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Highly sensitive bend sensor with hybrid long-period and tilted fiber Bragg grating

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ABSTRACT

We demonstrate a new type of fiber optic bend sensor with a hybrid structure made up of a long period grating (LPG) and a tilted fiber Bragg grating (TFBG). The sensing mechanism is based on the spectrum of power transfers between the core and cladding modes from a TFBG located downstream from a LPG. We show that the curvature of a beam can be determined by the reflected power difference between the core mode and the recoupled cladding modes. We further provide design rules for the LPG and TFBG to optimize and linearize the sensor response. In addition, the temperature cross-sensitivities of this configuration are also investigated for two different types of fiber.

1. Introduction

Fiber Bragg gratings (FBG) have been used in many configurations for applications in structural health monitoring. For instance, bend sensors have been proposed using two FBGs bonded to opposite sides of a beam [1]. The difference between the two Bragg wavelengths provides a measure of curvature of the beam. Other FBG bend sensors are also demonstrated based on bandwidth broadening due to a chirp in the period of FBGs with curvature [2,3]. It is also well known that the sensitivity of LPGs to bending is superior to that of FBGs and a number of LPG based bend sensors have been proposed recently. The typical mechanisms utilized for LPG bend sensors are based on a bend-induced wavelength shift, on the depth change of the attenuation band, or on the splitting of some attenuation bands [4–6]. Some researchers have also investigated the embedding of LPG sensors in some materials to discriminate the bending from some other measurands [7]. Some disadvantages of LPG sensors are that they operate in transmission and that they have a relatively wide attenuation band which causes difficulty in reading the exact wavelength of the loss dip. Alternatively, Baek et al proposed another kind of bend sensor based on a TFBG [8]. This sensor is based on the transmission loss change of low order cladding modes in a TFBG. Jin et al also used a TFBG for the same purpose but made it work in reflection by inserting a short section of multimode fiber (MMF) upstream of the TFBG written on a single mode fiber (SMF) [9]. The MMF has a larger core diameter compared to SMF and the mismatched interface between the fibers allows some low order cladding modes to recouple back to core mode of the SMF after going through the MMF. In that configuration, the bending changes the amount of power of the recoupled cladding modes but has no effect on the core mode reflection of (the Bragg reflection) of the TFBG. Therefore, the amount of bending can be measured by monitoring the reflected power differences between the core and the cladding modes. The disadvantage of this scheme is that the mode field mismatch at the two splices between MMF and SMF introduces a large insertion loss in the device. The wide bandwidth of reflected cladding mode spectrum is also a problem in signal processing.

In this paper, we demonstrate a hybrid structure consisting of an LPG and a TFBG for bending/curvature measurements. An LPG located upstream from the TFBG only recouples one of the cladding modes excited by the TFBG. Similarly to the above mentioned previous work on TFBG bend sensors, the reflections of core Bragg mode and of the recoupled cladding mode vary in opposite directions when the bending is applied. The differential power change of these two modes provides an efficient measure of bending with enhanced sensitivity. The advantage of the current configuration is that the combined reflection spectrum is relatively narrowband, thereby facilitating the interrogation of the two dominant reflection peaks, and that the introduction of the LPG does not compromises the mechanical integrity of the fiber (by opposition to splices or tapers). Our results further indicate how to properly design the TFBG and LPG spectra to optimize the combined response for the bending application. Finally, the temperature sensitivities of these devices are also studied for two different types of fiber.

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2. Operation principle

An LPG with a typical period of several hundred micrometers can induce co-directional coupling of the core mode and cladding modes in optical fibres. Contrary to the LPG, the TFBG with a much shorter period of several hundred of nanometres couples the incoming core light power into backward propagated core and cladding modes. But normally, the backward-propagating cladding modes in a TFBG are rapidly attenuated by the fibre jacket and cannot be seen in the reflected spectrum. In our proposed hybrid structure, a weak LPG is located upstream of TFBG to realize the cladding mode recoupling. Fig. 1 illustrates the schematic diagram of cladding mode recoupling in the hybrid LPG-TFBG structure. There are two types of cladding mode recouplings. In type 1, the core-guided light coupled to backward cladding mode by the TFBG is recoupled to the fibre core by the LPG. In type 2, the forward propagating cladding mode excited by the LPG is recoupled into the fibre core by the TFBG. As a result, we can see both the recoupled cladding mode and the Bragg mode in the reflection spectrum.

