



Concentration Sensor Design Using Wavelength Shift Based Photonic Crystal Fibre

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Abstract

The proposed sensor is designed to measure the concentration of liquids using the photonic crystal fibre (PCF) principles. The sensor has been implemented by splicing the two ends of the PCF piece to a single mode fibre (SMF). The air holes found in the splicing points are fully collapsed by the arc discharge. The wavelength shift occurs at the collapsed regions due to the excitation of combined core besides the cladding modes. The PCF was infiltrated by diluted olive oil to be tested in terms of the variation of sensing response with the wavelength shift in the transmission spectra. The sensitivity is 875 nanometre per refractive index unit (nm/RIU) that estimated in refractive index range between 1.43 and 1.47. Result also shows that the sensor has a small temperature sensitivity of $0.863 dBm/^{\circ}C$ in the range of $20^{\circ}C$ to $70^{\circ}C$. The proposed concentration sensor potentially can be applied in biomedical, biological and chemical applications.

Keywords: refractive index, sensors, hollow core fibres, photonic crystal fibre.

تصميم متحسس التركيز باستخدام ازاحة الطول الموجي في الالياف الضوئية البلورية

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الخلاصة

ان المتحسس المقترح مصمم بقياس تراكيز السوائل باستخدام مبادئ الالياف الضوئية البلورية (PCF). تم تنفيذ المتحسس بلحام نهاية واحدة من قطعة الليف الضوئي البلوري الى اخر ذو وضع واحد (SMF)، حيث تم سد جميع الفجوات الهوائية في مناطق اللحام بواسطة قوس التفريغ. ان الزحزة التي تحدث في الطول الموجي في مناطق سد الفجوات تكون نتيجة للاثارة وكذلك اوضاع الطلاء. ولذلك تم اختبار حقن الليف الضوئي بزيت الزيتون المخفف ليحدث تغيرات في استجابة التحسس مع زحزة الطول الموجي لطيف الانبعاث. حيث كانت الحساسية بحدود 875 نانومتر لكل وحدة معامل انكسار (nm/RIU) مقياسة عند مدى معامل انكسار بمقدار 1.43 و 1.4. كذلك بينت النتائج ان للمتحسس حساسية لدرجة الحرارة قدرها $0.863 dBm/^{\circ}C$ ضمن المدى من $20^{\circ}C$ الى $70^{\circ}C$. ان متحسس التركيز المقترح يمكن تطبيقه بكل موثوقية في مجالات الطب الاحيائي، المقاييس الاحيائية، والمقاييس الكيميائية.

Introduction

The fibre optic sensors (FOS) has been rapidly growing and developing in the last few years due to the many desirable advantages of such sensors in comparison with conventional electrical sensor. The most interesting advantages of FOS are: compactness, lightweight structure and robust, absolute

measurement capability, low loss, high resolution, immunity to electromagnetic interference, and suitability for in-situ and remote measurements. In recent years, the most interesting literatures are focused on using the FOS for measuring the refractive index (RI), which is an essential concentration element for medical, biological, and chemical applications. In the field of interest, many techniques were proposed for sensing the refractive index; most of them are depending on the transmission measurements. Such type of sensors are based on making successive splicing between different types of fibre that leads to excite the cladding modes for creating transmission effect with the core modes [1]. 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 depends 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 [2]:

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

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

$$\frac{n_o}{\lambda_o} = \frac{n_l}{\lambda_l} \quad (2)$$

Where, n_o is the refractive index of the material before the changing of the temperature, n_l is the refractive index of the material after the changing of the temperature, λ_o is the wavelength of the material before changing the temperature, and λ_l is the wavelength of the material after changing the temperature [3]. 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 its concentration [4].

Problem Statement

The manufacturing improvements are still needing to more accurate sensor device is specified for each application. Practical experiments showed that the use of photonic crystal fibres (PCFs) for establishing a sensing head is suitable for achieving accurate measurements; this is due to its high sensitivity for refractive index measurement and less sensitivity to temperature disturbance. Also, the structure of PCF contains unique modal properties and light guiding mechanisms that are not found in conventional optical fibres, this enable to obtain more accurate measurement results by means some simple and available PCF related tools. Thus, the search to find out more accurate and simple designed PCF based sensor has become the dominant objective of the modern scientific researches in the field of interest. Different types of PCF are used at different sensing objectives, each proposing a specific materials and tools for establishing developed sensor design based on PCF technology.

