

Refractive Index and Temperature Sensor by using HC-800 Infiltrating by Different Liquid Crystal

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Abstract: Photonic crystal fiber (PCF) is employed as a refractive index sensor (RIS) for solving a lot of problems in biological, physicochemical, medical, engineering fields and many environmental challenges, where it is using in many industries of food, medicines, chemical materials and diagnoses the materials. The kind of the PCFs was HC-800 with three wavelengths of laser source were used; 638nm, 850nm, and 1550nm that are useful for recording the intended transmitted signal intensity. Therefore, the measured RI was in between the range (1.469-1.455 RIU) at the temperature range (36-70) °C for the EBBA and it was (1.621-1.612 RIU) at the temperature range (22-42) °C for the MBBA. The results showed that the highest RI sensitivity was 56.815 dBm/RIU for the HC-800 infiltrated with MBBA using the laser of wavelength 850 nm, Also, the highest temperature sensitivity was 0.0281 dBm/°C for empty HC-800 using the laser of wavelength 638nm.

Keywords: refractive index sensor, temperature sensor, photonic crystal fiber, liquid crystal

1. Introduction

In such problems, the refractive index sensor (RIS) is either immersed the PCF into the solution of that materials or infiltrate a specific materials inside the PCF, which leads to shift the wavelength of the transmitted light after the infiltration, then RIS can be used to investigate the purity of the water or used to know the ratio of the drug in the medicines and endlessly applications. The sensitivity test also requires using different types of resources, such as: laser sources, PCF types, and infiltration materials.

Kuhlmeij B. T. et al. in 2009 have the study of the ultrasensitive photonic crystal fibers refractive index sensor, where they used the solid core photonic crystal fiber in directional coupler architecture to introduce the microfluidic refractive index sensor. The using the selective infiltration of any individual hole along the PCF and by this method of precisely infiltration they can design the sensor with high sensitivity through the coupling of the mode of the core which is in the adjacent waveguide that fluid-filled which is beyond the modal cutoff. They obtain that the sensitivity was 30,000 nm/ RIU and the detection limit was 4.6×10^{-7} RIU and for that date this is the highest sensitivity can be obtained [1]. Bing P. B. et al. in 2012 were studied a photonic crystal fiber based on surface Plasmon resonance temperature sensor with liquid core, where Glycerin liquid that has a high RI was filled the HC-PCF in its central air hole, i.e., the guiding mechanism will be TIR, that made the transmission bands be broaden. If there is an ambient temperature of the glycerin, it can be detected accurately by the change of the RI of the glycerin with change in the temperature resolution of the PCF-SPR temperature sensor was low about 4×10^{-6} RIU [2]. Ana M. R. Pinto and Manuel Lopez-Amo in 2012 had the studied of the HC-PCF refractive index sensor based on modal interference, where they splicing both ends of HC-PCF with a SMF by fusion splicing, there is an air collapse, the modal interference was formed by excite and recombine core and cladding modes.

They used the sugar solution to make the shifting in the wavelength in the interference spectra in the HC-PCF. The RI range was (1.333-1.3775) RIU. The resulted resolution and the sensitivity were 5.53×10^{-4} RIU and 36.184 nm/RIU, respectively and the temperature sensitivity about 19pm/°C with the using temperature range (35.5-60.5) °C and it can be used for chemical, biological and biochemical applications [3].

Abdulhadi A. H. and Al-janabi A. H. in 2012 were used the SC-PCF based on Mach-Zehnder modal interferometer for temperature and refractive index sensing, where they used a short length of the PCF splicing in both side with conventional SMF by fusion splicing and he used the laser (1525-1610) nm. The interference spectrum is unchanged as indicated at temperature range was (25-60)°C, while the heads of the sensor could realize very high temperature up to 550°C. DMSO was the liquid which was infiltration between the PCF piece and the tube of silica. The temperature sensitivity of the temperature was very high than the previous published work on the PCF sensors of temperature. Also (DMF) liquid was test and it shows a temperature sensitivity reached to 0.7 nm/°C. Yee O. S. in 2014 has the study of the refractive index sensor based on the hollow-core photonic crystal fiber, where he done this using the technique of modal interference, he obtained two kinds of sensor through this research, the first one was the refractive index sensor and the second one was the temperature sensor where he used to design the refractive index sensor, the arc fusion splicing to splice the PCF with the SMF, sure there is an air holes collapse region and the HC-PCF that used to do this splicing was short less than 1mm. He has monitoring experimentally the wavelength that appear in the transmission spectra. Beside the RIS he could obtain the temperature sensor. The results demonstrate for nD range (1.333 to 1.3775) that the measurement resolution was 5.53×10^{-4} RIU and the sensor sensitivity was 36.184 nm/RIU and the temperature range was (35.5-60.5)°C and the temperature sensor sensitivity was 19 pm/°C [4].

