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Optical sensors

Highly sensitive sensor for measuring material thermal expansion using a ring laser

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Abstract— A new thermal expansion sensor is presented in this research. It combines an interferometric fiber sensor and an erbium-doped fiber ring laser as the light source. The sensor consists of a combination of single-mode, hollow-core and no-core mirror fibers. The sensor was tested on two different types of based metal, such as aluminum and steel, giving sensitivities as high as 38.7 nm/ºC and 5.75 nm/ºC, respectively, showing good performance.

Index Terms—Erbium-doped fiber (EDF), Hollow-core fiber, optical sensors, ring laser.

I. INTRODUCTION

In many fields, such as aerospace and marine environmental monitoring, thermal expansion measurement is an important issue. The increase in length or volume suffered by a body (whether gas, liquid or solid) due to the increase in temperature, is known as coefficient thermal expansion (CTE), being thermal contraction the opposite effect. The CTE is defined as the fractional increase in length per unit rise in temperature. If the material is characterized by an equation of state, the values of thermal expansion could be predicted at all required temperatures and pressures [1]. For example, the CTE for aluminum is 23 x 10^{-6} ºC^{-1}, 12 x 10^{-6} ºC^{-1} for steel and 9 x 10^{-6} ºC^{-1} for glass, where they have larger CTE compared to pure silica, which is 4.1 x 10^{-7} ºC^{-1} [2]. For instance, aluminum exhibits a CTE of 23 x 10-6 ºC^{-1}, steel has a CTE of 12 x 10-6 ºC^{-1}, and glass possesses a CTE of 9 x 10-6 ºC^{-1}. Comparatively, these materials have larger CTE values than pure silica, which stands at 4.1 x 10-7 ºC^{-1} [2].

Considerations for thermal expansion play a crucial role when constructing civil infrastructures like bridges, tunnels, and skyscrapers, as well as in the development of railway lines. Expansion joints are implemented in road bridges to prevent damage caused by thermal expansion. Additionally, thermometers and bimetallic strips serve as notable examples of practical applications [3–5]. The design and functionality of an optical fiber device used for temperature sensing and measuring thermal expansion are detailed in [2]. By leveraging the distinct coefficients of thermal expansion between fused silica and metallic materials, highly effective temperature-sensitive sensors are achieved [6].

In recent years, there has been significant interest in optical fiber sensors, mainly due to their advantageous characteristics such as compact size, immunity to electromagnetic interference, and durability. Various techniques have been employed to develop fiber optic temperature sensors, including fiber Bragg gratings (FBGs) [7], long-period fiber gratings (LPFGs) [8,9], and different fiber interferometer configurations [10,11], all utilizing silica as the temperature sensing element. However, sensors solely based on fiber design exhibit minimal temperature sensitivity owing to the low thermal expansion coefficient of silica.

To enhance the sensitivity of fiber-optic sensing systems, researchers have recently proposed several approaches, such as employing cascaded interferometers or microfiber structures [12,13]. Among these methods, one of the most notable and effective techniques involves the integration of fiber lasers with fiber-optic sensors. Leveraging the advantages of fiber lasers, including high signal-to-noise ratio (SNR), excellent stability, and narrow bandwidth [14], fiber laser sensors offer a promising avenue for advancing sensing research [15,16].

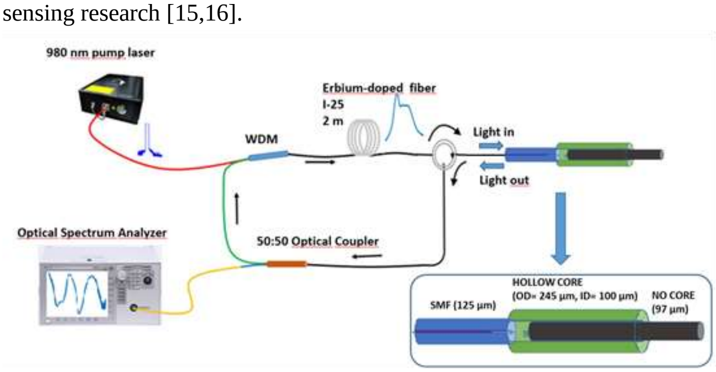

Fig. 1. Setup of the experiment. WDM: Wavelength-division multiplexer, SMF: Singlemode fiber.

