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Low Temperature Sensor Based on Etched LPFG with Different Materials Coating

Zahraa S. Alshaikhli[1*], Hui Wang[2]

[1] Laser and Optoelectronics Engineering Department, University of Technology, Baghdad 10066, Iraq
[2] School of Biomedical Engineering, University of Western Ontario, London, Ontario N6A 3K7, Canada

Corresponding Author Email: zahraa.s.qasim@uotechnology.edu.iq

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ABSTRACT

A low temperature sensor based on etched Long Period Fiber Grating LPFG is proposed and demonstrated. A chemically etched LPFG sensor coated with (Indium In, Aluminum Al, Silver Ag, Palladium Pd and Titanium Ti) embedded within a build low temperature setup. The sensor investigation was carried out under temperature range of 20°C to -150°C; and the resonance wavelength shift was collected with different cooling rates of (10, 15, 20, 25°C/min) in order to investigate the effect of cooling rates on the sensor performance. However, the experimental results show that 10 mm LPFG sensor with grating period of 400 µm offer temperature sensitivity of 1.5 times, 2 times, 2.5 times, 3 times and 3.5 times higher than bare LPFG for Ti-coated LPFG, Pd-coated LPFG, Ag-coated LPFG, Al-coated LPFG and In-coated LPFG respectively. The maximum measuring error is less than ±0.5°C, which confirms the effectively using of LPFG sensor in cryogenic application. Moreover, the overall resonance wavelength shifts are 1.213 nm, 1.532 nm, 1.935 nm, 2.015 nm, 2.397 nm and 2.671 for bare LPFG, Ti-coated LPFG, Pd-coated LPFG, Ag-coated LPFG, Al-coated LPFG and In-coated LPFG sensors respectively. According to the cooling rates, the results illustrate that as cooling rate increase, the sensor sensitivity decrease due to the sensor response. For more investigations, simulation work is carried out using MATLAB and the sensor shows a good agreement results between experimental and simulation measurements. It is worth to mention that the main findings will essentially contribute to choose suitable materials for coating LPFG for low temperature sensing purposes and will increase the existing knowledge about optical fiber sensor applications.

1. INTRODUCTION

Due to the fact of the light weight, precise size, immune to electromagnetic interference and fields, high sensitivity, and multiplexing amenability, optical fiber sensor FOS has been widely used among conventional sensor in different application for sensing different physical parameters such as temperature, vibration, rotation, linear and angular position, acoustics, acceleration, pressure, strain, humidity, chemical and viscosity measurements [1]. Additionally, the improvement of FOS technology was integrated with industry related to optical fiber communication and optoelectronics devices. Recently, different types of FOSs have been developed and used in different application such as gyroscopes and chemical prob. FOSs have a wide range of advantages, for example, geometric versatility and high sensitivity which made FOS plays a crucial role in sensing application. As a result, FOSs used in high corrosive, high temperature and high voltage environments because of the dielectric feature [2]. Fiber Bragg Grating FBG (grating period of hundred micron) and Long Period Fiber Grating LPFG (grating period of hundred nanometers) are the most common sensors used for temperature sensing, due to their advantages such as, real time detection, fast response, small size and easy to fabricate [1, 2]. However, sensor structure modifications have been widely and extensively studied in order to enhance the sensor sensitivity, for example, side polish fiber [3], etched fiber [4], taper fiber [5], D-shape [6] S-shape fiber [7], C-shape fiber [8, 9], and U-shape fiber [10]. Nevertheless, the polarization dependence issue rises because of the broken of fiber circular symmetry. Additionally, the fiber mechanical stability is weakening as well due to the asymmetric structure [11]. However, these problems have been overcome by coating the grating area with different materials such as metal and polymers [12]. Therefore, different fiber structures with different coating layers have been extensively investigated for temperature sensing.

