Chemical sensor based on a solid-core photonic crystal fiber interferometer

Rawaa K. Zarzoor, Hanan J. Taher

Institute of Laser for Postgraduate Studies, University of Baghdad, Baghdad, Iraq

E-mail: rawaa.kadhom@yahoo.com

Abstract

Photonic crystal fiber interferometers are used in many sensing applications. In this work, an in-reflection photonic crystal fiber (PCF) based on Mach-Zehnder (micro-holes collapsing) (MZ) interferometer, which exhibits high sensitivity to different volatile organic compounds (VOCs), without the needing of any permeable material. The interferometer is robust, compact, and consists of a stub photonic crystal fiber of large-mode area, photonic crystal fiber spliced to standard single mode fiber (SMF) (corning-28), this splicing occurs with optimized splice loss 0.19 dB In the splice regions the voids of the holey fiber are completely collapsed, which allows the excitation and recombination of core and cladding modes. The device reflection spectrum exhibits a sinusoidal interference pattern which shifts differently when the voids of the PCF are infiltrated with VOC molecules. The volume of voids responsible for the shift is less than 5microliters whereas the detectable levels are in the nanomole range. Laser diode with a wavelength 1550nm has been used as a pump light source. Two types of chemical liquids used (N-Hexane, and Propanol). The detection limits of our device associated with the maximum shifts of the wavelength is 4.4 nm for N-Hexane vapor when the length of the head sensor 20mm. In this work, the maximum sensitivity obtained of volatile organic compounds is 15420 nm/mol at the vapor of N-Hexane.

Key words

Photonic Crystal Fiber, Fiber optic sensors, Interferometry, Chemical analysis.

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بناء متحسس كيميائي باستعمال مقياس التداخل المستند على ليف بصري بلوري ذو قلب الصلب

رواء كاظم زرزور، حنان جعفر طاهر

معهد الليزر للدراسات العليا، جامعة بغداد، بغداد، العراق

الخلاصة

لقد استخدمت مقاييس تداخل الالياف البلورية الفوتونية في العديد من التطبيقات. وفي بحثنا هذا تم استخدام مقياس تداخل (ماخ- زندر) المستند على اليف البلوري الفوتوني ذو القلب الصلب، والذي يبدي حساسية عالية للتغيرات الحاصلة في معاملات الانكسار للمركبات العضوية المتطايرة المختلفة ومن دون الحاجة الى الى أي مواد قابلة للاختراق. يتكون مقياس التداخل المدمج القوي من نهاية ليف بلوري فوتوني يرتبط بالليف التقليدي (ذو النمط المفرد SMF-28) وبأدنى خسارة dB (0.19) في منطقة الارتباط، حيث تنهار فتحات فجوات الليف كليا، وتسمح بالتهيج واعادة التركيب للأنماط القلب والكسوة. ويعكس الجهاز الطيف الضوئي مظهرا نمط تداخل جديد هو دالة جيبية تبين ازاحة الطيف بشكل مختلف بعد تسلل جزيئات المركب العضوية المتطاير الى فتحات الليف الفوتوني البلوري. ان حجم الفرغات لليف البفوتوني البلوري المسؤلة عن ازاحة طول الموجة الليزر المستخدم اقل من (5µm) في حين ان المستويات التي يمكن الكشف عنها هي في حدود النانو متر. استخدم في بحثنا هذا ليزر الدايود كمصدر ضوئي وبطول موجي nm1550، حيث تم استخدام محلل الطيف

الضوئي(OSA) الحساس للغاية في رصد وتسجيل الطيف المنعكس ،كما استخدم نوعان من السوائل الكيميائية وهي (الهكسان، البروبانول) ان هذه السوائل وابخرتها تمتلك شفافية عالية في منطقة الطيف المرئي والمنطقة تحت الحمراء القريبة. وفي هذا البحث وجدنا افضل زمن استجابة لهذا المتحسس هو من (30-35) دقيقة لكميات قليلة جدا من هذه السوائل تقدر بمايكرو لتر، كما تم دراسة تأثير طول جهاز الاستشعار على قيمة الازاحة للطول الموجي، تم اختبار خمسة اطوال مختلفة mm (20 ,30 ,40 ,50 ,70) وكانت حدود الكشف المسجلة لجهازنا في ازاحة الطول الموجي هي 4.4 nm لبخار الهكسان عندما كان طول راس المتحسس 20 mm. كما ان الحد الاعلى للحساسية المستحصلة هي 15420 nm/mol لبخار الهكسان.

Introduction

Photonic crystal fibers (PCFs), also named as micro-structured optical fibers (MOFs), represent nowadays a new and intriguing typology of optical fibers suitable for sensing applications such as measurement of strain, refractive index, pressure, temperature, magnetic field. The PCF-based sensors are characterized by high sensitivity, small size, robustness, flexibility, offers many degrees of freedom, some advantages such as stability, compactness, no moving parts, and the ability for remote sensing.

Other advantages concern with the possibility to be used even in the exist of unsuitable environmental conditions such as strong electromagnetic fields, noise, nuclear radiation, high voltages, for explosive or chemically corrosive media, and at high temperatures [1,2].

Recently, photonic crystal fibers (PCF) have attracted researchers for their can be used in chemical sensing applications. Features which have encouraged photonic crystal fiber as a sensor are long interaction length, mode field overlap between the light and matter, and extremely small volumes of the sample, flexible, robust and allow remote measurements required for sensing [3,4].

The detection, sensing, or spectroscopic analysis of gases and liquids were the main interest after the using of the holey structure of photonic crystal fibers (PCFs) [5]. In PCFs a fraction of the power of the guided light penetrates into the voids thus making possible the interaction and detection of gases or liquids by means of spectroscopic techniques [4,6].

In addition to robustness and flexibility PCFs offer some advantages when used as gas or liquid cells. Firstly, the interaction lengths can be much longer than those achievable in conventional cells. On the other hand the sample volume required for filling the microscopic voids of a PCF or for measurements are much less than the volumes required in traditional gas cells. In the past few years, researchers have addressed two different issues to carry out gas spectroscopy in PCFs or to design functional PCF sensors. The first one is the optimization of the PCF microstructure to maximize or enhance the overlap between guided light and gas while the second one is the simultaneous coupling of light and gas into the PCF.

For example, in hollow core PCFs, which guide light by means of the photonic band gap effect- about 98% of the guided mode field energy can propagate in the core, therefore the interaction with the sample is direct [5,6,7]. As an alternative to hollow core PCFs, solid-core and air-suspended core fibers which guide light by total internal reflection have been proposed for optical sensing [8].

