Characterization study of Optical Fiber Refractive Index Sensor Based on Fabry-Perot Interferometer

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Abstract: In this work, an optical fiber refractive index sensor based on the Fabry-Perot interferometer technique is submitted. Single-mode fibers with different diameters (125, 60, and 50) µm were used. The chemical etching technique is used to reduce the fiber diameters. The sensor heads were immersed into liquids of different refractive indices. Two types of liquids were tested, salty and sugary liquids with different refractive indices. From the obtained results all the sensors have a high linearity and good wavelength and intensity sensitivity. For all tested sensors, the wavelength sensitivity was higher for sensors immersed in salty liquids. The sensitivity is 34338 pm/RIU for sensors with a diameter of 50 µm. The response of changing the intensity is also observed the higher intensity sensitivity is 1116.859 µW/RIU for sensors with a diameter of 125 µm immersed into sugary liquids.

Keywords: Optical Fiber Sensors, Refractive Index, Fabry –Perot Interferometer, Micro-fibers

1. Introduction

Fiber-optic sensor technology (OFS) is characterized by significant growth in electronic photovoltaic industries where fiber has been created as detectors in many applications of sensing in analytical chemistry, medical and biological sciences [1]. Optical fiber sensors (OFS) are instruments for measuring pressure, temperature, electrical currents, magnetic fields, displacement, and various other physical and environmental characteristics [2]. fiber optic sensing systems in sensing materials and structures where they have many advantages that distinguish them from other sensors such as their high sensitivity, their ability to operate in harsh environments, safe data transmission, electromagnetic immunity, integration, remote sensing and many others [3,5,6,8]. They have been successfully used in the electrical, mechanical, biomedical and chemical fields, where numerous technologies have been developed for optical fiber sensors, most of which rely on filter, interferometer or spectroscopy, such as linear edge filters, Fabry-Perot filter, Mach-Zehnder interferometer, Mickelson interferometer, Fourier conversion spectrometer [7]. Fiber-optic sensors operate by modifying one or more properties of light passing through fibers and can be widely manufactured as extrinsic and intrinsic in extrinsic sensor types using fibers as a means of transferring light to an external sensor system while in the intrinsic type light should not leave fiber-optic to perform sensor function [8]. the refractive coefficient (RI) is a key parameter for the characterization of analytical material and is widely applied in the detection of biomolecules for clinical diagnosis, pharmacological analysis and pollution control. In recent years, many optical sensors have emerged and have been widely used in biomedical measurement and environmental protection for their many advantages, including fiber-optic interferometry (Fabry-Perot),
fiber grid barriers (FBG). And other types that rely on specialized fibers, which have a high degree of sensitivity to RI measurement as their most important advantage, generally RI sensors based on resonance wavelength response can get high sensitivity and good accuracy to RI measurement, Optical fiber-based RI sensors provide hypersensitivity up to 18681.82nm/RIU [9].

The Fabry-Perot fiber interferometer (FPI) is used as a classical fiber component in large measure for different temperature, pressure, emotion and biomedical measurements applications [10]. Due to the importance of RI optical fiber applications, many articles had been published in this field.

In 2020 Ying et al. studying optical fiber refractor sensor techniques based on surface Plasmon resonance, the researchers concluded that the wavelength sensitivity of the proposed 0.925 lm/RIU sensor to refractor values was from 1.35 to 1.43 with a high value of 0.997. The proposed optical characteristic sensor could be used as a SPR sensor to measure moisture with polyvinyl alcohol media ranging from 1.35 to 1.43 refractors [11].

Also Meng et al. studying the sensitivity of the refractive index with the double-loss peaks of the optical fiber sensor depending on the surface Plasmon resonance, the results of the numerical simulation showed that the average wavelength sensitivities of the primary peak can reach the secondary value to 18900 and 17500nm / RIU in the range of refractive index. 1.35 and 1.38 and the corresponding readings are 5.291× 10⁴ and 5. 714× 10⁴ RIU This sensor can be used in the areas of double-loss peak detection, which improves practical sensor potential. In addition, this work will lead to a better understanding of the use of surface resonance field sensing [12].