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The implementation is started by splicing the PCF between two COF to align the light signal through the PCF and received it by a spectrometer to records the results. The gained experience enable to make the mechanical splicing (MS) instead of the fusion splicing (FS) that used in most researches, MS is considered as a cold splicing and prevents the holes collapse as a converse to the FS which provides a huge temperature reaches to 600°C that destroy the infiltrated materials and loss it natural properties and make distorted results although its low loss in the signal like the evaporation of the water. The used infiltration method was carried out using the standard medical syringe which was glued with the PCF using some kinds of the glue, which is pumped by human hand to push the material inside the PCF. This manual infiltration method pushes the materials for more than two centimeters inside the PCF, which is more reliable method than the conventional capillary method that cannot push the material a few centimeters only.

Two types of infiltration materials are used, they are nematic liquid crystals (LCs): EBBA (N-(4'-ethoxybenzylidene)-4-n-butylaniline) and MBBA (N-(4'-Methoxybenzylidene)-4-n-butylaniline). These materials have special properties are useful in the RIS tests; the temperature range is (36-80)°C for EBBA and (22-42)°C for MBBA. An appropriate oven has been designed and used throughout the implementation to vary the temperature of the PCF before and after the infiltration within the mentioned allowed ranges. The variation of the temperature affect the RI of infiltrated materials that can be measured to indicate the performance of the proposed RIS. To ensure the valid path of the implementation, the chemical properties of the used materials were tested using the FTIR, the optical properties were tested using the refractometer, while the microstructure was tested using the SEM and EDS.

2. PCF Based Temperature Sensor

The variation in the temperature affect the density of LC that directly proportional to the refractive index, when the temperature rises lead to a decrease in the density of LC due to high temperature make the LC to be stretched and loss the strength of attraction between molecules and thus get bigger distances between particles and increases the internal molecular movement [5]. The measurements are recorded from the oven regulator and OSA. The oven regulator control the degree of temperature in the oven that is same that of the PCF inside the oven. For different amounts of temperatures within allowed range, the OSA records the transmission power of the PCF measured in *dBm*. The graph between the recorded transmission power as a function of temperature indicates the behavior of the PCF against temperature. The sensor sensitivity can be determined by estimated the slope of transmission behavior with temperature variations [6].

3. PCF Based Refractive Index Sensor

RI is one of fundamental distinguishable optical properties for each material, where it considered as one of the physicochemical properties of the materials due to it specify

the effects of the electromagnetic waves on the material. RI dependents on the density and the wavelength, where the refractive index of some material is the ratio of the speed of light in vacuum to the speed of light in that material as indicated in the following relationship [6]:

$$n = \frac{c}{v} \quad (\text{unit less}) \quad (1)$$

Where, the material refractive index is n , the speed of the light in material is v , and the speed of light in vacuum is c . Therefore, the index of refraction makes to reduce the speed of light inside the medium according to the following relationship:

$$\frac{n_0}{\lambda_0} = \frac{n_1}{\lambda_1} \quad (2)$$

Where, n_0 is the refractive index of the material before the changing of the temperature, n_1 is the refractive index of the material after the changing of the temperature, λ_0 is the wavelength of the material before changing the temperature, and λ_1 is the wavelength of the material after changing the temperature [7]. The refractive index can be measured by the refractometer via two methods; the change the temperature or by specify the Brix degree i.e., by change the concentration of the material. It depends on the density and temperature, where the refractive index can be decrease when the temperature increase i.e., the density increase. Also, The refractive index can be specify the dispersive power of the prism and focusing power of lenses or can know the purity some materials like the water by specify the refractive index by the changing the concentration of it [8]. The experimental setup of the refractive index sensor is same as that of the temperature sensor shown in Figure (1). The measurements in such case are recorded between the variations of the transmission power using the OSA to the variation of the refractive index that occurred due to the variation of the temperature. Since the relation between the refractive index and temperature is inversely proportional, the graph that indicates the behavior of the transmission as a function of refractive index is the inverse of the behavior of the transmission as a function of temperature [7,6]. Also, the refractive index sensor can be act by changing the wavelength of the laser source that appropriate to the PCF and then recording the resulted wavelengths according to equation (1.2) where the refractive index of the materials can be computed when the two wavelengths before and after the infiltration are known via OSA, and the first RI of the air is also known. The existence of the materials will manipulate the laser transmission properties, the OSA providing the monitoring and measurement of some information about the transmitted light through the PCF in addition to the wavelength like the transmitted intensity in *dB* and by using equation (1.2) the transmitted intensity in *dBm* can be obtained. Then, the sensitivity of the refractive index sensor is equivalent to the slope of the graph that indicates the behavior of transmission power measured by *dBm* as a function to the refractive index [6].

4. Design Requirements and Setup

The analytical study shows there are different components are required to implement the proposed design of RIS. Such components are related to the devices, material, and tools that needed to establish the present work. Figure (1) shows the setup of the proposed design, the main components are explained with more details in the following:

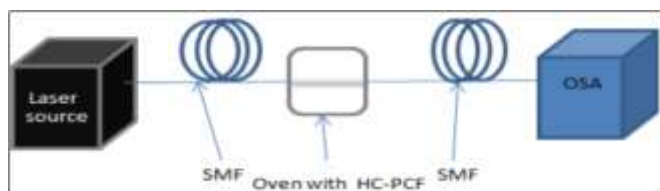


Figure 1: Requirements of RIS experiment set up.

- 1) Laser source: it is used to provide the light source to the experiment.
- 2) Single mode fiber (SMF): it is used to guide the laser light inside the measurement zone.
- 3) Connector: it is used to connect the SMF with the HC-PCF that found in the measurement zone.
- 4) HC-PCF: it is used to guide the laser light inside the measurement zone.
- 5) LC materials: they are used to fill the HC-PCF at different test situations.
- 6) Oven: it is used to provide a specific temperature for each test situation around the HC-PCF.
- 7) Optical spectrum analyzer (OSA): it is used to measure the output power of the laser light.

5. RIS Experiment Implementation

This research was consists of many steps such as oven design, LCs properties tests, laser insertion through the PCF and received it by the spectrometer, and LCs infiltration through the PCF, where the chosen PCFs were the hollow core (HC-PCF) such as HC-800, with an available appropriate laser wavelengths were 638nm, 850nm, and 1550nm, the using LCs were the N-(4'-ethoxybenzylidene)-4-n-butylaniline (EBBA) and N-(4'-methoxybenzylidene)-4-n-butylaniline (MBBA) and testing devices for their properties were the Fourier Transform Infrared Spectroscopy (FTIR) to test their chemical properties such as their purity, diagnosis the material itself, or checkup their performance, the optical properties were checkup via refractometer, where this device was provides the refractive index for different temperature, and the microstructure was tests by Energy Dispersion Spectroscopy (EDS) and the topography was pictured by Scanning Electron Micrograph (SEM), the oven was made of aluminum with temperature controller provided by thermocouple and regulator, the skills of insertion of the laser signal precisely inside the PCF and received it by the spectrometer with more accuracy results, where the using spectrometers were the optical spectrum analyzer (OSA) and the near infrared spectrum analyzer and these spectrometers have connectors appropriate to that used in the optical fiber (OF) and the using lasers were tunnel lasers that appropriate to the OF with low loss in the signal light, this process was done by preparing the surface of the PCF and the COF ends by using stripper, cleaner liquid, or cleaver and by mechanical splicing, the PCF was spliced between two

