Dual-optical-response photonic crystal fibre interferometer for multi-parameter sensing

Joel Villatoro[1,2*], Vladimir P. Minkovich[3], Joseba Zubia[1]
[1]Dept. of Communications Engineering, Escuela Técnica Superior de Ingeniería (ETSI) de Bilbao, University of the Basque Country (UPV/EHU), Alda. Urquijo s/n, E-48013 Bilbao, Spain.
[2]IKERBASQUE –Basque Foundation for Science, E-48011 Bilbao, Spain;
[3]Centro de Investigaciones en Optica A. C., 37150, Leon, GTO. Mexico.

ABSTRACT

An all-fiber mode interferometer consisting of a short segment of photonic crystal fiber (PCF) fusion spliced to standard single mode optical fiber and pressed on localized regions is proposed for multi-parameter sensing. In our configuration, the physical parameter being sensed changes the fringe contrast (or visibility) of the interference pattern and also causes a shift to the same. To achieve this dual effect the device is pressed on localized regions over a few millimeters. In this manner we introduce losses and effective refractive index changes to the interference modes, hence visibility and shift to the interference pattern. Our interferometer is suitable for monitoring diverse physical parameters such as weight, force, pressure, load, etc. The advantage is that no temperature or power fluctuations compensation is required.

Keywords: Photonic crystal fiber sensors, mode interferometers, optical fiber sensors, pressure sensors.

1. INTRODUCTION

Photonic crystal fibers (PCFs) are fibers with unique optical properties which are conferred by a pattern of microscopic voids present all over their entire length [1]. Some key features that define the optical properties of a PCF include: *i*) the composition of the material the PCF is made of, *ii*) the design of the array of voids that form the waveguide, and *iii*) the use of post-processing techniques, among others. All these features can be exploited for the development of new sensors or sensors with enhanced properties. That is why PCF have attracted considerable attention by the sensor community [2-4]. A number of PCF sensors have been proposed so far, however, those based on Bragg and long-period gratings [5-7] or mode interferometers [8-12] are more promising for practical applications due their compactness, robustness, high stability over time, operation in a broad wavelength range or at extreme temperatures. Typically, in grating- and interferometric-based PCF sensors the parameter being sensed modulates only one attribute of the guided light as e.g. phase or intensity. As a result, the wavelength position of the grating or the interference pattern shifts. An associated drawback of grating and interferometric PCF sensors is the fact that temperature also causes a detectable shift to the wavelength position of the grating or the interference pattern. Therefore, in a practical situation, PCF sensors will require a temperature compensation mechanism which can be accomplished by means of thermal isolation or with an additional reference or temperature sensor. The disadvantage of these solutions is that the complexity, and hence the cost of the sensor, increases. It is therefore important to devise new ideas or new solutions that overcome the limitations of PCF sensors without sacrificing their main advantages.

Here, we introduce a photonic crystal fiber interferometer in which the physical parameter being monitored changes the fringe contrast (or visibility) of the interference pattern, and also causes a shift to the same. To achieve the dual effect in a simple manner a PCF interferometer built via microhole collapsing [8,13] was subjected to periodic localized pressure over a few millimeters. The localized pressure on the PCF introduces phase changes and losses to the interfering modes, and hence it causes the interference pattern to shift and to experience changes in the visibility. The dual effect to the interference pattern was exploited to sense weight; however, the device can be used to sense diverse physical parameters such as pressure, load, force, etc. In the configuration here propose, power fluctuations or attenuation in the optical fiber do not affect the visibility measurements as they are self-referred intensity measurements.

*Corresponding author: agustinjoel.villatoro@ehu.es

23rd International Conference on Optical Fibre Sensors, edited by José Miguel López-Higuera, Julian Jones, Manuel López-Amo, José Luis Santos, Proc. of SPIE Vol. 9157, 91577J
 · doi: 10.1117/12.2058763

2. RESULTS

The photonic crystal fiber interferometer is sketched in Figure 1 along with some details of its interrogation. The interferometer consists of few centimeters of polymer-coated home-made PCF fusion spliced at the distal end of a standard optical fiber (SMF-28). The fabrication of the interferometer is simple as it is carried out by means of the well-established fusion splicing technique. This ensures high reproducibility, robust devices, and low fabrication cost. During the splicing process the voids of the PCF are intentionally collapsed over a microscopic region. To achieve high quality interferometers both splices need to be identical. The two collapsed zones in the PCF combined with the PCF geometry allow the excitation and recombination of core modes in the PCF. This makes the device reflection spectrum exhibit a regular interference pattern, see Fig. 1. The SMF at the tip was cleaved and coated with a highly reflecting mirror.

