structures A, B and C. In Fig. 5 one can identify the structures outline design in the graphs. The waveguides were considered to be immersed in water ($n = 1.327$ at 980 nm) and the refractive index of the polymer and particle was considered 1.52 and 1.40, respectively. The value of the refractive index of the fiber core and cladding at 980 nm was set to 1.458 and 1.451, respectively, as provided by the manufacturer.

In Fig. 5 the electromagnetic field intensity profiles for the three structures are shown. As follows from the graphs, generally the polymeric structures A and B act as diffractive structures, creating strong field gradients at their output creating some focusing spots. Structure C, on the other hand, has a mild focusing effect on the fiber output. Overall they all produce distinct output field distributions due to their different structural characteristics.

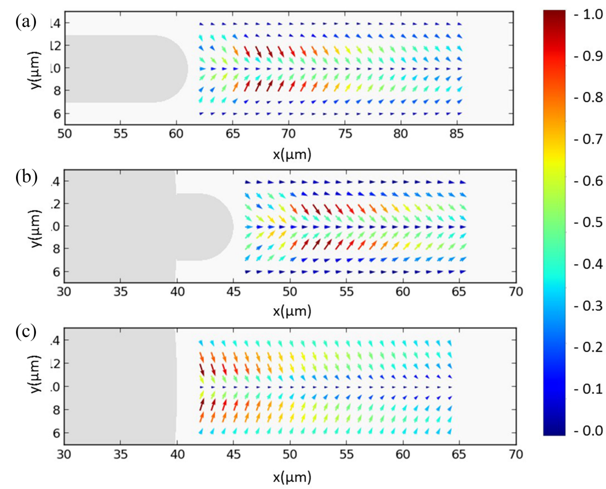

Fig. 6. Forces fields for a particle of 4 um diameter for lens A, B and C, respectively.

In case of structure A and B both produce a tightly focused profile, and the beam waist is located ∼7 μm from the polymeric tip end. This proves that the protective lens does not have an effect on the output of the optical field. Regarding the beam waist of lens C, on the other hand, it is located exactly in the lens to medium interface. The low focal power of the lens is caused by the high curvature radius, 65 μm. This way, structure C causes almost no focusing effect, but slightly reduces the divergence of the beam.

The calculations of the radiation force can be done for different positions of the particle, to obtain the spatial distribution of the optical forces. The resulting "force field" distributions for lens of type A, B and C can be observed in Fig. 6(a)–(c), respectively. According to the results, all the three tips produce a net force which attracts the particle into the optical axis, therefore, suitable for trapping experiments. Once again, there are details that differentiate them. Due to the similar intensity profiles, lens A and B cause an analogous force distribution. As can be seen in Fig. 6 when irradiated through these micro lenses the particles experience forces that redirect them to the optical beam axis and a transversal confinement is produced. For tips A and B the maximum gradient regions extend for 10 μm and are quite similar (see Fig. 6(a) and (b)). The difference between tip A and tip B is located in the outer regions. In the case of tip A, away from the beam axis, there are almost no optical forces acting to redirect the particle, whereas tip B produces a more intense force field as can be seen in Fig. 6(b) pushing the particles away. The tip C, also produces an attractive gradient distribution, characterized by a transversal confinement of the particle, however, this is located much closer to the end of the tip (see Fig. 6(c)). According to these simulations it is expected that tips A, B and C are able to guide and trap micro particles, although causing different force fields.

