Photonic crystal fibers and its applications in gas sensing—a review

Suman Mukherjee*, and Ashish P S Chouhan

Department of Physics, Lovely Professional University, Phagwara, Punjab, India

*E-mail: suman.21828@lpu.co.in

Abstract: For last couple of decades scientists and engineers made a significant progress in fabricating and developing photonic crystal fibers that show some of the very unique properties and because of this, photonic crystal fibers (PCFs) have the potential to revolutionize the fiber optic industry in way never happens before. These types of fibers are fabricated and designed on the scale of optical wavelength, a fraction of a micrometer or less. One of the many applications of photonic crystal fibers is the sensing of gas and consequently it could be used as a gas sensor. Many scientists have already reported the use of PCFs as a gas sensor. In this review article, the work done by other scientists using photonic crystal fibers as a gas sensor have been reported. We have also talked about the future applications of PCFs as a gas sensor in different industry.

Keywords: Photonic Crystal Fibers, Hollow-core photonic band gap crystal, gas sensor, Optical sensing and sensors.

Introduction:

When it comes to present day telecommunication there is one name that dominates the industry and it is fiber optics cable. From short distances to thousands of miles a fiber optic cable can do the job in a fraction of second by transmitting data from one place to another place and with minimum loss of signal compared to the conventional copper wire. While conventional fiber optic cable is in the market for quite a some time dominating the telecommunication industry, there is another type of product scientists and engineers developed silently a few decades back which not only do a better job than fiber optic cable but also versatile when it comes to transmitting electromagnetic waves through it and this wonder product is known as photonic crystal. Photonic crystals have special properties which are absent in conventional fiber optic cable. While a conventional fiber optic cable has a solid core and cladding and it uses TIR for transmitting light signal through it, on the other hand a photonic crystal fiber could have both a solid core or a hollow core and it can transmits as well all blocks several wavelengths depending upon its structural parameters and core cladding materials, which we can choose while fabricating.

The dimensions of the holes and solid materials inside a photonic crystal fiber is fabricated at a scale compared to the wavelength of the light to be transmitted inside these wonder materials and this technique acts as a game changer. Because of these special structure of the material, one can guide light through it in way that have never been possible before. Because of these periodic microstructures inside a photonic crystal fiber (PCF), its optical properties changes radically, which is absent in normal optical fiber. The performance of a PCF improves significantly with this structural properties compared to conventional fiber. One can make PCFs with different types of structures, viz. a bigger hole in the middle and smaller holes surrounding it both fabricated down the axis, a solid core in the middle and smaller holes surrounding it etc. Whenever a light or an electromagnetic wave travels between two media (reflection or transmission), the parallel component of its propagation \( n \kappa \sin \theta = L, \text{say} \) wave vector always remains unchanged. Where \( n, \kappa \) and \( \theta \) are the refractive index of the
medium, propagation wave vector and angle of incidence/reflection/refraction respectively. So if one needs to confine light in the core, the core cladding combination should be made in such a way that the light of given L does not exist or cannot propagate in the cladding, so it will get confined in the core only. No matter how far the light travels down the fiber it’s L value always remains same throughout the fiber and not only that light travelling in different regions of the PCFs (core, cladding, air holes etc) have selective L values allowed on that particular region, so that light cannot escape from that regions and stays confined in that region only. A PCF is fabricated in such a way that there are regions inside the fiber where there is no selective L value so that no light can travel there and consequently one can design a PCF where light travels in some selected regions of the fiber, where some L values are allowed. These regions of no L value is known a photonic band gaps and no light can be trapped inside them or travel through them. So, a PCF can be used to carry light signals of different frequencies in a single fiber and in different regions of the fiber, not only just inside the core which is a biggest advantage compared to the conventional optical fiber. A PCF also has very low loss compared to the conventional fiber optic cable.

