Control of the strain sensitivity using a suspended core photonic crystal fiber sensing head

S. Rota-Rodrigo*[1], M. Lopez-Amo[1], J. Kobelke[2], K. Schuster[2], J. L. Santos[3,4], O. Frazão[3,4]

[1]Departamento de Ingeniería Eléctrica y Electrónica, Universidad Pública de Navarra, Campus de Arrosadía, 31006 Pamplona – Navarra, Spain.

[2]IPHT—Institute of Photonic Technology, D-07745 Jena, Germany

[3]INESC Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal

[4]Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal

ABSTRACT

In this work a strain sensor based on a suspended core fiber is proposed. The sensor comprises a suspended core PCF between SMFs and is based on the multimode interference generated in these transitions. A strain sensitivity study for different sensing heads and stage separation lengths was carried out showing a sensitivity of -2.42 pm/με for the best case. Also the sensing head was tested for curvature and temperature, showing in the first case that it is insensitive to curvature effects, and secondly, that for small sensor lengths it was insensitive to temperature variations.

Keywords: Strain sensor, photonic crystal fiber, fiber optic sensor.

1. INTRODUCTION

Fiber optic sensors have attracted much interest because of their competitive application in the monitoring and control of some physical parameters. In particular, strain sensors has grown significantly in importance for heath monitoring of aerospace, marine or civil structures, and in fabrication processes, among others.[1,2]. A fiber optic sensor presents advantages such as their immunity to electromagnetic interferences, small size, reliability, remote sensing ability, and multiplexing capability. Some fiber-optic sensors use Photonic crystal fibers (PCFs), that consist of a regular array of air-holes along the entire length of a thread of pure silica glass. These optical fibers present diverse improved features compared with common single-mode fibers (SMFs) [3], one of the most important for strain sensors is the low sensitivity with temperature due that it is made of pure silica.

There are different ways to achieved strain sensors based on PCFs. There are strain sensors based on multimode interference by tapering a section of PCF to causes coupling between the multiple modes [4]. In [5] a study of the sensitivity variations with the taper waist diameter was presented (up to -3.12pm/με). Also a strain sensor was reported based on collapsing a short region between the SMF-PCF splice to allows the coupling of only two modes in the PCF (-2.8pm/με) [6].

Other authors reported strain sensors based on birefringent PCFs by detecting wavelength changes in a Hi-Bi PCF Sagnac interferometer configuration (1.21pm/με) [7] or by detecting amplitude variations in an in-reflection Hi-Bi PCF polarimetric interferometer sensor [8] and also using a 3 holes suspended core PCF in Sagnac configuration [9]. A strain

*sergio.rota@unavarra.es; phone (0034) 948 169841; fax (0034) 948 169720

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, 91571Y
 · doi: 10.1117/12.2055081

sensor was also reported by using a twin core PCF as Mach Zhender interferometer (0.31pm/με) [10]. A strain sensor was also accomplished in time domain through the cavity ring down technique [11].

In this work a strain sensor based on a suspended core fiber is proposed and studied. The sensor comprises a suspended core PCF between SMF's and is based on the multimode interference generated in these transitions [12]. Different lengths of the sensing head were characterized in strain, temperature and curvature.

2. EXPERIMENTAL SET UP AND RESULTS

The sensor is based on the multimode interference created by introducing a section of a suspended core PCF between two SMFs, Fig 1. This PCF presents a 3um core enclosed by four large holes and a multimode behavior. The SMF-PCF splices were done using a splice machine (Fitel S182PM) in manual mode, with an arc-power of 110 (splicer parameter) and an arc-duration of 750ms.

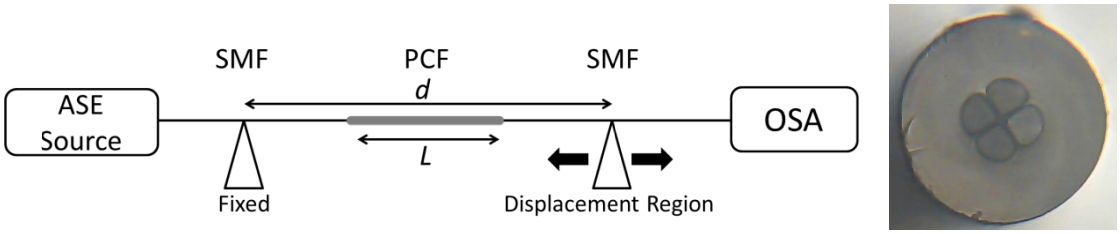

Figure 1. a) Schematic of the strain sensor system. b) Microscopy photograph of the Suspended Core PCF cross-section.