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In this paper, we report a very simple highly sensitive hollow-core fiber (HC) interferometer based on the significantly dissimilar coefficients of thermal expansion between pure silica and metallic materials, such as aluminum and steel. Those plates have been used because of their different coefficient thermal expansion at the range of temperature going from 23°C to 70°C, being interesting to study their behavior. The structure was inserted into an erbium-doped fiber ring laser cavity to interrogate the sensor to improved detection accuracy and to enhance the sensitivity measurements.

The proposed sensing structure improves on existing fiber optic sensors by utilizing a fiber optic ring laser setup, which can detect even the slightest changes in the length of the metal plate caused by thermal expansion. The optical feedback in the fiber ring laser amplifies the signal, resulting in a higher sensitivity than existing fiber optic sensors.

Two sensor systems have been analyzed in this work for creating cavities for fiber lasers. Experimental results have been carried out with these structures and good repeatability and stability have been shown. The proposed laser sensing system offers several advantages, including ease of implementation, robust stability, and high temperature sensitivity. As a result, it holds promising prospects for applications that demand precise temperature control within a relatively narrow measurement range. The integration of fiber lasers with fiber-optic sensors significantly enhances their performance, benefiting from attributes such as high signal-to-noise ratio (SNR), excellent stability, and narrow bandwidth.

II. PRINCIPLE AND SENSOR FABRICATION

The experimental setup is shown in Fig. 1. The sensor is built using three types of fibers: Single-mode fiber (SMF), hollow core fiber (HC) and no-core fiber (NC). As shown in Fig. 1, a ring laser cavity is proposed as part of the sensor configuration. The pump laser used is a 976 nm, 300 mW butterfly laser from PyroisTech, S.L., the 2 m of highly erbium-doped fiber named I-15(980/125) from FiberCore, with an absorption of 30 dB/m at 980 nm acting as the active medium and a wavelength division multiplexer coupler (WDM 980/1550 from Opneti) to insert the power into the cavity. The 3-port polarization insensitive optical circulator from Opneti was used to insert the reflected signals into the cavity and to ensure unidirectional operation, and therefore avoiding the spatial hole-burning (SHB) effect. A 50:50 optical coupler from Thorlabs was used to extract the laser output signal to be monitored by an Optical Spectrum Analyzer (OSA). The OSA model used was ANRITSU MS9740A with 0.01 nm minimum resolution bandwidth. The laser includes one ring cavity in a reflective way (as shown in Fig. 1). An optical loop mirror composed of SMF fiber with a 50:50 coupler is inserted in the ring cavity to provide the intensity dependent loss for the lasing wavelengths. Fig. 2 shows the spectrum obtained from the OSA.

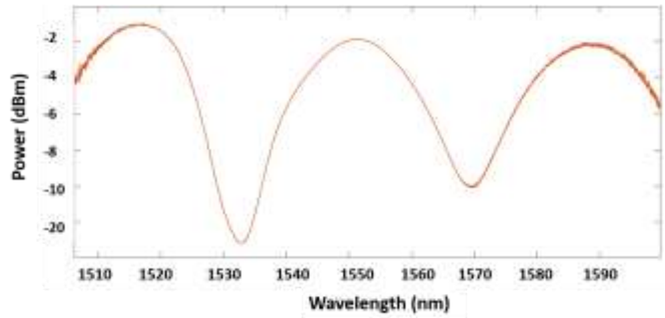

Fig. 2. Output spectrum obtained at the OSA: Optical Spectrum Analyzer.

