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RESEARCH ARTICLE

# High sensitivity strain sensor based on twin hollow microspheres

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**Abstract**
A sensor based on 2 hollow core microspheres is proposed. Each microsphere was produced separately through fusion splicing and then joined. The resultant structure is a Fabry-Perot interferometer with multiple interferences that can be approximated to a 4-wave interferometer. Strain characterization was attained for a maximum of 1350 με, achieving a linear response with a sensitivity of 3.39 ± 0.04 pm/με. The fabrication technique, fast and with no chemical hazards, as opposed to other fabrication techniques, makes the proposed sensor a compelling solution for strain measurements in hash environments.

KEYWORDS
Fabry-Perot, fiber optics sensors, strain measurement

## 1 | INTRODUCTION

Fabry-Perot-based fiber sensors have been proposed over the last decades. This interferometric configuration can be fabricated using chemical etching,[1–4] focused ion beam milling,[5,6] femtosecond laser,[7] or by the use of fiber Bragg gratings as mirrors.[8,9] Fusion splicing emerges as a fast and easy alternative, presenting no chemical hazards as opposed to chemical etching. The technique has been presented in literature for the fabrication of Fabry-Perot-based sensors for strain,[10,11] pressure,[12] and refractive index[13] measurements.

In 2011, Duan et al.[14], proposed a microbubble based sensor for strain measurements. The sensor, composed only by single mode fiber (SMF), was fabricated through fusion splicing and achieved a sensitivity of ~4 pm/με with a thermal sensitivity of 0.9 pm/°C. More recently, Liu et al.[11], demonstrated a strain sensor with a sensitivity of 6.0 pm/με for a cavity of 46 μm. A strain sensor based on an array of silica microspheres was proposed by Ferreira et al.[15] was also shown. Three configurations were studied for strain and temperature measurements, by varying the number of microspheres. A maximum sensitivity of −1.59 pm/με was achieved for a sensor with 3 microspheres and a temperature sensitivity of ~20 pm/°C for all the sensors was attained.

In this work a sensor based on 2 hollow microspheres is proposed as strain sensor. The sensor is fabricated by fusion splicing an SMF to a hollow core fiber (HCF). By applying 2 electric arcs to the HCF a hollow microsphere is formed. The connection of 2 tip structures with a hollow microsphere produces an in-line sensor with 2 microspheres. Strain measurements were performed, and high strain sensitivity was achieved.

## 2 | SENSOR FABRICATION

The fabrication process consists in using fusion splicing technique to produce hollow microspheres in the tip of a HCF, with 125 μm of outer diameter and an inner diameter of ~57 μm.

A Sumitomo 71C splicer machine in manual mode was used for the sensor fabrication, through the 4 steps shown in Figure 1. The first step of the fabrication process, schematized in Figure 1A, consisted in splicing the SMF to the HCF. The electric arc was set centered in the SMF, preventing the collapse or deformation of the hollow fiber while being able to join the 2 fibers. The electric arc was

  

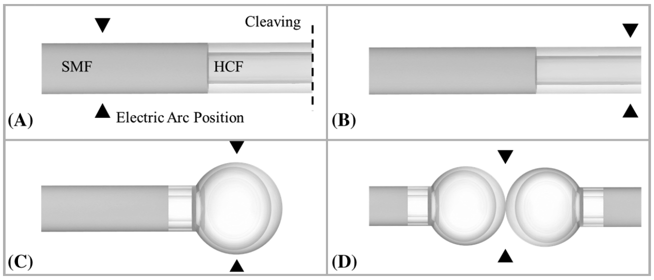


**FIGURE 1** Schematic of the fabrication process steps

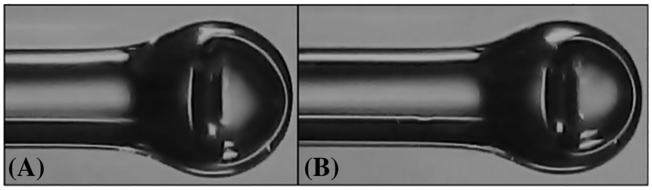


**FIGURE 2** Microscope photograph of the 2 structures of one microsphere: (A) sensor A and (B) sensor B

performed with a fusion time of 300 ms with 75 power units lower than of the standard SMF–SMF. The hollow core was cleaved to the desired length, by using a magnifier glass as presented in Figure 1A. The total length of the HCF influences the final shape and dimension of the microsphere.

