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ROBUST REFRACTIVE INDEX FIBER SENSOR BASED ON TWO UP-TAPERS PLACED IN DOWN-TAPER

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ABSTRACT. In this study, a novel tapered optical fiber sensor based on a Mach–Zehnder interferometer (MZI) for refractive index measurement is proposed. Our sensor is constructed with two up-tapers symmetrically placed in a down-taper single mode fiber. Although its waist diameter is as thick as 55 μm, the sensor can measure the refractive index. Simulation results demonstrate RI sensitivities of -94 nm/RIU and -125 nm/RIU at the lower and higher wavelength of the spectrum. The sensor is extremely robust, it can be easily manufactured and it can be used not only for RI but also for simultaneous strain and temperature measurements.

1. INTRODUCTION

Fiber optical sensors offer some unique advantages compared to traditional electrical sensors such as small size, immunity to electromagnetic interference, high sensitivity, ease of fabrication, low cost, ability to operate in harsh environments, remote sensing, simultaneous measurement applications and so on. Refractive index [1-2], pressure [3-4], temperature [5], strain [6], chemical and biological sensing [7-8] are widely measured parameters that can be sensed by fiber sensors. Recently, combinations of down-taper fiber (DTF) and up-taper fiber (UTF) have been widely researched to obtain a more robust sensor. The most common methods to fabricate DTF sensors are electrical arc discharge [9], flame-brush technique [10], CO_2 laser drawing [11], chemical etching [12] and fusion splicer drawing [13]. UTF sensors are fabricated by using some of the commercial fusion splicers via cleaving and splicing two fibers by built-in mode through setting the overlap parameters without changing the other splicing parameters.

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Previously, some sensor structures have been proposed for measurement of different parameters such as refractive index, strain, temperature, humidity, force etc. Zhao et al. [14] proposed a photonic crystal fiber interferometer which was formed by splicing a photonic crystal fiber between two single mode fibers having UTF joints. The sensitivity of this sensor was up to 252 nm/RIU. However, the sensing structure requires a special type of fiber so its cost is slightly high. Xiong et al. [15] fabricated an MZI based on concatenated two UTFs and a long period grating (LPG). UTF parameters were as follows: overlap was 150 μm, the diameter and length was 165 μm and 278 μm, respectively. LPG with a period of 550 μm and the length of 30 mm was fabricated by high frequency laser pulses. The corresponding sensitivity to measure refractive index in the range of 1.338-1.363 RIU was -108.16 nm/RIU but the fabrication of LPG is complicated and expensive. Furthermore Fu et al. [16] demonstrated a Michelson interferometer based on a UTF which is formed by pushing a single-mode and a multimode fiber while splicing. UTF excites several high order modes due to core mismatch and both core and high order cladding modes propagate in multimode fiber until it is reflected back from the end surface. Reflected modes recombine in UTF to interfere with each other. Sensitivity of this sensor reached -178.424 dB/RIU in the range between 1.351 and 1.4027 RIU. In a recent study, Zhang et al. [17] presented a UDF-DTF-UTF structure to measure refractive index, strain and temperature simultaneously. The length of the DTF was 250 μm and diameters of UTFs were 160 μm. The sensitivities of three dips in transmission spectrum were -131.93 nm/RIU, -22.875 nm/RIU and 0 nm/RIU in the range of 1.3211-1.3527 RIU. However, extinction ratio of the dip with highest RI sensitivity is too low. In another recent study, Ahsani et al. [18] proposed an MZI based optical fiber refractive index (RI) sensor constructed by uniformly tapering standard single mode fiber. The sensor with a cladding diameter of 35.5 μm and length of 20 mm exhibits RI sensitivity of 415 nm/RIU for RI range between 1.332 and 1.384. However, this sensor is not robust due to the thick cladding diameter.

Among the fabrication methods of DTF, electrical arc discharge come into prominence because it enables low cost, high reproducibility, disuse of hazardous chemicals and flexibility to configure desired sensor parameters. In this method, fabrication of tapered fiber requires stretching a fiber while heating it up to its softening temperature, typically 1500°C to compose a structure of diminishing both core and cladding diameter. In electrical arc discharge method, on the other hand, effective heat zone of electrodes has a direct unfavorable influence on adiabaticity. To overcome this problem DTF sensors are required to establish with small diameters less than about 35 µm but, in this way, more robust sensor could not be achieved.

