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Bi-Functional Coated Tapered LPFG Sensor: Gas and Temperature Sensing

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ABSTRACT

A bi-functional coated tapered Long Period Fiber Grating LPFG as a gas and a temperature sensor is proposed. Obtains a sensor with a high sensitivity is still a matter of challenge. In this work, a taper LPFG is used for sensing purposes. Besides, in order to increase the sensor performance, numbers of Cr and Al layers are coated on the taper region. In this work, different concentrations of four gases Ar, NH_3, CH_4 and N_2 are applied for temperature range (25℃ up to 80℃). however, the experimental results illustrate that the transmission loss is reduce which means a significant interaction between sensing medium and cladding mode is occurred successfully which leads to higher sensitivity. Nevertheless, from the main findings, the temperature sensitivities are 2.9 pm/℃, 4.9 pm/℃, 4.5 pm/℃ and 3.1 pm/℃ for 4% concentrations of Ar, NH_3, CH_4 and N_2 respectively. In addition, the gases sensitives are 0.213 nm%$^{-1}$, 0.41 nm%$^{-1}$, 0.39 nm%$^{-1}$, 0.201 nm%$^{-1}$ with limit of detection LoD of 0.061%, 0.024%, 0.032% and 0.073% for Ar, NH_3, CH_4 and N_2 respectively. Additionally, the sensor shows a good repeatability, recoverability and stability. In terms of stability, the sensor shows a stable value of wavelength shift under different values of gas concentration and temperatures which was estimated 1.55 µm. Besides, it shows a fast responsivity with 53 s and 60 s as response time and recovery time respectively. Interestingly, with less than 0.06 nm of standard deviation, the signal returned to its original resonance wavelength which confirms that this sensor has a good recoverability. From these results, a coated taper LPFG can be a promising candidate for medical and industrial applications.

1. INTRODUCTION

Temperature and gas sensors have been used widely in many industrial applications. Fiber optic based grating sensor has been utilized in many functions instead of conventional sensors due to its low cost, low weight, immunity to electromagnetic field, small size and its high sensing ability to different physical parameters such as temperature [1], pressure [2], acceleration [3], force [4], strain [5], displacement [6], high magnetic field [7] and chemical application [8]. Therefore, Fiber Bragg Grating FBG (few of hundred micrometers grating periods) and Long Period Fiber Grating LPFG (few of hundred nanometers grating periods) have been used for sensing several measurands. As a consequence, many studies have been conducted using FBG and LPFG on different fiber structures and different combination of FBG and LPFG by coating it with different materials [9]. For example, one study used five different apodization profiles based on FBG temperature sensor such as uniform, raised sine, sinc [10]. The study concluded that Nuttall profile gives a higher sensitivity of 0.01372 nm/℃ at 117.3℃. Another study proposed a S-shape taper optical fiber based on Mach Zehnder interferometer; the study showed that at range of 28-32℃, the temperature sensitivity was -15.66 nm/℃ [11]. A very recent study presented a hybrid structure of fiber optic based on a thin taper and an air bubble for temperature, refractive index and transverse load sensitivities [12]. However, the air bubble represents a Fabry Perot and Mach Zehnder interferometers; this structure gives 1.596 nm/N, 103.2 pm/℃ and -103.2 nm/RIU for transverses load, temperature and refractive index sensitivities respectively. D-shaped fiber based on LPFG as a strain and temperature sensor proposed; the etching and re-modulation method has a direct impact on the refractive index distribution which gives different coupling coefficients [13]. This structural gives a 10.75 pm/με and 0.14 pm/℃ for strain and temperature sensitivities respectively. Further explore on D-shape based on LPFG sensor was carried out for bending measurements [14]. This novel structure formed by splicing between multi-mode and single mode optical fiber. This sensor had the ability to discriminate the bending direction due to the asymmetric refraction index modulation. Moreover, a study illustrated that taper fiber based on FBG can be used in sensor of microsurgical force [15]. Another research approved that using taper FBG in medical field to identify cancers efficiently [16].

