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# Simple and compact reflective refractometer based on tilted fiber Bragg grating inscribed in thin-core fiber

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A simple and compact reflective refractometer based on a tilted fiber Bragg grating (TFBG) inscribed in an ultra-high photon-sensitive thin-core fiber is proposed and experimentally demonstrated. The reflective refractometer utilizes a short piece of thin-core fiber containing one TFBG to ensure the recoupling of cladding modes. The reflection spectra occur in two well-defined wavelength bands that correspond to the Bragg core mode and cladding modes, respectively. It is found that the power of the collected cladding modes changes with the external refractive index (RI), while that of the Bragg core mode remains unaffected and can be used as the temperature reference. High RI sensitivity and temperature immunity of the proposed reflective refractometer are experimentally achieved. © 2013 Optical Society of America

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With the rapid development of fiber grating fabrication techniques [1], optical fiber grating has become a key device in fiber-optic systems. Owing to superior advantages such as compactness, passive operation, remote sensing capability, and electromagnetic interference immunity, optical fiber gratings have attracted significant attention in the context of biosensing and chemical sensing [2–11]. One scheme is based on long-period grating (LPG) [2–4], using which the core mode is coupled to the cladding modes of the same direction while its evanescent field extends to the sensing environment. Although such LPG has been demonstrated for both chemical sensing and biosensing, the sensing performance is inherently limited by its large cross-sensitivity to temperature and large spectral width. In another scheme, where fiber Bragg grating (FBG) is used [5–7], the core mode is coupled to a new counter-propagating core mode. Although the FBG has a lower cross-sensitivity to temperature and a narrower spectral width as compared to the LPG, the sensitivity to external refractive index (RI) change is significantly reduced. Some special fibers and structures, e.g., small core photonic crystal fiber [5], H-shaped fiber [6], and single-mode–multimode–single-mode fiber structure [7], have been employed to construct sensitivity-enhanced RI sensors. However, a significant improvement on the sensitivity is not yet reported.

Tilted FBG (TFBG) is a special configuration of the FBG, in which the core mode can be efficiently coupled to another core mode and cladding modes that are traveling in the opposite direction [8]. It is noteworthy that the power of the excited cladding modes is highly sensitive to the external RI and that the structure has a low cross-sensitivity to temperature—two merits that are especially desirable for the refractometers. By incorporating the cladding modes recoupling elements upstream from the TFBG, single-probe configuration is possible for biosensing applications. Several reflective TFBG sensors have been proposed and demonstrated [9,10,12]. For example, a short piece of optical fiber containing a TFBG was spliced to another fiber in a core-offset-manner so that the cladding modes can be excited to construct a reflective TFBG with improved sensitivity [9]. An abrupt taper combined with a TFBG was proposed to construct a reflective accelerometer [12]. In our former work, we inserted a short section of modal mismatch fiber upstream from the TFBG to form the RI sensor [10]. However, the collected cladding modes of all the reported reflective TFBGs have a very low visibility, limiting their sensing performance. Moreover, sensors based on the abovementioned schemes suffer from either weak mechanical strength or complicated configuration.

In this Letter, we propose a simple and compact reflective refractometer based on a TFBG inscribed in the thin-core fiber. As shown in Fig. 1(a), a short piece of ultra-high photon-sensitive thin-core fiber (UHNA) containing a TFBG is spliced to the single-mode fiber (SMF). To the best of our knowledge, the collected cladding

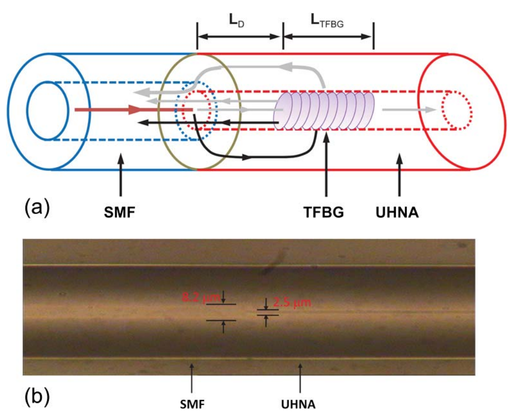


Fig. 1. (a) Schematic configuration of the reflective refractometer and (b) the microscope image of the splicing region between two different fibers.