In this study, a more robust sensor design is proposed by concatenating a UTF and DTF with higher diameters more than 35 µm to enhance the robustness. The proposed sensor is shown in Figure 1. When light is penetrated into UTF region, high-order cladding modes are excited because of the mismatch of the mode field diameter and it causes light to split into two parts, one propagating in the core and the other in the cladding. Down tapering provides evanescent field to access the surrounding environment because the light is confined by the boundary between the taper and surrounding environment. Changing the parameters of the environment stimulates different types of modes supported by the taper, which results in a shift of wavelength spectrum as a function of surrounding parameter.

2. Sensing Principles

The sensor structure consists of three parts. The first is the long part, which is ordinary DTF. The second and third are short identical sections placed in the first part, which are UTFs. The schematic diagram of the sensor structure is shown in Figure 1.a. Two standard single mode fibers are spliced to sensor ends to connect to the light source and optical spectrum analyzer.

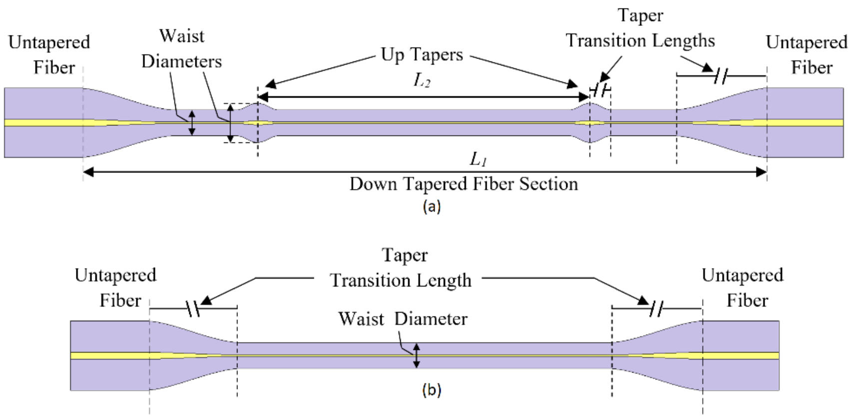

FIGURE 1. The schematic sensor structure, a) our sensor, b) Conventional DTF sensor.

Conventional DTF sensor structure given in Figure 1.b, similar to the long part of our sensor design, is fabricated by sufficiently reducing the fiber cladding diameter by using one of the methods mentioned in Introduction part. The cladding diameter in the thinnest region of the DTF is called waist diameter. The waist diameter can be reduced to less than 30-35 µm to obtain interference of forward guiding modes which cause resonant dips in wavelength spectrum. The changes in the measurands such as refractive index of the medium, temperature and stress will change the spectrum of light at the fiber output. However, measurable spectral changes can be achieved with thinner tapered SMF sensors. If the tapered fiber is further thinned, the optical power is preferably compressed into two modes leading to powerful oscillations in the spectrum. When the light is injected into tapered part of fiber, the transition section will excite the higher order modes. The interference of the optical modes in the waist region, which is thin enough, is formed according to not only the fiber guide but also by surrounding environment condition such as RI. The relative phase difference between two interfering modes can be expressed as;

$$\Delta\emptyset = \frac{2\pi}{\lambda}(\Delta n)L$$

where L is the length of the sensor section, λ is the wavelength of the light source and Δn is the effective refractive index difference. For the down tapered sensor with a sufficiently thin waist diameter, the fiber cladding acts as a core and surrounding medium of fiber replaces the cladding. In this case, the index difference can be expressed as $\Delta n = n_{eff}^{co} - n_{eff}^{sur,m}$. Here, n_{eff}^{co} and $n_{eff}^{sur,m}$ are the RI of core mode and mth-order surrounding medium mode, respectively. However, in the case of down taper single mode fiber with thick waist diameter, e.g. larger than 35-40 µm, propagating modes weakly form an interference.

