Optical sensors

Single-Mode-Multimode-Single-Mode Fiber (SMS): Exploring Environmental Sensing Capabilities

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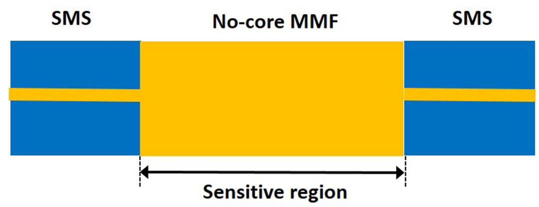

Abstract—In this letter, we study the environmental sensing capabilities of a single-mode-multimode-single-mode (SMS) fiber in a simple low-cost configuration. SMS fibers exhibit sensitivity to temperature, humidity, refractive index, and strain, making them suitable for numerous applications in telecommunications, environmental monitoring, and more. Experimental results demonstrate that the sensor achieves a maximum temperature sensitivity of 4.53 nm/°C. In addition, SMS fibers can also work as humidity sensors by absorbing or releasing moisture, leading to variations in the refractive index. Monitoring these changes allows for precise humidity measurements, with a sensitivity of 0.1548 nm/%RH. Moreover, SMS fibers show a refractive index sensitivity of 39.65 nm/RIU and strain sensitivities as high as 1.062 nm/$\mu\varepsilon$, indicating good performance.

Index Terms—Optical sensors, fiber optics single-mode fiber (SMF), multimode fiber (MMF), sensitivity.

I. INTRODUCTION

Optical fiber sensors are extensively employed across various industrial sectors owing to their compactness, lightweight nature, rapid response time, high sensitivity, immunity to electromagnetic fields, and ability to function effectively in harsh environmental conditions [1]. A diverse range of intrinsic optical fiber sensors utilizing different technologies are available, including single-mode-multimode-single-mode (SMS) configurations [2], [3], Fiber Bragg grating setups [4], and optical fiber surface plasmon resonance systems [5], [6], among others. Many of these technologies rely on interference phenomena, resulting in multiple dips and peaks in the wavelength spectrum. The SMS structure consists of two single-mode fibers (SMF) spliced at both ends of a multimode fiber (MMF), facilitating a straightforward fabrication process [7], [8]. The dip wavelength can be adjusted based on the length and radius of the MMF [9]. SMS sensors find utility in diverse applications, including strain measurement [10], [11], temperature sensing [11], [12], determination of refractive index (RI) [13], and monitoring relative humidity (RH) levels [14], among others.

Fiber optics has been a cornerstone of modern telecommunications and data transmission, revolutionizing the way we connect and communicate over long distances. Among the various types of optical fibers, SMS stands out as a specialized and intriguing choice. SMS fibers offer unique characteristics, making them particularly suitable for applications beyond traditional data transmission.

In this letter, we delve into the world of SMS fiber and explore its fascinating potential as a simple low-cost sensor for environmental variables, such as temperature, humidity, RI, and strain. The SMS fiber structure sensor can offer low cost and simple fabrication process. These capabilities have far-reaching implications for industries ranging from telecommunications to environmental monitoring.

II. SMS FIBER: AN OVERVIEW

A. Structure and Characteristics

SMS fiber is defined by a single core surrounded by a cladding layer. Unlike multimode fibers, SMS fibers support only a single propagation mode, which results in minimal signal dispersion. This characteristic makes them highly suitable for long-distance data transmission. The SMS configuration comprises two identical SMF spliced at both ends of a multimode no-core fiber (NCF). As the light beam travels from the SMF into the NCF, it excites a multimode propagating wave. Each mode within the NCF travels with a distinct propagation constant, leading to intermodal interference.

B. Sensing Capabilities

One of the lesser known aspects of SMS fiber is its sensitivity to external factors. This sensitivity arises due to changes in the core's RI, which can be influenced by environmental conditions.

Here, we discuss how SMS fiber can be used as a low-cost sensor for temperature, humidity, RI, and strain, following the setup of Fig. 1, resulting in the transmission spectra of Fig. 2, and being characterized by (1), where D and n are the NCF diameter and RI, respectively, and λ is the operational wavelength [15]. According to the experimental section, D is 125 μm for a standard SMF. Consequently, just by fixing the RI and the operational wavelength, the length of the NCF segment can be determined.

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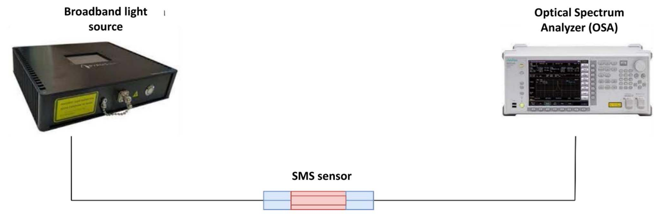

Fig. 1. Setup of the SMS fiber interferometer.

