Reflective fiber-optic refractometer based on a thin-core fiber tailored Bragg grating reflection

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A novel reflective refractometer based on a thin-core fiber (TCF) sandwiched between a leading single-mode fiber (SMF) and a fiber Bragg grating (FBG) imprinted SMF stub was demonstrated. The reflection from the fiber stub occurs in two well-defined wavelength bands, corresponding to the Bragg core mode and cladding modes. The TCF section functions as a tolerable bridge between the FBG core mode reflection and the surrounding refractive index (SRI). Linear response with enhanced sensitivity of 133.26 dB/refractive index unit for temperature-immune SRI measurement within the biologically desirable sensing range of 1.33–1.41 has been achieved via cost-effective power detection. © 2012 Optical Society of America

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Fiber-grating-based sensors are one of the most attractive schemes for surrounding refractive index (SRI) measurement. The key point for such a scheme lies in the capability of effectively coupling guided light from the fiber core to the cladding so that the evanescent field penetrates the surrounding medium, thereby perceiving SRI changes. One well-known technique is based on long-period gratings (LPGs), which can be directly used for SRI measurement because of the cladding-mode-based coupling mechanism [1–4]. However, LPG devices need transmission readout and typically suffer from large cross sensitivities to other parameters (temperature in particular). On the other hand, fiber-Bragg-grating (FBG)-based devices have been proven to be excellent sensors in, e.g., strain and temperature measurement [5,6], owing to their compact size, reflection mode operation, and high multiplexing capability. However, a normal FBG is essentially not sensitive to SRI. Suggested solutions to address this problem focus on the use of blazed gratings [7–9] or devices with specific postprocesses (e.g., wet etching, side polishing, and using D-shaped or H-shaped fibers) to bring the core mode into contact with the surrounding medium [10–13]. But these processes significantly degrade fiber mechanical strength and increase fabrication complexity. Recently, using a LPG to excite and recouple the cladding mode of an ordinary FBG, a cladding-mode-based FBG refractometer was reported [14]. Based on the same principle, single-mode–multimode–single-mode-fiber structure assisted FBG has also been explored to measure the SRI [15]. This is a promising technique, but the SRI information is wavelength encoded, and the SRI sensitivity is rather limited and drops rapidly for lower indices, restricting their use for many biological and environmental applications operated in water-based solutions where the indices are usually below 1.4.

In this Letter, we demonstrate a power-referenced and sensitivity-improved refractometer for temperature-immune SRI measurement. It is a fiber stub configuration consisting of a short section of thin-core fiber (TCF) followed by an FBG. The advantages of this sensor are ease of fabrication, reflective operation, and cost-effective power detection over the well-defined core reflection. More importantly, the SRI sensitivity (133.26 dB/RIU) is greatly enhanced within the desired measurable range from 1.33 to 1.41.

The schematic diagram of the proposed refractometer structure is shown in Fig. 1. A section of uncoated TCF is sandwiched between a leading single-mode fiber (SMF) and an FBG-imprinted SMF stub. When light is injected from the leading SMF into the TCF, multiple cladding modes of the TCF will be excited due to the core–diameter mismatch [16] and propagate along the fiber. These modes penetrate the surrounding medium with a strong evanescent field and, hence, perceive SRI changes. At the end of the TCF, these cladding modes interfere with each other, enabling the transmitted light to be SRI sensitive. For light coupled into the downstream SMF, a portion of light enters the core, while the remaining portion is coupled to the cladding. Both the core and cladding modes of the downstream SMF are excited and continue to travel along the fiber until they reach the FBG, as shown in Fig. 2(a), where they are partly reflected and recoupled back to the TCF, and, finally, to the backward guided mode of the leading SMF. Therefore, the reflection spectrum of the proposed device consists of two well-defined wavelength bands, namely, a broadband spectra containing several cladding mode reflections on the shorter wavelength side, and a single resonance corresponding to the core mode.

Fig. 1. (Color online) Schematic diagram of the TCF–FBG refractometer.

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reflection at the longest wavelength, as shown in Fig. 2(b). When the SRI changes, the transmission enveloping of the SMF–TCF–SMF structure shifts its wavelength [16], while the wavelength of the Bragg core reflection remains unaffected. As a result, the peak power of the core reflection is tailored with the SRI perturbation via the “invisible” SMF–TCF–SMF enveloping. By simply monitoring the power variation of the core reflection at a given wavelength, the SRI can therefore be determined.

