

Optical tweezers with tips grown at the end of fibers by photopolymerisation

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We present a method to build optical tip at the end of a single mode optical fiber. The tip is grown by self-writing process: photopolymerisation by the light coming from the optical fiber. We developed a technique to produce a flat end surface on the tip. The good optical quality of the tip and the output laser beam was demonstrated by the fact that a counter-propagating optical trap could be constructed by using the tips with parameters comparable to regular fiber traps. Due to the small size of the tips the tweezers require a much smaller space than regular fiber traps.

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1. Introduction

The optical trap has developed into a most versatile tool of micromanipulation. It offers powerful new possibilities to handle microscopic particles that revolutionized different areas: atomic physics [1], biology [2-4], even the study of the optical trapping itself resulted in interesting new physics [5]. Optical trapping utilizes the pressure of light that becomes significant in the microscopic regime with moderate light intensities readily available from modern lasers. There are different realizations for optical trapping. In the most common arrangement light is focused by a high numerical aperture microscope objective and objects with index of refraction larger than that of the surroundings are trapped in the focus [6]. This is probably the most common way of creating an optical trap. Very efficient traps can also be generated by two counter-propagating expanding light beams: a stable trapping position is produced where the intensities of the two beams are equal. In fact, this has been the layout of the original optical trap [7]. There are several advantages of this system: smaller light intensities are sufficient to generate efficient traps, and since here the scattering force of the light beams cancel, high numerical aperture is not needed, as a consequence, much larger working distances can be achieved. A very simple realization of the counter-propagating trap is the fiber trap. Here, two optical fibers are simply positioned collinearly and a stable trap is formed between them. This has been proven to be very useful, and has been used successfully in a number of novel applications, like the study of optical binding [8], or creating an optical stretcher [9,10] where the elastic properties of cells can be characterized.

In a typical fiber trap the distance of the fibers is about 200 micrometers, and it cannot be increased significantly because of the inherent divergence of the light leaving the fibers. The total diameter of the fibers is

typically about 100 micrometers, thus a corresponding volume is defined in the center where the trap is located. The geometry of the system limits the applications: the trap cannot be positioned arbitrarily close to a given point. This drawback could be overcome if at the end of the fiber the cladding with excess thickness could be eliminated.

It has been shown earlier that it is possible to grow tip at the end of single mode optical fibers by photopolymerization of light curing resins [11,12]. In the growing process, light propagating in the curable resin hardens the material, and since the hardened material has a higher index of refraction than the uncured resin, it forms an effective waveguide. As a result, long tips can be grown this way. Such tips form effective optical waveguides and the thickness is about equal to the core of the fiber. Consequently, if a fiber trap is created with such waveguides, the required space reduces to a minimum.

In this work we constructed a counter-propagating optical trap with optical waveguides grown at the ends of single mode fibers. In the process, we also developed a method to grow tips with controlled and good quality ends to allow good quality optical output.

2. Experimental

We have developed a procedure to grow good optical quality waveguides at the ends of fiber optic waveguides.

When choosing the optical fiber for the experiments, the wavelengths of both the curing light and that of the trapping light have to be considered. The resin to be photopolymerised was the Norland NOA 63 optical adhesive, a material with excellent optical properties after curing. It was photopolymerised with 405 nm light from a diode laser (SANYO DL-5146-101S). For trapping 1070 nm light was used from an Ytterbium Fiber Laser (IPG YLM-2-1070). We worked with optical fiber Nufern

630HP (Thorlabs), this is a compromise solution: it is not single mode for 405 nm, but it has sufficient transmission at 1070 nm.

The tip was grown in a specially built small chamber with brick shape. It had two opposite open ends, and when filled with the curable resin, the material was held inside by surface tension. The fiber was immersed through one open end (Fig.1). This arrangement had two crucial properties. First, the length of the tip to be grown is simply set by positioning the end of the fiber at the desired distance from the opposite end of the resin chamber. Second, the end surface of the tip will be flat because it is determined by the surface of the resin-air interface.