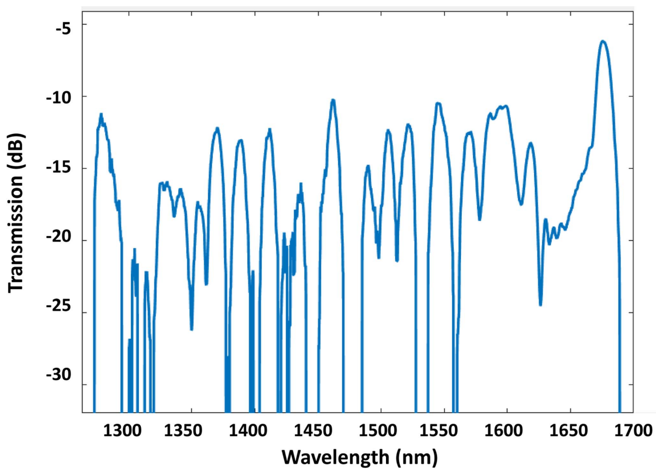

Fig. 2. Transmission spectra of the SMS fiber interferometer and equation for its behavior.

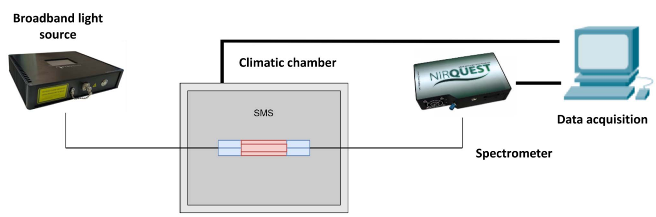

Fig. 3. Setup used to measure temperature sensing across the SMS fiber interferometer.

The effects of strain and temperature cross-sensitivities must be considered in sensor design. We maintained a constant environmental temperature, as practical applications often use temperature-stabilized systems to address temperature dependence. In addition, we fixed the optical fiber's sensing portion inside specially developed packaging to prevent strain, keeping it straight or slightly tensioned.

C. Temperature Sensing

Temperature plays a crucial role in various applications, including industrial processes, energy management, and environmental monitoring. SMS fibers exhibit changes in their optical properties in response to temperature variations. By measuring the shifts in the fiber's spectral response, temperature changes can be accurately detected.

The next point consisted of the measurement of temperature by means of the SMS structure. For this purpose, a 60 mm segment of NCF was used in the SMS. To control the temperature at which the SMS was, a climatic chamber has been used. An assembly summarized in Fig. 3 was made, in which the temperature inside the climatic chamber—and, therefore, of the optical fiber—is regulated by the user through a software installed on a computer.

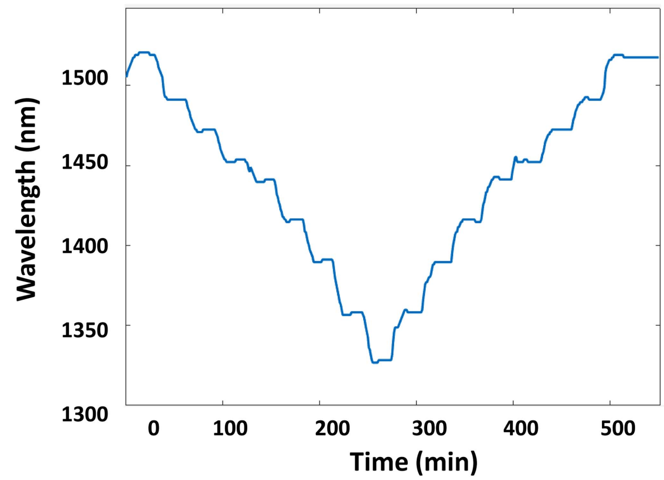

Fig. 4. Wavelength shift throughout the experiment.

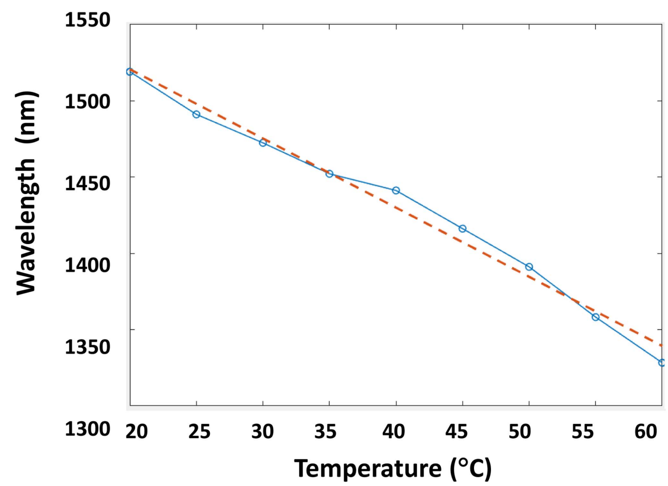

Fig. 5. Wavelength shift versus temperature, and linear adjustment.