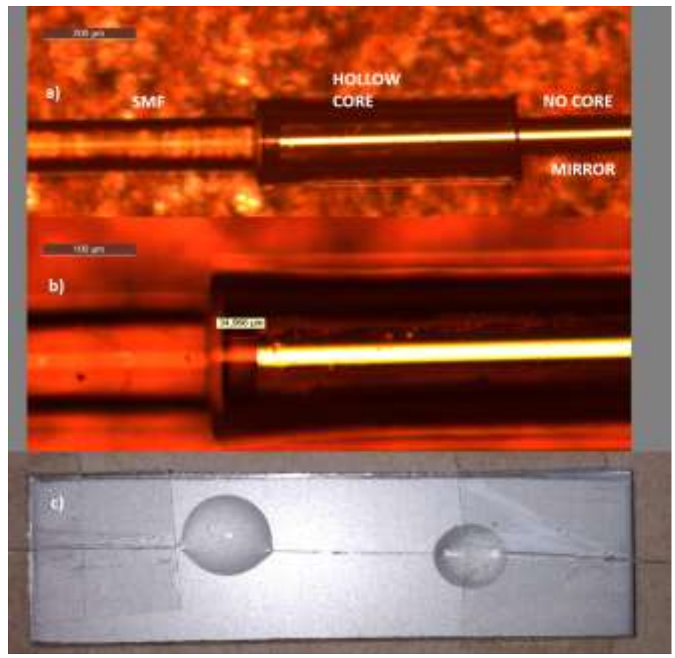

Fig. 3. Image of the sensor fiber microscope, a) Complete image of the sensor where the three fibers appear (SMF-HC-NC. b) Enlarged image where the length of the hollow cavity is appreciated. c) Image of the sensor showing both sides fixed using ultraviolet glue.

The experimental was run at room temperature. Light was propagated through the system and coupled into the sensor. The fiber structure was created by splicing a section of hollow-core multimode fiber (HC) to one end of a standard single-mode fiber (SMF) pigtail from Telnet Redes Inteligentes Inc., and the other end to a no-core multimode fiber from POFC Inc. Initially, the diameters of the SMF and HC were 125 µm and 200 µm, respectively.

To introduce the reflective no-core fiber or mirror into the HC's core, the fiber splicer was operated in manual mode. This allowed for reducing the arc power and splicing time to prevent any potential damage to the HC. Once the interferometer was constructed, both sides of the sensor were securely fixed using ultraviolet glue, as shown in Fig. 3(c).

The HC multimode fiber was subjected to an etching process with HF acid at 20% during 10 seconds, giving rise to a diameter of 100 µm. Also, it was included at the end of the no-core fiber, a silver mirror by using the sputtering technique during 10 seconds, to make it a reflective structure.

The SMF fiber used in our experiment has a core diameter of 8 μm and a cladding diameter of 125 μm, with a numerical aperture of 0.14. The HC fiber has a hollow core with an inner diameter of 100 μm and an outer diameter of 245 μm. The NC fiber has a diameter of 115 μm, which is reduced to 96 μm using the etching process. The core and cladding materials of fibers are silica (SiO2), with refractive indices of approximately 1.45 and 1.44, respectively.

The light received from the pump source arrives to the fiber structure and its reflection goes to an OSA. Regarding the path of the light, it follows the 8 μm core of the SMF in the form of confined beams with the same phase and trajectory until they reach the core of the hollow-core fiber of 100 μm. Then, the light is scattered and the modes follow different trajectories until reaching the reflective element (fiber of 96 μm with the mirror), where each of these trajectories bounce creating interferometries within the HC fiber. The manufacturing process was constantly monitored, as the no-core fiber was introduced into the HC fiber, analyzing the different interferometries generated.

The SMF receives the reflected light containing the information of the interference spectrum, and this light is sent through the circulator to the OSA, by using the 50% optical coupler, as shown in Fig. 1.

