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Hollow square core fiber sensor for physical parameters measurement

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Hollow square core fiber sensor for physical parameters measurement

Diana Pereira[1,*], Jörg Bierlich[2], Jens Kobelke[2], Marta S. Ferreira[1]

[1]i3N & Physics Department, University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal
[2]Leibniz Institute of Photonic Technology, Albert-Einstein-Straße 9, 07745, Jena, Germany

*Author's e-mail address: dsap@ua.pt

Abstract. The measurement of physical parameters is important in many current applications, since they often rely on these measurands to operate with the due quality and the necessary safety. In this work, a simple and robust optical fiber sensor based on an antiresonant hollow square core fiber (HSCF) is proposed to measure simultaneously temperature, strain, and curvature. The proposed sensor was designed in a transmission configuration where a segment of HSCF, with a 10 mm length, was spliced between two single mode fibers. In this sensor, a cladding modal interference (CMI) and a Mach-Zehnder interference (MZI) are enhanced along with the antiresonance (AR) guidance. All the present mechanisms exhibit different responses towards the physical parameters. For the temperature, sensitivities of 32.8 pm/ºC, 18.9 pm/ºC, and 15.7 pm/ºC were respectively attained for the MZI, AR, and CMI. As for the strain, sensitivities of 0.45 pm/με, -0.93 pm/με, and -2.72 pm/με were acquired for the MZI, AR and CMI respectively. Meanwhile, for the curvature measurements, two regions of analysis were considered. In the first region (0 m^{-1} – 0.7 m^{-1}) sensitivities of 0.033 nm/m^{-1}, -0.27 nm/m^{-1}, and -2.21 nm/m-1 were achieved, whilst for the second region (0.7 m^{-1} – 1.5 m^{-1}) sensitivities of 0.067 nm/m^{-1}, -0.63 nm/m^{-1}, and -0.49 nm/m^{-1} were acquired for the MZI, AR and CMI, respectively.

1. Introduction

In modern society, optical fiber sensors have a crucial role, being constantly applied in a wide variety of areas, where the monitoring of mechanical and physical properties such as strain, temperature, curvature, and pressure are fundamental [1]. On the other hand, antiresonant hollow core fibers (ARHCF) present several advantageous properties, for instance, low loss guidance [2], broad bandwidth [3], low dispersion and nonlinearities [4], arising as an exceptional element in the sensing field. In virtue of this, several optical fiber sensors based on ARHCF have been proposed to measure physical parameters [5-7].

In this work, an inline ARHCF sensor is proposed to measure temperature, curvature, and strain. The hollow square core fiber (HSCF) is an antiresonant (AR) fiber that when interrogated in a transmission configuration, enhances two more interferometers, namely the cladding modal interference (CMI) and the Mach-Zehnder interference (MZI). The purpose of this work settles in using the components that arise from the sensing structure to simultaneously monitor three parameters, and exploring its viability as an implementation of a multiparameter sensor.

2. Sensor design

Figure 1 depicts a microscopic image of the HSCF that was used in this work. This fiber belongs to the class of the ARHCF, and was developed in the Leibniz Institute of Photonic Technology, in Germany. It presents a squared air core of 11 µm, and, around this, silica strands of 1.7 µm of thickness. Further information regarding the fiber geometry can be found elsewhere [8].

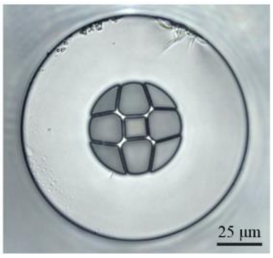

Figure 1 – Microscope photograph of the HSCF.

The sensor was interrogated in a transmission configuration, where a segment of the HSCF was fusion spliced between two single mode fibers. Arising from this sensor structure, two interferometers are enhanced, namely the CMI and the MZI, along with the AR guidance. Further details regarding these interferometers can be found elsewhere [8,9]Figure 2a shows the transmission spectrum of the 10 mm long sensor used. From the observation of the transmission spectrum, it is possible to ascertain the existence of a high frequency domain being modulated by a low frequency. The high frequency results from the MZI and the low frequency from both the CMI and the AR. The wavelength shift of the MZI component was attained by directly resorting to the transmission spectrum, and the wavelength shift of the CMI and AR components were attained by performing a band pass filter to the spectrum, as shown in Figure 2b.