By summarizing recent researches, it is found that taper fiber structure used for sensing application more than other structure and it takes a significant attention by researchers because of its high ability for sensing through the sensing taper region. Further studies on enhancing the senor sensitivity have been proposed by coating the sensor with different materials such as metal and polymer. For instance, one research presented an s-shape LPFG sensor coated by metal for magnetic field sensitivity [17]. The sensor shows that the metal layer has an impact on increasing the coupling coefficient and hence increases the transmission loss with increasing magnetic field. However, the sensitivity was estimated to be -0.0084 dB/Gauss [18]. In terms of polymer, one study proposed a temperature sensor based on LPFG coated by Poly-dimethylsiloxane (PDMS). The study confirmed that the sensitivity enhanced by four times that bare LPFG. The sensitivity reached to 255.4 pm/°C in the range of (20-80°C) [18]. Another interesting study combined FBG with TiO_2 coated LPFG for trucking organic solvents [19, 20]. However, more methods of LPFG and FBG combination have been proposed. For instance, a study used LPFG followed by FBG as a refractometer based on a cladding mode Bragg grating (CBG) for a compensation of temperature. The authors claimed that this sensor is a promising candidate for biochemical detection [21]. Another study proposed a tapered optical fiber connected with photonic structure and it operates for 1.55 µm. Interestingly, this design has been used as a sensor and utilized it for maximizing the coupling efficiency to the photonic structure [22]. Similarly, a study showed that fabricated an LPFG with grating period of 400 µm and length of 5 cm in a biconical tapered fiber with 3.2 cm length and 34 µm diameter which was used effectively for refractive index sensing [23]. A novel research showed a high sensitivity performance of Pd-Ag coated layer on tapered sensor was used to measure hydrogen and ammonia. This novel sensor was able to sense a gas with less than 4% concentration [24]. A periodically taper optical fiber sensor (PTOF) was proposed as a temperature sensor for temperature values from 20°C to 70°C, this study proved that the number of waists could have a significant impact on the temperature sensing [25]. Furthermore, another study used the same concept of periodically tapered sensor but for gas sensing. The authors reported that this sensor can be sufficiently utilized for in-situ fuel adulterations tracking [26]. A novel pressure sensor reported for the first time, this sensor is a periodic tapered structure that has a diameter ranging from 115 µm to 120 µm. the sensor gives an accurate pressure sensitivity equal to 5.1 pm/bar. This novel sensor fabricated by assembled equipment using arc discharge controlled by computer [27].

This study is proposed a dual function of temperature and gas sensitivity using tapered optical fiber based on LPFG coated by metal layer. Metal coating layer is selected for this study due to its advantages on increasing the temperature sensitivity.

2. SENSING CONCEPT

As mentioned earlier, LPFG is periodic structure of several hundreds of micrometers grating. This periodic structure is a fiber core refractive index modulation which leads to light coupling between core and cladding modes. In general, the basic concept of optical fiber sensor based on grating is relying on wavelength shifting. In other words, wavelength shifting is induced by any changing in grating period and any modulation in the refractive index. However, sensing concept of LPFG is based on grating period changing Λ and modulation between refractive indices of n_{co} and n_{cl}. The following basic expression can summarize the concept in terms of Bragg wavelength λ_{BLPG} and grating period Λ [19]:

$$\lambda_{co} = 2n_{co}\Lambda \tag{1}$$

$$\lambda_{cl} = 2n_{cl}\Lambda \tag{2}$$

$$\lambda_{B_{LPFG}} = (n_{co} - n_{cl})\Delta_{LPFG} \tag{3}$$

where, $(n_{co}-n_{cl})\,\Delta_{LPFG}$ is the refractive index change of LPFG. The transmission spectrum modified if any external physical factors have applied on the sensor, especially, gas or temperature as it will explain in this work. This will lead to shifting in LPFG resonance wavelength and hence the transmission spectrum will change. In this work a thin layer of metal coating will be covered the tapered region of the sensor. This will have an impact on the sensitivity performance as it will be explaining the following sections. However, in terms of temperature sensitivity, the expression of transmission spectrum will be as follows taking into account the coating material [21].

$$\Delta\lambda_{LPFG} / \Delta T_{LPFG} = \lambda_{LPFG}(\Delta_{nd}\alpha_{co}\alpha_{coating} + 2\xi) + f(\Delta n) \tag{4}$$

where, $\Delta\lambda_{LPFG}$ and ΔT_{LPFG} are wavelength change and temperature change for LPFG respectively. Δ_{nd} is $(n_{co} - n_{cl})$. $f(\Delta n)$ is nonlinear function that explains the LPFG sensing for refractive index modulation. From Eq. (4), it is clear that the changing in LPFG resonance wavelength depending linearly on the changing in temperature and refractive index. According to gas concentration pressure sensitivity for LPFG can be expressed by the following equation:

