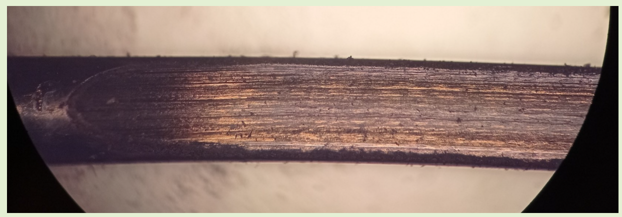
Plasmonic Temperature Sensor Using Side-Polished Plastic Optical Fiber With Gold Coating

A. Fresno-Hernández, B. García-Cámara, and C. Vázquez, *Senior Member, IEEE*



***Abstract*—All-optical sensors offer promising solutions by reducing fabrication complexity, power requirements, and enabling distributed architectures. However, challenges remain in enhancing performance and reducing costs. In this study, we propose a novel temperature sensor design based on a side-polished plastic optical fiber (OF) covered with a gold layer, achieving a high sensitivity of −0.09 nm/°C over a wide temperature range (10 °C–70 °C). In addition, we experimentally explore the influence of various fabrication parameters, including polishing depth, polishing length, and gold sputtering time, on sensor performance, identifying them as critical in the fabrication process. In the considered samples, we found that polishing depths between 0.18 and 0.33 mm and gold deposition times between 20 and 40 s are adequate ranges, with the best performance achieved at a polishing depth of 0.32 mm and a gold sputtering time of 20 s. Our design integrates side-polished OFs with surface plasmon resonance (SPR) sensing, providing high sensitivity and rapid response times. This will facilitate real-time temperature monitoring with high precision, even in hard-to-reach or hazardous environments. The transmission-based measurement method enhances sensor mobility and practical utility. Moreover, our approach demonstrates a simple, cost-effective fabrication process, offering significant advantages over existing SPR-based sensors.**

***Index Terms*— Gold layer, plastic optical fiber (OF), surface plasmon resonance (SPR), temperature sensor.**

I. Introduction

In recent years, sensors have become increasingly essential across various industries, including medicine, manufacturing, and households. They serve to enhance security, expand our understanding and control of different processes, and ultimately improve quality of life. Among these sensors, temperature sensors hold particular significance in numerous fields due to their impact on industrial processes and biological systems. As a result, there is a growing demand for precise temperature measurement, especially in hazardous environments where electronic sensors are impractical. A viable solution in such cases is the use of all-optical sensors [1], particularly optical fiber (OF) sensors. OFs are immune to electromagnetic interference and safe for use in explosive environments, offer excellent galvanic isolation and low attenuation, and are lightweight. In addition, sensors using polymer OF (POF) offer distinct advantages over silica fiber sensors, such as high flexibility, affordability, and ease of manufacturing [2], [3]. They also exhibit superior sensitivity compared to silica fiber sensors due to their larger diameter [4], along with the high thermo-optic coefficient (TOC) of polymers. Moreover, the overall cost, including required optoelectronic components, is low.

Several technologies are available for fabricating temperature sensors in OFs [5]. Many of these technologies rely on structures such as multimode interference (MMI) in silica fibers, which exhibit a sensitivity of −0.068 nm/°C [6]. This sensitivity can be enhanced to −0.082 nm/°C by introducing a misalignment in the input single-mode fiber (SMF) [7], [8], up to −0.1 nm/°C by applying a coating of a polymer with high TOCs(e.g., polydimethylsiloxane (PDMS) or silicone rubber [9]) or even to 0.5857 nm/°C by incorporating tapers into the fiber [10]. Alternatively, sensitivities as high as −4.677 nm/°C can be achieved by employing complex-structure fibers such as noncore fibers (NCFs) [11], hollow-core fibers (HCFs) [12], photonic crystal fibers (PCFs) [13], or four-core fibers [14]. Unfortunately, the fabrication of

Manuscript received 19 July 2024; revised 15 August 2024; accepted 19 August 2024. Date of publication 4 September 2024; date of current version 16 October 2024. This work was supported by grant PID2021-122505OB-C2 funded by MICN/AE 10.13039/501100011033, and by "ERDF A way of making Europe", grant FPU19/04133 funded by Ministerio de Universidades. Funding for APC: Universidad Carlos III de Madrid (Agreement CRUE-Madroño 2024). The associate editor coordinating the review of this article and approving it for publication was Dr. Xuehao Hu. *(Corresponding author: A. Fresno-Hernández.)*

The authors are with Electronics Technology Department, Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain (e-mail: afresno@ing.uc3m.es; brgarcia@ing.uc3m.es; cvazquez@ing.uc3m.es).

