

Article

Compact Dual-Wavelength Optical Fiber Sensor for the Simultaneous Measurement of the Refractive Index and Temperature of Liquid Samples

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Abstract: This study proposes the development of a dual-wavelength optical fiber sensor (DWOFS) that integrates two optical fiber structures in a multimode transmission line to measure the refractive index and temperature of a liquid concurrently. One structure is based on a refractive index sensor that utilizes surface plasmon resonance, comprising a 5 mm long single-mode fiber (SMF) section coated with chromium/gold (Cr/Au) films. The secondary structure employs a multimode interferometer with a 29 mm long no-core fiber (NCF) section covered with a thick layer of polydimethylsiloxane (PDMS) to measure temperature. The measurements obtained reveal two distinct drops in the transmission spectrum at approximately 600 nm and 1550 nm, respectively, enabling precise measurement of the two parameters. The sensor demonstrates a high degree of sensitivity to both refractive index and temperature, spanning the visible (2770.30 nm/RIU) and infrared ($-0.178 \text{ nm}/^{\circ}\text{C}$) regions of the spectra, respectively. Furthermore, the thermo-optical coefficient for water ($-0.9928 \times 10^{-4} \text{ RIU}/^{\circ}\text{C}$) was estimated. The proposed sensor offers a compact solution for the simultaneous measurement of refractive index and temperature in liquid samples for a variety of applications, including biological, environmental, and healthcare research.

Keywords: thermo-optic coefficient; optical fiber; surface plasmon resonance; multimode interference; refractometer; temperature sensor



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1. Introduction

The refractive index (RI) is a physical property of matter that governs the light propagation through a medium and its interaction with the material. For years, RI has been traditionally identified as an optical parameter, but nowadays it is well-known that RI measurement can be used as an alternative method to monitor the course of certain production processes in several transformation industries. The instruments and techniques developed to measure the RI are known with the generic name of refractometers. With these instruments, it has been possible to assess the sugar content of a beverage, the total dissolved solids, or abnormalities [1] in liquid samples, and identify and even quantify innocuous [2] or harmful biological agents [2,3]. Refractometers have also demonstrated their potential for standardization and control of processes in food and beverage industries [2,4,5]. In

many of these applications, it is possible to use bulky refractometers; however, they are not a feasible option in some applications, where the sample amount is limited or when the measurement must be performed in a restricted area. In recent years, the synergy of new technologies such as nanomaterials, metamaterials, plane waveguides, and fiber optics has enabled the development of refractometers with more compact and versatile structures [6]. Additionally, these technologies provide the means to evaluate the RI of a liquid sample over a broad range (i.e., from the optical to the terahertz regime) [7,8].

On the other hand, the unique characteristics of fiber optics have been key elements for the successful development of refractometers at the micrometric scale [9]. In most of the optical fiber refractive index sensors (OFRIS) proposed recently, the interaction of the evanescent wave with the surrounding medium is exploited as a sensing mechanism. Accordingly, the perturbations caused in the external medium can be correlated with the changes induced in the properties of the propagating light. Coating the optical fiber with thin metal films, responsive, biological, or nanostructure materials [10,11] offers the possibility to develop sensors for specific physical [12,13], chemical [14], or biological perturbations [15]. Among them, the hetero-core (HTC) fiber structures are popular due to their unique spectral features, simple fabrication process, and the fact that they do not require sophisticated equipment.

The hetero-core (HTC) fiber structures can be defined as a discontinuity in the optical fiber transmission line to modify the propagation conditions of the guided light. Such discontinuity can be created by inserting a small piece of an optical fiber with a different core diameter. The fabrication process is straightforward, since it only involves two procedures: fusion splicing and cleaving, which are routinely performed in optical fiber laboratories worldwide. The most common HTC is the SMS structure, in which a short section of standard multimode fiber (MMF) is fusion-spliced between two SMFs. However, this multimode interferometer is not responsive to refractive index changes, since the evanescent field does not interact with the surrounding media [16], i.e., the modes are confined and propagated within the MMF core. In this sense, strategies such as modifying the MMF section, either by polishing [17] or etching [18] the cladding, enable the exposure of the evanescent field but contribute to the weakness of the device. Recently, a number of refractometers based on evanescent field interaction of cladding modes, through the use of specialty fiber [19–21] or HTC fiber schemes with a significant core diameter mismatch [22], including the use of no-core fiber (NCF), have been proposed.

Among the significant number of HTC that can be created today, due to the large catalog of optical fibers available, the multimode–single-mode–multimode fiber structure (MSM) suggested in 1999 [23] is still one of the most used methods to develop RI sensors. In this MSM structure, the light is initially guided in a multimode regime through the core of the lead-in MMF, which is coupled to the core and cladding of the single-mode fiber (SMF) section. Part of the energy from the core and cladding modes is recoupled to the core of the lead-out MMF. The cladding modes are affected by the optical characteristics of the external medium surrounding the SMF section. Recently, a version of the MSM fiber structure has been proposed [24], in which the SMF was substituted by a NCF, enhancing the sensitivity of the sensor. Both the MSM and the multimode–no-core–multimode (MNM) hetero-core fiber structures have been mainly used for RI measurement.