$$\begin{aligned}\Delta\lambda_{LPFG} / \Delta P_{LPFG} = \lambda_{LPFG}[-\frac{(1-2\sigma_{co})}{E_{co}} + \frac{n_{co}^2}{2E_{co}} \\ +(1-2\sigma_{co})(2p_{12} + p_{11}) - \frac{\sigma_{Al} r_{Al}^2}{E_{Al}\sigma_{Al}(r_{Al}^2 - r_{co}^2)}]\end{aligned} \tag{5}$$

where, σ_{co}, r_{co} and E_{co} are core axial stress, radius and young's modulus respectively. And p_{12} and p_{11} are the index of Pockel. Besides, E_{AL}, σ_{AL} and r_{AL} are Young's modulus, axial stress and radius Al layer respectively. This paper presents a bi-function tapered sensor for temperature and gas sensitivity coated by Al thin layer in order to improve the sensitivity performance.

3. SENSOR PREPARING PROCESS

A silica Multi Mode Optical Fiber MMF was used in this study. It has 62 µm as a core diameter and 125 µm as a cladding diameter. The refractive indices are 1.45 and 1.44 for core and cladding respectively. The first step was preparing the taper region. A tapered region of optical fiber can be achieved by heating required position of the optical fiber and stretching it carefully. It can be heated by for example flame, arc discharge or laser radiation with high power. In addition, the taper region can be achieved by polishing and chemical etching [20]. As a result of these processes, the core of optical fiber become thinner along with the fiber itself. The thinner region can be few of millimeters. In the current work, the MMF was heated and stretched uniformly and its parameters were controlled based on the following expression which clearly explains the exponential shape transition of the optical fiber [20].

$$d = d_o \exp(-z/2L) \tag{6}$$

where, d_o is the overall MMF diameter and d is the diameter of waist region. Besides, z is the elongation distance and L is the waist length as shown in Figure 1.

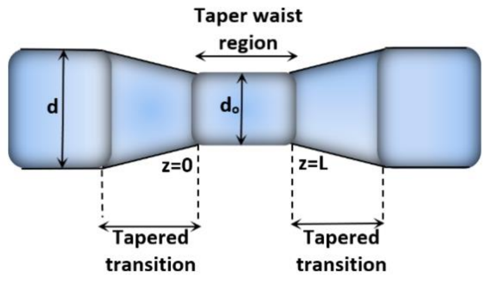

Figure 1. Tapered optical fiber

The taper fabrication setup used in this work is similar to what was reported in Ref. [22]. A flame torch was fixed on a 3D transition stage controlled by motor, securing that the flame will apply uniformly on whole area of interest of optical fiber sensor. The two ends of optical fiber were fixed on linear transition stages which were fixed in opposite directions. One end of optical fiber was connected to Smart Scan Interrogator SSI and the second end connects to Optical Spectrum Analyzer OSA in order to monitor the changing in the transmission spectrum in real time as depicted in Figure 2.

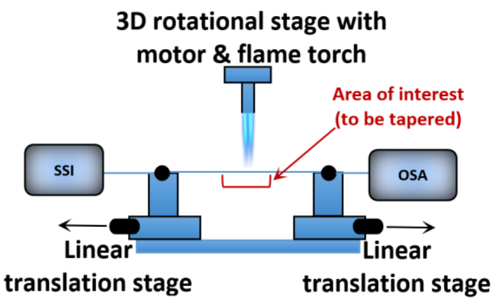

Figure 2. Tapered MMF process

According to the grating inscription of Tapered Multi Mode Optical Fiber TMMF sensor, amplitude mask technique was used. This method involves on exposing the fiber core to excimer laser through amplitude mask, but firstly, increasing the photosensitivity of fiber core is essential step. For three days, our TMMF was exposed to Hydrogen aiming to increase the photosensitivity and hence, maximizing the rate of grating inscription. However, in this work, TMMF was exposed to 248 nm and power of 16 mJ of excimer laser KrF. A UV light was passed through an amplitude mask making a pattern of light and dark shades on the core. These patterns referred to the grating made on the fiber core. The grating period was 250 µm. Moreover, in order to increase the sensitivity performance, the TMMF will be coated by a metal of a thin layer of Al. A thermal vapor deposition was employed. Before Al coating, a thin layer of almost 3 nm of Cr was sputtered on the tapered region in order to maximize the adhesion rate of Al on tapered region. Besides, this step will prevent the Al layer from peeling off during the cleaning process. Then by using thermal vapor deposition, a layer of 19 nm of Al was deposited on tapered region. The Al layer thickness was monitored and controlled in real time by tracking the quartz crystal in deposition machine. It is important to highlight that the TMMF sensor was fixed on rotational platform to ensure that the metal deposited uniformly. The overall process of preparing the coated tapered LPFG sensor is shown in Figure 3.