Because of the effective excitement of both low-order and high-order cladding modes of the SMF–TCF–SMF structure, high-sensitivity SRI measurement can be achieved as these cladding modes (especially the high-order modes) propagate close to the cladding/surrounding boundary with the evanescent field overlapping strongly with the surrounding medium. When the SRI changes, the effective refractive index (RI) of the TCF cladding changes, and, hence, the excitation coefficient of each cladding mode in the TCF will change, resulting in changes for the interference of these modes and the transmission wavelength of the sandwich structure [16,17]. In this case, the TCF-based sandwich structure functions as a bridge between the SRI and the FBG core mode reflection, and its bridging efficiency can be modified by controlling the TCF length, as the experiments show in Fig. 6.

The sensor was fabricated by fusion splicing. Standard SMF with core/cladding diameters of 9/125 μm, uncoated TCF with diameters of 5/120 μm, and an FBG with grating length of 10 mm and reflectivity of 90% were used. The length of the TCF section was 10 mm and the distance between the end of the TCF and the beginning of the FBG was 3 mm, which were carefully selected through trial and error to ensure a good excitement, coupling efficiency, and compact size. Figure 2 shows the measured reflection spectra (from the TCF end and the FBG end).

Both the core and cladding mode reflections are observed as expected when measured from the TCF end.

Experiments based on the fabricated device were carried out. Figure 3 shows the experimental setup for SRI measurement. A broadband source (BBS) was used to illuminate the sensor through an optical circulator and the reflections were recorded using an optical spectrum analyzer (OSA). Two fiber holders were used to keep the sensor straight and strain constant to eliminate the influence of bend and stress. A rough fiber end is to avoid the unwanted background noise caused by the fiber tip reflection. A series of glycerol solutions with different volume concentrations was prepared as samples and the corresponding indices, calibrated by an Abbe refractometer, ranged from 1.33 to 1.41. For each measurement of a specific RI value, a pipette was used to drop a small quantity of the solution onto a microscope slide placed on an adjustable stage to immerse the sensing element. During consecutive tests, the sensor was cleaned with distilled water and dried in air. In all cases, the spectrum returned to its original state when the sensor was cleaned. The spectral response of core mode reflection to the change of SRI is shown in Fig. 4. The peak power of the core mode reflection increases linearly with the SRI, while the wavelength remains unchanged, which indicates its potential to simultaneously measure temperature and SRI through simultaneous wavelength and power detection. The power variation as a function of the SRI is plotted in Fig. 5. The linear fitting shows a sensitivity of 133.26 dB/refractive index unit (RIU) within the desirable sensing range, which is the highest value reported so far.
far in the literature (reference only the core mode) to our knowledge.

To study the thermal effect, we fixed the sensor on a heating board in air (SRI = 1). Over the temperature range from 25 °C to 95 °C, peak-to-peak power fluctuations of the concerned core reflection are less than 0.1 dB, as the inset shows in Fig. 5, identifying the sensor’s ability to perform a temperature-immune SRI measurement via such cost-effective power detection.

For comparison, sensors with different TCF lengths but identical grating parameters were fabricated and their SRI responses were measured, as shown in Fig. 6. Sensitivities of 111.78, 37.20, and −89.11 dB/RIU were achieved with the TCF lengths of 12, 15, and 20 mm, respectively. This means the proposed refractometer can potentially achieve its optimized sensitivity (both positive and negative) by properly controlling the sandwiched TCF length. Meanwhile, it should be noted that the exact relationship between the length of the TCF and the sensitivity is also dominated by the splicing loss on both sides and the presetting wavelength of the Bragg core reflection, which is supposed to be a piecewise function based on the experimental results in hand. For the exact relationship, further experiments and detailed theoretical investigation are ongoing.

In conclusion, we have proposed a novel refractometer TCF-based sandwich structure that introduces a considerable evanescent field and, therefore, makes the propagating light become highly SRI dependent. The SMF–TCF–SMF transmission enveloping was sensitive to SRI and further transformed the SRI information into power fluctuation of the Bragg core reflection. An interesting linear response with a greatly enhanced sensitivity of up to 133.26 dB/RIU within the biologically desirable sensing range of 1.33–1.41 for this compact refractometer, together with a tailorable sensing capability and a potential of simultaneous temperature and SRI measurement, makes it an ideal candidate for sensing in chemical and biological applications.

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