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Investigations on sensing properties of tapered photonic crystal fiber refractive index sensor

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In present study a multi-mode fiber (MMF) stubbed tapered photonic crystal fiber (PCF) has been fabricated for refractive index and temperature sensing. The sensing probe has been formed by stubbing MMF and tapered PCF with varying tapering length, between two standard single-mode fibers (SMF). It has been observed from the experiment that the tapering of PCF and its tapering length affect the sensitivity of proposed sensor. Maximum sensitivity of 1891 µW/RIU and 900 µW/RIU has been achieved for single and dual point tapered PCF, respectively and a good linear response for high refractive indices has been obtained by measuring the optical output powers. The fabricated sensor has also been characterized for temperature sensing. The temperature sensitivity of 30 nW/°C and 19 nW/°C has also been measured from both single and dual point tapered PCF, respectively, for the temperature variation from 30 °C to 80 °C at the interval of 5 °C.

Keywords: Tapered, PCF, Refractive index, Sensitivity, Fusion splicing

1 Introduction

Refractive index plays a crucial role in the fundamental properties of any material; hence it requires an accurate measurement for several chemical and biological applications[1-4]. Various advantages like high sensitivity, low cost fabrication, immune to electromagnetic field, optical fiber have been used in every sensing area[5-9]. In 2006 a refractive index sensor based on core diameter mismatch has been fabricated which leads the excitation of cladding mode of SMF due to core mismatch[10]. The excitation of cladding mode attracts new generation to fabricate innovative fiber sensors. The core diameter mismatch results in low sensitivity which was overcame by the tapering of fiber. In the tapered fiber maximum portion of evanescent field propagates inside the cladding due to which the travelling waves are more sensitive toward any changes in its surrounding media[11-13].

PCFs are the special kind of fiber which uses the properties of modified total internal reflection and photonic band gap in photonic crystal. From several years researchers are interested towards the fabrication of PCF based fiber sensors[14-16]. In line SMF stubbed Mach-Zhender interferometry based PCF (MZI-PCF) refractive index sensor was fabricated by using simple fusion splicing[17-19]. The splicing of PCF with fibers contains the collapsing of its air holes; consequently the cladding modes of PCF get excited at first splicing part and recombine at the second splicing part with the light propagated in core. The recombination of excited cladding and core light causes interference at the splicing point, and the excited cladding of this MZI-PCF are too much sensitive towards the changes in its surrounding environment[20-22]. A MMF stubbed PCF based sensor was reported earlier with sensitivity 440.32 µw/RIU, 267.48 µw/RIU and 195.36 µw/RIU with varying sensing length of 2.10 cm, 5.50 cm and 7.20 cm, respectively, in which PCF was spliced between a small section of MMF and SMF[23]. Due to the less interaction of propagated light with its surrounding causes low sensitivity in this work. The drawback of this sensor regarding low sensitivity is minimized by using tapered PCF.

In this paper, intensity modulated tapered PCF based refractive index sensor have been fabricated and demonstrated for the first time in our knowledge. Here we have reported an enhanced sensitivity and comparative study of single and dual point tapered PCF sensor with various tapering length. The proposed sensor shows high sensitivity of 1891 µW/RIU, than the previously reported article[23]. The fabricated sensor offers various advantages such as

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high sensitivity, durability against harsh environments, and immunity to electromagnetic interference.

2 Sensing Structure and Setup

Sensing probe contains in line SMF-MMF-tapered PCF-SMF, in which PCF (LMA-8) was purchased from NKT Photonics and SMF and MMF were purchased from Thorlabs. In the experiment the diameter of core of SMF and MMF were 8 µm and 50 µm, respectively, with 125 µm cladding in both, and the used PCF has air holes diameter 2.58 µm with pitch value 5.6 µm and outer diameter 125µm with solid core. A simple fusion splicing method was used to splice the PCF with SMF and MMF fibers by using SUMITOMO fusion splicer type-39. Splicing of PCF with other fibers was done by collapsing air holes of PCF and joining with other fibers by giving extra arc. The optimized condition for SMF-PCF was used as previously reported article[23]. Before splicing, all the used fibers were cleaved by using fiber cleaver. During the splicing of conventional fibers, the cleaved edge of fibers are heated above their soften point and pressed together to form a joint fiber. However, in PCF when this heating temperature exceeds to soften point the surface tension will become greater than their viscosity and leads to the collapsing of air holes[24,25]. The rate of their air hole collapse may be written[26] as Eq. (1):