The electric field amplitude distributions of two DTF sensors with different waist size are shown in Figure 2.a and 2.b obtained from beam propagation simulation results. Beam propagation simulation is a well-known technique in the literature and there are many commercial software. As the waist diameter increases, the amplitude of evanescent field decreases and thus the interference intensity is reduced as shown in Figure 2.b. This results in weak dips in the transmission spectrum and poor sensitivity. Therefore, the transmission spectrum of the sensor exhibits weak dips corresponding to the resonance wavelengths as given in Figure 3 where the waist size is reduced from 55 µm to 8 µm. Since poor interference leads to low resolution, the dynamic spectrum is desirable to obtain high resolution measurement. This can be achieved by the powerful interference of the fiber modes that propagate along sensor section.

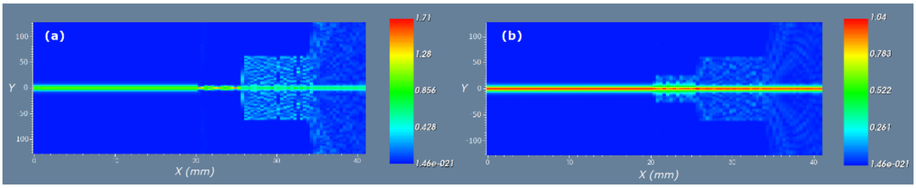

FIGURE 2. The electric field amplitude distributions of DTF sensor for different waist size, (a) 8 µm (b) 55 µm.

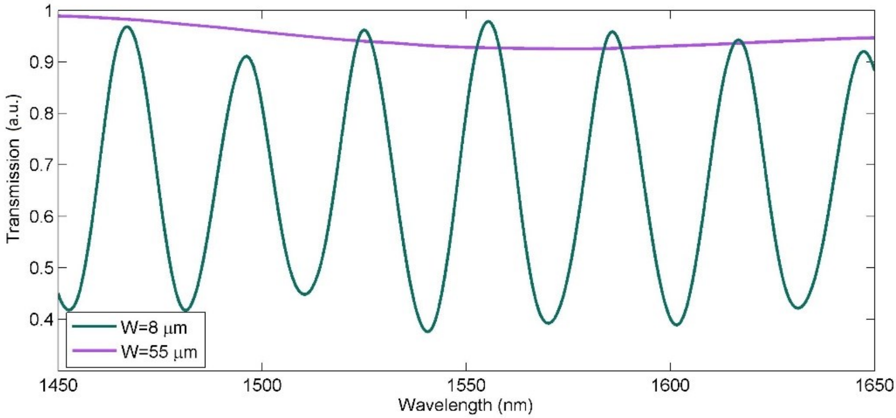

FIGURE 3. The transmission spectra of DTF sensor for waist size of 8 µm and 55 µm.

In this study, we propose to place two up-tapered sections in the down-tapered fiber with a length of 30 mm as shown in Figure 1. DTF region excites a few leaky modes, but these modes will be quite poor due to the thicker waist diameter so the interference spectrum originating from DTF itself will not be strong enough to sense the environment. The placement of UTF sections in the DTF region can strengthen leaky modes and the sensor designed as a MZI can be activated. The next section presents simulation results and discussion to test the RI sensitivity of the proposed sensor.

3. Results and Discussions

In this section, we carried out simulations of proposed fiber sensor by using beam propagation method in two dimensional structure. UTFs were positioned symmetrically with respect to the axis of symmetry in the center of the DTF section. The waist diameters UTFs and DTF were set to 85 µm and 55 µm, respectively. The length of the DTF section, L_1 is 32 mm and the distance between the UTF tapers is 22 mm. The taper transition lengths of UTF and DTF sections were set to 300 and 1000 µm, respectively.

Figure 4 shows the transmission spectra of our sensor for different refractive indexes of environment. The spectrum was obtained for a wide wavelength range between 1.3 µm and 1.8 µm. Two dip points were observed in the spectrum where the transmission amplitude decreased to about 0.6 and less. As the refractive index increases the spectrum shifts to lower wavelengths called as blue-shift in contrast to conventional DTF sensors that experience red-shift.

