Evanescently coupled optical fiber refractometer based a tilted fiber Bragg grating and a D-shaped fiber

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Abstract: A novel tip-reflective and power-referenced refractometer based on strong fiber-to-fiber optical coupling for a large range of surrounding refractive index (SRI) (from 1.33 to 1.45) is proposed and experimentally demonstrated. A short D-shaped fiber stub is placed in parallel and close contact to another standard circular fiber containing a weakly tilted Bragg grating (TFBG). The TFBG couples the light from the circular fiber’s core into its cladding where it remains guided. Apart from the direct light coupling over the contact interface, the evanescent field from the guided cladding modes penetrates the surroundings and reaches the D-fiber core by tunneling across the medium into which the fiber pair is located. The amount of tunneling depends strongly on the SRI so that the total amount of light collected by the D-fiber provides a measure of the SRI. Sensitivities ranging from ∼1000 to 13000 nW/RIU (Refractive Index Unit) have been obtained and the result is independent of temperature (within +/-10 nW of uncertainty). The measurement can be temperature-referenced through measurement of the TFBG spectrum if needed.

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1. Introduction

Tilted fiber Bragg gratings (TFBGs) based refractometers can effectively couple the fundamental core mode to fiber cladding and generate strong evanescent fields for high sensitive surrounding refractive index (SRI) measurement, which have been proved to be an appealing solution for rapid, sub-microliter dose and highly sensitive detection of analytes at low concentrations in medicine, chemical and environmental monitoring [1]. To make detection process convenient (especially for microliter or sub-microliter dose of analytes), a “single-ended” detection is required, meaning that the TFBG must be interrogated in reflection. Various kinds of “in-fiber” configurations have been reported to re-couple the backward transmitted cladding modes into fiber core so as to allow this. These methods include a large lateral offset splicing [2], a core-diameter-mismatched fiber section [3], hybrid with a long period grating (LPG) [4–6] and a double-clad fiber coupler [7]. However, all above “in-fiber” TFBG refractometers can only re-couple a relatively narrow band cladding modes (the low order cladding modes [2,3] or those with resonances within the LPG spectral window), which limits the ranges for which SRI measurements can be made, especially for the low SRI (close to 1.33) encountered in biochemical solution measurements.

In this work, we designed and experimentally demonstrated a new “fiber-to-fiber” sensing configuration for refractive index measurement. Different from early studies of light coupling between two in parallel LPGs (which are mainly used as wavelength-selective bandpass filters or multiplexers [8–12]) and fibers with singlemode-multimode-singlemode configuration [13,14], we take advantage of a D-shaped fiber [15–17] as a broad bandpass “bridge” to re-capture the evanescent field of high-order cladding modes of TFBGs with high efficiency. All these cladding modes are re-coupled in the reflection of D-shaped fiber and directly measured by a simple photoelectric detector (making spectral filters unnecessary). The proposed sensor provides a much improved sensitivity for large range of SRI measurement including for water-based solutions with RI close to 1.33. While the operating principle is inherently insensitive to temperature, the temperature information can be unambiguously measured if necessary by directly monitoring the wavelength of the core mode reflection from the TFBG.

2. Sensor design and fabrication

As shown schematically in Fig. 1, the basic idea behind this configuration is to recapture backward propagating cladding modes into the fiber core of D-shaped fiber. In general, the backward propagating cladding modes exited by TFBG cannot propagate for a long distance along the fiber cladding due to the absorption of the high-index jacket material, nor can it go
back into the fiber core again. So the reflection spectrum of a TFBG only consists of a single and narrow band resonance from the core mode reflection. Obviously, the core mode reflection is insensitive to SRI and can be used to monitor the local temperature without ambiguity (because the endpoint configuration is also inherently strain-free). While previous TFBG refractometers worked on the principle of perturbations of the transmission spectrum due to SRI changes, the new design is based on the impact of SRI on penetration depth of the evanescent field of cladding modes: the higher the index, the longer the penetration depth. Quantification of this effect is through recapture of the evanescent field with a D-shaped fiber where the core is located in close proximity to the flat side of the fiber cladding. The two fibers are in parallel contact to each other and can be fixed permanently such. Once the tunneling light is re-coupled into the core of the D-fiber it can travel essentially without loss over a long distance for interrogation.