$$v_{\text{collapse}} = \frac{\gamma}{\eta} \quad \ldots (1)$$

where γ is the surface tension which is almost constant and η is the viscosity of the glass which decreases with temperature. The length of collapsed region was controlled by arc conditions[27]. In the present work, fabricated device was tapered by cost effective hydrofluoric acid (HF) based micro droplet etching method[28]. Figure 1 shows the schematic diagram of fabricated tapered PCF sensor. The micro droplet method is shown in the inset of Fig. 1. The inset diagram contains two fiber clamps to avoid the movement of spliced in line fibers, placed on the acid resistant-dish. First of all sensing probe was placed horizontally on a dish with the help of clamp and micro droplets of HF acid of 20% concentration were dropped carefully on the selected region to be tapered. The immersion depth was used to control the tapering length.

The three sensing probes of different tapering length were fabricated under fixed time periods as listed in Table 1. There are three ways available to enhance sensitivity of sensor, decreasing waist diameter, increasing tapering length and minimizing the fusion loss between fibers. In our fabricated sensor the concentration of HF acid and etching time were kept constant to obtain the same waist diameter for all three lengths. The decrease in the diameter of PCF due to tapering enhances the evanescent field and also leads interaction with the external environment[29]. The schematic diagram for setup used for characterization has been shown in Fig. 2. The experimental setup consist of a laser source (1550 nm) an optical spectrum analyzer (OSA, Yokogawa AQ6370) and a flow cell.

The basic principle of this experiment is based on MZI. When the light is launched from laser source, the higher order core modes of MMF are leaked into cladding mode of PCF and excite their cladding. When these excited cladding modes reach to the tapering portion they interact with the external

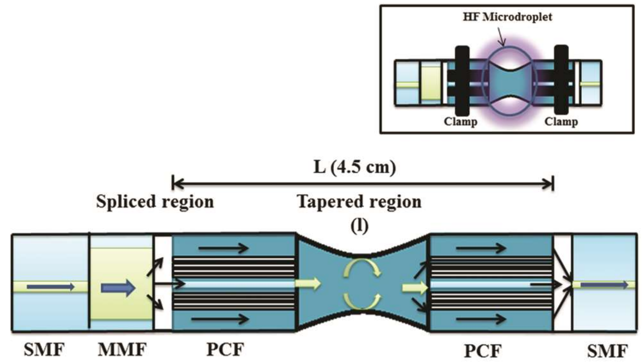

Fig. 1 — Schematic diagram of tapered PCF sensor.

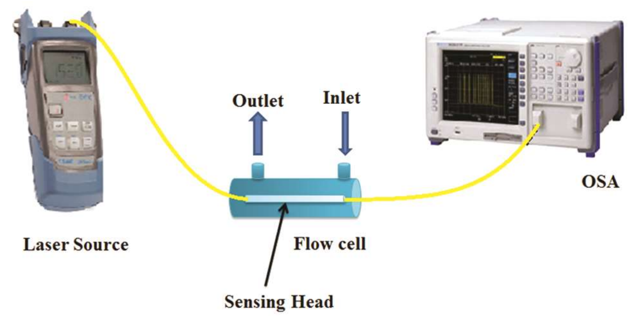

Fig. 2 — Schematic diagram of experimental setup used for characterization.

Table 1 — Parameters used for the fabricated sensing probe at room temperature (28 °C)