The software that monitors the conditions inside the climatic chamber is called APT-COM4. This software allows to define a temperature and humidity program that the climatic chamber must follow and put it into operation during the times established for each of the intervals.

As in the measurement in the previous section, a broadband source is used to generate the signal. This signal is filtered by the SMS and is captured by NIRQuest, an infrared frequency spectra analyzer—but that covers the frequency band of interest, around 1550 nm. The NIRQuest sends the data via a USB port to the computer, where it can be viewed and saved with the OceanView software.

$$Z_i = \frac{4D^2 n}{\lambda} = 54.21 \text{ mm}. \quad (1)$$

Once the data have been stored in ASCII files, it is necessary to create a program that is capable of processing it and representing the corresponding graphs. MATLAB scripts were used, given the large computing capacity it presents and the ease with which it transforms data into matrices, and operates with them.

Fig. 4 represents the SMS transmission spectrum with respect to time when the temperature is increased. It is possible to assign the corresponding temperature value to each frequency step, making it possible to represent the wavelength as a function of temperature, in order to calculate the sensitivity of the SMS. Based on Fig. 5, it is

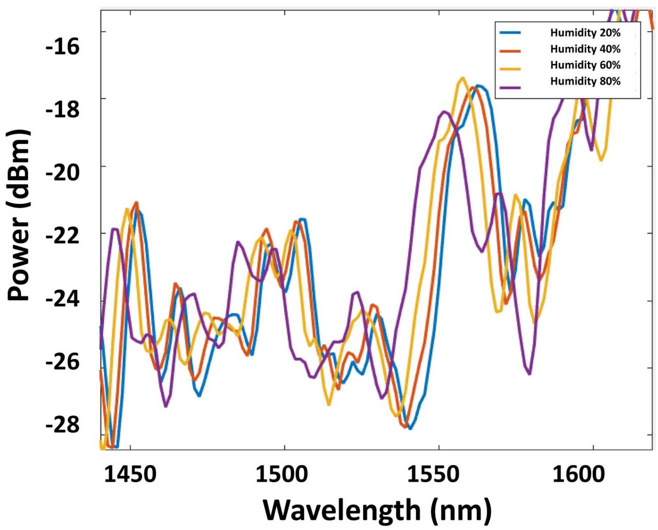

Fig. 6. Power variation with 20%, 40%, 60%, and 80% relative humidity changes (RH).

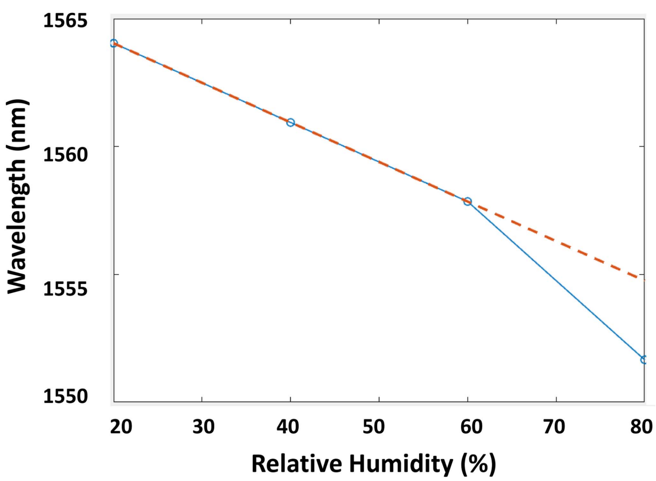

Fig. 7. Wavelength shift with RH changes.

possible to conclude that the fiber behaves linearly against temperature. The sensitivity of the SMS against temperature changes is 4.53 nm/°C.

D. Humidity Sensing

Humidity levels influence a wide range of industries, from agriculture to air conditioning systems. SMS fibers can serve as humidity sensors by absorbing or releasing moisture, leading to RI variations. Monitoring these changes allows for precise humidity measurements in various settings, as shown in Fig. 6. According to Fig. 7, the humidity sensitivity obtained is 0.1548 nm/%RH.

E. RI Sensing

The RI of a medium is a fundamental property that affects the speed of light propagation. SMS fibers are highly sensitive to changes in RI, making them valuable for detecting alterations in the surrounding medium. This capability has applications in chemical sensing and liquid detection. Table 1 represents the RI cross-sensitivity for different solutions.