Many OFRISs based on the SMS structure, MNM, and MSM schemes operate mainly in the near-infrared range (NIR), where the multimodal interference (MMI) phenomenon occurs [17,25]. However, these OFRISs can also operate in the visible range (VIS) through the surface plasmon resonance (SPR) phenomenon generated when a thin film of noble metal (Au or Ag) is deposited on the central section of the HTC [24,26]. The SPR-based OFRISs that operate in the NIR range, particularly at the telecommunication wavelengths,

require sophisticated platforms such as tilted fiber Bragg grating (TFBG) [27]. It is essential to notice that both phenomena, SPR and MMI, provide a characteristic dip, and the changes in the RI of the surrounding media modify the wavelength position of both dips. The interrogation of these OFRISs is often based on tracking the wavelength position of the dips with respect to a reference position when the surrounding medium is air. The physical characteristics of the optical fiber sensor (OFS) determine the reference position. For example, the interference dip in an HTC structure blue-shifts as the length of the device increases [28]. Meanwhile, the SPR dip shifts toward longer wavelengths when depositing a thicker metal film, polymer [29], or composite film structure [30] on the HTC structure [31,32].

In the OFRISs, the high sensitivity is beneficial for detecting minimal RI changes, but its precision is affected by the temperature in the environment. Diverse schemes have been proposed to prevent temperature effects on the measurement of RI. In this regard, the dual-channel SPR sensors [33–36] are appealing schemes where a section of the metal-coated OFS is embedded within a temperature-sensitive material with a high RI. The other section is used for the RI measurement of the liquid sample [37,38]. However, the dynamic range of the dual-channel SPR sensors is limited by the short wavelength separation of the channels. Other schemes have also been based on connecting two distinct fiber structures, such as Bragg grating, interferometers, and microstructures [39–44]. In these hybrid OFSs, the optical signal comprises two individual responses, but their short wavelength separation could cause them to overlap. Accordingly, the response interrogation requires systems with expensive and complex optoelectronic elements [45]. In addition, signal analysis demands a set of algorithms to reduce the uncertainty in the OFS performance [46].

Estimating the thermo-optical coefficient (TOC) (dn/dT) of a sample is possible when the changes in the refractive index due to temperature can be assessed. This parameter is relevant in a variety of disciplines, including electronic [47], optical [48], food [49], and biological applications [50]. It was demonstrated that the TOC of liquid samples could be determined using a dual-wavelength optical fiber sensor (DWOFS), capable of simultaneously measuring the temperature and RI.

In this study, we propose a novel optical fiber sensor for the simultaneous measurement of a liquid sample's refractive index and temperature, employing a DWOFS constructed with two different HTC structures in a multimode transmission line where the SPR and MMI phenomena take place independently. The SPR-based HTC (HTC_{SPR}) consists of an MSM fiber structure that is coated with chrome (Cr) and gold (Au) films, while the MMI-based HTC (HTC_{MMI}) consists of an MNM fiber structure with a NCF section. The transmission spectra of the DWOFS exhibit two well-defined and separated dips at around 600 and 1550 nm when both HTC are immersed in a liquid sample. Under these conditions, it is possible to measure the RI at two different wavelengths. It is also important to mention that the overlapping between the plasmonic and interference responses does not occur. Both peaks are red-shifted when the refractive index of the medium is increased, but the sensitivity of the SPR dip is 10 times higher than that of the MMI dip. The HTC_{MMI} was capped with polydimethylsiloxane (PDMS) to enhance its sensitivity to temperature and isolate it from the RI changes of the liquid sample. It was possible to reach an RI and temperature sensitivity of 2770.30 nm/RIU and -0.178 nm/°C, respectively.

By tracking the wavelength shifts of the dips of both HTC-based sensors, it was possible to determine the TOC of water (-0.9928×10^{-4} RIU/°C). The DWOFS proposed here overcomes the limiting refractive index sensing range observed in all previously proposed two-channel SPR sensors [28,31,35]. It has been observed that the shape of both SPR dips is influenced by each other, and their full-width at half maximum (FWHM) is distorted, complicating the identification of the wavelengths of the SPR dips [51]. Compact packaging

of this DWOFS is proposed to demonstrate that this device provides an efficient alternative for measuring the TOC in liquid samples and other potential sensing applications.