Sample	HF etching time	Tapering length (mm)
1	60 min	3
2	60 min	5
3	60 min	7

environment due to decrease in diameter[30], hence this decrease in diameter directly enhances evanescent field and so the sensitivity. After leaving the taper region this excited modes again recouple with other modes propagating through core at collapse air hole region. The corresponding transmission function of the interferometer can be expressed[31,32] as Eq. (2):

$$I_{\mathrm{T}} = I_{\mathrm{core}} + I_{\mathrm{cladding}} + 2\sqrt{I_{\mathrm{core}}.I_{\mathrm{cladding}}}\cos(\delta) \qquad \ldots (2)$$

where, I_{core} and I_{cladding} represent the intensity of light propagating through core and cladding, respectively. I_{T} is the total intensity of interference signal and δ represents the phase difference between core modes and cladding modes arises due to changes in external RI and defined as Eq. (3):

$$\delta = \frac{2\pi}{\lambda}\int(n_{\mathrm{cladding}} - n_{\mathrm{core}})dz \qquad \ldots (3)$$

where λ is wavelength n_{cladding} and n_{core} are effective indices of core modes and cladding modes of PCF, respectively. The transmission of our sensor was directly proportional to the differences of these effective indices. Sensitivity was calculated by the linear fitting of obtained output powers. The fabricated single and dual point tapered PCF sensor with various tapering length was characterized for refractive index and temperature sensing. In the experiment various concentrations of glycerol were used to obtain different refractive index varied from 1.344 to 1.395. For making the completely soluble mixture the solution was stirred on magnetic stirrer for 10 min on room temperature. After refractive index sensing the same sensing probes were used for temperature sensing.

3 Results and Discussion

Study on refractive index sensing is carried out using tapered PCF sensor. Here, the advantage of using MMF is to launch maximum part of light in PCF. The launched light propagated in SMF is allowed to transmit in proposed tapered PCF fiber followed by MMF. In the proposed experiment the refractive index sensing has been obtained by using beam-through method.

The experiment was performed on three different tapering lengths of PCF. After each measurement the fiber was cleaned by using ethanol and left it for 5 min of drying for the accurate sensing. The experiment was done on both kind of single and dual point tapered PCF. The setup was placed on optical bench and the experiment has been performed at room temperature. The fabricated probe was tested over the wide range of refractive index varied from 1.344 to 1.395. Figure 3(a,b,c) shows the plot for single point tapered PCF. It is observed from figure that the output power decreases with the increase in refractive index due to the absorption of evanescent field[33].

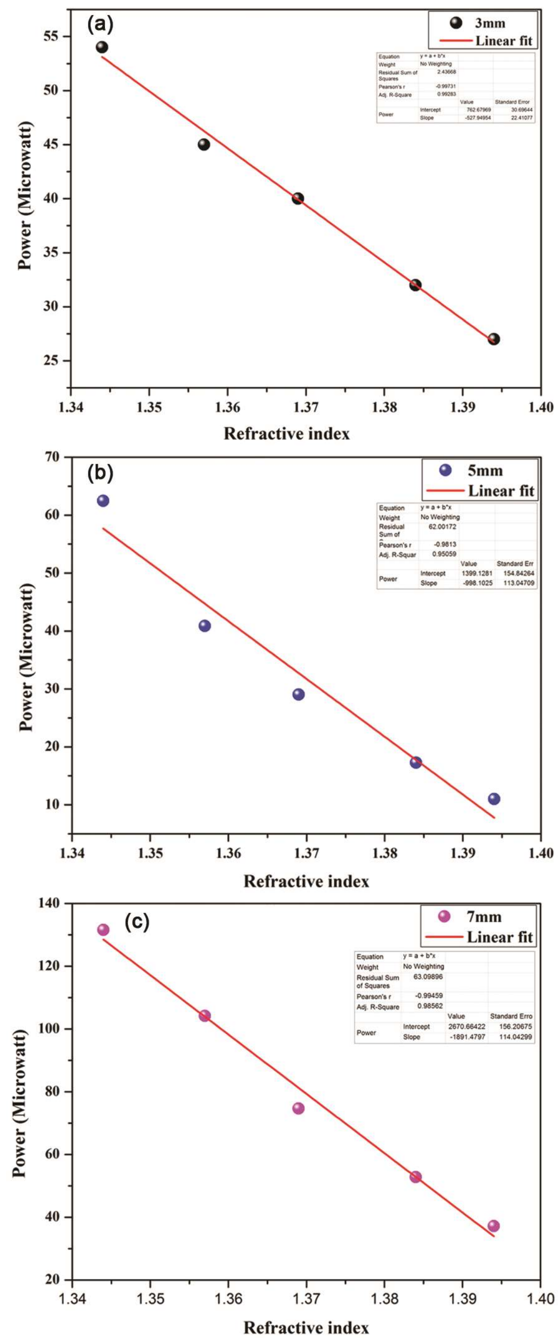

Fig. 3 — Variation of power with RI for single tapered at (a) 3 mm, (b) 5 mm and (c) 7 mm tapering length.