The second step, shown in Figure 1B, consisted in forming the microsphere by applying 2 consecutive electric arcs at the top of the HCF. These electric arcs had a fusion time of 2000 ms with 100 power units higher than the standard value. The first electric arc collapses the HCF, creating a microsphere with thick silica walls, while the second electric arc thinners the microsphere walls. The 2 produced structures of one-microsphere, named Sensor A and Sensor B, are presented in Figure 2. The last step of the fabrication process, in Figure 1D, consisted in joining 2 sensor tips by applying one electric arc at the joining point. The electric arc had a fusion time of 600 ms with electric power 50 units lower than the standard. The resultant sensing structure is presented in Figure 4.

## 3 | PRINCIPLE OF OPERATION

### 3.1 | One-microsphere structure

The one-microsphere structures, named Sensor A and Sensor B, are presented in Figure 2. The reflected spectra of the sensors, presented in Figure 3A,C, respectively, were attained using an interrogation system composed by a broadband source of 100 nm bandwidth, centered at 1550 nm, an

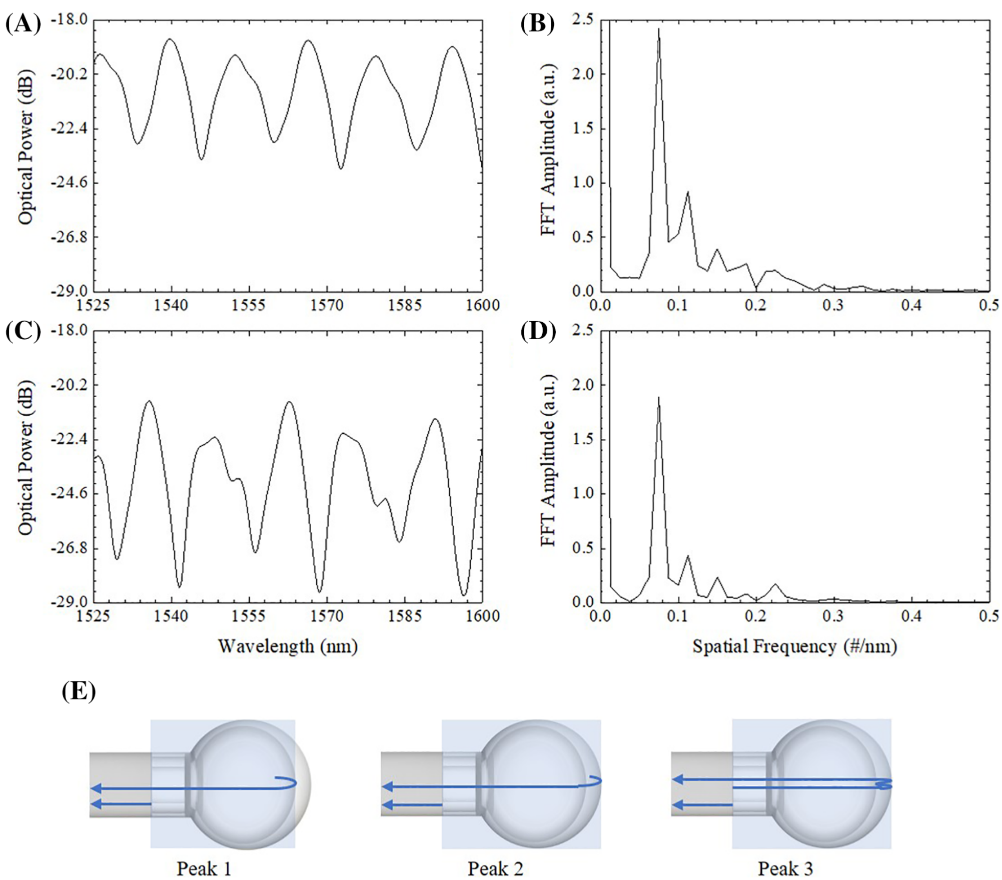


**FIGURE 3** Reflection spectrum of sensor A (A) and sensor B (C). FFT (B) of sensor A and (D) sensor B. (E) Schematics of the cavities related to each peak present in the FFT signal [Color figure can be viewed at wileyonlinelibrary.com]

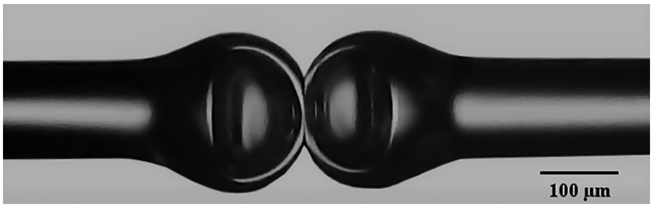


**FIGURE 4** Microscope photograph of the resultant 2-microspheres structure with sensor A on the left and sensor B on the right

optical circulator and an optical spectrum analyzer (OSA), with a resolution of 0.05 nm.