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**Table 1. Comparison between the Proposed Reflective TFBG Sensor and Other Structures in Reported Literatures**

| Structure | Core-Offset Fiber [9] | Fiber-Taper [12] | Core-Diameter Mismatch Fiber [10] | Structure Proposed in This Work |
|---|---|---|---|---|
| Mechanical strength | Weak | Weak | Strong | Strong |
| Repeatability | Low | Low | Low | High |
| Spectral visibility | Low | Low | Low | High |
| Available interrogation methods | Intensity method | Intensity method | Intensity method | Intensity and spectral methods |

modes have the highest visibility among the reflective TFBG configurations. The proposed reflective refractometer has stronger mechanical strength and simpler configuration as compared to previously reported reflective TFBG sensors [9,10,12]. The comparison is shown in Table 1. Its high RI sensitivity and temperature immunity have been experimentally demonstrated.

The operation principle of the proposed reflective refractometer is based on the cladding modes recoupling through TFBG and the modal mismatch between different fibers. As shown in Fig. 1(a), the incident light follows two trajectories: One portion of the light is coupled to the cladding modes when it reaches the interface of SMF and UHNA and these coupled cladding modes are then coupled back to the backward propagating core mode by the TFBG (black curve); the remaining portion of the light propagates along as core mode, which is later reflected by the TFBG into backward propagating cladding modes and core mode, where the reflected cladding modes eventually couple into the core as the core mode (gray curve). In order to verify how the cladding modes are excited through modal mismatch, we use the beam propagation method (BPM) (Rsoft Design Group) to analyze light propagation along the SMF and UHNA. Core diameters of the SMF and UHNA are set at 8.2 and 2.5 μm, respectively. The cladding diameters of the SMF and UHNA are 125 μm. Figure 2 shows the stimulated amplitude distribution of the light propagating along the SMF and UHNA. It is observed that the incident light beam expands to the high-order cladding modes at the interface of the SMF and UHNA ($Z = 1000$ μm); the excited cladding modes are then reflected by the boundary of the cladding and surrounding medium (air) to propagate along the fiber. Both the cladding modes and core mode reflected by the TFBG experience a reverse mode coupling in their return trip (not shown in the unidirectional BMP model we used), leading to the capture of reflected cladding modes and core mode. The reflective TFBG extends its evanescent field considerably into the test medium, making it a promising candidate for the RI sensing.

The TFBG is inscribed in a thin-core fiber with ultra-high photon-sensitivity (Nufern UHNA1, core diameter: 2.5 μm, NA: 0.28). Because of a rich concentration of germanium doping in its core, the fiber has a high photon-sensitivity so that grating fabrication is feasible. A phase mask-based fiber grating fabrication platform using a 244 nm argon laser is employed to fabricate the TFBG by tilting the phase mask at an angle of 3°. The fabricated TFBG has a length ($L_{\mathrm{TFBG}}$) of 8 mm. The whole piece of the UHNA is then spliced to the SMF. The microscope image of the splicing region is shown in Fig. 1(b). To obtain a high coupling efficiency for high-order cladding modes, it is necessary to keep the TFBG a short distance ($L_D = 3$ mm) away from the splicing point. The other end of the UHNA is angle cleaved to avoid end-face reflection.