As the outer diameters of the SMF and the PCF is the same (125 μm); and the fibers are permanently aligned, thus there is axial symmetry in our device. On the other hand, the collapsed zones in the PCF introduce a mode field mismatch, and thereby, cause a broadening of the beam when it propagates from the SMF to the PCF, or vice versa. The broadening of the beam combined with the axial symmetry and the modal properties of the PCF are what allow the excitation (and recombination) of modes that have similar azimuthal symmetry. The modes excited in the PCF have different effective indices (or different propagation constants), thus they travel at different speeds. As a result, the modes accumulate a phase difference as they propagate along the length of PCF. Due to the excitation and recombination of modes in the device, the reflection spectrum exhibits a series of maxima and minima as those shown in Fig. 1.

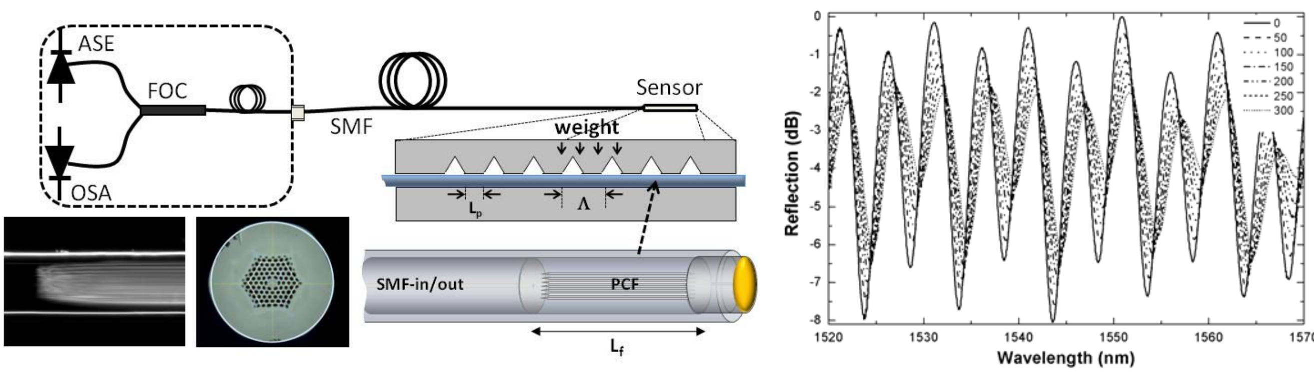

Figure 1. (Left) Drawings of the PCF interferometer, the schematic representation of its interrogation set up and illustration of the mechanical piece to apply periodic localized pressure on the device. The micrographs show details of the PCF-SMF junction and the PCF cross section. ASE stands amplified spontaneous emission, FOC fiber optic circulator, SMF single mode fiber, and OSA optical spectrum analyzer. L_f is the interferometer (or PCF) length. (Right) Normalized reflection spectra for weight in the 0-500 g range observed in an interferometer built with 5.1 cm of PCF. The mechanical piece that pressed the PCF had L_p = 1mm and Λ = 7.5 mm.

When two modes participate in the interference the reflected intensity (I_R) can be expressed as:

$$I_R = I_1 + I_2 + 2(I_1 \cdot I_2)^{1/2} \mathrm{Cos}\,(\Delta\phi). \qquad (1)$$

In Equation (1), I_1 and I_2 are, respectively, the intensity of the fundamental core mode and the higher-order core mode, and $\Delta\phi = 2\pi \Delta n L_f/\lambda$ is the total phase shift. $\Delta n = n_f - n_h$, n_f and n_h being, respectively, the effective refractive index of the fundamental core mode and the higher-order core mode. L_f is the physical length of the PCF, or length of the interferometer, and λ the wavelength of the optical source. The visibility (V) of our two-mode interferometer can be defined as [13]:

$$V = -10 \cdot \log_{10}[1\text{-}2 \cdot (k)^{1/2}/(1+k)], \qquad (2)$$

where $k = I_2/I_1$.

A PCF mode interferometer can be used for sensing applications, see for example Refs. [8-12]. In these cases it is a common that the parameter being sensed modulates Δϕ which results in a shift of the interference pattern (a relative measurement). Another possibility is when the parameter being sensed modulates the intensity of the interfering modes [14]. In this case the visibility of an interferometer (an absolute measurement) will change. The advantage of monitoring V is that it is easy to monitor and a low-resolution OSA can be used. In addition, V is immune to temperature as well as to power fluctuations as demonstrated by several groups [14-16].