The 1-microsphere structure will create multi-beam interference between the reflected waves at the several silica/air interfaces. In Figure 3A,C, the reflection spectrum of Sensors A and B is respectively presented. Performing a fast Fourier transform (FFT), is possible to attain the main components of the resultant spectrum. The FFT signals of Sensor A and B are presented in Figure 3B,D, where is visible multiple peaks. The spatial frequency of the several peaks is related to the multiple cavities formed in the sensing structure. The first peak is related to the air cavity of the sensors, with a calculated length of 91.6 and 90.5 µm for Sensors A and B, respectively. The second peak is related to the cavity composed by air and the silica wall, as schematized in Figure 4E. The calculated cavity length for Sensor A was 29.6 and 31.7 µm for Sensor B. The third peak corresponds to the cavity formed by the light that travels in the air gap and twice in the silica wall, interfering with the light reflected in the SMF/air interface, as schematized in Figure 3E in Peak 3.

## 3.2 | Two-microsphere structure

The 2-microsphere structure was characterized using an interrogation system in transmission mode composed by a broadband source and an OSA. The broadband optical source had a bandwidth of 100 nm, centered at 1550 nm, and the OSA had a resolution of 0.05 nm. The optical source was connected to the side of the sensor corresponding to Sensor A. The normalized transmitted signal and the respective FFT presented in Figure 5A,B correspondingly, can be used to determine the cavity lengths of the structure.

From the spatial frequency of the FFT peaks is possible to attain the major contributions to the transmitted signal, as shown in Figure 5C. The first peak of the FFT signal relates to the silica cavity, schematized in Figure 5C, with a cavity length of 76.7 µm which corresponds to a length of 53.1 µm for a refractive index of 1.444. The second peak is related to the air and silica cavity formed, corresponding to a length of ~164 µm (~ 77 + 90 µm), agreeing with the value calculated for the air cavity Sensor B. The third peak relates to the light that is reflected at the air/silica interface and travels twice in the silica cavity before being transmitted to the SMF, corresponding to a cavity length of ~238.3 µm (~2 × 76.7 + 90 µm).

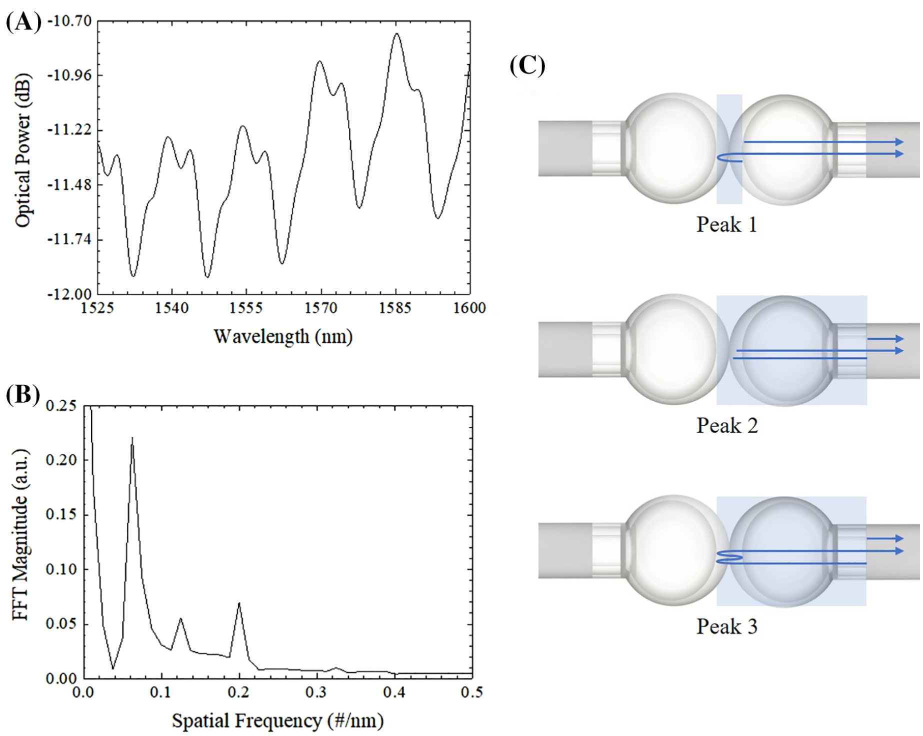


**FIGURE 5** (A) Transmission spectrum of the 2-microsphere structure and (B) respective FFT; (C) schematics of the cavities related to each peak presented in the FFT signal [Color figure can be viewed at wileyonlinelibrary.com]