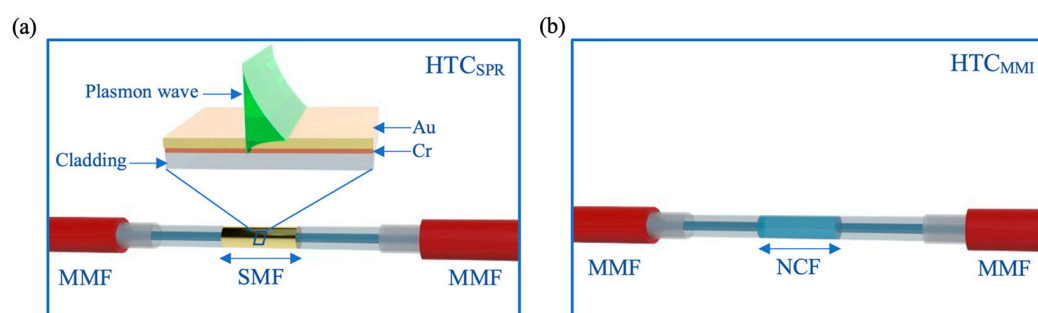
2. Materials and Methods

2.1. Materials and Equipment

The following materials were used: commercial single-mode optical fiber (SMF, FIS-Fiber Instrument Sales, Oriskany, NY, USA) with a core/cladding diameter of 9/125 μm , commercial multimode optical fiber (MMF; 62.5/125 μm , FIS-Fiber Instrument Sales, Oriskany, NY, USA), and commercial non-core optical fiber (NCF, 0/125 μm , Thorlabs, Newton, NJ, USA); polydimethylsiloxane (PDMS, SYLGARD 184, DOW, Auburn, MI, USA); a refractive index liquid set (series AAA, $n_D = 1.3000 \pm 0.0002$ to 1.3950 ± 0.0002 at 589.3 nm and 25.0 $^{\circ}\text{C}$; Cargille Labs, Cedar Grove, NJ, USA); gold pellets (Au, 99.999%, Kurt J. Lesker, Jefferson Hills, PA, USA), chromium pieces (Cr, 99.98–99.99%, Kurt J. Lesker, Jefferson Hills, PA, USA); Norland Optical Adhesive (NOA61, Norland Products Inc., Cranbury, NJ, USA); Ender Printer 3D (model 3 Pro) and polylactic acid (PLA) filament from Creality, Longhua, Guangdong, China; an optical spectrum analyzer (OSA, model AQ-6315A, Ando Electric Motors Inc., Long Beach, CA, USA); and a white-light source (model AQ-43038 Ando Electric Motors Inc., Long Beach, CA, USA).

2.2. Design and Fabrication of the Dual-Wavelength Optical Fiber Sensor (DWOFS)

The DWOFS was fabricated by connecting two HTC structures in series. For the first structure, HTC_{SPR} , a segment of 5 mm of a commercial SMF was cleaved and spliced between two MMFs in the transmission line. Using the electron beam evaporation technique, a chromium thin film of 3 nm thickness was deposited over the surface of the SMF section, followed by the deposition of a 30 nm thick gold layer on top of the chromium layer by thermal evaporation (see Scheme 1a). The second structure, HTC_{MMI} (shown in Scheme 1b), was fabricated by splicing a no-core fiber section of 29 mm between two segments of MMF in the transmission line to generate the multimodal interference phenomena. Once the device has been independently characterized, the MMF ends are spliced to obtain a single device, known as DWOFS.

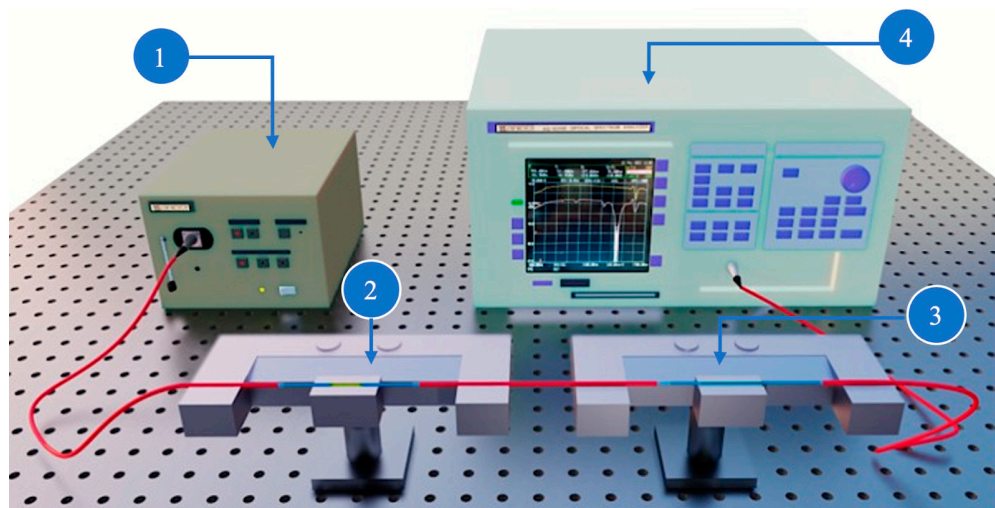


Scheme 1. The dual-wavelength optical fiber sensor (DWOFS) comprises (a) a multimode–single-mode–multimode fiber device, known as HTC_{SPR} , and (b) a multimode–no-core–multimode fiber device, known as HTC_{MMI} .

2.3. Optical Characterization

For the optical characterization, we employed an experimental setup (see Scheme 2). First, the white-light source (Ando Electric Motors Inc., AQ-43038, see Scheme 2 (1)) was connected to one end of the MMF for the HTC_{SPR} structure, and the other end was connected to the optical spectrum analyzer (OSA, Ando Electric, AQ-6315A, see Scheme 2 (4)). The transmission spectra in air were obtained and recorded as Reference 1 (R1). Then, the HTC_{MMI} device was connected to a white-light source and the OSA, and the transmission

spectra in air were collected and recorded as Reference 2 (R2). For the DWOFS characterization, one end of the HTC_{SPR} structure was connected to white-light, the other one was connected to the HTC_{MMI} structure, and its free end was connected to the OSA. The transmission spectra in air were obtained and recorded as Reference 3 (R3). All spectra were collected from 400 to 1700 nm.



Scheme 2. Experimental setup for optical characterization: (1) a white-light source, two metallic mounts with V-grooves to clamp (2) the HTC_{SPR} , (3) HTC_{MMI} structures, and (4) the optical spectrum analyzer (OSA).