The proposed reflective refractometer is illuminated by a tunable laser (ANDO AQ 4321D) with ultra-high stability, while the reflected signal is recorded by an optical spectrum analyzer (ANDO AQ 6317B) through a circulator. Both the cladding modes and core mode are collected as shown in Fig. 3. It is observed that all the cladding modes start from the same baseline, i.e., the lowest power level where noise and signal cannot be distinguished. It means that only the cladding modes contribute to the collected power in the wavelength range from 1540 to 1566 nm. Compared with other reflective TFBGs [9,10,12], the proposed reflective TFBG yields a series of cladding modes with much better visibility, enabling monitoring of specific cladding mode. It is observed that the collected cladding modes split at shorter wavelength; the reason is that the mode degeneracy disappears in the cladding and the polarization dependent

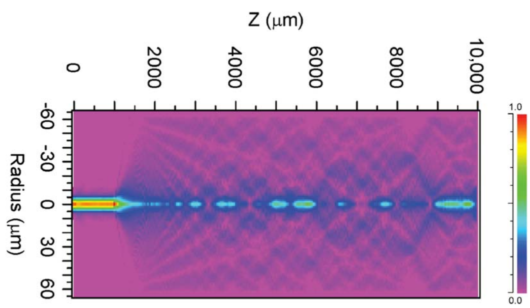


Fig. 2. Contour map of the beam propagation along SMF and UHNA.

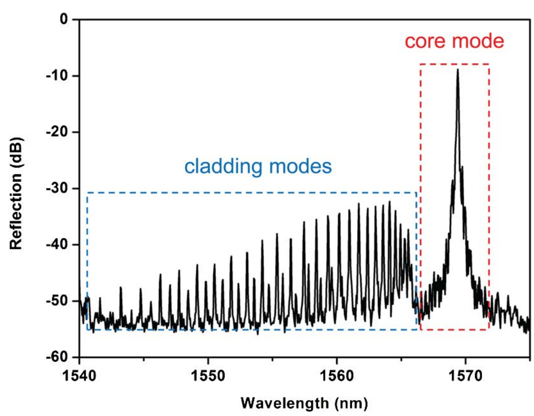


Fig. 3. Reflection spectrum of the proposed reflective refractometer.

vector modes begin to appear as closely split resonances [8]. The polarization state of the incident light is fixed in all our experiments to rule out the polarization effects in the reflected spectrum.

To investigate the sensing performance, the reflective refractometer is immersed into a series of glycerine-water solutions with different glycerine concentrations. The cladding modes of the TFBG would gradually vanish as the external RI increases from the index of air to that of the cladding. We monitor the power of the collected cladding modes to observe the external RI changes. Figure 4 shows the collected cladding modes power, which is normalized to the input power. When the RI of glycerine-water solution increases from 1.333 to 1.428, the high-order cladding modes gradually shift into radiation modes and disappear from the shorter wavelength spectrum as shown in the inset of Fig. (4). Furthermore, the power of the collected cladding modes decreases linearly at a rate of −8.8 dB/R.I.U (R.I.U: refractive index unit). When the RI further increases from 1.428 to 1.459, more low-order cladding modes disappear until only the Bragg resonance is left. In this case, the power of the collected cladding modes decreases rapidly at a rate of −229.5 dB/R.I.U. In all the measurement, the baseline of the collected cladding modes keeps constant, confirming that the collected power is due to the cladding modes only. Meanwhile, the peak wavelength of the Bragg reflection keeps constant, making it an ideal temperature reference.

To study the temperature response, the reflective refractometer is put in a water bath, while the temperature is monitored by a commercial thermometer. Five minutes are allowed for the temperature of the refractometer to stabilize at each new setting before the reflective spectra are recorded. Figure 5 shows the collected cladding modes power, which is normalized to the input power. When the temperature increases from 25°C to 70°C, the peak wavelength of the Bragg reflection shifts to a longer wavelength at a rate of 11.5 pm/°C, a value that is comparable with any other TFBG and FBG sensors [6]. Meanwhile, the Bragg wavelength is inherently insensitive to the external RI changes, making it an *in situ* thermometer. The sensor is therefore able to efficiently eliminate the temperature effect from its measurements. When temperature increases from 25°C to 70°C, the power of the collected cladding modes increases, and