There are two kinds of PCFs. One type is known as high index guiding fiber and the other one is called low index guiding fiber. High index guiding fibers transmits light by modified total internal reflection (M-TIR), inside a solid silica core (Figure 1(a)) and the light gets reflected from the interface between this solid core and a micro structured air-filled region, which has a lower RI. On the other hand, low index guiding fiber guides light through a hole (Figure 1(b)) filled with material of lower RI (Air or any other gas) by photonic band gap (PBG) effect and this makes light to travel to the micro-structured cladding region impossible. The strong wavelength dependency of the effective refractive index and the inherently large design flexibility of the PCFs allow for a whole new range of novel properties. Such properties include endlessly single-mode fiber, extremely nonlinear fiber and fiber with anomalous dispersion in the visible wavelength region.

Figure 1(a): Solid Core Fiber and Figure 1(b): Hollow Core Fiber [1]

Among these one of the photonic crystals is of interest to us which is known as hollow core photonic bang gap fiber (HC-PBGF). Here, the light propagates through a low RI (gas filled region) surrounded by micro-structured holes and thus creating band gaps and because of that only light with certain frequency bands can travel inside this hollow core region and the rest are eliminated and
cannot propagates through this low RI core region. Guiding light in a hollow core holds many promising applications like high power delivery without the risk of fiber damage, gas sensors or extreme low loss guidance in vacuum. Furthermore, this class of fiber has other spectacular properties not found in any other fiber type. They are almost insensitive to bending (even at very small bending radii) and they have dramatically reduced sensitivity to Kerr effect (>50), temperature transients (∼6.5), and Faraday effect (>10). Also, extreme dispersion properties, such as anomalous dispersion values in the thousands of ps/nm/km regimes is easily obtained. Due to a negligible contribution from the core material (air), the total dispersion of PBG fibres is to a high degree dominated by waveguide dispersion.

1. Hollow-core photonic bang gap fiber (HC-PBGF) as a gas sensor:
   One of the most interesting photonic crystal fibers is hollow core photonic band gap fiber (HC-PBGF). In this type of fiber, the light is guided through a hollow core filled with gas. Because of the creation of photonic bands or photonic band gaps, light with selected frequency can be guided through it, while ignoring the other frequencies. This kind of fiber can be used to detect different gasses, filled in the hollow core. In this review article, a brief description of the applications of HC-PBGF as gas sensor has been discussed. Many scientists have already been reported this unique application of PCFs, although a lot of works needed to be done in this area to get it in the commercial market. Using this as a gas sensor not only brings down the price of the sensor down, it can also reduce the size of the sensor a lot.

![Figure 2(a): Schematic of the compact sensor [2]](image1)

![Figure 2(b): Detailed outlined of the sensor [2]](image2)
Figure 2 shows a schematic of the arrangement of the detection of gas by a hollow core fiber. Figure 2(a) shows a small, compact schematic arrangement of a gas sensor using HC-PBGF, where a LASER source can be used as a source of light. There is one inlet and one outlet to let the desired gas get into the fiber and get out of the fiber. A compact detector is also there to detect the gas absorption or transmission of light through the gas and from the absorption lines or absorption, the nature of the gas can be predicted. A detailed schematic is shown in Figure 2(b). The gas is flown in the hollow core region through the inlet, here the light gets enough length to interact with the gas throughout the fiber length for a near perfect detection of the nature of the gas. Here MOF stands for the modes of operation, since it’s a photonic band gap fiber only the desired modes of light can travel through the fiber. The number of modes could be anything from one to more than one, depending upon the requirement. A suitable, compact LASER can be used for this operation. A DFB diode LASER can be used for this type of detection, which is very compact. Currently several DFB LASERS are available in the market and a suitable LASER, which emits a particular wavelength or a cascade DFB LASER which emits several wavelengths can be used depending upon the gas to be detected. For Methane detection 1654 nm and 3270 nm DFB cascade interbond LASER can be used. These LASERs are manufactured by Nano plus Nano systems and Technologies GmbH, Germany.