2. LITERATURE REVIEW

The majority of researches have been concentrated on sensing high temperature based on FBG or LPFG or mixture configurations between both [13, 14]. However, sensing low temperature is still limited. One study proposed a cascade LPFG with Fabry Perot LPFG-FP for temperature and strain sensing by using point by point method. The authors claimed that the results gave a satisfactory temperature sensing performance estimated by 6.8 pm/℃, 21 pm/℃ and 7.1 pm/℃ of three dips [15]. This study concluded that the LPFG-FP can be used as dual function sensor for temperature and strain measurements. A simulation study introduced a few modes LPFG (FM-LPFG) as a temperature sensor written by CO_2 laser. The temperature sensitivity was about 0.058 nm/℃. The authors mentioned that their sensor could be functionalized for multi parameters measurements [16]. Another interesting study proposed a taper (FM-LPFG) written by CO_2 laser and fusion tapering. The temperature sensitivity was reached -0.0393 nm/°C for temperature range (30°C – 90°C). Although the FM-LPFG was used for sensing temperature only, the authors claimed that their sensor could be utilized in variety environmental applications related to temperature due to the easy fabrication of the taper reign [17]. Moreover, a low cost and high temperature sensor based on LPFG proposed. The study stated that with temperature range of (25°C - 875°C), the sensor gave 0.37 nm/°C as temperature sensitivity due to small diameter achieved by micro heater brushing method and the thermo-optic effect [18]. Recent study proposed S-taper embedded in LPFG sensor by using CO_2 laser and fusion splicer for creating s-shape. The sensor based only on single mode fiber gave a temperature sensitivity of 70 pm/°C for temperature range of (30°C – 90°C). The authors stated that this sensor could be effectively used for simultaneous stain and temperature measurements without taking into account the other types of optical fiber [19]. Another recent research presented reflective LPFG coated by 60 cm long of fiber after LPFG grating area. The sensor showed a temperature sensitivity of 0.046 nm/°C for temperature range of (23°C – 200°C) [20]. However, the advantage of this work was creating a cost-effective method for metal coating. According to the low temperature sensitivity, on a large mode fiber, a low temperature sensor based on LPFG was fabricated effectively using CO_2 laser. The study proved that the temperature sensitivity estimated to be 3.91 pm/°C. Interestingly, the authors claimed that this sensor minimized the cross sensitivity between temperature and strain with an estimated error of 0.5 µƐ/°C [21]. Another study investigated FBG sensor for low temperature sensitivity by coating it firstly with nickel and then with different metal layers that have high thermal expansions in order to increase its sensitivity. However, the temperature sensitivity was enhanced by three times than bare FBG; and the authors indicated that their sensor could be easily functionalized in cryogenic applications [22]. This study did not provide explanation about the hysteresis responses of the FBG during the process of cooling which was addressed in the next study. A similar research conducted by using FBG for liquid natural gas storage safety. The sensor showed a linear relation between resonance wavelength shift and temperature changing with estimated error less than ± 0.35 K [23]. The authors claimed that their sensor showed an excellent performance similar to RTD sensor. Moreover, a study proposed a low temperature crosstalk sensor based on D-shape LPFG which was created by polished technique. The sensor showed 57 pm/°C as temperature sensitivity for dip A and 57.14 pm/°C for dip B. The authors stated that this sensor can sense the strain changing with high temperature sensitivity [24]. Finally, interested research presented on LPFG for both high and low temperature by using optical path interference of Sagnac and Mach-Zehnder. The sensitivity of LPFG was 0.083 nm/°C for temperature values (40°C – 120°C) which was 10 times higher than FBG sensitivity. The study stated that this sensor used for measuring the precise change in temperature. However, the study proved that LPFG is 10 times highly sensitive than FBG with 0.12°C as temperature resolution [25]. Nevertheless, motivated by the previous proposed ideas, this paper presents an investigation of etched LPFG low temperature sensor coating with different materials in order to protect the grating area and enhance the temperature sensitivity. For further investigation, a simulation work is carried out by using MATLAB; yield a good agreement with experimental measurements. The main findings of this study will significantly contribute to choose suitable materials for coating LPFG for low temperature sensing purposes and will increase the existing knowledge about optical fiber sensor applications. However, in this paper, section 3 will explain the experiment work in details in terms of sensor preparation, coating process and low temperature sensing. In section 4, the main findings will state related to transmission spectrum characteristics, sensor performance and sensor responsivity. The final section is the conclusion which will summarize the outcomes of this work.

