Fiber Optical Beam Shaping Using Polymeric Structures

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ABSTRACT

A method to control the output intensity profile of optical fibers is presented. Using guided wave photo-polymerization in multimode structures the fabrication with modal assisted shaping of polymeric micro lenses is demonstrated. Results showing that a given linear polarized mode can be selectively excited controlling the intensity distribution at the fiber tip are presented. This pattern is then reproduced in the polymeric micro structure fabricated at the fiber tip thus modulating its output intensity distribution. Such structures can therefore be used to obtain at the fiber tip predetermined intensity patterns for attaining optical trapping or patterned illumination.

Keywords: Photo-polymerization, Optical Fiber Lens, Optical Beam Shaping, Beam Profile Shaping

1. INTRODUCTION

In the last decades, the shaping of laser beams has proven to be useful in a wide variety of fields, for instance, in industry, micro-fabrication, optical sensing, optical trapping of biologic samples or even medicine. Optical fiber (OF) beam shaping setups have been implemented using several techniques and distinct types of fibers, such as: abrupt single mode tappers [1], microstructures OFs [2], chemical etched OFs [3] and the combination of distinct OFs and micro-fabrication femtosecond laser machining [4].

In this work a preliminary implementation and study of OF laser beam shaping using polymeric micro structures will be presented. The polymeric tips are fabricated by guided photo-polymerization and explore the modal distribution in multimode waveguides. Therefore, in section 2 the fabrication process as well as some aspects of multimode propagation in step index OFs will be described. The third section presents the results and some considerations, and finally in the conclusions some final remarks will be given about the preliminary work presented in this paper.

2. FABRICATION METHOD

The photo-polymerization process consists of linking monomers into chain-like polymers using light as a trigger. The polymerization is initiated by a photochemical process induced by the energy of a radiation source of a suitable wavelength. A catalyst is used to support a reasonable rate of polymerization. This catalyst is normally a free-radical which can be generated either thermally or photo-chemically. In the second case, the free-radical is created by a photo-initiator which reacts with a photon. Then the photo-initiators are converted into reactive initiator molecules, which react with a monomer molecule, finally forming the polymer. The polymerization process happens in a fast chain reaction and will occur until an inhibitor stops it. In this particular case, the monomer used was pentaerythritol triacrylate (PETIA) which is a tri-functional acrylate monomer and the photo-initiator was Irgacure 819, which has a working wavelength range from 375 nm to 450 nm.

The fabrication process of the micro-lens was based on the coupling of 405 nm laser to an OF and subsequent illumination of the polymer placed at the extremity of the fiber. This can be seen in Figure 1. First, an OF was cleaved to form a flat end surface Figure 1 (a). Then it was placed on a support, and a drop of liquid was deposited onto the tip of the fiber Figure 1 (b), (c). A laser beam (405 nm) was focused by an objective and thus coupled to the OF. The light emerging from the tip causes polymerization of the drop. After exposure (Figure 1 (d)) the fiber was rinsed in ethanol and a polymer tip was visible as an extension of the fiber core (Figure 1 (e)). The polymer tip is formed by self-guiding photo-polymerization. As the polymer solidifies, its refractive index increases, creating a guiding effect that prevents the radiation from scattering in the remaining of the drop. This way, a waveguide with a diameter close to that of the fiber core and a length determined by the drop thickness is obtained.