Fig. 1. Experimental schematic of sensing system (a); fiber-to-fiber recoupling between a TFBG and a D-shaped fiber in parallel contact (b); microscope images of sensor probe and cross section of D-shaped fiber (c).

In fabricating the sensor probe, it must be noted that the azimuthal light distribution from the TFBG is predominantly directed along the tilt plane direction [18,19]. So the coupling of efficiency between the TFBG and the D-shaped fiber can be optimized by orienting the TFBG tilt plane along the plane in which the two fibers are located, as shown in the Fig. 2 reflection spectra. In order to find the maximum “fiber-to-fiber” coupling efficiency, we used a fiber rotator to rotate the TFBG fiber while keeping the D-shaped fiber fixed. Following this alignment step, we fix and package the two fibers into a capillary in the upstream side and glue both fibers at the downstream tip point to ensure the robustness and reproducibility of the sensing results. Please note that the D-fiber is connected with a SMF upstream which the SMF part is packaged in the capillary. So the D-fiber will not be influenced by the capillary.

The D-shaped fiber used here is directly drawn into this particular shape at the University of New South Wales (Sydney), which is significantly more convenient than polishing an ordinary cylindrical fiber and provides much lower device loss. The inset photograph of Fig. 1 shows the D-shaped fiber cross-section, with a core diameter of 5.9 μm, top cladding diameter of 10.1 μm and bottom cladding diameter of 114 μm. We used a commercial ARC fusion splicer to connect the D-shaped fiber (20 mm in-length) with single mode fiber in order to facilitate measurements. The TFBG used had a length of 10 mm, a tilt angle of 10° and it was
inscribed in hydrogen-loaded standard single-mode fiber using a pulsed 193 nm excimer laser and a phase mask.

3. Experimental results and discussion

As shown in Fig. 1(a), the initial characterization of the sensor was carried out by launching light from an erbium amplified spontaneous emission broadband source (BBS) into the TFBG fiber through a 3 dB coupler. We measured the power reflected by the TFBG (i.e. the core mode reflection only) and the power recaptured by the D-shaped fiber with two photodiodes, PD1 and PD2 respectively. PD2 provides an absolute power reference against which the recoupled power can be compared unambiguously. For the purposes of this paper, but not necessary in practical use, the optical spectra of the same two outputs were measured with an optical spectrum analyzer (OSA) using a wavelength resolution of 0.05 nm. A transmission spectrum of the TFBG was also measured separately as shown by the blue curve in Fig. 2. In the same figure, the red and green lines give the spectra of the re-coupled light into the D-shaped fiber, but with different azimuthal rotation of the TFBG relative to the D-shaped fiber (flat plane direction). These measurements confirm that there is a preferred orientation of the cladding mode light distribution around the TFBG and that lining up the maximum of this distribution with the D-fiber flat side provides maximum recoupling. The hollow red arrow in Fig. 2 indicates the inscription direction of the TFBG and hence the orientation of the tilt plane, so in principle there is no need to search for the best orientation when packaging the devices as long as we keep track of the direction from which the laser beam was incident on the fiber when the TFBG was fabricated.

![Image of a graph showing transmission and reflection spectra](image)

Fig. 2. Transmission of TFBG (blue curve) and reflections from D-shaped fiber with maximum (red curve) and minimum (green curve) re-coupled spectra. Insets show the fixed D-shaped fiber with two orthogonally positioned TFBGs (red arrows indicate the azimuthal orientation of the cladding mode maxima).