According to the couple-mode theory, the resonance wavelengths of different order cladding modes in a LPG and TFBG are determined by the phase matching condition. The resonance wavelengths of the *i*-order cladding mode can be expressed as follows for the LPG and TFBG respectively [10]:

$$\lambda_L^{(i)} = \left(N_{\text{eff}}(core) - N_{\text{eff}}^{(i)}(clad)\right) * \Lambda_L \quad (1a)$$

$$\lambda_B^{(i)} = \left(N_{\text{eff}}(core) + N_{\text{eff}}^{(i)}(clad)\right) * \Lambda_B / \cos(\theta) \quad (1b)$$

where Λ_L and Λ_B are the grating periods of LPG and TFBG, θ the tilt angle of the grating planes, $N_{\text{eff}}(core)$ and $N_{\text{eff}}^{(i)}(clad)$ are the effective index of the core mode and *i*-order cladding mode. Combining Eqs. (1a) and (1b), the wavelength of the recoupled cladding mode λ_C can be calculated as

$$\lambda_C = \lambda_B\left(1 - \frac{\Lambda_B / \cos(\theta)}{\Lambda_L + \Lambda_B / \cos(\theta)}\right) \quad (2)$$

where $\lambda_B = 2N_{\text{eff}}(core)\Lambda_B/\cos(\theta)$ is the Bragg wavelength of the TFBG. Considering the broad transmission bandwidth of the LPG, only one cladding mode reflected by TFBG can satisfy the phase matching condition and recoupled into the core by the LPG. The reflected power of recoupled cladding mode and Bragg mode (P_c,P_b) in this hybrid grating device can be written as [11]

$$P_c = 2T_L^{(i)}\left(1 - T_L^{(i)}\right)R_B^{(i)} \quad (3a)$$

$$P_b = \left[T_L^{(i)}\right]^2 R_B^{(0)} \quad (3b)$$

where $T_L^{(i)}$ is the transmission of the LPG at the wavelength at which the *i*-order cladding mode is recoupled. $R_B^{(0)}$ and $R_B^{(i)}$ denote the reflectivity of Bragg mode and recoupled *i*-order cladding mode in the TFBG. The maximum value of P_c is $R_B^{(i)}/2$ when $T_L^{(i)} = 1/2$.

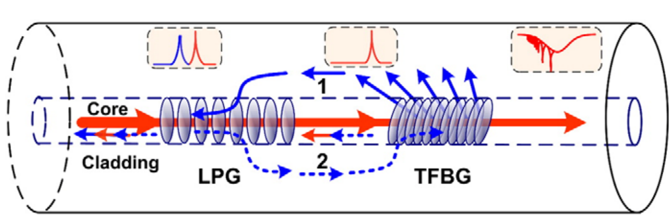

Fig. 1. Schematic diagram of cladding mode recoupling mechanism in the hybrid LPG-TFBG structure.

As the hybrid grating is bent, the transmission of the LPG and the reflectivity of the cladding modes of the TFBG will change. The curvature can be determined by monitoring the reflected powers of the Bragg mode and of the recoupled cladding mode. Furthermore, the differential power ($P_b - P_c$) of these two reflected modes is employed to eliminate the power fluctuations of the light source and enhance the sensitivity to curvature.