In these types of fibers the interaction with the sample is via evanescent waves. The transmission bandwidth of index-guiding PCFs is broader than that of band-gap fibers, but the energy of the evanescent fields is weaker, between 10 to 40% of the total energy of the guided mode field[6].

Infiltrating gas into the PCF holes is a challenge, in many cases vacuums or pumping systems are required. Some alternatives that have been proposed for infiltrating gas or sample into the holes include perforation of the Photonic crystal fiber in one side. However, a controlled perforation is not simple; as a consequence the fiber may become weak, lossy, and fragile.

They demonstrate a scheme based on in reflection two-mode PCF interferometry in which the difficulty of coupling light and sample is significantly reduced. The interferometer consists of a stub of PCF spliced to standard optical fiber, which exhibits high sensitivity to different volatile organic compounds (VOCs). In the splice the holes of the PCF are fully collapsed, which is causing the splitting and recombination of two core modes. The other end of the photonic crystal fiber is cleaved and the holes are left open [3, 9].

The first aim of the present work is to fabricate Mach-Zehnder (Micro-Holes Collapsing) interferometer based on large mode area (LMA) photonic crystal fiber of solid core. The second aim is to evaluate this interferometer through using it in remote sensing without vacuum, and without need of any permeable material which is a key issue in addition to high sensitivity and high stability.

Photonic crystal fibers

Photonic crystal fibers (PCFs), also named as micro-structured optical fibers (MOFs), represent nowadays a new and intriguing typology of optical fibers suitable for sensing applications such as measurement of strain, sensors are characterized by high sensitivity, small size, robustness, flexibility, offers many degrees of freedom, some advantages such as stability, compactness, no moving parts, and the ability for remote sensing [3].

Optical interferometer

Optical interferometers offer high resolution in metrology applications, the fiber optic technology additionally offers many degrees of freedom and some advantages such as stability, compactness, and absence of moving parts for the construction of interferometers. The two commonly followed approaches to build a fiber optic interferometer are: two arm interferometer and modal interferometer [10].

Two- arm interferometer involves splitting and recombining consists of two monochromatic optical beams that propagation in different fibers. These two-arm interferometers typically require several meters of optical fibers and one or two couplers. The other approach consists of exploiting the relative phase displacement between two modes, typically the first two modes like the LP01 and LP11. Interferometers based on the latter approach are known as modal interferometers. These have inherent advantages when compared to their two-arm counterparts. Since the modes propagate in the same path [1].

In modal interferometers compared to their two-arm counterparts the susceptibility to environmental fluctuations is reduced because the modes propagate in the same path or fiber. Therefore, modal interferometer is better to use in optical fiber sensing[11]. Recently the unique properties of the photonic crystal fiber have attracted the sensor community. Design of PCF based interferometers in particular is interesting owing to their proven high sensitivity and wide range of applications. Photonic crystal fiber based modal interferometers include PCFs in a fiber loop mirror [1], interferometer built with long period gratings, interferometers built with tapered PCFs and interferometers fabricated via micro-hole collapse [10]. These interferometers have lots of advantages, including high resolution, simple configuration, good electromagnetic interference immunity, and low cost. But PCFs give those important advantages, broad operating wavelength range and high stability over time [12].

Interferometers built via micro-holes collapsing

This type is new interferometers based on microhole collapse have been demonstrated [1]. This technique is simple since it only involves cleaving and splicing, processes that can be carried out in any fiber-optics laboratory. The key element in these interferometers is a microscopic region in which the voids of the PCF are completely collapsed. Basically, the collapsed region is what allows the excitation of two modes in the PCF[13]. The appeal of the interferometers fabricated with this approach is that the devices can be used for a variety of applications ranging from sensing strain (and all the parameters that can be translated to strain) or temperature to refractive index (biosensing) and volatile organic compounds (VOCs). In addition, the devices are compact, robust, and highly stable over time. For their interrogation a light emitting diode (LED) and a conventional fiber Bragg grating (FBG) interrogator or spectrum analyzer or a tunable laser and a single photodetector can be employed [13].

It is known that when splicing together two PCFs, or a PCF and a conventional optical fiber, with the standard electric-arc method, the air-holes of the PCF collapse completely in the vicinity of the splice. The length of the collapsed region is typically less than 300 or 400 μm [1,14].

Some advantages of the PCF interferometers fabricated using microhole collapse are that since interferometers are fabricated by fusion splicing the splice is highly stable even at high temperatures and also its characteristics will not degrade over time [14].

Interferometers micro-holes collapsing working principle

In a PCFI the excitation and recombination of modes can be carried out by the hole collapsed region of the PCF.A microscopic image of the PCFI and a schematic of the excitation and recombination of modes in the PCFI, the fundamental SMF mode begins to diffract when it enters the collapsed section of the PCF. Because of diffraction, the mode broadens; depending on the modal characteristics of the PCF and the hole collapsed region, the power in the input beam can be coupled to the fundamental core mode and to higher order core modes or to cladding of the PCF [15]. The modes propagate through the PCF until they reach the cleaved end from where they are reflected. Since the modes propagate at different phase velocities, thus in a certain length of PCF the modes accumulate a differential phase shift. Therefore, constructive or destructive interference occurs along the length of PCF. The phase velocities and phase difference are also wavelength dependent; therefore the optical power reflected by the device will be a maximum at certain wavelengths and minimum at others[14]. As shown in Fig. 1.

When the reflected modes re-enter the collapsed region they will further diffract and because the mode field of the SMF is smaller, the core acts as a spatial filter and picks up only a part of the resultant intensity distribution of the interference pattern in the PCF [1].

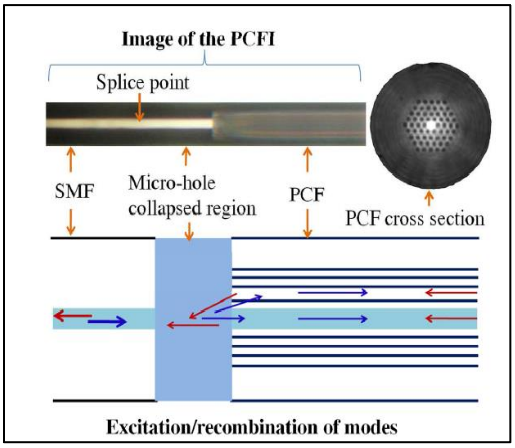

Fig.1: Microscope image of the PCFI (upper) and a schematic of the excitation/recombination of modes in the hole collapsed region (lower)[16].