3. EXPERIMENTAL WORK

3.1 Optical fiber and etch LPFG preparation

The optical fiber used in this work was multimode fiber with core and cladding refractive indices were 1.45 and 1.448 respectively. And the diameter of the core and the cladding were 62.5 µm and 125 µm respectively. The first step was LPFG inscription but before this step, the optical fiber was immersed in H_2 for one week in order to increase the optical fiber photosensitivity. After that, gratings were written on the fiber core by using amplitude mask method by applying a UV light through the grating mask. Nevertheless, the LPFG length was 10 mm and the grating period was 400 µm. the final step of the LPFG preparation was annealing in order to stabilize the grating. The next step was removing 12 µm from the cladding by soaking the fiber in Hydrofluoric Acid at 50°C with etching rate 1.3 µm/min. However, the remaining etchant was removed by using alcohol and deionized water for 15 min.

3.2 Coating etched LPFG process

According to the coating process, several studies were used casting [26], dipping [27], sputtering [28] and vacuum evaporation [29] as metal coating techniques. However, the thickness control in the above methods is limited; therefore, electroplating technique was used in the current work. The thickness layer was controlled by adjusting the parameters and compositions of the solution which were derived from the previous study [22].

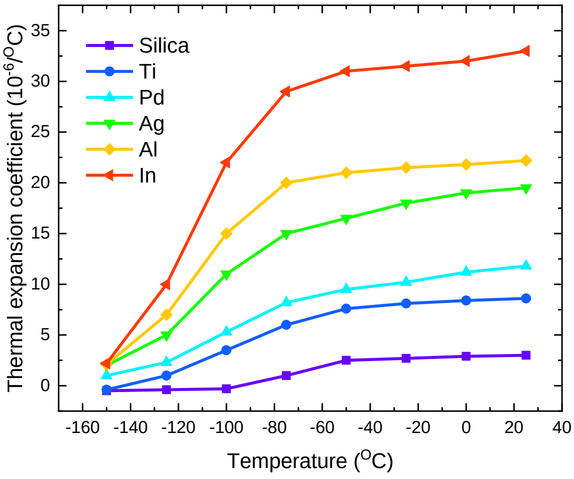


Figure 1. Thermal expansion coefficient as a function of low temperatures for optical fiber, Ti, Pd, Ag, Al and In

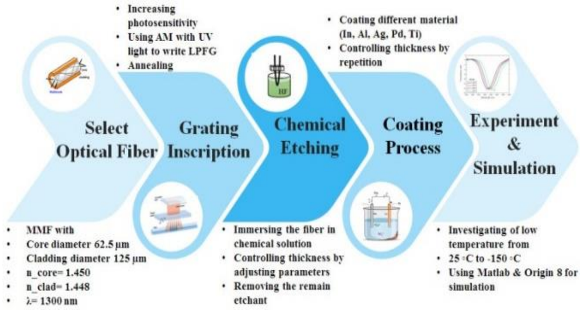


Figure 2. Steps of experimental and simulation work

Nevertheless, five different metals were selected to be coated on the etched LPFG which are In, Al, Ag, Pd and Ti because these metals have relatively high thermal expansion coefficients within the temperature range of 20℃ to -150℃ as Figure 1 shows. The metal thickness layers were 22.3 µm 25.7 µm 19.4 µm 26.1 µm and 23.5 µm for In, Al, Ag, Pd and Ti respectively. Figure 2 shows simple steps of the current work.