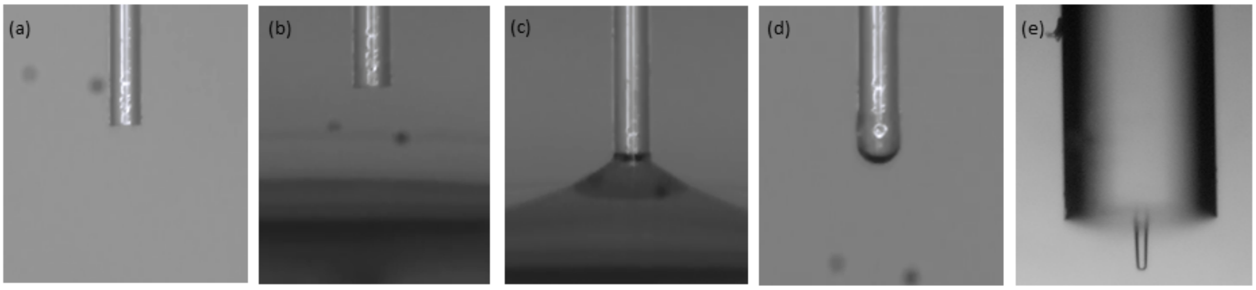

Figure 1 Fabrication process of polymeric structures at the extremity of OFs: (a) the OF is cleaved and placed vertically; (b) a drop of polymer placed in a glass slab approaches the end of the fiber; (c) the fiber is dipped in the drop of polymer; (d) the slab with the drop of polymer is removed and the laser is turned on to illuminate the polymer on the top of the fiber; (e) the fiber is rinsed in ethanol and the non-polymerized polymer is removed from the top of the fiber revealing the micro lens.

With this fabrication process tips of distinct shapes can be fabricated on the top of the fibers [5]. The OFs used are typically SMF 28, which means that they are single mode at 1550 nm but will behave as a multimode fiber at 405 nm. In this regard, the structure of the tips will depend on the specific mode that is excited by the laser in the multimode waveguide. Therefore, using a setup that allows controlling the angles of the input laser beam it will be possible to fabricate very specific structures (Figure 2). The 405 nm laser light is coupled to the OF using an objective and two mirrors. The beam input angles can be controlled either by adjusting the mirrors or by setting the controls of the alignment platform where the objective and the fiber are supported. The process of mode selection is then monitored using a second objective which projects the mode distribution into a flat surface.

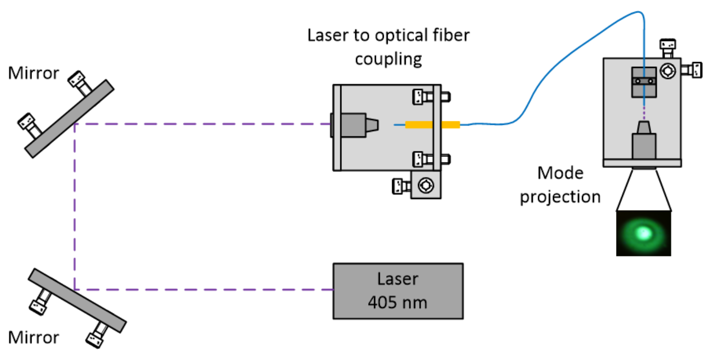

Figure 2 Experimental setup used to fabricate the polymer tips. The optical modes are selected according to the light input angle. The light is coupled using a 10x objective. Using another objective, the output modes are projected into a flat surface.

The number of modes that a multimode step index fiber supports is defined by the cutoff frequency, which depends on the wavelength (λ), the core radius (a), and the refractive index of the core (n_{core}) and the cladding ($n_{cladding}$). The normalized cutoff frequency is given by

$$v = \frac{2\pi a}{\lambda}\sqrt{n_{core}^2 - n_{cladding}^2}\,. \tag{1}$$

For SMF 28 at 405 nm the normalized frequency is approximately 8.3. The single mode propagation is ensured when the v parameter is smaller than 2.45, therefore this means that the SMF 28 will be multimode waveguide at 405 nm.

In the following section the experimental results obtained using the presented setups and techniques will be demonstrated.

3. RESULTS AND DISCUSSION

In this preliminary work, two micro structures were fabricated, exciting two distinct linear polarized modes of the SMF 28. For the fabrication of the first structure the LP_{02} mode was excited, as can be seen in Figure 3 (a). To fabricate the structure the process presented in last section was followed. The fabrication parameters used were: 4 µW @ 405 nm (measured at the end of the fiber using an Optical Power Meter) with an exposure time of 10 s. The resulting structure is shown in Figure 3 (e) and (f) where is visible the curved shape at the end of the polymeric tip. The tip has a diameter (measured in the base) of the order of the diameter of the core, which is ~7 µm, the length is ~30 µm and the curvature radius of the micro tip apex is ~5-6 µm.