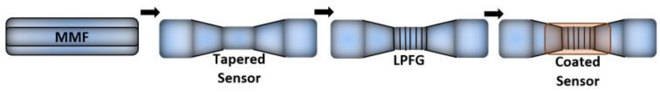

Figure 3. Schematics of preparing process coated tapered LPFG sensor

The TMMF has the specifications of 15 mm as whole length, 8 mm as tapered region, 10 µm as waist diameter and 19 nm as coating thickness of Al. Besides, the operating wavelength was 1500 nm < λ < 1550 nm.

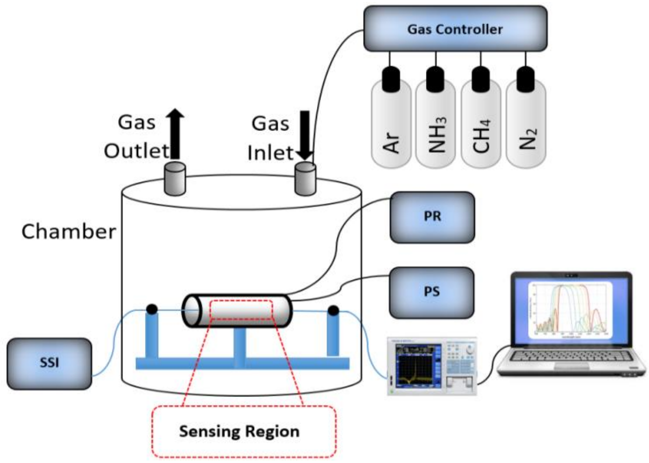

Figure 4. Schematics of bi-function sensor setup

4. EXPERIMENTAL WORK

In order to test the sensor performance for gas and temperature sensitivity, a simple setup was employed for this purpose and it is shown in Figure 4. The sensor was fixed on two fixed stages with glued points. The sensing region was inside an aluminum tube wrapped with heating foil for temperature testing purpose. The heating foil was connected to heating system which consists of thermocouple, Pico Recorder PR, and power supply PS. The two ends of TMMF were linked to Smart Scan Interrogator SSI, OSA and PC. The sensing region setup was enclosed by cylindrical chamber with 1-liter volume for gas testing purpose. The applied temperatures were from 25°C up to 80°C while and for gas testing, four gases have been applied and controlled in this work Ar, NH_3, CH_4 and N_2. The cylindrical chamber has two ports for gas inlet and gas outlet. However, by changing the applied voltage from PS, the temperature of heating foil arises and heats the surrounding environment of TMMF sensor. Besides, by adjusting the gas controller, the amount and type of applied gas are controlled.

5. RESULTS AND DISCUSSION

5.1 Sensor characterization

Firstly, the sensor transmission spectrum before and after Al coating is shown in Figure 5. From the figure, it observes clearly that the spectrum extra emerged due to the impact of the metal layer (Al coating layer) which increased the sensitivity performance of the TMMF sensor. The spectrum has two loss peaks at approximately 1513 nm and 1536 nm which referred to successful inscription of LPFG on the core. Furthermore, the loss peak at 1536 nm has a transmission loss of -14 dB which is less than the loss of other loss peak hence has larger coupling efficiency compared to other peak. The minimum loss means that this loss peak produces a significant interaction between sensing medium and cladding mode hence produces significant sensitivity. In the following context, it has been concentrated only on the loss peak at 1536 nm in terms of the sensing performance. Moreover, the relation of different Al thicknesses with the wavelength shift has been shown in the inset Figure 5. At 19 nm thickness of Al, the sensor achieves the highest sensitivity. The final step was monitored the sensor by a Spectroscopic Ellipsometer in order to check the quality of deposition process.

