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Tapered Splicing Points SMF-PCF-SMF Structure based on Mach-Zehnder interferometer for Enhanced Refractive Index Sensing

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Abstract: Photonic crystal fiber interferometers (PCFIs) are widely used for sensing applications. This work presented solid core-PCFs based on Mach-Zehnder modal interferometer for sensing refractive index. The general structure of sensor was applied by splicing short lengths of PCF in both sides with conventional single mode fiber (SMF-28).To apply modal interferometer theory collapsing technique based on fusion splicing used to excite higher order modes (LP_{01} and LP_{11}). A high sensitive optical spectrum analyzer (OSA) was used to monitor and record the transmitted wavelength. This work studied a Mach-Zahnder interferometer refractive index sensor based on splicing point tapered SMF-PCF-SMF. Relation between refractive index sensitivity and taper waist diameter were studied through simulation and experiments. The experimental and simulation results show that sensitivity would be increased with a decrease of taper waist diameter. The response of the PCFI is observed for a range of refractive index values from (1.33 to 1.38). When the length of PCF was (4)cm with different taper waist diameter (125,107,90,60)µm, the maximum refractive index sensitivity of (20 pm / RIU) was achieved. When taper waist diameter became (60)µm, the rate of increase in sensitivity was 12.4% compared with the taper waist diameter (125)µm.

Keywords: *Mach-Zehnder interferometer, High sensitivity, wavelength, shift, Splicing points tapering, photonic crystal fiber (PCF).*

Introduction

Refractive index measurement has become one of the most important issues in the research of optical fiber sensing technology and has become attractive for chemical, biological, biochemical sensing with aqueous solutions, as well as for civil engineering and environmental monitoring applications [1, 2]. All-fiber refractive index sensors are attractive, owing to their small size, flexible design, immunity to electromagnetic interference and the aptitude for remote measurement [3]. The Mach–Zehnder interferometer is one of the most widely used structures in optical and photonic devices. Sensors based on the MZI have been demonstrated due to its high sensitivity to the surrounding medium. A typical MZI has a reference and a sensing arm. A fiber coupler is used to split the incident light into two arms which are then recombined by a second coupler. The two lights recombine at the second coupler and produce interference fringe depending on the optical path difference (OPD) between the two arms. For MZI based ambient RI sensing, the reference arm is kept isolated while the sensing arm is exposed to solutions of variable RI. The signal deviation in the sensing arm induced by ambient RI changes the OPD of the MZI that can be sensed by examining the variation in the interference pattern [4, 5].

Photonic crystal fibers (PCFs) witnessed a rapid development over the past decade due to their unique microstructures and dispersive properties [1-4]. PCFs, which are also called microstructured is a unique type of optical fiber incorporating an array of air holes that run along its length reminiscent of a crystal lattice, which gives to this type of fiber its name [6].

PCF sensors open a new possibility for the measurements of refractive index.

A tapered PCF shows good characteristics in sensing, since it shows much higher sensitivity than tapered SMF. The aim of this work is to take advantage of the high sensitivity given by the combination of both the tapered PCF and the MZI for RI measurements. Because of the strong evanescent field of the tapered region, a slight change of the ambient RI will lead to the shift of the transmission spectra of MZI. Therefore, the refractive index measurement can be realized by measuring the corresponding wavelength shift [3].

The paper fabricated a kind of Mach-Zehnder mode interferometer refractive index sensor, which is based on splicing points tapered SMF-PCF-SMF (SMF, single-mode fiber; PCF, photonic crystal fiber) structure. In this work, we fabricated the RI sensor by tapering two splicing points regions between photonic crystal fiber and single mode fiber. The higher order cladding modes can be stimulated and coupled between the SMF core and PCF cladding. For this reason, the effective refractive index of photonic crystal fiber cladding high order modes are found to be more sensitive to surrounding refractive index changing. The refractive index measurement and sensitivity of splicing points tapered SMF-PCF-SMF Mach-Zehnder mode interferometer can be further enhanced.