Randhir Bhatnagar et all reported a HC-PCF based gas sensor at around 1531 nm wavelength sensing acetylene (C₂H₂) gas by measuring absorption spectroscopy inside a PCF [3]. The authors measure the transmittivity of the LASER by comparing the light beam before entering the PCF and after it gets out of the PCF interacting with the desired gas. The interaction length has been kept sufficiently enough, so that maximum amount of light gets absorbed by the gas. Finally, when the light gets out of the fiber, the transmittivity of the light was measured. It has been observed by the authors that the transmittivity of the LASER get increases with the increase of the concentration of the gas.

Ritari et all demonstrated hollow core photonic band gap fiber as a gas sensor using several gasses and reported increased sensitivity over conventional sensor [4]. The authors used both tunable LASER and LED at around 1500 nm region to study the absorption spectrum of acetylene gas. They also reported absorption of methane at around 1300 nm wavelength using different fiber. In both the case hollow core based photonic band gap fibers have been used. The core diameter of the fiber filled with acetylene gas and methane gas are 10 µm and 11.6 µm respectively. The splicing of the input ends of the PBFs was done to a standard single mode fiber (SMF) terminated by a fiber connector. The fibers used to measure the absorption spectrum of acetylene gas and methane have loss less than 0.2 db/m and 0.1 db/m respectively at the desired wavelength mentioned before. The absorption spectra at the other end of the fiber were measured with a calibrated optical spectrum analyzer (OSA). In both cases the authors observed distinctive absorption lines for both the gasses at the desired wavelengths mentioned above.

A.M.Cubillas et all demonstrated detection of methane gas at 1670 nm using HC-PBBGF with a minimum detectivity of 10 ppmv, which is quite promising [5]. The long length interaction of gas with the light inside a hollow core photonic fiber is quite advantageous for methane detection because later has very weak absorption compared to many other other gasses. The authors used a 5.1 m long fiber with a core diameter of 12 µm and the fiber has a loss of 100 dB/km. The experimental set-up is similar to adopted by the other researchers, i.e. the HC-PBGF was connected to a tunable diode LASER in one side and a power meter to the other side through two SMFs and an inlet and outlet facilities of gas, to measure its absorption inside the fiber. Nicolas Gayraud et all demonstrated the detection of methane gas based on FTIR using HC-PBGF in the mid-infrared region [6]. The authors used an 80 cm long HC-PBGF filled with nitrogen and methane in a volume ration of 95:5 at a pressure of 2 bar. The methane absorption spectrum was measured at the wavelength range of 3.19 µm-3.36 µm with the highest SNR ratio. A set of different concentrations of methane gasses was used to measure the absorption spectrum. Figure 3(a) to 3(d) shows the absorption lines of methane with concentrations of 5%, 1%, 0.5 % and 0.1 % respectively (taken from [6]). The authors consulted
the experimental data with the theoretical data taken from HITRAN database. It is clearly seen that the experimental observation quite satisfactorily matches with the theoretical data, as shown in figure 3 (a-d), even at lowest concentration of methane.

**Figure 3:** Measured (solid curves) and theoretical (dash curves) absorption lines of methane for concentrations of (a): 5%; (b): 1%; (c) 0.5%; and (d) 0.1%. Theoretical values taken from HITRAN database. [6]