A regular interference pattern in the reflection spectrum of the PCFI suggests that only two modes are interfering in the device. In our reported work on a PCFI using LMA 10 fibre, based on the fact that higher order modes can exist in the core of a PCF with a short length, the interfering modes in the PCF are considered as two core modes. However, in a later experiment, which involved varying the refractive index surrounding the cladding of a PCFI, good ambient refractive index sensitivity is observed for a PCFI fabricated using the same LMA 10 fibre [13, 16].

This suggests that the interfering modes are a core mode and a cladding mode of the PCF, a conclusion that is supported for an LMA10 fibre. Thus, considering a core mode and a cladding mode as the interfering modes of the PCFI and designating the effective refractive indexes of the core mode as nc and cladding mode as ncl, the accumulated phase difference is [17]:

$$2\pi\Delta n(2L)/\lambda \quad (1)$$

where Δn=nc-ncl, λ the wavelength of the optical source, and L the physical length of the PCFI.

The power reflection spectrum of this interferometer will be proportional to

$$\cos(4\pi\Delta nL/\lambda). \quad (2)$$

The wavelengths at which the reflection spectrum shows maxima are those that satisfy the condition

$$4\pi\Delta nL/\lambda=2m\pi \quad (3)$$

With m being an integer. This means that a periodic constructive interference occurs when [17]:

$$\lambda m = (2\Delta nL/m) \quad (4)$$

If some external stimulus changes Δn (while L is fixed) the position of each interference peak will change, a principle which allows the device to be used for sensing [17].

Interferometers micro-holes collapsing fabrication

Fusion splicing of the PCF to the SMF is undertaken using the electric arc discharge of a conventional arc fusion splicer. During the splicing process the voids of the PCF collapse through surface tension within a microscopic region close to the splice point [1]. In fabricating such an interferometer, one critical condition for good sensor performance is achieving a regular interference pattern and good interference fringe visibility. The visibility of the interferometer depends on the power in the excited modes, which in turn depends on the length of the collapsed region. However a long collapsed region length causes activation of many cladding modes and therefore degrades the sinusoidal nature of the interference patterns and furthermore increases the splice loss. Therefore, for an improved sensor performance, only one cladding mode is preferred due to its simple interference with the core mode. The collapsed region length can be controlled by the arc power and duration. In this experiments, PCF (LMA10, NKT Photonics) designed for an endless single-mode operation was used. It has four layers of air holes arranged in a hexagonal pattern around a solid silica core. The light guidance mechanism in such a fibre is by means of modified total internal reflection[15]. The dimensions of the LMA-10 PCF simplify alignment and splicing with the SMF with a standard splicing machine and minimize the loss due to mode field diameter mismatch compared to other PCFs. For the interferometer fabricated in our study the total length of the collapsed region was 300-400 µm. After fusion splicing, the PCF was cleaved using a standard fibre cleaving machine so that the end surface of the PCF acts as a reflecting surface [18].

When the interferometers operate in reflection mode novel sensing applications are possible. For example, an in-reflection interferometer fabricated by fusion splicing a stub of 5-ring PCF see Fig.1.4 at the distal end of a standard optical fiber (Corning SMF-28) can be used to detect different volatile organic compounds at room temperature. The key point here is to leave the voids of the PCF open to allow infiltration of some gases, chemical vapor, or molecules [15]. The interaction of the compounds with the interfering modes takes place in the first rings of voids which have a total volume in the picolitters range [19].

Note that the interferometer saturates owing to the limited volume of the voids. They can house a maximum number of molecules. The interferometer slowly returns to its original position which indicates the reversibility of the devices. The response time of the device is long because the experiments were carried at normal conditions. In addition, the infiltration of the volatile organic compound vapor into the microscopic voids of the PCF is a diffusion process which is typically slow [1].

Experimental device

Photonic crystal fiber interferometers based on micro-hole collapse have attained great importance in recent times due to the simple fabrication process involved and excellent sensing performance. A reflection-type PCFI consists of a stub of the PCF was a fusion spliced to standard optical fiber (Corning SMF-28) with a conventional splicing machine. The PCF (LMA10, NKT Photonics) designed for an endless single-mode operation was used. It has four layers of air holes arranged in a hexagonal pattern around a solid silica core as shown in Fig.1.2, the fiber has a core size diameter of 10µm, voids with a diameter of 3.1µm, pitch of 6.6µm and outer diameter of 125µm. The dimensions of our PCF simplify the aligning and splicing with the SMF-28 with a standard splicing machine. A default program for splicing single mode fibers were used to ensure repeatability of the process as well as to minimize the fabrication time. Under such splicing conditions the voids of the PCF collapse completely over a microscopic region whose total length is typically~300-400µm [2,10]. The collapsing of the PCF voids introduces overall optical losses in the (0.18 - 0.19) dB range. After the splicing, the PCF is cleaved with a standard cleaving machine so that the end of the PCF behaves as a reflecting surface. (Mirror) (due to Fresnel reflection) [3,11,12,13]. On the other side of the PCF the voids of the PCF are left open which simplifies the infiltration of gas, chemical vapor, molecules, or any other sample. Fig.2 shows the experimental setup.

Fig.3 shows a Diagram of the experimental setup. Fig. 4 shows the PCFI and Fig. 5 shows a micrograph of the described PCF, a drawing of the interferometer, and a diagram of the setup to interrogate it. The light source is (MW3116) was 1550nm wavelength.

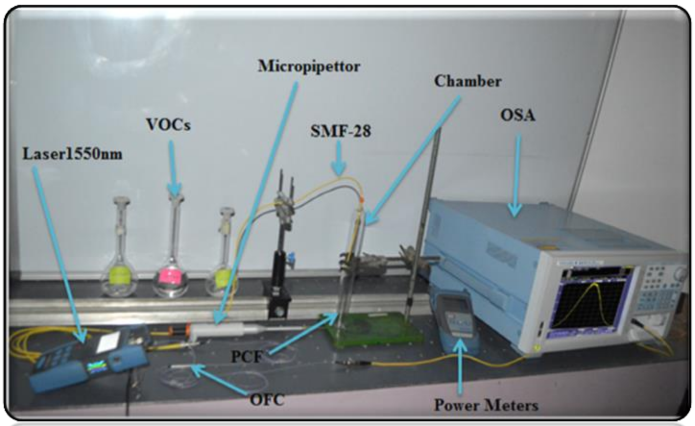

Fig. 2: The experimental setup.