Related Work and Contribution

The problem of PCF based sensor design has attracted a lot of research. The applications field was still searching about an accurate method that can be used to improve the sensitivity results. The most interested researches besides to our contribution are briefly explained in the following subsections:

Related Work

There are many papers devoted to FOS, they differ in many aspects such as; used materials, setup design, or even the infiltrated liquid. The feasibility of proposing different methods to design different applicable sensors is investigated in [5]. There is a detailed discussion for some issues involved in designing such methods are presented. This prepares to find out a hybrid techniques to evolve more sensitive parameters and materials as presented in [6]. In [7], the achieved sensitivity is 21.4 nm/RIU for refractive index in between 1.33 and 1.4. The solid core PCF is directly spliced with single mode fibre (SMF) that make the collapsed region are created in splicing regions to couple and recombine the PCF core with cladding modes. The highest sensitivity in such scheme was about 40 nm/RIU when the computed resolution of about 2×10^{-3} RIU. While in [8], the solid core PCF based fibre tip refractive index sensor is designed in reflection manner to achieve maximum sensitivity of about 100 nm/RIU with resolution value of 10^{-4} RIU. The single core PCF based RI sensor is splicing to SMF at both

ends in SMF-PCF-SMF configuration is demonstrated [9]. The maximum sensitivity achieved was about $3mm$ in which the PCF section was $70.2 nm/RIU$ for RI range in between $1.33\sim 1.35$. In other work, a solid core PCF coated by SiNx nano film in same configuration of SMF-PCF-SMF that gave a maximum sensitivity $874 nm/RIU$ [10]. Also, a RI based sensor contains two large core and air clad of PCF is demonstrated that gave maximum sensitivity is $800 nm/RIU$ at resolution of about 3.4×10^{-3} [11]. While, a hollow core based PCF was butt-coupled to SMF to achieve high sensitivity of about $5000 nm/RIU$ that showed interaction of measure with light [12]. Recently, it is shown that the RI sensors based on PCF can easily achieve ultrahigh sensitivity that can be reached to 1000 times in comparison to the conventional RI sensor that based on prism. Therefore, some processing modifications like metal coating and filling the air holes with tested liquid were greatly enhance the sensitivity of RI sensor [13]. Nevertheless, the construction of sensors becomes expensive and more complex. The fill of air holes of PCFs with liquid make the RI sensors to be usable. The process of holes filling consumes some time due to the micro size of PCF holes [14]. In spite of such difficulties, the search about more suitable RI sensor is still continuing, and the publications of PCF related sensors are found in different approaches.

Contribution

Previous studies referred to the robustness of using PCF for obtaining accurate sensors with high precision. Therefore, the effect of RI variation with different olive oil concentrations filtrated inside a PCF is handled to establish an accurate concentration sensor. The contribution in this work is the use of olive oil that possess optical properties are near to that of fused silica, which is almost used in optical sensing systems. In present case, the RI varies with the variation of temperature, whilst the optical properties remain reserved in spite of the dilution impact olive oil concentration. The temperature variation needs existing a heating oven within the experimental components of the sensor, the process of manufacturing such oven was a great challenge facing accomplishment of the proposed sensor design. This oven is designed and implemented with some specifications suit the proposed design. Furthermore, the proposed sensor is designed to contain less splicing points as least as possible due to the splicing regions leads to loss the traveled light intensity inside the PCF, such that one splicing point is found for connecting the used PCF with the SMF of spectrometer, which is connected by newly modified connector.

Material and Methods

In this paper, Hollow core PCF based concentration sensor is proposed and demonstrated. The proposed concentration sensor is implemented by splicing both ends of the PCF section to SMF. At the two splicing regions, the air holes of the PCF are fully collapsed by the arc discharge during splicing. The guided light that passes through SMF is diffracted when reaching the collapsed region of the PCF. Such diffraction leads to occur mode broadening and make an excitation in the core and then cladding modes in PCF section. Such that, the higher order modes are resulted by the efficient excitation that in turn form a modal transmission is employed for the purpose of sensing. The following subsections explain more details about the used material and proposed method. Later, the setup of the proposed sensor is shown to indicate the basic components of the proposed system, where each pointed part in the experiment setup is defined in the previous two stages.