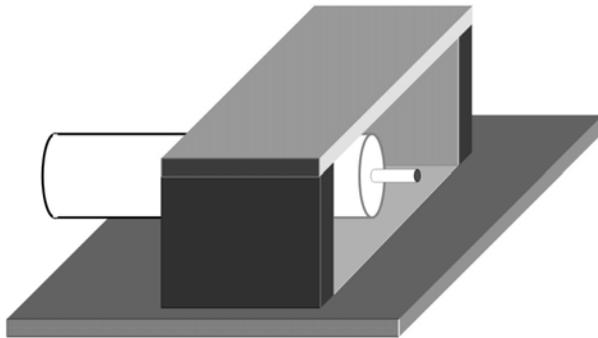


Fig.1. Scheme of the chamber to grow the tip by photopolymerisation. The left and right sides of the brick shaped chamber are open, and the resin is held in place by surface tension.

The procedure for growing the tip by photopolymerisation took into account the changes of the optical properties of the material during hardening. First, the fiber was immersed into the curable resin and polymerization was initiated by introducing 405 nm light into the fiber. The index of refraction of the cured resin is higher than that of the uncured form. As photopolymerisation proceeds, the index of refraction of the irradiated part approaches its highest value (that of the totally cured state) [13]. This effect keeps the shape of the fiber compact [14]. In the hardening process, polymerizing impulses of 500 ms duration with intensity of 30 mW at the input were used subsequently to create a channel of polymerized resin from the end of the fiber to the air-resin interface. After hardening, the fiber with the tip was pulled from the chamber and the uncured resin was removed by flushing with a 1:1 mixture of acetone and ethanol. Finally, a long term, low power (10 min, 3 mW) illumination was applied to fully polymerise the tip. The process to final curing was tracked by observing the pattern of the light output from the tip, and final curing was determined when this did not change anymore. Figure 2. shows a typical tip produced by this procedure. This procedure resulted in tips with good mechanical and optical qualities: tips of length up to several hundred microns could be readily produced and uniform light output pattern could be achieved.

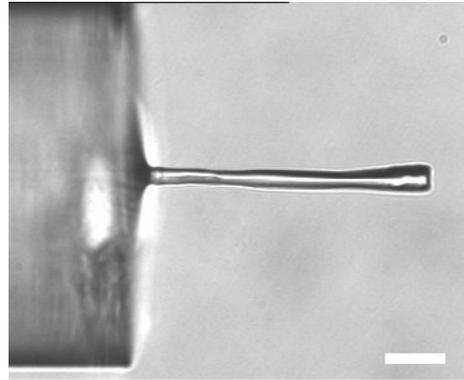


Fig. 2. Image of a typical tip grown at the end of the optical fiber. One can notice the flat end. The white bar represents 20 micrometers.

Dual beam optical tweezers were generated by pointing two optical fibers with tips grown at the ends. The experiments were carried out in a Zeiss Axiovert 200 (Germany) microscope, equipped with a motorized stage. The optical fibers were both mounted on mechanical micromanipulators (Helmut Saur Laborbedarf, Germany), they could be positioned independently. The fibers were immersed into a sample chamber (same structure as shown in Figure 1) filled with distilled water containing 1 micron diameter beads (Polybead Carboxylated Microspheres, Polysciences Inc., USA) to be used as test objects in order to characterize trapping.

The manipulators were mechanically separated from the microscope stage and the sample chamber with the dispersed particles could be moved relative to the fibers giving opportunity to move the trapping domain freely inside the sample chamber.