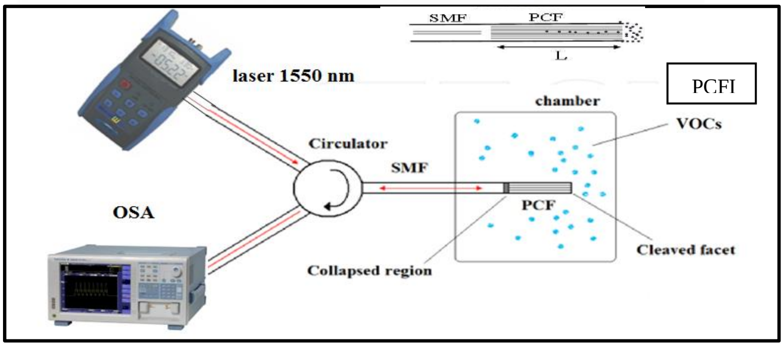

Fig. 3: Schematic of the chemical sensor based on PCF interferometer.

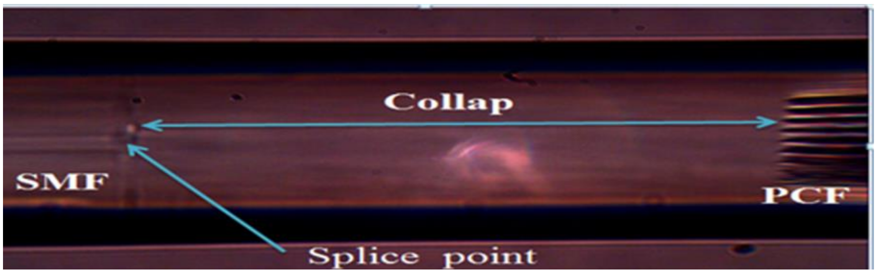

Fig.4: Microscope image of the PCFI shown Microscope image of the splice zone between PCF (LMA-10) on the right, and the SMF-28 on the left. The collapsed length is ~340.7 µm when the magnification power (65 X).

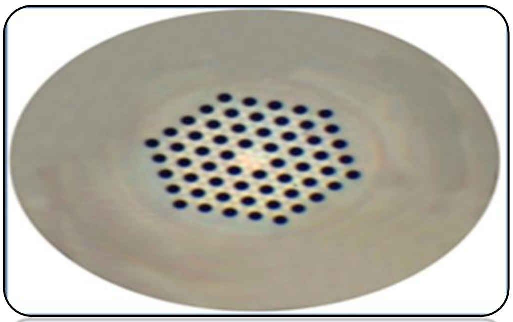

Fig. 5: The cross section of the PCF used for the experiment, when the magnification power of microscope (20 X).

Transmission spectrum of chemical vapor

Two types of chemical liquids were evaporated inside the chamber to fill the cladding of the PCF, These VOCs are N-Hexane, and Propanol. The chemical liquids were evaporated inside the chamber were used to infiltrate with vapor liquid at the end of the PCF is cleaved and the voids are left open, and the PCF has been obtained at the room temperature (25C°), by using UV-VIS-NIR spectrophotometer and it is shown in Figs. 6 and 7. The reason behind taking these chemicals is their safe handling and the other important reason is the central subject of the chemical sensing in the present study. The sensing relies on the change in the refractive index. Thus, we have to use materials with low absorption of the laser beams being used. Figs.6 and 7. show transmission spectrum of liquids and this spectrum exhibit high transparency after the wavelength approximately 900 nm after this wavelength does not have any absorption.

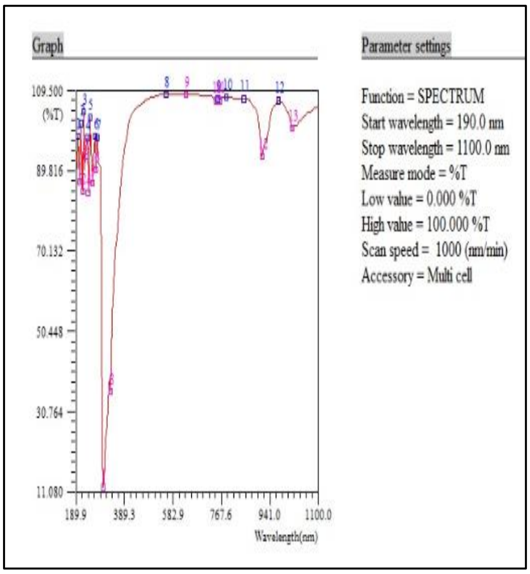

Fig. 6: Transmission spectrum of n-hexane at room temperature (25 C°).

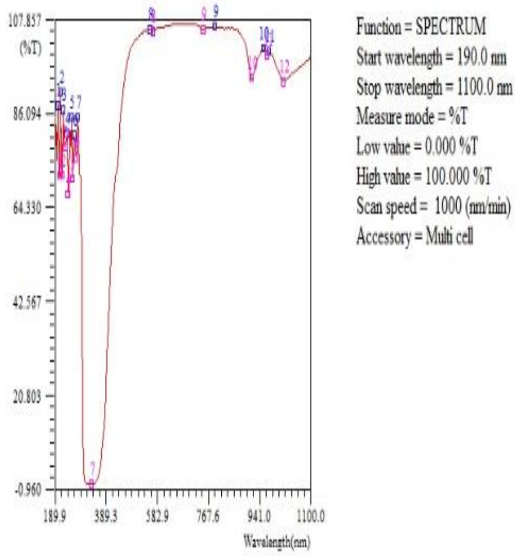

Fig. 7: Transmission spectrum of propaol room temperature (25 ^{o}C).

In Fig. 8 shows the laser mode stability of diode laser model type (MW3116), 1550 nm. The beginning step of the present study is to test the stability of laser diode that's being utilized to pump the optical interaction cavity via optical spectrum analyzer of each device, This is done after hours of operation. After fabricating interferometer process, PCFI Placed in a chamber and be empty of any vapor or liquid and record the track by using (OSA) as show Fig. 9 illustrated the Output Spectrum of diode laser 1550 nm after the fusion spliced (SMF-28/PCF (LMA-10)) with a conventional splicing machine.

