Polymer Microtips Fabricated at the Extremity of Photonic Crystal Fibers

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Abstract: In this paper, a simple method of manufacturing micrometer-sized polymer elements (microtips) at the extremities of the photonic crystal fibers (PCFs), which are replacing standard optical fibers in many applications due to their unique properties, is presented. The method of microtips fabrication is based on the phenomena of photopolymerization, which is successfully used by the first time, to be best of our knowledge, to manufacture microtip at PCF. The three component photopolymerizable formulation consists of photo-initiating system and multifunctional triacrylate. The photopolymerization is carried out by green laser with the microtip growth controlled by the light exposure parameters (i.e., power and time). Results of microtip fabrication on standard fiber (SMF-28e+) and large mode area PCF (LMA-10) are provided. The influence of the initial process parameters on the final microtip characteristics (i.e., length, diameter and profile) is discussed. The potential applications of such polymer microtips are near-field scanning optical microscopy, coupling light sources with fibers and sensing.

Key words: Microtip, photopolymerization, photonic crystal fiber, polymer microstructure.

1. Introduction

In recent decades different methods of fabricating microtips at the extremities of the optical fibers working as micro-lenses have been developed. The main methods are: electric arc melting [1], laser micromachining [2], chemical etching [3] and exposition of a photosensitive film to the UV light [4]. Unfortunately, all of them are time and energy consuming and difficult for accurate control of geometrical microtip parameters. From the above reason a new method, presented firstly in 2001 by Bachelot et al. [5], of growing a polymer microtip as extension of the optical fiber core seems to be of much better practice. In this method, the practical microtip is formed by light guided through an optical fiber in a photopolymer liquid solution put at fiber end. Such microtip is directly aligned with the fiber core and could be applied as the probe in the near-field scanning optical microscopy (NSOM) [6], local light source to illuminate the sample in scanning optical microscopy [7], coupling element between laser and optical fiber [8], fiber optical tweezers [9], sensing element in Fabry-Perot refractometer [10] or others.

The method of photopolymerization is easy and low cost. The photopolymerizable formulation is made up of three basic components: sensitizer dye (Eosin Y disodium salt), co-initiator (methyl diethanolamine, MDEAN) and multifunctional acrylate (triacrylate) monomer (penthierythritoltriacrylate - PETA), mixed in a weight proportion described previously by Bachelot et al. [5]. Sensitizer dye (Eosine Y) absorbs light in a wavelength range from 450 nm to 550 nm (maximum for 530 nm), hence the green laser with
wavelength of 532 nm can be used to initiate the process of photopolymerization. Hemispherical drop of the photopolymerizable mixture is deposited at the cleaved end of the optical fiber and maintained by surface tension, next polymerization is carried out by energy of absorbed light. Polymer microtip grows as an extension of the fiber core due to self-guiding effect of the light beam in photopolymerizable medium. Light is confined by the polymerized solution, which has higher refractive index then the solution itself, and does not diverge outside. Moreover, the control of the level of absorbed energy gives possibility to manufacture the polymer microtip with different dimensions (length and diameter) and shape of the tip extremity. However, above microtip parameters are limited by the volume of the deposited drop [11].

Up to now such microtips were prepared mainly on standard single mode fibers [5, 11-15]. There is no report on the manufacturing of such microelements on photonic crystal fibers (PCFs), which may be caused by some problems occurring during preparing such elements, for instance pulling photopolymerizable mixture into the air holes of PCFs. However, growing microtips on PCFs enables the use of special properties of these fibers (e.g., endlessly single-mode operation, tailored dispersion properties, extremely high numerical apertures, etc.) and thus is very interesting from the scientific and application point of view. Therefore, the main objective of this paper is to study the manufacturing process of polymer microtips on PCFs.

2. Materials and Experiments

The standard single mode fiber SMF-28e+ (Corning) and large-mode area photonic crystal fiber LMA-10 (NKT Photonics) have been chosen for experimental works. The main reason of this choice was the similar numerical aperture (NA) as well as mode field diameter (MFD) for above fibers at the wavelength of 1,550 nm as it is shown in Table 1.

However, it should be noticed that SMF and PCF described above have different dispersive characteristics regarding NA and MFD. Whereas SMF-28e+ has constant NA and growing MFD with wavelength (Fig. 1a) [16], the LMA-10 fiber has constant MFD and wavelength depended NA, as shown in Fig. 1b [17].