Experimental Work

The fabrication of the refractive index sensor involved removing the coating of the two fibers (PCF and SMF -28) by using a mechanical stripping. Then, The second step was both PCF and SMF cleaved by fiber cleaver. Then, the length of PCF (LMA-10) was (4) cm spliced between two conventional optical fiber in both sides with different taper waist diameter (125,107,90,and60) µmusing fusion splicer FSM-60S.

The fiber sensing head fixed in the experiments tube was connected to diode laser source (1550nm) and optical spectrum analyzer (OSA) through single-mode fiber. Figure (1) shows the schematic of Tapered Splicing SMF-PCF-SMF MZI Structure. The structure maintained the conditions of strain, bending, temperature and humidity quite stable of PCFs during the experiment in the laboratory.

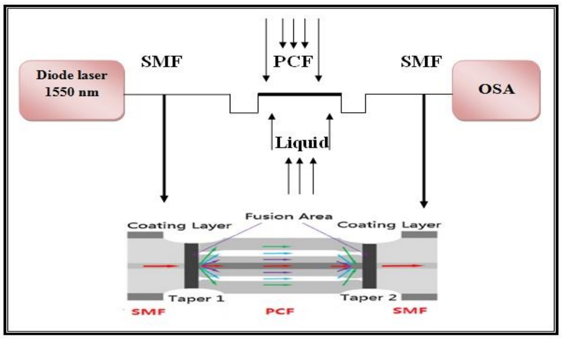

Fig. (1): Schematic of Tapered Spliced SMF-PCF-SMF MZI Structure.

The three methods to improve the sensor sensitivity are increasing the taper length, decreasing the taper waist diameter and the fusion loss between the PCF and SMF. The first two methods are to support stronger evanescent wave and the last is to reduce the noise. By controlling the taper waist diameter and length, the performance of the interferometer can be adjusted [3].The tapering length was ~99 µm, as shown in Figure (2). Tapering waist diameter between the PCF and SMF was ~107µm.When light passes through single- mode fiber into first taper, the fundamental mode in fiber core excites high-order modes in the first taper area and couples into the cladding. Then the high-order modes transmitted in cladding produce a strong evanescent field in the interface of cladding and external environment. The light in fiber core and cladding will be transmitted at the same time, and then they reach the second taper.Light in fiber cladding will be coupled back to fiber core and interfere with thelight in fiber. The core and the cladding of the PCF play the role of arms of a Mach-Zehnder modal interferometer, and tapering points act as couplers dividing and combining the light in the arms of the interferometer [7,8].

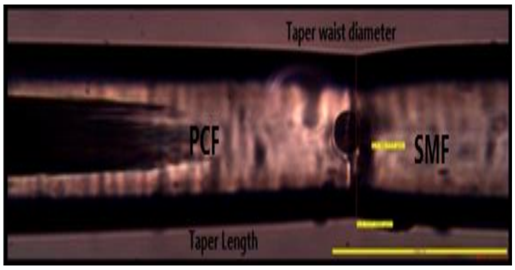

Fig. (2): Microscope image of the taperingsplice zone between PCF (LMA-10), on the left, and the SMF, on the right. The tapering length ~99µm. the tapering waist diameter between PCF and SMF was ~107 µm

In these experiments, the concentrations of NaCl solution (0%, 5%, 10%, 15%, 20% and 25%) used as a solution to evaluate the sensitivity of this sensor. A taper waist diameter of Photonic crystal fiber was used to show the sensitivity dependence. The specific experimental operations are as follows:

1. Connecting diode laser source (1550nm) optical fiber sensing head-optical spectrum analyzer (OSA).
2. The spectrum of fiber sensing head in the (air) is measured and saved as a reference spectrum.
3. The distilled water is injected into a tube with syringe, and then the spectrum was measured and saved.
4. Liquid is removed from the tube and the tube is dried with compressed air, until the spectra become the same as the reference spectra in air.
5. The interference spectra of NaCL solution with different refractive indices are measured as (1.34,1.35,1.36,1.37,and 1.38) by previous steps.

