Journal of Physics: Conference Series

Capillary based hybrid fiber sensor in a balloon-like shape for simultaneous measurement of displacement and temperature

Capillary based hybrid fiber sensor in a balloon-like shape for simultaneous measurement of displacement and temperature

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Abstract. In this work, a hybrid sensor based on a silica capillary in a balloon-like shape for simultaneous measurement of displacement and temperature is proposed for the first time, to the best of our knowledge. The sensor is fabricated by splicing a segment of a hollow core fiber between two single mode fibers (SMF) and by bending the fiber in a balloon shape with the capillary at the top-center position. In a transmission scheme, the SMF-capillary-SMF configuration excites an antiresonant (AR) guidance and the balloon shape enhances a Mach-Zehnder interferometer (MZI). The different responses of the interferometers to external displacement and temperature variations are conducive to a hybrid application of the sensor for simultaneous measurement of these parameters. Experimental results show that, for a capillary length of 1.2 cm and a balloon length of 4 cm, AR is insensitive to displacement and its sensitivity to temperature is 14.3 pm/°C, while the MZI has a sensitivity to displacement of 1.68 nm/mm and twice the sensitivity of AR to temperature, of 28.6 pm/°C. The proposed fiber sensor consists of only one sensing element in one configuration exciting two interferometers at the same time, which makes it of simple fabrication as well as low cost.

Keywords: Antiresonant, Mach-Zehnder, Balloon-like, Displacement, Temperature

1. Introduction

The measurement of displacement is of high demand for optical-based devices in multiple applications including aeronautics and microimaging [1]. Various configurations based on optical fiber sensors have been reported in literature. Namely, for displacement fiber sensors, these usually adopt either a grating structure, such as Bragg gratings, long period and tilted gratings, or an interference-based principle, including multimode, Fabry-Perot, and Mach-Zehnder interferometers (MZI) [2-4]. Regarding the latter interferometer, balloon-like fiber sensors have been developed in different configurations for hybrid measurements [5-8]. To date, balloon-like sensors have only been developed with a single mode fiber (SMF) to enhance an MZI.

In this work, a hybrid fiber sensor for simultaneous measurement of displacement and temperature based on a silica capillary tube spliced between two single mode fibers in a balloon-like structure is proposed. This configuration results in two interferometers occurring simultaneously in a single sensing element: antiresonant guidance (AR) and MZI.

2. Sensor configuration and spectral results

The silica capillary tube, as seen in the microscopic picture shown in Fig. 1a, is a hollow core fiber with a pure silica cladding layer and a core that is made of air. Its inner diameter is of 57 µm and the outer diameter is of 125 µm.

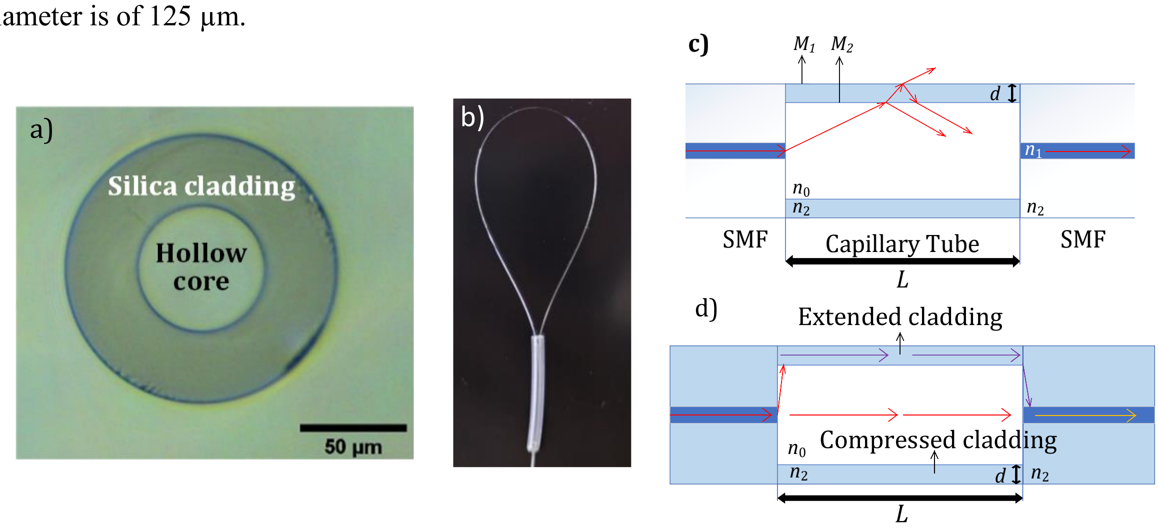

Fig. 1. (a) Microscope image of the silica capillary tube cross-section. (b) Picture of the fabricated balloon-like sensor. (c) Antiresonant reflecting optical waveguide mechanism in the capillary. (d) Mach-Zehnder interferometer schematic diagram.