3. Experiments

3.1. Fabrication and experimental setup

TFBGs and LPGs were fabricated by using the phase mask technique and the amplitude mask technique respectively. In order to study the effect of the transmission loss of the LPG on the sensor's curvature sensitivity, two LPGs were made in two segments of photosensitive fiber (PS1250/1500 from Fibercore, Ltd) with different transmission losses of 5.2 dB and 18.0 dB, respectively. They have the same length of 20 mm and different periods of 375 μm and 377 μm. Their resonance wavelengths (for coupling to the 9th order cladding mode) are near 1557 nm and 1561 nm respectively. Another LPG with attenuation of 5 dB was fabricated in a standard single mode fiber (Corning SMF-28) with a resonance wavelength of 1557 nm for the investigation of the temperature cross-sensitivity. After the inscription of the LPGs, three TFBGs were inscribed in the same segment of fiber at a distance of 5 mm from each LPG. The TFBGs have the same tilt angle of 2° and Bragg wavelength of 1548.6 nm. Fig. 2 schematically shows the experimental setup for the curvature measurement. A broadband source (BBS: C+L band ASE source from JDSU Corporation) was used to interrogate the grating from LPG side. The reflected light was extracted by an optical circulator and monitored by using an optical spectrum analyzer (OSA). The hybrid grating sensor was inserted into a polymer capillary with the inner diameter of 280 μm and outer diameter of 900 μm. The capillary was bonded to a steel beam with dimensions of 150×12×0.5 mm. The beam was laid on two movable supports located 116 mm apart and bent with a micrometer driver in the middle. One end of the steel beam was clamped on the support. The position of the hybrid gratings with respect to the center of bending could be varied by shifting the fiber in the capillary fixed on the steel beam. In our experiment, the sensor was located in the middle of the beam. To avoid the introduction of axial strain on the sensor, only one end of the fiber was fixed on the beam.

The bent fiber is normally approximated as an arc of circle. So the sensor's curvature C is given by [12]

$$C = \frac{2 \cdot d}{l^2 + d^2} \quad (4)$$

where *d* is the central deflection of the steel beam and *l* is the half distance between the edges of the two supports.

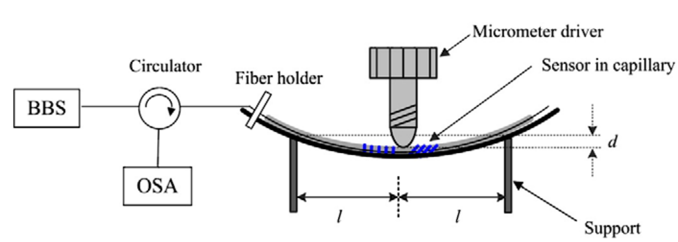

Fig. 2. Schematic diagram of the experimental setup for curvature measurement.

3.2. Curvature sensitivity

The bending experiments are done using the two sensors that were fabricated in photosensitive fiber. Figs. 3a and b show the evolution of the transmission and reflection spectra with curvature for the sensor made with the "weak" LPG (transmission loss of 5.2 dB). The recoupled cladding modes and Bragg mode from the TFBG are located on the short wavelength side of the left attenuation band of the LPG, where the transmission losses of the LPG alone are ~3 dB and 3.9 dB respectively. From Fig. 3a, we can see that the transmission loss of the LPG decreases as the curvature increases and thus impacts the recoupling from the TFBG, as seen in Fig. 3b. As expected, the reflection from the recoupled cladding mode decreases with the increasing curvature, while the reflection of the Bragg mode increases. Fig. 3c summarizes the peak reflection changes for the two kinds of modes against applied curvature. The curvature sensitivity is improved to 2.36 dB/m^{-1} by using the differential power between the Bragg mode peak and the peak recoupled cladding mode to measure the curvature.

