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Optimization of cascaded fiber tapered Mach–Zehnder interferometer and refractive index sensing technology

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ABSTRACT

A novel refractive index sensor with high sensitivity based on Mach–Zehnder interferometer formed by cascaded two single-mode fiber tapers was proposed and experimentally demonstrated. The dip of the measured spectrum signal caused by Mach–Zehnder interference shifted obviously when the surrounding refractive index changed. The approximate linear relationship between surrounding refractive index and spectrum dip wavelength shift was obtained experimentally. The measurement sensitivity up to 158.4 nm/RIU was showed with the surrounding RI ranged from 1.33 to 1.3792, which meant the measurement resolution about 6.3×10^{-6} could be implemented if wavelength shift measurement resolution of the optical spectrum analyzer is 1 pm. Meanwhile, its ease of fabrication makes itself a low-cost alternative to existing sensing applications.

1. Introduction

In recent years, optical fiber sensors have become a hot research topic due to their advantages of compact structure, small size, light weight, quick response, high sensitivity, anti-electromagnetic interference, remote detection and so on, leading to broad application prospect in many sensing fields, such as refractive index, temperature, pressure and so on [1–3]. Various optical fiber devices have been proposed for refractive index (RI) sensing, including fiber Bragg grating (FBG) [4–7], long period fiber grating (LPFG) [8,9], tilted fiber Bragg grating (TFBG) [10], a series of optical fiber interferometers based on core diameter mismatched fiber [11], double-cladding fiber [12], single-mode fiber tapers [13–17], or core-offset attenuator [18,19]. The grating-based (FBG, LPG, TFBG) RI sensors have a response to RI with high sensitivity in a broad range. However, they require precise and expensive phase masks and stringent photolithographic procedures. The Michelson interferometers based on LPG, fiber tapers, and core-offset attenuator often require complex metal-coated fiber tip.

Refractive index sensors based on tapered fiber interferometer have drawn more and more domestic and researchers attention because of their excellent characteristics of ease to fabrication, low cost, applicability for remote sensing and so on [20]. In 2009, Lu fabricated two tapered optical fibers on a single-mode fiber using a fusion splicer, composing a Mach–Zehnder interferometer structure. The sensitivity of refractive index measurement could reach up to 26.087 nm/RIU [21], which is at the low level at present. In 2011, Liao proposed a liquid refractive index sensor with Micro/Nano fiber optic coupler structure, the RI measurement sensitivity of the sensor was up to 2735 nm/RIU, but the fabrication of sensing structure was quite complex [22]. In 2012, Li proposed a type of refractive index sensor based on Mach–Zehnder interferometer formed by fiber tapers, and they thinned the ordinary single mode fiber via chemical etching method, then draw it into the cascaded biconical fibers. The measurement sensitivity up to 286.2 nm/RIU was shown in the surrounding RI range from 1.33 to 1.3811 [23]. Nevertheless, the structure not only increased the difficulty of fabrication but also introduced a large insertion loss (up to 22 dB). In 2013, Chen proposed a refractive index sensor with joint-taper-joint structure, and the sensitivity of refractive index measurement could reach up to 3751 nm/RIU, but the mechanical strength of the sensor structure was not high [24]. In 2014, Yadav proposed an interferometer refractive index sensor with single-mode tapered fiber, and the principle of the sensor is based on mode coupling between the core mode and the cladding mode excited by the fundamental core mode. The RI measurement sensitivity of the sensor was up to 1500 nm/RIU, it was mainly used in protein concentration detection [25].

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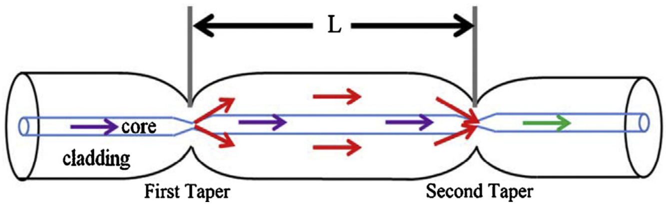

Fig. 1. Schematic diagram of MZI formed by cascaded two fiber tapers.

In this paper, a refractive index sensor of Mach–Zehnder interferometer formed by cascaded two single-mode fiber tapers was investigated, which is based on Mach–Zehnder interference principle. The sensor structure is Mach–Zehnder interferometer formed by cascaded two fiber tapers, and the length of the tapered region measured was 1 mm, while the waist diameter was 20 μm, the distance between the two tapers was 4 cm. When the RI value of water-based NaCl solution changed from 1.33 to 1.3792, the output spectrum dip shifted with the sensitivity up to 158.4 nm/RIU.

2. Sensing principle

Fig. 1 shows the structural diagram of Mach–Zehnder interferometer (MZI) proposed which was constructed by cascaded two fiber tapers fabricated in a standard single-mode fiber (SMF-28, Corning Inc.), the cascaded two optic fiber tapers are separated by a distance of *L*.

When light propagates into the first taper, fundamental mode in SMF core will be coupled to cladding modes LP_{0m}. At the same time, a part of energy left in the core continues propagating forward. A part of the light passing through the interferometer arm, part of the light traveling inside the cladding is coupled back into the core at the second taper. A Mach–Zehnder interferometer is formed due to the phase difference between fundamental mode in fiber core and higher order modes in fiber cladding. The interference light propagates forward in single mode fiber core, the spectra of which can be recorded by an optical spectrum analyzer (OSA).

