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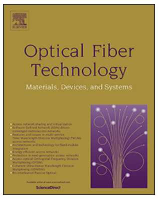

Low cost non-adiabatic tapered fiber for high-sensitive temperature sensing

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ABSTRACT

A non-adiabatic tapered fiber sensor was fabricated, and its applications in refractive index (RI) and temperature sensing were investigated in both theory and experiment. The experiment results demonstrated that the tapered fiber sensor with a diameter of 8 μm had RI sensitivity as high as 1800 nm/RIU and temperature sensitivity of about −300 pm/°C. Then, taking advantage of its high refractive index sensitivity property, an improved temperature sensor structure was proposed by encapsulating it in a glass microtube and filling the microtube with high thermo-optical coefficient liquid. This improved sensor structure showed a higher temperature sensitivity of around −900 pm/°C. The improved sensor structure is simple, low cost and easily fabricated. Besides, this temperature sensor has high sensitivity, good mechanical strength and strong anti-disturbance ability.

1. Introduction

Measurement of temperature plays an important role in the fields of biochemical analysis, environment monitoring, and healthy lifestyle [1]. Therefore, to realize the temperature measurement on various occasions, it is needed to develop a high-sensitive, steady and credible temperature sensor. Compared with the widely used electrical sensors, optical sensors behave many peculiar advantages such as small size, fast response, intrinsic safety, excellent magnetic immunity and possibility for remote measurement [2–4]. Especially in recent years, many optical fiber sensors based on different structures have been proposed and demonstrated for temperature sensing [5]. Among these sensors, fiber grating [6] and in-fiber Mach-Zehnder interferometer [7] are the most popular structures, but their sensitivities are relatively low. Other structures based on surface plasmon resonance (SPR) [8] and Fabry-Perot interferometer [9] have high sensitivity, but their fabrications are difficult and costly.

Recently, the applications of tapered single mode fibers are attractive due to their advantages of miniature size, low cost, flexible structure and high sensitivity [10,11]. A tapered fiber with a diameter of micron scale can be fabricated by simultaneously heating and stretching a short section of single-mode fiber (SMF). The tapered waist region will leak evanescent field near the fiber surface and the light will be highly confined on the fiber surface. According to the coupling condition between the core mode and surface mode, the tapered fiber can be divided into two types, namely, adiabatic type (small taper angle [12]) and non-adiabatic type (large taper angle [13]). For the adiabatic tapered fiber, most of the light remains in the core mode as it propagates along the tapered region, while for the non-adiabatic tapered fiber, some light travel in the cladding with high order modes and then couple with core mode when they propagate along the tapered region. Any slight changes of surrounding environment may lead to changes in the output spectrum of the non-adiabatic tapered fiber. It has been demonstrated that non-adiabatic tapered fiber sensors can be used for sensing gas [14], biomolecules [15,16], and refractive index [17], which behave ultra-high sensitivity and low cost. However, they all exist the disadvantages of low mechanical stability, poor resistance to surrounding environments, and fragile structure.

In this paper, we first analyze the principle and properties of non-adiabatic tapered fiber sensor in the applications of refractive index and temperature measurement. Based on these, we propose and design a new temperature sensor structure, which is fabricated by encapsulating the non-adiabatic tapered fiber in a liquid-infiltrated glass microtube. This sensor not only has high sensitivity and low cost, but also behave good mechanical strength.

2. Sensing principle

When the light is propagating in the standard SMF, total reflection occurs at the interface between the core and the cladding, in which case the evanescent field is generated at the interface. However, the penetration depth of the evanescent field is much less than the thickness of the cladding. Therefore, it cannot interact with the external materials surrounding the fiber surface to achieve sensing. To make the

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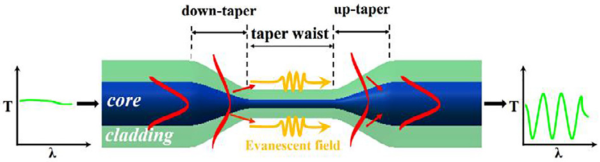

Fig. 1. Schematic diagram of a non-adiabatic tapered fiber.

evanescent field penetrates the cladding, one effective method is to pull the fiber while heating, which can reduce the fiber diameter to a certain degree. After the tapering process, the diameter of the optical fiber at the uniform tapered region is a few microns, and the tapered fiber is composed of three parts as shown in Fig. 1, including the down-taper, the uniform taper waist and the up-taper.

When the input light propagates along the down-taper to the taper waist, some of the light with the fundamental mode (LP_{01}) will couple into the high order cladding modes. Afterwards, the high order cladding modes will couple with the fundamental mode in the up-taper region, resulting in a comb spectrum at the output. Furthermore, since the diameter of the uniform taper waist is significantly reduced, a large part of the evanescent field of the non-adiabatic tapered fiber spreads into the external environment. In this way, the sensing properties of the non-adiabatic tapered fiber are significantly affected by the external environment, such as external refractive index (RI) and temperature. Moreover, the smaller the diameter of the taper waist, the higher the sensitivity of the sensor [18]. For a non-adiabatic tapered fiber, the output result of modal interference can be expressed by [19,20]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\phi) \tag{1}$$

