

Single mode tapered fiber-optic interferometer based refractive index sensor and its application to protein sensing

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Abstract: We demonstrate refractive index sensors based on single mode tapered fiber and its application as a biosensor. We utilize this tapered fiber optic biosensor, operating at 1550 nm, for the detection of protein (gelatin) concentration in water. The sensor is based on the spectroscopy of mode coupling based on core modes-fiber cladding modes excited by the fundamental core mode of an optical fiber when it transitions into tapered regions from untapered regions. The changes are determined from the wavelength shift of the transmission spectrum. The proposed fiber sensor has sensitivity of refractive index around 1500 nm/RIU and for protein concentration detection, its highest sensitivity is 2.42141 nm/%W/V.

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OCIS codes: (060.2370) Fiber optics sensors; (060.2340) Fiber optics components.

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1. Introduction

Bio-photonic sensors are optical devices based on optical phenomena to measure biological species such as cells, proteins, and DNA [1]. Because of their efficiency, accuracy, low cost and convenience, bio-photonic sensors are promising alternatives to traditional immunological methods for biomolecule measurements. Nowadays, there are various types of refractive index (RI) sensor, but long period grating [2, 3] and etched fiber Bragg grating [4, 5] are the most popular apparatus. Despite their popularity, these sensors have two weaknesses, which are low sensitivity and stringent fiber fabrication process [6, 7]. Surface plasmon resonance is one of the comprehensive techniques with high sensitivity but the cost is high due to the use of expensive metal film and complex coating technology [8]. In recent years, researchers have paid close attention towards the application of single mode taper fiber (SMTF) structure in sensing fields [9–11].

In tapered fibers, coupling between the core and surface modes occurs over a broad wavelength range. The fabrication of SMTFs with different shapes and properties depends upon the fabricating conditions. On the basis of coupling, the fiber tapering may be divided into two categories: adiabatic and non-adiabatic [12–14]. A tapered fiber can be categorized as adiabatic if most of the power remains in the fundamental mode and does not couple to higher order modes as it propagates along the taper. In this case, the change in the taper radius has to be very gradual (small taper angle). In general, the adiabatic tapered fiber has been used for the fabrication of surface plasmon resonance sensor highly sensitive to RI. Whereas in the case of nonadiabatic tapering, some power travels in the cladding mode and it couples with fundamental core mode as it propagates along the tapered region. In this case, the taper angle has to be large enough to facilitate this effect. Ju *et al.* have fabricated nonadiabatic tapers based on air-core photonic band gap fibers [15]. In their work, Mach-Zehnder interferometers were formed by utilizing such tapers for strain and temperature measurement.

RI measurement in small volumes plays a vital role in many areas of biophysics, biochemistry and biomedicine. For example, the RI can be used to determine the concentration of sugar or proteins. Gelatin is one type of protein produced by the partial hydrolysis of native collagen. It is widely used in food, pharmaceutical, cosmetic and photographic applications. In the detection of protein concentration, many bio-photonic sensors have been developed so far. In 2002, Balcer *et al.* [16] optimized a reusable fiber optic immune sensor for the detection of protein concentration.

In this paper, we propose an SMTF interferometer RIs sensor for potential applications of protein concentration detection. The shift in the transmission spectrum depends on the surrounding medium in the waist length region. Thus, the transmission of the SMTF is quite

sensitive to the refractive index of the external medium, which makes it possible to be deployed as an RI sensor. The proposed sensor is also utilized as bio-photonic sensor to detect protein concentration.

2. Sensing principle

Fiber tapering refers to the process of pulling a fiber while heating, such that the overall diameter of the fiber at the tapered region is less than the original diameter. Currently, two types of tapered fiber geometries in biosensing application are favorable; tapered tips and continuous tapered fibers. In a tapered tip fiber, it consists of an optical fiber which gradually decreases in diameter until it becomes a tiny tip that later becomes the sensing element. On the other hand, a continuous tapered fiber is an optical fiber that is gradually decreasing in diameter (downtaper), which reaches a constant-diameter waist region, and then gradually increases (uptaper) back to the original diameter (see Fig. 1).