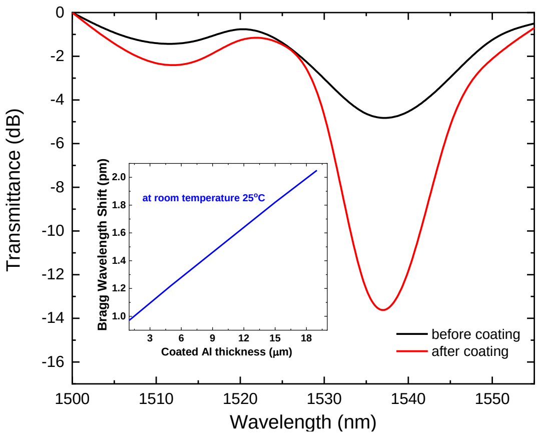

Figure 5. Transmission spectrum of the TMMF before (black line) and after (red line) metal deposition. The impact of Al coated thickness on the wavelength shifting was shown in the inset

5.2 Sensor performance

Gas sensing performance was investigated for four gases Ar, NH_3, CH_4, and N_2. For each gas four different gas concentrations were investigated. It is found that the TMMF sensor shows higher sensitivity for NH_3 and CH_4 than Ar and N_2. The transmission spectrums are shown in Figure 6. The transmission spectrum confirms that after exposing the sensor to different gas concentrations, the transmission loss is incrementally reduced and the wavelength is shifted. For example, in 4% of NH_3, the resonance wavelength shifts from 1536 nm to 1538.5 nm with significantly decreases in loss from -13 dB to -15 dB. Besides, these results confirm that the Al layer and the taper waist region contributed in improving the evanescent field intensity on the fiber core and hence, enhancing the fiber core mode conversion efficiency as many studies proven that [23]. In other words, when the gas concentration around the sensing region increase, the effective refractive index of Al layer is increased as well. This is because of the diffusion of the gas molecules into Al layer which caused improving the interaction between this region and evanescent field intensity and hence, transmission spectrum modified with less power loss. The sensor shows a similar performance scenario for CH_4. In terms of Ar and N_2 the sensor shows a small value of resonance wavelength shifts compared with other two gases which was estimated to be around 0.5 nm for 4% gases concentration.

A temperature TMMF sensor was experimentally investigated along with the impact of applying gas on it. The applied temperatures were from room temperature up to 80°C at 4% of each Ar, NH_3, CH_4 and N_2. Four temperature degrees were selected 30°C, 40°C, 50°C and 75°C in order to illustrate the transmission spectrum. Figure 7 shows how different temperatures can modify the transmission spectrum along with impact of gas concentrations. It can be seen that the sensor shows a significant responsivity to temperatures sensitivity. Figure 7 demonstrates the transmission spectrum under the effect of applied temperatures and gas concentrations which leads to a higher shift in the resonance wavelength. For example, for 4% NH_3, the resonance wavelength shifts from 1536 nm to 1550.2 nm when the temperature reached 75°C. In addition to, the enhancement in the results belong to the existence of the metal layer which boosts the ability of the sensor to be more sensitive to small amount of temperature as many researches confirmed that [24]. Furthermore, the taper waist region contributes in positive aspect for enhancing the temperature sensitivity since, the applied temperatures will be direct to the sensing region which consist of the grating structure and the metal coating layer. This is why many researches have been preferred using tapered structure as a temperature sensor [20,21]. Nevertheless, the temperature sensitivities for 4% of Ar, NH_3, CH_4 and N_2 were 2.9 pm/°C, 4.9 pm/°C, 4.5 pm/°C and 3.1 pm/°C respectively.

Moreover, to investigate the linearity performance of the TMMF sensor, the resonance wavelength shifts are estimated as a furcation of both gas concentrations and different temperatures which were extracted from Figures 6 and 7. These linear fit relations were plotted as Figure 8 illustrated. However, the sensor shows a good linearity performance under different gas concentrations. The correlation coefficients of 4% for each of Ar, NH_3, CH_4 and N_2 were 0.995,0.998, 0.997 and 0.994 respectively; besides, the sensitivities for these gases are 0.213 nm$\%^{-1}$, 0.41 nm$\%^{-1}$, 0.39 nm$\%^{-1}$, 0.201 nm$\%^{-1}$ with congruent limit of detection LoD of 0.061%, 0.024%, 0.032% and 0.073% respectively. However, using metal layer with taper structures gives more enhanced linear sensor performance by factor 4 compared with [20, 24].