Digital Object Identifier 10.1109/JSEN.2024.3451016

these MMI sensors is challenging due to the need for splicing complex fibers, aligning them precisely, and often applying polymer coatings.

Another technology for temperature sensing is fiber Bragg grating (FBG)-based sensors, which exhibit sensitivities ranging from 0.0075 [6] to 0.149 nm/°C when inscribed on POF fibers [15], [16]. However, inscribing FBGs on POF requires special fibers and specialized equipment such as high-power lasers or interference writing systems [15], [17]. In addition, achieving optimal performance of FBGs as temperature sensors requires precise alignment and meticulous control of inscription parameters, making the fabrication process complex and costly.

Another type of POF-based sensor is the intensity sensor, offering a cost-effective solution with a simple interrogation system and sensitivities of 1.92×10^{-3} °C^{-1} [18]. However, these sensors require self-reference techniques to mitigate the negative effects of optical power drifts during measurements [19].

Surface plasmon resonance (SPR)-based sensors overcome some of these drawbacks. When the interface between a thin metal film and a dielectric material is illuminated with a specific wavelength, the light can excite the natural oscillation frequency of the free electrons at the metal–dielectric interface, producing the phenomenon known as SPR. There is a strong confinement of the light in the interface, leading to a significant decrease of the reflectivity on it. The spectral position of the plasmon resonance is strongly sensitive to changes of the refractive index (RI), making it ideal as a refractrometric sensing mechanism [20], [21]. In addition, SPR sensors can also be used to sense other quantities that indirectly affect the RI, such as temperature or humidity, among others.

Over the past years, several SPR-based OF sensors have been developed to detect and monitor chemical, physical, and biological parameters [22]. Since SPRs cannot be excited with direct illumination, conventional OFs cannot be used due to their field confinement via total internal reflection. Therefore, it is necessary an evanescent field to excite the plasmon resonance. This is achieved by tapered OFs [23], single-side polished OFs [24], double-side polished OFs [25], and U-bent OFs.

There are silica-based SPR temperature sensors that typically use a gold (Au) layer in conjunction with PDMS. For instance, when integrated into MMI structures, they achieve sensitivities of −2.85 nm/°C [26]. Others are based on depositing gold on the tip of an SMF, creating a reflective mirror and offering sensitivities of −2.02 [27] or −2.58 nm/°C [28]. Another approach involves creating a taper on a SMF and coating it with silver (Ag), which yields a sensitivity of −0.52 nm/°C [29]. Some sensors are designed to measure multiple parameters simultaneously by fusing multimode fibers (MMFs) with other specialized OFs coated with various metals, achieving temperature sensitivities of −1.29 nm/°C [30], −1.802 nm/°C [31], and −2.82 nm/°C [32]. However, in all of them, the fabrication process is challenging, involving fiber splicing, PDMS deposition, and complex fibers such as NCFs, HCFs, or PCFs. Furthermore, other works suggest that the sensor performance can be improved through the OF surface roughness produced by the polishing [33], [34].

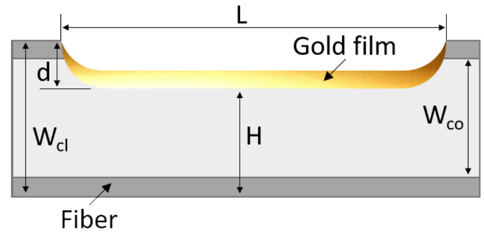


Fig. 1. Schematic of the side-polished POF sensing probe.

