Lateral Force Sensor Based on a Photonic Crystal Fiber Mode Interferometer

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Abstract: A highly-sensitive fiber optic lateral force sensor is introduced. The device is based on a mode interferometer consisting of a short section of photonic crystal fiber fusion spliced to standard single-mode optical fiber.

OCIS codes: (060.2370) Fiber optics sensors; (060.5295) Photonic crystal fibers.

1. Introduction

Photonic crystal fibers (PCFs) offer outstanding potential for the development of diverse kinds of sensors [1,2]. However, most PCF sensors are sensitive not only to a parameter of interest but also to other environmental parameters such as temperature. In addition, PCF sensors may also be susceptible to drifts and noise induced by variations of the optical source or mechanical perturbations on the optical fibers and connectors. Therefore, in a practical situation, all these factors must be compensated. The inconvenience of a compensation mechanism is that it may entail thermal isolation or additional reference sensors. To avoid these solutions several groups have proposed hybrid configurations, as for example, a combination of PCF interferometers with long period gratings or Bragg gratings [3-5]. Such hybrid configurations allow the monitoring of the parameter of interest and temperature. The disadvantage of a compensation mechanism or a hybrid configuration is a certain degree of complexity of the sensor which increases its cost.

Here, we report on a lateral force sensor based on a PCF mode interferometer built via microhole collapsing [6,7]. The interferometer was sandwiched between two parallel plates, one of them was flat and the other was serrated, see Fig. 1. The external force on the serrated plate was converted to localized pressure on the PCF [8]. As a result, the visibility of the interference pattern changed. The advantage of the configuration here proposed is that temperature, power fluctuations or mechanical perturbations in the optical fiber or connectors do not affect the measurements. In addition, the sensor sensitivity can be enhanced by improving the visibility of the interference pattern. The device here proposed can also be used to sense pressure, load, weight, liquid level, etc.

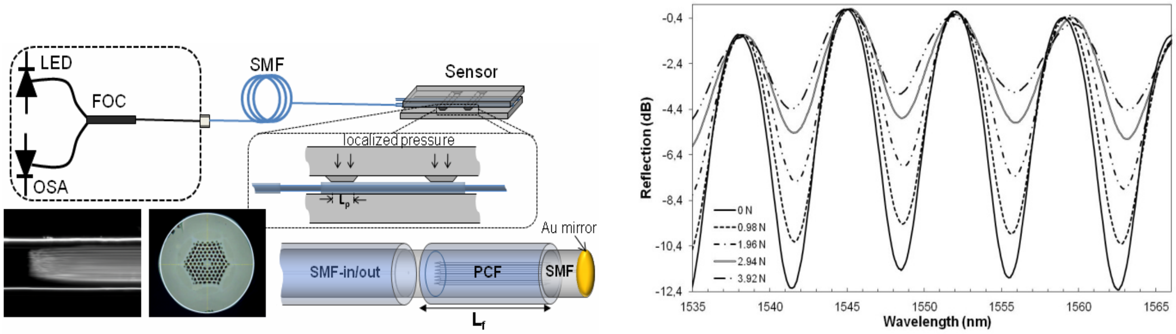

Fig. 1. Drawings of the PCF interferometer, schematic representation of its interrogation and illustration of the mechanical piece to apply localized pressure on the device. LED stands for light emitting diode, FOC for fiber optic circulator, OSA for optical spectrum analyzer. The micrographs show details of the PCF-SMF junction and the PCF cross section. The plot shows the normalized reflection spectra observed at different forces in an interferometer built with (L_f) 37 mm of PCF.

2. Results and discussion

The photonic crystal fiber interferometer is sketched in Fig. 1 along with some details of its interrogation. The interferometer consists of few centimeters of polymer-coated PCF, described in [9], fusion spliced to a standard single mode optical fiber (SMF-28). The section of SMF spliced to the PCF at the distal end avoids contamination of the PCF voids while the mirror ensures high reflectivity. The fabrication of the interferometer is simple as it is carried out by means of the well-established fusion splicing technique. During the splicing process, the voids of the PCF are intentionally collapsed over a microscopic region. To achieve high quality interferometers both splices were carried out under identical conditions. The outer diameters of the SMF and the PCF are the same and the splicing process makes them to be permanently aligned. Therefore, there is axial symmetry in our device. On the other hand, the collapsed zones in the PCF cause a broadening of the propagating beam when it travels from the SMF to the PCF, or vice versa, and thereby, introduce a mode field mismatch between the fibers. The latter combined with the axial symmetry and the modal properties of the PCF are what allow the excitation (and recombination) of two core modes. As the modes travel at different speeds, thus they accumulate a phase difference as they propagate along the length of PCF. Therefore, the reflection spectrum of the device exhibits a series of maxima and minima, see Fig. 1.