For each single point tapering, the sensitivity of 527 µw/RIU, 998 µw/RIU and 1891 µw/RIU was obtained for tapering length 3, 5 and 7 mm, respectively. The same experiment was performed by using dual tapered PCF keeping same etching time and sensitivity of 195 µw/RIU, 608 µw/RIU and 900 µw/RIU was obtained for the tapering length of 3 mm, 5 mm and 7 mm, respectively. Figure 4(a,b,c) shows the variation of transmitted output power with refractive index for dual point tapered PCF.

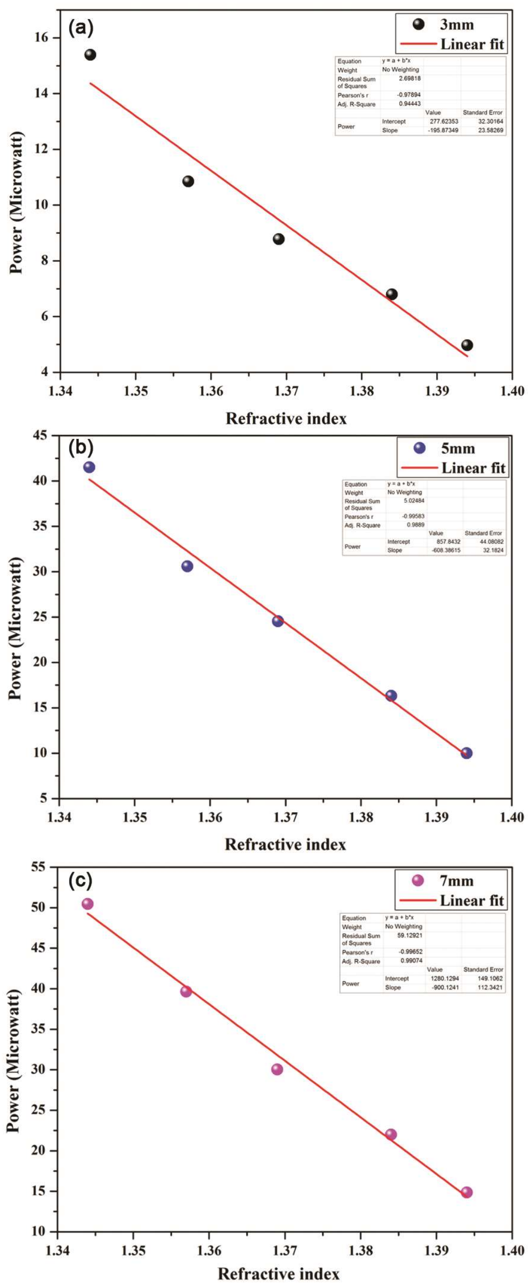

Fig. 4 — Variation of power with RI for dual tapered at (a) 3 mm, (b) 5 mm and (c) 7 mm tapering length.

The maximum sensitivity of 1891 µw/RIU and 900 µw/RIU was obtained for single and dual point tapering, respectively, for 7 mm tapering length. The obtained sensitivity is four and two times higher than previously reported article[23]. Figure 5 shows the variation in sensitivity with respect to its tapering length. Here we can see that the increment of tapering length enhance the sensitivity accordingly but after a certain length it might get decrease due to the loss of coupling light, hence proper tapering length and diameter are required for sensitivity improvement. Since the increasing of tapering length causes the increase in the interaction length through which our enhanced evanescent wave propagate and make susceptible to external medium. While in multi-point tapering, the leakage of light takes place at two points which causes more loss of optical power. This loss in recoupling leads to decreases insensitivity of dual point tapered PCF sensor.

After refractive index sensing the same probe was used for temperature sensing. The experiment was performed by placing the sensor in the temperature controlled heating chamber. In the experiment we increase the temperature from 30 °C to 80 °C at the interval of 5 °C. After each increment of temperature the chamber was left for 10-15 min until it became stable.