5.3 Sensor responsivity

The response characteristics of the TMMF sensor were tested further. For example, repeatability and stability tests were performed successfully. Experiments were carried out by applying 4% of NH_3 on the TMMF sensor. The resonance wavelength shifts as a function of time for both gas and temperature sensors were plotted in Figure 9 and 10. In Figure 9a and for gas sensor, the stable value of wavelength shifts under 4% of NH_3 was estimated to be 1.55 pm. The response time (t_{res}) related to the TMMF sensor under the mentioned conditions was measured to be 53 s and the recovery time (t_{rec}) was calculated to be 60 s. Additionally, with less than 0.06 nm of standard deviation, the signal can return to its original resonance wavelength which confirms that this sensor has a good recoverability. According to the temperatures sensor, a repeatability test is shown in Figure 9b. The test was carried out at 4% of NH_3 under temperatures range from room temperature up to 75°C. The time taken for two cycles was approximately 3 hours. Throughout this time, the sensor shows a good recoverability and repeatability under the same measurements conditions.

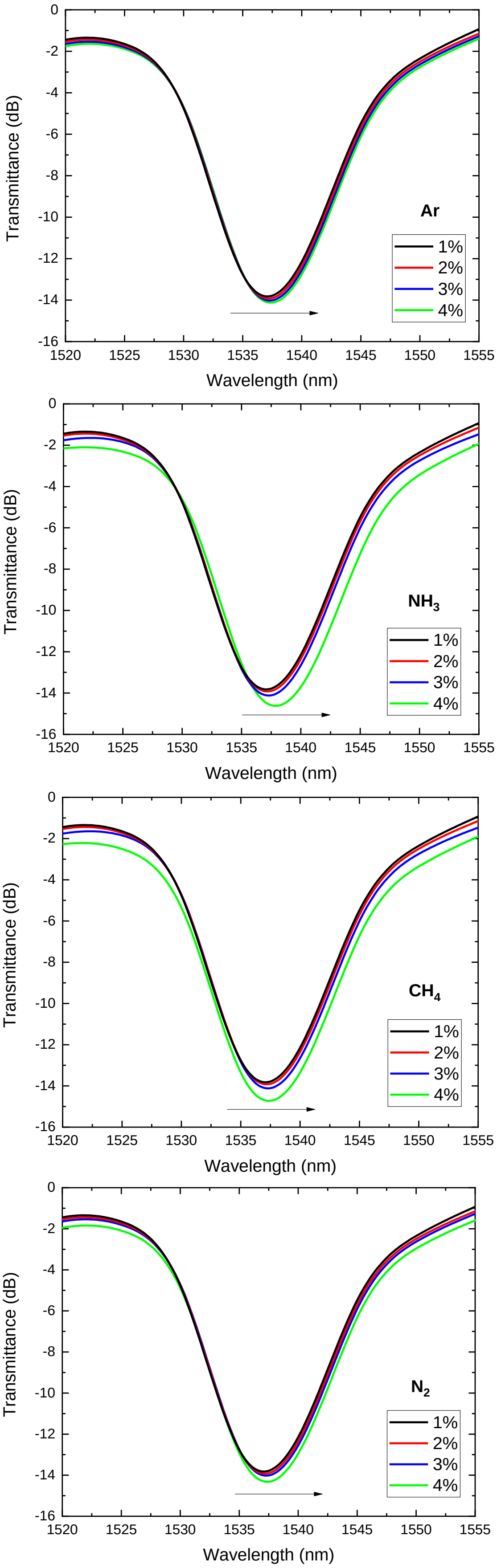

Figure 6. Transmission spectrum of the TMMF gas sensor (different gases concentrations)