3.3 Low temperature sensing experiment

The aim of the current study is investigating the low temperature coated etched LPFG sensor; so that, there was no strain, bending or any other external factors affect the sensor except the low temperatures. The experiment was simply carried out using the setup shown in Figure 3. On end of the coated etched LPFG sensor was connected to broadband light source (MPB communications, EPS-7210) and the other end was connected to the optical spectrum analyzer OSA (AQ6374 with a wavelength range of 350 nm to 1750 nm and wavelength accuracy ± 0.05 nm and a very high resolution of 0.05 nm to 10 nm). The OSA was connected to PC for wavelength shift recording. The sensing area of the LPFG sensor was enclosed in a box within a cylindrical container which contains a tube for injecting the liquid nitrogen for sensing purposes. A thermocouple was attached to the container wall in order to sense the temperature changes. The thermocouple was linked to the Pico Log Recorder in order to record the temperature change through the PC. The sensor was cooled from room temperature to -150℃ by injection of liquid Nitrogen through the inlet tube of the cylindrical container. The sensor wavelength shift was tracked and recorded at every 1℃ temperature fall using OSA through the PC, besides, the temperatures were tracked using the Pico Log Recorder through the PC. In order to accurately investigated the impact of the cooling rate on the coated etched LPFG sensor sensitivity of temperature, four cooling rates (10, 15, 20, 25℃/min) were selected to be studied and compared. The reliability of the sensor sensitivity was achieved by repeating the cooling process at least three times with the four different rates mentioned above under the same experiments conditions. Additionally, MATLAB and OriginLab 8 were used for further investigation and analyzing of temperature sensitivity and the performance of the sensor.

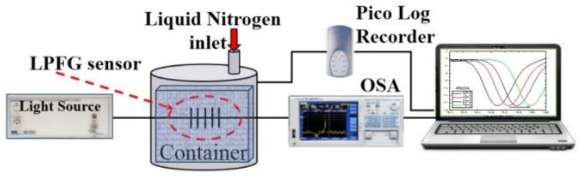


Figure 3. Setup of low temperature sensing

4. RESULTS AND DISCUSSION

4.1 Transmission spectrum characteristics

During the deposition process, the transmission spectrum of coated LPFG was affected; this is due to the fact of deformation or inhomogeneous stress occurred through the deposition process [5, 22]. However, for the current low temperature's sensor setup, temperature sensitivity and responsivity were measured for bare LPFG and coated LPFGs as the broadband light was passed through the fiber core. As the test progressed, the refractive index and thermal expansion coefficient in the gratings area altered. Furthermore, the perturbations in the gratings leads to resonance wavelength shift and obviously it will be noticeable on the change of transmission spectrum. Figure 4 illustrates the transmission spectrum of LPFG sensors at different temperatures ranging from room temperature to -150℃. However, these graphs obtained when the cooling rate was 10℃/min. The overall resonance wavelength shifts were 1.213 nm, 1.532 nm, 1.935 nm, 2.015 nm, 2.397 nm and 2.671 for bare LPFG, Ti-coated LPFG, Pd-coated LPFG, Ag-coated LPFG, Al-coated LPFG and In-coated LPFG sensors respectively. According to the graphs, all the transmission spectrums of LPFG sensors are similar under temperatures changes. When the temperature decreases, the transmission spectrum shifts with no chirp or split effect and birefringence caused by coating thermal stress of sensor. At temperature -75℃, the temperature coefficient of In-coated LPFG showed 73.8% enhancement compared with bare LPFG (|11.3-6.5|/6.5) refereeing to enhancement in low temperature sensitivity. Thus, In-coated LPFG could be effectively used for low temperature application such as cryogenics temperatures.

