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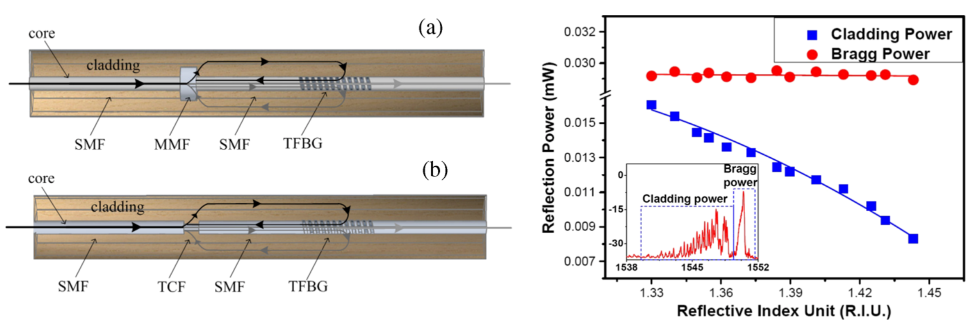

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Cladding-Mode-Recoupling-Based Tilted Fiber Bragg Grating Sensor With a Core-Diameter-Mismatched Fiber Section

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Abstract: We demonstrate a reflective fiber-optic sensor with a core-diameter-mismatched fiber section and cladding-mode recoupling in a tilted fiber Bragg grating (TFBG). High-order cladding modes are efficiently excited by either a multimode fiber or a thin-core fiber section and recoupled back to the core mode by the TFBG. A special reflection spectrum with recoupling of cladding mode is then obtained to exploit the applications of evanescent waves in an optical fiber. Experimental results of the sensor to measure the external refractive index are presented.

Index Terms: Fiber optics, fiber Bragg grating (FBG), fiber-optic sensor, refractive index sensor.

1. Introduction

Optical fiber gratings have become a key technology in fiber-optic devices and applications, particularly with development of fiber-grating-fabrication techniques [1], [2]. Based on a coherent scattering mechanism, the fiber gratings can be used as in-fiber reflector or filter for fiber-optic communications and sensors. It is well known that fiber Bragg gratings (FBGs) introduce a contra-directional coupling of the fundamental mode, whereas the long-period gratings (LPGs) introduce a codirectional coupling from the fundamental mode to cladding modes [2], [3]. Recently, some special-mode couplings in, e.g., paired LPGs or FBGs [4]–[7] or LPG and FBG hybrid structures [8], [9], have attracted a lot of research attention because of their unique spectral properties for designing novel photonic devices and sensors [10], [11].

One of the mode-coupling interactions of interest is the cladding-mode-assisted recoupling, which is particularly suitable for constituting in-fiber interferometers or exploiting the evanescent wave of cladding mode. For example, a compact in-fiber Mach–Zehnder interferometer can be fabricated if one makes two identical 3-dB LPGs in the same fiber [5]. If use a FBG and LPG hybrid structure [9], one can make a reflective fiber devices with recoupling of cladding mode. Compared with transmissive fiber-optic devices, the reflective one is desirable for making a single-point sensor, e.g., *in vivo* bioprobe.

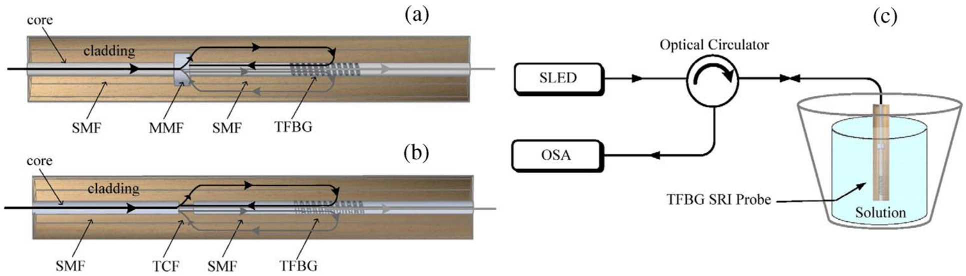

Fig. 1. Schematic diagrams of the reflective TFBG sensors and the sensing principle. (a) and (b) Two different mode-excitation and recoupling schemes using different CDMF sections. (c) Test setup for measuring glycerin-water solutions. SLED: superluminescent LED; OSA: optical spectrum analyzer.