In Fig. 9 will notice a drastic fall valued the power of laser and interpretation of this is due to the presence of Fiber Optic Circulator this devise is reflects 10% of total power, Pink color represents the output of the laser 1550 nm directly from the device and Yellow color represents the output laser 1550nm after fusion splicing process.

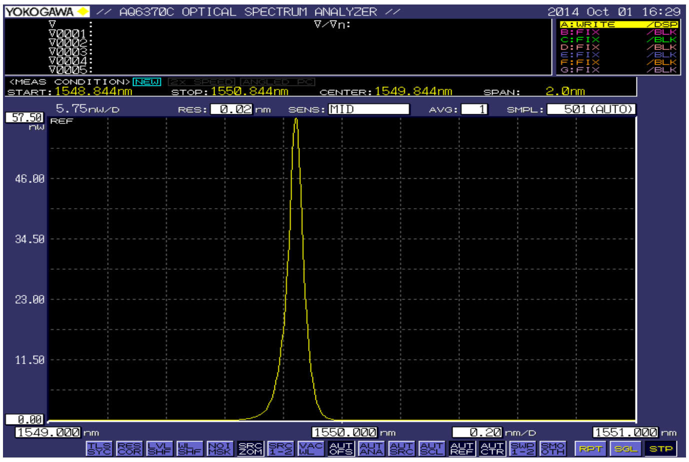

Fig. 8: Output Spectrum of diode laser 1550 nm.

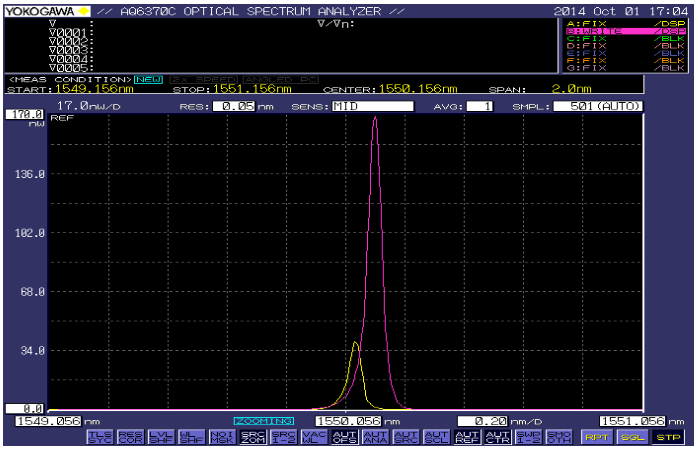

Fig. 9: Output Spectrum of diode laser 1550 nm after the fusion spliced (SMF-28/PCF (LMA-10)).

Spectroscopy test results

The first run was to check the validity of our system for detection. A small amount of VOC (N-Hexane) (10μL) was injected inside the container during 20- 35 minute by evaporating this volume of VOC at room temperature, Fig. 10 shows the spectrum shift in the central peak, which represents the reference beam in all measurements.

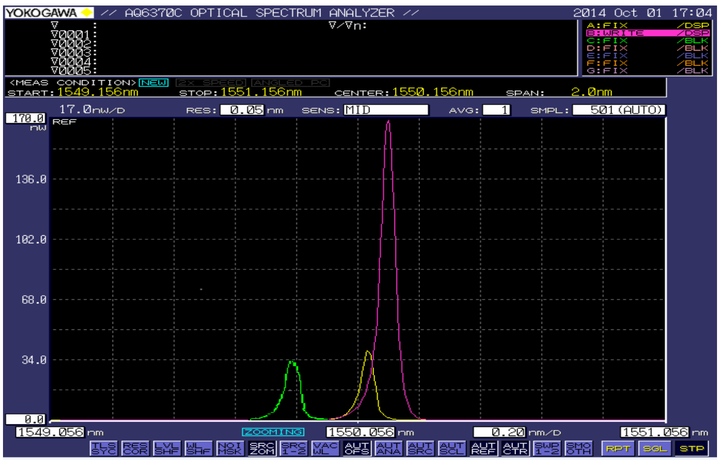

Fig. 10: Optical Spectrum Shift.

Interferometers are extremely sensitive to phase changes. In our device a minute change in Δn can displace the interference pattern. The modes in our interferometer can be perturbed via evanescent waves which reach only the ring of holes adjacent to the core, as shown in Fig. 10. Our calculations show that ~99% of the field of the LP01 mode and ~97% of the LP11 mode are in the first ring of holes of the PCF when it is filled with air. These values do not change significantly for indexes in the 1.001-1.1 range (index of some gases). However, Δn does change and cause a detectable shift in the interference pattern. This means that our interferometer can detect the presence of some gases, chemical vapor or molecules if they are present in the first ring. This ring has five holes, each hole with a diameter of ~3.1µm. Thus, when the length of PCF is 20 mm the volume is ~140µl. Such a volume is extremely small. Infiltrating gas or chemical vapor in the voids of the PCF interferometer and simultaneously launching light into it is not an issue in the proposed device.

Calculating the number of moles for (VOCs)

We will calculate the number of moles for two types of VOCs (N-Hexane, and propanol) by using this equation:

Number of moles = weights/(molecular Wight) (5)

Wight = density * volume (6)

Tables 1 and 2 show, calculate the number of moles for two types of VOCs N-Hexane, and propanol.

Table 1: The number of moles for each volume of N-Hexane.

Volume (µL)	5	10	15	20	25	30	35
Number of moles * (10^{-4})	0.390	0.7798	1.1696	1.5595	1.949	2.3393	2.7292

Table 2: The number of moles for each volume of propanol.

Volume (µL)	5	10	15	20	25	30	35
Number of moles * (10^{-4})	0.668	1.338	2.007	2.676	3.344	4.013	4.682

Response time to vapor of (VOCs)

Depending on the result Fig. 11 show the shift of the interferometer in which length of PCF was 20 mm when exposed to the vapor of N-Hexane, propane, methanol. The shift observed when the same interferometer was exposed to vapors of propanol. These data were collected separately by firstly dispensing 5µl of compound until it was totally evaporated. Once a steady state was attained, we added 10 more µl until it evaporated completely and measured the response. Finally, we dispensed a further 20µl and recorded the track. Thus the total volume evaporated was 35µl. During Fig. 11 the first 1-13 minutes no changes are seen because the tracking of the position of the interference peaks was stated before dispensing the VOCs in the chamber. After this time the shift increases slowly and the spectrum became larger and larger as time went by because more and more molecules evaporated and diffused into the voids of the PCF.