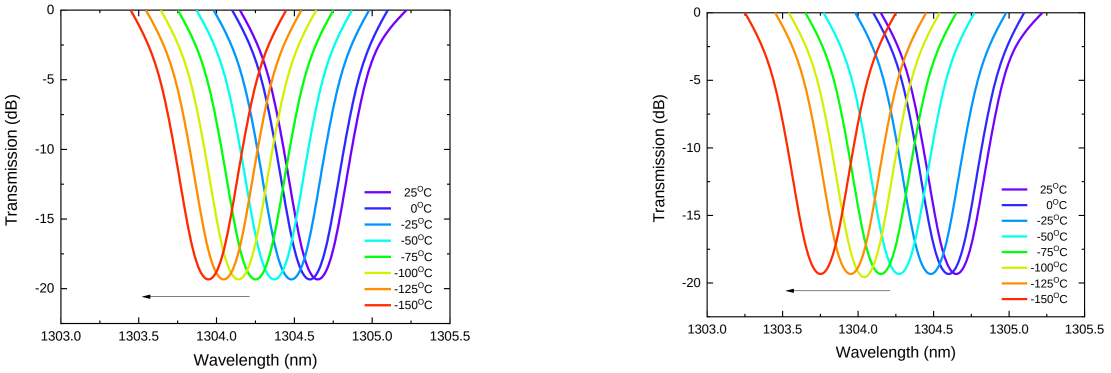
4.2 Sensor performance

The aim of this study is investigation of low sensor performance based on etched LPFG coated with different materials. It is noteworthy that the coating materials could be play as a protect layer for the gratings are of LPFG sensors and these layers improve the sensor sensitivity. Figure 5 shows the resonance wavelength shifts of bare LPFG, Ti-coated LPFG, Pd-coated LPFG, Ag-coated LPFG, Al-coated LPFG and In-coated LPFG sensors at four cooling rates (10, 15, 20, 25℃/min). From the graphs, it is obviously that the sensors performances are non-linear when the temperature decreases due to the fact that optical fiber thermal expansion and thermo-optic coefficients become smaller at low temperatures which coincident with some previous studies [2, 25].

It is noticed that before and after -75℃, the sensor performance is linear. In addition, the temperature sensitivity for bare LPFG before -75℃ is 6 nm/℃ which decreases to 3 nm/℃ after -75℃. In case of coated LPFGs for example Al-coated LPFG and In-coated LPFG, the temperature sensitivities after -75℃ are 18 nm/℃ and 20 nm/℃ respectively due to the fact that the thermal expansions of AL and In are closed and higher than other materials. According to the cooling rates, as cooling rate increases, the temperature sensitivity of coated and uncoated sensors is decrease. This might be indicated that through the fast cooling process, the LPFG sensor cannot response in time due to the rapid change in temperatures.