The three components of photopolymerizable mixture from Sigma Aldrich have been used as a base material for microtips fabrication. This medium was mixed in proportions presented before by Bachelot et. al. [5] (Table 2). The optical refraction index of this medium depends mainly on PETA monomer state.

Table 1  The main parameter of used fibers at the 1,550 nm wavelength.

| Fiber     | Producer         | Core diameter (µm) | NA      | MFD (µm) |
|-----------|------------------|--------------------|---------|----------|
| SMF-28e+  | Corning          | 8.2                | 0.14    | 10.4 ± 0.5 |
| LMA-10    | NKT photonics    | 10.1 ± 0.5         | 0.14 ± 0.02 | 9.0 ± 1.0 |

Fig. 1  Spectral dependences of MFD and NA for two classes of fibers: (a) SMF-28e+ [16] and (b) LMA-10 [17].
Table 2 Percentage composition of the photopolymerizable medium.

| Component                        | Weight percent |
|----------------------------------|----------------|
| Sensitizer dye: Eosine Y disodium salt | 0.5 wt.%      |
| Co-initiator: MDEAN              | 8.0 wt.%       |
| Monomer: PETA                    | 91.5 wt.%      |

and changes as the function of the cross linking degree of the polymer from 1.48 (0% for unpolymerized medium) to 1.52 (100% for polymerized medium) [18]. The Eosin Y together with co-initiator MDEAN are the photo-initiating system. Eosin absorbs light, excites into triplet state and oxidizes co-initiator which creates free radicals. Free radicals trigger polymerization and the monomer develops into three-dimensional network [19]. Above reaction depends on optical energy absorption from light in the range of 450-550 nm. Polymer structure is formed as waveguide with the higher refractive index inside (core region), because more energy is absorbed at the extension of the fiber core, and the lower refractive index around, where less energy is absorbed and mixture is not fully polymerized. It should be noticed that the remaining unpolymerized medium can be easily removed with alcohol.

The setup for microtips fabrication is shown in Fig. 2. We used an optical variable attenuator for controlling optical power introduced to optical fiber structures and gravitation phenomena for symmetrical drop deposition for microtip manufacturing. Because the SMF-28e+ is a multimode structure for used wavelength (the cut-off wavelength is 1,260 ± 50 nm), the mode stripper has been used to achieve uniform and similar in each experiment mode distribution at the fiber output.

3. Results and Discussion

3.1 Microtips on Single Mode Optical Fibers

The knowledge about SMF microtips manufacturing process gives some information about mechanism of polymer microtip formation and optical and mechanical properties of obtained structure. It gives possibility to explore how the light propagates in the structure and allows to choose the optimized parameters for preparing microtips with desirable properties. The control of parameters such as output power allows to obtain polymer microtips with different shapes and diameters. The shape of the tip body can be easily anticipated knowing the mode distribution at the fiber output. Because in SMF-28e+ single mode guidance exists for wavelength higher than 1,260 nm, the application of green light (532 nm) in manufacturing procedure provides operation in multimode guidance. Hence, the cladding modes have been evanesced and fundamental mode together with higher order modes have been mixed by application of mode stripper to provide guidance with mode distribution close to the shape shown in Fig. 3. For such intensity profiles the manufactured polymer microtips at SMF-28e+ have cylinder shape at high...
values of the output power or cone shape at low values of the output power.

With the increase of output power the diameter at the base of the tip (bottom diameter) increases as well (Fig. 4 and Table 3). The change of time of exposition to the light has small influence on the microtip shape prepared on standard single mode fiber SMF-28e+.

An increase of the absorbed light energy by photopolymerizable mixture results in a flattening of the tip extremity. The process of photopolymerization arises rapidly and even 1 s of exposition allows obtaining tips as long as after 30 s. There is a possibility of polymer tip preparation in the shorter time, however such microtip does not have good mechanical properties because of irregularly polymerized structure. This situation is probably because of a competitive reaction of the free radicals with oxygen placed inside the photopolymerizable mixture and ambient oxygen around the drop.