Let us suppose now that the PCF interferometer is subjected to localized pressure with a serrated mechanical piece as that sketched in Fig. 1. Unlike fiber-optic sensors based on periodic microbending, in our configuration the optical axis of the PCF is not bended. The localized pressure on the PCF causes two effects on the interference pattern. On the one hand, it will make the modes that participate in the interference lose power. The higher-order core mode will experience higher loss than the fundamental core mode. Therefore k will decrease, and consequently, V will decrease. On the other hand, the effective index of the interference modes will also change; hence $\Delta\phi$ will change and will give rise to a shift of the interference pattern. Note that that the dual effect on the interferometer is achieved in a simple manner, only a serrated mechanical piece is required.

The plot on the left-hand side of Fig. 1 shows the reflection spectra of a 5.1 cm-long interferometer when calibrated weights were placed on it. The spectra were obtained by launching light from an ASE source to the interferometer and the reflected light was analysed with an optical spectrum analyser. The two effects on the interference pattern are evident. The corresponding changes of V and shift of the of the interference pattern as a function of weight are shown in Fig. 2. The dual behaviour can be exploited to accurately measure many other physical parameters such as pressure, load, force, liquid level, etc., as they can also cause changes of V and shift to the interference pattern.

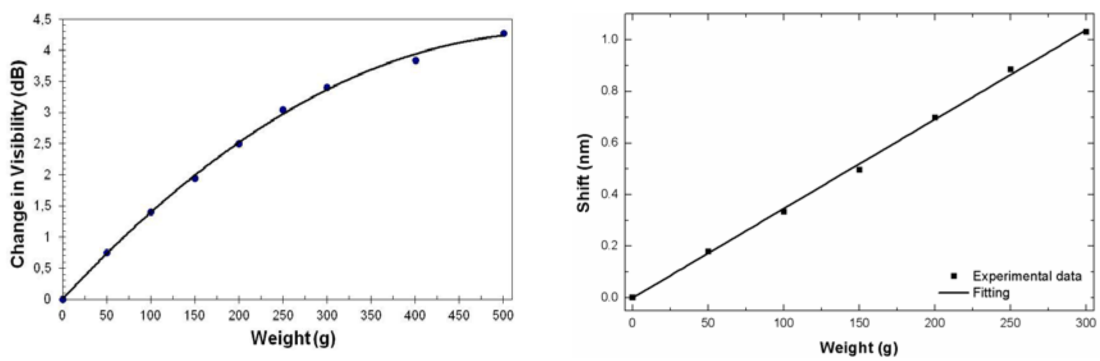

Figure 2. (Left) Visibility changes versus weight. (Right) Shift of the interference pattern versus weight. In all cases the length of PCF was 5.1 cm and the mechanical piece that pressed the PCF interferometer had L_p = 1 mm and Λ = 7.5mm.

The effect of L_p on the sensor sensitivity was studied; our results are summarised in Figure 3. Note that the changes in visibility are more prominent for the shorter L_p. This is so because as the area becomes smaller the pressure becomes higher, and thus, the interfering modes experience higher losses or index changes. The results shown in Fig. 3 suggest that the sensitivity of our sensor can be tailored by simply changing the value of L_p of the mechanical piece.

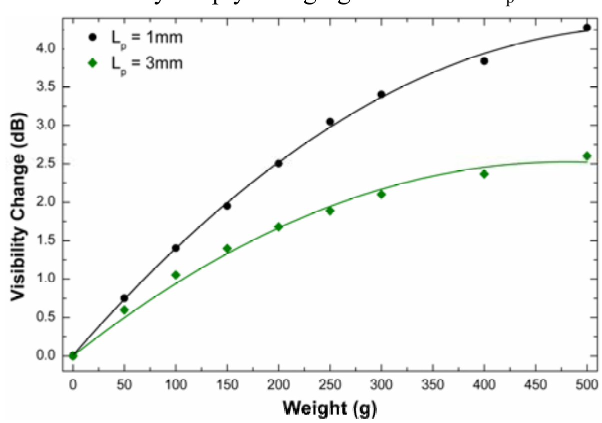

Figure 3. Visibility changes as a function of weight for two values of Lp. In both cases Λ = 7.5 mm and L_f = 5.1 cm.