The sensor is achieved by splicing a section of the silica capillary tube between two SMFs. The splicing is performed in the manual mode of the fusion splicer Fujikura FMS-40S with an arc power of 20 arb. un. and a discharge time of 1500 ms, without an offset applied. These parameters were chosen in order to achieve stronger splices that can withstand smaller bending diameters, without collapsing the capillary.

Furthermore, the sensors were bent in order to obtain a balloon-like shape where the silica capillary is placed at the top-center position of the balloon, as seen in Fig 1b. For that purpose, the SMFs were fed through a Tygon® capillary tube that is moved upwards and positioned accordingly. Once the desired bending diameter was obtained, the fiber was glued with UV curable resin on both tips of the Tygon® capillary tube. The length, bending diameter, and radius of the balloon are termed as L_b, d_b, and r_b, respectively, as depicted in Fig. 2a.

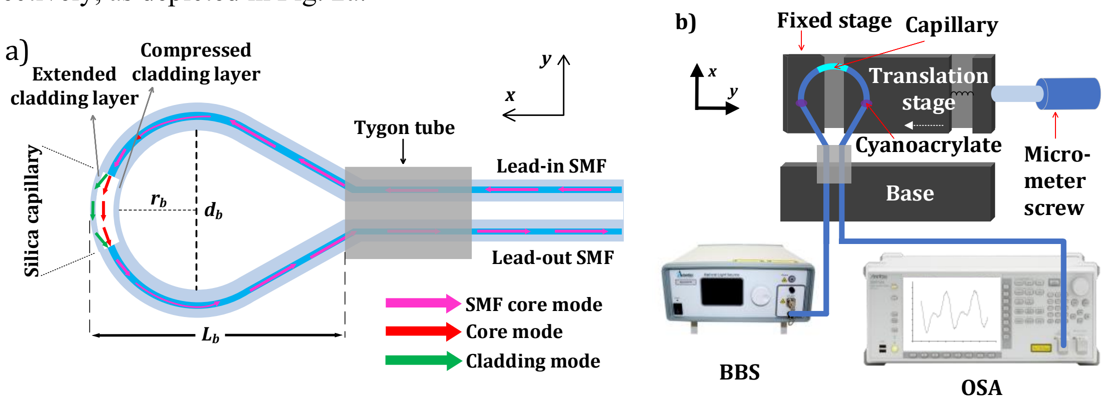

Fig. 2. (a) Schematic diagram of the balloon-like sensor. (b) Schematic diagram of the displacement setup.

The sensors spectra were obtained in a typical transmission scheme with one end of the sensor connected to a broadband light source (BBS) that emits on the C+L band while the other end was connected to an optical spectrum analyzer (OSA, Anritsu MS9740A) with a resolution of 0.05 nm.

Journal of Physics: Conference Series **2407** (2022) 012041 doi:10.1088/1742-6596/2407/1/012041

In Fig. 3b the spectra of different balloon lengths were obtained for the same capillary length. For larger balloon lengths (9 cm), only an AR guidance is present, a mechanism depicted in Fig. 1c, corresponding to the wide lossy dip that satisfies the condition [9]

$$\lambda_m = \frac{2d}{m}\sqrt{n_2^2 - n_0^2}, \quad (1)$$

where λ_m is the resonant wavelength condition of the cladding, m is the resonance order, d is the cladding thickness, and n_2 and n_0 are the refractive indices of the silica capillary and the hollow core, respectively.

However, as the bending diameter decreases (6.3 cm), a low visibility high frequency oscillation begins to take place, corresponding to the enhancement of an MZI. Due to the bending resulting from the balloon-shape, when light reaches the capillary, a portion of the light is forced to penetrate into the extended cladding layer, exciting the cladding mode, later coupling back to the core of the SMF, interfering with the core mode of the capillary, as shown in Fig. 1d. The wavelength dip can be expressed as [6]

$$\lambda_m = \frac{2L\Delta n}{2m+1}, \quad (2)$$

where m is an integer, Δn is the difference of refractive indices of the capillary cladding and core, and L is the capillary length.