D. Experimental Results

1) Optical Manipulation of Yeast Cells: In order to test the optical probes fabricated, an experimental setup was assembled. It is composed by an inverted microscope connected to an image acquisition system, enabling the visualization of the optical fiber

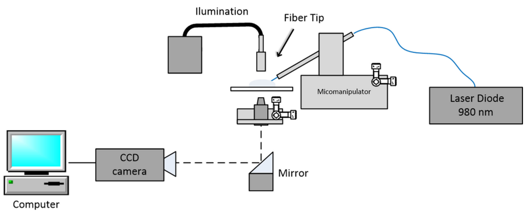

Fig. 7. Optical manipulation setup.

micro lenses immersed in a sample. The setup can be seen in Fig. 7. A pigtailed 980 nm laser diode was connected to the optical fiber probes. The micro lensed fiber was placed within a capillary and then it was carefully positioned on a 4 axis motorized micromanipulator (*x, y, z* and angular). The probe was tilted at 35°. After this, a drop of the sample was placed on a glass slide over the inverted microscope setup, and the tip was immersed. The sample was composed by yeast cells with average diameters of 4 μm in deionized water. Average laser powers of 40 mW were used.

The video frames of the trapping experiments are presented in Fig. 8. The first set of images show the trapping of yeast cells by a probe of type A (see Fig. 4(b)). The cell marked as A was first isolated from the other cells (see Fig. 8(a)). Then, it was trapped by the fiber probe and was pushed towards cells in position B. When irradiated the cells in B were aligned due the transversal force field (see Fig. 8(b)). In Fig. 8(c) the three cells were aligned together. In Fig. 8(d) and (e), it is visible the particles being pulled to $+x$ and $-x$ directions. This shows that this type of structures produce strong enough transversal gradient fields to pull the particles along the x directions. However, pulling the particles along the $-y$ direction was not possible, it was only possible to push and align them along the $+y$ direction.

The second group of images shows the 2-D trapping of yeast cells by tip of type B (see Fig. 4(c)). The cell marked by the square is the reference yeast that does not move during the whole experiment. Therefore the reader can use it as a reference to identify the movement of the trapped cell. One yeast cell was first trapped (see Fig. 8(f)), then it was pulled along the $-y$ direction (see Fig. 8(g)). In Fig. 8(h) the cell is moved along $+x$ direction. After this it was pushed along the $+y$ direction (see Fig. 8(i)), and then it was moved towards the reference cell (see Fig. 8(j)).

The last group of images also shows the 2-D trapping of yeast cells using tip of type C (see Fig. 4(d)). Once again the cell in the square is the reference cell and the trapped yeast is in marked by the circle (see Fig. 8(k)). First the yeast is driven in the $-y$ direction, and then it is moved along the $+x$ direction. After this, it is pushed along $+$y and finally it is dislocated along $-x$. These results clearly demonstrate 2-D trapping of yeast cells using polymeric micro lenses.

Although the lens of type A have shown effective trapping of the cells, overall these lenses produced a weaker trapping effect than in structures of types B and C, both enabling 2-D trapping. For structure A it was observed that the minimum power necessary to trap the cells was higher when comparing to tips B and C. This can be caused by the losses at fiber to polymer interface, reducing the overall power available in the focal point. In addition, these types of lenses are more fragile, meaning that they are likely to break or detach from the fiber when in use. Tips B and C, on the other hand, did not displayed considerable losses at the fiber polymer interface, and are both very resistant due to the second protective polymer layer. Considering tip B and C, tip B demonstrated to be more effortless in positioning and moving the cells than tip C.

2) Optical Manipulation of Organelles of Plant Cells: The large dimension of plant cells is normally out of the OT manipulation range. In this regard the manipulation of the cell itself, using the relatively low powers needed to avoid damage, is hardly feasible. However, the cells present an internal structure having several organelles with sizes of a few microns. Therefore, these internal structures of the plant cells, are suitable targets for manipulation using optical trapping effects.

Indeed, using the reinforced version of the polymer tweezers it was possible to demonstrate for the first time the ability to manipulate internal organelles of *Medicago Sativa* cells. This demonstration configures a truly non-invasive way of manipulating the internal structure of a cell.

An example of such features can be observed in the set of images in Fig. 9 where the movement of some organelles inside a vegetable cell by action of the optical tweezer is shown.

