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Enhancing refractive index sensitivity using micro-tapered long-period fiber grating inscribed in biconical tapered fiber

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ABSTRACT

A novel micro-tapered long-period fiber grating refractive index sensor is demonstrated in this study. Its transmission characteristics are investigated numerically and experimentally. The sensor is fabricated by inscribing periodical micro-tapers in a biconical single mode optical fiber (SMF-28) using a low cost electric arc heating technique. The periodical tapering in SMF enables the fundamental core mode to be coupled into the cladding modes resulting a resonant wavelength in the transmission spectrum. The resonant wavelength shifts linearly with the variation of surrounding refractive index. The refractive index sensitivity of 8188 nm/RIU has been experimentally achieved which is much higher than the previously reported refractive index sensitivity values for the sensors based on long period fiber grating. The effects of varying the number of periodical tapers, amount of grating period and waist diameter on the sensitivity have been analysed both numerically and experimentally. Our presented sensor features a low cost, a simple structure and a high sensitivity. The results presented in this study would be useful in both chemical and bio-sensing applications.

1. Introduction

In recent decades, long period fiber gratings (LPFGs) and many associated devices are at the forefront of researches. They have been studied and investigated extensively due to the unique advantages that they offer in the field of optical communication systems, such as gain flattening and wavelength rejection filters [1–3], and optical sensing applications [4,5]. One of the important properties of LPFGs which has received considerable attention in the last few years is their high sensitivity to external perturbation changes such as temperature, pressure, stress, curvature and refractive index (RI) of liquids [6–9]. Refractive index LPFGs sensors have a present tremendous potential interest in sensing systems due to low cost, ease of fabrication, compact size, fast response, high sensitivity and resolution [9]. They show distinct strength in RI sensing with their ability to measure various parameters. The phase difference between the supported modes of the periodically tapered region is directly affected by any change in RI of surrounding medium.

LPFGs are commonly fabricated by exposing photosensitive optical fiber to a UV laser irradiation [10,11] but this technique is complex, expensive and time-consuming. After that, several non-UV methods have been reported, such as using CO_2 laser beam [12], femtosecond laser pulses [13], lateral mechanical stress [14], and periodically tapering with electric arc discharges [15]. The electric arc discharge technique has gained great attention in recent years because it is a cost effective method, it does not need an expensive UV or CO_2 laser and complicated phase mask. The periodicity of LPFGs within a few hundreds of micrometers causes light to couple from the fundamental guided mode to the forward-propagating cladding modes. In conventional LPFGs, it is known that the cladding mode is tightly confined, which limits the sensing ability of LPFGs. Therefore, to enhance the sensitivity of LPFGs, periodically tapered fiber using heat source is the best candidate to increase the extension of the evanescent field into the external environment, which, in turn, affects the resonant wavelength and spectral response characteristics [16,17].

It should be noted that in recent years, many papers proposed micro-tapered long-period fiber gratings (MT-LPFG) written in optical fiber for sensing refractive index [18,19,25], strain, temperature and pressure [20–23]. The maximum sensitivities for the RI sensing with tapered long period gratings were achieved as 261.9 nm/RIU, 226 nm/RIU and 1418 nm/RIU around RI of 1.33 and also 3762 nm/RIU around RI of 1.383.

In this paper, extremely high sensitive RI sensors based on MT-LPFG technique written in tapered fiber are presented and their sensing properties to different RI of solutions are numerically and experimentally investigated. Our sensors are easily fabricated using only electric

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arc discharge to form a desired fiber taper and micro-taper. Compared with the previous RI sensors, our scheme offers advantages of simple fabrication, enhanced sensitivity, time-saving, low cost, enhanced robustness and easy handling without the need of complex optical tuning and alignment devices. The propagation of light in our MT-LPFG sensor has been simulated employing Finite Difference Time Domain (FDTD) method. We have investigated and reported the effects of the grating period and the number of micro-tapering on the sensor sensitivity.

2. Principal analysis and numerical simulations

A periodically tapered LPFG is a wavelength selective filter whose transmission spectrum is like to that of typical LPFG exhibiting several resonances due to coupling between the fundamental guided mode LP_{01} and the LP_{0r} cladding modes at wavelengths obeying the resonance condition [23,25],

$$\lambda_r = ({n_{eff}}^{co} - {n_{eff}}^{cl,r})\Lambda/q \tag{1}$$

where Λ is the grating period, λ_r is the resonance wavelength, ${n_{eff}}^{co}$ and ${n_{eff}}^{cl,r}$ represent the effective refractive indices of the fundamental guided mode and the r-th order cladding mode and q is the diffraction order. At the resonant wavelength, the coupling of the guided mode to a cladding mode introduces the minima in the transmission spectra due to the strong attenuation of the cladding modes. In the case of refractive index sensing, the dependence of the resonant wavelengths on external medium refractive index can be expressed by [7,9],

$$\frac{d\lambda_r}{dn_{ext}}\lambda_r\delta\varepsilon_{ext} \tag{2}$$

where δ is the general sensitivity factor and ε_{ext} defines the LPFG's response coefficient to the external RI variation. By applying many arc discharges on the entire length of the fiber, the glass is compressed axially. This will change the diameter of the fiber periodically, producing a tapered LPFG. In the periodically tapered region, the evanescent waves are generated and light is leaked out. The effective RI of the eigenmodes would be changed significantly.

