



Core–cladding mode recoupling based fiber optic refractive index sensor

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ABSTRACT

We present a compact and robust fiber optic refractive index sensor based on a tilted fiber Bragg grating (TFBG) inscribed in a thin-core fiber that is spliced to a standard single-mode fiber (SSMF). Due to the core mismatch between the SSMF and the thin-core fiber, cladding modes generated from the TFBG can be back into SSMF for detection. Since the effective refractive index of a cladding mode is dependent on the surrounding refractive index (SRI), the cladding-mode resonances can be used for measurement. We fabricate the sensor probe and test it in a series solution with different SRIs, and the experimental results agree with the theoretical analysis. The repeatability of the sensor is also tested in the same SRI range. We demonstrate its capability and simplicity to use this sensor for a wide range SRI measurement.

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1. Introduction

Fiber Bragg grating (FBG)-based devices have been proven to be excellent sensors for many measurements due to their small size, reflection mode operation, and multiplexibility [1–3], and their application for SRI sensing has been studied in past decades [4,5]. In order to perform SRI sensing using an FBG, specialty fibers such as D-shaped or H-shaped fibers need to be used or the fiber needs to be thinned through wet etching [6–8] or side polishing [9], to bring the core mode into contact with the surrounding medium. All these procedures significantly degrade the fiber mechanical strength and increase fabrication complexity, which restrict the sensor performance and application greatly. In addition, they suffer from high cross-sensitivity to temperature. Tilted fiber Bragg grating (TFBG) does not require the use of specialty fibers and post processing because a TFBG can couple the core mode to the back-propagating core mode and a large number of back propagating cladding modes whose effective refractive indices are sensitive to SRI [10,11]; there are several major drawbacks of these TFBG sensors such as they are typically demodulated in transmission mode which are inconvenient in practical applications, a large number of mode resonances may cause ambiguity in identifying the coupling wavelength, etc. Some reflected TFBG sensors are proposed for refractive index measurement, using both core mode and cladding mode resonances, SRI and temperature can be measured simultaneously [12,13], but these sensors measure RI changes by monitoring recoupled power which are easily effected by the power fluctuation from either light source or external

environments; also the additional field mismatch is needed for sensor fabrication. C. F. Chan et al. proposed another reflected TFBG sensor for refractive index measurement by monitoring wavelength shift of narrow-band cladding–core resonance [14]; the cleaved end must be isolated with the detected medium, or a metal coating process is needed for sensor fabrication. Although pairing a long-period-grating (LPG) and a TFBG to select only a single cladding mode resonance for detection in the reflection mode [15], the use of an LPG significantly increases the size of the sensor and cross sensitivity to bending.

In this letter, we propose and demonstrate a novel, compact fiber optic SRI sensor by using core to cladding mode generation and recoupling mechanism through the core mismatch between two different fibers and a TFBG. Fig. 1 schematically illustrates the sensor structure, which consists of a TFBG inscribed in a piece of thin-core optical fiber (TCF) that is spliced with standard single-mode fiber (SSMF), which can realize the core-mode light recoupling from a few selected cladding modes that are excited by the TFBG in TCF. Compared to the reflection based fiber optic refractive index sensor reported by C. F. Chan [14], the reflector in this proposed sensor is only a tilted fiber Bragg grating, which is simple and easy for sensor fabrication and packaging.

2. Operating principle

As shown in Fig. 1, at the TCF–SSMF junction, due to core mismatch between two fibers, the light propagating in the SSMF core both the core mode and multiple cladding-modes will be excited in the TCF. The cladding modes are coupled by the TFBG in the TCF. Specifically, the cladding modes can be coupled to the core mode; the core mode can also be coupled to a large number

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of cladding modes; and core mode can be coupled to the back-propagating core mode. The wavelengths at which these couplings occur are determined by the phase match conditions. The back-propagating core mode can be coupled back to the lead-in SSMF for detection. Only those cladding-modes whose coupling efficiency to the SSMF core mode is not zero can be recoupled into the core of the SSMF for detection, so we can observe only a few

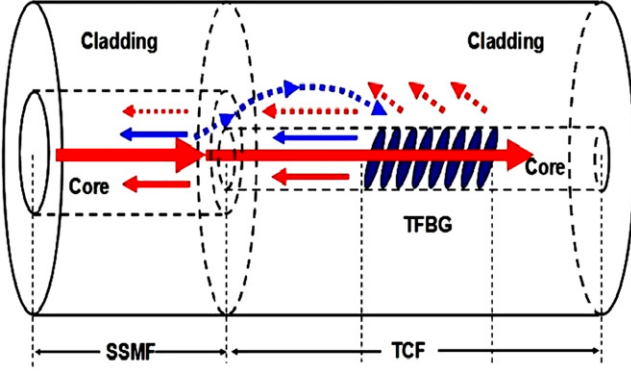


Fig. 1. Schematic diagram of a TFBG inscribed in thin-core fiber that is spliced with standard single-mode fiber for RI measurement.