Used Material

The used model of the PCF is employed the hollow core (HC) in which there are seven cells of hollow cores, this PCF was manufactured by NKT Photonics. Such PCF is designed to be contains a central wavelength of $580nm$, core diameter $10\mu m$ and cladding diameter $125\mu m$. The used mechanical splicing is carried out manually using modified connector for connecting the SMF-HCPCF, the suitable setting leads to perform successful splicing. The proposed oven is made of aluminum (AL) rod and heater was coiled around the AL rod, the poles of the heater were connected to the thermostat to control the temperature, where it is provided by a thermocouple for sensing the temperature inside the oven, and for more precisely temperature control regulator was connected between the oven and the thermostat. The oven needs to the heater of (220v) to change the temperature of the oven, the heater of 1m length which made of copper overwound around the groove on the aluminum cylinder. The heater poles were connected to the thermal controller of kind (DT 107A) to control the oven temperature to heat infiltrated PCF in different heating degrees, the controller has a thermocouple of kind (TTC type J) to sense the temperature inside the oven.

Sensing Principle

In the interferometer modal that based on PCF, the guided light pass through SMF is diffracted when reaching the collapsed region of the PCF. This diffraction is leading to make mode excitation into core and then cladding in PCF section. The differences between propagation constants belong to the core and cladding modes producing a phase difference. The resulted phase difference is depending on the used wavelength of the guided light, and also on the travelling distance of the modes. Such diffraction makes the light to be recombined when the modes reach another collapsed end. This effect is employed for forming the transmission modal for purpose of sensing [15].

Proposed Method

Different concentrations of the olive oil mixture that diluted 1000 times using HCl acid are prepared, the Dilution process is carried out to enable infiltrated the mixture inside the PCF. The experimental tests are implemented by using the calibrated brix refractometer (ATC) and brix chart. The variation of concentration of olive oil mixture leads to obtain refractive indices from 1.430 to 1.47. At each measurement, the sensing part is flushed with water and then blows it to ensure its dryness. Table-1 shows the refractive indices of olive oil mixture with different concentrations measured by ATC. A digital thermometer of is used to observe the ambient temperature. There is a temperature variation of about 5°C was recorded throughout the measurement. Thus, little correction is required due to the ambient temperature was near to the required temperature. The Brix-meter operating temperature is between 10-30°C with automatic temperature compensation. The temperature sensitivity of PCF based RI sensor is also being tested by continuous heating of the sensor underwater from 20°C up to 70°C.

Table 1- Refractive indices of olive oil mixture with different concentrations.

Concentrations (%)	Refractive indices
0	1.430
5	1.450
10	1.455
15	1.460
20	1.465
25	1.470

Experiment Work and Setup

It is necessary first to ensure that all air holes are fully collapsed, and adjust the arc and its power to avoid the damage may occur in the PCF. The position of the arc is longitudinally offset towards SMF side in order to afford more heat to SMF than PCF. The axial offset is set to zero prior the arc. Such that, the core offset becomes about 1µm after the arc due to two reasons: the V-groove movement in the splicer and the differences of cladding diameters. The proof test is pulling the PCF and SMF apart that leads to disable situation is occurring.

Figure -1 shows photographs of splicing machine and using digital microscopy from Italy (Altay Biolabline). The length of the used PCF was about 2mm, the cladding diameter was 5µm of the SMF, which is greater than the PCF cladding diameter, and a taper is noticeable to be formed at the splice point. Thus, the air holes of PCF are collapsed during the arc discharge. This will increase the cladding diameter differences between SMF and PCF. The lengths of both un collapsed PCF and collapsed region are pointed in the second image, where the lengths are measured by pixel counting. Figure -2 shows the experiment setup of PCF based RI sensor. The Pro's Kit MT-7508 source with , the output power that used to illuminate the sensor is 5mW. The PCF is spliced in both ends to SMF of FC connectors. Also, there is an optical spectrum analyser of type AvaSpec-2048XL is used to monitor the spectrum variations as the RI increasing with increasing the olive oil concentration in HCL mixture.