There are also temperature sensors that aim to combine the advantages of SPR with those of POF fibers to enhance sensitivity and versatility. These sensors involve polishing the fiber and depositing Au and PDMS, achieving sensitivities of −0.596 nm/°C [35], −0.7 nm/°C [36], or −0.83 nm/°C [37]. However, the fabrication process is again complex due to the need of symmetrically polishing the OF on two sides and depositing PDMS on one of them.

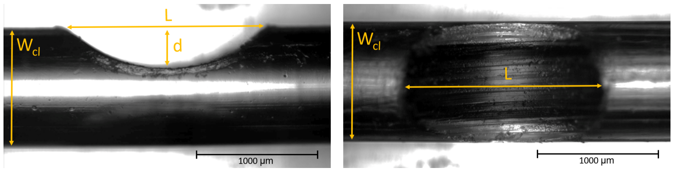
This article presents a temperature sensor based on a single side-polished POF coated with a layer of gold by sputtering. Our sensor provides a wide temperature range and exhibits a sensitivity comparable to other techniques. Moreover, it features a simple and cost-effective fabrication process.

II. Sensor Probe Structure and Manufacturing

The sensing probe is a gold-coated side-polished POF, as shown in Fig. 1, where L represents the length of the polished area; d denotes the polish depth; W_{co} and W_{cl} are the fiber core and cladding diameters, respectively; and H is the residual diameter of the fiber, corresponding to $H = W_{cl} - d$. The OF used in this study is a step-index POF (Rayon Eska SH-4001), with the core and cladding made of polymethylmethacrylate resin (PMMA) and fluorinated polymer, respectively. The core has an RI of 1.49 at 25 °C, a TOC of -1.15×10^{-4} °C^{-1}, and a diameter $W_{co} = 980$ μm; whereas the cladding has a RI of 1.403 at 25 °C, a TOC of -3.5×10^{-4} °C^{-1}, and a diameter of $W_{cl} = 1000$ μm. This configuration has been explored for other kinds of optical sensors, demonstrating the successful excitation of the SPR at the considered wavelength [24], [38], [39].

The initial fabrication step involves peeling and polishing the fiber to remove part of the cladding in the area where the gold layer will be deposited. This process breaks the field confinement, allowing the excitation of plasmon resonances. This side-polished fiber (SPF) can be created using various methods; however, in this study, the wheel side-polishing technique [40] is employed. To ensure consistency and repetitivity, a homemade polishing machine was constructed using a sander and micropositioners, achieving a high accuracy of ±4 μm. The polished fibers resemble those depicted in Fig. 2 [lateral view of an example with $d = 350$ μm and $L = 1.7$ mm in (a) and top view in (b)]. As illustrated in Fig. 2(b), the polishing exhibits a smooth surface, devoid of significant irregularities.

Subsequently, a gold layer is uniformly deposited over the polished region using a sputtering machine LEICA EM ACE 200, obtaining the sample shown in Fig. 3.



(a) (b)

Fig. 2. Manufactured sensor. (a) Lateral view of the polishing. (b) Top view of the polished surface where Au is deposited.

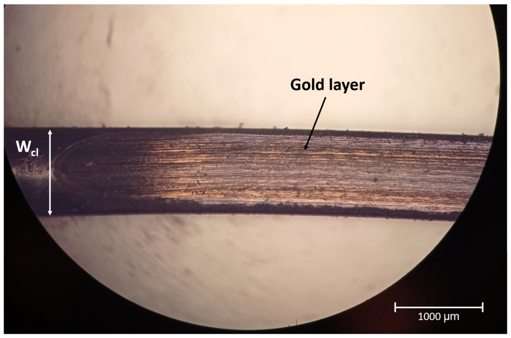


Fig. 3. Au layer deposited on the POF polished surface.

In this work, as it will be described in Section IV, various fiber patchcords with differing degrees of polishing and gold deposition times have been analyzed in order to compare their response and evaluate the influence of the different parameters.