Tilted FBG (TFBG) is a special FBG which can efficiently couple the light between the core mode and cladding modes [12]–[17]. Thus, it is an ideal element for constituting a reflective fiber device based on cladding-mode recoupling. Several reflective TFBG devices have been proposed after introducing some special cladding-mode exciting or recoupling element. For example, a misaligned fusion splicing technique was used to excite cladding modes and combined with a TFBG to form a fiber-optic sensor for vibration and refractive index (RI) measurement [18], [19]. It was also proposed to use a tapered fiber to recouple the cladding modes coupled by the TFBG to form a reflective fiber-optic accelerometer [20]. However, both schemes will introduce a deleterious effect on the mechanical strength of the device, and the repeatability of the processes is not ideal because they are not a well-established operation of optical fibers.

In this paper, we present a new TFBG sensor structure with a section of the core-diameter-mismatched fiber (CDMF). As shown in Fig. 1, the mode-exciting approach based on the core-diameter-mismatching scheme is flexible, and both the multimode fiber (MMF) and the thin-core fiber (TCF) sections can be used to selectively excite the cladding modes. The excited cladding modes will be recoupled back to the core mode by the TFBG and partially pass through the CDMF to form a reflective TFBG sensor with cladding-mode recoupling. The gray curves in Fig. 1(a) and (b) show the other possible light path, i.e., the core-mode light going through the other core gets reflected into a cladding mode backwards by the TFBG and then recoupled into the core at the MMF or TCF section. The attenuation of this light path is believed to be relatively higher than that shown by the black curves, since the MMF or TCF section here functions as a mode expander but not a bidirectional coupling element. Compared with the misalignment- or tapered-fiber-based reflective TFBG sensor, such a fiber device is expected to have better mechanical strength and reproducibility of a recoupling amount, which are desirable merits for further functionalizing the fiber sensor. The designed TFBG sensors are experimentally fabricated and tested in experiments for measuring glycerine-water solutions.

2. TFBG Sensor With a CDMF Section

The operation principle of the reflective TFBG sensor is schematically shown in Fig. 1. An MMF (or TCF) section is used to excite cladding modes, and the excited cladding modes will be recoupled back to the fiber core by the TFBG due to the reciprocal mode-coupling mechanism. Therefore, such a fiber device will have strong evanescent waves only between the MMF (or TCF) and the TFBG. For a specific cladding mode, the reflection of light from the device can be expressed as

$$R(\lambda) = E_{CDMF} \cdot C_{TFBG} \cdot T_{CDMF}$$

where E_{CDMF} is the excitation ratio of the cladding mode, C_{TFBG} is the coupling ratio of the cladding mode to the core mode, and T_{CDMF} is the transmissivity of the core mode passing through the MMF (or TCF), respectively.

In order to verify how the core mode in the single-mode fiber (SMF) will be excited to high-order cladding modes by the MMF or TCF, a commercial beam propagation method (BPM) is used to