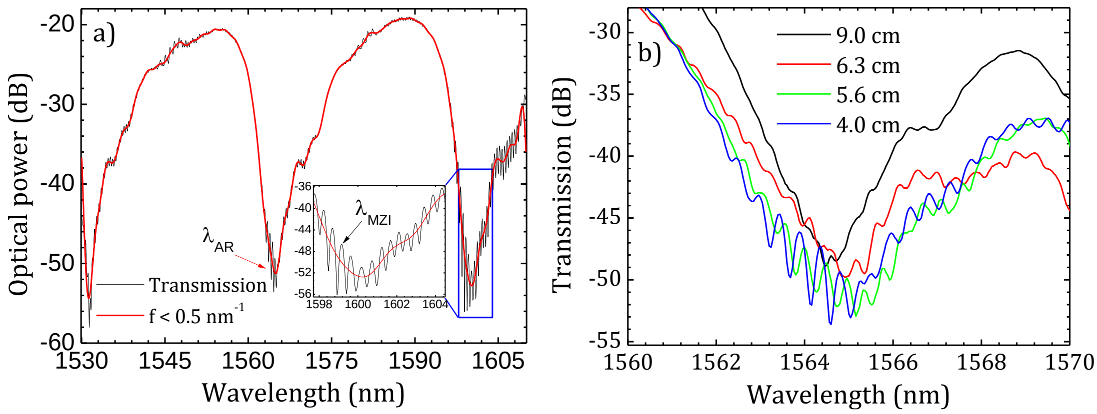

Fig. 3. (a) Transmission spectrum for a 1.2 cm sensor with 4.0 cm balloon length. Inset: Zoom-in of the spectrum in the 1598-1604 nm region. (b) Transmission spectrum for a 1.2 cm sensor with different balloon lengths in the 1560-1570 nm region.

Fig. 3a shows the transmission spectrum for a sensing head of 1.2 cm in a 4.0 cm balloon length. Both interferometers are present in the spectrum with the MZI corresponding to the high frequency oscillation, present throughout the spectrum, primarily on the dips of the AR. Additionally, the signal is modulated by a low-frequency signal, the AR, highlighted by the red line in the curve, which is obtained through a 0.5 nm^{-1} low-pass filter, explained by the AR (green) and MZI (pink) regions of the FFT spectrum given in Fig. 4.

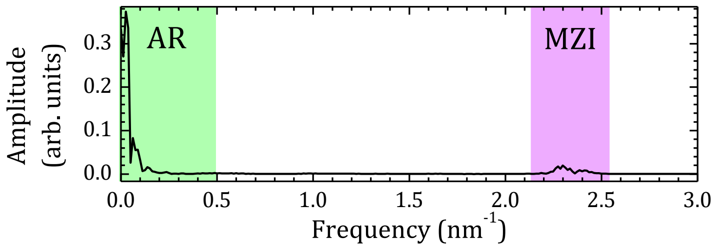

Fig. 4. FFT spectrum of the 4.0 cm balloon length sensor.

3. Results

For displacement measurements, the experimental setup is given in Fig 2b. The balloon is placed between two stages and glued with cyanoacrylate at both sides. One stage is fixed while the other moves horizontally in the *y* axis through the retraction of a micrometer screw, applying incremental displacement on the balloon. The wavelength shift for both interferometers was measured in a displacement range of 0 to 5 mm. The results, presented in Fig. 5a, show different responses for the interferometers. The MZI showcases a shift towards longer wavelengths with a sensitivity of (1.68 ± 0.01) nm/mm (R^2 = 0.9986) while the AR component is practically insensitive to displacement, with a sensitivity (0.11 ± 0.01) nm/mm (R^2 = 0.8646). This behaviour is correlated with the elasto-optic effect of silica during bending which increases the refractive index of the extended cladding layer and decreases the refractive index of the compressed cladding layer.

For temperature characterization, the balloon was placed in a climate chamber (Weiss Technik) with controllable temperature and relative humidity, where the temperature was varied from 15 °C to 35 °C with steps of 2.5 °C and the relative humidity was kept constant at 60% RH. Both interferometers are sensitive to this parameter with a red shift, as shown in Fig. 5b. The MZI sensitivity is twice the AR sensitivity, of (28.6 ± 0.1) pm/°C for MZI versus (14.3 ± 0.1) pm/°C for AR. Both results have high linearity with R^2 = 0.9955 and R^2 = 0.9939 for MZI and AR, respectively. The behaviour of the interferometers is explained by the thermo-optic and thermal expansion coefficients of silica.