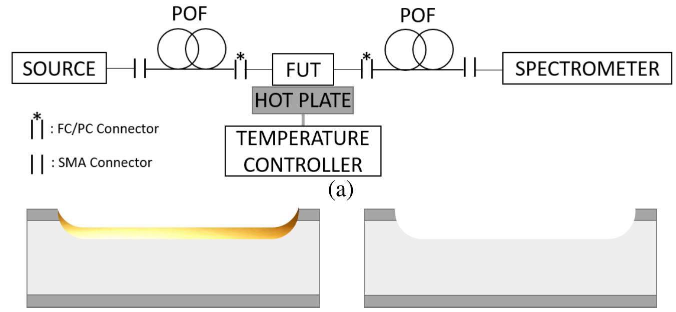
III. Experimental Setup

The proposed sensor is based on the well-established principle of the spectral shift of the plasmon resonance as the RI of the surrounding medium changes. This principle has been extensively documented in previous research about SPR sensors [21], [41], [42]. In this case, the temperature induces a change in the RI of the plastic OF due to its TOC. This change of the RI causes the spectral shift, which will be observed by measuring the spectrum of the transmitted beam through the OF, as shown in Fig. 4(a). Since the sensor relies on the change of the RI with temperature, it is capable of detecting temperature variations continuously and in real time.

As shown in Fig. 4(a), light is directly injected into the fiber using a broadband source with a wavelength range from 360 to 2400 nm (Ocean Insight HL-2000) and detected by a spectrometer (Ocean Insight Flame-S-VIS-NIR). In the characterization process, the three-cord reference method [43] is employed to take into account losses from both connections to the fiber under test (FUT). In addition, since POFs are multimode OFs, precise alignment is critical to ensure consistent illumination. The temperature of the FUT is varied within a range between 10 °C and 80 °C in steps of 10 °C using a hot plate (Instec TS102GXY) controlled by a temperature controller (Instec mk2000), as shown in Fig. 4(a). To ensure uniform temperature across the sample, it is glued to the base of the hot plate with Kapton tape, and the hot plate lid is placed on top to close it.

To isolate the contribution of the plasmon resonances during the measurements, for each temperature, the spectral evolution of the transmitted intensity through the polished OF with the Au layer [FUT 1, Fig. 4(b)] is acquired, corrected by the reference of the sample without Au [FUT 2, Fig. 4(c)], and normalized by the microscope light spectrum (NORM), as can be seen in the following equation:

$$\text{Au signal} = \frac{\text{FUT 1} - \text{FUT 2}}{\text{NORM}}. \quad (1)$$



(a) (b) (c)

Fig. 4. (a) Measuring system of the FUT. Source: ocean insight HL-2000, spectrometer: ocean insight flame-S-VIS-NIR, hot plate: Instec TS102GXY, and temperature controller: Instec mk2000. (b) FUT 1, fiber probe with Au layer. (c) FUT 2, fiber probe without Au layer.

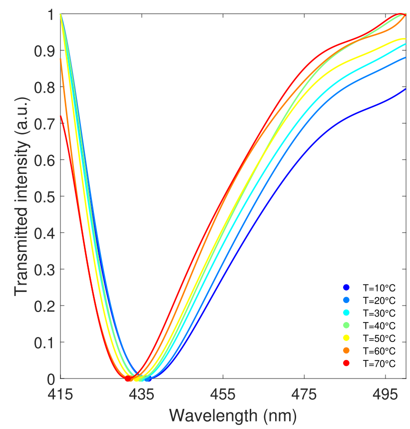


Fig. 5. Spectral transmitted intensity at different temperatures.

IV. Results and Discussion

Fig. 5 shows the spectral measurements for a probe with $d = 0.32$ mm, $L = 13.70$ mm, and 20 s of sputtering time. The transmitted intensity displays distinct minima corresponding to the SPR excitation. As expected, changes in temperature cause a noticeable shift in the plasmon resonance, attributed to variations of the RI of the OF.

Plotting the resonant wavelength as a function of temperature (see Fig. 6) reveals a consistent trend: an increase in temperature correlates with a blue shift of the spectral minima. Furthermore, the data aligns closely with a linear regression fit using least squares in MATLAB, yielding an R^2 value of 0.98, which underscores the viability of the sensor design.