Samavati et al. manufacturing a highly sensitive fiber optic probe, the livery was chemically drilled in an easy and economical way to 100nm by immersion in the acetone/methanol mixture to obtain the required cladding diameter. Dynamic drilling observation using photovoltaic energy transported through fiber (850nm) was used to determine the optimal solvent concentration in which the probe's sensitivity is highest, and was used to detect refractive coefficient changes of saline solution and ore-graded oil accumulations. Maximum sensitivities of 9.1 and 24.2 dB/RIU were obtained were obtained, the optimal markers for a high-sensitivity sensor are a mixture of 40/60 aceton/methanol and 15 °C solvent temperature. The researchers concluded that this proposed high-performance sensor to detect refractive coefficient changes is highly sensitive and can be used commercially [13].

In (2020) Fang wang et al. study of the refractive index (RI) temperature sensor on a multi-pattern, pointered flooded-tapered multimode-no-core (FTMN) and its presentation experimentally where the FTMN contains the Mach Zehnder interferometer Extra (MZI) which is inserted into folded multi-pattern fibers (FTMn) And with the inherent multi-pattern overlap (MMI) and MZI, this synthetic composite interference improves traditional fiber-optic sensing (RI) performance in the low band The researchers concluded from the experimental results that the sensitivity of 1191.5nm/RIU could be achieved within a linear RI ranging from 1.3405 to 1.3479, which is larger than the conventional interferometer structure. The fiber structure (FTMN) has great application potential in the biological and chemical sensing fields [14].

In this work, the optical fiber refractive index sensor designed and submitted based on the Fabry-Perot interferometer technique using a single-mode optical fiber with different diameters.

2. Experimental Work

In this work, commercially available single-mode fibers (SMF) had been used for manufacturing the sensor head. The chemical etching method was used to reduce the diameter of the SMF. In the inscription process, the fiber's diameter changes at room temperature using a distilled HF solution, where the source's experimental arrangement consists of a single-mode SMF optical glass with a diameter of 125 micrometers, the chemical etching achieved using 40% concentration HF diluted with distilled water (DW) with percentage (1 HF:2 DW) for 60 minutes and 90 minutes to obtain an area of high sensitivity to the surrounding concentrations. This part of the fiber is called (sensor head). The diameter of the fibers were measured using optical microscope (Nikon Eclipse ME600) The diameters after the chemical etching were 60 µm for etching time 60 minutes and 50 µm for etching time 90 minutes. Figure 1 shows...
the microscopic images of sensors heads. The magnification ratio of the optical microscope was 500 µm as it clear in figure 1.

Figure 1. Microscopic image of sensor head, (a) standard SMF, (b) SMF with 60 µm diameter, and (c) SMF with 50 µm diameter.

Different concentrations of sodium chloride and sugar solution in water have different indexes of refraction (RI) so that it can be considered as a sensor medium. The refractive index of the refractive indices of the both salty and sugary solutions was measured with a Refractometer (BOECO Digital ABBE Refractometer). Table 1 shows the refractive indices of both solutions.

Table 1. The RI’s of both salty and sugary liquids

| Concentration (mol/litre) | RI (Salty liquid) (RIU) | RI (Sugary liquid) (RIU) |
|--------------------------|-------------------------|--------------------------|
| 0.05                     | 1.3436                  | 1.3454                   |
| 0.1                      | 1.344                   | 1.3481                   |
| 0.15                     | 1.3445                  | 1.3503                   |
| 0.2                      | 1.3451                  | 1.353                    |
| 0.25                     | 1.3456                  | 1.3553                   |
| 0.3                      | 1.3461                  | 1.358                    |
| 0.35                     | 1.3468                  | 1.3604                   |
| 0.4                      | 1.347                   | 1.3631                   |
| 0.45                     | 1.3476                  | 1.3654                   |
| 0.5                      | 1.3481                  | 1.3682                   |

Figure 2 shows the photographic image and schematic diagram of optical fiber RI sensor based on Fabry-Perot interferometer.
Figure 2. (a) The photographic image of experimental setup, (1) laser and power supply, (2) 2x1 optical coupler, (3) sensor head, (4) solution, and (5) OSA with PC. (b) Schematic diagram of the experimental setup.