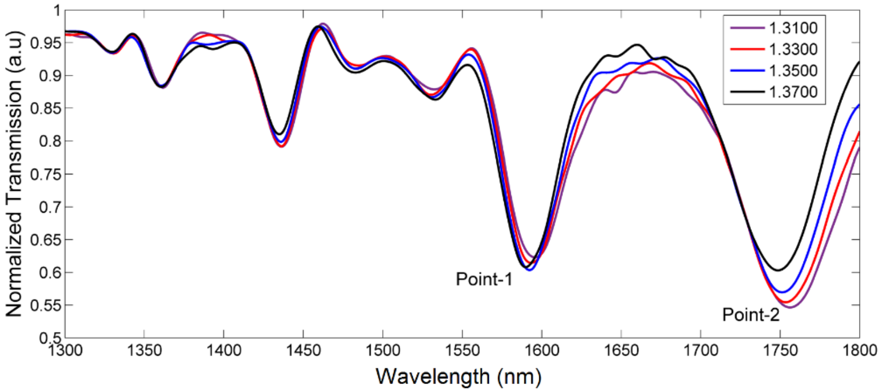

FIGURE 4. Normalized transmission spectrum obtained for RI range of 1.31-1.37.

In order to test RI sensitivity characteristic of sensor, four simulation data were obtained by changing the RI in the range of 1.31-1.37. The sensitivity can be defined as $\Delta\lambda/\Delta RI$ which is ratio of wavelength change in the transmission spectrum to RI change in the surrounding medium. Figure 5 presents wavelength shifts obtained from two dip points, namely Point-1 and Point-2.

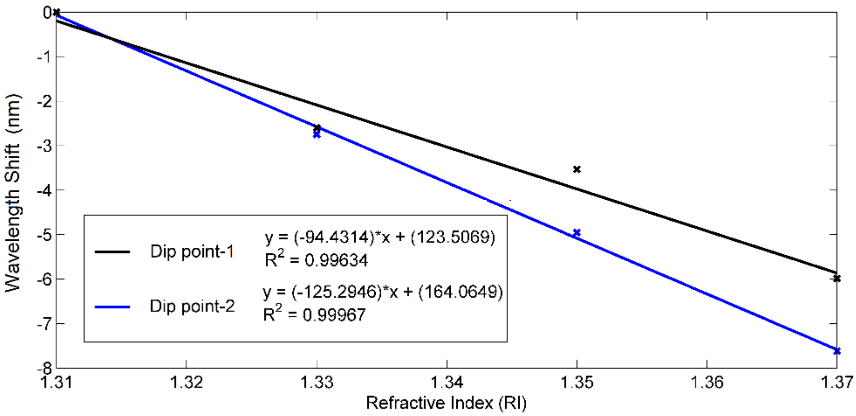

FIGURE 5. Sensor sensitivities calculated from point-1 and point-2.

As shown in the Figure 5, calculated sensitivities were about -94 and -125 nm/RIU at point-1 and point-2 corresponding to wavelengths of about 1590 nm and 1755 nm, respectively. It is clear that the dip point close to higher wavelengths exhibits higher sensitivity than the dip point at lower wavelengths. On the other hand, relation between RI and wavelength shift can be evaluated by a well-known parameter called linear correlation coefficient, R^2. Figure 5 indicates that our sensor has responded linearly to RI with a high linear correlation coefficient greater than 0.99.

4. Conclusion

In conclusion, a novel type of MZI fiber sensor based on placed two UTFs into the waist region of a DTF for measurement of refractive index is proposed and investigated theoretically in this paper. Simulation results show that first and last UTFs act as mode splitter and combiner, respectively, while the DTF is responsible for evanescent field to interact with surrounding environment. Furthermore, the results show that such an optical fiber sensor can work over a wide refractive index range of 1.31-1.37 with a sensitivity up to -125.29 nm/RI. Such a sensor structure including a UTF can be a good choice to satisfy the adiabaticity criteria without requiring thin waist diameters for DTF so that a robust sensors can be realized. Robustness and simple fabrication make it a good candidate for not only refractive index measurement but also strain and temperature measurements in a wide range of potential applications such as chemistry, biology, biomedical or photonics.

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