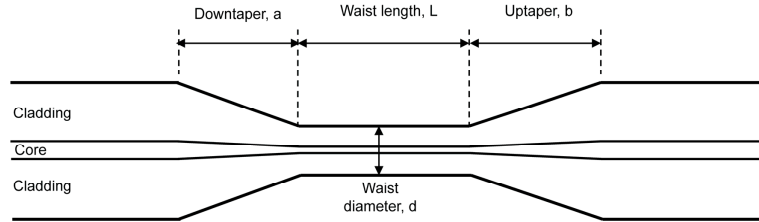


Fig. 1. Schematic diagram of SMTF, the downtaper (a) and uptaper regions (b) are the transition regions where the coupling and recombination of modes occur.

Light enters from untapered region to tapered region at one end thus exciting higher order modes in the tapered region. Then the fundamental modes and higher order modes coupled together in untapered region at the other end to form interferometric pattern due to large difference in indices between air and glass. For the sake of convenience, we assume that only two modes having effective indices; core refractive index, n_{co} and cladding refractive index, n_{cl} exist in the uncollapsed section of the SMTF. Thus, the resultant intensity at the end of the SMTF is [17],

$$I_T = I_{co} + I_{cl} + 2\sqrt{I_{co}I_{cl}}\cos(\Delta\phi) \quad (1)$$

where I_{co} and I_{cl} are the intensities of the core and cladding modes, respectively and $\Delta\phi$ is the phase difference between these two modes i.e. the phase of the resultant interferometry intensity pattern. The relative phase difference between the two interfering modes can be described by,

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

where λ is the central wavelength of the light source. Since only one cladding mode is excited, we will have the interferometer in which physical lengths (waist length, L) are exactly the same but the optical lengths are different to each other due to the difference in indices of core and cladding. Multiplying it with the difference in indices ($\Delta n = n_{eff}^{co} - n_{eff}^{cl}$) of each excited mode gives the optical path difference of the two interfering modes, where n_{eff}^{co} is the effective index of the core mode and n_{eff}^{cl} is the effective index of the cladding mode. Thus by changing the refractive index of the surrounding medium, the phase difference, $\Delta\phi$ changes, which leads to a shift in the transmission spectrum.

3. Experimental setup

For the fabrication of tapered fiber, Vytran GPX-3400 machine is utilized in our experimental works. The Vytran GPX-3400 machine is a highly precise, computer-controlled glass processing machine that utilizes filament as a heat source. The machine also offers high reproducibility of the taper and the convenience of changing the profile of the tapered fibers. To ensure the uniformity of the taper fabricated in this experiment, the pulling speed of the fiber holding blocks is kept at a constant rate of 1 mm/s while the heat is set at 38 W. In this research work, three different taper profiles will be investigated as tabulated in Table 1, the waist diameter is maintained at 15 μm . Example of tapered fiber microscopic images for S_1 is represented in Fig. 2; (a) tapered region and (b) waist region.

Table 1. Taper Profiles with Waist Diameters, d Is Fixed at 15 μm

Sensor ID	Downtaper, a (mm)	Uptaper, b (mm)	Waist length, L (mm)
S_1	5	5	10
S_2	5	5	15
S_3	5	5	20

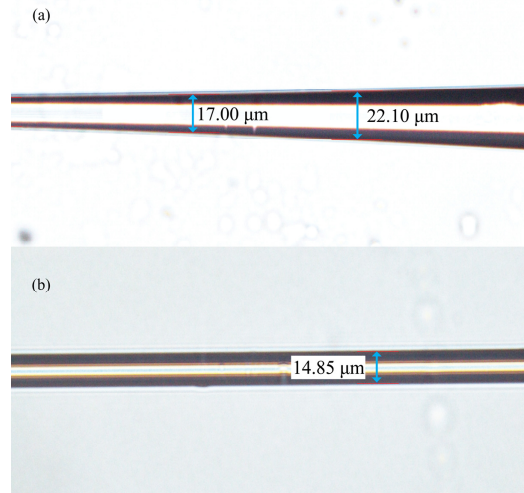


Fig. 2. Microscopic image of S_1 at (a) tapered region and (b) waist region.