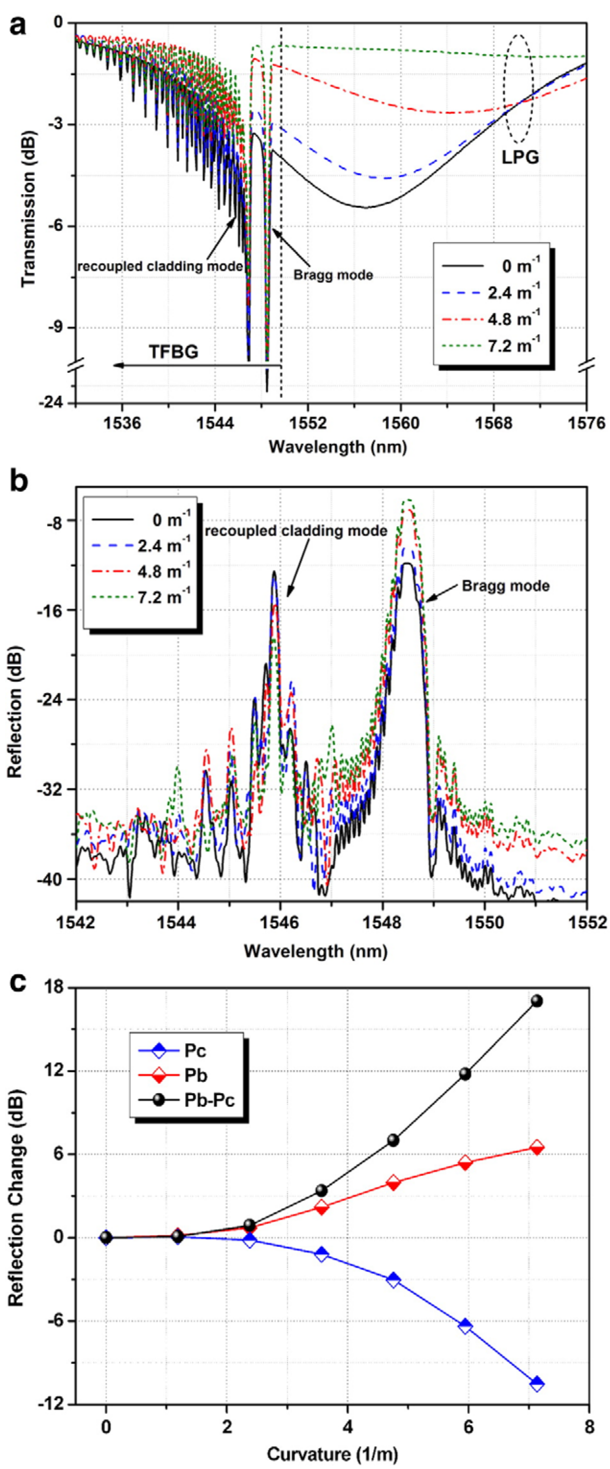

Fig. 3. a) Transmission and b) reflection spectrum evolution of the bent hybrid grating sensor (Transmission loss of the LPG is 5.2 dB) c) reflection changes against the applied curvature.

Fig. 4a illustrates the same measurements carried out with the sensor made with the "strong" LPG (transmission loss of 18 dB). The recoupled cladding mode and Bragg mode from the TFBG are also located on the short wavelength side of the attenuation band of the LPG, but at spectral locations where the LPG has transmission losses of ~4.5 dB and 5.1 dB, respectively. As a result of this small difference, the reflection spectra behave differently with curvature, as shown in Fig. 4b. The reflection of the Bragg mode peak still increases monotonically with the applied curvature. However, the reflection from the recoupled cladding mode increases at the beginning but then decreases. These differences stand out in the summarized results for the peak reflections in Fig. 4c. The reflection from the recoupled cladding modes increases with curvature in the range of 0 m^{-1} to 1.8 m^{-1} and decreases from 1.8 m^{-1} to 7.2 m^{-1}. This different response can be explained using Eq. (3a). The reflection of the cladding mode (P_c) increases up to a maximum value when the transmission loss of the LPG ($T_L^{(i)}$) reaches to the optimum value of 3 dB. It then decreases as $T_L^{(i)}$ moves away from 3 dB and the lowering reflectivity of cladding mode $R_B^{(i)}$ takes over with increasing curvature. We cannot get a monotonously rising curve in the differential power change. The maximum curvature sensitivity is only 1.2 dB/m^{-1} with the curvature up to 7.2 m^{-1}. This results shows that the position of the TFBG within the attenuation band of the LPG will affect the sensitivity of the sensor greatly. To achieve a monotonous response and highest sensitivity, the resonance wavelength of the TFBG (especially the recoupled cladding mode resonance) must be located on the short wavelength side of the LPG transmission curve, at a location where the LPG has an attenuation of around 50%.

