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Fabry-Perot cavity for curvature measurement in a medical needle

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ABSTRACT

A reflective fiber optic sensor based on a Fabry-Perot cavity made by splicing two sections of multimode fiber is demonstrated to measure the needle curvature. The sensing structure was incorporated into a medical needle and characterized for curvature and temperature measurements. The maximum sensitivity of -0.152dB/m^{-1} was obtained to the curvature measurements, with a resolution of 0.089m^{-1}. When subjected to temperature, the sensing head presented a low temperature sensitivity, which resulted in a small cross-sensitivity.

Keywords: Curvature sensing, Fabry-Perot microcavities, graded-index, fiber optic sensors.

1. INTRODUCTION

The needle insertion procedures are commonly used for surgical interventions, diagnostic and therapeutic applications. Therefore, it is extremely important developing miniaturized sensors that are capable of being incorporated into such needles and be capable of measuring physical, chemical, or biochemical parameters [1, 2].

The Fabry–Perot (FP) interferometers can be a type of sensing structure to be explored due to the ability of producing sensing probes that can be optically interrogated in a reflection configuration. A popular configuration is the fiber microsphere to form FP interference. The first works based on the use of spherical air bubbles as sensing element were applied for strain sensors [3, 4], since then, several works with air bubbles have been presented [5-8]. The optical fiber offers a great solution for curvature measurements due to its intrinsic characteristics, such as compact dimensions, lightweight, capability of multiplexing, immunity to electromagnetic interference, chemical inertness, and the resistance to corrosion [5]. For the case study, curvature sensing in medical needles, optical fiber sensors based on fiber Bragg grating sensors have already been reported [1, 9-11].

In the present work, the development of a FP air cavity made by splicing two sections of multimode fiber is proposed. The sensor was incorporated into a medical needle and characterized for curvature measurements. To the best of our knowledge, it is the first time that the curvature of a medical needle with a Fabry-Perot sensor has been studied.

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1 Fabrication process and experimental setup

The FP cavity developed in this work was obtained by producing an air bubble between two sections of multimode fiber (MMF GIF625, supplied by Thorlabs, Newton, NJ, USA) using a splicing machine (Fujikura 62S) and aligned using the manual mode. The procedure used to fabricate the sensing devices is adapted from [5]. The parameters used to produce the microcavities were found empirically. However, once they were set, it was possible to reproduce the sensor and fabricate it with the desired dimensions. The length of the sensing device was measured through microscope photograph, whereas the two adjacent peak wavelengths were obtained from the sensing head spectral response, and it was determined to be of 225 µm.

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The spectral response of this sensing structure was observed by connecting it to an optical circulator. A broadband optical source (bandwidth of 50 nm, centered at 1550 nm), and an optical spectrum analyzer (OSA Yokogama, AQ6370C) were connected to the other two ports of this optical component, in a typical reflection scheme, as shown in Figure 1. The circulator provides interrogation of the sensing head in reflection and the OSA reads the spectral response of the sensing head with a resolution of 0.1 nm and 0.01 dB.

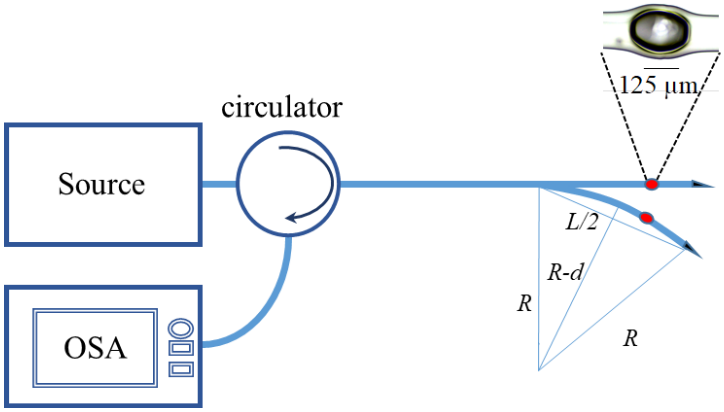

Figure 1. Scheme of the experimental setup and microscope image of the curvature sensor.

