Temperature-Independent Curvature Sensor Using FBG Cladding Modes Based on a Core Misaligned Splice

C. Gouveia, P. A. S. Jorge, J. M. Baptista, and O. Frazão

***Abstract*—A fiber-optic curvature sensor based on a core offset single-mode fiber (SMF) combined with a fiber Bragg grating (FBG) is presented. The FBG cladding modes are efficiently excited by the large core misalignment. The curvature of the fiber can be obtained by the ratio between the recoupled cladding mode power and the reflected core mode power. These measurements are independent from temperature variation.**

***Index Terms*—Cladding modes, curvature sensor, fiber Bragg grating (FBG).**

I. INTRODUCTION

FIBER Bragg grating (FBG) sensors have generated great interest in recent years because of their many industrial and structural health monitoring applications. Based on the diffraction mechanism, the FBG can be used as fiber mirror or filter for fiber optic sensing and communications. FBG sensors have been widely used for strain and temperature measurement [1]. A tilted FBG (TFBG) was recently studied for temperature and strain measurement by Zhang *et al.* [2]. The transmitted spectrum of a TFBG is composed of several discrete modes that arise from two different mechanisms. The modes at the longest wavelength come from the self coupling of the core mode while the other modes are due to the backward coupling with the cladding modes. The temperature and strain were measured from the wavelength shift of the core and cladding modes. The different sensibility to temperature and strain of the cladding and core modes enabled simultaneous measurement of both parameters.

Several configurations have been proposed for measurement of curvature using FBGs. An etched chirped FBG was used by Yu *et al.* [3]. The bent radius was measured by the reflected power of the grating. This technique is simple but needs a reference power, and is also known that the etching induces fragility in the structure. Other works were reported using a TFBG, where the high effective index cladding modes are sensitive to curvature and their amplitudes decrease as a function of bent radius.

Caucheteur *et al.* [4] presented a TFBG for simultaneous measurement of curvature and temperature, measured from Bragg resonance wavelength shift. This configuration uses spectral interrogation and typically the cladding modes of TFBG require transmission readout. Coupling light from the core mode to the cladding mode in the FBG forward direction enables the cladding mode reflection readout. Recently some authors explored this possibility. Using a short multimode fiber section, Jin *et al.* [5] showed a reflection operation of a TFBG configuration for curvature sensing. Based on the same principle and on the curvature sensitivity of the TFBG a core offset section was explored by Guo *et al.* [6] and Huang *et al.* [7] for vibration sensing. Recently an long period grating (LPG)/TFBG hybrid sensing head was also studied by Shao *et al.* [8]. In this case, due to LPG sensitivity to bending, both reflected peaks are affected by the measurand, and the difference of the power was used to obtain the curvature. These configurations use TFBGs, whose cladding modes are spectrally not so well resolved and almost all of them use spectral interrogation.

In this letter we present a high reflectivity FBG combined with a core-offset-splice in a single mode optical fiber. This technique enables the possibility to readout simultaneously in reflection the cladding mode and the core mode. For curvature measurements the core mode is not sensitive, while the optical power of the cladding mode is affected. The analysis of both modes allows a self-referenced optical power measurement of curvature. Since the measurement is peak wavelength independent, a wavelength division multiplexer (WDM) and two photodetectors were used for signal detection. The implemented curvature sensor is temperature-independent.

II. EXPERIMENT

The sensitive system is formed by a high-reflectivity FBG (Reflectivity $\approx 98\%$, 6 mm in length). The grating has been written in a hydrogen loaded SMF-28 fiber by UV (Ultraviolet) beam scanning phase mask technique. The fiber segment containing the grating was cleaved approximately 5 mm distance from the FBG. Another long piece of fiber previously connected to an optical circulator was cleaved. Both cleaved fibers were placed into a splice machine. To monitor the spectra behavior and optimize the cladding modes, the splice was real time monitored in reflection using an Advantest Q8384 (OSA) Optical Spectrum Analyzer. In order to obtain a dominant cladding mode, a lateral core-offset was induced. In the distal end of the sensing head, an index matching gel was used to avoid undesirable reflections. There are two different types of mode recoupling mechanisms. In the first one, the guided light coupled from core to the cladding modes by the misaligned section is

---

Manuscript received January 05, 2011; revised March 17, 2011; accepted March 26, 2011. Date of publication April 05, 2011; date of current version May 25, 2011. This work was supported by the National Portuguese Science Foundation (FCT) in the framework of the Associated Laboratory funding program.