In this situation it is desirable to manufacture polymer microtips in time longer than 10 s to obtain fully polymerized structure with higher stiffness of the material, hence all microtips have been prepared in time t = 60 s. The length of the polymer microtip depends on the height of the drop deposited at the end of the fiber and it is around 34-38 µm for SMF-28e+ (Table 3) while the height of the deposited drop is around 40 µm for SMF-28e+.

Finally, it should be remarked that the polymer microtips grow as the extension of the fiber core. This remark is confirmed by tomographic measurement of the microtip inner structure according procedures described before [14, 20, 21]. As an example, the results of the tomographic measurements of the microtip shown in Fig. 4b are presented in Fig. 5. The microtip is composed of core-like region with refractive index near the value of 1.52 and cladding like region with refractive index varying near 1.50.
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Table 3  Diameters and lengths of the microtips on SMF-28e+ (t = 60 s) according to the output power of the green light.

| Output power (µW) | Bottom diameter of the tip (µm) | Length of the tip (µm) |
|------------------|--------------------------------|------------------------|
| 5                | 16                             | 38                     |
| 1                | 13                             | 38                     |
| 0.5              | 12                             | 34                     |
| 0.1              | 8                              | 33                     |

The visible outer ring with higher values of refractive index (Fig. 5b) is mainly due to the influence of immersion liquid which has the refractive index of approximately 1.54.

3.2 Microtips on Photonic Crystal Fibers

The preparation of the microtips on the standard single mode optical fibers is relatively simple, the problem appears with the photonic crystal fibers because the photopolymerizable mixture is pulled by capillary forces into the air holes of the fiber cladding. The mixture has higher refractive index than glass and this causes the changes in the light propagation inside the fiber, which is observable in spectral characteristics as the local power losses around three wavelengths: 650 nm, 900 nm and 1,450 nm (Fig. 6). Such situation disrupts normal transmission of the light inside the fiber, the light is going out from the core region and propagates in the photonic cladding. The images of the near field of the light beam emerging from such filled photonic structure and pure PCF are shown in Fig. 7.

The presence of the mixture inside the air holes results in a creation of microtips without the cone shapes even for output power as low as 0.1 µW (Figs. 8a-8c). The lower output power allows to obtain microtips with smaller diameter as in the case of SMF-28e+. Hence, reduction of the power below 0.1 µW gives the possibility of obtaining microtips with the cone shape (Fig. 8d) as the energy is too low between the air holes to initiate the polymerization in this region. The diameter of manufactured microtips at the LMA-10 fiber is in the range from 38 µm for the highest output power (Fig. 8a) to 10 µm for the lowest output power (Fig. 8e). The lengths of the microtips range from 42 µm to 18 µm. It seems like the length decreases as the output power reduces, but such large differences of the microtip lengths are the result of a different time which elapses since the deposition of a drop of mixture to the switching on the light source. If this time is long, the greater amount of mixture is drawn into air holes and the microtips are shorter.

Fig. 5  The tomographic reconstruction of a refractive index distribution in SMF-28e+ microtip presented in Fig. 4b: (a) vertical cross section in the middle of microtip and (b) horizontal cross section at the A-A plane.
To avoid filling of air holes by photopolymerizable medium, the filling of air holes by other substance has been applied. The substance with refractive index lower than refractive index of the silica has been used to not affect transmission of the light in the PCF. Fig. 9 shows the light intensity distribution in a near field for the LMA-10 fiber filled by such substance compared with a near field of unfilled PCF. As can be seen, the transmission is not disrupted largely in opposite to the LMA-10 fiber filled by PETA polymer.

Fig. 10 presents polymer microtips obtained on the LMA-10 fiber with air-holes filled with the substance with low refractive index. As one can see, the microtips grow with the cone shape at optical output power below 5 µW. Above 5 µW the tip extremity flattens but microtip does not cover air-hole cladding as occurred for the LMA-10 fiber without preliminary filled air holes and thus the transmission is not disrupted. Lengths of the microtips are around 30 µm in all cases, which confirms that the PETA polymer is not pulled into air holes.
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Fig. 10  Polymer microtips obtained in t = 60s on the LMA-10 fiber with filled air holes by low refractive index substance for different guiding optical power P: (a) P = 10 µW, (b) P = 5 µW, (c) P = 1 µW, (d) P = 0.5 µW and (e) P = 0.1 µW.

