Fabrications of Tapered Optical Fibers by Laser Induced Photopolymerization Technique

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Abstract. Taper shaped optical fibers have been much investigated because it may enhance the evanescent wave formation on the surface of the fiber, which can be utilized for sensing. In this paper, we report the fabrication of tapered optical fiber by employing laser induced photopolymerization (LIP) technique from hybrid organo-siloxane polymer precursor. This precursor was prepared by the sol-gel method for creating the inorganic cross-links. The photopolymerization process then made the organic cross-links and transformed it into the solid phase. The taper structure formation was strongly dependent on the laser power and time duration. A typical condition for taper structure formation was the laser power of 2 μW and the fiber drawing speed in the range of 20 μm/s - 40 μm/s. The resulted tapers lengths were around 1.5 mm – 5.5 mm with the diameter around 100 μm at the beginning of the taper and less than 5 μm at the end of the taper. The optical propagation and evanescent wave profile in this kind of tapered optical fiber was also studied computationally by using Finite Difference Time Domain (FDTD) method.

Keywords hybrid polymer, tapered optical fiber sensor, optical waveguide, evanescent wave

1. Introduction

Generally, a sensor has a function to detect or measure a physical quantity such as temperature, field, heat, light etc., which is then commonly converted into an electrical quantity by a transducer. In biochemical sensors, the change in measurable physical quantities may be related to the presence or the change of a substance due to either physical process, such as adsorption or phase change, or chemical process, such as chemical reaction or redox reaction. A fiber optic sensor is functioning by measuring the change of light related physical quantities, such as light intensity or light polarization, which happen due to refractive index change of the surrounding medium. There are several fiber optic sensors that have been developed in more sophisticated configuration for improving the efficiency, such as in the form of interferometric configuration, Bragg grating structure or involving metal nanolayer or nano-particles for generating surface Plasmon resonance (SPR). However, there are still more simple modifications for improving the sensitivity, such as by using a bent fiber optic or tapered optical fiber structure [1]. In such structure, the evanescent wave may be extensively formed on the
fiber surface into the surrounding medium. Figure 1 illustrates the formation of evanescence wave on the glass plate \((n_1)\) that extent to the adjacent dielectric medium \((n_2)\). Larger penetration depth of this evanescent wave may produce better sensing sensitivity.

The fabrication of taper structure in silica or glass based optical fiber requires high temperature. In addition, it is not easy to attach functional sensing or ligand molecules on the silica or glass surface. It is then interesting to develop the tapered optical fiber from polymer, which relatively easier to bind organic molecules. Such structure may be fabricated by laser induced polymer (LIP) or laser self writing (LSW) technique. There are many reports on the formation optical waveguide or fiber by this technique [2,3].

![Evanescent wave profile in TE mode](image)

**Figure 1.** Evanescent wave profile in TE mode [3].

The electric field of evanescent wave \(E_{ew}\) is given by:

\[
E_{ew} = E_{02} e^{-\delta z} e^{-j(\omega t-k_{2x})}
\]

where the depth penetration parameter is

\[
\delta = \frac{\lambda_0}{2\pi n_2^2 \sin^2 \theta_1 - n_2^2}
\]

**2. Experiment**

**2.1. Hybrid polymer precursor preparations**

Hybrid polymer precursor used in this work was made from a kind of organically modified siloxane monomer, namely 3-(Trimethoxysilyl) propyl methacrylate (TMSPMA, Aldrich), by sol-gel technique as reported in our previous work [4,5]. This hybrid polymer can be used to make various nano-structure with high transparency. Photo-initiator agent, namely Irgacure-369 (Ciba Speciality Chemical Inc), was dissolved into this hybrid polymer precursor solution in order to polymerize organic part of the monomer.

**2.2. Laser-induced photopolymerization**

Experimental setup for LIP process is presented in Figure 2. This experiment used a plastic optical fiber with 100 \(\mu m\) in diameter, where the taper structure was then formed at the one end of the taper. For that purpose, a blue laser producing light with 450 nm in wavelength was injected into the fiber to initiate photo-polymerization. The shape of resulted tapers was varied by varying the laser intensity by using a motorized variable neutral density (ND) filter and the drawing speed of the stepper motor.