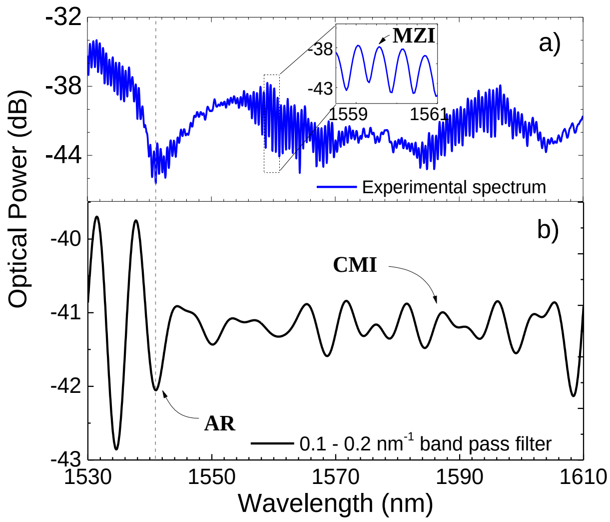

Figure 2 – (a) Transmission spectrum of the HSCF with a zoom in showing the monitored MZI peak. (b) Band pass filter applied to monitor the CMI and AR.

3. Results

In Figure 3 is presented the responses attained by the MZI, CMI and AR to the temperature (Fig.3a), strain (Fig.3b), and curvature (Fig.3c). For the temperature results, sensitivities of 32.8 pm/ºC, 18.9 pm/ºC, and 15.7 pm/ºC were respectively attained for the MZI, AR, and CMI. The responses verified by these components are mediated by the thermal expansion effect and also by the thermo-optic effect. Notice that the CMI component is also sensitive to variations of the refractive index of the outer medium, as previously reported [9], meaning that there is an influence of the refractive index change of the surrounding medium in the temperature sensitivities. However, when considering the air medium, the dependence can be neglected due to the low thermo-optic coefficient. As for the strain results, the MZI component achieved a sensitivity of 0.45 pm/με, while the AR and CMI attained values of -0.93 pm/με, and -2.72 pm/με, respectively. These behaviors are influenced by the elasto-optic property of the silica material, and also by the variation of the sensors' length due to the application of strain. Meanwhile, for the curvature measurements, nonlinear responses were attained by the AR and CMI, which led to a sensitivity analysis in two different ranges of curvature. For the first range, 0 m^{-1} to 0.7 m^{-1}, sensitivities of 0.033 nm/m^{-1}, -0.27 nm/m^{-1}, and -2.21 nm/m^{-1} were respectively achieved for the MZI, AR and CMI, whilst for the second region (0.7 m^{-1} – 1.5 m^{-1}) sensitivities of 0.067 nm/m^{-1}, -0.63 nm/m^{-1}, and -0.49 nm/m^{-1} were attained. The nonlinear behavior observed by the AR and CMI may be justified by the asymmetrical distribution of the refractive index in the fiber [10] due to the elasto-optic effect, that arises when the fiber is bent, whilst the low sensitivity of the MZI may be due to its proximity to the neutral bending plane, where no strain is applied, and thus, no significant variation in the refractive index is verified [10].