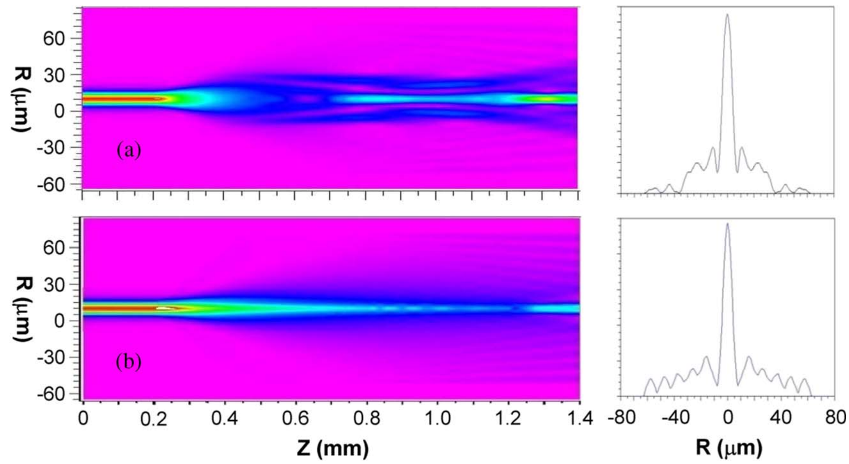

Fig. 2. Contour maps of the beam propagation through (a) an MMF section or (b) a TCF section, and their corresponding calculated far fields.

analyze the light passing through a section of MMF or TCF with length of 1 mm. The core diameters of the MMF and TCF are set to be 40 and 3 μm, respectively. In order to yield an accurate simulation of such a structure with RI discontinuities, a nonuniform grid scheme has been applied in those discontinuous interfaces. As shown in Fig. 2(a), for the light passing through MMF, the laser beam gradually expands in the first 150 μm, and then, the central portion of the light will reflected back from the core/cladding interface and propagates along the fiber core. High-order cladding modes are excited when the light reaches again the SMF. Fig. 2(b) shows that the laser beam propagates through a section of TCF. The laser beam gradually expands and reaches the internal wall when the length of the TCF is around 600 μm. If comparing with the excited far fields, as shown in the right two subdiagrams in Fig. 2, one can see that the cladding modes excited by the MMF encircle closely around fiber core, whereas the cladding modes excited by the TCF are spread around the whole fiber cladding. Therefore, one can expect to selectively excite the cladding modes by presetting the diameter of the inserted fiber section.

3. Fabrication and Test of TFBG Sensor

The designed reflective TFBG sensors are fabricated in our experiments and tested to measure glycerin-water solutions. The TFBGs were fabricated in a boron/germanium-codoped photosensitive SMF. This fiber was hydrogen loaded at 110 °C under pressure of 10 MPa for three days to enhance the photosensitivity. A phase-mask-based FBG fabrication platform with a pulsed 248-nm KrF excimer laser is used for the grating fabrication. The TFBGs were fabricated by tilting the phase mask with a small angle (the relationship between the internal tilted angle of the grating plane and the tilted angle of phase mask is ruled by Snell's Law). The transmission spectrum of a TFBG with 2.5° tilt angle is shown in Fig. 3. A strong ghost mode and tens of other high-order cladding modes appear at the shorter wavelength side of the normal Bragg wavelength.

After the fabrication of TFBG, a short section of CDMF, i.e., MMF or TCF, that is 1 mm long is fusion spliced 10 mm from the TFBG. The inserted MMF or TCF section is pretty short so that it avoids the effects of multimode interference [21]. Fig. 4(a) and (b) show the reflection spectra of the fabricated reflective TFBG sensors made with the MMF and TCF section, respectively. As shown by the microscope in the insets, the core diameters of the used MMF and TCF are 40 μm and 3 μm, respectively, whereas the core diameter of the normal SMF is 8 μm. As shown in Fig. 2, such a CDMF section can efficiently excite the cladding modes. If the compared the measured reflection spectra of the fabricated TFBG sensors are shown in Fig. 4, one can see that many cladding modes are excited by both reflective TFBG sensors. The power of the core mode reflected by the reflective TFBG with MMF is relatively higher than that reflected by the reflective TFBG with TCF. It can be