The characterization of the PCF sensing head response to strain variations was measured through the experimental setup presented in Figure 1a. The experimental configuration consisted of an erbium-doped fiber amplifier (EDFA, Fiberamp-BT 1400) as broadband source, the sensing head and an optical spectrum analyzer (OSA, Advantest Q8384) with a maximum resolution of 10 pm. The fiber was fixed by two translation stages in order to apply strain by moving one of the stages while the other remains fixed. For this characterization, a series of measurements for three different stages separations, d=0.125, d= 0.25 and d=0.50m, and for different sensor lengths (*L*) was carried out.

Figure 2 shows the variations of the optical spectrum of the sensing head for two cases, a) *L*=5mm with d=0.5m and b) *L*=20mm with d=0.5m, for three different strain values. This figure also shows a linear behavior of both sensors with strain, however their sensitivities were different.

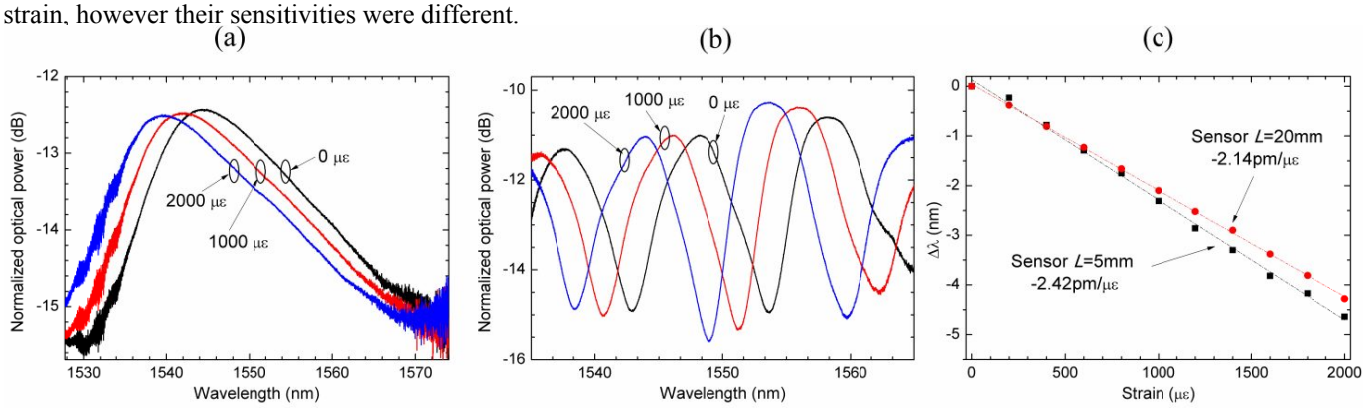

Figure 2. Variations of the optical output spectrum at different strain values for sensor L=5mm (a) and L=20mm (b) with a d=0.5m, and its wavelength dependence with strain (c).

Figure 3 shows the sensitivity of the sensing head depending on the sensor length (*L*) and the stage lengths (*d*). From these results there are two conclusions to be drawn. Firstly the sensitivity was increased with the stage lengths (d), this effect is because the Young module of the PCF is less than the SMF´s one [13]. Taking in this to account, for a constant

L sensor length, when the stages length is increased, is necessary a major displacement to obtain the same strain, this way the PCF, with a lower Joule module than SMF, experiments a major displacement that constitute a major sensitivity.

