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Tapered optical fibers using CO_2 laser and their sensing performances

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Abstract. In this paper, we proposed a simple tapering process of optical fibers using controlled CO_2 laser. This is a response to the call for the rapid development of affordable, efficient, and reliable optical sensors. A laser with power of 36 W was focused on a small section of three optical fibers having core/cladding diameters in micrometer of 10/125 (sensor A), 62.5/125 (sensor B), and 200/225 (sensor C). The sensors were tested on solutions having refractive indices of 1.3325 to 1.4266. Our investigation revealed that sensor C offered highest sensitivity. Therefore, further characterizations on its sensing characteristics were conducted. Over 6 times repetitive measurement, sensor C showed excellent repeatability with average sensitivity and detection limit of 4.5941(78) a.u./RIU and 3.97×10^{-4} RIU, respectively. The tapered large core fiber also had good reversibility. Furthermore, the stability test by applying sensor C to solutions with low, medium, and high refractive indices also showed that the sensor was relatively stable. Within 60 minutes measurement, we noticed increasing trends of normalized intensities. However, the intensity increment percentages were relatively small, i.e., 0.27%, 1.17%, and 1.75% respectively for refractive indices of 1.3325, 1.3921, and 1.4266. Thus, excellent tapered optical fiber sensor could be produced using CO_2 laser.

1. Introduction

Recently, evanescent wave based optical fiber sensor has been extensively studied for various applications ranging from biochemistry to road safety fields [1]. High sensitivity, good monitoring efficiency, affordable cost, small size, temperature resistance, and immunity to electromagnetic interference are considered as the features why optical fibers are explored as sensors [2]. The sensitivity of optical fiber is strongly dependent on the interaction between evanescent wave spreading at the penetration depth with the surrounding medium [3]. Therefore, many scientists attempt to modify the geometrical structure of optical fibers to increase their sensitivity. One of the most preferrable approaches is through optical fiber diameter reduction, i.e., tapering the optical fibers [4,5].

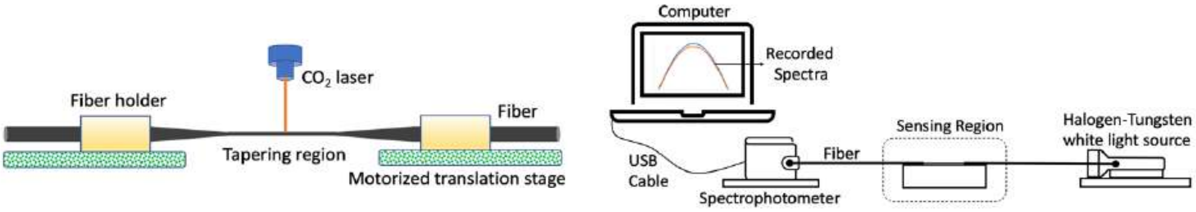
Many publications have reported the tapered optical fibers sensing performances due to their evanescent field mechanism. However, the existing studies commonly focused on one type of optical fibers. For example, some focused on tapered single mode fibers [1,6] and some others focused on multimode fibers [7–9]. To the best of our knowledge, it is very little known the comparison of different tapered optical fibers on their refractive index sensing performances.

Previous studies suggested that smaller waist diameter would promote better optical properties of the microfiber [10]. Jali et al. could produce high sensitivity of tapered microfiber-based loop humidity sensor with waist diameter of 7 μm [11]. Wang et al. studied the effect of tapered diameter on the transmitted intensity [12]. They found that reducing the waist diameter from 60 μm to 20 μm both for single mode and multimode fibers reduced the light transmission intensity [12]. They furthermore explained that the reduced light intensity is caused by more evanescent field due to smaller waist diameter [12]. However, they did not report the sensing characteristics of the tapered microfiber on different media. Again, there is a gap that need to be bridged in this photonic field. Therefore, this study is aimed to close the current research gap. This study is designed to compare three different tapered optical fibers for their real application as refractive index sensor.

The key procedure of tapering optical fiber is by pulling apart the fiber while heating its small section. Some commonly used heating source for tapering techniques include flame brush [4], microheater [13], arc-discharge [14], and CO_2 laser [15]. Among the techniques, CO_2 laser offer more benefits due to its capability to provide localized heat, large thermal gradient, short heating time, and suitable for all silica-based fibers [6]. Therefore, CO_2 laser tapering approach is used in this study.