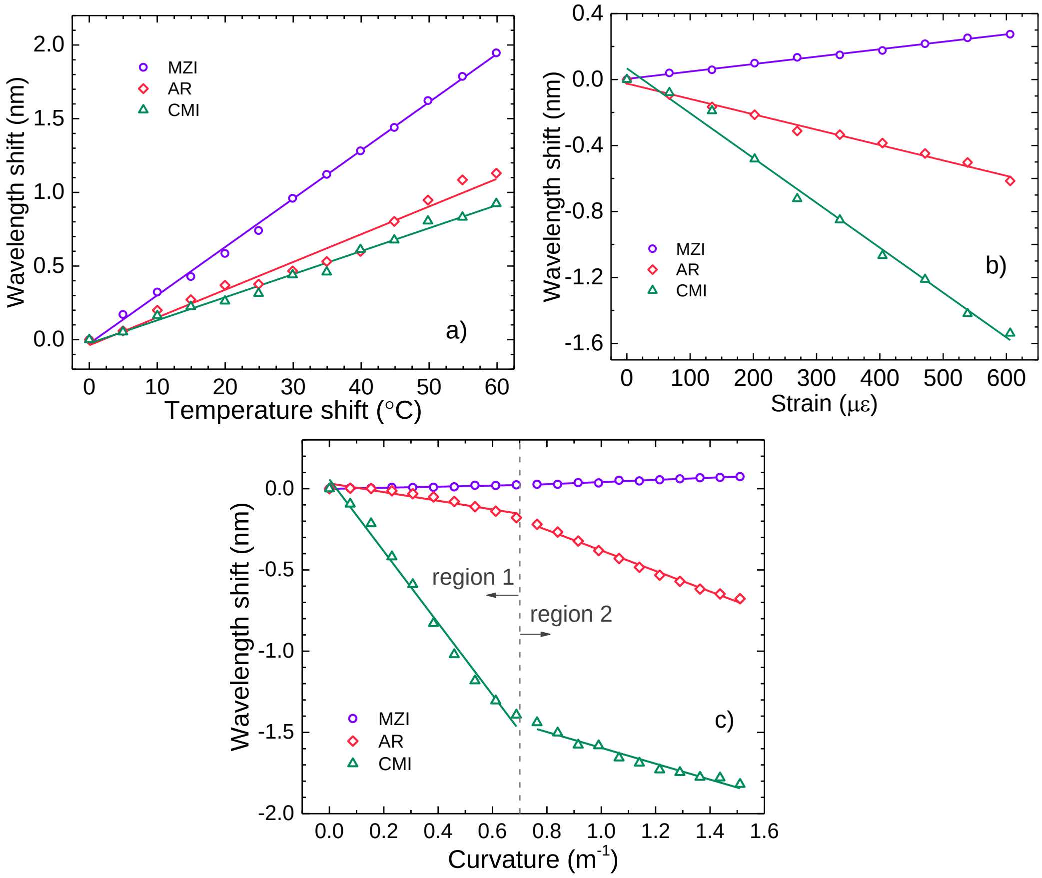

Figure 3 – (a) Temperature responses, (b) strain responses, and (c) curvature responses attained by the MZI, AR, and CMI.

With the acquired sensitivities attained for each component of the sensor, a variation of the studied parameters can be easily attained by the matrix:

$$\begin{pmatrix} \Delta\varepsilon \\ \Delta C \\ \Delta T \end{pmatrix} = \begin{pmatrix} 0.6361 & -1.2374 & 0.16067 \\ -0.00062 & 0.00163 & -0.00066 \\ 0.02238 & 0.01533 & -0.00153 \end{pmatrix} . \begin{pmatrix} \Delta\lambda_{MZI} \\ \Delta\lambda_{AR} \\ \Delta\lambda_{CMI} \end{pmatrix}$$

where $\Delta\varepsilon$, ΔC and ΔT are the respective strain, curvature and temperature variations, and $\Delta\lambda_{\mathrm{MZI}}$, $\Delta\lambda_{\mathrm{AR}}$ and $\Delta\lambda_{\mathrm{CMI}}$ the responses of the MZI, AR and CMI components, respectively. Notice that the units of $\Delta\varepsilon$, ΔC and ΔT are με, m^{-1}, and ºC, respectively.

Given the distinct responses acquired for each component, towards the temperature, strain and curvature, this sensor shows to be a good candidate to conduct a simultaneous measurement of these three parameters.

4. Conclusion

In summary, an inline sensor based on a HSCF was proposed to measure the temperature, strain, and curvature. The respective sensor presented two interferometers, the CMI and MZI, as well as the AR, which exhibited different responses towards the physical parameters. The proposed sensor revealed a maximum temperature sensitivity of 32.8 pm/ºC for the MZI, while for strain, the highest sensitivity, of -2.72 pm/με, was attained by the CMI. For the curvature, two different regions were analyzed, attaining, in the first region (0 m^{-1} – 0.7 m^{-1}), a maximum curvature sensitivity of -2.21 nm/m^{-1} for the CMI, whilst for the second region (0.7 m^{-1} – 1.5 m^{-1}), a sensitivity of -0.63 nm/m^{-1} for the AR.

This sensing device is robust and easy to manufacture, and shows great promising in the simultaneous measurement of three parameters, thus achieving a good criteria for a multiparameter sensor.

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