3.3. Temperature sensitivity

It is well known that LPGs are also very sensitive to temperature. Hence, we investigated the temperature effect on the hybrid grating bend sensors in two different types of fiber: photosensitive fiber (Fibercore PS1250/1500) and standard single mode fiber (Corning SMF-28). As described in Section **3.1**, the LPGs have similar parameters, transmission losses of 5 dB and resonance wavelength of 1557 nm. The TFBGs are also located on the short wavelength side of the LPGs, at wavelengths where the two LPGs have similar values of transmission loss. Figs. 5a and b show the temperature-induced reflection changes of two hybrid grating bend sensors in different type of fibres. We can see that the device fabricated in a photosensitive fiber has a much larger temperature sensitivity compared with the sensor in a SMF-28 fiber. As shown in Fig. 5a, the reflections of the Bragg mode and of the recoupled cladding mode do not change monotonously. This temperature effect is due to the fact that the spectrum of the LPG shifts strongly to shorter wavelengths while the spectrum of the TFBG shifts very little (10 pm/°C) to longer wavelengths as the temperature increases. So both the Bragg mode and recoupled cladding mode become attenuated as the peak attenuation of the LPG shifts over their spectral location and recover as the LPG minimum continues to shift with further temperature increase. The temperature-induced differential power change is quite large (from −1.5 dB to 2.2 dB) when the temperature increases from 25 °C to 55 °C. On the other hand, the reflection changes of the sensor on SMF-28 are monotonous and near-linear within that temperature

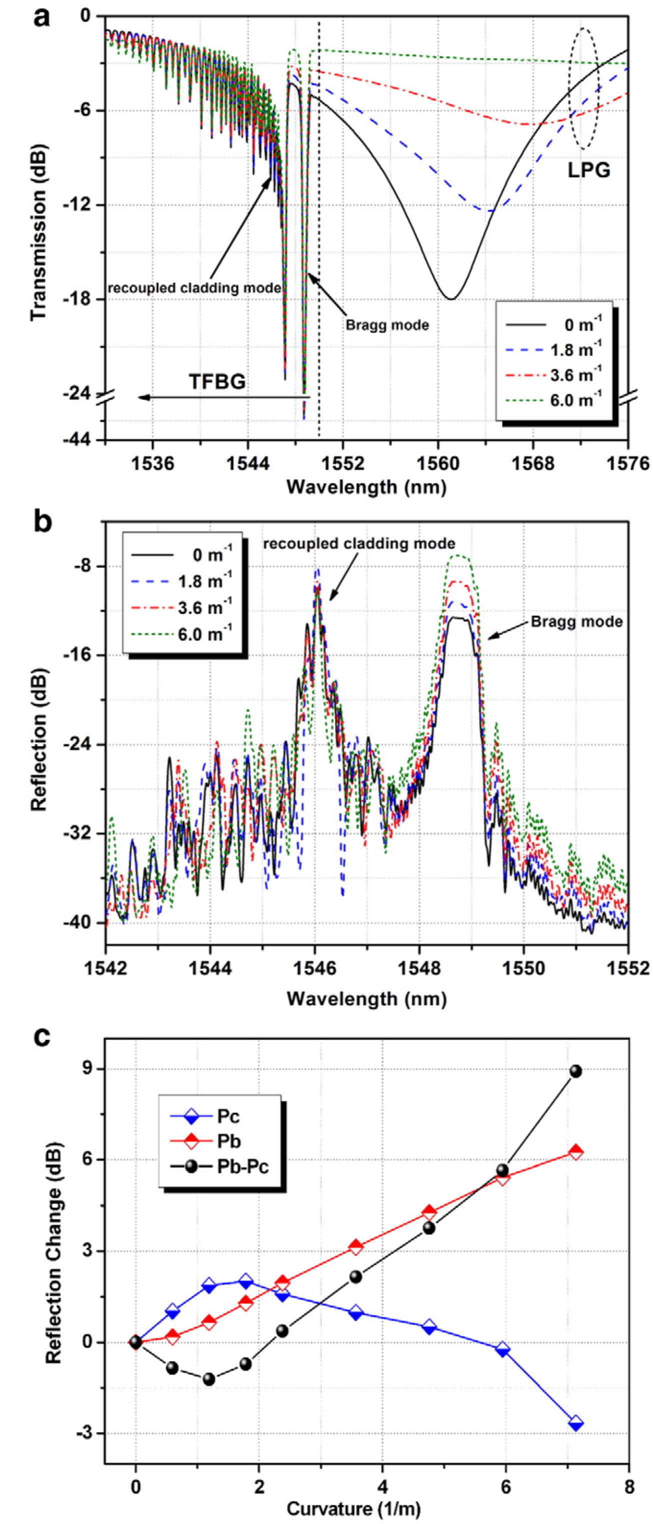

Fig. 4. a) Transmission and b) reflection spectrum evolution of the bent hybrid grating sensor (transmission loss of the LPG is 18.0 dB) c) reflection changes against the applied curvature.