The red line shows the re-coupled cladding spectrum has a broad wavelength range over 30 nm and the maximum spectral SNR is about 30 dB, which is much higher than early reports of in-fiber cladding-to-core re-coupling schemes [2–7]. The integrated SNR, of the total recoupled power (by PD2) is at least as high as well. It is also important that the re-coupled spectrum does not contain the core mode reflection so that it is totally under the
influence of the SRI (without a background fixed power level that would not change with SRI). The total transfer function from the core of the TFBG to the core of the D-fiber is apparently stronger for low order cladding modes (at wavelengths close to the Bragg wavelength of the core reflection) but this will be shown to have little effect on how the refractometric sensitivity changes with SRI.

Fig. 3. SRI information detection by monitoring the fiber-to-fiber re-coupled cladding mode reflection (a); Temperature information detection by monitoring the in-fiber core reflection and showing that the SRI signal (recoupled power) is independent of temperature (b).

In order to demonstrate the sensing capability of the sensor, we measured sucrose-water solutions. Small quantities of liquids with various refractive indices were dispensed with a pipette onto the sensor. The sucrose-water solutions used had a RI range from 1.33 to 1.45. The refractive indices of the solutions were measured at a wavelength of 589 nm with an Abbe refractometer (the refractive indices at the wavelength of operation of the sensor are different but this has no impact on the measurement, following sensor calibration for a given application). The test results are presented in Fig. 3. In detail, Fig. 3(a) shows the re-coupled cladding modes for five values of SRI. With the SRI increasing, the short wavelength side of the re-coupled cladding spectrum disappears gradually because the fields from higher order cladding modes become radiative instead of evanescent and therefore cannot be re-coupled as

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guided modes of the core of D-shaped fiber. However, the increasing index extends the penetration depth of the modes that remain cladding guided and hence the net total power recaptured by the D-fiber increases. A combination of the two effects (cladding to radiative transition and increased penetration depth of still guided modes) results in the fact that the highest sensitivity point of the proposed sensor is located near RIs of 1.38–1.40, with a maximum value of 13634 nW/RIU. However, we still get a large sensitivity of 1356 nW/RIU in pure water (RI at 589 nm of 1.33). It should be noted that we cannot remove all the cladding mode coupled into D-fiber by increasing the surrounding RI even when the it is up to 1.46 (the red reflection shown in Fig. 3(a)). The residual low-order cladding modes may come from the direct coupling between TFBG and D-fiber over the contact interface between two fibers. The exact shape of the RI response curve (Fig. 3(a)) is strongly dependent on the initial TFBG transmission spectrum, i.e. on the envelope of the cladding mode resonances. It is expected that increasing the tilt angle of the TFBG would shift the sensitivity maximum to another value of SRI but the current device appears to be a good compromise for a wide range of SRI values. Meanwhile, a linearly polarized input light with the polarization orientation relative to the grating tilt will increase the coupling efficiency between TFBG and D-shaped fiber. Moreover, if needed (and at the cost of adding a spectrum analyzer or FBG interrogator system) Fig. 3(b) shows that temperature information can be simultaneously measured by directly monitoring the core reflection wavelength of the TFBG (for a strain free fiber probe, the core mode is only sensitive to temperature but immune to the SRI). Alternatively, an absolute power-based temperature measurement can be achieved by add a wavelength-matched edge filter to interrogate the shift of the core resonance [20], which can also be used as a power reference to calibrate the potential power fluctuations of light source. However, even with the two diodes only system shown here, any power fluctuations can be referenced out since the core mode reflected power provides a SRI insensitive measurement of the power at the device.

4. Conclusion

The feasibility of fiber-to-fiber power-referenced refractometry based on a TFBG and a D-shaped fiber has been experimentally demonstrated. Strong cladding guided modes over a broadband wavelength range have been recaptured in the core of D-shaped fiber in reflection. The power of these re-coupled cladding modes varies significantly with SRI changes and the sensitivity (and SNR) obtained is much higher than reported in-fiber sensing schemes. Temperature information can be simultaneously measurement by monitoring the core reflection of the TFBG. The compact size and cost-effective power detection scheme make it a good candidate for sensing in chemical and biological applications.

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