As a sensor, an interferometer based on hollow-core fiber is used in reflection mode combining the three different types of fibers.

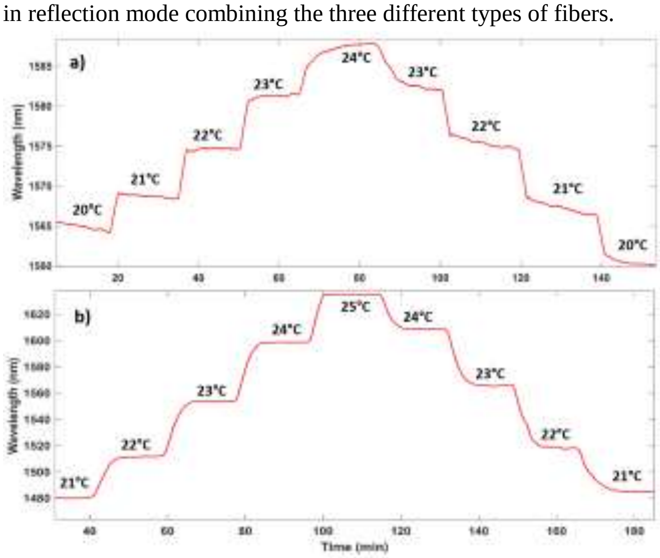

Fig. 4. Wavelength variation when the temperature is changed in steps of 1ºC with the sensor based on a steel plate (a) and with the sensor based on an aluminum plate (b).

III. EXPERIMENTAL RESULTS

The primary objective of this study is to investigate the potential and constraints of a fiber sensor configuration for measuring the thermal expansion of steel and aluminum plates. These materials were specifically selected for analysis due to their disparate coefficients of thermal expansion within the temperature range from 23°C to 70°C. Examining the behavior of these materials under varying temperatures provides valuable insights for the research. This study aims to experimentally investigate the effectiveness and limitation of a sensor configuration for measuring the thermal expansion with temperature of two different metal plates subjected to a local constant temperature. Thus, the aim is to examine the effectiveness of the sensor configuration in measuring the temperature-related changes in the two metal plates, one based on a steel plate and another on aluminum. This sensor is located in a climatic chamber to carry out the temperature measurements.

The interferometer fiber sensor is placed on a steel or aluminum plate and it is submitted to temperature changes. As the temperature of the plate changes, it expands or contracts, causing the lenth of the late to change. The interferometer fiber sensor is part of a ring laser setup, and any change in the length of the sensor changes the laser output signal. This change in wavelength is detected by the optical spectrum analyzer and recorded as a signal. By analyzing the signal, we can determine the coefficient of thermal expansion of the metal plate with high sensitivity. However, there are potential sources of measurement error in this process. One common source of error can be thermal gradients across the metal plate, which can cause uneven expansion or contraction and lead to inaccurate measurements. This have been mitigated by ensuring that the metal plate is uniformly heated or cooled during the experiment and by using temperature sensors to monitor and correct for any temperature gradients.

The focus of this analysis is to evaluate the performance of the sensor configuration as a material thermal expansion sensor. A wavelength measurement is conducted while subjecting the system to temperature variations ranging from 20ºC to 24ºC. The temperature is incrementally adjusted in 1ºC intervals, starting from 20ºC and reaching 24ºC, as depicted in Fig. 5. Initially, the setup presented in Fig. 1 is used with a steel plate, and the corresponding results are displayed in Fig. 4(a). Subsequently, the same setup from Fig. 1 is employed, but this time positioned on an aluminum plate. An experiment is conducted, wherein the temperature is varied between 21ºC and 25ºC in 1ºC steps, ascending to 25ºC and then descending back to 21ºC, as shown in Fig. 4(b).