conventional OF that of single mode fiber (SMF) and multimode fiber (MMF) kinds to increasing the sensing process for some cases like the HC-800 instead of the MMF with MMF or SMF with the SMF, infiltration of the liquid crystal inside the PCF was done by using the standard medical syringe by gluing it with the PCF using some kind of glue and the LC was infiltrated by the pressure, this processes were done for each PCF with each LC and by specifying the wavelength shift of the peak after the infiltration of the LCs according to the relationship $\frac{n_0}{\lambda_0} = \frac{n_1}{\lambda_1}$ and calculate the sensitivity for each case and specify which one of these cases was the more sensitive than the other.

6. Results and Discussion

Practically, Figures (2-11) show that the transmission is appeared inversely proportional to the temperature, whereas it is directly proportional to the refractive index.

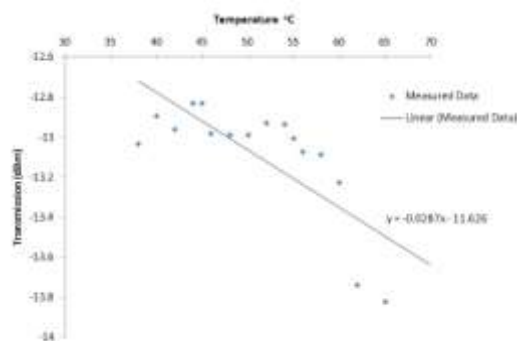


Figure 2: Transmission with different temperature for HC-800 at wavelengths 638nm.

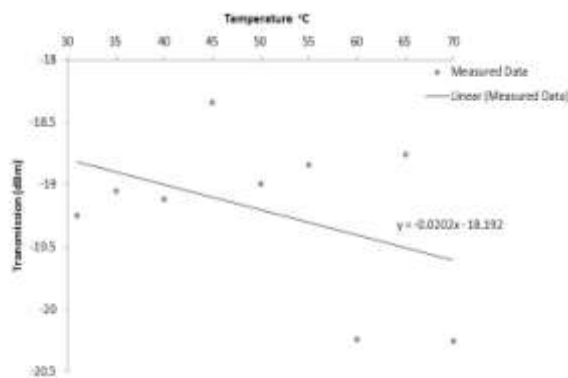


Figure 3: Transmission with different temperature for empty HC-800 at 850nm.

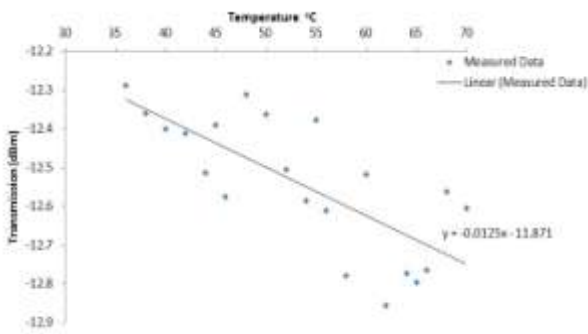


Figure 4: Transmission behavior with temperature variation of HC-800 infiltrated with EBBA for 638nm.

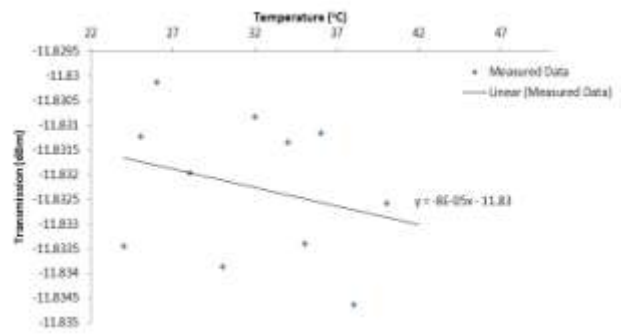


Figure 8: Transmission behavior with temperature variation of HC-800 infiltrated with MBBA for 638nm.