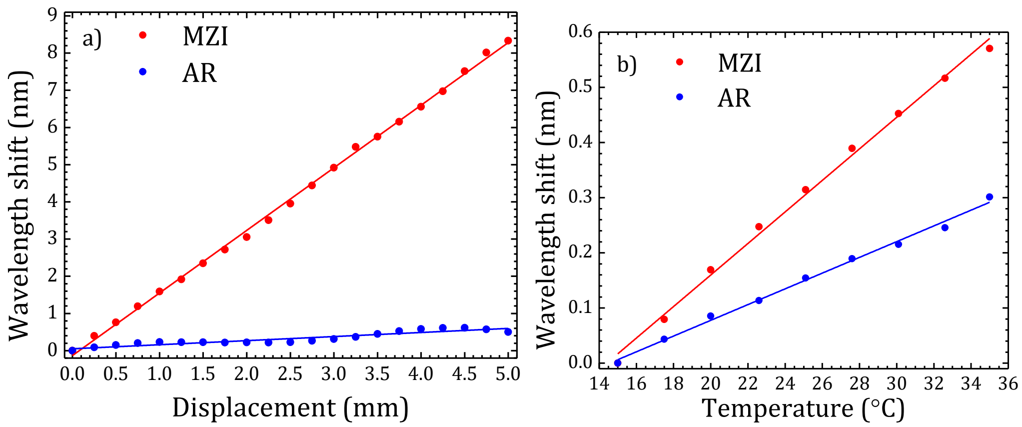

Fig. 5. Sensor response to (a) displacement and (b) temperature variations.

Since the sensitivities of the interferometers were different for both parameters, this sensor is a good candidate to perform simultaneous measurement of displacement and temperature. A demodulation matrix can be established to calculate the changes of temperature (*T*) and displacement (*D*), which are given by

$$\begin{bmatrix} \Delta\lambda_{MZI} \\ \Delta\lambda_{AR} \end{bmatrix} = \begin{bmatrix} \kappa_{MZI}^{D} & \kappa_{MZI}^{T} \\ \kappa_{AR}^{D} & \kappa_{AR}^{T} \end{bmatrix} \begin{bmatrix} \Delta D \\ \Delta T \end{bmatrix}, \tag{3}$$

where $\Delta\lambda$ is the wavelength shift (in nm) and κ is the sensitivity (in nm/°C or nm/mm). By inserting the previously calculated sensitivity coefficients, the variation of displacement and temperature can, thus, be expressed in the following matrix

$$\begin{bmatrix}\Delta D\\ \Delta T\end{bmatrix} = \frac{1}{0.020878}\begin{bmatrix}14.3\times10^{-3} & -28.6\times10^{-3}\\ -0.11 & 1.68\end{bmatrix}\begin{bmatrix}\Delta\lambda_{MZI}\\ \Delta\lambda_{AR}\end{bmatrix}, \tag{4}$$

where the ΔD, ΔT, and $\Delta\lambda$ units are mm, °C, and nm, respectively.

4. Conclusions

In summary, a silica capillary-based fiber sensor based in a balloon-like shape was developed, with the capillary placed at the top-center position of the balloon. This configuration was proposed for the first time, to the best of our knowledge. The antiresonant guidance and the MZI have different sensitivities to displacement and temperature, thus simultaneous measurement of these parameters can be achieved. The sensitivity of MZI to displacement and temperature was 1.68 nm/mm and 28.6 pm/°C, respectively, while AR was insensitive to displacement and its sensitivity to temperature was of 14.3 pm/°C. The proposed fiber sensor has only one sensing element in one configuration which makes it of simple fabrication as well as low cost, with high measuring ranges of displacement, between 0 and 5 mm.

Acknowledgements

This work was financially supported by the project AROMA, funded by FEDER, through CENTRO2020-Programa Operacional Regional do Centro, CENTRO-01-0145-FEDER-031568, and by national funds (OE), PTDC/EEI-EEE/31568/2017, UIDB/50025/2020 & UIDP/50025/2020, through FCT/MCTES. The work of M. S. Ferreira was supported by the research fellowship CEEC-IND/00777/2018. The work was also funded by the German Federal Ministry of Education and Research (BMBF): "The Innovative Growth Core TOF" (Tailored Optical Fibers, FKZ 03WKCV03E) as well as the bilateral cooperation FCT/DAAD (FLOW, Project ID: 57518590).

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