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Temperature independent refractive index measurement using a fiber Bragg grating on abrupt tapered tip

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ABSTRACT

A fiber Bragg grating was inscribed in an abrupt fiber taper using a femtosecond laser and phase-mask interferometer. The abrupt taper transition allows to excite a broad range of guided modes with different effective refractive indices that are reflected at different wavelengths according to Bragg's law. The multimode-Bragg reflection expands over 30 nm in the telecom-C-band. This corresponds to a mode-field overlap of up to 30% outside of the fiber, making the device suitable for evanescent field sensing. Refractive index and temperature measurements are performed for different reflection peaks. Temperature independent refractive index measurements are achieved by considering the difference between the wavelength shifts of two measured reflection peaks. A minimum refractive index sensitivity of 16 ± 1 nm/RIU was obtained in a low refractive index regime (1.3475–1.3720) with low influence of temperature (−0.32 ± 0.06 pm/°C). The cross sensitivity for this structure is 2.0×10^{-5} RIU/°C. The potential for simultaneous measurement of refractive index and temperature is also studied.

1. Introduction

Fiber Bragg gratings (FBGs) are one of the most essential fiber sensing elements. They have been designed and developed for a wide variety of sensing applications, including: strain [1], temperature [2], pressure [3], and bending [4]. An FBG is a periodic modulation of the refractive index along the optical fiber, which is created by exposing the fiber core to an intense periodic optical beam, for example, using an ultraviolet femtosecond laser [5,6]. FBGs are generally created in photo-sensitive glass using an UV laser. In the case of optical fibers, hydrogen loading is needed for enhanced photosensitivity, since silica is non-photosensitive [7]. However, the use of femtosecond laser FBG inscription allows to address non-photosensitive optical materials such as optical fiber tapers. The focused ion beam technique is also used to create Bragg gratings in microfibers. Such structures can achieve sensitivities up to 660 nm/RIU [8].

FBGs in conventional fiber are insensitive to changes in the external refractive index since they are not directly exposed to the outside medium. However, sensitivity can be gained by either thinning or etching the fiber before or after the FBG inscription [9], or by using suspended core microstructured optical fibers [10].

FBGs have been used for refractive index sensing for two decades, with numerous configurations proposed for different applications [11–19]. For example, FBG Fabry-Perot cavities incorporating microchannels show a linear refractive index response with sensitivities of 9 nm/RIU between 1.43 and 1.49 for a broad microchannel, and 1 nm/RIU between 1.3 and 1.7 for a narrow microchannel [13]. Fabry-Perot cavities based on high-birefringence FBGs can be used for refractive index and temperature sensing of liquids by monitoring the visibility as a function of refractive index and the wavelength shift as a function of temperature [14]. FBGs in microstructured optical fibers have also been studied for refractive index sensing [15–17]. A micro FBG for temperature compensated refractive index sensing was presented by Ran et al. [18]. Such sensor could achieve a maximum sensitivity of −9.47 nm/RIU. Also for refractive index monitoring, an intensity sensor using a reflective tilted fiber Bragg grating was demonstrated using strong cladding to core recoupling [19]. This sensor is able to measure surrounding refractive index as low as 1.33.

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In this paper, an FBG inscribed on an 18 μm diameter abrupt tapered fiber tip is demonstrated for refractive index and temperature sensing. We show that it is possible to achieve temperature insensitive refractive index measurements by monitoring the difference between two reflection peaks. The proposed sensor is structurally and spectrally different, allowing to excite higher order modes than the sensor presented by Ran *et al.*, obtaining greater refractive index sensitivity. Such a micro-sensor will have applications in bio-sensing, particularly where temperature fluctuations need to be considered.

2. Fabrication and characterization

The abrupt taper, with an 18 μm diameter waist and a length of 40 mm, was fabricated using a CO_2 laser technique. In order to create the abrupt transition region, a constant tension was applied to the fiber from the beginning until the end of the whole taper production process. This tension is provided by the velocity difference of the translation stages in the CO_2 laser system. To obtain an 18 μm diameter waist a leading stage velocity of 4000 μm/s and a rear stage velocity of 20 μm/s were used. Such constant tension created a taper transition region of approximately 300 μm in length. Although it is long, a microfiber with an 18 μm diameter waist is more resistant than a normal single mode fiber and presents high flexibility. Such mechanical properties are inherent to microfibers with diameters around this dimension or lower.

An FBG was inscribed in the abrupt taper using a phase-mask interferometer driven by a Ti:Sapphire laser with third harmonic generation providing femtosecond pulses in the UV range (267 nm) [20]. Regarding the dimensions of the taper waist (18 μm), the setup was adjusted to obtain a reflection wavelength of the fundamental mode near 1550 nm by using a diffraction mask with a period of 1075 nm. Since the taper has an 18 μm diameter waist it is mainly composed of pure silica (n = 1.444 at 1550 nm). Thus, it has low photosensitivity and a long inscription time of 10 min was used. A laser power of 200 mW was used during the inscription.