The signal is transmitted from a single-mode fiber pigtailed Laser diode source (Thorlabs) of center wavelength 1550 nm, and power 1.5 mw. This source was connected to the input arm of 1x2 optical coupler with splitting ration (50%:50%). one of the outputs arms connected to the sensor head. Three sensor heads with different diameters were investigated; (125, 60, and 50) µm. The above sensor heads were immersed into salty and sugary liquid with different refractive indices. The reflected spectrum of the end tip of the sensor head travelling through the second arm of the optical coupler, which is connected, to the Optical Spectrum Analyzer (OSA). THORLABS (OSA 203) with a wavelength range of 1000 to 2600 nm, and resolution 0.1 nm was used to record and analyzing the reflected spectra for each case.

3. Results and Discussions
The influence of variation the refractive indices of the surrounding medium of the sensor head on the optical properties of the reflected spectra was studied for the optical fiber sensors heads with different diameters (125, 60, and 50) µm. These sensors heads were immersed into solutions with different
refractive indices. Figure 3 shows the reflected spectra from sensor head with diameter (125) µm immersed in salty and sugary solutions.

From figure 3 it could be noticed that the intensity of reflected spectra was decreased due to increase of refractive index of both sugary and salty liquids. Also, there is a slightly wavelength shifting towards the red region due to refractive index increasing. The intensity and wavelength sensitivity calculated from the slope of the linear relationship as it clears in figure 4.
Figure 4. The wavelength and intensity sensitivity of, (a) sugary, and (b) salty liquids for sensor head with diameter (125µm).

From figure 4, the wavelength sensitivity equal to 700 pm/RIU and 875 pm/RIU for sugary and salty liquids respectively. And the intensity sensitivity equal to (-) 201 µW/RIU and (-)1116.958 µW/RIU for sugary and salty liquids respectively. The minus sign refer to decreasing of intensity due to RI increase. As it clear, that the sensitivity is higher for sensors immersed into salty liquid and the intensity influence is higher than the wavelength influence.

To enhance the sensor performance, the sensor head diameter decreased to (60) µm and (50) µm. figure 5 shows the reflected spectra from sensor head with diameter (60) µm immersed in sugary and salty solutions.

Figure 5. The reflected spectra from sensor head with diameter (60µm) for (sugary), (b) salty liquids.

The behavior is the same of 125 µm but the influence is stronger. This is because that when the fiber diameter more light modes leakage from the fiber tip and then more light interact with the surrounding
The intensity and wavelength sensitivity of the sensor can be calculated from the slope of the linear relationship shown in Figure 6.

![Fig 6](Image)

**Figure 6.** The wavelength and intensity sensitivity of, (a) sugary, and (b) salty liquids, for sensor head with diameter (60) µm.

From Figure 6, the wavelength sensitivity is equal to 950 pm/RIU and 1041 pm/RIU for sugary and salty liquids respectively. And the intensity sensitivity is equal to (-)210 µW/RIU and (-)2171.5 µW/RIU for sugary and salty liquids respectively.

Figure 7 shows the reflected spectra of optical fiber sensor of sensor head diameter (50) µm. and Figure 8 shows the intensity and wavelength sensitivity of this sensor.

![Fig 7](Image)

![Fig 8](Image)
Figure 7. The reflected spectra from sensor head with diameter (50 µm) for (sugary), (b) salty liquids

Figure 8. The wavelength and intensity sensitivity of, (a) sugary, and (b) salty liquids, for sensor head with diameter (50 µm).
From figure 8, the wavelength sensitivity equal to 1000 pm/RIU and 34338 pm/RIU for sugary and salty liquids respectively. And the intensity sensitivity equal to (-) 300 µW/RIU and (-)440 µW/RIU for sugary and salty liquids respectively. Table 2 shows comparison of sensor performance due to variation of sensor diameter head.

Table 2. Comparison of sensor performance due to variation of sensor diameter head.

| Fiber diameter (µm) | Wavelength sensitivity (pm/RIU) | Intensity sensitivity (µW/RIU) |
|---------------------|---------------------------------|-------------------------------|
| Sugary liquid       | Sugar liquid                    | Salty liquid                  |
| 125                 | 700                             | 201                           |
| 60                  | 950                             | 141                           |
| 50                  | 1000                            | 270                           |

From the above figures and table 2, it is very obvious that an enhancement in sensing parameters were achieved through the decreasing of sensor head diameter the wavelength sensitivity was clearly increased for both solutions. This enhancement was stronger for samples immersed into salty liquids. This is due that the refractive index variation of salty liquids is higher than the sugary liquids. The shifting in peak wavelength because the interacting of light with liquids lead to increase the optical bath difference and thus shifting towards the higher wavelengths. The intensity sensitivity also enhanced due to the decreasing sensor head diameter but it decreed in case of using (50µm) we couldn’t find a logic reason for this behavior.