range as shown in Fig. 5b. The maximum temperature-induced differential power change is only 0.33 dB under a temperature change of 30 °C which is about 10 times smaller than that of the sensor in photosensitive fibre. The reason for this difference lies in the different temperature coefficients of the LPG and (to a much lesser extent) the TFBG in photosensitive fibre and standard SMF. The reported temperature sensitivities of LPGs in these two types of fibre are

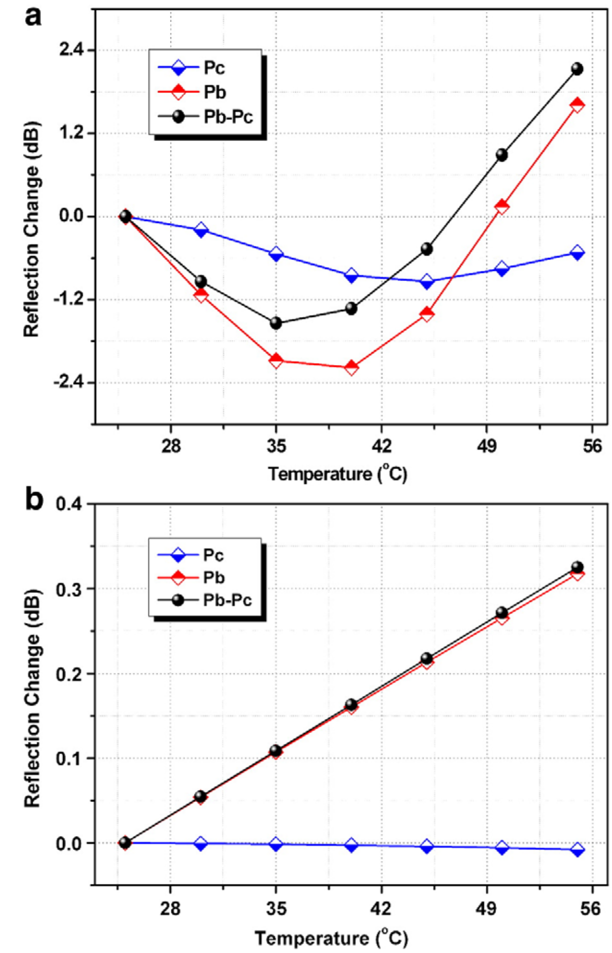

Fig. 5. Temperature-induced reflection changes of hybrid grating bend sensors in a) photosensitive fiber (Fibercore PS1250/1500) b) standard single mode fiber (Corning SMF-28).

−0.34 nm/°C and 0.03 nm/°C [13]. But the TFBGs have similar temperature sensitivities of 0.01 nm/°C. The large difference between the temperature sensitivity of the TFBG and that of the LPG in photosensitive fibre has a strong impact on the measured reflections, especially when the temperature-induced wavelength shift of the LPG causes its attenuation maximum to move across the spectral region of the TFBG main resonances. Meanwhile, in the SMF-28 fiber, the LPG and TFBG have similar temperature sensitivity (for this mode of the LPG) and the sensor shows a reduced temperature sensitivity. In order to eliminate the temperature cross-sensitivity completely we could choose photonic crystal fibre (PCF) to fabricate a temperature-insensitive LPG [5,14]. However, TFBGs have not been demonstrated in PCF fibres yet. The closest solution may be having a standard FBG written in a PCF with a non-guiding germanium-doped inclusion that provides coupling to several "inner" cladding modes [15]. A hybrid LPG-FBG configuration in this kind of PCF could work well here.