Figure 6(a,b) represents the variation in output power with temperature for single and dual point tapered PCF, respectively. From figure it can be seen that with increase in temperature a small linear variation in output power is observed in all three sensing probe. The low sensitivity may be due to low thermo-optic and thermo-expansion coefficients[22] of

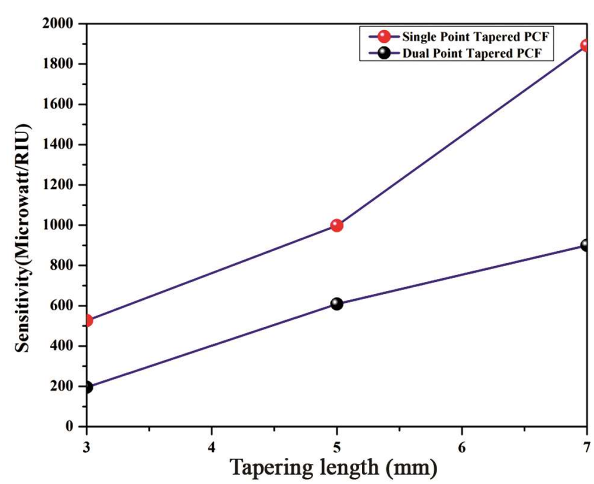

Fig. 5 — Variation in sensitivity for both devices with respect to its tapering length.

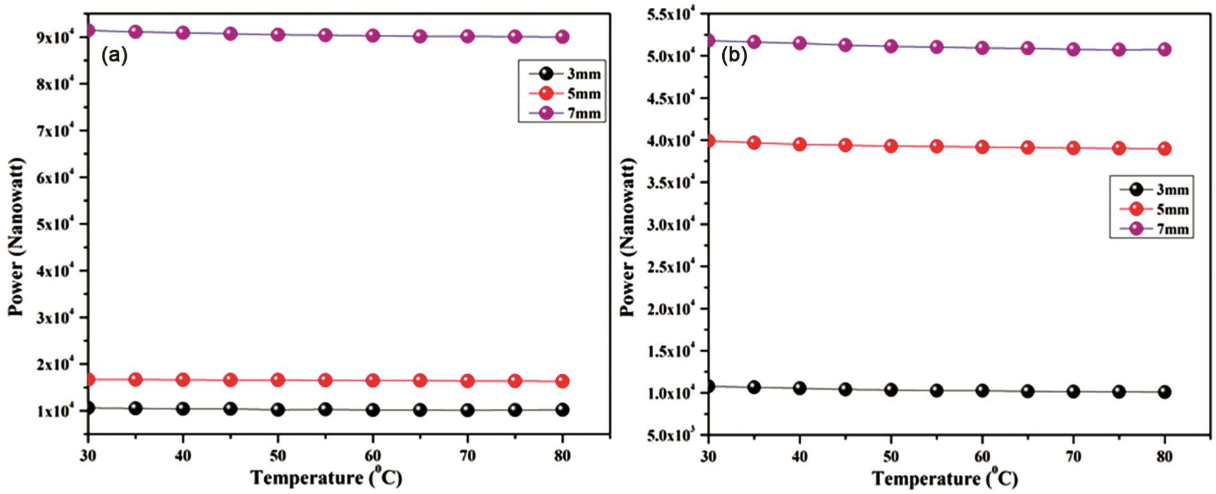

Fig. 6 — Variation in power with respect to temperature is shown for (a) single point tapered and (b) dual point tapered.

PCF. The sensitivity was obtained by linear fitting of graph. Among of various tapering length we use result of 7 mm single and dual point tapered PCF and sensitivity of 30 nW/ °C and 19 nW/ °C, respectively, is obtained.

4 Conclusions

In conclusion, a simple MMF stubbed tapered PCF sensor was fabricated and demonstrated as refractive index and temperature sensor. The tapered fiber was fabricated by using low cost simple micro droplet etching method. The output power decreases with increase in outer refractive indices due to absorption of evanescent waves. The maximum sensitivity of 1891 µW/RIU and 900 µW/RIU was obtained for single and dual point tapered PCF, respectively, for 7 mm tapering length. The same sensing probe was used for temperature sensing and sensitivity of 30 nW/ °C and 19 nW/°C was obtained for single and dual point tapered PCF, respectively, for the same sensing length.

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