4. Conclusions

Optical fiber refractive index sensor based on Fabry-Perot interferometer technology had been submitted in this work. Different fiber sensors diameters were tested to enhance the performance of system. These sensors head were immersed into liquids with different refractive indices. The immersion process lead to decrease the peak intensity of the reflected spectra and shifting the wavelength towards the higher wavelength (redshift). The sensitivity for all samples increases due to optical fiber sensor diameter decrease. The decrease in optical fiber diameter lead to more leakage of optical modes outside the fiber and thus interact with the surrounding environments (salty and sugary liquids). All sensors performance with high linearity and sensitivity. This type of technique could be very successful in environments, chemical or biological applications.

References

[1] D. I. Al-Janabi, A. M. Salman, and A. Al-Janabi, 2020 “High-sensitivity balloon-like thermometric sensor based on bent single-mode fiber,” Meas. Sci. Technol., vol. 31, no. 11, p. 115106, doi: 10.1088/1361-6501/ab9458.
[2] Werneck, Marcelo M., and Regina Célia SB Allil. Optical fiber sensors. INTECH Open Access Publisher, 2011.
[3] H. Bal. Optical fibre refractive index, voltage and strain sensors: fabrication and applications. Diss. Victoria University, 2011.
[4] Y. Zhan, J. Luo, H. Wu, and M. Yu, “An all-fiber high resolution fiber grating concentration sensor, 2012 ” Optik (Stuttg)., vol. 123, no. 7, pp. 637–640.
[5] Q. Jiang, D. Hu, and M. Yang, , 2011 “Simultaneous measurement of liquid level and surrounding refractive index using tilted fiber Bragg grating,” Sensors Actuators A Phys., vol.
170, no. 1–2, pp. 62–65.

[6] J. Castrellon-Uribe, “Fiber optic sensors, 2012 ” Optical Fiber Sensors: An Overview. InTech, pp. 112–139.

[7] G. Rajan. Optical fiber sensors: advanced techniques and applications. CRC press, 2017.

[8] A. L. Chaudhari and A. D. Shaligram, 2012 “Fiber optic sensor for the measurement of concentration and refractive index of liquids based on intensity modulation,” in International Journal of Modern Physics: Conference Series,vol. 6, pp. 589–593.

[9] X. Li, Y. Shao, Y. Yu, Y. Zhang, and S. Wei, 2016 “A highly sensitive fiber-optic Fabry–Perot interferometer based on internal reflection mirrors for refractive index measurement,” Sensors, vol. 16, no. 6, p. 794.

[10] R. Wang and X. Qiao, 2014 “Intrinsic fabry-perot interferometric sensor based on microfiber created by chemical etching,” Sensors, vol. 14, no. 9, pp. 16808–16815.

[11] Y. Ying, J. Wang, N. Hu, K. Xu, L. Sun, and G. Si, 2020 “Determination of refractive index using surface plasmon resonance (SPR) and rigorous coupled wave analysis (RCWA) with a D-shaped optical fiber and a nano-gold grating,” Instrum. Sci. Technol., vol. 48, no. 4, pp. 376–385.

[12] X. Meng et al., 2020 “An optical-fiber sensor with double loss peaks based on surface plasmon resonance,” Optik (Stuttg.), vol. 216, p. 164938.

[13] Z. Samavati, A. Samavati, A. F. Ismail, N. Yahya, M. A. Rahman, and M. H. D. Othman, 2020 “Effect of acetone/methanol ratio as a hybrid solvent on fabrication of polymethylmethacrylate optical fiber sensor,” Opt. Laser Technol., vol. 123, p. 105896.

[14] F. Wang, K. Pang, T. Ma, X. Wang, and Y. Liu, 2020 “Folded-tapered multimode-no-core fiber sensor for simultaneous measurement of refractive index and temperature,” Opt. Laser Technol., vol. 130, p. 106333.