Hollow Core Photonic Crystal Fibre (HC-PCF) based Gas Sensor

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ABSTRACT
We report the feasible design of the gas sensor based on Hollow-Core Photonic Crystal Fibers (HC-PCF) operating in the mid-IR. Hollow core photonic band gap fibres (HC-PBFs) are employed as gas cells due to their compactness, good integrability in optical systems and feasibility of long interaction lengths with gases. The challenge is in development and assembly of HC-PCF based gas cell where in alignment of two dissimilar fiber i.e. PCF and single mode fiber (SMF) with small gap of the order of 7-10 micron is reported(1). The selective absorption of laser light depicts the concentration of gas and preliminary results of Acetylene gas sensing are demonstrated.

Keywords
Hollow-Core Photonic Crystal Fibers; gas sensor; interaction lengths; selective absorption; Acetylene gas (key words)

1. INTRODUCTION
In recent decades, gas sensors play a significant role in numerous application areas such as environment monitoring, industrial production and safety, strategic, medical diagnosis for the toxic and harmful gases (2). It is important to monitor the carcinogenic, inflammable gases with high sensitivity and accuracy. The most common gas sensors are on semiconductor and chemical platform (3). These sensors are cheap and easy to use, but at the same time, they are very sensitive to surface poisoning, prone to calibration drifts and lack of selectivity

Optical absorption spectroscopy, on the other hand, is very well suited for gas sensing due to its high spectral resolution, high selectivity, and immunity to poisoning and electromagnetic interferences. Furthermore, fibre-based detection systems offer additional advantages over conventional systems such as small size, light weight and possibility of remote and distributed measurements (4). Up to date, different conventional fibre designs have been investigated as gas cells but, in most cases, they failed to achieve sufficient detection sensitivity (5).

Recently, Mircostructured Optical Fibres and, in particular, Hollow-core Photonic Bandgap Fibres (HC-PBFs) have proved their potential for gas sensing applications When the hollow core of these fibres is filled with gas, long interaction lengths between light and the gas can be readily achieved, thus enabling high detection sensitivity and an increased flexibility (tuneable to other gas species, tuneable in length, etc) (6). The ability to create extremely long interaction lengths with low attenuation for the guided light has also been extensively exploited for distributed parameter sensing (e.g. temperature, stress) (11) with very high spatial resolution. Furthermore, HC-PBFs can be coiled, achieving very compact devices (7), and can be integrated with conventional fibres. However, for the purpose of actual applications, there were still two challenges for HC-PCF sensors. The first one was to couple the light between the SMF and HC-PCF with high efficiency. The second one was to fill the measured gas into the HC-PCF within a short time.

In this work, we report the use of Hollow Core Photonic Bandgap fibers (HC-PBGFs) designed for operation at 1531nm for spectroscopic absorption measurements of acetylene (C_2H_2) gas and demonstrate the potential of this approach in terms of increased sensitivity and suitability for detection of gas species in this wavelength range.

2. THEORITICAL ANALYSIS
2.1 Sensing Principle
In Fig.1, when incident light with the intensity of I_o passed through the core layer of HC-PCF filled with measured gas, the power of the light would suffer from attenuation if the incident light was absorbed by the gas molecules. The relationship between the output light intensity and the gas concentration could be described by described by the Lambert–Beer law in as in Equation 1 (8).

$$I(\lambda) = I_0(\lambda)\exp(-\alpha(v)CL) \simeq I_0(\lambda)(1 - \alpha(v \quad (1)$$

Here, α is the absorption coefficient of the gas (cm^{-1}). C, concentration of the measured gas (volume fraction). L represent the interaction length for gas and the light, which is equal to the length of HC-PCF (12). When gas concentration is low, the exponential function in equation 1, could be simplified as linear function according to Taylor expansion, therefore one can obtain (9)

$$C = \frac{I_0(\lambda) -}{I_0(\lambda)\,\alpha} \quad 2)$$

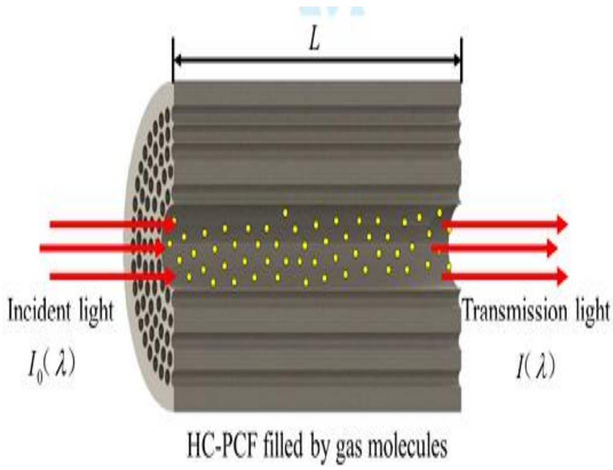

Fig.1. Schematic diagram of absorption principle of HC PCF gas sensor

From Equation 2, if the absorption coefficient and the absorption length both are known, one can measure the gas concentration by comparing the power of the transmission light before and after the gas filling process (10).