To test the sensitivity and verify the practicability of our proposed RI sensor, the numerical simulations were firstly carried out using FDTD method. The analysis of mode propagation in the periodically tapered fiber takes account the refractive index profile and the periodicity of the waist diameter over the whole cross section. In the simulation, the SMF has core and cladding diameters of 9 µm/125 µm with refractive indices of 1.45/1.445. The fiber taper-up and down regions are set to be 1 mm in length and are assumed to be symmetrical. The total sensor length including 32 micro-tapered gratings with a period of 560 µm is equal to 19.92 mm. To analyze the transmission spectra of our periodically tapered fiber sensors, we simply changed the grating period, grating depth and refractive index of the surrounding medium while the other parameters were set to be fixed and then we analyzed the transmission spectrum of the sensor for different number of taper. The MT-LPFG is considered as a three-layer structure, which consists of a core embedded in the cladding layer of 125 µm surrounded by an external environment. Fig. 1 shows the amplitude distribution of the calculated field. The strong mode interference occurs within the tapered section of the fiber as seen from Fig. 1. The grating period, the grating depth and the number of tapering denoted by Λ, d and N are 560 µm, 6 µm and 32, respectively. It can be seen that weak confinement of the light takes place at the periodically tapered regions because of decreasing the core and cladding diameter, so light is leaked out into the surrounding medium.

3. Fabrication of periodically tapered sensor

In order to fabricate the RI sensor, a piece of standard communication single mode fiber from Corning (SMF28) was used in whole experiments. The polymer coating was carefully removed from the middle part of the fiber and cleaned with isopropanol before tapering process. To monitor the transmission spectrum and record the wavelength shift of the sensor during the fabrication, one terminal of the optical fiber was connected to the broadband light source (Thorlabs SLD 1550 nm) which covers a wide wavelength range of 1450–1650 nm and the other terminal was connected to the Optical Spectrum Analyzer, OSA (Thorlabs OSA-202 with wavelength range of 600–1700 nm). The stripped fiber was fixed into two motorized linear translation stages. One stage was used for feeding the fiber and the other stage was used for pulling the softened fiber while heating with controllable speed and pulling distance. The stages moved at very low speeds in order to fabricate the desired tapered fiber. We implemented an electrical arc discharge to the bare fiber segment positioned between two electrodes which are used in fusion splicer devices to reach temperatures above 1350 °C at which silica starts to soften [26]. This temperature is sufficient to stretch and taper the fiber. The distance between the arc electrodes was about 3 mm. To control the fabrication process of micro-tapering with desired geometrical parameter avoiding unexpected micro-bending, the linear translation stages and the electric arc discharge units were employed with a computer software and worked simultaneously. The electric arc discharges were produced by controlling the voltage pulse power with a PWM signal. After a start pulse which has 30 ms of pulse duration at high power level of 17 W, the arc power was reduced to 40% of this level. While the arc power was being gradually increased to an appropriate level according to the geometric profiling to be applied, the motors were activated with an appropriate speed and acceleration. A special software has been developed for this entire process. When the pulling stage stopped moving, the electric arc unit and feeding stage were immediately stopped. The stability and same environmental conditions were ensured in all the experiments. Our translation stages have a minimum step size of 0.1 µm which can provide high resolution mobility. Reproducibility success rate with a maximum deviation of 1 µm in the fiber diameter is above 95% if the waist diameter of micro-taper is higher than 10 µm. The entire measurements were carried out at room temperature (26 °C) to avoid the cross-sensitivity between the temperature and the RI of solutions. The schematic of the MT-LPFG fabrication is illustrated in Fig. 2.

The fabrication process was carried out by following two steps to obtain the tapered optical fiber sensor with the desired geometric design. In the first step, a single biconical tapered structure was produced with a waist length of about 2 cm and a waist diameter of 25 µm on the fiber. MT-LPFG structure was formed in the second step. At the beginning of production, an object of 10 g weight was attached to one end of the fiber to provide same tension, and then both ends of the fiber were fixed. Different sensor geometry forms were fabricated by changing the grating period, grating depth and the number of tapering. A waist diameter as small as 8 µm was achieved with grating depth range between 6 and 10 µm. The grating period was easily reduced to 500 µm by controlling the pulling distance, velocity and acceleration parameters of the translation stage. Since the axial temperature profile formed by the arc discharge between the two electrodes is much wider than a well-focused laser beam, the achievement of shorter grating periods is limited. However, shorter grating periods can be obtained by applying several number of arc discharges with well-tuned pulse duration and using a high voltage power source having a feedback loop that keeps a constant electric current [16]. A microscopic view of the resulting MT-LPFG with Λ = 730 µm is shown in Fig. 3. It is seen that the geometrical structure of the fiber optic sensor is symmetrical with respect to the fiber axes and the micro-tapers are equally separated.

4. Results and discussion

As a starting point, the guiding mechanism of the RI sensors was simulated using FDTD method. To investigate the RI sensing capability,