C. Gouveia and J. M. Baptista are with INESC Porto, 4169-007 Porto, Portugal, and also with the Centro de Competências de Ciências Exactas e de Engenharia, Universidade da Madeira, 9300-390 Funchal, Portugal.

P. A. S. Jorge and O. Frazão are with INESC Porto, 4169-007 Porto, Portugal.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2011.2138125

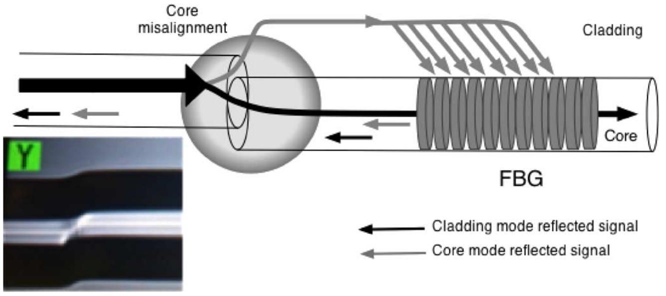

Fig. 1. Sensing head formed by a high reflectivity FBG and a misaligned core splice, where the dominant recoupling mechanism is described. In the inset, the splice with a lateral core offset of $\sim 9\ \mu$m is shown.

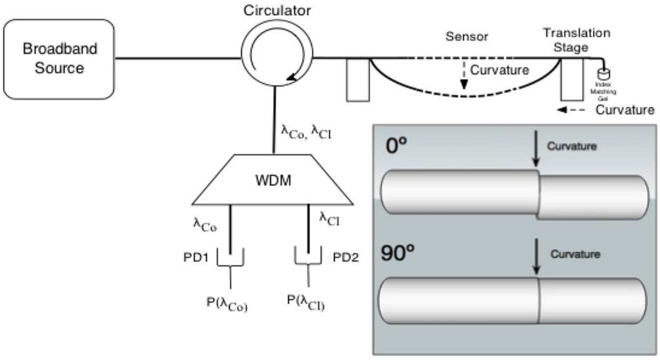

Fig. 3. Experimental setup for curvature measurement.

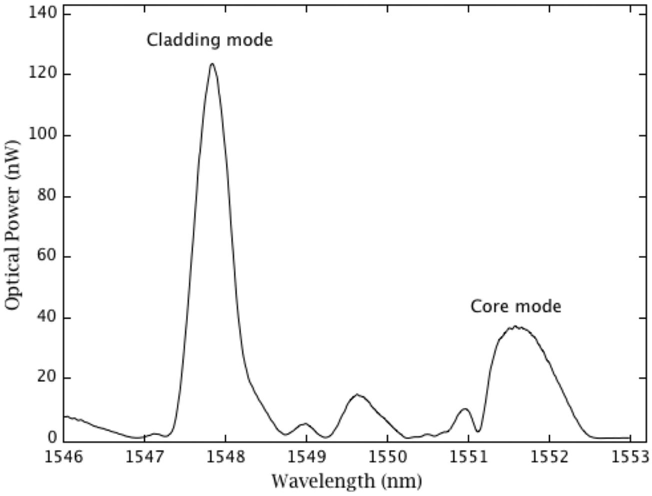

Fig. 2. Reflection spectrum of the sensing head.

recoupled to the backward guided mode by the FBG. In the second mechanism, the guided light is coupled to the backward cladding modes by the FBG and is recoupled to the guided mode by the lateral core offset section [9]. In this sensing head, the first mechanism represents the major contribution to the overall reflected signal, whilst the second one has a residual contribution, due to the multiple reflections that occur in the diffractive structure. Fig. 1 illustrates the dominant recoupling mechanism. The inset on Fig. 1 shows the misaligned splice, where the lateral core offset was approximately 9 μm.

Fig. 2 illustrates the reflection spectrum of the sensing head. The two main peaks are related to the dominant cladding mode and to the core mode, respectively, being separated by 3.75 nm. The cladding mode corresponds to the high effective index cladding mode, in resonance with the grating period, centered in 1547.84 nm and with a full width at half maximum of 0.50 nm. The core mode peak, which satisfies the Bragg condition, is centered in 1551.58 nm, and presents a full width at half maximum of 0.85 nm. The difference of power of the dominant cladding mode to the core mode is approximately of 5 dB.