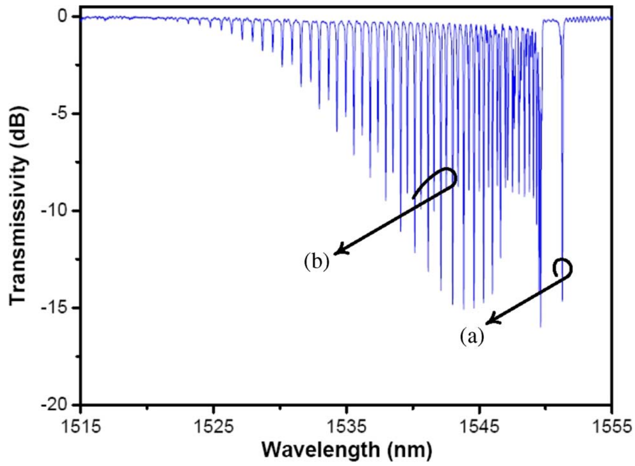

Fig. 3. Transmission spectrum of the fabricated 2.5°-tilted TFBG in a hydrogen-loaded boron/germanium-codoped photosensitive fiber. (a) Coupling to backward core mode. (b) Coupling to backward cladding modes.

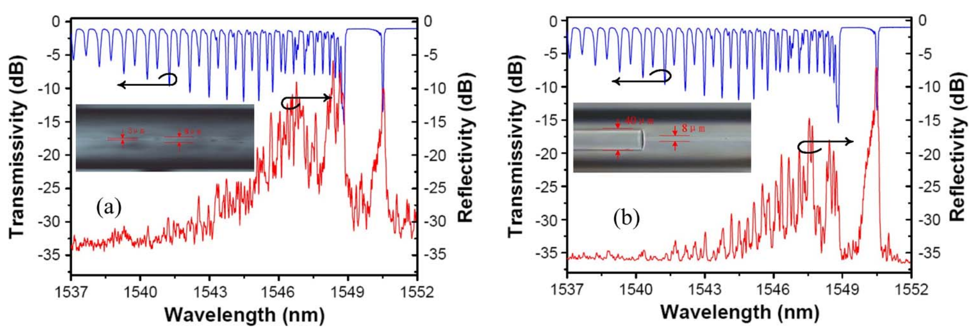

Fig. 4. Comparison of the TFBG sensors' reflection spectra using different CDMFs [3 μm versus 8 μm for (a) and 40 μm versus 8 μm for (b)]. The insets are microscope images of the spliced joints between two fibers. The upper curves of (a) and (b) are transmission spectra of the TFBG.

explained by the simulation results shown in Fig. 2 that transmissivity of the core mode passing through the MMF section is higher than that passing through TCF section, which thus results in a lower reflectivity for the core mode (since it passes twice through the MMF or TCF section). Moreover, the patterns of reflection spectra show more complicated than those of transmission spectra. The causes of such a difference include the core-mismatched-fiber-induced multimode interference and the attenuation-induced lowering of pattern contract.

Such a reflective TFBG is a good candidate for, e.g., evanescent-wave-based sensing applications. The light wave will be coupled into cladding modes and finally reflected back to the fiber core in that local fiber section. Thus, one can utilize the evanescent wave of cladding modes to determine the induced change of RI or the absorption of surrounding media. On the other hand, the reflected power by the coupling between forward and backward core mode can be used as a reference signal to determine the temperature or eliminate the effect of the power variation of light source. The maximum deviation can be observed to be 0.00029 mW, which is less than 1% (the reflection power is 0.0292 mW). It is noticeable that the shift of resonant peaks of TFBG is not as significant as that of LPG for RI measurement, though the change of external RI alters the effective RIs of cladding modes because the resonant wavelength of an LPG depends on the difference between the effective RIs of the core mode and the cladding mode, whereas the resonant wavelength of a TFBG is determined by the sum of the two effective RIs.