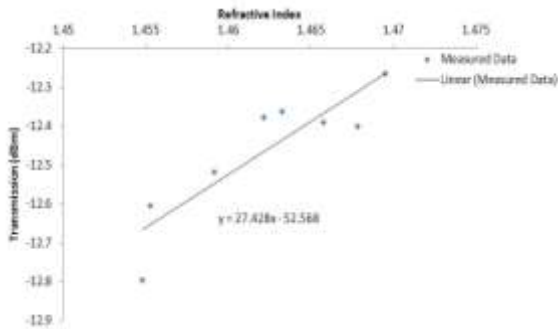


Figure 5: Transmission behavior with refractive index variation of HC-800 infiltrated with EBBA for 638nm.

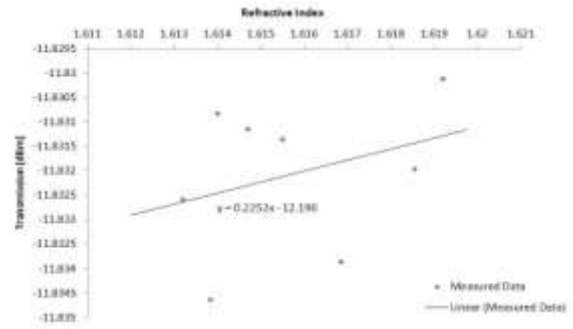


Figure 9: Transmission behavior with refractive index variation of HC-800 infiltrated with MBBA for 638nm.

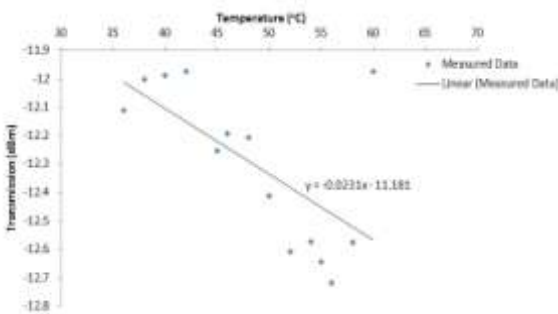


Figure 6: Transmission behavior with temperature variation of HC-800 infiltrated with EBBA for 850nm.

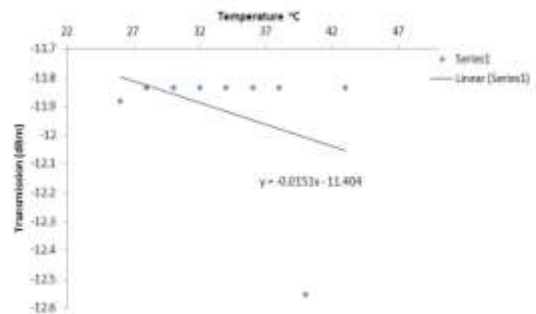


Figure 10: Transmission behavior with temperature variation of HC-800 infiltrated with MBBA for 850nm.

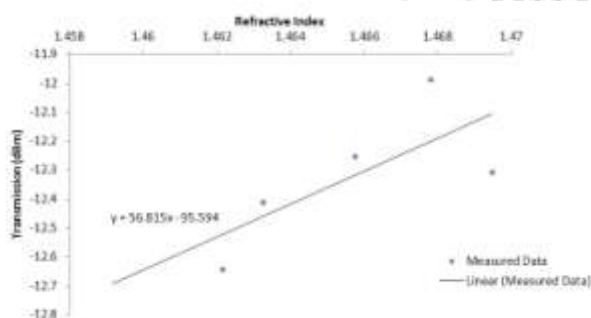


Figure 7: Transmission behavior with refractive index variation of HC-800 infiltrated with EBBA for 850nm.

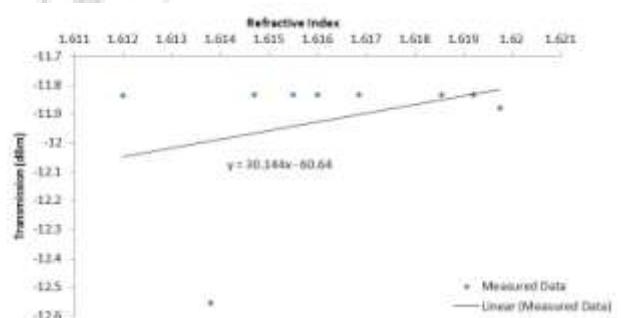


Figure 11: Transmission behavior with refractive index variation of HC-800 infiltrated with MBBA for 850nm.