Secondly the sensitivity varies with the sensor length. These variations are due to the combination of the different modes of the PCF. When the light is coupled from the SMF to the PCF, few modes are excited, each one with a different propagation constant β, that produce a phase delay among modes. In the transition from the PCF to the SMF the different modes are combined with its respective phase differences, generating the interference pattern that can be expressed by:

$$P_{PCF-SMF} = \left|a_1^2 + a_2^2 e^{i(\beta 1-\beta 2)(L)} + \cdots + a_j^2 e^{i(\beta 1-\beta j)(L)}\right|^2$$

Where a_j and β_j are, respectively, the amplitude and the propagation constant of each mode, and L is the PCF sensor length. When a strain is applied to the sensor an increment of the length ΔL is produced and the interference equation is expressed now by:

$$P_{PCF-SMF} = \left|a_1^2 + a_2^2 e^{i(\beta 1-\beta 2)(L+\Delta L)} + \cdots + a_j^2 e^{i(\beta 1-\beta j)(L+\Delta L)}\right|^2$$

This way each mode experiments a different change in its phase. This effect that depends on the sensor lengths, in combination with the different amplitude of the modes, provokes the changes of the sensing head sensitivity shown in figure 3. The best values of strain sensitivity, -2.42pm/με and 2.40pm/με, were achieved for L=0.5 and L=7.5cm sensor lengths, respectively, with a 50cm stages separation.

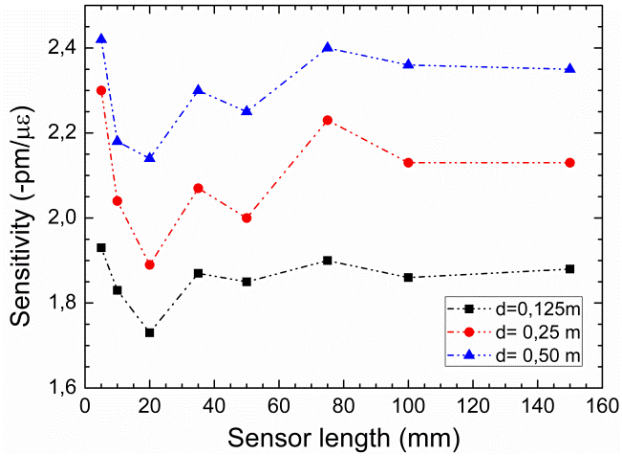

Figure 3. Sensor´s sensitivity characterization in function of the sensor length (L) and the stage lengths (d).

Taking into account this strain characterization, a temperature study for the 5mm and 75mm sensor lengths was carried out. Figure 4 shows that for the 75mm sensor a sensitivity of 5.93pm/ºC was achieved. However, for the 5mm sensor the temperature effect is negligible due to its short length.

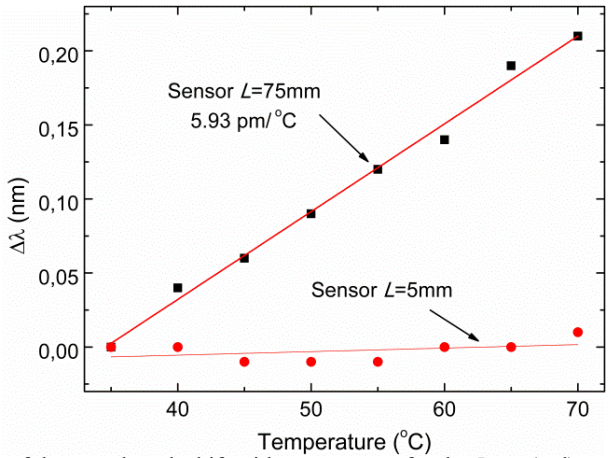

Figure 4. Characterization of the wavelength shift with temperature for the 5mm (red) and 75mm (black) sensor length.

Also, a curvature study effect was carried out showing that the behaviour of the sensor remains constant for bending radios higher than 0.25 m. This is due to the sensor is based on a multimode interference that depends of its total length and the propagation constants´difference and modes field amplitudes are not significantly altered when curvature is applied.