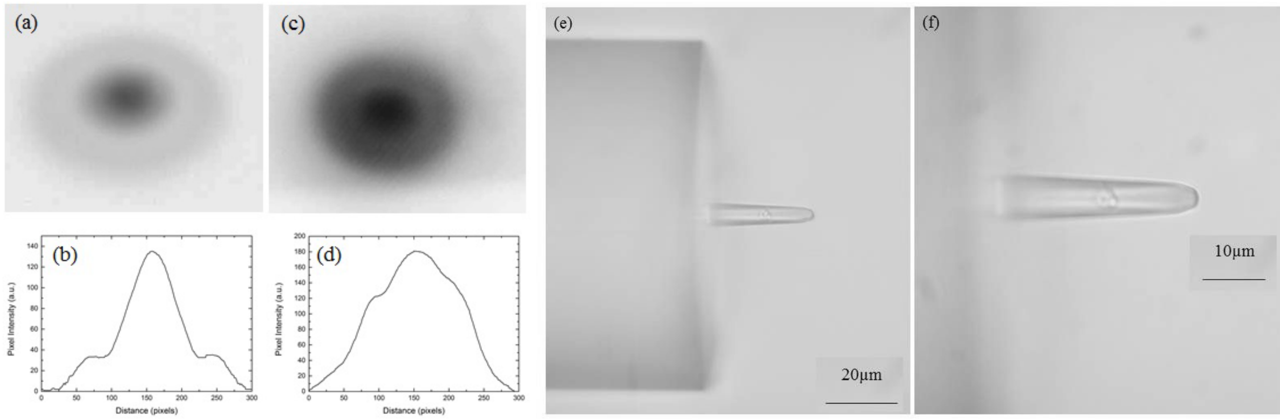

Figure 3 Considerations on the fabrication of the first polymeric tip: (a) excited mode LP $_{01}$ projected by the cleaved OF before the growth of the tip; (b) transversal pixel intensity profile of the excited mode LP $_{01}$; (c) field intensity profile projected by the fabricated polymeric tip (fiber tip spliced to a pigtailed SM 980 laser diode); (d) transversal pixel intensity profile of the field projected by the micro tip; (e) 50x microscope image of the polymeric tip; (f) 100x microscope image of the polymeric tip, showing a pronounced discontinuity of the spherical tip structure due to the profile of the LP_{01} mode.

After fabricating the tip, a 980 nm laser source was coupled to the fiber and the output field shape was projected on a flat target and analyzed. This wavelength was selected since it is frequently used in optical trapping experiments due to its low damage on biological samples [6]. The resulting output pattern is presented in Figure 3 (c). A similar field pattern was obtained before and after the fabrication of the tip. Using imageJ software for image processing, transversal pixel intensity profiles (at the center of the image) were obtained as depicted in Figure 3 (b) and (d). The LP_{02} mode is composed by a concentric maximum and a surrounding ring, the intensity profile decreases from the center to the boundaries, presenting a minimum between the inner maximum and the surrounding ring. This is clearly visible in Figure 3 (b). The profile of the field projected by the polymeric tip also presents a maximum, and two adjacent peaks. However these peaks are less defined and the intensity profile is nearly Gaussian. In the microscope images of the polymer tips it is visible (Figure 3 (e) and (f)) a transition region where the tip diameter gets larger. This aspect is responsible for the resulting output power distribution. It is expected that controlling the exposure time or the power at the fabrication stage this feature could be made more or less pronounced, allowing some control over the output intensity profile.

In the second structure the LP_{31} mode was excited, as can be seen in Figure 4 (a). This second tip was fabricated using the same parameters (power of 4 µW, 10 s exposure, and 405 nm laser light). The produced tip is shown in Figure 4 (e), (f) and (g). It has a base diameter of ~6-7 µm and a length of ~31 µm. At the very end the irregular structure produced by the particular mode distribution is visible. The LP_{31} mode is composed by six intensity maxima arranged in a circular distribution with a zero at the center (Figure 4 (a)). From the picture of the projected transversal intensity profile of the mode it can be seen that in practice the obtained minimum is not near zero (Figure 4 (b)). This happens due to the superposition of the multiple modes that are guided in the OF core. At 405 nm the SMF 28 fiber is highly multimodal, therefore is not straightforward to isolate a single mode without having any contribution from the others. The projected output intensity profile presented in Figure 4 (c) is the result of the coupling of the 980 nm laser to the fiber tip. In this case there is a mixing of a diffractive pattern (the concentric rings) and the projection of the structure (maxima regions arranged in a circular distribution). The diffraction is caused by the features with size of the order of the wavelength (980 nm) or even smaller. Doing the analysis of the pixel intensity of the projected distribution at 980 nm, as in the previously tip, two regions were identified (Figure 4 (c)), namely (A) and (B). The differences between the two regions are observable in the outer regions where the smaller peaks are almost unnoticeable in region (B). This means that there is a modulation of the diffraction maxima by the structure. However, further studies have to be made in order to properly analyze these behaviors.