2. Methods

Table 1 shows the three different optical fibers used in this study. A mechanical stripper was used to remove the jacket (length = 2 cm) from the middle section of the optical fibers. Prior to tapering process, the stripped region was cleaned using isopropyl alcohol to remove offending dirt. A CO_2 laser with power of 36 W was employed to taper the stripped region of the optical fibers. The as prepared 50 cm optical fiber was placed on a precision motorized translation stage in a way that the CO_2 laser beam could heat up the stripped region. During heating, the fiber was pulled at speed of 1000 rpm by high precision two stepper motors. The total time for fiber heating and pulling to produce tapered fiber was 5 s. The taper-based optical fibers were placed in a closed chamber for further protection. The schematic diagram of tapering process is depicted in figure 1(a).



(a) (b)

Figure 1. Schematic diagram of (a) optical fiber tapering process using CO_2 laser and (b) refractive index sensing measurement set-up.

Table 1. Three different optical fibers under study.

Fiber code	**Fiber type**	**Diameter (μm)**		
		Core	**Cladding**	**Jacket**
A	Single mode	10	125	250
B	Multimode	62.5	125	250
C	Large core multimode	200	225	500

The tapered diameter of the optical fibers was confirmed by transmitted light microscope, AmScope. Meanwhile, the optical response of the fibers due to different external refractive indices was tested by implementing experimental set-up shown in figure 1(b). One end of the stripped optical fibers was connected to a Halogen-Tungsten white light source via suitable fiber connectors, depending on the cladding diameters of the optical fibers. The tapered region was placed on a glass slide, and it was set as the sensing region to apply ethylene glycol solutions. A CCS 200 compact spectrophotometer was connected to the other end of the optical fiber. The output transmission optical spectra were recorded by a computer using Throlabs OSA software in response to the ethylene glycol solutions with refractive indices from 1.3325 to 1.4266. The optical spectra of all untapered and tapered fibers in ethylene glycol solutions were captured for comparison. The sensor with highest sensitivity was further tested in terms of its reversibility, repeatability, and stability.

3. Results and Discussion

Figure 2 shows the micrographic images of the tapered optical fibers for sensor A (single mode fiber), sensor B (multimode fiber), and sensor C (large core multimode fiber). The graph displays different waist diameters for distinctive fibers under the same CO_2 laser power and pulling rate. The waist diameter of sensor A, B, and C were 35.63 µm, 22.34 µm, and 51.77 µm, respectively. Therefore, the CO_2 laser tapering process, in this experiment, could produce the smallest waist diameter of around 22 µm for multimode fiber. Good uniformity of the tapered fibers can be seen from the micrographic images. For the same multimode fiber, previous research had also obtained similar tapered waist diameter (22.60 µm) using flame-brush approach [4]. Furthermore, table 2 shows the process time of tapering optical fiber using different techniques. It is clearly seen that our CO_2 laser technique offers the fastest route to produce tapered optical fibers with good uniformity. Our method is 720 faster as compared to wet etching method.

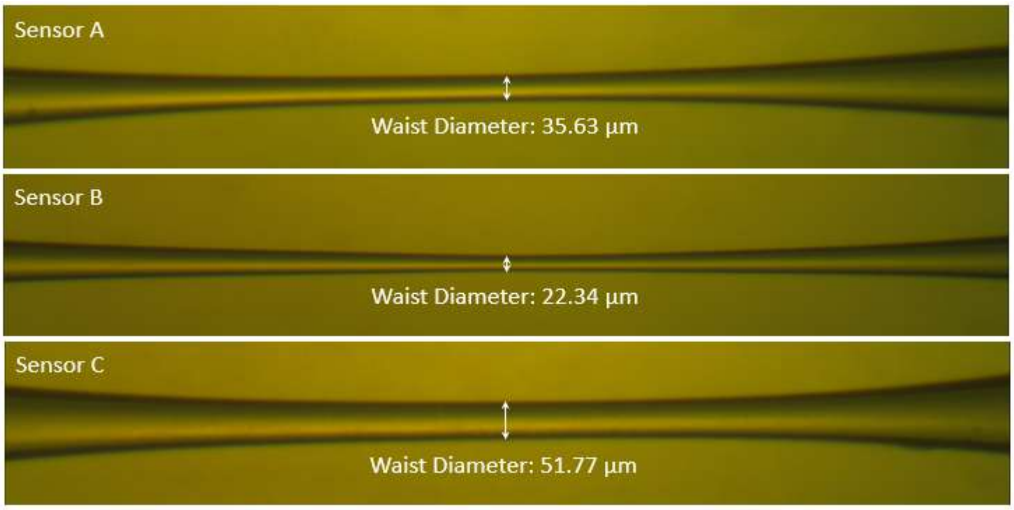


Figure 2. Tapered optical fiber profiles.