Fig. 11  Comparison of spectral characteristics of output optical power for microtip manufactured at the LMA-10 fiber without and with air holes filling. The reference measurement presents the optical power transmitted through the LMA-10 fiber without microtip.

It should be noticed (red line in Fig. 11) that proper choice of low refractive index substance for air holes filling does not change largely transmission of the light in photonic crystal fiber. Hence, the spectral characteristics of microtip manufactured on the LMA-10 fiber filled with low refractive index substance shows that the local power losses in wavelengths 650 nm, 900 nm and 1450 nm has been omitted. Fig. 11, which presents comparison of spectral characteristics obtained for microtips at the LMA-10 fiber without (black line) and with (green line) preliminary filled air holes, confirms the above statement. Additionally, it can be seen that microtip grown on the LMA-10 fiber with air holes filled by low refractive index substance generates lower spectral losses than microtip obtained on the LMA-10 fiber without preliminary fillment.

Finally, we present in Fig. 12 the comparison of polymer microtips obtained at the LMA-10 fiber with and without initial air holes filling. It is hard to obtain microtip with a cone shape on PCF without initial air holes filling. In such situation the best microtip, which does not cover the cladding area, was obtained for the light intensity below 0.1 µm, which is identified as level of the detector noises. However, the initial filling of air holes provides possibility for obtaining microtips with the cone shape at higher level of absorbed energy.

For such kind of microtips, their shape reflects the mode field outgoing from the fiber. From the above reason such microtips work as the microlenses, which are ideally aligned to the fiber core. Fig. 13 presents
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Fig. 13 Simulation (Lumerical FDTD Solution) of light beam outgoing from the LMA-10 fiber without (a, b) and with microtip beheading cone shape with round (c, d) and flat (e, f) top. Figures (a, c, e) present intensity distribution in plane yz (white line the contour of LMA fiber and microtip) whereas Figures (b, d, f) 3D intensity distribution in plane xy of fiber or microtip end.

the simulation results showing how the light is focused in the microtip compared to the PCF without microtip. Two types of microtips, with round and flat top, were considered. For simulations we used microtip presented in Fig. 12d with parameters: 7 µm of diameter at base, 25 µm of length and 1 µm of diameter at the top of tip. Because the tomographic reconstruction presented in Section 3.1 has spatial resolution of about 1.5 µm, we have not got possibility for proper measurement of refractive index distribution in microtip presented in Fig. 12d. Therefore, we used the refractive index distribution of microtip presented in Fig. 5 (step-index model with 1.52 inside and 1.50 outside) for our simulations. Such procedure is justified because the photopolimerization process is similar for microtips fabricated with the same exposure time and guided optical power for SMF and LMA fiber.

As it can be seen (please compare Figs. 13a, 13b with Figs. 13c, 13d) the microtip manufactured on the LMA-10 fiber focuses the beam at the microtip end. Moreover the round profile of the top for beheading cone shape of the microtip (Figs. 13c and 13d) gives sharper output intensity distribution than microtip with flat top (mode field diameter in distance 100 nm in 13e and 13f), but focusing properties of both are similar.

4. Conclusions

The first systematic results, to the best of our knowledge, regarding a manufacturing process of polymer microtips at a PCF with the use of photopolymerization have been reported. Despite the fact that PCFs, due to its unique properties, are used more and more frequently in different kind of applications, the process of microtip fabrication has been described only for standard telecommunication fibers. The main problem with manufacturing of microtips at PCFs is pulling of photopolymerizable mixture into air holes of PCFs. The PETA monomer, which is commonly used in such process, has higher refractive index than silica glass and therefore it changes propagation condition in the PCF. The light is not confined in the core and the fabricated microtip covers the microstructured cladding of the fiber. Our study have shown, that the problem with disrupted
transmission of PCFs can be solved by proper air holes filling by substrate with appropriate refractive index. In such situation the desired microtips with cone shape can be manufactured. We provided a detailed analysis showing how, in such conditions, time and optical power influence the shape of the microtips.

The polymer microelements on PCFs demonstrated in this paper are of special interest because of the special properties of these fibers which could be easily adapted to different applications. Endlessly single mode operation with such microlenses makes them even more interesting. Near-field scanning optical microscopy, coupling fibers with lasers and sensing are just a few of many fields of application of polymer microtips.

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