The plot in Figure 1 shows the reflection spectra at different forces observed in a 3.7 cm-long interferometer when it was squeezed with a serrated mechanical piece with $L_p = 1.5$ mm. The spectra were obtained when a series of lateral forces, in steps of 0.490 N, were applied on the mechanical piece. To do so, calibrated masses of 50 g were placed manually on top of the mechanical piece. It is important to point out that only two points of the PCF were subjected to localized pressure. To ensure a uniform compression of the interferometer and equilibrium of the mechanical piece, a stub of polymer-coated SMF was placed parallel to the PCF, at a distance of 2 cm. It can be noted from Fig. 1 that as the weight increases the interference pattern shrinks.

To understand the effect of lateral force on the interference pattern we need to analyze the effect of the localized pressure on the interfering modes. Let us suppose that two modes participate in the interference. In this case the reflected intensity (I_R) can be expressed as:

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

In Eq. (1), I_1 and I_2 are, respectively, the intensity of the two interfering modes which in our case are a fundamental and a higher-order core mode as demonstrated in a previous work [7]. $\Delta\phi = 2\Delta n L_f/\lambda$ is the total phase shift. $\Delta n = n_1 - n_2$, n_1 and n_2 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 the interferometer can be defined as [10]:

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

where $k = I_2/I_1$.

Now, if the PCF interferometer is subjected to localized pressure as shown in Fig. 1, then the interfering modes will lose power and change their effective indices due to elasto-optic effects [11,12]. In our case, the higher-order core mode is more sensitive to the external pressure and experiences higher loss than the fundamental core mode. Therefore, the localized pressure on the PCF interferometer makes k to decrease, and consequently, the interference pattern is compressed. This is the reason why the interference pattern is squeezed as the weight on the serrated mechanical piece increases. It is important to point out that the optical axis of the PCF is not bended during the measurements as it is supported on a flat surface, see Fig 1.

Figure 2 shows the changes of V of the interference pattern measured for different forces when the interferometer had V = 20, 12, and 5.5 dB (at 0 g). It can be noted that the sensitivity is higher when the visibility of the interference pattern is high. The temperature dependence of our sensor is being studied; the results will be presented during the conference. However, other groups have demonstrated that the visibility of a mode interferometer does not depend on temperature [13]. We would like to point out that the force sensor here proposed is simpler than those reported by other groups, see for example [14,15].

3. Conclusions

In conclusion, a mode interferometer comprising a few centimeters of PCF fusion spliced at the distal end of a standard single mode fiber and squeezed with a simple serrated mechanical piece is proposed for lateral force sensing. The external force on the device results on localized pressure on the PCF which introduces attenuation losses on the interfering modes due to elasto-optic effects. As a consequence, the visibility of the interference pattern changes. The measurement of force (weight) was demonstrated but the configuration here proposed is suitable for sensing many other physical parameters such as load, pressure, impact, liquid level, etc., as these will cause visibility changes to the interference pattern. To do so, probably, minor modifications on the sensor packaging will be necessary. The main advantage of the configuration here proposed include: compactness, simplicity, low cost, immunity to noise induced by power variations of the optical source or random attenuation in the optical fibers and connectors. In addition, the sensor sensitivity can be improved by enhancing the visibility of the interference pattern.

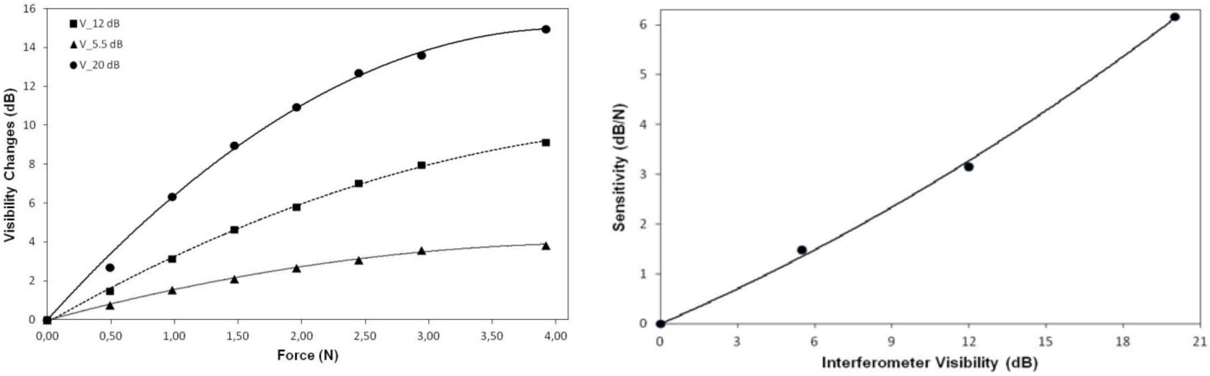

Fig. 2. (Left) Visibility changes as a function of force observed in a 3.7 cm-long PCF interferometer with different visibilities. (Right) Sensitivity as a function of the visibility of the interferometer. In all cases L_p = 1.5 mm and the sensitivity was calculated in the linear (0-1.5 N) range.