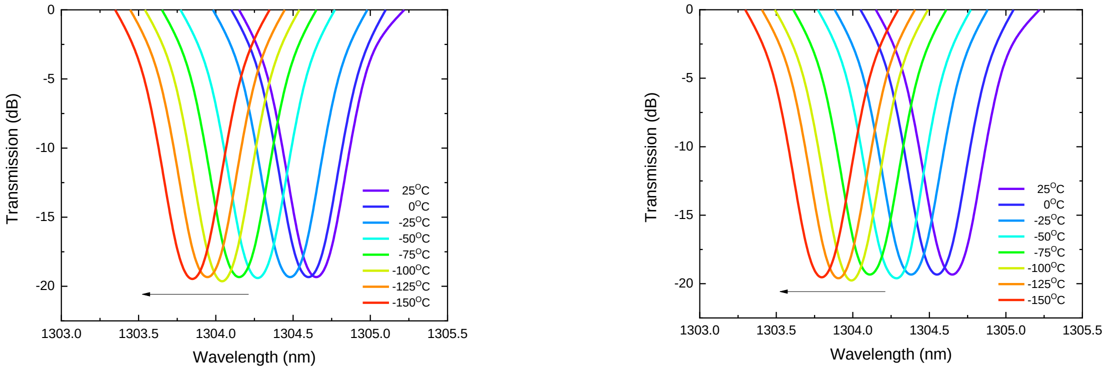
4.3 Sensor responsivity

Response characteristics were further explored for In-coated LPFG and Ti-coated LPFG. Because, In-coated LPFG showed outstanding results compared with other sensor such as Ti-coated LPFG in the current study. Firstly, repeatability test was carried out successfully be exposing both sensors to 25℃ and -75℃ at cooling rate 25℃/min; the signals were recorded every 6 s. The response time tres of both sensors were estimated to be 30 s for In-coated LPFG and 37 s for Ti-coated LPFG. Moreover, recovery time trec was measured as well and it was 26 s for In-coated LPFG and it was 28 s for Ti-coated LPFG as shown in Figure 6. However, it can be concluded that with 0.04 nm stander deviation the signal can recover to its initial value for In-coated LPFG sensor. This confirms that the In-coated LPFG sensor have good recoverability. Secondly, the reusability of In-coated LPFG and Ti-coated LPFG were inspected. The sensors were exposed to range of temperature 25℃ to -150℃. the data was collected every 20 s and the resonance wavelength shift is plotted with time as shown in Figure 7. Obviously, as both sensors exposed to different temperature, the wavelength shift increase and decrease based on applied temperature. However, after several cycles, the In-coated LPFG shows a wavelength shift fluctuation of 0.035 nm and Ti-coated LPFG gives 0.05 nm indicated a good reusability for both sensors. Finally, Figure 8 shows the final test which is stability for all sensors at 25℃ and -75℃ at cooling rate of 25℃/min. for one hour, the sensors were exposed to fixed temperature of 25℃ and -7℃ for another one hour. The resonance wavelength shifts for all sensors were quite similar and stable. The percentage errors were calculated to be 1%, 1.3%, 1%, 1% and 1.2% for Ti-coated LPFG, Pd-coated LPFG, Ag-coated LPFG, Al-coated LPFG and In-coated LPFG sensors respectively at 25℃. besides, the percentage errors were calculated to be 1%, 1.1%, 1.1%, 1% and 1.1% for Ti-coated LPFG, Pd-coated LPFG, Ag-coated LPFG, Al-coated LPFG and In-coated LPFG sensors respectively at -75℃. However, during the sensor responsivity investigations, it has been focused on maintain the same experiment conditions in order to obtain an accurate result. Thus, because of metal layer and the chemical etching on the LPFG, the sensors were showed a good performance and responsivity under low temperatures; and this could be utilized in low temperatures application such as cryogenic.