**3. Simulation**

Finite Difference Time Domain (FDTD) is a method to calculate electromagnetic propagation by solving numerically the differential forms of Maxwell’s equations. This method firstly introduced by
Yee, who proposed the numerical calculation algorithm for solving those Maxwell’s equations [6]. In this algorithm, the electric field and magnetic field was calculated as followings,

\[
E_x^{n+\frac{1}{2}}(k) = E_x^{n-\frac{1}{2}}(k) + \frac{\Delta t}{\sqrt{j}} (E_x^n)
\]

\[
H_y^{n+\frac{1}{2}}(k+1/2) = H_y^n(k+1/2) + \frac{\Delta t}{\mu_0 c \Delta z} (E_y^n)
\]

where the discretization is done in both spatial and time domains. In the present work, this FDTD calculation was carried out by using a software which is called as OptiFDTD. The calculations were done by providing parameter inputs such as the taper geometry and refractive indices as well as the light or laser wavelength. Based on Liu’s simulation work [7], because the evanescence is effectively formed only on the tip of the taper structure, the simulation calculations here were then performed only for the tip region in order to reduce the memory use and time computation. The parameters used in the calculation of this tapered optical fiber were the taper length of 50 µm, the taper front face width of 10 µm, the taper end face of 1 µm, the light beam width of 5 µm with Gaussian beam profile, the light wavelength of 0.63 µm, the light power input of 10 mW, the core refractive index of 1.45, and the cladding refractive index of 1.3.

4. Results and Discussions

4.1. Experimental Results

The formation of cross-linked polymers as the result of photo-polymerization was firstly confirmed by FTIR spectroscopy. The FTIR spectrum after photo-polymerization (not shown here) shows the reduction of the absorption bands located at 880-995 cm\(^{-1}\) in comparison to that in the spectrum before photo-polymerization, which can be assigned to the transformation of C=C bond into C-C bond.

The fabrications parameters of the taper structure and their images resulted in this work are presented in Table 1 and Table 2. In this work, we used three steps of laser illuminations, namely:

1. The first illumination is to initiate radicals and generate polymerization seed on the end face of the optical fiber.
2. The second step is to provide photo-polymerization for taper growth, which is in combined with the fiber drawing. In this second step, we used relatively weaker light intensity in comparison to that in the first step, which was achieved by using a rotating neutral density filter to reduce the laser intensity.
3. The last illumination step is done to complete this fabrication by a termination step, which is required for just improving the polymer cross-linking without being followed further by taper growth. This step is done after removing the taper from the precursor solution.

Table 1 shows the taper fabrication parameters and the resulted tapers with drawing speed of 20 µm/s. Meanwhile, Table 2 shows for the drawing speed of 40 µm/s. The resulted tapers have around 100 µm in diameter at the beginning of taper. The diameter then decreases up to less than 5 µm at the end of the taper. The taper length varies depending on the laser power and drawing speed as well as laser illumination procedures. As shown by the images of the resulted taper structure in the tables, the taper shape may also vary, either in a linear, concave or convex shapes.

| Laser power (µW) | Fabrication parameters | Resulted taper length (mm) | Resulted taper image |
|-----------------|------------------------|-----------------------------|---------------------|
|                 |                        |                             |                     |
1.0 s without filter, 5 minutes by filter, 5 minutes termination ± 2.0

1.8 1 minute without filter, 5 minutes by filter, 1 minute termination ± 1.5

3.8 15 s without filter, 5 minutes by filter, 5 minutes for termination ± 2.5

Table 2. Similar table as Table 1 but with the drawing speed of 40 μm /s

| Laser power (μW) | Fabrication parameters | Resulted taper length (mm) | Resulted taper image |
|------------------|------------------------|---------------------------|---------------------|
| 2.2              | 3 minutes by filter, 5 minutes termination | ± 2.0                    |                     |
| 2.3              | 30 s without filter, 3 minutes by filter, 5 minutes termination | ± 3.0                    |                     |
| 3                | 5 minutes by filter, 5 minutes termination | ± 5.5                    |                     |

4.2. Simulation Results
We investigated three kinds of taper structures, namely linear, concave and convex shaped structure. As indicated in the previous section, such structures can be obtained by adjusting some fabrication parameters using this LIP technique. The taper structure dimensions used in the simulation did not match exactly with the actual structure of the fabricated tapers above. In the present stage, we just concern on the taper shapes. Figure 3 illustrates xz plane cross-section of the taper structure with concave shape used in the simulation calculation, where the vertical axis represents the refractive index pattern in the core and the cladding regions. The length of the taper is 50 μm with the right end face has a diameter of 10 μm and the left end face has a diameter of 1 μm. The core material is the hybrid polymer used in the experiment where the refractive index was supposed to be 1.45. The cladding material is water with the refractive index of 1.3, which is the medium to be sensed in the application of this sensor. The light wavelength was set to 0.63 μm, which is the wavelength of red diode laser. The simulation calculations were performed for TE mode, where the electric field was polarized along the y-axis.