In order to demonstrate the sensing capability of the sensor, we used the fabricated TFBG with the MMF section to measure the glycerine-water solutions. The concentrations of glycerine-water

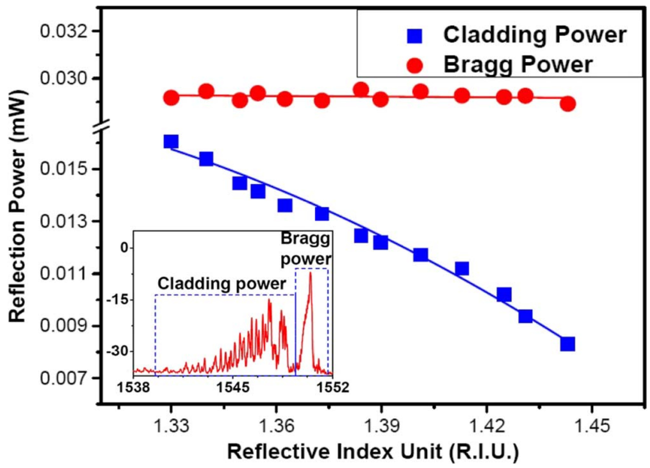

Fig. 5. Reflection power versus R.I.U. The reflected Bragg power keeps constant, while the recoupled cladding power decreases as SRI increases. The inset shows the definition of the "Bragg power" and the "cladding mode." The Bragg power is the total energy of the Bragg reflected core mode, while the cladding power is the total energy of the recoupled cladding modes.

solutions are from 0 to 95.0% in volume percentage, and the corresponding RI is from 1.33 to 1.47. The test result is presented in Fig. 5. The inset shows the definition of the "Bragg power" and "cladding power." One can see that the reflected Bragg power almost remains unchanged, whereas the reflected cladding power decreases smoothly and significantly with an increase of the RI of surrounding media. Although the RI resolution of those preliminary results is not very high, it can be improved if one uses cladding-reduced fiber for sensor fabrication or coats the sensor with gold nanocoating to measure RI with plasmon resonances [16].

It is known that the sensitivity of a specific cladding mode to the surrounding RI depends on the order of the cladding mode. Normally, the higher order cladding mode is more sensitive to surrounding RI than the lower ones. Since tens of cladding modes are excited and recoupled back to the fiber core, this reflective TFBG sensor is a compromised one: The higher order cladding modes play the key role when the surrounding RI is lower, whereas the lower order cladding modes work when the surrounding RI is higher (i.e., close to the RI of fiber cladding). Therefore, the operation dynamic range of the sensor is expected to be much wider than that based on one cladding mode.

4. Conclusion

In conclusion, we have demonstrated a new reflective TFBG sensor and tested the sensor for measuring glycerine-water solutions. A short section of CDMF was inserted between the SMF and the TFBG with specific distance to introduce a local excitation of cladding modes. Compared with other designed mode-excitation approaches, this design offers desirable features, e.g., a stronger mechanical strength and good repeatability of recoupling amount. It is believed that such a special reflective TFBG device is a good candidate to exploit the sensing capability of the evanescent wave of fiber cladding modes.

References

[1] K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1263–1276, Aug. 1997.
[2] T. Erdogan, "Fiber grating spectra," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1277–1294, Aug. 1997.
[3] V. Bhatia and A. M. Vengsarkar, "Optical fiber long-period grating sensors," *Opt. Lett.*, vol. 21, no. 9, pp. 692–694, May 1996.
[4] T. Allsop, R. Reeves, D. J. Webb, I. Bennion, and R. Neal, "A high sensitivity refractometer based upon a long period grating Mach–Zehnder interferometer," *Rev. Sci. Instrum.*, vol. 73, no. 4, pp. 1702–1705, Apr. 2002.

[5] A. P. Zhang, Z. G. Guan, and S. He, "Low-coherence reflectometry based on long-period grating Mach–Zehnder interferometers," *Appl. Opt.*, vol. 45, no. 22, pp. 5733–5739, 2006.