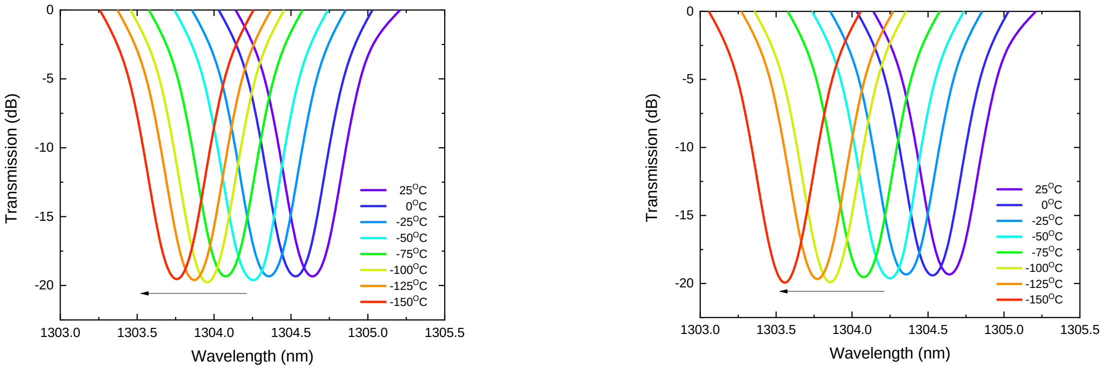
(a) Bare LPFG

(b) Ti-coated LPFG



(c) Pd-coated LPFG

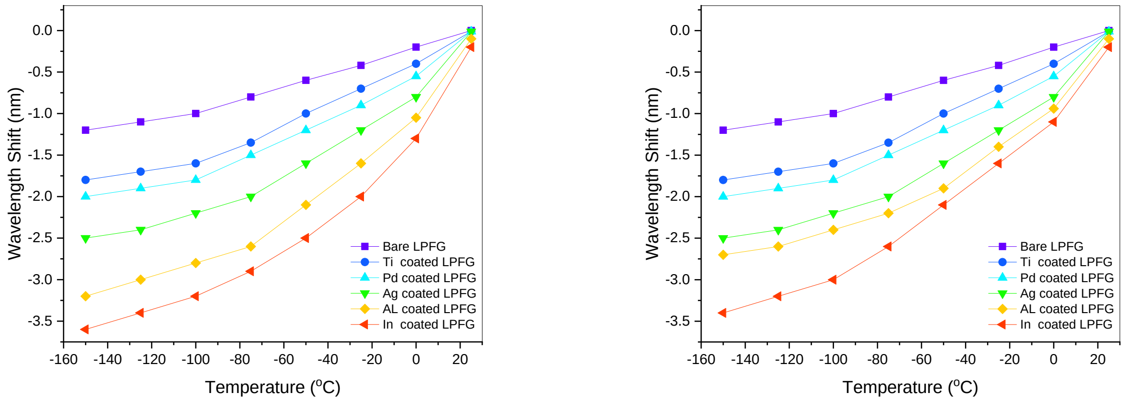
(d) Ag-coated LPFG



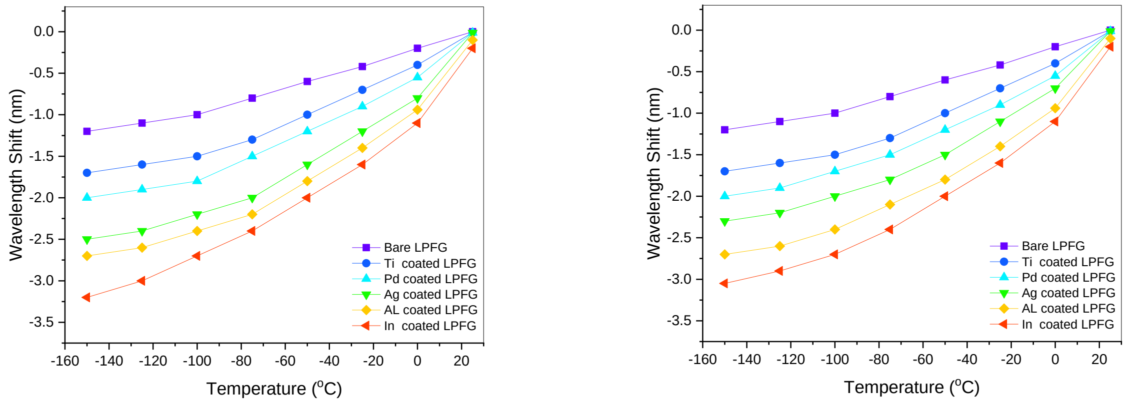
(e) Al-coated LPFG

(f) In-coated LPFG sensors

Figure 4. Transmission spectrum as a function of wavelength

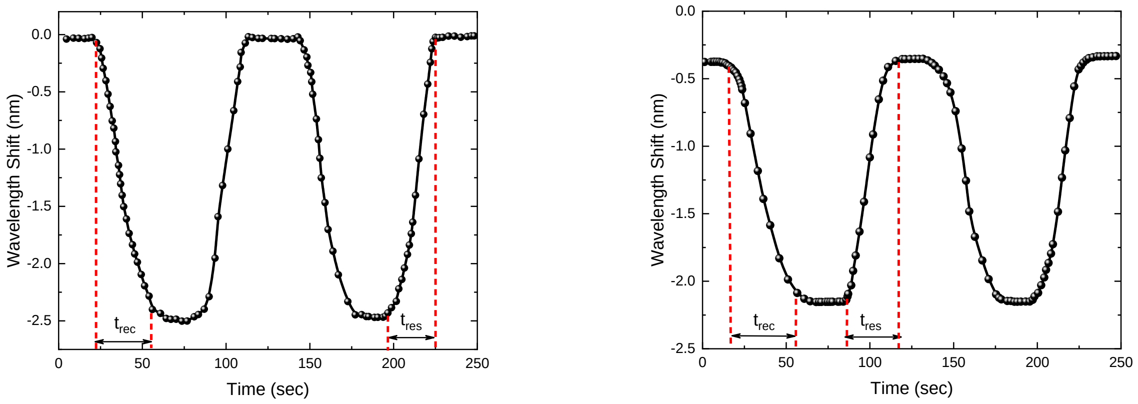


(a) 10℃/min (b) 15℃/min



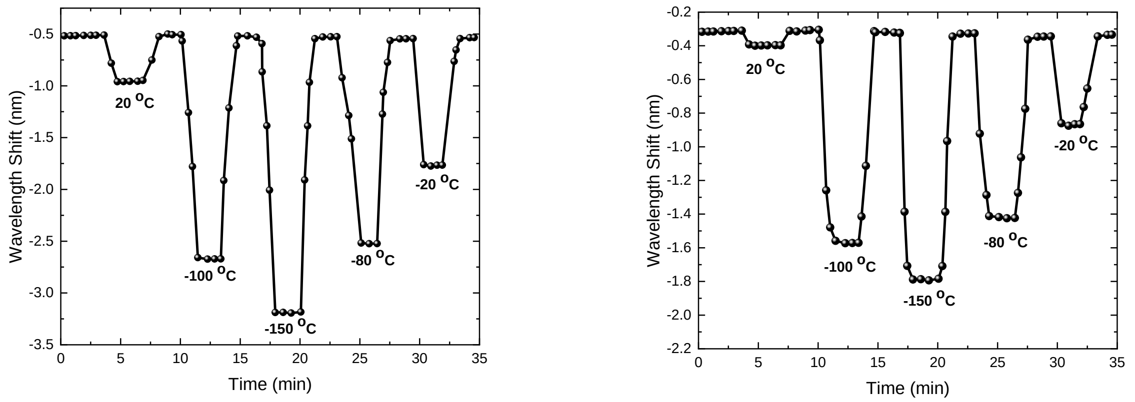
(c) 20℃/min (d) 25℃/min

Figure 5. Sensor performance at different temperatures for cooling rates



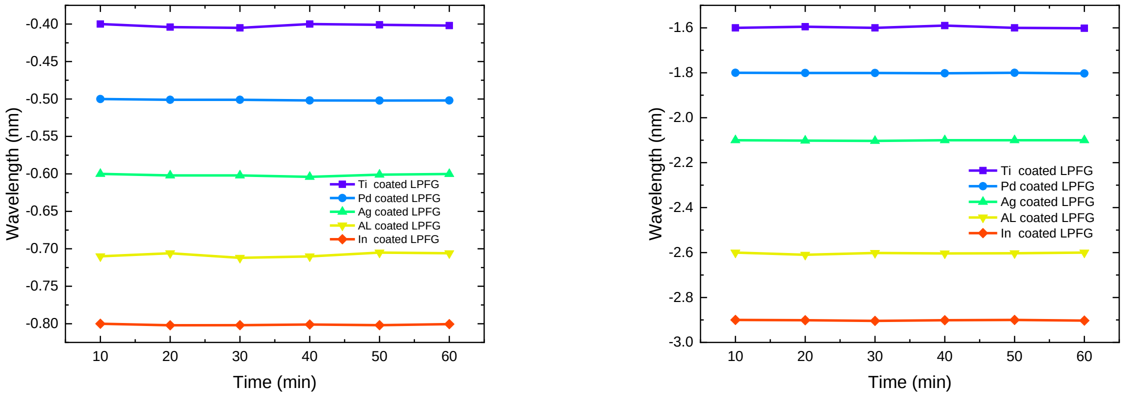
(a) In-coated LPFG (b) Ti-coated LPFG

Figure 6. Repeatability test under 25℃ and -75℃ at cooling rate 25℃/min



(a) In-coated LPFG (b) Ti-coated LPFG

Figure 7. Reusability test under different temperatures at cooling rate 25℃/min



(a) 25℃ (b) -75℃

Figure 8. Stability test for In-coated LPFG at cooling rate 25℃/min

5. CONCLUSIONS

In summary, a low temperature sensor based on different materials coating etched LPFG was investigated. The results illustrated that the low temperature sensitivities of Ti-coated LPFG, Pd-coated LPFG, Ag-coated LPFG, Al-coated LPFG and In-coated LPFG sensors are enhanced approximately 1.5 times, 2 times, 2.5 times, 3 times and 3.5 times of bare LPFG sensor, respectively. Moreover, from obtained results, it can be concluded that at higher cooling rates, the sensors slightly gave lower temperature sensitivities due to the sensors responsivity for the rapid temperature change. Again, the In-coated LPFG showed an excellent repeatability, reusability and stability under low temperatures; which confirmed that it is effectively protected and enhanced the sensor sensitivity for low temperatures compared with other materials due to its high thermal expansion coefficient. One major limitation in this study was monitoring the reflection spectrum modulation during different materials thickness under the real time cooling process. For future work, further considerations should be given to material and coating types, coating thickness and optical fiber dimensions with controlling of LPFG parameters.

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