Table 2. Process time of different tapering approaches.

Tapering method	Process time (s)	Ref.
Wet etching	3600	[16]
Flame	180	[17]
Microheater	N/A	[13]
Arc-discharge	55	[14]
CO_2 laser	5	This Work

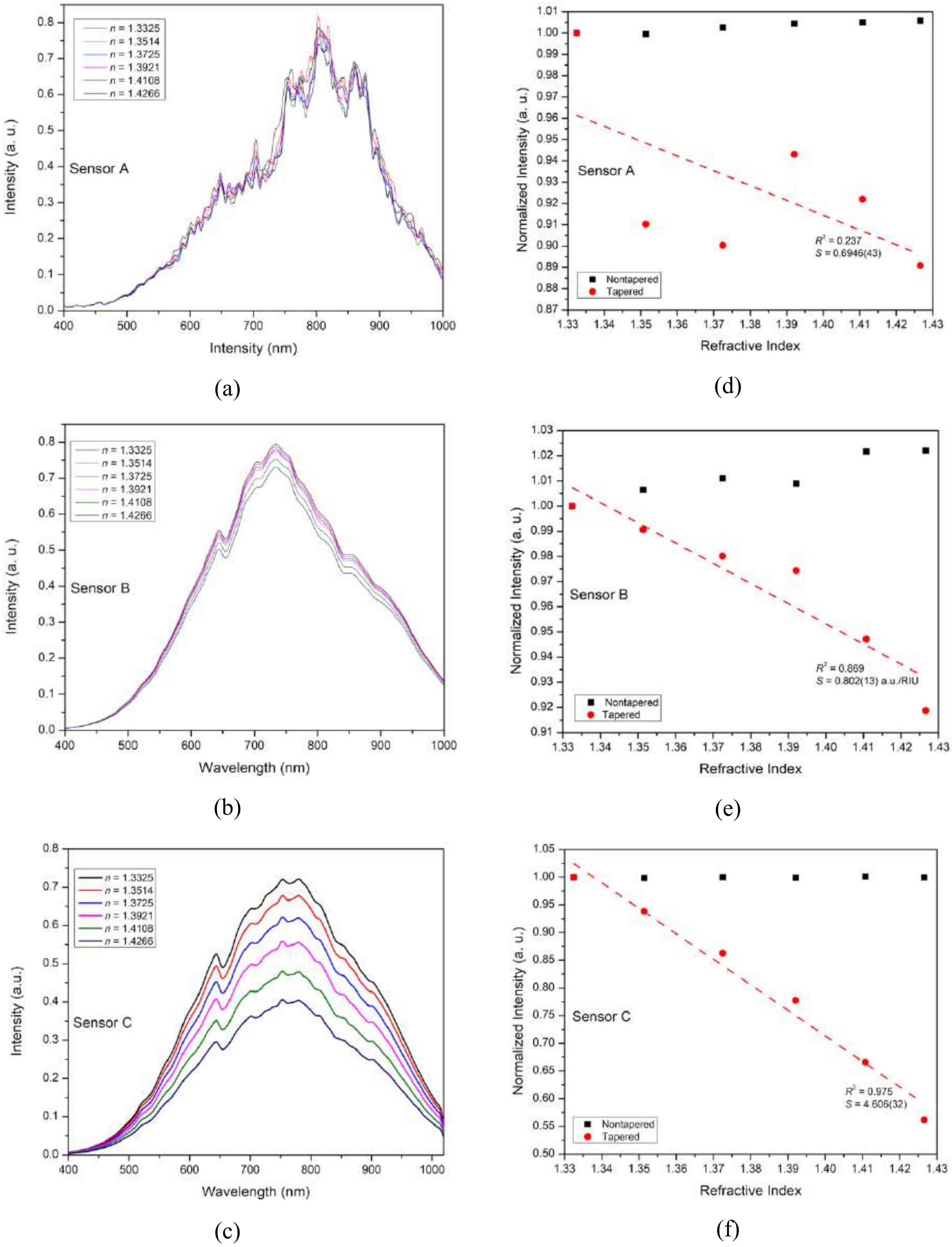
Figure 3 shows the transmission optical spectra of the three different sensors due to varying refractive indices and their respective sensitivities. The sensitivity is obtained from the slope of the intensity-refractive index graph. Consequently, the degree of linearity or coefficient of determination (i.e., R^2 value) supports the justification of the sensitivity value. This is because R^2 dictates the goodness-of-fit of the linear regression model and R^2 is used as scientific standard metric for regression evaluation [18]. In our case, both sensitivity and R^2 must be taken into consideration to justify the performance of sensor. Although sensors A and B had similar sensitivities, their coefficient of determinations could bring significant implications. The R^2 of sensor A was 0.237 which means that the sensor does not linearly respond to the refractive index change. On the other hand, sensor B, with R^2 = 0.869, offered good optical response linearity under varying refractive index media. Unlike sensor B and C, sensor A exhibited non-identical optical spectra at different refractive indices. It implied that sensor A had degradation of optical properties due to varying media [19]. Thus, sensor A is not good for refractive index sensor. Furthermore, sensor C had the highest sensitivity (S = 4.606(32) a.u./RIU) with excellent coefficient of determination (R^2 = 0.975). The sensitivity of sensor C (tapered large core multimode fiber) is 5.75 times higher than that of sensor B (tapered standard multimode fiber). By comparing the sensitivity and coefficient of determination of the three tapered optical fibers, it is rationalized that sensor C is the best for refractive index sensor. Therefore, sensor C underwent further sensing performance tests, i.e., reversibility, repeatability, and stability.