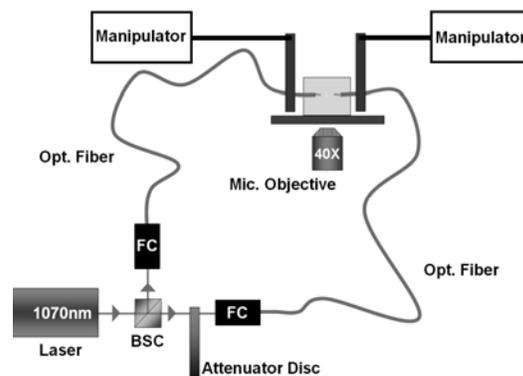


Fig.3. The schematics of the optical tweezers setup. The beam of the 1043nm laser was divided in to two by a beam splitter cube (BSC). The two beams than were coupled (FC) in to the optical fibers while the two other ends were hold by two independent manipulator in the test volume which took place on the motorized stage and was observed by the objective of the inverted microscope from the bottom.

The light of the near infrared fiber laser was divided into two and then fed into the optical fibers forming the traps. The intensities of the two beams could be changed separately: this compensated for the imperfectly controlled incoupling and this way also the relative intensities of the output beams forming the trap could be freely varied, i.e. the position of the trap could be controlled. The schematics of the experimental setup is shown in Fig. 3.

The sample chamber was observed with a TV camera, and the trapping was monitored with this and subsequently after digitization and computer analysis of these movies the experiments were characterized quantitatively. Figure 4. shows one of the frames used for tracking the trapped bead.

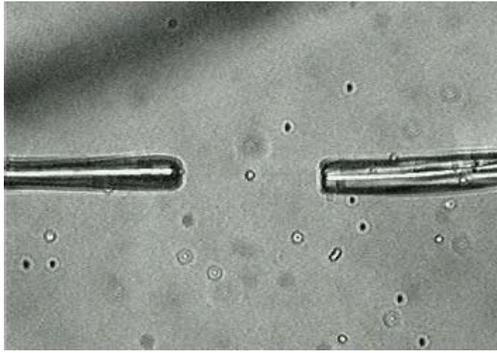


Fig. 4. An image of the tweezers trapping a bead.

The images were processed in order to determine the histogram of the axial and the transversal positions of the trapped bead. Before processing the recorded movie was edited and the central part the most significant area -where the bead possibly moves- was cropped out resulting smaller frames with strongly reduced number of pixels that speeded up the image processing without any loss of accuracy.

3. Results and discussion

The trapping properties of the system were characterized in detail at different light intensities. Trapping could be achieved with moderate laser power: less than 10 mW at the output of the tips was sufficient for stable trapping. Traps with characteristics identical to those of regular fiber traps could be created. In addition to trapping single beads halfway between the tips, several beads could be trapped with relative distances of which was determined by optical binding, as described in detail for fiber traps [15]. Figure 5. presents an example of optical binding between the two tips: 4 simultaneously trapped beads in line at 2mW laser power.

For the quantitative characterization of the trap, the motion of the trapped particle was analyzed from the recorded movies.

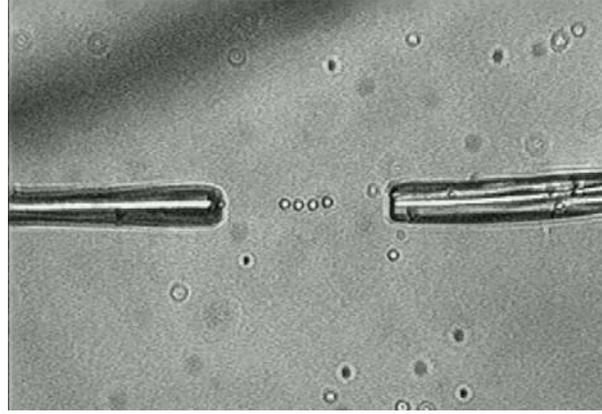


Fig. 5. Optical binding observed. The optical forces hold four beads in line between the tips.