3. EXPERIMENTAL SET UP

The gas sensing system based on HC-PCF is shown inFig.2. The gas mixing system, which provide acetylene gas with constant concentration in the experiments. The gas cell depicts the optical path of the sensing system. In our experiments, the HC-PCF(HC-1550-02, M/s.NKT Photonics) with the core diameter of (10±1) µm (13). Two gas chambers are designed and introduced in the system. One is vacuumed through the pump, and the other is filled with the Acetylene gas mixture. The pressure difference between the two chambers has effectively reduced the filling time. During the gas filling process, the variation of transmission power monitored by a state-of-the-art commercial mid-IR optical spectrum analyzer (OSA)Yakogawamodel no. AQ6370C

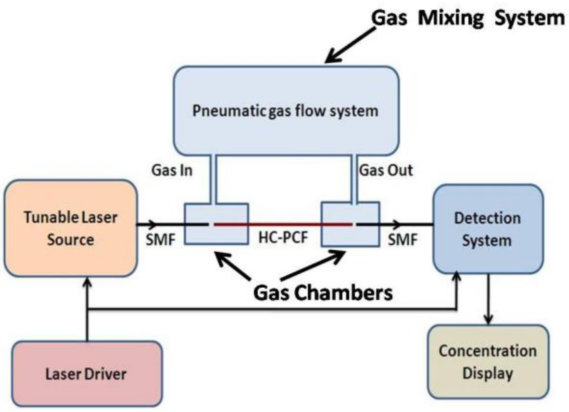

Fig.2 Schematic diagram of HC-PCF gas sensor

4. RESULTS AND DISCUSSION

4.1 Gas Sensing Experiment

The leakage in the gas mixing chamber and the gas cell has been thoroughly checked using soap bubble method.After this, the nitrogen gas is filled in the gas cell to eliminate the anyremaining impurity gases. The nitrogen was employed to clean the gas sensing system, because the near-infrared light was not absorbed by the nitrogen molecules.The measurement of gas concentration was carried out as shown in figure 3.

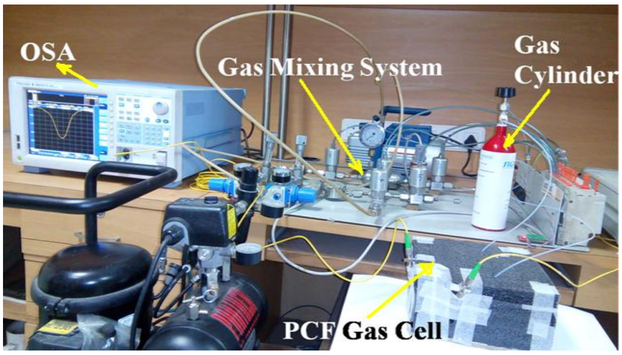

Fig.3. Gas sensing Lab Experimental set up

The Acetylene gas with variable concentration was filled in the gas chambers, and the absorption spectra at the steady states was obtained and recorded by OSA. amplified spontaneous emission (ASE) light source was employed in themeasurements the transmission spectra for different gas concentrations were shown in Fig.4.

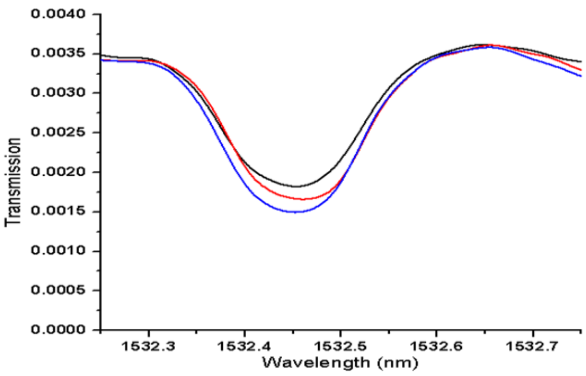

Fig.4 Transmission Profile of Different Concentration of Acetylene gas through HC- PCF gas cell

It is observed that with the increase of gas concentration, the transmission powerof 1531.45nm was reduced. From Equation 1 for the gas with low concentration, the relationship between the output light power and the input power could be expressed as linear function. The light power at the peak wavelength 1531.45nm was extracted from the spectrum in Fig.4. From Fig. 4 it can also be seen that our results are in agreement with the theHITRAN database (14).

5. CONCLUSION

We have demonstrated specific spectral absorption measurements ofAcetylene gas using HC-PBGF's designed for operation at mid-IR wavelengths. In this experiment, the HC-PCF worked as the optical waveguide to confine the propagation of light in the air core, as well as the gas for its concentration measurement. The advantages of using PBFs as gas sensors include large long optical path interaction length between the gas and light mode field and require only a small sample volume of gas of the order of nanolitre. The proposed system has the advantages of high sensitivity and flexiblity, which is suitable for trace of gas detection using tunable laser diode. The proposed work can be extended for measurement of absorption spectra of methane and ammonia.

6. ACKNOWLEDGMENT

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