The schematic diagram of experimental setup of SMTF optic interferometer is shown in Fig. 3(a). The wavelength range of the broadband light source is from 1520 nm to 1570 nm. The spectral measurement is done via an optical spectrum analyzer (OSA) with resolution bandwidth set at 0.05 nm. In this experiment, the optical spectrum before and after tapering processes is recorded for S_1 as depicted in Fig. 3(b). The difference between these two optical spectra defines the transmission spectrum of the fabricated sensor. The interference fringe is created from the interaction between the fundamental and higher-order modes in the tapered region. The minimum transmission loss at the peak of the fringes is recorded around 0.4 dB and its spacing between two peaks (free spectral range) is about 20 nm. The SMTF (sensing element) is placed in a U-shape iron groove. One end of the SMTF is connected to broadband light source and other end to OSA. For RI measurement, we have prepared 20%, 25%, 30%, 40%, 50% and 100% of 1 mole NaCl solution as the RI liquid samples for the measurement. The corresponding RIs are 1.3325, 1.3329, 1.331, 1.3339, 1.3349 and 1.3377 which is certified by an ATAGO PAL-refractometer. For each measurement, a small quantity of the solution is dropped into the U-shape groove until the sensing element is fully immersed. After the measurement, the sensor is cleaned with deionized water and dried in air. The

transmission spectra of different water–NaCl solution is recorded for different taper profiles by maintaining the waist diameter of 15 μm as tabulated in Table 1.

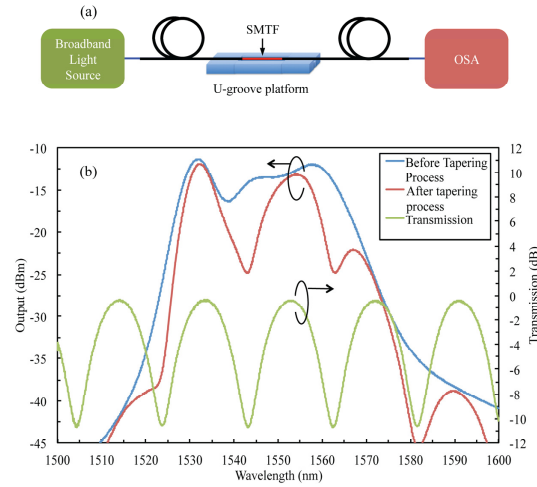


Fig. 3. (a) Experimental setup of RI and protein sensors based on SMTF and (b) measured optical spectrum before and after tapering process.

4. Results and discussions

Figure 4(a) shows the transmission spectrum of SMTF sensor (S_3) with different RIs of NaCl solution and Fig. 4(b) illustrates the corresponding wavelength shift for S_1 , S_2 and S_3 , respectively. It can be observed that the dip is shifted to the longer wavelength side (red shift) as RI increases. When the RI changes from 1.3325 to 1.3377, the dip shifts by about 8.2 nm, 8.8 nm and 7.9 nm for S_1 , S_2 and S_3 , respectively. The wavelength shift of the proposed sensor turns lower with the waist length increasing. Different RI sensitivity of 1545.355 nm/RIU, 1656.354 nm/RIU and 1487.489 nm/RIU are achieved for S_1 , S_2 and S_3 , respectively which is higher than other reported RI optical sensors; 282 nm/RIU [18], 430.2 nm/RIU [19], 851.3 nm/RIU [20] and 936 nm/RIU [21]. The wavelength responses have good linearity with linear fitting of 0.959, 0.996, and 0.919 for S_1 , S_2 and S_3 , respectively. Based on our findings, the increment of waist length does not necessarily provide better sensitivity. This is owing to the disparity effect of waist length towards the phase difference and fringe spacing. Referring to Eq. (2), the phase difference is directly proportional to the waist length. On the other hand, the spacing between two peaks is inversely proportional to the waist length as reported in [22].