Finally, it got into a stable state after 30 min and the total shift caused by the 35µL of VOC was 4.4nm. When 35µl of the liquid VOC was injected into the chamber the interference spectrum had a remarkable shift in 30min to N-Hexane, propanol. The small voids of our PCF (LMA-10) which used lead to response time longer than the response time of PCF (LMA-25) which used in the report [19].

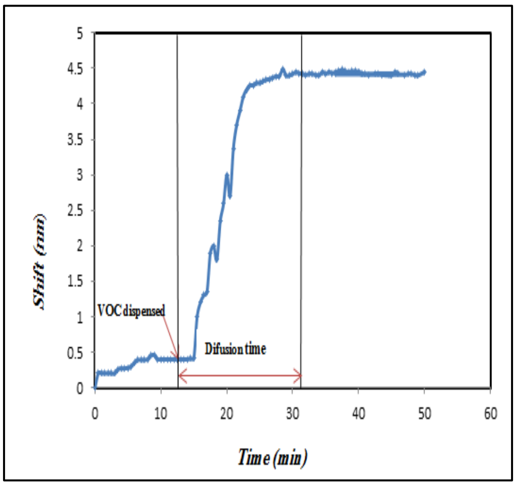

Fig. 11: The interference pattern shift as a function time observed in a device fabricated with 20mm of PCF when exposed to different volumes of N-Hexane and propanol and showing both the injection and diffusion time. The light source was a diode laser with peak emission at 1550 nm.

Fig.11 shows the graph obtained from N-Hexane and propanol around the minute -15-20. The region inside the vertical dotted lines indicates the time in which the VOC was dispensed and that in which 90% of shift was reached. Response time (the time required for a device to reach 90% of signal change) in the 5-8 minute range was calculated in our devices. Such long response times are a consequence of the fact that the experiments were carried at normal conditions. Approximately between 1 and 2 minutes were needed to evaporate completed the volume of liquid dispensed in the chamber since the boiling point of the studied VOC were in the 65-83 °C. In addition, the infiltration of the VOC vapor or gas into the microscopic holes of the photonic crystal fiber is a slow diffusion process [5]. The direct introduction of gaseous samples along with smaller chamber dead volumes could lead to increased response times.

Optical sensing with PCFs

In solid-core and air-suspended core fibers which guide light by total internal reflection have been proposed for optical sensing. In these types of fibers the interaction with the sample is via evanescent waves. The transmission bandwidth of index-guiding PCFs is broader than that of the band-gap fibers, but the energy of the evanescent fields is weaker, between 10% to 40% of the total energy of the guided mode field. Infiltrating gas into the PCF voids is a challenge, in many cases, controlled perforation is not simple; as a consequence the fiber may become loss, weak, and fragile. Therefore the interaction with the sample is direct. The interaction lengths can be much longer than those achievable in conventional cells. On the other hand the sample volume required for filling the microscopic voids of a PCF or for measurements are much less than the volumes required in traditional gas cells [20]. When the interferometer is operating in the reflection mode can be used in sensing applications. In this work, an in-reflection interferometer is fabricated by fusion splicing a stub of the PCF of 5-ring with the end of a standard optical fiber (Corning SMF-28) can be used for detecting the different VOCs at temperature of room. The main point here is leaving the holes of the PCF open to allowing of chemical vapor, some gases, or molecules to infiltrate. The interaction of the VOCs (which have a total volume in the microliters range) with the interfering modes occurs in the first rings of holes. The shift of an interferometer in which L was PCF (70, 50, 40, 30 and 20) mm respectively. When exposed to the vapor of liquid (N-Hexane, and propanol) in a closed chamber. Fig. 12 and 13 depict the spectrum shift with the number of moles VOC after injecting the chamber into the liquid (N-Hexane, and propanol). with the aforementioned five lengths of the PCF was collected by evaporating 35µl of liquid (N-Hexane, methanol and propanol) in a closed chamber. The shift increases owing to the exist of the vapor. Fact is that the curve plateaus indicates that the chamber was properly sealed. Note that the interferometer saturates owing to the limited volume of the holes. They are Peristaltic a maximum number of molecules. The interferometer slowly returns to its original position which indicates the reversibility of the devices. The response time of the device is long because the experiments were carried at normal conditions. In addition, the infiltration of the our VOC vapor into the microscopic voids of the PCF is a diffusion process which is typically slow. We would like to point out that the combination of different fibers to forming interferometers has been achieved during many years. In these cases the splicing process is critical since it is determining the excitation or recombination of the interfering beams. The selecting of the fiber which in it two modes are excited is also crucial. It can be noted that, after a certain value, dispensing more compound into the chamber (increasing the number of moles) would not lead to more appreciable shifts. The signal plateau owing to the limited volume of the PCF voids which can only house a certain number of molecules.

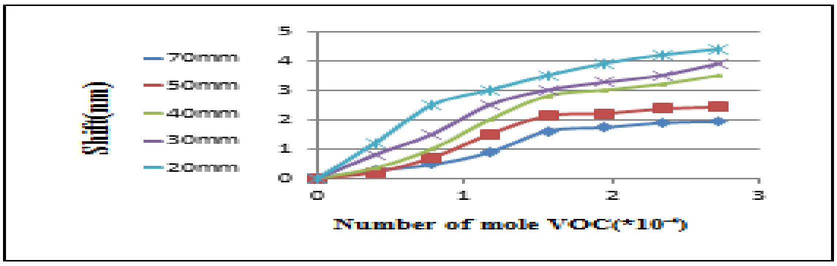

Fig. 12:The shift of the interference pattern as a function of volume to the VOCs showed in a device fabricated with length of PCF (70,50,40,30 and 20)mm behaver of all length in 30 of N-Hexsane (min) at room temperature (25 C°).

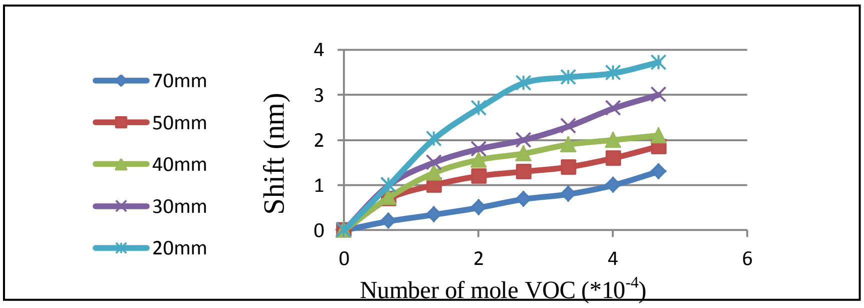

Fig.13:The shift of the interference pattern as a function of volume to the VOCs showed in a device fabricated with length of PCF (70,50,40,30 and 20)mm behaver of all length in 30 of propanol (min) at room temperature (25 C°).