2.2 Curvature sensing

In curvature study, the handle of the needle was fixed on the adjustable platform and stacked on the surface of the steel ruler. The displacement along the needle was applied with a translational platform. The needle used throughout this work is 70 mm long, an internal diameter of 0.34 mm, whereas the uncoated optical fiber diameter is 0.125 mm. The location of the sensor is about 10 mm from the tip of the needle. The curvature expression could be calculated by the geometric relationship [12]:

$$C = \frac{1}{R} = \frac{2d}{d^2 + L^2} \quad (1)$$

A curvature study was carried out using a translation stage and subjecting the needle with the sensor to curvature variations. The needle was placed parallel to the translation stage and a displacement was applied (recall Figure 1). In Figure 2 are shown the reflection spectra of the developed cavity, during the curvature tests in the needle. As it is possible to observe there is a variation in light intensity. This is due to the variation of the curvature radius which will influence the coupling efficiency of the FP mirrors.

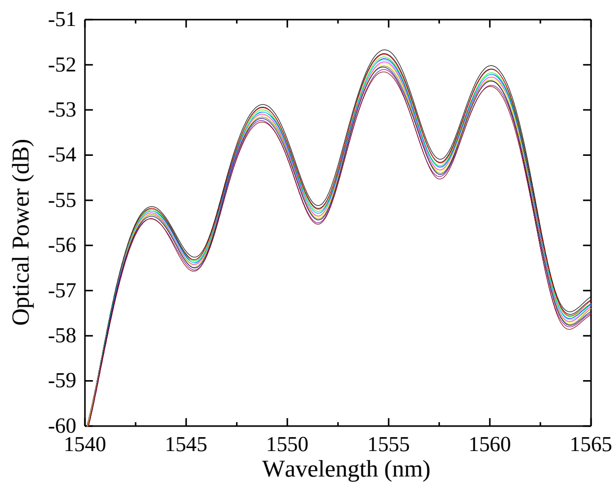

Figure 2. Spectral response of the FP cavity during the curvature tests.

Figure 3 shows the optical power response of the both rotations on the needle. The experimental data was well adjusted for a linear function. All the experiments were performed several times and by considering both the increase and decrease of curvature. There was good reproducibility of the results, evidencing the reversibility of the sensing structure. From Figure 3, it is visible the relationship between the sensing structure and the rotation of the needle. By turning the needle 90º (Figure 3b), the sensing structure presents a residual sensitivity to curvature, while with a 0° rotation of the needle, a maximum sensitivity of -0.152 ± 0.006 dB/m^{-1} is obtained (Figure 3a).