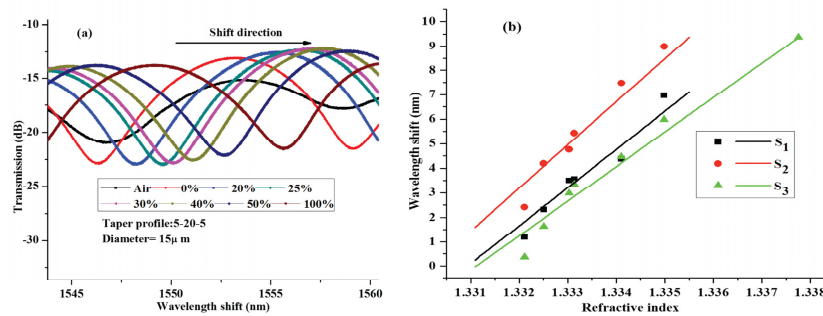


Fig. 4. (a) Transmission spectra of SMTF sensor (S_3) with different RIs of NaCl and (b) wavelength shift of SMTF sensors (S_1 , S_2 and S_3) with different RIs of NaCl.

To demonstrate its application for protein detection, the same sensors are deployed in the subsequent experiment. Figure 5(a) illustrates the change of transmission spectrum with respect to different concentrations of gelatin (protein) sample for S_1 . The variation of wavelength shift with different concentrations of gelatin (protein) for all sensors (S_1 , S_2 and S_3) is shown in Fig. 5(b). The wavelength shift in the transmission spectra are found to be a red-shift of 12.62 nm, 12.05 nm and 9.67 nm and the corresponding concentration sensitivities are 2.4214 nm/%W/V, 1.79143 nm/%W/V and 1.6657 nm/%W/V for S_1 , S_2 and S_3 respectively. It is observed that the sensitivity of the proposed sensor S_1 is comparatively good with S_2 and S_3 for gelatin concentration sensing. The sensitivity of the proposed sensor to the surrounding medium can be applied for the detection of the growth rate of any bacteria by introducing bacteria sensitive materials to the taper waist region. This approach will be applied in our future work on sensors. Apart from the simplicity of our proposed sensor fabrication, their performance is also comparable with previously reported RIs sensors. In fact, the sensitivity is better than the sensors reported in [18–21]. With this clear advantage compared to other fabrication methods that involve more complicated setup, our simple and reproducible fabrication method proves to be a better alternative.

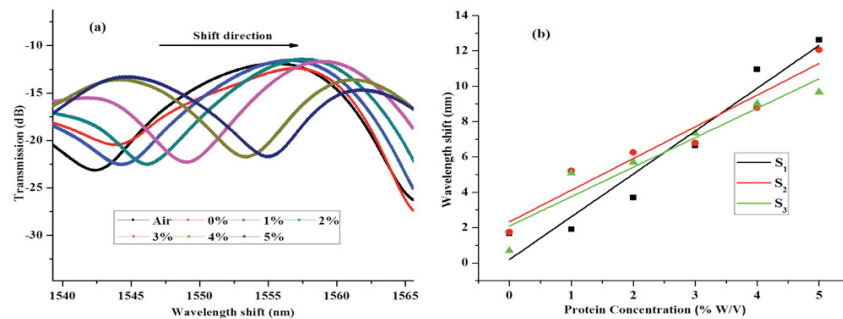


Fig. 5. (a) Transmission spectra of SMTF sensor (S_1) with different concentration of gelatin and (b) wavelength shift of SMTF sensors (S_1 , S_2 and S_3) with different concentration of gelatin.

5. Conclusion

In conclusion, we have developed a single mode tapered fiber interferometer based refractive index sensor and evaluated its sensitivity around 1500 nm/RIU. The detection of gelatin has also been demonstrated by this optic interferometer sensor with highest sensitivity of about 2.42141 nm/%W/V. This simple and highly sensitive fiber-optic biosensor is suitable for the detection of protein concentration in water. The sensitivity of the proposed sensor with surrounding medium can be applied for the detection of the growth rate of any bacteria by introducing bacteria sensitive materials to the taper waist region.

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