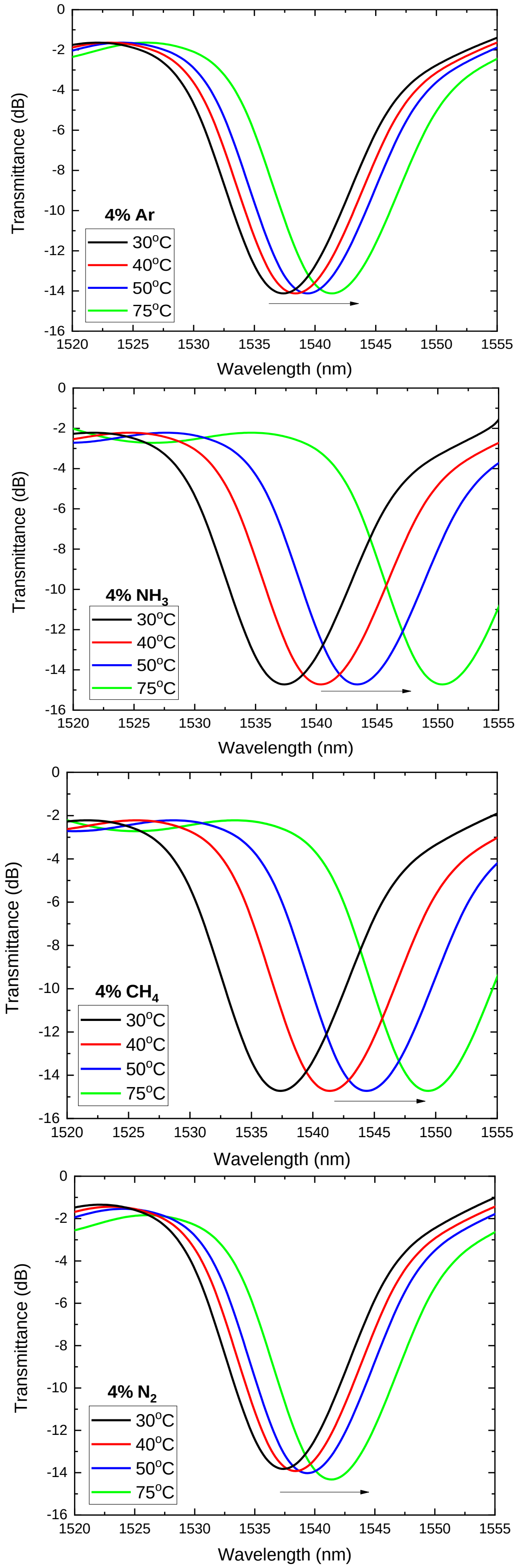

Figure 7. Transmission spectrum of the TMMF temperature sensor

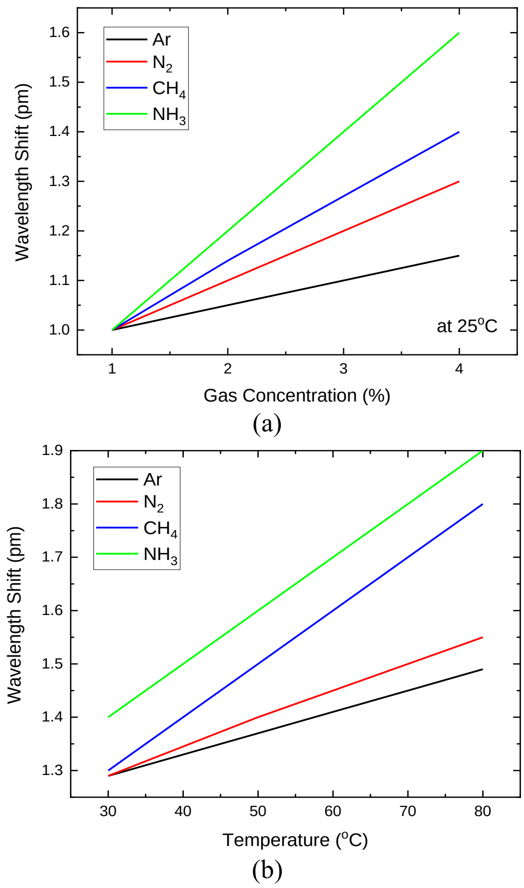

Figure 8. Resonance wavelength shift as a function of (a) gas concentrations at 25°C and (b) temperatures changes