Three main parameters, related to the fabrication process, can affect the sensor sensitivity: polishing depth, polishing length, and gold sputtering time (or gold thickness). To characterize their influence, five sensors with varying characteristics have been fabricated, as detailed in Table I. This table

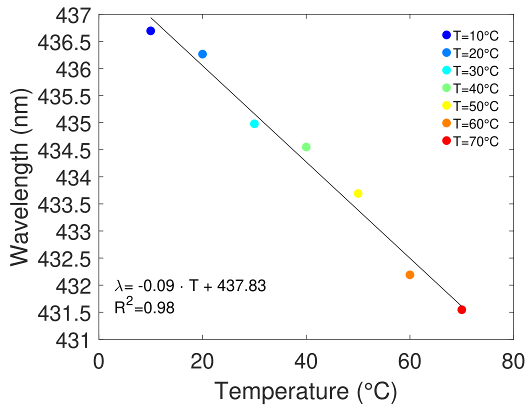


Fig. 6. Measured SPR sensor probe calibrated versus temperature. Dot (measurements) and line (linear adjustment). The dot colors match the colors in Fig. 5.

TABLE I
POLISHED FIBER PATCHCORDS USED IN THIS STUDY

	1	2	3	4	5
d (mm)	0.32	0.18	0.13	0.33	0.30
L (mm)	13.70	12.49	7.55	13.11	13.28
Gold sputtering time (s)	20	40	60	20	40
Sensitivity (nm/°C)	-0.09	-0.10	-0.05	-0.08	-0.08
Temperature range* (°C)	10-70	20-60	10-70	10-50	30-80
R^2	0.98	0.96	0.46	0.98	0.97

*Temperature range in which the sensitivity of the sensor is calculated.

also summarizes the measured sensitivity and the R^2 value for comparison. Specifically, the data previously analyzed (Figs. 5 and 6) corresponds to patchcord 1, while the measurements of the other patchcords are reported in Fig. 7(a)–(d).

When comparing patchcords 1, 4, and 5, which have similar polishing depths and lengths, it is evident that their sensitivities are also quite similar. This suggests that within a certain range, the gold layer thickness does not significantly impact the sensitivity. However, increasing the gold thickness slightly affects the linearity of the measurements. This is illustrated by the drop of R^2 values from 0.98 for 20 s of sputtering time to 0.97 for 40 s of sputtering time [refer to Figs. 6 and 7(c) and (d)]. As shown in Fig. 8, the increased thickness of gold broadens the signal, compromising peak accuracy and hindering linear adjustment. Consequently, excessive gold thickness impedes proper sensor operation, as evidenced by the low R^2 value of 0.46 for patchcord 3, depicted in Fig. 7(b), and where a clear deviation from a linear fit is observed.

On the other hand, a comparison between patchcords 1 and 4 [Figs. 6 and 7(c)] reveals that a slight increase of the polishing length results in improved sensitivity. This improvement is due to the increased interaction area between the gold layer and the evanescent field of the optical fiber. Therefore, increasing the polishing length enhances the ability of the sensor to detect temperature changes more accurately.

Polishing depth plays a similar role in sensor performance. Theoretically, a greater polishing depth should increase the sensitivity of the sensor by exposing more of the fiber core to the evanescent field. However, excessive polishing can lead to increased power losses, thereby reducing the resolution of the measurements. This is evident when comparing patchcords 1, 4, and 5, with similar depths and lengths, with patchcord 3 [Fig. 7(b)], where a significant reduction in sensitivity is observed.