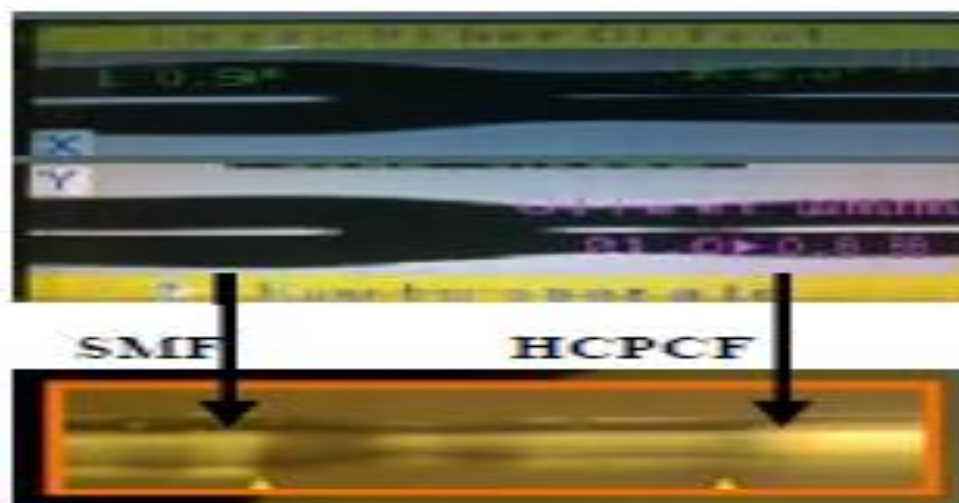


Figure 1- The Photographs of splicing Machine.

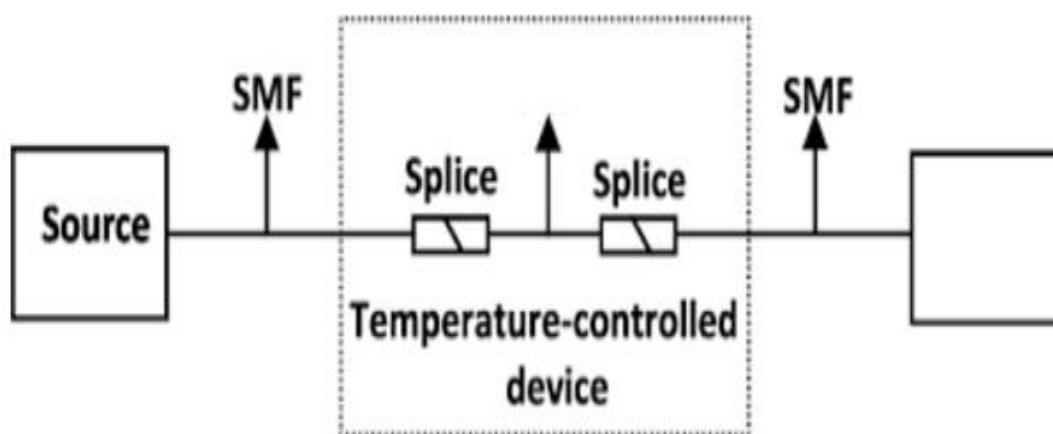


Figure 2- Experiment Setup.

Results and Discussion

The use of liquid samples of refractive indices: 1.43, 1.45, 1.455, 1.46, 1.465 and 1.47 gave resultant transmission spectra of PCF sensor shown in Figure -3. The olive oil mixture is added to the sensing head for examining the effect of RI on the transmitted light. The wavelength separation between two successive valleys is about 50nm . It is shown that there are three peaks and two valleys in the transmission spectra, each for different response. By inspection, it is found that the third peaks (pointed) are nearly to exhibit the behaviour of linear response. The shift that happens in the wavelength of the valleys is from 550nm to 655nm , which is equal to 105nm total wavelength shift as Figure -3 shows. Thus, the achieved sensitivity is $875\text{nm}/\text{RIU}$. Figure -4 shows the shift in the wavelength between valleys with increasing temperature of olive oil. The shift occurs in the power spectra of PCF is due to the difference between the thermo optical of silica and air. When the temperature increases from 20 to $70.^\circ\text{C}$, the wavelength of the valley in the transmission is varied from 530 to 570nm , which is a total shift in the wavelength that equal to 40nm show in Figure -5. Such shift has almost a linear relationship with the variation of temperature and temperature sensitivity of about $0.863\text{ dBm}/^\circ\text{C}$ as Figure -6 shows.. Practically, it is found that the measurement of refractive index requires adding temperature compensation mechanism that necessary to avoid Undesirable disturbance

caused by temperature effect. Nonetheless, the dependency of the temperature is quite small in comparison with the typical response of interferometer modal.