Optical Sensing PCFs with Infiltrating the (LMA-10) by N-Hexane and propanol

Depending on the Fig. 12 and 13 can be calculated the refractive index sensitivity of the Optical Sensing PCFs as shown in the Table 3.

Table 3: Summary results of the high sensitivity different volatile organic compounds (VOCs) of three types.

Length of PCF(mm)	Number of mols of (VOC) sensitivity (nm/mol)	
	N-Hexane	Propanol
70	7951	2608
50	10033	3345
40	13908	4108
30	14223	5713
20	15420	8556

Note from the Table 3 the highest value of the sensitivity is 15420 nm/mol when filing the vapor N-Hexane to void of PCF, This result is due to the vapor hexane has a refractive index higher than propanol, such a volume is the highest one reported so far in fiber-based gas sensors.

Length of the optical sensing PCFs with shift

The value of the shift of the center wavelength for the PCF was increased with decrease the length of the photonic crystal fiber as it is shown in Fig. 14 and 15. Depending on the Eq. (3).

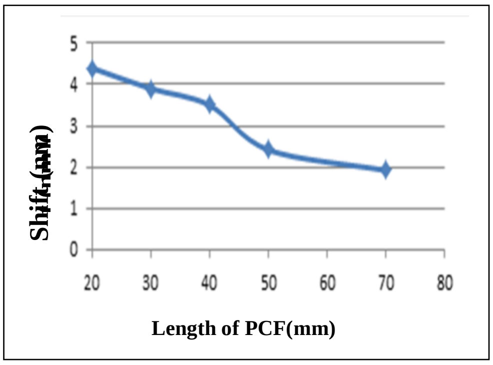

Fig.14: Relationship between of length of PCF and shift of the wave length to N-Hexane at 30 min.

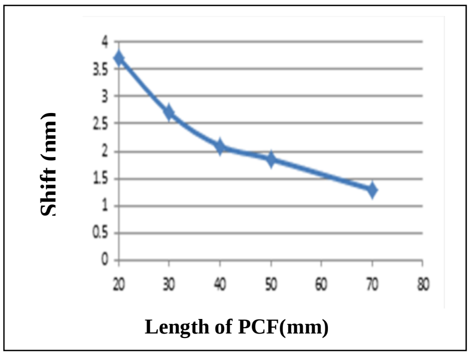

Fig.15: Relationship between of length of PCF and shift of the wave length to propanol at 30 min.

Fig. 16 shows that the increase in the refractive index leads to increase the shift in the wavelength and thus the liquid, which has a higher refractive index has a value of shift is very clear.

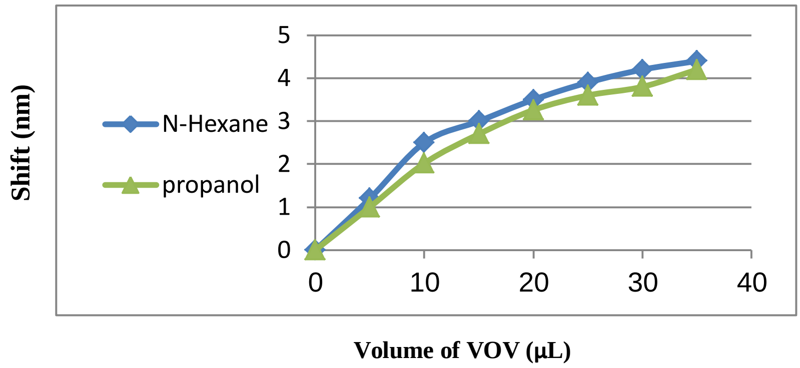

Fig. 16: PCF (LMA-10) optical sensing with 20mm at 1550nm.

Simulated modeling

Solid core PCF is utilized to design chemical sensor based on interferometer, evanescent wave interacts with analytes involved in cladding air holes. The fundamental mode transmission at specific wavelength must be considered. The designed PCF must transmit exciting light as fundamental mode and has a large mode area. Based on this. By COMSOL Multiphysics using the program a photonic crystal fiber solid core (LMA10, NKT Photonics) was used is designed, it has a core size diameter of 10µm, voids with a diameter of 3.1µm, pitch of 6.6µm and outer diameter of 125µm. The structure was displayed in Fig. 17. The fiber has a core size diameter of 10µm, voids with a diameter of 3.1µm, pitch of 6.6µm and outer diameter of 125µm.

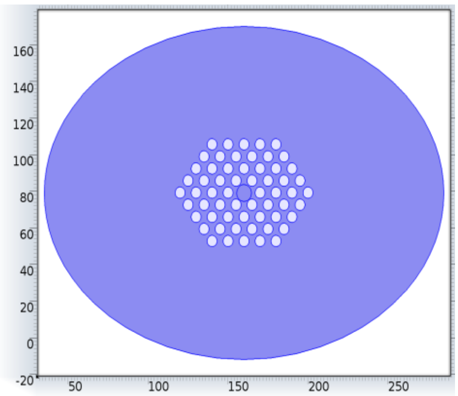

Fig.17: The structure of designed solid core PCF (LMA-10) with refractive index of Silica glass to core and air to cladding.

Experimental results for COMSOL multiphysics program for solid core PCF (LMA-10)

1. Empty solid core PCF (LMA-10)

First of all, the solid core of the empty PCF (LMA-10) was investigated by The transmission of the laser with wavelengths (1550nm) was obtained theoretically using COMSOL multiphysics program as it is shown in Figs. 18.

2. Infiltrating the solid core PCF (LMA-10) by N-Hexane

After the solid core PCF (LMA-10) was infiltrated by N-Hexane, the maximum transmission obtained is about 100% at 1550 nm with refractive index 1.379 at room temperature (25 Co). Fig. 20 as show laser Beam Profile that exist from PCF (LMA-10) after filling the cladding with gas by the COMSOL simulation program.