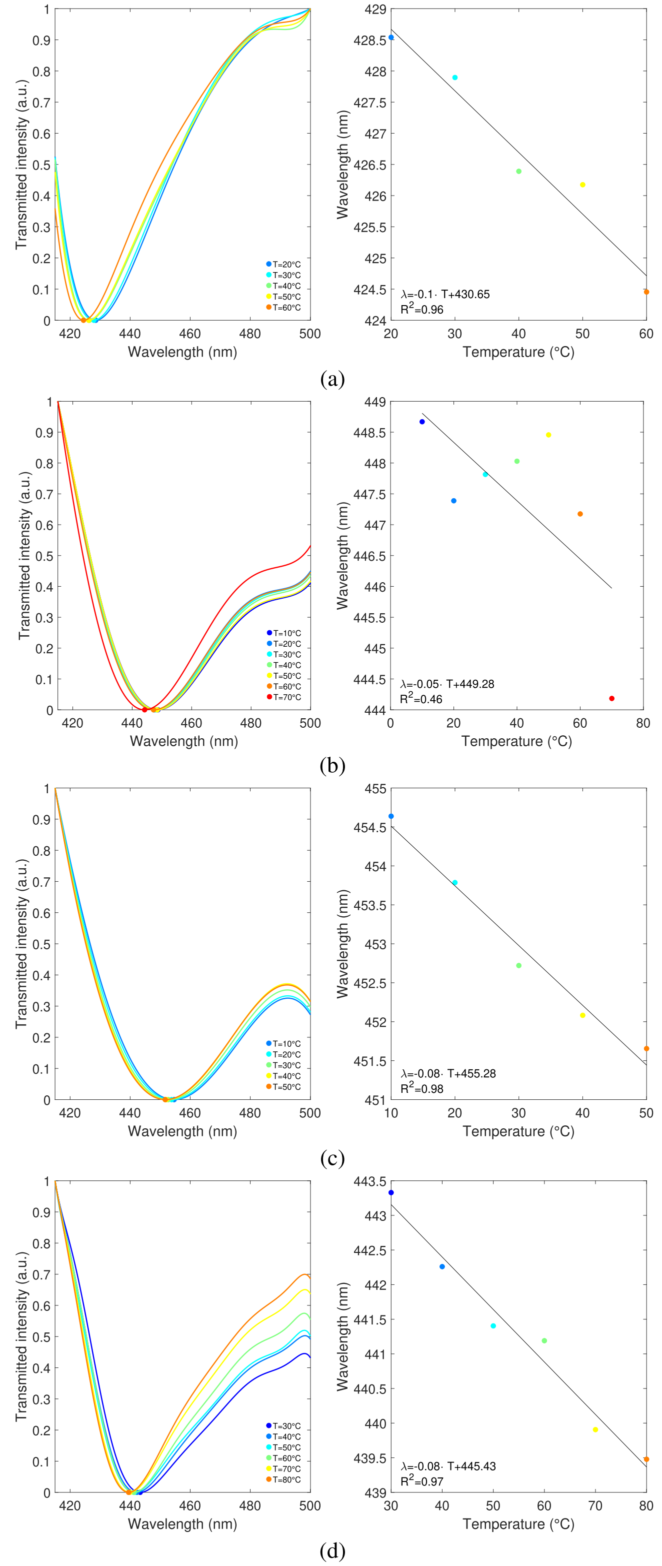


Fig. 7. Spectra of the transmitted intensity (left) and spectra minimum versus temperature (right) for (a) patchcord 2, (b) patchcord 3, (c) patchcord 4, and (d) patchcord 5.

TABLE II
COMPARISON BETWEEN THE PROPOSED SENSOR AND OTHER STATE-OF-THE-ART SENSORS

Sensor type	Sensing technique	Type of fiber	Temperature range (°C)	Sensitivity (nm/°C)	Fabrication complexity	Reference
MMI	misaligned SMF-SMF-MMF-SMF	Silica	25-60	0.082	FS, MA *	[7]
FBG	PMF with FBG	Silica	20-120	0.0075	BG *	[6]
FBG	POF with FBG	POF	20-60	0.149	BG *	[15]
MMI and FBG	SMF-MM POF-SMF. Etched and FBG	Silica and POF	45-80	0.1036	BG, FS *	[44]
SPR	Double SPF U-shape+Au+PDMS	POF	30-80	-0.596	DP, PD *	[35]
SPR	Double SPF+Au+PDMS	POF	30-80	-0.7	DP, PD *	[36]
SPR	Single SPF with Vgrooves+Au+PDMS	POF	20-80	-0.83	DP, PD, VG *	[37]
SPR	**SPF+Au**	**POF**	**10-70**	**-0.09**		**This work**