2.4. Refractive Index Measurement

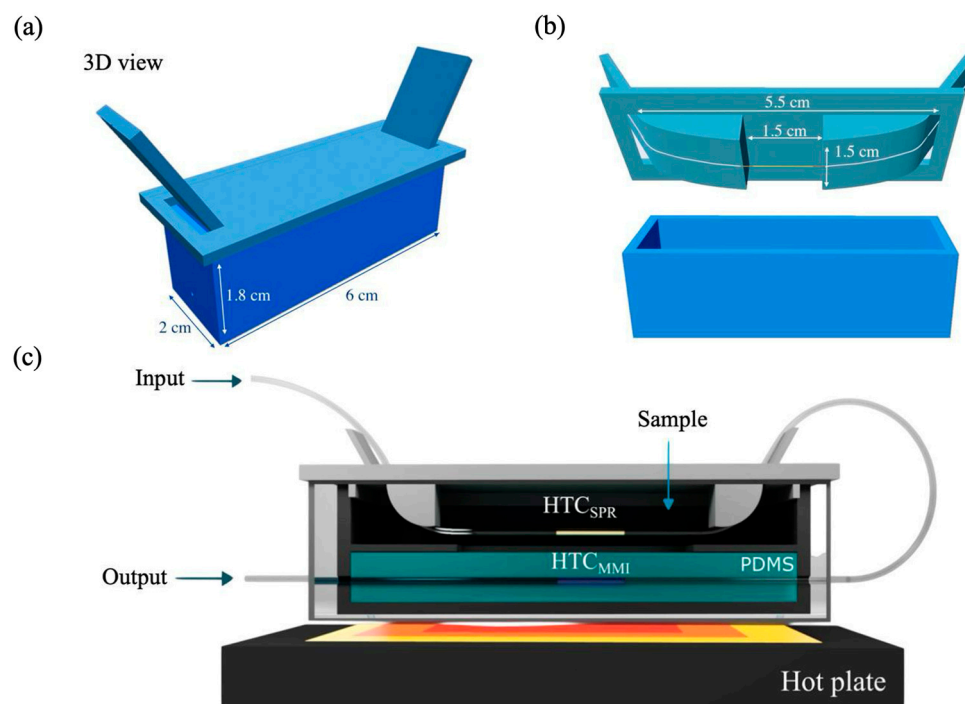
To perform the refractive index measurement properly, the HTC_{SPR} and HTC_{MMI} were fixed to a pair of metallic mounts in which a V-groove was machined, see Scheme 2, (2) and (3). The HTC was positioned, guaranteeing that the SMF and NCF sections were centered in the V-groove without touching the walls. Then, both HTCs were cleaned by washing and drying with distilled water, isopropyl alcohol, and air. For the refractive index characterization, the DWOFS was immersed in Cargille oils with different calibrated refractive indices, and the transmission spectra were recorded using the OSA from 400 to 1700 nm.

We first proceed to the characterization of the HTC_{SPR} , the corresponding V-groove was filled with the Cargille oil refractive index of 1.3000 until the NCF section was fully covered. Subsequently, the same Cargille oil sample was deposited, but in the other V-groove where the HTC_{SPR} was attached, thus the transmitted spectrum was recorded. The oil sample was removed from the HTC_{SPR} and its surface was cleaned as described above. This procedure was repeated with the other Cargille oil samples from $n_D = 1.3000$ to 1.3800 with 1×10^{-2} intervals, while the HTC_{MMI} remained immersed in the initial sample. For the HTC_{MMI} characterization, the corresponding V-groove was filled with different Cargille oil from $n_D = 1.3000$ to 1.3800 at intervals of 1×10^{-2} , while the corresponding V-groove to HTC_{SPR} remained fixed, immersed in the Cargille oil.

2.5. Simultaneous Measurements of Temperature and Refractive Index

The DWOFS device was installed in a container with two horizontal compartments designed with Blender software (v. 3.4.1) and fabricated by 3D printed Ender 3 Pro using PLA as filament (see Scheme 3a,b). The HTC_{MMI} was placed in the bottom cavity of the container and filled with PDMS (10:1 base elastomer: curing agent ratio) and cured for 3 h at 80 °C. After the process, the HTC_{SPR} was positioned and fixed in the container cap, and the air cavity was filled with distilled water (see Scheme 3c).

The container with both HTC was placed on a hot plate (Echotherm, TORREY PINES SCIENTIFIC, Carlsbad, CA, USA), and the white-light source and the OSA were connected to the input and output ends of the fiber optic structure. The hot plate was set at an initial temperature of 30 °C for 15 min, and the transmitted signal was recorded. Then, the temperature was increased by 5 °C, and after 15 min, the spectrum was recorded. The process was repeated until 60 °C.



Scheme 3. Representation of the 3D printed pieces used in the experimental configuration for the temperature measurement of a liquid sample. Three-dimensional view of the (a) assembled and (b) disassembled container fabricated to install the DWOFS and immersed it in the sample. (c) Packaging of the DWOFS to measure the RI and the temperature of a liquid sample simultaneously.

2.6. Data Processing and Analysis

For the optical characterization and RI measurement, when the transmission spectrum for HTC_{SPR} (Reference 1, R1) and HTC_{MMI} (Reference 2, R2) in air was collected and recorded, the external RI was changed, and the transmitted spectra of the DWOFS were recorded and normalized with respect to Reference 1.