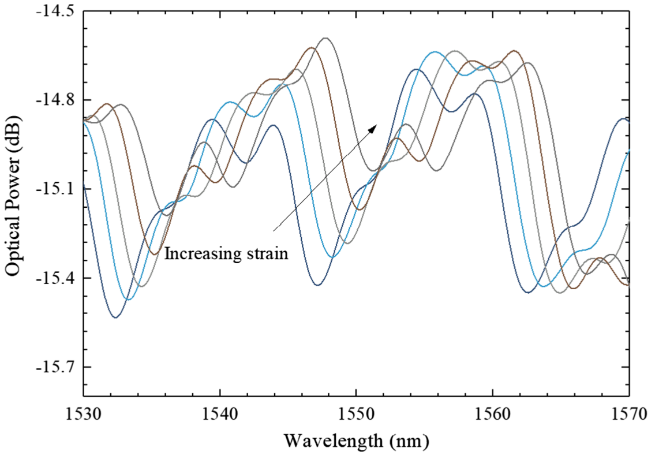


**FIGURE 6** Spectral variations due to the applied strain [Color figure can be viewed at wileyonlinelibrary.com]

## 4 | EXPERIMENTAL RESULTS

The sensing structure was characterized in strain and temperature using a transmission setup, with a broadband source and an OSA, with 0.05 nm resolution. The strain characterization was performed by placing the side corresponding to Sensor A on a fixed block, while the side corresponding to Sensor B placed on a translation stage with 0.01 mm resolution. By varying the distance between the 2 fixed points, strain was applied to a maximum of 1350 με. The strain caused deformation on the structure, varying the cavity lengths and, thus, the spectrum as presented in Figure 6.

By tracking a local minimum centered at 1550 nm, the wavelength shift was attained as presented in Figure 7. The 2-microsphere structure presents a linear response on the studied range with a strain sensitivity of 3.39 ± 0.04 pm/με. This result is almost 4 times higher than the one achieved for 2 solid microspheres, as proposed by Ferreira et al.,[15]where an absolute sensitivity of 0.87 pm/με was attained. In Figure 7, the line marked as reference15 represents a linear equation with a slope of 0.87 pm/με (absolute sensitivity), as achieved from,[15] for comparison with the strain sensitivity achieved in this work (3.39 pm/με).

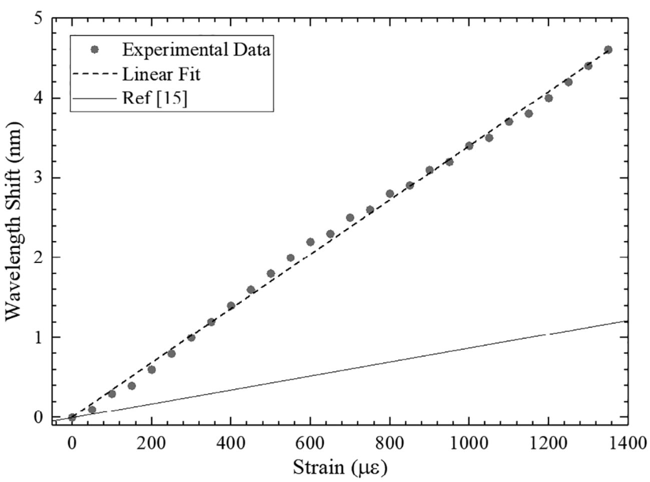


**FIGURE 7** Strain characterization for values between 0 and 1350 με, attaining a sensitivity of 3.39 ± 0.04 pm/με. The line marked as Ref. 15 represents the strain sensitivity achieved in Ref. [15]

For the temperature characterization, a similar sensor was placed in a tubular oven with varying temperature. The transmission interrogation system was used for acquiring data. Temperature variations create a variation on the refractive indexes of the air and silica due to the thermo-optic effect as well as cavity length variations due to thermal expansion of the silica.

The temperature was varied between 400 and 800°C, with decreasing temperature. In the studied range, the response is non-linear due to the multiple effects that occur in the structure. By performing a linear fit is possible to attain an average sensitivity of ~4.7 ± 0.5 pm/°C. The attained sensitivity is around 4 times lower than the achieved for solid microspheres (~ 20 pm/°C).[15]

## 5 | CONCLUSIONS

In this work, a Fabry-Perot-based sensor was proposed for strain measurement. The sensing structure, composed by 2-coupled hollow core microspheres, was fabricated using fusion splicing. The sensor was subjected to strain, achieving a sensitivity of 3.39 ± 0.04 pm/με for a 1350 με maximum strain. When compared with a similar sensing structure presented in literature, the sensor has an almost 4 times higher strain sensitivity. Temperature characterization was also performed, for temperatures between 400 and 800°C. In the studied range, an average sensitivity of 4.7 ± 0.5 pm/°C was achieved. The easy and fast fabrication process, with no chemical hazards, combined with suitability to be used in harsh environments makes the proposed sensor a compelling solution for strain measurements.


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