2. **Applications of hollow core photonic crystal fiber as a gas sensor:**
In this short review article, a few of the gas sensing applications of HC-PBGF have been discussed above. There are many other works which have not been reported here but most of them are sensing of acetylene and methane gasses. Why research in this area is so important and lucrative for the industry lies in the portability of system and low cost of manufacturing. Modern day gas sensors, available in the commercial market, can be classified in the following categories: Metal Oxide based gas Sensor, Optical gas Sensor, Electrochemical gas Sensor, Capacitance-based gas Sensor, Calorimetric gas Sensor, Acoustic based gas Sensor etc. All these available sensors are very bulky in nature and their sensitivity is also very low compared to the detection sensitivity of HC-PBGF. A smoke detector (CO/CO₂) can only trigger alarm when the gas concentration is sufficiently high. Although they are quite feasible if used inside a building or a factory but because of their bulky nature, one cannot use them in remote inaccessible region. Photonic crystal fibers are tiny in dimension and they can be carried to almost anywhere, might be difficult to reach by human, by tiny drone or some unmanned vehicle. Apart from that, sensitivity of photonic crystals when it comes to gas sensing is very high, so a small portion of the gas could very easily be detected. Another advantage of optical sensing by photonic fiber is, it is unaffected by electromagnetic interference, thermal noise or other types of interferences. It has tremendous potential in oil and natural gas industry, where detection of toxic and flammable gasses is so important.

3. Conclusion:

In this review article a brief discussion of potential applications of hollow core photonic bang gap fiber as a gas sensor is discussed. This kind of fiber plays a very important role when it comes to transmitting light through a hole surrounded by solid silica cladding and it has very low loss compared to the conventional fiber. Several works have been reported here and the results are quite impressive. Mostly detection of acetylene and methane gasses have been performed by experiments by absorption and transmission spectroscopic measurement. Inside the fiber the targeted gas gets enough length to interact with light and this gives a great sensitivity in the measurement. A small amount of gas can also be detected using this method. However, a lot of works needed to be done in this area. Until now all the works have been done inside a laboratory set-up. Naturally question comes about the viability of this kind of fiber as a gas sensor for commercial purpose. Since HC-PBGFs are very tiny, a very compact gas sensor can be made. If a suitable tunable LASER is selected for the light source, one type of fiber can be used for several gas detection. Again, different gasses have different absorption length and sensitivity, so to build one system to detect many gasses could be a potential challenge for the research community. A very low loss inside these fibers is very promising and a very small fraction of the gas can also be detected, which put it ahead of the race. If we can commercialize this technology, lots of industries will be benefitted. It got the potential to detect many hazardous gasses and a tiny device like this can be mounted in drone or UAV to guide it to some remote areas without taking risks of human lives. All depends upon how future progress happen in the detection technology using HC-PBGF.

References

1. Ramsay, R. Photonic-crystal fiber characteristics benefit numerous applications. 2008; Available from: https://spie.org/news/1371-photonic-crystal-fiber-characteristics-benefit-numerous-applications?SSO=1.

2. Richardson D J, Wheeler N V, Chen Y, Hayes J R, Sandoghchi S R, Jasion G T , Bradley T D, Fokoua E N, Liu Z, Slavik R, Horak P E, Petrovich M N, and Poletti F 2017 Hollow core fibres and their applications Optical Fiber Communications Conference and Exhibition (OFC) Los Angeles, CA IEEE.
3. Choudhary R, Singh A, and Bhatnagar A 2016 Hollow core photonic crystal fiber based methane gas sensor *13th International Conference on Fiber Optics and Photonics* Optical Society of America.

4. Ritari T, Tuominen J, Ludvigsen H, Petersen J C, Sørensen T, Hansen T P, and Simonsen H R 2004 Gas sensing using air-guiding photonic bandgap fibers *Optics Express* 12(17) P 4080-87.

5. Cubillas A M, Silva-Lopez M, Lazaro J M, Conde O M, Petrovich M N, and Lopez-Higuera J M 2007 Methane detection at 1670-nm band using a hollow-core photonic bandgap fiber and a multiline algorithm *Optics Express* 15(26) P 17570-76.

6. Gayraud N, Kornaszewski L W, Stone J M, Knight J C, Reid D T, Hand D P and MacPherson W N 2008 Mid-infrared gas sensing using a photonic bandgap fiber *Applied Optics* 47(9) P 1269-77.