[6] Z. G. Guan, D. Chen, and S. He, "Coherence multiplexing of distributed sensors based on pairs of fiber Bragg gratings of low reflectivity," *J. Lightw. Technol.*, vol. 25, no. 8, pp. 2143–2148, Aug. 2007.

[7] A. P. Zhang, H. Y. Tam, and X. M. Tao, "Mode recoupling in a novel Bragg grating pair," *Opt. Lett.*, vol. 28, no. 7, pp. 519–521, Apr. 2003.

[8] H. J. Patrick, G. M. Williams, A. D. Kersey, J. R. Pedrazzani, and A. M. Vengsarkar, "Hybrid fiber Bragg grating/long period fiber grating sensor for strain/temperature discrimination," *IEEE Photon. Technol. Lett.*, vol. 8, no. 9, pp. 1223–1225, Sep. 1996.

[9] A. P. Zhang, X. M. Tao, W. H. Chung, B. O. Guan, and H. Y. Tam, "Cladding-mode-assisted recouplings in concatenated long-period and fiber Bragg gratings," *Opt. Lett.*, vol. 27, no. 14, pp. 1214–1216, Jul. 2002.

[10] P. S. Westbrook, T. A. Strasser, and T. Erdogan, "In-line polarimeter using blazed fiber gratings," *IEEE Photon. Technol. Lett.*, vol. 12, no. 10, pp. 1352–1354, Oct. 2000.

[11] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, "Fiber grating sensors," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1442–1461, Aug. 1997.

[12] T. Erdogan and J. E. Sipe, "Tilted fiber phase gratings," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 13, no. 2, pp. 296–313, Feb. 1996.

[13] K. S. Lee and T. Erdogan, "Fiber mode coupling in transmissive and reflective tilted fiber gratings," *Appl. Opt.*, vol. 39, no. 9, pp. 1394–1404, Mar. 20, 2000.

[14] S. C. Kang, S. Y. Kim, S. B. Lee, S. S. Choi, and B. Lee, "Temperature-independent strain sensor system using a tilted fiber Bragg grating demodulator," *IEEE Photon. Technol. Lett.*, vol. 10, no. 10, pp. 1461–1463, Oct. 1998.

[15] G. Laffont and P. Ferdinand, "Tilted short-period fibre-Bragg-grating induced coupling to cladding modes for accurate refractometry," *Meas. Sci. Technol.*, vol. 12, no. 7, pp. 765–770, Jul. 2001.

[16] Y. Y. Shevchenko and J. Albert, "Plasmon resonances in gold-coated tilted fiber Bragg gratings," *Opt. Lett.*, vol. 32, no. 3, pp. 211–213, Feb. 2007.

[17] E. Chehura, S. W. James, and R. P. Tatam, "Temperature and strain discrimination using a single tilted fibre Bragg grating," *Opt. Commun.*, vol. 275, no. 2, pp. 344–347, Jul. 2007.

[18] T. Guo, A. Ivanov, C. Chen, and J. Albert, "Temperature-independent tilted fiber grating vibration sensor based on cladding-core recoupling," *Opt. Lett.*, vol. 33, no. 9, pp. 1004–1006, May 2008.

[19] T. Guo, H. Y. Tam, P. A. Krug, and J. Albert, "Reflective tilted fiber Bragg grating refractometer based on strong cladding to core recoupling," *Opt. Express*, vol. 17, no. 7, pp. 5736–5742, Mar. 2009.

[20] T. Guo, H. Y. Tam, P. A. Krug, and J. Albert, "Tilted fiber grating accelerometer incorporating an abrupt biconical taper for cladding to core recoupling," *Opt. Express*, vol. 17, no. 23, pp. 20 651–20 660, Nov. 2009.

[21] W. S. Mohammed, P. W. E. Smith, and X. Gu, "All-fiber multimode interference bandpass filter," *Opt. Lett.*, vol. 31, no. 17, pp. 2547–2549, Sep. 2006.