3. Results and Discussion

The operation principle of the DWOFS can be described as follows: the light at the MMF-SMF interface of the HTC_{SPR} is partly coupled to the SMF core due to the core diameter mismatch, and the rest is coupled as cladding modes. The evanescent field of the cladding modes interacts with the Au film, exciting the surface plasmon waves; see Scheme 1a. Then, the cladding and core modes of the SMF section arrive at the SMF-MMF interface, where these are recoupled in the MMF core. Thereby, the light propagates along the MMF that connects the two HTC fiber structures, and when it passes through the MMF-NCF interface of the HTC_{MMI}, it is coupled and transmitted into the NCF section; see Scheme 1b. The excited modes interfere with each other, producing the multimode interference, which is based on the self-image effect. Finally, the light is coupled to the core of the lead-out MMF and propagates to the OSA, where the optical spectra are registered from 400 to 1700 nm. The fabrication process of the HTC_{SPR} and HTC_{MMI} is described in detail in our previous studies [25,52]. The transmission losses of the final device are high,

around 5 dB. We have observed that the length of the MMF section between the two HTC fiber structures does not affect the characteristics of the transmitted spectra.

3.1. Characterization of the Dual-Wavelength Optical Fiber Sensor to Refractive Index

The black line plot in Figure 1 displays the normalized spectrum of the DWOFS in air, where no response of the HTC_{SPR} is observed, since the transmission and reference spectra are the same in the visible range (the green-shaded area). However, a transmission dip arises at long wavelengths in the blue-shaded area, corresponding to the interferometric response of the HTC_{MMI} . The wavelength of the MMI dip (λ_{MMI}) is 1567.4 nm, and its position depends on the NCF section length. In this case, using an HTC_{MMI} of 29 mm length, it was possible to obtain a dip of 14 dB. When the DWOFS is immersed in a liquid sample with a refractive index of 1.3000, the λ_{MMI} is red-shifted, as shown in the red dashed plot. The SPR is also observed as a transmission dip at short wavelengths in the green-shaded area. The wavelengths of the SPR dip (λ_{SPR}) and the MMI dip are 548.2 nm and 1576.5 nm, respectively. It can be noticed that the MMI dip is narrower and deeper than the SPR-dip. In the same way, when the DWOFS is immersed in a liquid with a higher refractive index (1.3500), both dips are red-shifted, as can be seen in the blue dot-plot of Figure 1. It is evident that the sensitivity of the SPR is higher than that of the MMI. It is important to note that the wavelength separation between the two dips is, to our knowledge, the largest ever reported for two devices inserted into the same transmission line. This separation is expected to contribute to the isolation of the two dips. Since the devices are connected in series, the transmission loss of each HTC is added when the surrounding refractive index is different from 1.0000, and the total transmission loss is increased in the whole wavelength span from 400 to 1700 nm.

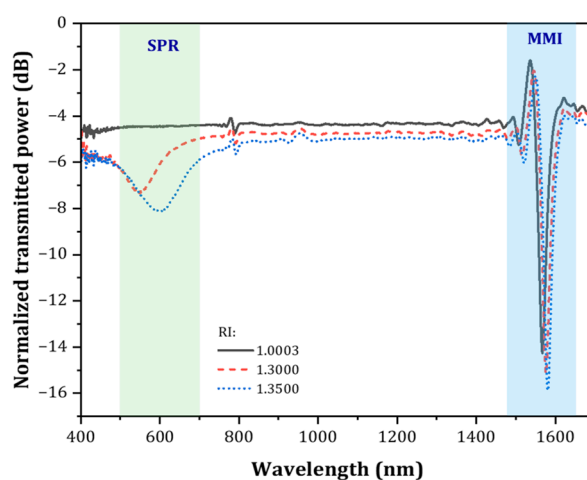


Figure 1. Normalized transmission spectra of the DWOFS when immersed in three samples with different refractive index values.

To analyze the response of the DWOFS to refractive index changes, the transmission spectra were obtained when the HTC_{MMI} was immersed in the liquid with a refractive index of 1.3000. Then, HTC_{SPR} was immersed in different Cargille oils with a calibrated refractive index ranging from $n_D = 1.3000$ to 1.3800 in intervals of 1×10^{-2} . The transmitted spectra registered for each sample were normalized and are displayed in Figure 2a. It can be noticed that the λ_{SPR} is shifted to longer wavelengths when the refractive index increases. Furthermore, the FWHM of the SPR dip is broadened as the refractive indices are increased. This broadening of the SPR dip is the main drawback in the dual-channel SPR sensors proposed so far, where the two resonance dips are closer, so the changes in one of the channels produce a distortion in the other. Importantly, in the DWOFS proposed here, the

MMI dip is not significantly altered by the displacement of the SPR dip, and the λ_{MMI} remains constant in each measurement, as shown in the inset of Figure 2a.