Tapering optical fiber down to a micrometre range promotes evanescent wave which can be implemented for refractive index sensor [4]. The physical treatment of tapering process is to gradually reduce the optical fiber's diameter. The reduction of core and cladding diameters enables the spread out of evanescent fields into the cladding area [20]. The evanescent wave spreading out in the reduced cladding area interacts with surrounding medium but limited by penetration depth [4]. The refractive index of the medium is directly proportional to the evanescent wave extinction in the cladding area [21]. It implies that higher refractive index will promote stronger evanescent wave and, in this experiment, recorded by lower light intensities. The decrease of light intensities due to stronger evanescent wave was also reported by the previous study [22]. Stronger evanescent wave excitation in the tapered region can be obtained by reducing the tapered waist diameter. Therefore, creating smaller waist diameter is preferable as the way to improve evanescent wave in tapered optical fiber sensors [23]. When waist diameter is smaller than that of the original core diameter, the tapered fiber shows better sensitivity. The evanescent wave sensing mechanism explains (1) why the transmitted light intensity decreased as the increment of refractive index, (2) why sensor B was better than sensor A and (3) why sensor C showed the highest sensitivities.

Figure 4 displays the sensor C (tapered large core fiber) sensing characteristics in terms of (a) reversibility, (b) repeatability, and (c) stability. The reversibility of a sensor can be tested by measuring the response in ascending and descending order of sensing variables. A good responsibility is an important factor for sensor practical applications [24]. Meanwhile, repeatability is the sensor's ability to perform the same results under the same measurement [25]. Stability can be viewed as sensor's ability to keep stable signal over a sufficient period of time [26].

From figure 4(a), it is clearly seen that the descending and ascending order of refractive index did not significantly affect the measurement results. Both values of goodness-of-fit and sensitivities for the descending and ascending measurements were very close. It means that our fabricated sensor is reversible and therefore can be operated either in descending or ascending order of change of refractive index.

The tapered large core fiber was also applied for refractive index sensor up to 6 repeatable measurements. As depicted in figure 4(b), it is obvious that sensor C performed repetitive results. Therefore, it can be said that our fabricated sensor is also capable for repetitive measurements. From these 6 repetitive measurements, the average sensitivity of the fiber was 4.5941(78) a.u./RIU. Other studies reported that D-shape fiber optic sensor could have sensitivity of 2.8271 a.u./RIU [27]. Therefore, tapered large core multimode fiber could performed better sensitivity than that of D-shape fiber. In addition, the detection limit of the sensor C was obtained with value of 3.97×10^{-4} RIU.