Results and Discussion

PCF interferometer is able to detect change in the surrounding solution. Different concentrations (0%, 5%, 10%, 15%, 20%, 25%) of these solution were used to show the least detection of the refractive index. The values of these liquids are shown in Table1.

Table (1): Refractive index of different concentrations of NaCl solution.

Refractive index	Concentration%
1.33	0
1.34	5
1.35	10
1.36	15
1.37	20
1.38	25

Figure 3(a)shows the transmission spectra of the splicing point tapered SMF-PCF-SMF at taper waist diameter 125µm. Figure 3 (b) shows the transmission spectra of the splicing point tapered SMF-PCF-SMF at taper waist diameter 107µm.Figure 3 (c) shows the transmission spectra of the splicing point tapered SMF-PCF-SMF at taper waist diameter 90µm.Figure 4 (d) shows the transmission spectra of the splicing point tapered SMF-PCF-SMF at taper waist diameter60µm.

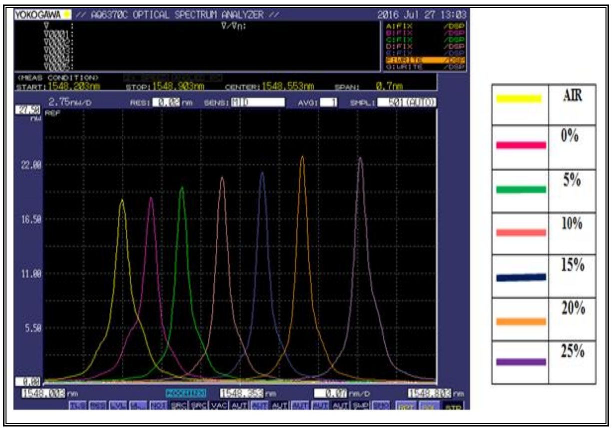

Fig. (3): (a)Interference spectrum of splicing points tapered SMF-PCF-SMF MZI at taper waist diameter of Ǿ =125 µm

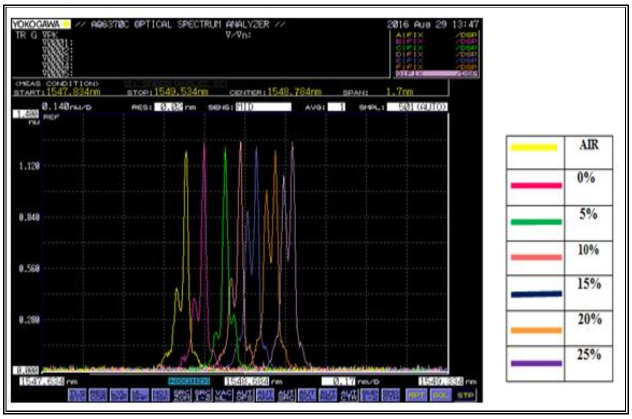

Fig. (3): (b)Interference spectrum of splicing points tapered SMF-PCF-SMF MZI at taper waist diameter of Ǿ =107µm.

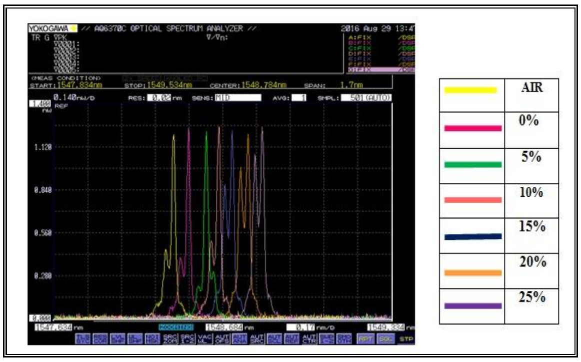

Fig. (3): (c)Interference spectrum of splicing points tapered SMF-PCF-SMF MZI at taper waist diameter of Ǿ =90μm.