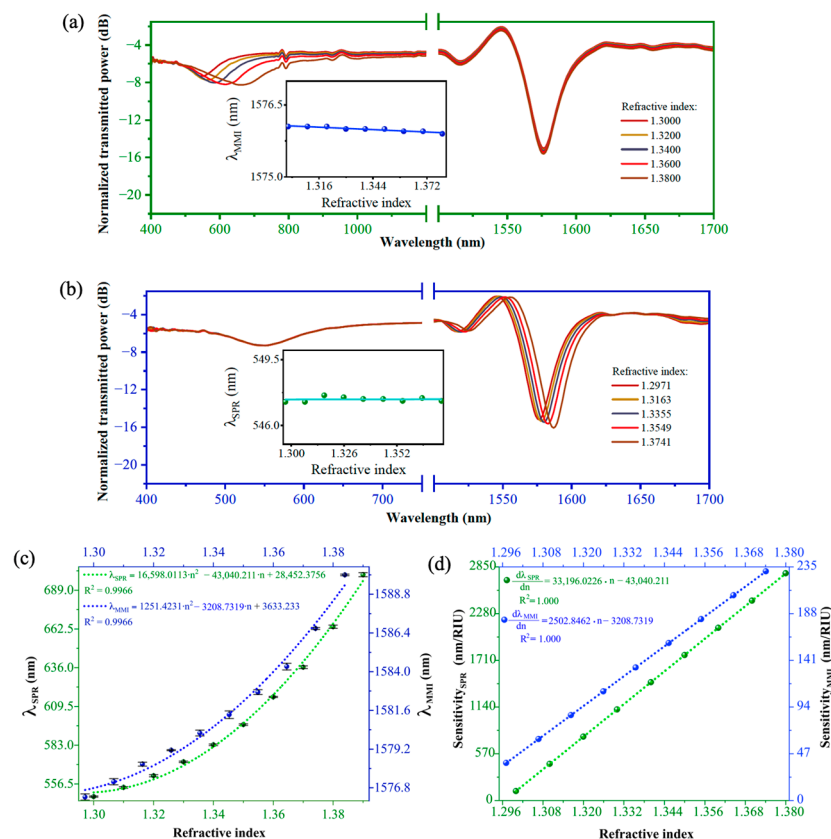


Figure 2. Transmitted spectra of the DWOFS when evaluated to refractive index while (a) the HTC_{MMI} and (b) the HTC_{SPR} remain immersed in a sample with a refractive index of 1.3000, respectively. (c) Correlation between the wavelength position of the SPR dip (green plot) and the MMI dip (blue plot) of the DWOFS for different values of the external refractive index; polynomial curves were fitted to the experimental data. (d) Relation of the sensitivity of the SPR dip (green plot) and the MMI dip (blue plot) at different refractive index values.

When the HTC_{SPR} was covered with a small sample of a Cargille oil, let us say 1.3000, the HTC_{MMI} was evaluated for changes in refractive index using the same Cargille oil sample. Here, it is worth recalling that the sample's refractive index depends on the wavelength of the light. The refractive index values of the Cargille oils, as written on the front container label, correspond to n_D , i.e., the refractive index measured at 589.3 nm. Using the Cauchy equation [53] and the dispersion values provided by the supplier, the refractive index of each Cargille oil at 1550 nm, the wavelength where the MMI dip occurs, was calculated. The normalized spectra of the HTC_{MMI} , assessed with different Cargille oils and their calculated refractive index values, are displayed in Figure 2b. The λ_{MMI} dip position is also red-shifted when the refractive index increases, as illustrated in Figure 2b. It is important to note that the λ_{SPR} is not shifted. In this case, the FWHM of the HTC_{MMI} does not broaden at high refractive indices, in contrast to the FWHM of the HTC_{SPR} when evaluated under the same conditions. The characterization of the HTC_{SPR} and HTC_{MMI} was carried out three times to assess the performance of the DWOFS.

The transmitted response of the DWOFS does not require more robust demodulation techniques, which is another advantage of this device compared to other OFRIS proposed so far, in which the RI and temperature were measured simultaneously [46,54]. In such cases, there is a noticeable overlap between the dips in the final spectra; therefore, diverse

algorithms for smoothing, filtering, and processing the optical transmission spectra were required. The refractometric response of the DWOFS at the visible range, shown in the green dashed curve in Figure 2c, is defined by the displacement of λ_{SPR} according to the changes in the refractive index. The characterization of the DWOFS response in the NIR range is displayed by the blue dashed curve in Figure 2c, where λ_{MMI} is related to the refractive index values calculated at that operating wavelength. Tracking the two attenuation dips was carried out using traditional techniques, which involved identifying the wavelength of the minima of the transmitted spectra dips.

The RI characterization process was repeated thrice, and the results were used to obtain the characterization curves observed in Figure 2c. Both characteristic curves are well-fitted to a second-order polynomial. Now, these polynomial curves can be used to determine the RI of an unknown sample in the VIS and NIR regions by simply substituting the λ_{SPR} and λ_{MMI} positions from the experimental spectrum. Finally, in Figure 2d, it can be seen that the calculated sensitivities of each device increase as the refractive index of the Cargille oil is augmented. The maximum refractive index sensitivity observed in the SPR dip was 2770.30 nm/RIU, while that for the MMI dip was 230.429 nm/RIU at refractive indices of 1.3800 and 1.3741, respectively.

3.2. Characterization of the Response of Dual-Wavelength Optical Fiber Sensor to Refractive Index and Temperature Changes

One of the most challenging aspects of a refractive index sensor is the temperature dependence. To consider the temperature effects in the refractive index measurement, we propose to adapt one of the HTC as a thermometer by covering it with a polymer whose refractive index changes with the temperature, such as PDMS. To measure the temperature and the refractive index of a liquid sample simultaneously, we designed a container in which the two HTC devices were installed. This container was fabricated through 3D printing using PLA. The 3D view and dimensions of the printed platform are shown in Scheme 3a. It is composed of a container with two horizontal compartments and a grooved cap, as can be seen in Scheme 3b. First, the HTC_{MMI} was placed in the bottom cavity of the container, and its ends were clamped to the platform structure with optical adhesive. Then, the bottom section of the platform was filled with PDMS and cured following the recommendations of the supplier (see Scheme 3c). After the process, the HTC_{SPR} was positioned and fixed in the cap groove while it remained connected in series with the HTC_{MMI}. In this case, the air cavity was filled with the sample, distilled water, and then the cap with the HTC_{SPR} was assembled in the container. The platform was designed to prevent evaporation of the liquid sample; the HTC_{SPR} is immersed in water, and the HTC_{MMI} in PDMS.