To determine the behavior of the sensor, the minimum that appears at 1480 nm of the interferometer signal was selected. The graph resulting from the monitoring of the maximum with respect to temperature changes is shown in Fig. 5.

Concerning the repeatability, it is observed in Fig. 4 that the data traces of increasing temperature nearly coincide with those of decreasing temperature, implying that no obvious hysteresis effect is caused by the steel plate of the sensor for repeated changes in temperature. The sensor presents good stability for the same reason. The resulting sensitivity using the sensor based on a steel plate was approximately 5.75 nm/ºC with a thermal expansion coefficient of the steel of $12x10^{-6}$ $°C^{-1}$ (see Fig. 5).

On the other hand, using the sensor based on an aluminum plate, it can be observed that the behavior of the sensor is also repeatable and stable, implying that no obvious hysteresis effect is caused by the aluminum plate of the sensor for repeated changes in temperature. In this case, a best resulting sensitivity of approximately 38.7 nm/ºC is obtained. This is due to the higher thermal expansion coefficient of the aluminum, which is $23x10^{-6}$ $°C^{-1}$ (see Fig. 5). In both sensors, the small deviations could likely be caused by the slightly inadequate transfer of thermal expansion from the steel or aluminum plates to the fiber. Nevertheless, in both cases, the thermal expansion sensitivity is higher than conventional fiber laser sensors, whose temperature sensitivity is about 10 pm°C^{-1} [17].

Concerning the repeatability of the experiment, as shown in Fig. 5, it was obtained a standard deviation of the coefficient of thermal expansion less than 55 nm/°C over five measurement cycles for sensor S1 and less than 0,43 nm/°C for sensor S2. This indicates that our proposed sensing method has good repeatability and can be used for accurate measurement of thermal expansion coefficients.

The dependence of thermal expansion on temperature is summarized in the equation [1]:

$$\Delta L / \Delta T = \alpha L \quad (1)$$

where L is the original length of the material, ΔL is the change in length L of the material owing to the temperature change of ΔT, and α is the coefficient of thermal expansion. As α is nearly constant and also very small, for practical purposes, we use the linear approximation:

$$\Delta L = \alpha L \cdot \Delta T \quad (2)$$

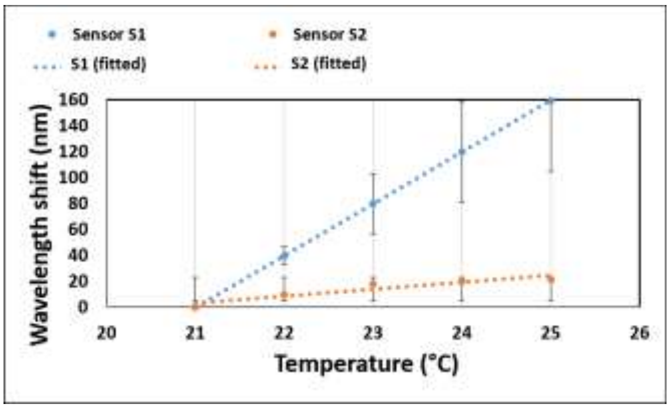

Fig. 5. Wavelength variation with temperature for the sensor S1 based on an aluminum plate in red and for the sensor S2 based on a steel plate in blue.

IV. CONCLUSION

A highly sensitive thermal expansion sensor was developed by integrating SMF-HC-NC fibers into an erbium-doped fiber ring laser configuration. Utilizing the distinct coefficients of thermal expansion between aluminum and steel, thermal expansion measurements were conducted on these structures, revealing excellent stability. Notably, the system employing the aluminum plate demonstrated superior thermal expansion sensitivity, measuring at 38.7 nm/ºC, whereas the system utilizing the steel plate showed a sensitivity of 5.75 nm/ºC. These results underscore the effectiveness of the sensor as a thermal expansion measurement tool. Furthermore, both systems exhibited higher thermal expansion sensitivity compared to conventional fiber laser sensors.

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