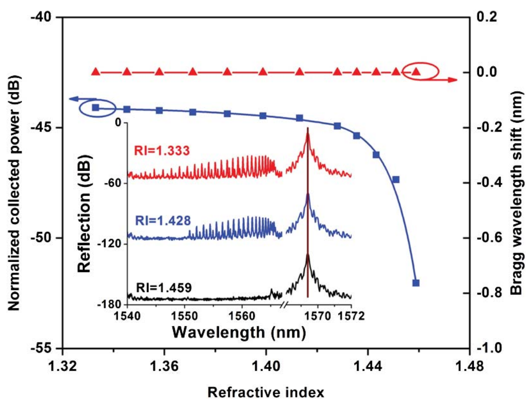


Fig. 4. Response of the reflective refractometer versus the external RI. Inset shows the measured reflection spectra.

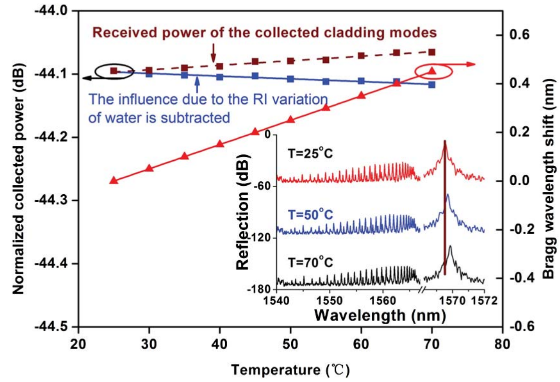


Fig. 5. Response of the reflective refractometer versus the external temperature. Inset shows the measured reflection spectra.

the maximum variation is 0.027 dB (as shown in the dashed line in Fig. 5). As the temperature increases, the RI of water changes at a rate of $-1.3 \times 10^{-4}$ R.I.U/°C [13]. In order to accurately evaluate the temperature effect, the influence on power response due to RI variation of water is subtracted by assuming a linear RI response at around 1.333. The power of the collected cladding modes decreases linearly at a rate of $-5.3 \times 10^{-4}$ dB/°C (as shown in the blue solid line in Fig. 5). Such variation is due to the temperature induced RI changes in fiber. Then we can deduce that the temperature effect on the sensing performance is very small and the temperature induced RI measurement error is $6 \times 10^{-5}$ R.I.U/°C, which is comparable with the high performance modal interferometric sensor ($9 \times 10^{-5}$ R.I.U/°C) [14].

Given the high visibility of the cladding modes (as shown in Fig. 3) and the fact that core mode has the same temperature sensitivity with cladding modes, the temperature effect of the proposed reflective refractometer can be totally eliminated by measuring the relative wavelength shift between the core mode and a specific cladding mode [8,15]. This effect can be seen by zooming in the insets of Figs. 4 and 5: A selected cladding mode with a high-$Q$ peak shifts its spectral position as the external RI changes, while the core mode keeps constant; as the external temperature changes, the selected cladding mode and the core mode shift at the same rate. The temperature effect is hence totally eliminated. The fact that few applications using spectral interrogation of cladding modes are reported in the reflective TFBG configuration is just due to the poor mode visibility. The proposed reflective refractometer can fill in this gap, which will be the subject of our further investigations.

In conclusion, we have demonstrated and tested a new reflective refractometer based on a TFBG inscribed in the thin-core fiber. The simple structural configuration not only eases the fabrication requirements but also improves the compactness and portability of the whole sensing system. Numerical simulation shows that the refractometer produces a profound evanescent field that extends into the sensing medium, potentially enabling a high refractive index sensitivity. The experimental results show that the reflective refractometer has a high sensitivity to the external RI but a low cross-sensitivity to temperature. Compared with other refractometers, the proposed refractometer offers various advantages, including low cost, strong mechanical strength, and simple and compact structure. Such a reflective refractometer would make challenging applications such as remote single-point monitoring biosensors and disposable low-cost fiber-optic bioprobes possible.

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