4. Conclusions

In conclusion, hybrid LPG-TFBG bend sensors have been implemented and packaged by inserting the fibre into a polymer capillary that was bonded to a steel beam. One of the backward propagating cladding modes excited by the TFBG is recoupled into the core with the assistance of the upstream LPG. The differential reflected power changes of the Bragg mode and recoupled cladding mode are employed to determine the curvature of the sensor. A relatively high curvature sensitivity is achieved up to 2.36 dB/m^{-1} in the range of 0 m^{-1} to 7.2 m^{-1}. The experimental results also show that the position of TFBG in the attenuation band of the LPG is the key factor to the sensor's performance. The wavelength of the recoupled cladding mode of the TFBG should be designed to be located on the short wavelength side of the LPG resonance, at a wavelength where the LPG has approximately 3 dB transmission loss. In addition, the temperature cross-sensitivity of these sensors made in two types of fibre were investigated and showed that using standard SMF is better than using photosensitive fiber but that PCF would be the ideal platform to fabricate the LPG and thus reduce the temperature cross-sensitivity.

Most importantly, since the dual grating structure operates on low order modes that have little power reaching the cladding surface and thus that are relatively unaffected by the material located outside the fiber cladding, this kind of sensor can be packaged inside a relatively solid protective material (unlike most LPG sensors) without compromising its performance as a bend sensor for structural health monitoring applications. Since the exact wavelength measurement of the signals are not required but only the reflected powers in limited spectral bands are measured, a high resolution spectral measurement equipment (like an OSA) is not necessary. A real interrogation system for our sensor would work with lower cost photodetectors associated with bandpass filters [16]. Finally, this hybrid grating sensor suffers from the same predicament as other solutions based on LPGs and TFBGs: they occupy a large chunk of optical spectrum and are thus difficult to multiplex serially. In real applications a parallel multiplexing approach would be needed, unless a variant of the system proposed in [17], where an optical time-domain reflectometer (OTDR) was used to interrogate a TFBG refractometer, could be implemented. But that will be the object of future work.

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References

[1] M.G. Xu, J.-L. Archambault, L. Reekie, J.P. Dakin, Int. J. of Optoelect. 9 (1994) 281.
[2] X.Y. Dong, H.Y. Meng, G.Y. Kai, Z.G. Liu, X.Y. Dong, Smart Mater. Struct. 10 (2002) 1111.
[3] Y.-S. Yu, Z.-Y. Zhao, Z.-C. Zhuo, W. Zheng, Y. Quian, Y.-S. Zhang, Microwave Opt. Technol. Lett. 43 (2004) 414.
[4] L.-Y. Shao, J. Zhao, X.Y. Dong, H.Y. Tam, C. Lu, S. He, Appl. Opt. 47 (2008) 1549.
[5] T. Allsop, K. Kalli, K. Zhou, Y. Lai, G. Smith, M. Dubov, D.J. Webb, I. Bennion, Opt. Comm. 281 (20) (2008) 5092.
[6] Y. Liu, L. Zhang, J.A.R. Williams, I. Bennion, IEEE Photon. Technol. Lett. 12 (2000) 531.
[7] C.C. Ye, S.W. James, R.P. Tatam, Opt. Lett. 25 (2000) 1007.
[8] S. Baek, Y. Jeong, B. Lee, Appl. Opt. 41 (2002) 631.
[9] Y.X. Jin, C.C. Chan, X.Y. Dong, Y.F. Zhang, Opt. Comm. 282 (2009) 3905.
[10] T. Erdogan, J. Opt. Soc. Am. A 14 (1997) 1760.
[11] A.P. Zhang, X.-M. Tao, W.-H. Chung, B.-O. Guan, H.-Y. Tam, Opt. Lett. 27 (2002) 1214.
[12] H.J. Patrick, C.C. Chang, S.T. Vohra, Electron. Lett. 34 (1998) 1773.
[13] L.-Y. Shao, A.P. Zhang, J.H. Yan, S. He, Proc. of SPIE 6019 (2005) 60191S.1-60191S.8.
[14] C.-L. Zhao, M.S. Demokan, W. Jin, L.M. Xiao, Opt. Comm. 276 (2007) 242.
[15] C. Chen, A. Laronche, G. Bouwmans, L. Bigot, Y. Quiquempois, J. Albert, Opt. Expr. 16 (2008) 9645.
[16] T. Guo, H.-Y. Tam, P.A. Krug, J. Albert, Opt. Expr. 17 (2009) 5736.
[17] C. Caucheteur, M. Wuilpart, C. Chen, P. Mégret, J. Albert, Opt. Expr. 16 (2008) 17882.