Overall the results obtained demonstrated the suitability of guided wave photo polymerization as a very attractive technique for the fabrication of OFT. It is a rapid low cost process suitable for batch processing. Combination of this technique with different fibres, selective modal polymerization and indicator dyes has a strong potential for the design of new OFT with advanced capabilities of manipulation and sensing.

IV. Concluding Remarks

The ability to trap and manipulate micro particles and single cells with light is already established as a very useful tool for many applications. More recently, efforts are being made to bring the trapping abilities to the tip of optical fibers, thus increasing the versatility and usefulness of optical tweezers while decreasing overall system complexity. In this context, a diversity of different techniques is being explored for the fabrication of microstructures at the fiber tip, capable of creating the strong intensity gradients needed for optical trapping. Most successful methods include, polishing, thermal pulling, chemical etching and micromachining. Most important features of each technique were discussed in this paper, and are summarized in scheme of Fig. 10, alongside with the new photo-polymer based OFTs reported here.

Polishing is a low cost and reproducible technique allowing batch fabrication of OFTs. However, the geometries of the fiber tips are restricted to spherical or elliptical profiles, with low focusing ability, being most of the times limited to 2-D manipulation of the specimens. More complex 3-D trapping is only attainable using multiple fibers. Nevertheless, the polishing of annular or multiple core fibers enables multiple beam OFT with improved trapping capabilities.

Thermal based processes share similar limitations in terms of achievable tips shapes (spherical and elliptical). While it is also a low cost technique it lacks reproducibility and is not amenable to batch processing. Nevertheless, it is an attractive technique for straightforward OFTs applications, and more advanced features

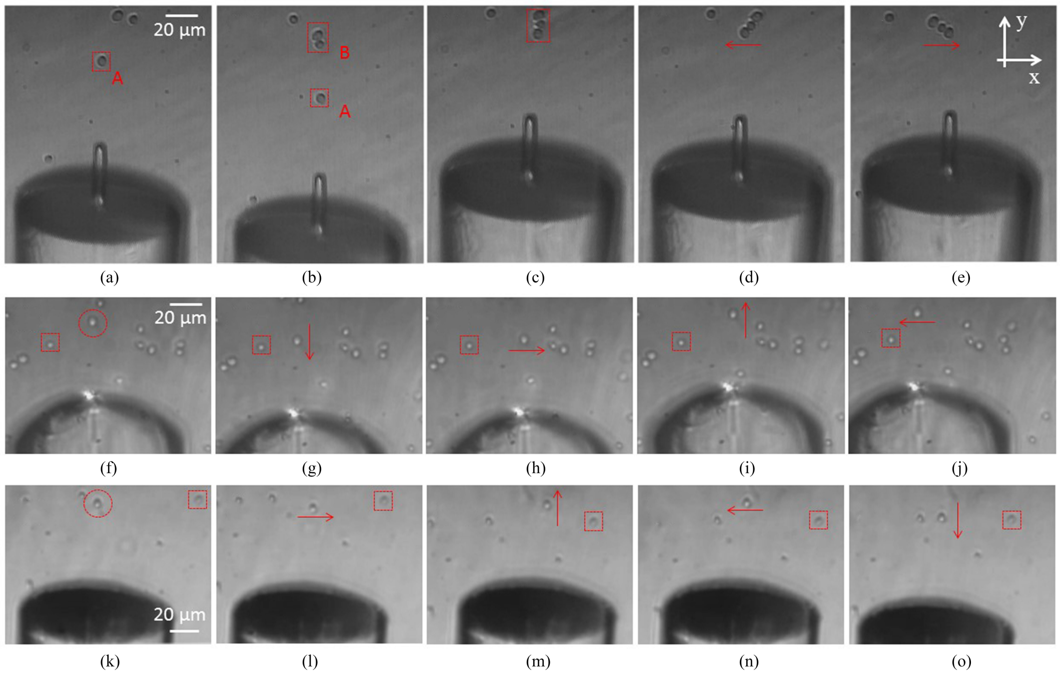

Fig. 8. Video frames of optical trapping of yeast cells (∼4 μm diameter) experiments using tip A, (a) to (e), tip B (f) to (j), and tip C (k) to (o).