For characterization of the sensing head, the experimental setup showed in Fig. 3 was used. An erbium-doped fiber source illuminated the sensor through an optical circulator which enabled the Fiber Bragg reflected signal to be readout in reflection. Using a WDM (wavelength demultiplex) to separate the core reflection from the cladding reflection enabled the corresponding optical powers to be readout by two simple photodetectors.

A. Curvature Measurements

The amount of guided light which is recoupled from the backward cladding mode is highly dependent on the fiber curvature, enabling the possibility to measure the curvature as a function of the reflected optical power of the cladding mode. In order to avoid axial strain, the bend sensitivity measurements were performed by loosely fixing the two ends of the fiber containing the sensing probe on two blocks, being one mounted on a translation stage in order to curve the fiber. The sensing head was placed in the middle of the two blocks (as shown in Fig. 3). The resulting curvature $1/R$ is simply given by the following expression [4], $1/R = 2h/[h^2 + (d/2)^2]$ where d is the distance between the two blocks and h is the bending displacement. The curvature is applied in a range of 0 to 1.75 m^{-1}. When curvature was applied, the reflected optical power of the dominant mode decreased, at the same time the reflected optical power by the core mode remained constant. The measurements were obtained by computing the optical power difference between the cladding mode and the core mode. The dependence of the curvature with the fiber position was also studied. The inset of Fig. 3 clarifies schematically the fiber position for 0° and 90°, respectively. The fiber was rotated from 0° to 90°. For 0°, maximum sensibility was observed. For 90°, no curvature sensitivity was observed. Fig. 4 shows the effect of bending on the reflected spectrum for three different curvature values, no wavelength shift was observed. The normalized optical power as function of the curvature is shown in Fig. 5, where a nonlinear behavior was observed (fitted by second order polynomial). In a first order approximation, a variation in the cladding mode optical power of ~5 dB was observed when curvature was changed between 0 m^{-1} and 1.75 m^{-1}.

B. Temperature Measurements

The thermal effects were also studied. For temperature measurement the sensing probe was fixed in a chamber filled with water. The sensing head was submitted to variation of the temperature from 25° to 70°. The observed changes in the reflected power of the cladding and core modes were minimal. Fig. 6 illustrates the variation of the power difference as function of

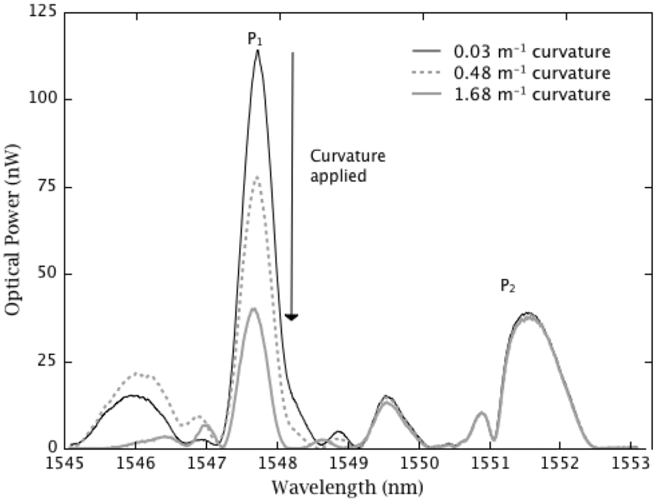

Fig. 4. Reflection spectrum of the sensing head for three different curvatures.

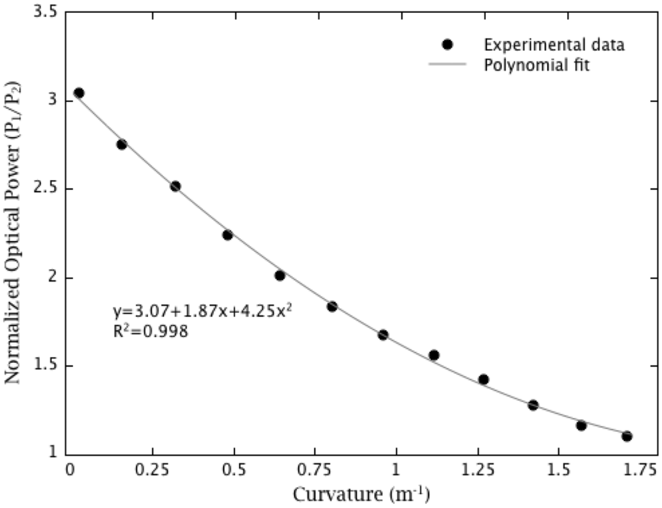

Fig. 5. Curvature characterization of the sensing head.

the temperature. The temperature changes did not affect the reflected optical power, which means that through this technique, it is possible to obtain curvature measurements independent of the temperature. The variation of optical power due to temperature change is less than $1\%/^\circ$C, which corresponds to a variation of curvature of $0.15\ \mathrm{m}^{-1}$ for $50\ ^\circ$C of temperature variation.