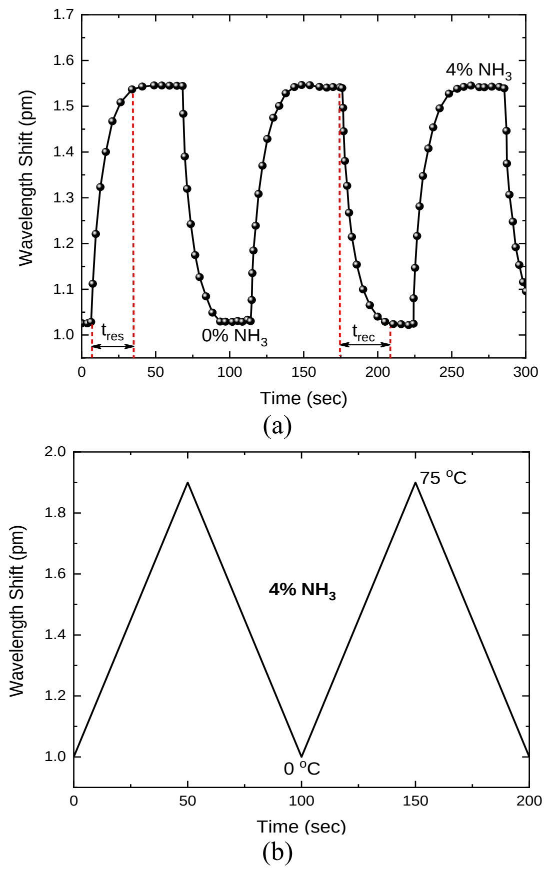

Figure 9. Repeatability response of TMMF as (a) gas sensor to 4% NH_3 and (b) as a temperature sensor at 75°C

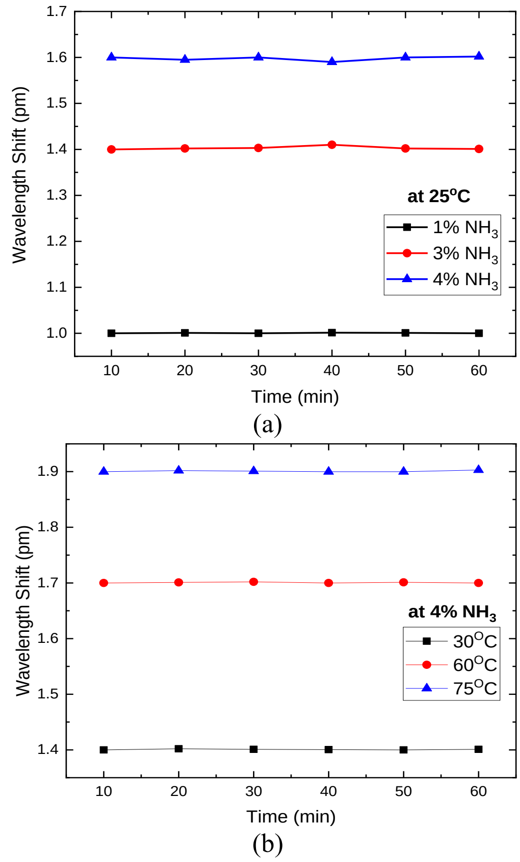

Figure 10. Stability test for TMMF sensor performance for (a) gas sensor at 25°C and (b) temperature sensor at 4% of NH_3

In terms of stability test of the TMMF sensor, Figure 10 illustrates the performance of the gas and temperature sensors. Firstly, the sensor was exposed to the three different concentrations of NH_3 gas at room temperature for one hour, however, the sensor shows good stability measurements as shown in Figure 10a. The resonance wavelength shift was almost the same with an estimated percentage error of 1%, 2% and 2.5% for NH_3 concentrations 1%, 3% and 4% respectively. Then, the sensor was exposed to fixed NH_3 concentrations at different temperatures 30°C, 60°C and 75°C for one hour. Similarly, the sensor shows a good and similar wavelengths shift measurements with percentages error of 1% for all applied temperatures which indicates that the TMMF sensor has efficient performance as gas and temperature sensor at the same time; the test outcomes shown in Figure 10b. Again during these tests, it has been concentrated on keeping the performance of these tests under the same conditions. As a result, due to the metal coated layer (Cr and Al deposition) and the taper MMF structure, the sensor performance and sensor responsivity were enhanced significantly compared with other reported studies as mentioned earlier. Additionally, writing long period grating within the fiber tapered section could have impact on the interference of the excited cladding modes with the propagating light inside the core. This interference yields directed spectrum within the LPFG resonance bands envelop.

6. CONCLUSIONS

In this study, a bi-functional coated tapered LPFG sensor for gas and temperature sensitivity was fabricated and investigated. The effectiveness of the proposed methods has an impact on the sensor performance in terms of gas and temperature sensitivities which were enhanced significantly compared with other reported studies. The metal layer increases the heat conductivity, mechanical strength and temperature range of the fiber. Besides, the taper region and its structure increase the evanescent field intensity and conversion efficiency on the fiber core. However, the temperature sensitivity was calculated to be 4.9 pm/°C under fixed NH_3 concentration. The gas sensitivity of 4% NH_3 at room temperature was estimated to be 0.41 $nm\%^{-1}$. The sensor shows a good recoverably, repeatability and stability for different applied gases concentrations and temperatures. It is important to mention that more consideration should be taken into account for the dimensions of the taper structure and the coated material thickness during the sensor fabrication process.

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