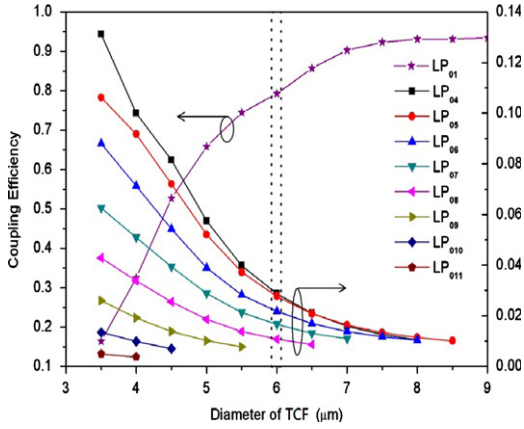


Fig. 2. Theoretical analysis of mode coupling efficiency from SSMF to TCF with diameters of TCF.

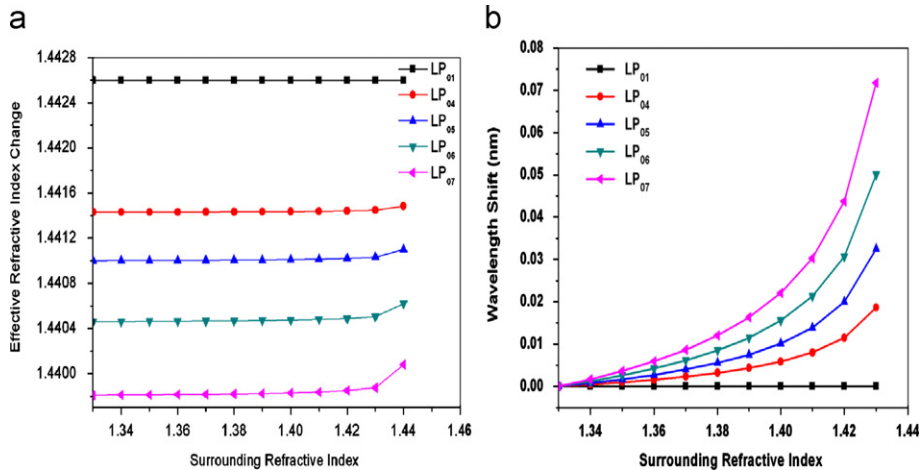


Fig. 3. Theoretical analysis of (a) effective refractive indices of modes change with surrounding refractive index; and (b) simulated results of resonance modes' wavelength shifts.

specific cladding-modes that are excited by the TFBG and core mode resonances in the reflection spectra.

The Bragg wavelength λ_0 for core–core mode coupling is given by

$$\lambda_0 = 2n_{eff} \Lambda_g / \cos\theta \quad (1)$$

where $n_{eff}(\lambda_0)$ is the effective index of the core mode at the Bragg wavelength, Λ_g is the period of the FBG and θ is the tilt angle of the TFBG. Similarly, cladding-mode resonances can be found through

$$\lambda_i = (n_{eff}(i) + n_c(i)) \Lambda_g / \cos\theta \quad (2)$$

where $n_{eff}(i)$ is the effective index of the core mode at the wavelength of the i th cladding-mode resonance, and $n_c(i)$ is the cladding-mode effective index at the same wavelength.

The SRI sensitivity of the core–cladding mode coupling wavelength is given by

$$\Delta\lambda_i / \Delta n_{sur} = \Lambda_g / \cos\theta * \partial n_c(i) / \partial n_{sur} \quad (3)$$

The actual grating period Λ_g is a constant that is usually determined by the phase mask, so theoretically, for a certain cladding mode, the sensitivity of SRI measurement only depends on the tilt angle of TFBG and diameter of fiber cladding.

We utilized a beam propagation method [16] to analyze the mode coupling efficiency from SSMF to TCF and the SRI sensitivity of different modes as shown in Fig. 2. We assumed that the diameter of SSMF is 9 μm and the power of light transmitted in the core of SSMF is 1. Fig. 2 illustrates the dependence of mode coupling efficiency on amount of core mismatch obviously; the mode coupling efficiency of a certain mode increases rapidly with increasing amount of core mismatch, and more and more modes are excited by mode coupling mechanism.

According to Fig. 2, the lower order modes have greater coupling efficiencies than higher order modes, because the coupling efficiency depends on the mode field mismatch at the junction. The overall efficiency of the reflected cladding modes depends also on the couplings occurring at the TFBG. If we want to obtain higher order modes with higher coupling efficiency, we should select fiber with smaller core diameter. For a 6 μm diameter TCF, we obtain six modes with observable coupling efficiencies that are LP₀₁ (core mode), LP₀₄, LP₀₅, LP₀₆, LP₀₇ and LP₀₈, and the mode coupling efficiencies for all the modes are approximately 80%, 3%, 3%, 2.2%, 1.7% and 1%, respectively.

For the above sensor design with 6 μm TCF, utilizing the beam propagation method, we analyzed the effective refractive indices as a function of external RI of different modes, as shown in Fig. 3.

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