The trap position and stiffness was determined from the distribution of the bead positions [16-17]. The particles suspended in water undergo a Brownian motion. The trap exerts a linear restoring force on the beads:

$$F = -kx \quad (1)$$

where k is the spring constant of the trap and x is the distance from the equilibrium position. The potential for this elastic force is $E = \frac{1}{2}kx^2$ and the Boltzmann formula with the above potential gives the probability density function of positions:

$$\rho(x) \propto \exp(-\frac{1}{2}kx^2 / k_B T) \quad (2)$$

The distribution of positions follows a Gaussian in this case, and the width of the Gaussian immediately yields the spring constant of the trap. Note that the quality of the fit to a Gaussian also characterizes the harmonic nature of the trap in the region covered by the position values.

The evaluation was carried out for two directions of motion: in the axial direction (along the axes of the waveguides) and in the transversal direction. It is reasonable to assume that the system has cylindrical symmetry, therefore in the two transversal directions (of which we can only follow one, that in the plane of the image) the spring constants are identical.

Fig. 6 shows the distribution of bead positions in the X (axial) and Y (transversal) directions for a laser power of 7.5 mW at the output of the waveguides. From these data spring constant in the two characteristic (axial and transversal) directions could be determined: $k_a = 1.62 \times 10^{-8}$ N/m and $k_t = 5.5 \times 10^{-8}$ N/m, respectively.

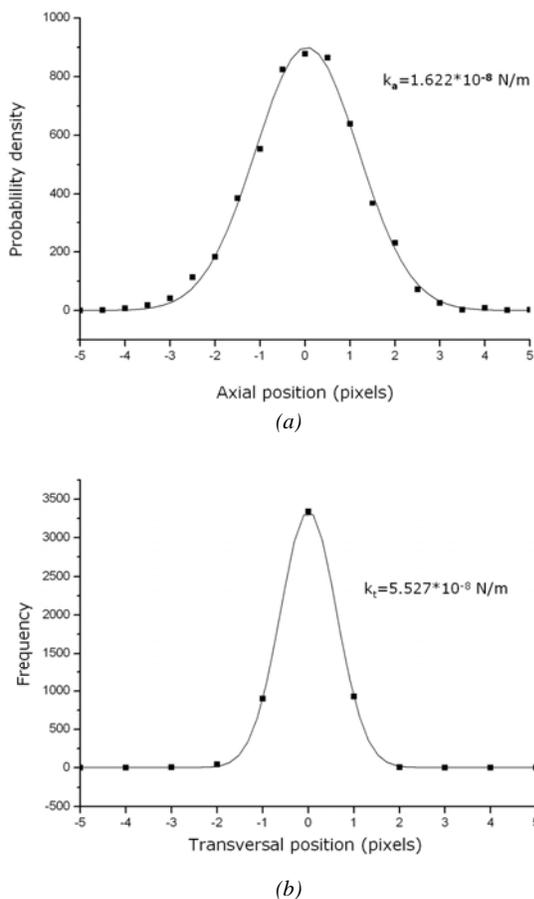


Fig. 6. The distribution of the positions of the bead undergoing Brownian motion in the trap. The figure shows the histogram of bead positions (black squares) and the fitted Gaussian curve (continuous line) in the axial (a) and transversal (b) direction. The corresponding spring constants of the optical trap are inserted.

Note that the stiffness of the transversal trap is about three times higher than the axial one – this property is inherent to the system, a consequence of the different trapping mechanisms in the two directions. In the transversal direction trapping is a result of gradient forces, while in the axial case an equilibrium of the scattering forces yields the stabilized position. The details of these forces are determined by the divergence of the light leaving the waveguide.

4. Conclusions

We introduced a method to create long and stable waveguides at the end of optical fibers. An efficient procedure was developed to grow the waveguides by self-writing photopolymerisation that results in tips with good mechanical and optical quality.

We built optical tweezers from two such self-written waveguides. The tweezers work similarly to the traditional

fiber traps with comparable parameters, but due to their much smaller dimensions they can be applied in much smaller volumes, thereby extending the application possibilities.

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