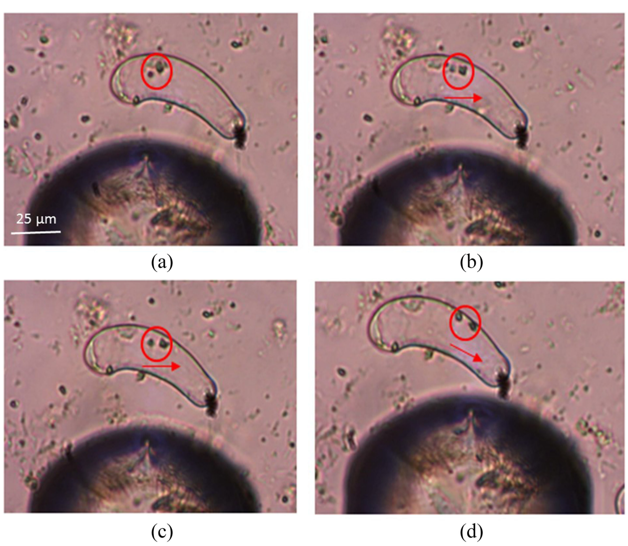

Fig. 9. Manipulation of inner organelles of *Medicago Sativa* plant cell.

Polishing	Chemical Etching
- Low Cost - Slow (min-hours) - Batch Fabrication - Limited to spherical/elliptical profiles - Very good reproducibility	- Low Cost - Slow (min-hours) - Batch Fabrication - Fabrication of Axicons (Bessel Optical Beams) - Moderate to good reproducibility
Heating and Pulling	**High resolution methods**
- Low Cost - Fast (min) - Single fiber fabrication - Limited to spherical/elliptical profiles - Moderate to good reproducibility	- Expensive - Slow (min-hours) - Single fiber fabrication - Complex shape designs - Very good reproducibility
Photo-Polymerization	
- Low Cost - Fast (sec-min) - Some flexibility in shape designs - Simultaneous use for trapping and sensing - Good reproducibility	

Fig. 10. Summary of main features of the more popular fabrication techniques of OFTs.

can still be explored using multistep pulling or fibers with several cores.

As long as the processing parameters are carefully controlled, chemical etching provides well established methods for obtaining good quality OFTs. In particular, it is the most direct way to obtain conical shaped axicon lens, very attractive for OFTs applications. Relaying on the use of dangerous chemicals, etching is nevertheless compatible with large scale batch processing. And while its versatility is limited when applied to standard fibers, a strong potential for the design of more advanced shapes is still to be explored using special fibers with tailored refractive index profiles.

High resolution techniques such as FIB milling or TPL are another class of fabrication methods. Being usually associated with expensive equipment and time consuming procedures, they provide, nevertheless, the ability to accurately micro machine the fiber tips. This way, they stand out as preferred methods for rapid prototyping and test of new ideas.

In addition to the established techniques, new approaches exploring the combination of special intrinsic characteristics of fibers, such as polarization and modal profiles, with distinct fabrication methods promises to open new possibilities for more advanced micromanipulation tools.

In this context, the technique of guided wave photo-polymerization here presented, introduces some new interesting possibilities by allowing a very fast fabrication process and some versatility in the control of the shape. The combination with the use of special fibers, exploring complex modal profiles, and the manipulation of the polymer composition introducing, for instances, fluorescent sensing dyes, will improve further the capabilities of OFT creating new opportunities both for trapping and simultaneous sensing.

Overall, the new trends in the fabrication of OFT are exploring the combination of different methods with special fibers and modulation of the modal profiles as a way to obtain more advance trapping and manipulation features. With the consolidation of these techniques and the introduction of sensing capabilities into the fiber probe, a new generation of optical tweezer with analytical capabilities is bound to appear fulfilling a critical need of single cell analysis.

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