The proposed packaging container for the DWOFS, as illustrated in Scheme 3c, was filled with distilled water. We obtained transmission spectra as a function of temperature, ranging from 30 °C to 60 °C; this behavior is depicted in Figure 3a. The positions of λ_{SPR} and λ_{MMI} correspond to the conditions of the HTC_{SPR} and the HTC_{MMI} when immersed in distilled water and PDMS, respectively. As the temperature of the hot plate increased, the MMI dip generated by the HTC_{MMI} in the near-infrared (NIR) range shifted toward shorter wavelengths. This trend is highlighted in the blue square insert in Figure 3a. This shift occurs due to the sensitivity of PDMS to temperature changes. Additionally, the SPR dip in the visible range also shifted toward shorter wavelengths, as shown in the green square insert. The behavior of the SPR and MMI dips is linked to the change in the refractive indices of distilled water and PDMS, respectively, caused by the increase in temperature.

The characterization of the DWOFS to temperature changes at the two wavelengths of operation is displayed in the graphs of Figure 3, where the displacement of λ_{SPR} , see Figure 3b, and λ_{MMI} , see Figure 3c, are related to the temperature values. Both

characteristic curves are well-in a first-order polynomial, where the DWOFS presents a sensitivity $-0.1364 \text{ nm}/^{\circ}\text{C}$ at the visible range and $-0.1785 \text{ nm}/^{\circ}\text{C}$ the NIR range. The sensitivity of DWOFS in the NIR range is higher than the visible range due to the high sensitivity of PDMS to temperature. With the temperature sensitivities obtained from the DWOFS, the response of the DWOFS when the refractive index and temperature of the liquid sample change simultaneously can be obtained through the sensitivity matrix discussed in the next section.

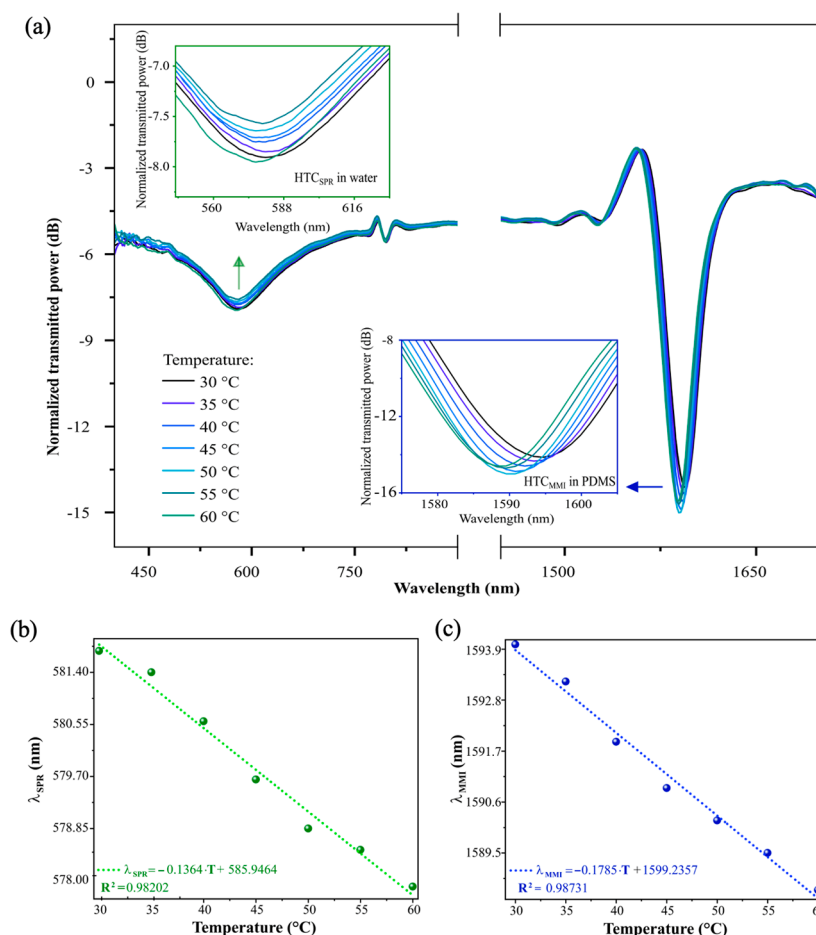


Figure 3. (a) Transmitted spectra of the DWOFS when subject to temperature changes. Inset: the green graph and blue graph correspond to the zooms of the SPR and MMI wavelengths that are appreciated in the VIS and NIR, respectively. Relation of temperature vs. the displacement of (b) SPR dip and (c) MMI dip.