In this work the SMF 28 was used because it is the standard fiber used in the telecommunications, however in order to avoid having multimode propagation at the characterization and operation wavelength (980 nm), a single mode fiber at 980 nm can be used instead. In addition, choosing a fiber which only guides a smaller number of modes also means that the choice of a specific mode will be easier; this will give a better definition to the fabricated structures. Nevertheless, these preliminary results shown that it is possible to fabricate structures with different designs according to the excited modes, and that by adjusting the power and the exposure time different results may be achieved.

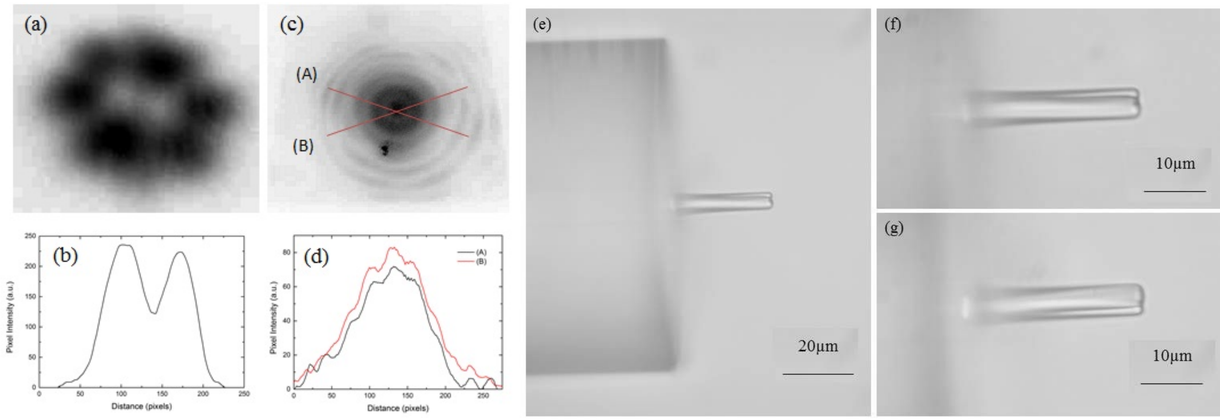

Figure 4 Considerations on the fabrication of the second polymeric tip: (a) excited mode LP $_{31}$ projected by the cleaved OF before growing the tip; (b) transversal pixel intensity profile of the excited mode LP $_{31}$; (c) field intensity profile projected by the micro tip (@ 980 nm); (d) pixel intensity profile of the field projected by the tip for two regions (A) and (B); (e) 50x microscope image of the polymeric tip; (f) 100x microscope image of the polymeric tip; (g) 100x microscope image captured from other point of view.

4. CONCLUSION

With the development of this preliminary work it was possible to demonstrate that polymeric micro tips can be fabricated (by photo-polymerization) in the extremity of OFs mimicking the modal distribution of the polymerizing radiation, thus allowing some control over the output intensity distribution. In the case of multimode OFs the excited modes can be chosen among those supported by the waveguide structure. The fabrication parameters such as the power and the exposure time can also be adjusted according to the desired results. A more detailed study of the fabrication parameters including not only the modal distribution but also power, energy and exposure time is required in order to attain a more precise control over the final shape of the resulting tips.

AKNOLEDGMENTS

This work was supported by project n.º FCOMP-01-0124-FEDER-027589 (Refª. FCT EXPL/BBB-IMG/0500/2012) and Rita Ribeiro would like to acknowledge the financial support of FCT (SFRH/BD/87542/2012).

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