Figure 3. The xz plane cross-section of the taper structure with concave shape used in the simulation calculation, where the vertical axis represents the refractive index. (note that the scale is not proportional)
Figure 4 The $E_y$ electric field distribution (in arbitrary scale) calculated for taper structures with (a) linear, (b) concave and (c) convex shapes. The taper was set from 5 μm up to 55 μm along the x-axis. (note that the geometrical scale is not proportional) shows the distribution of electric field in y direction ($E_y$), where the blue color represents zero $E_y$ electric field while green and red colors represent medium and large electric field. In comparison to linear shaped taper, the concave shaped taper has more intense electric field distribution inside the structure as indicated by stronger green color. The distribution also may indicate more light leakage in comparison to other shapes. The convex shaped taper shows weaker electric field distribution inside the taper but strong electric field distribution at the surface near by the taper tip. However, the convex shaped taper seems showing the smallest light leakage in comparison to other shapes.

Figure 5 shows the distributions of electric field (in black color lines) showing evanescent wave and leakage wave at position $z = 7$ μm from the left end of the tip for (a) linear, (b) concave and (c) convex shaped taper structures. The blue lines indicate the profile of refractive index formed by the core and cladding regions at 7 μm from the left face of the taper. The widths of the cores are not same because of different shapes of those tapers. For all structures, we can see side peaks that may attributed to leakage waves, which are much larger in the concave shaped taper in comparison to other structures. However, this concave shape generates more extensive evanescence wave as indicated by penetration of electric field at the surface of the taper. It may be seen as the black line that crossing the vertical blue lines.
Figure 5. Distribution of electric field showing evanescent wave and leakage wave at position $z=7 \mu m$ from the left end of the tip for (a) linear, (b) concave and (c) convex shaped taper structures.

5. Conclusions
We have demonstrated the formation of tapered optical fiber by LIP technique from hybrid a polymer precursor with the diameter less than 100 $\mu m$. Although further systematical works are required, at the present stage we can see that the length and shape of the taper can be varied by controlling some fabrication parameters, such as laser intensity and fiber drawing speed. The concave shape is interesting because the simulation results show more extensive evanescence formation in comparisons the other two shapes investigated here. Such structure may be useful for building more complex sensor structures such as microchannel based sensors or photonic noses.

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References
[1] Tian Y, Wang W, Wu N, Zou X and Wang X 2011 Tapered Optical Fiber Sensor for Label-Free Detection of Biomolecules Sensors 11 p 3780-3790; doi:10.3390/s110403780
[2] Sugihara O et al 2004 IEEE Photonics Technology Letters 16 no 3 p 804-6
[3] Yamashita T; Kawasaki A; Watanabe O; Kagami M; Tomiki M; and Sakata H 2012 Light-induced self-written polymeric waveguides for low-cost integration of single-mode devices IEEE Optical Interconnects Conference; DOI: 10.1109/OIC.2012.6224426
[4] Hidayat, R., Hidayat, S., Fitrilawati, F., Herman, Tjia, M. O., Fujii, A. and Ozaki, M. 2012
Distributed feedback grating fabricated from hybrid polymer precursor gel by employing short-pulse laser interference for photopumped polymer laser applications Polym. Adv. Technol. 23 p 1264–1270. doi:10.1002/pat.2039

[5] Hidayat R, Gomulya W, Pitriana P, Irmansyah R, Miranti R, Herman, Hidayat S, Fitrilawati, Fujii A and Ozaki M 2012 Siloxane based Organic-Inorganic Hybrid Polymers and their Applications for Nanostructured Optical/Photonic Components ITB Journal of Engineering Science 44 p 207-219. DOI: 10.5614/itbj.eng.sci.2012.44.3.1

[6] Sullivan DM 2013 Electromagnetic simulation using the FDTD method (John Wiley & Sons)

[7] Liu Z, Guo C, Yang J, and Yuan L 2006 Tapered fiber optical tweezers for microscopic particle trapping Opt. Expr. 14 p 12510