Practically, Figure (2) shows the transmission temperature relationship for HC-800 PCF of 638nm for the connection of PCFs between multimode fiber and single mode fiber, while Figure (3) shows the transmission temperature relationship for HC-800 PCF of 850nm. It is shown that the transmission is appeared inversely proportional to the temperature.

In case when the PCF is infiltrated with EBBA, it is found that the variation of the transmission with the temperature of HC-800 PCF infiltrated with EBBA at wavelengths 638nm and 850nm in Figure (4) shows the transmission temperature relationship for HC-800 PCF infiltrated with EBBA of 638nm for the connection of PCFs between multimode fiber and single mode fiber, while Figure (5) shows the transmission and refractive index relationship for HC-800 PCF infiltrated with EBBA of 638nm for the connection of the photonic crystal fiber between multimode fiber and single mode fiber. Figure (6) shows the transmission temperature relationship for HC-800 PCF infiltrated with EBBA of 850nm while Figure (7) shows the transmission and refractive index relationship for HC-800 PCF infiltrated with EBBA of 850nm for the connection of the photonic crystal fiber between multimode fiber and single mode fiber.. It is shown that the transmission is appeared inversely proportional to the temperature, whereas it is directly proportional to the refractive index.

In case when the PCF is infiltrated with MBBA, it is found that the variation of the transmission with the temperature of HC-800 PCF infiltrated with MBBA at wavelengths 638nm and 850nm is given in. Figure (8) shows the transmission temperature relationship for HC-800 PCF infiltrated with MBBA of 638nm for the connection of PCFs between multimode fiber and single mode fiber, while Figure (9) shows the transmission and refractive index relationship for HC-800 PCF infiltrated with MBBA of 638nm for the connection of the photonic crystal fiber between multimode fiber and single mode fiber. Figure (10) shows the transmission temperature relationship for HC-800 PCF infiltrated with EBBA of 850nm while Figure (11) shows the transmission and refractive index relationship for HC-800 PCF infiltrated with MBBA of 850nm for the connection of the photonic crystal fiber between multimode fiber and single mode fiber. It is shown that the transmission is appeared inversely proportional to the temperature, whereas it is directly proportional to the refractive index.

7. Conclusions

The most important conclusions that indicated throughout the design and implementation of the present work are given in the following:

- 1) The mechanical splicing between PCF and COF for inserting and receiving the laser signal more suitable than the fusion splicing, where the FS provides temperature more than 600°C to the spliced ends of the spliced PCFs that leads to damage the infiltrated materials, implies that the results were wrong although the low loss in the output signal using FS.
- 2) The infiltration using the medical syringe and the pressure by the hand was better than the capillary method since the capillary method infiltrated the PCF for a few centimeters while infiltration by human hand using medical syringe infiltrated more length of PCF, which leads to increase the sensitivity of the PCF to the parameters of the infiltrated materials.
- 3) The increase of the temperature is leading to decrease the intensity of the output signal that transmitted in the PCF.
- 4) The laser of $\lambda=638nm$ was appropriate to be used with the used three types of PCF, the sensitivity is maximum when the λ was near the operating λ .
- 5) The infiltration materials were usually resisting passed laser signal.
- 6) There is two peaks were appearing in the spectrometer diagram between the intensity and λ .
- 7) 3D-stage device can be used with the mechanical sleeves after the infiltration in order to decrease the loss that happens in output intensity.
- 8) The MS enables to splice the PCF at different cases that may employ to increase the S: like the splicing of MMF-PCF-MMF that suitable for laser of $\lambda=850nm$, which is a case that cannot achieved by FS.
- 9) The highest RI sensitivity was 56.815 dBm/RIU for the HC-800 infiltrated with the MBBA using the laser of wavelength 850 nm. While the highest temperature sensitivity was 0.0281 dBm/°C for empty HC-800 using the laser with wavelength 638 nm. The intensity loss in the output signal affected the measured sensitivity values.

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