We believe that the sensing configuration proposed here can be attractive to fiber optic sensor community as it can be adapted for the development of new highly-functional fiber optic sensors.

4. References

[1] A.M.R. Pinto, M. Lopez-Amo, ”Photonic crystal fibers for sensing applications,” J. Sens. 2012, I.D. 598178 (2012).

[2] A.M. Cubillas, S. Unterkofler, T.G. Euser, B.J.M. Etzold, A. C. Jones, P.J. Sadler, P. Wasserscheid, P. S. J. Russell, “Photonic crystal fibres for chemical sensing and photochemistry” Chem. Soc. Rev. 42, 8629-8648 (2013).

[3] Y. Zhou, W. Zhou, C.C. Chan, W.C. Wong, L.-Y. Shao, J. Cheng, and X. Dong, “Simultaneous measurement of curvature and temperature based on PCF-based interferometer and fiber Bragg grating,” Opt. Commun. 284, 5669-5672 (2011).

[4] D. J. J. Hu, J. L. Lim, M. Jiang, Y. Wang, F. Luan, P. P. Shum, H. Wei, and W. Tong, “Long period grating cascaded to photonic crystal fiber modal interferometer for simultaneous measurement of temperature and refractive index,” Opt. Lett. 37, 2283-2285 (2012).

[5] S. Zhang, X. Dong, T. Li, C. C. Chan, P. P. Shum, “Simultaneous measurement of relative humidity and temperature with PCF-MZI cascaded by fiber Bragg grating”, Opt. Commun. 303, 42-45 (2013).

[6] J. Villatoro, V. P. Minkovich, V. Pruneri, and G. Badenes, “Simple all-microstructured-optical-fiber interferometer built via fusion splicing.” Opt. Express 15, 1491–1496 (2007).

[7] G. Coviello, V. Finazzi, J. Villatoro, and V. Pruneri, “Thermally stabilized PCF-based sensor for temperature measurements up to 1000ºC,” Opt. Express 17, 21551-21559 (2009).

[8] J. Villatoro, V. P. Minkovich, and J. Zubia, “Locally pressed photonic crystal fiber interferometer for multi-parameter sensing,” Opt. Lett., accepted for publication (2014).

[9] V. P. Minkovich, A.V. Kiryanov, A. B. Sotsky, and L. I. Sotskaya, “Large-mode-area holey fibers with a few air channels in cladding: modeling and experimental investigation of the modal properties,” J. Opt. Soc. Am. B 21, 1161-1169 (2004).

[10] G. A. Cardenas-Sevilla F. C. Fávero, J. Villatoro, “High-visibility photonic crystal fiber interferometer as multifunctional sensor,” Sensors, 13, 2349-2358 (2013).

[11] A. Bichler, S. Lecler, B. Serio, S. Fischer, and P. Pfeiffer, “Mode couplings and elasto-optic effects study in a proposed mechanical microperturbed multimode optical fiber sensor,” J. Opt. Soc. Am. A 29, 2386-2393 (2012).

[12] A. Sánchez, S. Orozco, A.V. Porta, M. A. Ortiz, “Elasto-optical behavior model of a step-index fiber under localized pressure” Mater. Chem. Phys. 139, 176-180 (2013).

[13] B. Dong and E. J. Hao, “Temperature-insensitive and intensity-modulated embedded photonic-crystal-fiber modal-interferometer-based micro-displacement sensor,” J. Opt. Soc. Am. B 28, 2332-2336 (2011).

[14] Y. Yang, J. Li, W. Duan, X. Zhang, W. Jin, and M. Yang, “An embedded pressure sensor based on polarization maintaining photonic crystal fiber”, Meas. Sci. Technol. **24** 094004, (2013).

[15] M. Karimi, M. Fabian, L. R. Jaroszewicz, K. Schuster, P. Mergo, T. Sun, K. T.V. Grattan, “Lateral force sensing system based on different photonic crystal fibres,” Sens. and Actuat. A: Physical, **205**, 86-91 (2014).