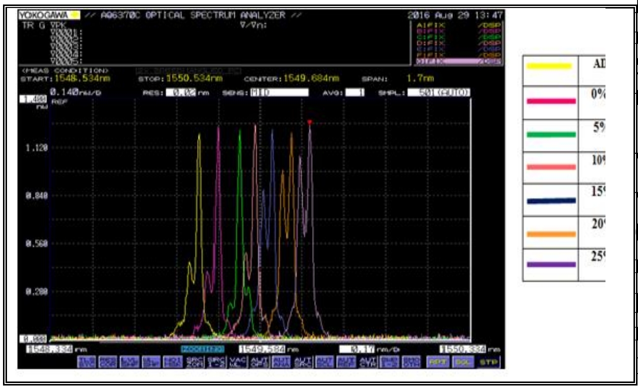

Fig. (3): (d) Interference spectrum of splicing points tapered SMF-PCF-SMF MZI at taper waist diameter of Ǿ =60μm

From Figure 3(a)-(b), it can be seen that splicing points of tapering measurements can improve the sensitivity to detect the refractive indices of SMF-PCF-SMF Mach-Zehnder interferometer. The sensitivity will increase with the decrease of taper waist diameter. Since decreasing the fiber diameter, more high order modes will stimulate and infiltrate into external environment solution. The power of higher order modes are easy to be leaked out into surrounding RI as a form of evanescent wave through the taper region. So the interaction between evanescent wave and external solution will increases. The surrounding refractive index changing will influence cladding mode transmission greatly. That is to say, it will result in wavelength shift increasing and sensitivity improvement.

Figure (4) shows the relation between wavelength shift and different refractive indices of splicing points of tapered SMF-PCF-SMF Mach- Zehnder interferometer. It can be seen that splicing points tapering can improve refractive index measuring sensitivity of SMF-PCF-SMF Mach-zehnder interferometer.

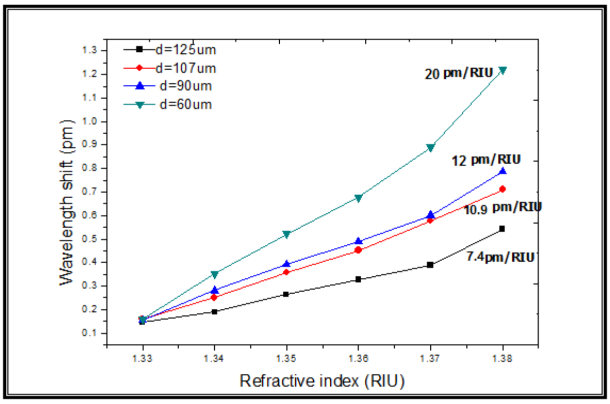

Fig. (4): Relation between wavelength shift and refractive index of splicing points tapered SMF-PCF-SMF Mach-zehnder interferometer with different taper waist diameter (125,107,90,60)μm

When photonic crystal fiber length is L=4cm with different taper waist diameter (125,107,90,and 60)μm, the refractive index measurement sensitivity is 7.4pm/RIU,10.9 pm/RIU 12.0 pm/RIU ,and 20 pm/RIU respectively. So the sensitivity increased by 12.6 % from taper waist diameter 125μm.

Simulation Result for COMSOL Multiphysics Program for Soild Core PCF(LMA-10)

Empty Soild Core PCF(LMA-10)

First of all, the solid core of the empty PCF (LMA-10) was investigated by the transmission of laser with wave length (1550nm) for simulation using COMSOL multiphysics program as shown in Figure 5(a).

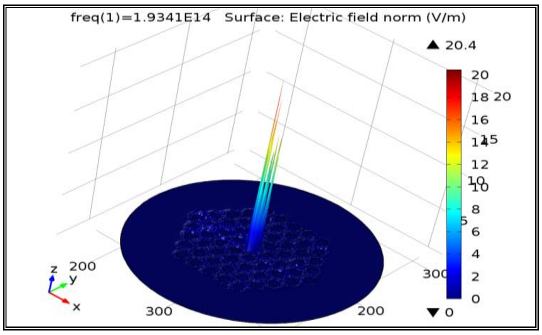

Fig.5: (a) Laser beam profile that exists from PCF(LMA-10) without being immersed in external solution