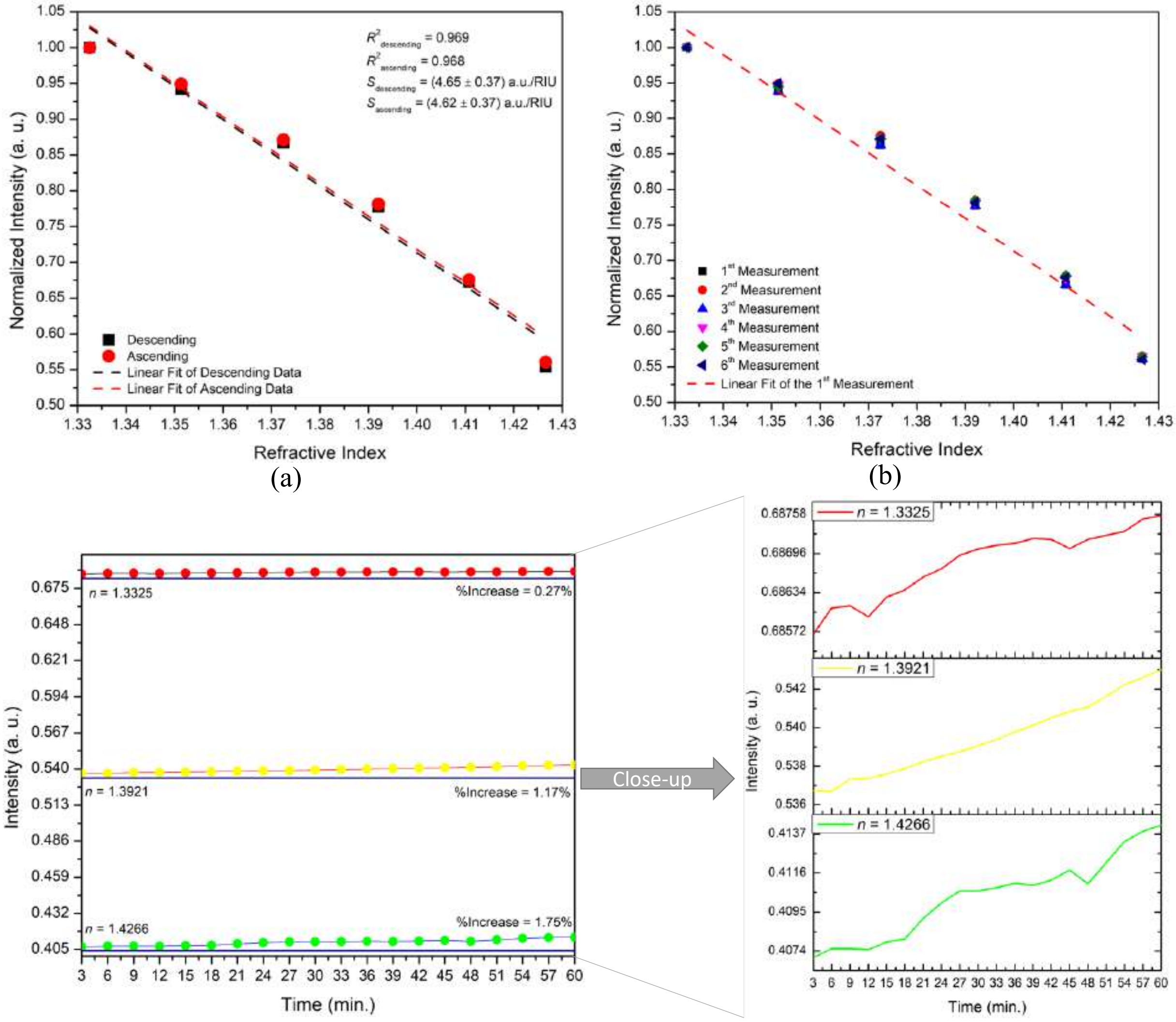


(a) (d)

(b) (e)

(c) (f)

Figure 3. Optical spectra of (a) sensor A, (b) sensor B, (c) sensor C and (e-f) their respective sensitivities.



(a) (b)

(c)

Figure 4. Tapered large core fiber tests for its (a) reversibility (b) repeatability and (c) stability.

Lastly, the stability performance of sensor C is shown in figure 4(c). The stability test was done under three extreme values, i.e., low (n = 1.3325), medium (n = 1.3921), and high (n = 1.4266) refractive indices. The measurement was recorded every 3 minutes for an hour. Figure 4(c) dictates that sensor C tended to record higher intensity in the stated period. However, the %increase is very small, i.e., 0.27%, 1.17%, and 1.75% respectively for low, medium, and high refractive index media. The good stability of tapered optical fiber sensor is consistent with the previous result [4].

4. Conclusion

In this paper, three different optical fibers were tapered using CO_2 laser. The experiment concluded that the tapering optical fiber using CO_2 laser could save the production time. Compared to other techniques, CO_2 laser could yield a good uniformity of taper in only 5 s. Tapered large core multimode fiber (sensor C) showed the most sensitive sensor. The sensitivity of the tapered large core multimode fiber was nearly 6 times higher than that of tapered standard multimode fiber. The average sensitivity of sensor C was 4.5941(78) a.u./RIU with detection limit of 3.97×10^{-4} RIU. All sensing performance tests on the sensor C reported in this study suggested that the tapered large core fiber can be considered as sensitive, repeatable, reversible, and stable refractive index sensor.

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