III. CONCLUSION

In this work a compact and simple curvature sensor system is described. The sensor is based on a simple fiber Bragg grating spliced to a core offset fiber. This configuration permits to read the cladding mode of the Bragg grating reflected spectrum. For curvature, the optical power of the cladding mode is sensitive to fiber bending, while the core mode is not sensitive. Dividing both reflected optical powers, it is possible to obtain a self-referenced measurement of curvature. This configuration is temperature insensitive for small variations of temperature.

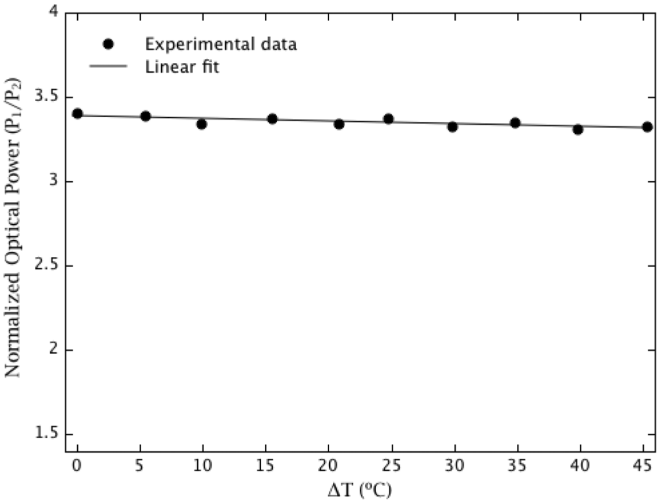

Fig. 6. Temperature characterization of the sensing head.

The sensing head presents important advantages when compared with tilted FBG based configurations. A standard FBG was used, which is easier to fabricate. Moreover, by varying the core offset magnitude of the misaligned splice, it is possible to change, in a simple manner, the excited cladding modes and the amount of light that is going to the cladding. This process results in well-resolved spectral peaks simplifying the interrogation mechanism and enhancing the measurement accuracy. In addition, preliminary results showed that sensitivity and measurement range can also be optimized.

REFERENCES

[1] A. D. Kersey, 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. 1442–1463, Aug. 1997.

[2] W. Zhang, B. Yang, Z. Tong, Y. Miao, B. Liu, and X. Dong, "Temperature and strain sensing characteristics of the tilted fiber Bragg grating," *Optoelectron. Lett.*, vol. 6, p. 355, 2010.

[3] Y. S. Yu, Z. Y. Zhao, Z. C. Zhuo, W. Zheng, Y. Qian, and Y. S. Zhang, "Bend sensor using an embedded etched fiber Bragg grating," *Microw. Opt. Technol. Lett.*, vol. 43, no. 5, pp. 414–417, 2004.

[4] C. Caucheteur, K. Chah, F. Lhomme, M. Blondeland, and P. Megret, "Simultaneous bend and temperature sensor using tilted FBG," in *Proc. 17th Int. Conf. Optical Fibre Sensors*, 2005, vol. 5855, p. 707.

[5] Y. X. Jin, C. C. Chan, X. Y. Dong, and Y. F. Zhang, "Temperature-independent bending sensor with tilted fiber Bragg grating interacting with multimode fiber," *Opt. Commun.*, vol. 282, no. 19, pp. 3905–3907, 2009.

[6] 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, 2008.

[7] Y. Huang, T. Guo, C. Lu, and H. Y. Tam, "VCSEL-based tilted fiber grating vibration sensing system," *IEEE Photon. Technol. Lett.*, vol. 22, no. 16, pp. 1235–1237, Aug. 15, 2010.

[8] L. Shao, A. Laronche, M. Smietana, P. Mikulic, W. J. Bock, and J. Albert, "Highly sensitive bend sensor with hybrid long-period and tilted fiber Bragg grating," *Opt. Commun.*, vol. 283, p. 2690, 2010.

[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, 2002.