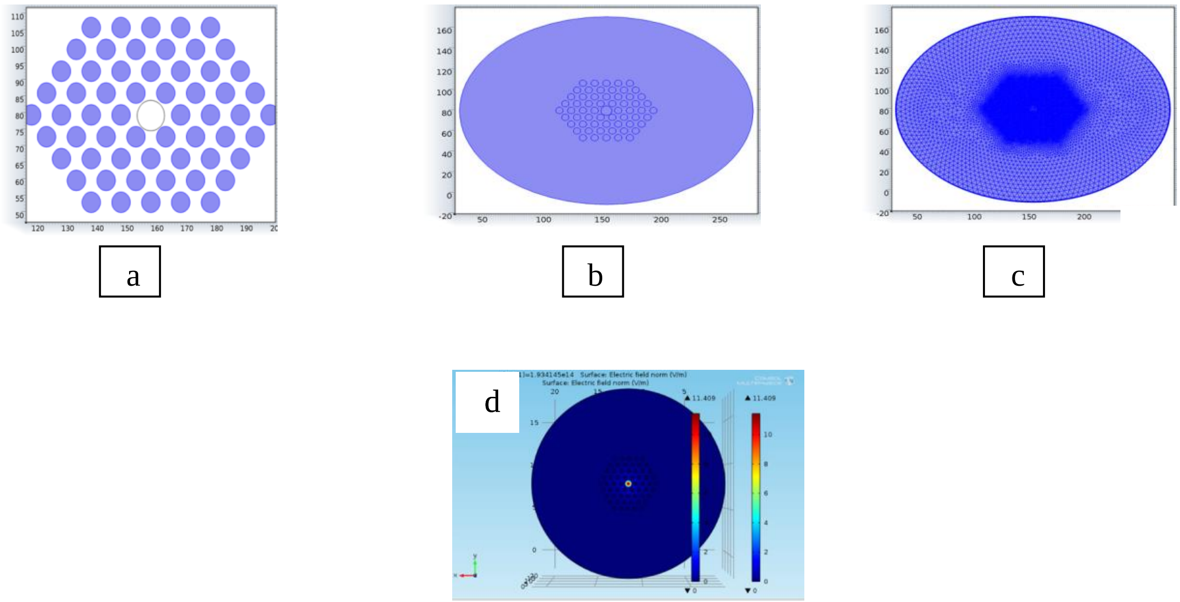

Fig. 18: (A) geometry of cladding PCF with refractive index of air = 1 (B)electromagnetic waves, frequency domain (C) Mesh of PCF(D) Electric field pattern of designed PCF Laser Beam Profile that exist from LMA-10 without filling (empty) by COMSOL simulation program at room temperature (25 C^o).

3. Infiltrating the solid core PCF (LMA-10) by propanol

The solid core PCF (LMA-10) was infiltrated by propanol. This liquid has a maximum transmission at 1550 nm with refractive index 1.348 at room temperature (25 C^o). Fig. 21 as show laser Beam Profile that exist from PCF (LMA-10) after filling the cladding with gas by the COMSOL simulation program.

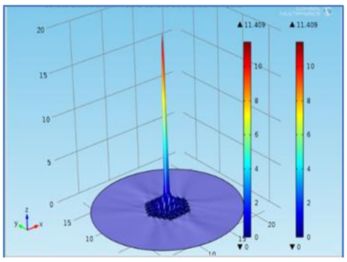

Fig. 19: Electric field pattern of designed PCF laser beam profile that exist from LMA-10 when impty by COMSOL simulation program at room temperature (25).

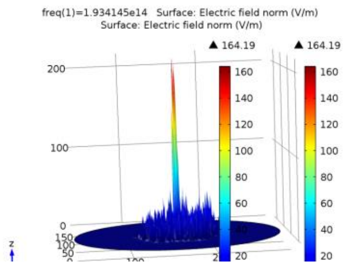

Fig. 20: Electric field pattern of designed PCF laser beam profile that exist from LMA-10 with filling by N-Hexane by COMSOL simulation program at room temperature (25 Co).

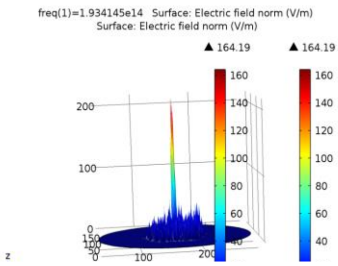

Fig.21: Electric field pattern of designed PCF laser beam profile that exist from LMA-10 with filling by propanol by COMSOL simulation program at room temperature (25 Co).

Fig. 19 shows the light guidance for the solid core (LMA-10) at wavelength 1550 nm when the PCF is empty. The peak of the laser is very clear and very smooth. Fig. 20 and 21 demonstrates the results of the infiltration of the air holes for the PCF by liquids instead of air. When this liquid to infiltrate the solid core PCF (LMA-10) which leads to change in the effective refractive index of the PCF, which in turn affect the transmission of the laser inside the PCF due the value of the refractive indices of the VOCs. The figures show that the power of the transmission spectrum of laser decreased after infiltration with change in the center wavelength of the laser diode the reason is that after PCF infiltration, the effective refractive index has been changed, but still within the total internal reflection which lead to the loss of some fundamental modes, in turn lead to decrease power of the transmission spectrum, the reason is the peak of the laser is not smooth.

Conclusion

A compact, robust and simple photonic crystal fiber interferometer that operates in reflection mode was proposed for the high number of moles of volatile organic compounds (VOCs), refractive index sensors based on solid core-photonic crystal fiber is demonstrated. The fabrication of the sensor is simple because it involves only cleaving and splicing by different length of LMA-10 photonic crystal fiber (PCFs) with standard single-mode fibers (SMF-28). A microscopic collapsed region in the PCF is the key element for exciting and recombining two core modes. The following conclusions are obtained:

1. The interferometers exhibit regular interference patterns which shift remarkable when the voids of the fiber are infiltrated with molecules of volatile compounds.
2. Optimization of the PCF structure (holes diameter and separation between holes) may enhance the resolution even further.
3. The response time is longer due to the small voids of our PCF.
4. The value of the shift of the center wavelength for the PCF was Increased with increase the value of the refractive index of the liquid.
5. The value of the shift of the center wavelength for the PCF was increased with decrease the length of PCF.
6. Maximum sensitivity of the VOC is 15420nm/mol with N-Heaxe via a length of PCF 20mm.
7. Easiness of the system with a rapid sensing readout.
8. The total volume of the PCF voids responsible for changes in the detected signal is less than (140) microliter, such a volume is very small compared with the fiber-based gas sensors.

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