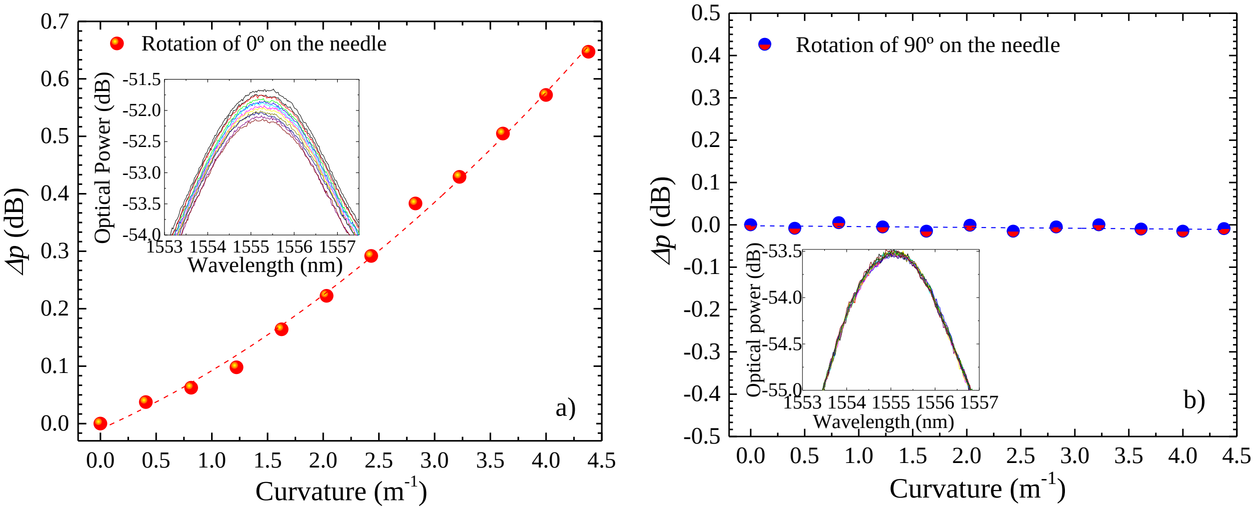

Figure 3. Curvature responses of the sensor head for two different rotation on the needle.

The required needle curvature depends on the clinical application under consideration. In Figure 4, it is presented the relation between the optical and the radius of curvature. This result shows that the sensor is suitable for radius of curvature between ~ 228.22 mm and ~ 818.16 mm, ideal for a few medical applications [13, 14].

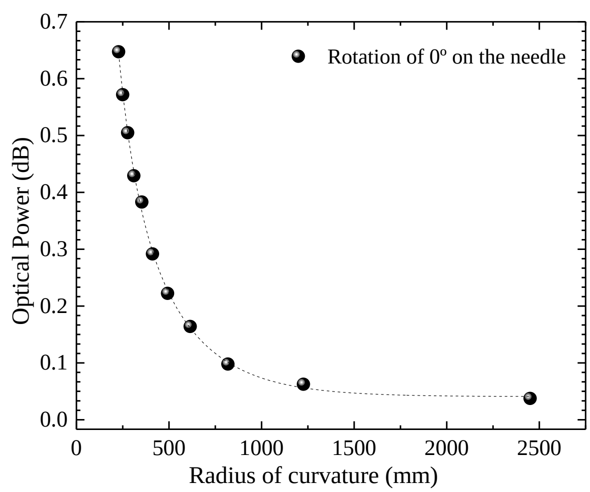

Figure 4. Radius of curvature response of the sensing structure.

The temperature response of the FP was also studied. It was used a thermal chamber (Model 340, challenge Angelantoni Industry) and the optical power variations were monitored by using the same interrogation scheme as shown in Figure 1. The temperature was raised in steps of 10 °C, from 10 °C until 100 °C, and maintained ca. 30 min at each step in order to ensure temperature stabilization. The same process for the cooling was followed. The proposed sensor exhibited very low thermal dependence (4.87×10^{-3} ± 0.002dB/ºC). The cross-sensitivity between this parameter and curvature was 0.03m^{-1}/ºC.

3. CONCLUSIONS

In summary, a microcavity sensor was fabricated by using the electric arc discharge technique to create an air bubble between two sections of a multimode fiber. The sensing head was subjected to curvature measurements, and it was evident the relationship between the sensing structure and the rotation of the needle. By turning the needle 90º, the sensing structure only has a residual sensitivity to curvature, while with a 0° rotation of the needle, a maximum sensitivity of -0.152 ± 0.006 dB/m^{-1} was obtained. The sensor was also tested to the temperature variations and the proposed FP demonstrated a residual sensitivity to the temperature, proving a maximum cross-sensitivity of 0.03m^{-1}/ºC. This kind of measurements can be considered an added value both for industry (in the manufacture of medical needles) and medicine, i.e., in different surgical procedures that require precision when inserting the needles into different soft tissues.

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