In this table, the symbol - is used to denotate a splice, and + to denotate a layer deposition
* FS:= Fiber splice, MA:= misalign, BG:= Bragg grating inscription, SF:= Special fibers, VG: Vgrooves, DP:= Double polishing, PD:=Polymer deposition

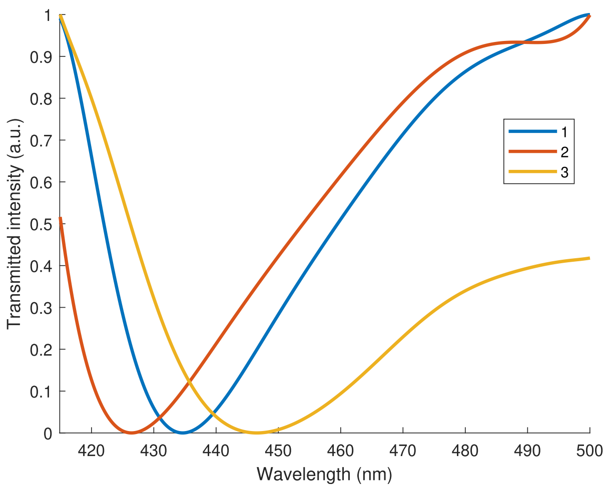


Fig. 8. Spectra of the transmitted intensity at 40 °C for patchcords 1–3, normalized and plotted in the same scale.

Comparing patchcords 1 and 4 [Figs. 6 and 7(c)] with patchcord 2 [Fig. 7(a)], which all have similar polishing lengths, reveals that patchcord 2 has a lower polishing depth. Given this lower depth, one would expect patchcord 2 to exhibit reduced sensitivity. However, patchcord 2 maintains sensitivity levels comparable to those of patchcords 1 and 4, despite its shallower polishing depth. This suggests that the loss of sensitivity due to reduced polishing depth can be offset by increasing the gold layer thickness. Nonetheless, this approach has its limits; if the gold layer becomes too thick, as seen in patchcord 3 [Fig. 7(b)], it severely impacts the linearity, thereby compromising overall performance.

Hence, while increasing the gold layer can compensate for reduced polishing depth, excessive thickness degrades sensor performance by reducing linearity, as demonstrated in Fig. 7(b).

In conclusion, the gold layer thickness emerges as the most critical parameter for achieving optimal sensor performance. Increasing the gold layer increases sensitivity, but excessive thickness can degrade linearity, preventing the sensor from functioning properly. On the other hand, polishing length and depth should be optimized within practical limits to maximize sensitivity. In patchcord 3, it can be seen how linearity is compromised due to the excessive thickness of the gold layer, and how sensitivity is reduced due to a smaller d and L.

Therefore, the analyzed data indicate that a high-sensitivity and linear temperature sensor can be effectively manufactured. From Table I, we can infer that optimal manufacturing involves using fibers polished between 0.18 and 0.33 mm with thin gold layers (sputtered for 20–40 s). The most favorable scenario for achieving high sensitivity with the widest temperature range implies a moderate polishing depth (0.32 mm) and a low gold thickness (20 s). In this configuration, the calculated sensitivity is −0.09 nm/°C [Fig. 7(a)]. Although this sensitivity is somehow lower than other SPR sensors found in literature, summarized in Table II, the fabrication of the sensor is much simpler and cheaper, and it can operate over a wider temperature range (from 10 °C to 70 °C). In addition, it is competitive in terms of sensitivity with other technologies such as MMI and FBG that do not involve depositing polymers but have a more complex fabrication. Table II includes an analysis of the different sensor types and fabrication complexity summarizing the different processes involved along with other parameters.

V. CONCLUSION

We have designed and characterized a temperature sensor using a polished plastic OF covered with a gold layer by sputtering deposition. This design yields a maximum sensitivity of −0.09 nm/°C from 10 °C to 70 °C. The sensitivity of the sensor compares favorably with some sensors reported in literature fabricated with complex technologies, such as MMI and FBG, and also offers a larger temperature range than other SPR-based sensors.