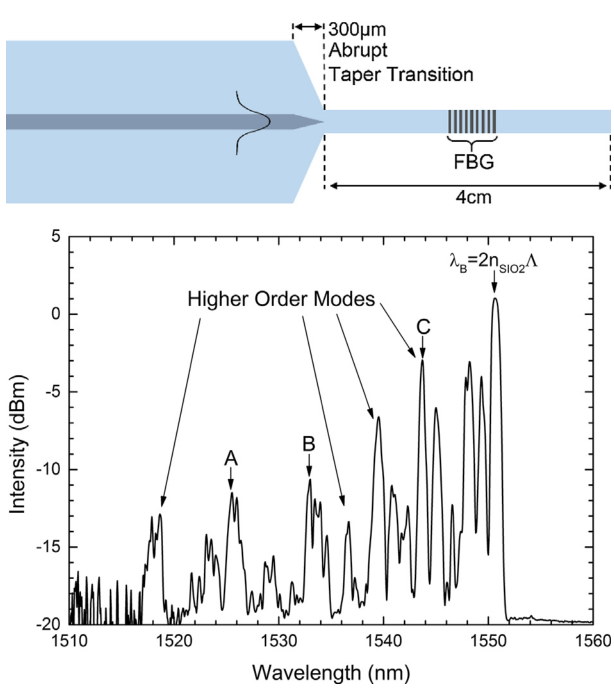

Fig. 1. Schematic of the sensor tip and its reflection spectrum in ethylene glycol (n = 1.3475).

The taper was then broken at one of the transition regions in order to create the tip.

Fig. 1 shows a schematic of the FBG inscribed in the abrupt fiber taper tip and its reflection spectrum when immersed in an ethylene glycol solution (n = 1.3475). The sensor spectrum was measured using an optical circulator and a broadband source with a central wavelength of 1550 nm and a bandwidth of 100 nm. The broadband source was connected to the optical circulator and the reflection spectrum was observed in an optical spectrum analyzer with 0.05 nm resolution. The fundamental mode peak is centered at 1550.6 nm. The Bragg wavelength, λ_B, is given by:

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where n_{eff} is the effective refractive index of the considered mode and Λ is the Bragg grating period. Since the Bragg grating period is 537.5 nm and the reflection peak is centered at 1550.6 nm, according to Eq. (1) the effective refractive index of the fundamental mode should be 1.4424.

Due to the abrupt transition region of the taper tip, many modes with different effective refractive indices are excited providing reflections at different wavelengths. These reflection peaks would, in principle, extend until a Bragg wavelength of 1075 nm, which correspond to the refractive index of air (a "mode" propagating in air). However, as seen in Fig. 1, the last mode excited is located at 1517.9 nm corresponding to an effective refractive index of 1.4120, according to Bragg's law. The number of modes supported by the taper structure can be estimated using the generalized frequency (V), which in this case is 38. So, the number of modes supported by the taper region (estimated as $V^2/2$) is around 722. However, in reality, there is a certain higher order mode for which the power is at noise level. So, only a few modes carry enough power to be observed. The considered reflection peaks A and B are centered at 1525.52 nm and 1533 nm, respectively with effective refractive indices of 1.4191 and 1.4260.

For refractive index sensing, several solutions of ethylene glycol at different concentrations were used, resulting in a refractive index range from 1.3475 to 1.420. The sensing tip was immersed in each solution and the wavelength shift for the fundamental mode and the higher order modes A, B, and C (see Fig. 1) were measured. Fig. 2(a) shows the reflection spectra under different refractive index solutions. The intensity of the higher order modes decreases as the solution refractive index increases. Regarding this, the higher order mode A was considered since peaks corresponding to lower effective indices decrease below the noise when measuring refractive index (i.e., A is the last detectable peak at n = 1.420). The wavelength shift as a function of refractive index for the four considered modes is depicted in Fig. 2(b). A polynomial fit was calculated for the higher order mode reflection peak A ($121.7\Delta n^2 + 18.5n$). The sensitivity is non-linear, but the higher order mode reflection peaks B and C can still be assumed as linear with a sensitivity of 11.4 ± 0.4 nm/RIU and 6.5 ± 0.2 nm/RIU, respectively, in the range of refractive indices considered. For the fundamental mode, a sensitivity of 1.4 ± 0.1 nm/RIU was recorded.

Theoretically, the fundamental mode will be less sensitive to refractive index changes than higher order modes since the optical field is more confined within the taper, hence less affected by the external medium. A measurement of the amount of field that is inside of the taper can be obtained through the normalized propagation constant. The normalized propagation constant is given by [21]:

$$b = \frac{n_{eff}^2 - n_{clad}^2}{n_{core}^2 - n_{clad}^2} \quad (2)$$

where n_{eff} is the effective refractive index, n_{core} is the refractive index of the taper (n_{core} = 1.444) and n_{clad} is the refractive index of