The interference spectrum is formed mainly by the fundamental core mode and the lowest order cladding mode, then the interference equation of the fundamental core mode and the cladding mode can be expressed as Eq. (1).

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\varphi \tag{1}$$

where I_1 and I_2 are the light intensity of the fiber core fundamental mode and the lowest order cladding mode, respectively. The phase difference φ between the two modes experience the same distance *L*, which could be expressed as Eq. (2).

$$\varphi = \frac{2\pi \Delta n_{\mathrm{eff}} L}{\lambda} \tag{2}$$

where Δn_{eff} is the difference of the effective refractive index between fiber fundamental core mode and the lowest order cladding mode, and λ is the input optical wavelength. When the phase difference satisfies the condition $\varphi = (2m+1)\pi$, $m = 0, 1, 2, \ldots$, the interference light intensity reaches minimum value, then the spectrum dip wavelength can be expressed as Eq. (3).

$$\lambda_m = \frac{2\Delta n_{\mathrm{eff}} L}{2m+1} \tag{3}$$

The spacing between the adjacent dip wavelength is given by Eq. (4).

$$\Delta\lambda_m = \lambda_m - \lambda_{m-1} \approx \frac{\lambda^2}{\Delta n_{\mathrm{eff}} \cdot L} \tag{4}$$

When the surrounding RI (SRI) is increased by δn, effective RI of the cladding mode is increased by $\delta n_{\mathrm{eff,\,cl}}$. Because RI of the fiber fundamental core mode is nearly constant, Δn_{eff} is decreased by $\delta n_{\mathrm{eff}} \approx \delta n_{\mathrm{eff,\,cl}}$, the interference spectrum dip wavelength λ_m shifts to the short wavelength $\lambda_{m'}$ by $\delta\lambda_m$.

$$\delta\lambda_m = \frac{2\Delta n_{\mathrm{eff}} L}{(2m+1)} - \frac{2(\Delta n_{\mathrm{eff}} - \delta n_{\mathrm{eff}})L}{(2m+1)} = \frac{2\delta n_{\mathrm{eff}} L}{(2m+1)} \tag{5}$$

According to the Eq. (5), we can calculate the change of the surrounding refractive index by tracking the shift $\delta\lambda_m$ of interference spectrum dip wavelength, so as to realize the measurement of solution refractive index.

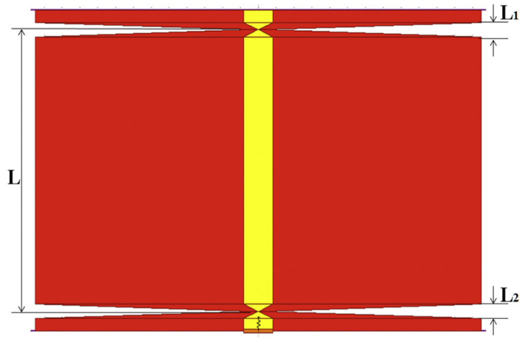

Fig. 2. Schematic diagram of cascaded biconical fibers structure. The yellow part represents fiber core of a single-mode fiber, the red part denotes fiber cladding, and *L* is the distance of the cascaded biconical fibers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Numerical simulation

In order to obtain the cascaded biconical fibers structure parameters with best interference contrast, the analysis of influence different structure parameters on refractive index sensing sensitivity has been conducted. This paper described Rsoft simulation analysis on influence of different structural parameters on optical field transmission characteristics, and influence of different structural parameters on interference spectral contrast of the cascaded biconical fibers and sensitivity of refractive index measurement.

Fig. 2 shows cascaded biconical fibers structure simulated with Rsoft. The yellow part represents fiber core of a single-mode fiber, the red part denotes fiber cladding, and *L* is the distance of the cascaded biconical fibers. SMF parameters for simulation are core diameter with 8.2 μm, cladding diameter with 125 μm, wavelength of incident light with 1550 nm, cladding refractive index with 1.4612, core refractive index with 1.4679, the NA of the SMF is 0.14, the refractive index of background with 1.33. Fig. 3 shows the refractive index distribution map of the structure.

Fig. 4(a) shows the coupling proportion of biconical fiber with waist diameter 5.2 μm, while Fig. 4(b) represents the coupling proportion of biconical fiber with waist diameter 10 μm, different color represents intensity of light propagates in fiber core. The length of tapered region was set to 1 mm. As it is shown in Fig. 4(a), when transmission distance in the fiber is within the range of 0–10,000 μm, the transmittivity is almost 100% and loss is zero, energy of LP_{01} mode is almost constant. When transmission distance in the fiber is 10,000 μm to 10,500 μm, energy of the fiber core fundamental mode drops quickly to about 35% at the fiber length of 10,500 μm, namely at the point of taper waist. As diameter of the fiber gradually becomes larger, evanescent wave on fiber surface returns into fiber core, leading to fiber core fundamental mode energy gradually increases. In the end, when fiber taper waist diameter increases gradually to the standard single-mode fiber diameter 125 μm, energy of fiber core fundamental mode gradually stabilizes. The normalized energy value of output is about 0.35, which means energy of fiber core fundamental mode has lost about 65% at