Solid Core PCF(LMA-10) With 125μm Taper Waist Diameter Immersed in External Solution

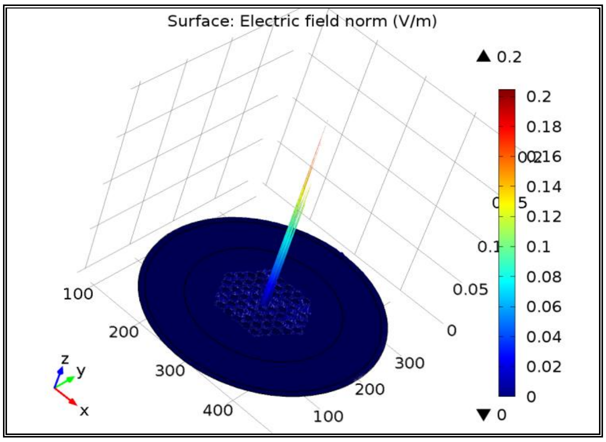

Fig. (5): (b) laser beam profile that exist from PCF(LMA-10) of taper waist diameter =125µm with immersed in the external solution with refractive index 1.38

Solid Core PCF(LMA-10) With 107µm Taper Waist Diameter Immersed in External Solution

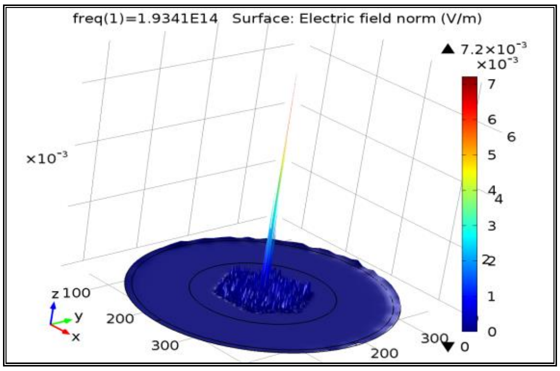

Fig. (5): (c)laser beam profile that exist from PCF(LMA-10) of taper waist diameter =107µm with immersed inthe external solution with refractive index 1.38 .

Solid Core PCF(LMA-10) With 90µm Taper Waist Diameter Immersed in External Solution

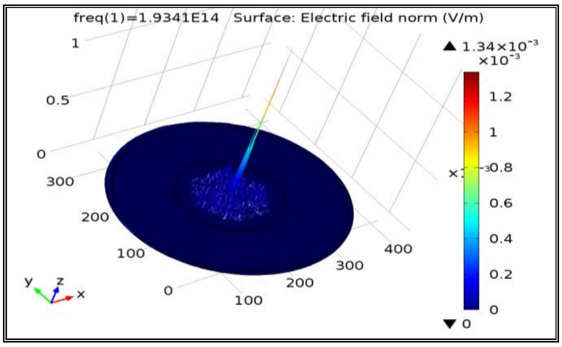

Fig. (5): (d)laser beam profile that exist from PCF(LMA-10) of taper waist diameter =90µm with immersed in the external solution with refractive index 1.38.

Solid Core PCF(LMA-10) with 60µm Taper Waist Diameter Immersed in External Solution

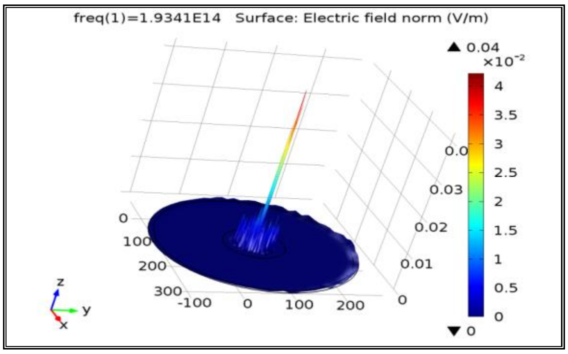

Fig. (5): (f)laser beam profile that exist from PCF(LMA-10) of taper waist diameter =60 µm with immersed in the external solution with refractive index 1.38