3. CONCLUSIONS

A mode interferometer comprising a few centimeters of PCF fusion spliced at the distal end of a standard single mode fiber combined with a mechanism to press it in on localized regions is proposed for multi-parameter sensing. The interferometer is pressed on localized regions with a serrated mechanical piece. This simple configuration has two effects on the interference pattern; it causes visibility changes and shift due to changes of intensity and index of the interfering modes. The measurement of weight was demonstrated but the interferometer is suitable for sensing many other physical parameters such as force, load, pressure, etc. The main advantage of the configuration here proposed include: compactness, simplicity, low cost, immunity to temperature and power fluctuations. In addition, it seems possible to adjust the sensor sensitivity by simply adjusting the length of the section that makes contact with the PCF. We believe that the sensing configuration proposed here is new; hence, it can be attractive to fiber optic sensor community.

ACKNOWLEDGEMENTS

This work has been sponsored by the institutions Ministerio de Economía y Competitividad under project TEC2012-37983-C03-01, the Gobierno Vasco/Eusko Jaurlaritza under projects AIRHEM-II, S-PE12CA001, GIC07/156-IT-343-07, and by the University of the Basque Country (UPV/EHU) through program UFI11/16.

REFERENCES

[1] P. St. J. Russell, "Photonic-crystal fibers", J. Lightwave Technol. 24, 4729–4749 (2006).
[2] O. Frazao, J. L. Santos, F. M. Araujo, and L. A. Ferreira, "Optical sensing with photonic crystal fibers," Laser Photon. Rev. 2, 449–459 (2008).
[3] Pinto, A.M.R. , Lopez-Amo, M. "Photonic crystal fibers for sensing applications," J. Sens. 2012, I.D. 598178 (2012).
[4] Cubillas, A.M., Unterkofler, S., Euser, T.G., Etzold, B.J.M., Jones, A.C., Sadler, P.J., Wasserscheid, P., Russell, P.S.J. "Photonic crystal fibres for chemical sensing and photochemistry" Chem. Soc. Rev. 42, 8629-8648 (2013).
[5] C. Martelli, J. Canning, N. Groothoff, and K. Lyytikainen, "Strain and temperature characterization of photonic crystal fiber Bragg gratings," Opt. Lett. 30, 1785–1787 (2005).
[6] V. M. Churikov, V. I. Kopp, and A. Z. Genack, "Chiral diffraction gratings in twisted microstructured fibers," Opt. Lett. 35, 342–344 (2010).
[7] L. Rindorf and O. Bang, "Sensitivity of photonic crystal fiber grating sensors: biosensing, refractive index, strain, and temperature sensing," J. Opt. Soc. Am. B 25, 310–324 (2008).
[8] Villatoro, J.; Minkovich, V.P.; Pruneri, V.; Badenes, G. "Simple all-microstructured-optical-fiber interferometer built via fusion splicing." Opt. Express 15, 1491–1496 (2007).
[9] Huaping G., Haifeng S., Xiaorui L., Jianfeng W., Xinyong D., "An optical fiber curvature sensor based on photonic crystal fiber modal interferometer," Sens. Actuators A 195, 139-141 (2013).
[10] Geng, Y., Li, X., Tan, X., Deng, Y., Hong, X. "Compact and ultrasensitive temperature sensor with a fully liquid-filled photonic crystal fiber Mach-Zehnder interferometer" IEEE Sens. J. 14, 167-170 (2014).
[11] Mohd Noor M. Y. *et al.* "Temperature-insensitive photonic crystal fiber interferometer for relative humidity sensing without hygroscopic coating," Meas. Sci. Technol. 24 105205 (2013).
[12] Favero F. C., Spittel R., Just F., Kobelke J., Rothhardt M., Bartelt H., "A miniature temperature high germanium doped PCF interferometer sensor," Opt. Express 21, 30266-30274 (2013).
[13] Cardenas-Sevilla G.A., Fávero F. C. Villatoro J. "High-visibility photonic crystal fiber interferometer as multifunctional sensor," Sensors, 13, 2349-2358 (2013).
[14] Dong B., Jianzhong Hao E., "Temperature-insensitive and intensity-modulated embedded photonic-crystal-fiber modal-interferometer-based microdisplacement sensor," J. Opt. Soc. Am. B 28, 2332-2336 (2011).
[15] Ran Z. L., Rao Y. J., Liu W. J., Liao X., Chiang K. S., "Laser-micromachined Fabry-Perot optical fiber tip sensor for high-resolution temperature-independent measurement of refractive index," Opt. Express 16, 2252-2263 (2008).
[16] Gouveia C., Jorge P. A. S., Baptista J. M., Frazão O., "Fabry–Pérot cavity based on a high-birefringent fiber Bragg grating for refractive index and temperature measurement," IEEE Sens. J. 12, 17-21 (2012).