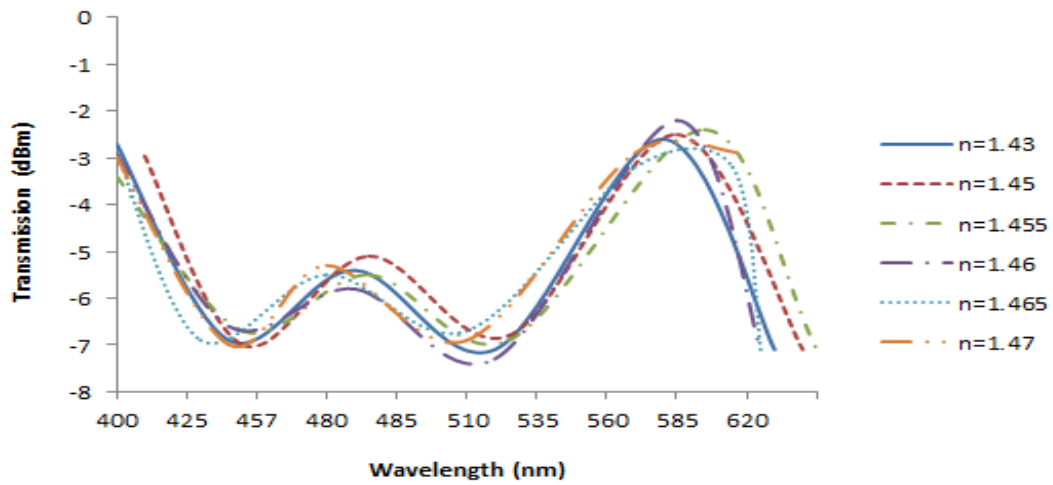


Figure 3- Resultant transmission spectra of PCF sensor for different refractive indices

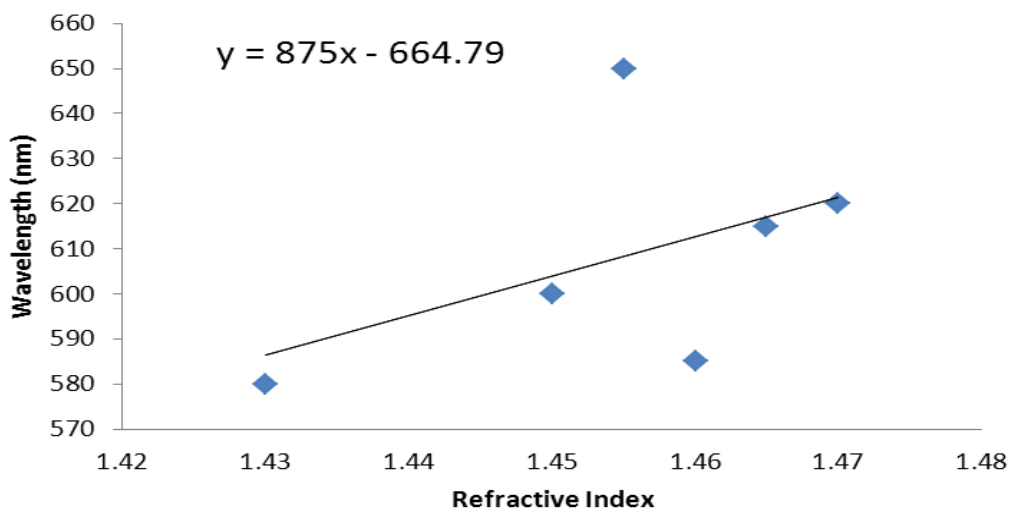


Figure 4- Refractive indices vs. with shifted wavelength.