where I is the output light intensity, I_1 and I_2 are the intensities of the fundamental and the cladding modes, respectively, $\Delta\phi$ represents the phase difference between the fundamental mode and the cladding mode, which can be given by:

$$\Delta\phi = \frac{2\pi}{\lambda_m}\Delta n_{eff} L \tag{2}$$

where λ_m represents the center wavelength of the m-th interference valley, L is the waist length, Δn_{eff} is described as the effective RI difference of the two interfering modes and equals to ($n_{eff}^{c}-n_{eff}^{cl}$), in which the n_{eff}^{c} and n_{eff}^{cl} are the effective indices of the fundamental mode and the cladding modes, respectively. Moreover, according to Eq. (1), the output light intensity reaches the minimum when the $\Delta\phi$ is an odd multiple of π [21]. According to Eq. (2), when $\Delta\phi = (2m + 1)\pi$, λ_m can be given by:

$$\lambda_m = \frac{2Ln_{eff}}{2m + 1} \tag{3}$$

When the RI of the medium around the non-adiabatic tapered fiber increases by n, the n_{eff}^{c} and the n_{eff}^{cl} also increase, while the n_{eff}^{c} increases more [16]. Consequently, the difference of the effective index of the two interfering modes, Δn_{eff}, increases by (Δn_{eff}), which causes red shift of the center wavelength of the m-th interference valley. The center wavelength of the attenuation valley also shifts, when the temperature around the non-adiabatic tapered fiber changes. If the temperature changes, the relative Δn_{eff} and the difference in propagation constants will be modified, resulting in a wavelength shift. Above all, the variations of external refractive index and temperature will all change the resonant wavelength of modal interference formed by a non-adiabatic tapered fiber.

3. Experimental fabrication and measurements

3.1. Experimental fabrication

The schematic diagram of the experimental setup used for RI measurement and temperature sensing is shown in Fig. 2. Firstly, the light from a broadband amplified spontaneous emission (ASE) light source with the wavelength ranging from 1520 nm to 1620 nm was launched into a non-adiabatic tapered fiber. Then, the transmission spectrum of the non-adiabatic tapered fiber was monitored by an optical spectrum analyzer (OSA, Yokogawa AQ6370D) with a resolution of 0.02 nm.

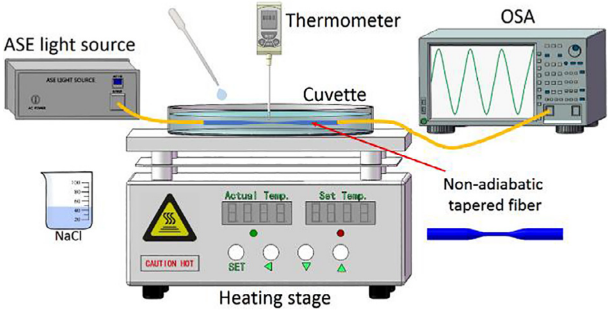

Fig. 2. Experimental setup used for RI measurement and temperature sensing.

In order to investigate the responses of the non-adiabatic tapered fiber sensor to external RI changes, we put it in a transparent glass cuvette. Then, the salt solutions with different RI were added to the cuvette with a plastic dropper until the sensing component was completely covered. The salt solutions of different RI were obtained by diluting high-concentration NaCl solution with pure water. The RI of the salt solutions were measured by digital Abbe refractometer (WAY-2S) with a resolution of 0.0001. For studying the temperature characteristics of the sensor, we observed the shift of the transmission spectrum caused by temperature change in solution. Firstly, a proper amount of solution was poured into the cuvette, which was supported by a heating stage. Then the sensor was immersed into the solution. The solution temperature was controlled by the heating stage, ranging from 24 °C and 38 °C, and was measured by a digital thermometer (Ebro TFX 430) with a resolution of 0.01 °C.

In our work, we used fused taper method to fabricate our non-adiabatic tapered fiber. The polymeric coating layer of a SMF (Coning SMF28) with a length of 10 mm was removed by mechanical stripping. After cleaning the stripped section with alcohol, we used a butane-oxy flame to heat the stripped section back and forth. In addition, using a computer controlled stepper motor platform to stretch the fiber while moving the flame. The structural parameters of the non-adiabatic tapered fiber were controlled by changing the flame temperature, heating time and motor moving speed. After the tapering process, the diameter of the taper waist was about 8 μm and the length was around 20 mm. The tapered fiber microscopic image is shown in Fig. 3.

3.2. Measurement of RI

Fig. 4(a) shows the transmission spectrum of the non-adiabatic tapered fiber sensor with different RI of salt solution. To evaluate the sensitivity, wavelength shifts of the three typical dips are observed, and their dip values at different RI are given in Fig. 4(b). It can be seen that all three typical dips shift to the longer wavelength, and the wavelength shifts are about 21.9 nm, 24.8 nm and 20.4 nm for dip 1, dip 2 and dip

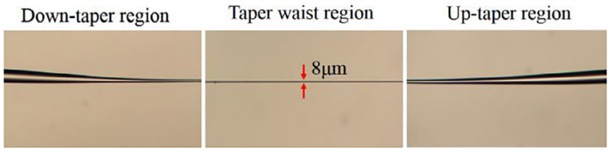

Fig. 3. Microscopic image of the down-taper region, the taper waist region and the up-taper region.