3. CONCLUSIONS

To summarize, a strain fiber optic sensor based on multimode interference was presented and demonstrated. The sensing head was accomplished by using a suspended core PCF in transmission. A characterization study of the influence of the length of the sensor and the applied strain in the sensitivity of the system was carried out. This study shows that the sensitivity was increased with the separation of the stages separation and also shows an optimal sensor length of 5mm and 75mm with the higher sensitivities, for a 0.5m stage separation, of -2.42pm/με and 2.40pm/με respectively. For this sensor length values a temperature characterization was also carried out, showing that the best length sensor option is the 5mm, that is practically insensitive to temperature variations, whereas the 75mm sensor has a sensitivity of 5.93pm/ºC. Also the insensitivity of system to the curvature effect was demonstrated.

ACKNOWLEDGMENTS

The authors are grateful to the Spanish government project TEC2010-20224-C02-01, to the European Cooperation in Science and Technology (COST) Action TD1001, and Project "NORTE-07-0124-FEDER-000058" that is financed by the North Portugal Regional Operational Programme (ON.2 – O Novo Norte), under the National Strategic Reference Framework (NSRF), through the European Regional Development Fund (ERDF), and by national funds, through the Portuguese funding agency, Fundação para a Ciência e a Tecnologia (FCT).

REFERENCES

[1] J. M. Lopez-Higuera, L. Rodriguez Cobo, A. Quintela Incera, A. Cobo, "Fiber Optic Sensors in Structural Health Monitoring," *IEEE J. Light. Techn.* **29**, 587-608, (2011).

[2] H. N. Li, D. S. Li, G. B. Song, "Recent applications of fiber optic sensors to health monitoring in civil engineering," *Eng. Struct.* **26**, 1647-1657, (2004).

[3] A.M.R. Pinto, M. Lopez-Amo, "Photonic Crystal Fibers for Sensing Applications," *J. Sens.* art. no. 598178, (2012).

[4] J. Villatoro, V. P. Minkovich, D. Monzon-Hernandez, "Temperature-independent strain sensor made from tapered holey optical fiber," *Opt. Lett.* **31**, 305-307, (2006).

[5] R. M. André, S. O. Silva, M. Becker, K. Schuster, M. Rothardt, H. Bartelt, M. B. Marques, O. Frazão, "Strain sensitivity enhancement in suspended core fiber tapers," *Photonic Sensors* ,**3**, 118-123, (2013).

[6] J. Villatoro, V. Finazzi, V. P. Minkovich, V. Pruneri, G. Badenes, "Temperature-insensitive photonic crystal fiber interferometer for absolute strain sensing," *Appl. Phys. Lett.* **91**, 091109, (2007).

[7] O. Frazao, J. M. Baptista, J. L. Santos, "Temperature-independent strain sensor based on a Hi-Bi photonic crystal fiber loop mirror," *IEEE Sens. J.* **7**, 1453-1455, (2007).

[8] S. Rota-Rodrigo, M. Bravo, A.M.R. Pinto, M. López-Amo, " An In-reflection strain sensing head based on a Hi-Bi photonic crystal fiber ," Sensors, **13**, 8095-8102, (2013).

[9] M. Bravo, A. M. R. Pinto, M. Lopez-Amo, J. Kobelke, K. Schuster, "High precision micro-displacement fiber sensor through a suspended-core Sagnac interferometer," *Opt. Lett.* **37**, 202-204, (2012).

[10] K.K. Qureshi, Z. Liu, H.Y. Tam, M.F. Zia, "A strain sensor based on in-line fiber Mach-Zehnder interferometer in twin-core photonic crystal fiber," *Opt. Commun.* **309**, 68-70, (2013).

[11] W. Zhou, W.C. Wong, C.C. Chan, L.Y. Shao, X. Dong, "Highly sensitive fiber loop ringdown strain sensor using photonic crystal fiber interferometer," *Appl. Opt*. **50**, 3087-3092, (2011).

[12] P.R.Horche, M.López-Amo, M.A.Muriel, J.A.Martín-Pereda "Spectral behavior of a low-cost all-fiber component based on untapered multifiber unions" *IEEE Photonics Technology Letters,* **1**, 184-187, (1989).

[13] O. Frzão, S.F.O. Silva, A. Guerreiro, J.L. Santos, L.A. Ferreira, F.M. Araújo, " Strain sensitivity control of riber Bragg grating structures with fused tapers," *App. Opt*. **46**, 8578-8582, (2007).