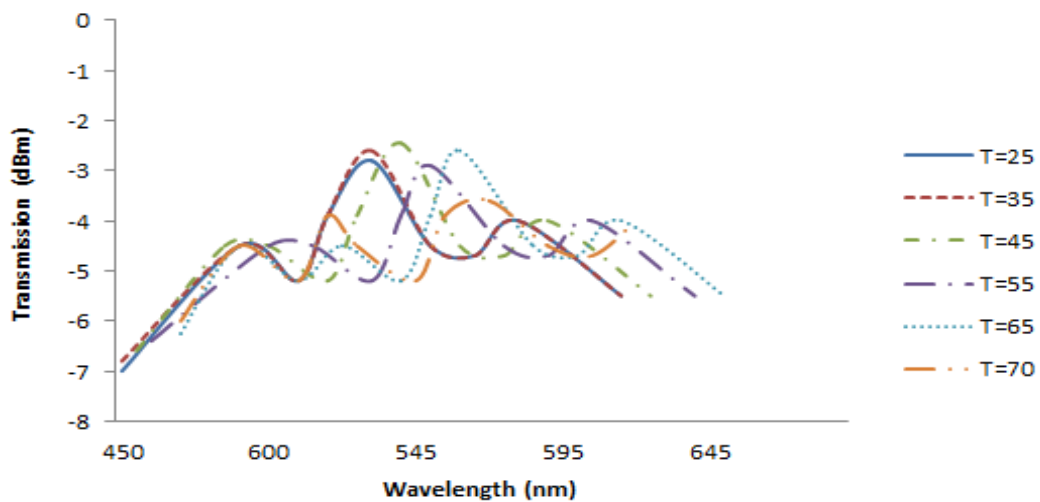


Figure 5- Resultant transmission spectra of PCF sensor for different temperature

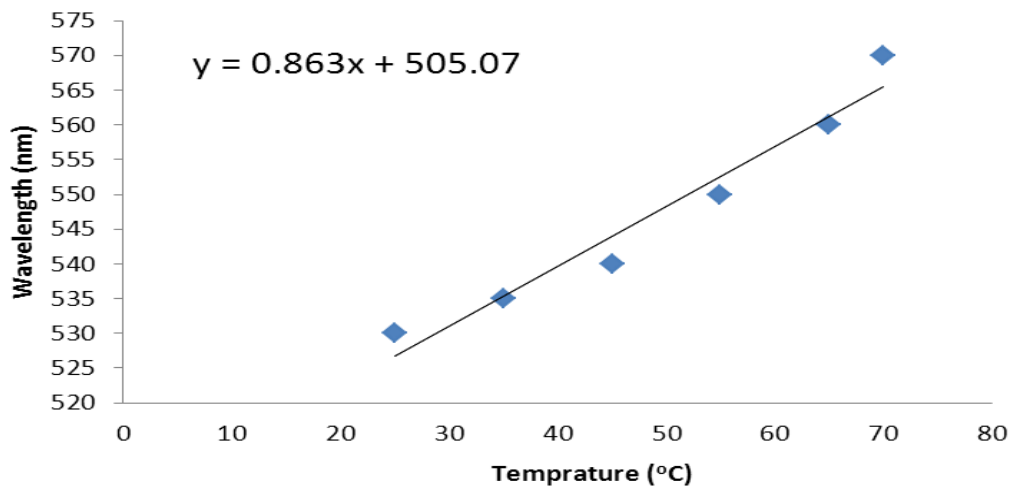


Figure 6- Temperature vs. with Wavelength shifted

Conclusion

It was concluded that the refractive index sensor based on modal interferometer PCF is simply constructed by splicing both ends of PCF section to SMF. The collapsed regions are created at splicing regions, in which the core and cladding modes are diffracted and recombined to form interferometer modal that employed for purpose of sensing. Such sensor can be easily established using conventional splicing process. The sensor showed a sensitivity of 875nm/RIU range between 1.430 and 1.470. The proposed sensor is found exhibiting small temperature sensitivity of 0.863dBm/°C in temperature range between 20°C and 70°C, which is a promising results comparing with other types of optical refractive index sensor. The proposed sensor possesses some advantages over traditional ones, which are: simple, flexible, small size, and convenient fabrication. These characteristics of proposed sensor may suggest new applicable sensors related to biomedical, biological and chemical sensing fields.

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