Furthermore, our approach enables easy handing transmission-based temperature measurements with OFs. Our investigations reveal that optimal sensor manufacturing requires POF polished within the range of 0.18–0.33 mm, and thin gold layers deposited for a time duration between 20 and 40 s. The best sensor in terms of sensitivity and linearity was obtained for a POF polished to 0.32 mm and sputtered with Au for 20 s.

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A. Fresno-Hernández was born in Madrid, Spain, in 1996. She received the B.S. degree in physics from the Autonomous University of Madrid, Madrid, in 2018, and the M.S. degree in photonics engineering from Carlos III University of Madrid, Leganés, Spain, in 2019, where she is currently pursuing the Ph.D. degree.

She was a Teaching Assistant at the Carlos III University of Madrid from 2018 to 2019 and obtained a scholarship for her master's degree in 2018, where she worked as a Research Support Technician with the Department of Electronic Technology from 2019 to 2020. She received the Excellence Grant from the Community of Madrid in 2015 and the FPU Grant from Spanish Ministry of Universities (FPU19/04133) in 2020. Her research interests include nanomaterials, optical invisibility, dielectric structures, and light direction with interdipole forces.

Ms. Fresno-Hernández received the Nicolás Cabrera Award for Young Researchers in 2017 and the Best Academic Record and Extraordinary Award for the Interuniversity Master in Photonics Engineering for the term of 2018–2019.

B. García-Cámara received the B.S., M.S., and Ph.D. degrees in physics from the University of Cantabria, Santander, Spain, in 2005, 2008, and 2010, respectively.

From 2010 to 2012, he was a Research Assistant with the Optics Group, University of Cantabria, and the NanoBiosensors and Bioanalytical Applications Group, Catalan Institute of Nanoscience and Nanotechnology (ICN2), Barcelona, Spain. From 2012 to 2019, he was an Assistant Professor with the Department of Electronic Technology, Carlos III University of Madrid, Leganés, Madrid, Spain, where he has been an Associate Professor since 2019 and a member of the Group of Display and Photonic Applications. He has authored or co-authored more than 60 research works, and four book chapters and two inventions. His research interests include light management at the nanoscale, resonant dielectric nanostructures, light directionality, energy harvesting for efficient solar cells, single-photon sources, and photonic sensors.

C. Vázquez (Senior Member, IEEE) received the M.Sc. degree in physics (electronics) from the Complutense University of Madrid, Madrid, Spain, in 1991, and the Ph.D. degree in photonics from the Telecommunications Engineering School, Polytechnic University of Madrid, Madrid, in 1995.

She received a fellowship at TELECOM, Denmark, in 1991, working on erbium-doped fiber amplifiers. From 1992 to October 1995, she worked at the Optoelectronics Division, Telefónica Investigación y Desarrollo, Madrid. She was involved in III–V integrated optics devices characterization, design, and fabrication. In October 1995, she joined the Carlos III University of Madrid, Leganés, Madrid, where she is currently a Full Professor with the Department of Electronics Technology and the Head of the Displays and Photonic Applications Group. She was a Visiting Scientist with the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA, from August 2012 to July 2013, working on silicon photonics. She was also the Head of the Department for three years and the Vice-Chancellor for four years. She has authored or co-authored more than 300 scientific publications and holds ten patents. She has participated in different European projects and networks in the ESPRIT, RACE, and IST framework programs such as PLANET, OMAN, HEMIND, SAMPA, EPhoton/One+, Building the Future Optical Network in Europe (BONE), and BlueSpace, and has led several national researching projects and consortium such as 6G-Xtreme and SINFOTON-CM. Her research interests include photonics integrated circuits, optical communications and instrumentation including, plastic optical fibers, broadband access networks and monitoring techniques, power over fiber, RoF systems, filters, switches, fiber optic sensors, and WDM networks.

Dr. Vázquez is a Fellow of the SPIE.