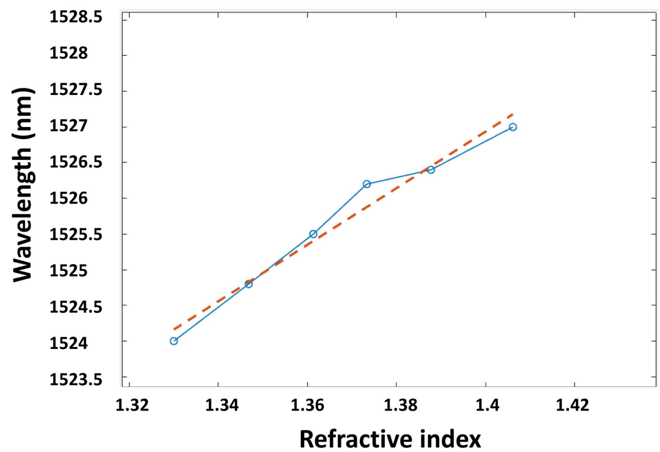

Fig. 8. Variation of wavelength with respect to RI changes.

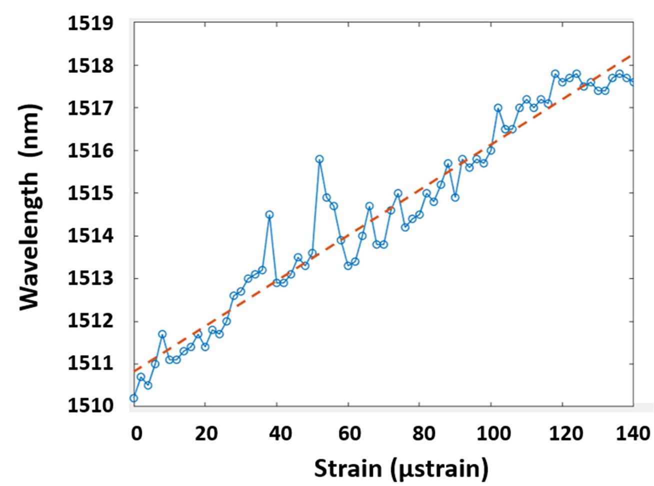

Fig. 9. Wavelength shift versus strain, and linear adjustment.

TABLE 1. Refractive Indices and Position of the Transmittance Peak for Each Solution

Solution	Refractive index	Transmittance peak position (nm)
Water	1,33	1524
Gliceryn 10%	1,3468	1524,8
Gliceryn 20%	1,3613	1525,5
Gliceryn 30%	1,3733	1526,2
Gliceryn 40%	1,3877	1526,4
Gliceryn 50%	1,4061	1527

Regarding Table I, the sensor was immersed in water and different glycerol in water solutions (10%, 20%, 30%, 40%, and 50%, respectively). These solutions correspond with refractive indices 1.33, 1.3468, 1.3613, 1.3733, 1.3877, and 1.4061, as shown in Table I. In view that the maximum variation from water to glycerol 50% is 3 nm, it can be said that the cross-sensitivity to RI in the RI range 1.33–1.4061 is 39.42 nm/RI unit (nm/RIU). According to Fig. 8, the sensitivity to the RI is 39.65 nm/ RIU.

F. Strain Sensing

The frequency shift of the SMS transmission spectrum was studied. In our measurements, we tracked the highest peak in the transmission power spectrum within the band of interest for the SMS.

Specifically, the peak located at 1510.2 nm was followed. As can be seen in Fig. 9, the SMS shows a linear behavior: the spectrum moves to higher wavelengths as it is subjected to greater deformations. A mobile platform was used, which allows to move by means of a wheel with great precision. The displacements can be 50 parts of a millimeter, that is, 20 μm.

A microdeformation unit of elongation, equivalent to 20 μm, shall henceforth be defined. Based on data from Fig. 9, a linear interpolation can be performed, the slope of which is 0.0531 nm per $\mu\varepsilon$. Therefore, the sensitivity of SMS is 1.062 nm/$\mu\varepsilon$.

III. CONCLUSION

In summary, SMS is not just a medium for data transmission; it possesses unique properties that makes it an excellent candidate for environmental sensing. With its sensitivity to temperature, humidity, RI, and strain, SMS fiber opens up a world of possibilities for applications in telecommunications, environmental monitoring, and beyond. In addition, it is a simple, low-cost, and easy to fabricate sensor, enhancing its appeal for various fields. The experimental results show that the sensor accomplish a maximum temperature sensitivity of 453 nm/°C. SMS fibers also offer a humidity sensitivity of 0.1548 nm/%. They are highly sensitive to changes in RI, making them valuable for detecting alterations in the surrounding medium. According to experiments, the sensitivity to the RI is 39.65 nm/RIU. This capability has applications in chemical sensing and liquid detection. Finally, the sensitivity of SMS to strain is 1.062 nm/$\mu\varepsilon$.

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