Figure 5 (a) shows the light guidance for solid core PCF (LMA-10) at wavelength 1550nm when the PCF is empty (air) as a reference spectrum. The peak of the laser is clear and very smooth. Figure (b), (c), (d) and (f) demonstrates the simulation result. When the diameter of the photonic crystal fiber is cross section is decreased (107,90, 60 µm) for less than the diameter of the single-mode fiber (83 µm), it is believed that this will excite higher order modes at different diameters of their collapse region. Simulation results show that when taper waist diameter decreases from (125-60) µm cladding modes gradually couple to outside of the photonic crystal fiber cross section. There will be more evanescent wave penetration into external solution. This indicates that the sensitivity of the sensor is improved with the decrease of taper diameter. The simulation and experimental results show that when taper waist becomes smaller, the sensitivity of the sensor can be improved.

Conclusions

The theoretical and experimental results show that central wavelength of interference spectrum is red shifted as the surrounding refractive indices values (1.33-1.38) increase. The sensitivity will increase with the decrease of taper waist diameter (125, 107, 90, and60) µm. The higher order cladding modes can be stimulated and split between the SMF core and PCF cladding. For this reason, the effective refractive index of PCF cladding is more sensitive to the surrounding refractive index changing. The maximum sensitivity of the sensor when taper waist diameter is 60µm which has a sensitivity of about 20pm/RIU compared with sensitivity of 7.4 pm /RIU of taper waist diameter 125µm, the sensitivity increased by 12.4%. The refractive index measurement at splicing points tapered SMF-PCF-SMF Mach-Zehnder mode interferometer can further enhance the sensitivity.

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تدبيب نقطة اللحام بين الليف البلوري الفوتوني والليف التقليدي ذو النمط المنفردالمستند على مقياس التداخل ماخ-زندر لتحسين الحساسية لمعامل الانكسار

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الخلاصة: استخدمت مقاييس تداخلات الالياف البلورية الفوتونية بشكل واسع لتطبيقات التحسس. في هذا البحث تم استخدام الالياف البلورية الفوتونية ذات القلب الصلب المستندة على مقياس تداخل ماخزندر النمطي لتحسسمعامل الانكسار . يتضمن التركيب الاساسي للمتحسس قطع صغيرة من الالياف البلورية الفوتونية ذات القلب الصلب مرتبطة بكلا الاتجاهين بالالياف التقليدية ذات النمط المنفرد(SMF-28). لتطبيق النظرية النمطية لمقياس التداخل:تقنية الاستدقاق وبالاستناد على اللحام المنصهر. تم تحفيز الانماط العالية (LP_{01} وLP_{11}). تم استخدم مصدر دايود ليزر كمصدر ضوئي بطول موجي (1550) نانومتر .و كذلك تم استخدام محلل طيفي بصري عالي التحسس لمتابعة وتسجيل الاطياف النافذة. في هذا العمل تم تصنيع متحسس لمعامل الانكسار بالاعتماد على مقياس التداخل ماخ- زندر والذي يعمل على تقنية التدبيب نقطة اللحام بين الليف البصري الفوتوني والليف التقليدي ذات النمط المنفرد وتم دراسة العلاقة بين الحساسية وقطر تدبيب نقطة اللحام .من خلال النتائج العملية والنظرية قد اوضحت ان الحساسية تزداد مع نقصان قطر التخصر لنقطة اللحام وكانت الاستجابة لهذا المقياس ضمن مدى لمعاملات الانكسار (1.38- 1.33) .عندما كان طول الليف البلوري الفوتوني (4) سنتمتر وباقطار تخصر مختلفة (60 ,90 ,125,107) مايكرون وقد استحصل اعلى مقدار للحساسية (20)بيكومتر لكل وحدة من معامل الانكسار عند قطر تخصر(60) مايكرون وكانت النسبة الزيادة في حساسية 12.4% عن قطر التخصر(125) مايكرون.