3.3. Measurement of the Thermo-Optic Coefficient of the Distilled Water and PDMS

In previous sections, the DWOFS was evaluated separately for changes in refractive index and temperature. Through the two wavelengths of operation, λ_{SPR} and λ_{MMI} , the DWOFS demonstrate different sensitivities to RI (see Figure 2) and temperature (T) (see Figure 3). The DWOFS exhibits maximum refractive index sensitivities of 2770.30 nm/RIU and 230 nm/RIU at visible and NIR ranges, respectively. Meanwhile, the temperature sensitivities of the DWOFS are $-0.1364 \text{ nm}/^{\circ}\text{C}$ and $-0.1785 \text{ nm}/^{\circ}\text{C}$, respectively. Through the sensitive matrix of the DWOFS, it is possible to determine the n and T of a liquid sample simultaneously.

$$\begin{bmatrix} \lambda_{SPR} \\ \lambda_{MMI} \end{bmatrix} = \begin{bmatrix} 2770.30 & -0.1364 \\ 230.429 & -0.1785 \end{bmatrix} \begin{bmatrix} n \\ T \end{bmatrix} \quad (1)$$

Therefore, knowing the wavelength of λ_{SPR} and λ_{MMI} obtained from an experimental spectrum, it is possible to determine the temperature and RI of the liquid sample by using

$$\begin{bmatrix} n \\ T \end{bmatrix} = -\frac{1}{463.068} \begin{bmatrix} -0.1785 & 0.1364 \\ -230.429 & 2770.3 \end{bmatrix} \begin{bmatrix} \lambda_{SPR} \\ \lambda_{MMI} \end{bmatrix} \quad (2)$$

The DWOFS was designed to be sensitive to the refractive index, but it was seen as the SPR and MMI dips also shifted with the temperature. This is due to an intrinsic property of the matter known as the thermo-optic coefficient. In this work, the TOC of distilled water was estimated by tracking the displacement of λ_{SPR} generated by the temperature changes (Figure 3) and substituting the values into the refractive index calibration curves of DWOFS, obtained in Section 3.1, to obtain the corresponding refractive index. In Figure 4, the calculated refractive index of the distilled water at each temperature is shown. A linear curve was adjusted to the obtained data, and its slope represents the TOC of distilled water. The calculated TOC for distilled water is -0.9928×10^{-4} RIU/°C, a result consistent with previous studies, which determined the TOC through alternative methodologies [55]. The refractometric response can be observed in two distinct regions of the electromagnetic spectrum, visible and infrared, with sufficient separation to avoid overlap in the dips. Therefore, this DWOFS can be used to measure the TOC of unknown liquid samples or to simultaneously measure the temperature and refractive index of a liquid sample with accuracy.

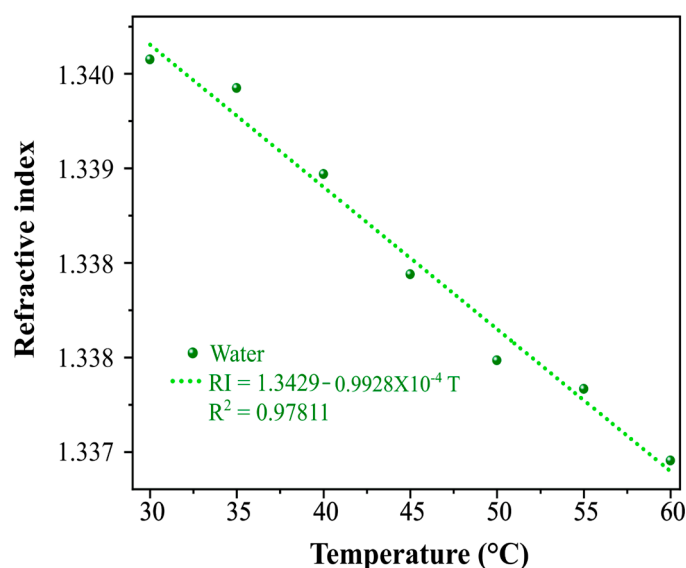


Figure 4. Relationship between refractive index vs. temperature for obtaining the thermo-optic coefficient (TOC) of distilled water and PDMS.

4. Conclusions

A novel, compact device using a dual-wavelength fiber optic sensor has been proposed to identify and characterize liquid samples by measuring their refractive index in the visible and infrared regions. The fiber refractometer features two hetero-core structures arranged in the MMF transmission line. A significant advantage of this device is its ability to perform measurements simultaneously, exploiting SPR and MMI phenomena. The large wavelength separation between the SPR and MMI sections prevents them from overlapping over a wide range of refractive indices. When the MMI section is immersed in PDMS, changes in the refractive index of a liquid can be evaluated when subjected to temperature changes. As a proof of concept, we demonstrate that the thermo-optic coefficient of a liquid sample (water; -0.9929×10^4 RIU/°C) can be estimated using this device. This device offers a

simple and compact solution for the simultaneous measurement of refractive index and temperature in liquid samples for several applications, including biological, environmental, and healthcare research.

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Abbreviations

The following abbreviations are used in this manuscript:

Au	Gold
Cr	Chromium
DWOFS	Dual-wavelength optical fiber sensor
FWHM	Full width at half maximum
HTC	Hetero-core fiber
HTC _{MMI}	HTC structure MMI is based on MCM fiber structure with a NCF section
HTC _{SPR}	HTC structure SPR is based on MSM fiber structure that is coated with Cr and Au films
MMF	Multimode fiber
MNM	Multimode—no-core—multimode fiber structure
MSM	Multimode—single-mode—multimode fiber structure
NCF	No-core fiber
NIR	Near infrared range
OFRIS	Optical fiber refractive index sensor
OSA	Optical spectrum analyzer
PDMS	Polydimethylsiloxane
SMF	Single-mode fiber
SPR	Surface plasmon resonance
TFBG	Tilted fiber Bragg grating
TOC	Thermo-optical coefficient
Vis	Visible range
λ_{MMI}	Minimum wavelength of the MMI-dip
λ_{SPR}	Minimum wavelength of the SPR-dip

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