

High sensitive Methane Sensor based on a Photonic Bandgap Fiber

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ABSTRACT

Monitoring methane (CH₄) concentration is essential in many industrial and environmental applications. Hollow-core photonic bandgap fibers (HC-PBF) have emerged as a promising technology in the field of gas sensing. The long interaction pathlengths achievable with these fibers are especially advantageous for the detection of weakly absorbing regions of methane. In this paper, a novel methane sensor based on HC-PBF capable of measuring CH₄ concentrations down to 0.1% in air has been demonstrated.

Keywords: Hollow-core Photonic Bandgap Fibers, Absorption Spectroscopy, Gas sensors, Methane.

1. INTRODUCTION

Methane detection is extremely important for safety monitoring in chemical facilities, gas plants, landfill sites, mines and domestic environments [1]. The major risk in all these areas is an explosion hazard, which may occur if methane reaches its Lower Explosive Limit (LEL) of 5% concentration in air. For that reason, it is necessary to develop gas sensors to monitor that methane levels are below this value.

Methane shows molecular absorption lines at different regions of the infrared spectrum. In particular, weak absorption lines are present in the near infrared $\nu_2+2\nu_3$ band at 1.3 μm [2]. Gas sensors operating at this wavelength range benefit from the low cost light sources and detectors fully developed for telecommunication applications. However, conventional spectroscopic gas cells typically show interaction pathlengths of few centimeters, which makes difficult the detection of methane in this region [3].

Recently, hollow-core photonic bandgap fibers (HC-PBF) have emerged as a powerful technology in the field of gas optical spectroscopic sensors. HC-PBF can guide over the 99% of the light in the holey regions of the fiber. In this way, if a gas is confined in the hollow-core of the fiber, strong interaction between the gas and the light going through the fiber can be achieved. Hollow-core photonic bandgap fibers are also insensitive to macrobending, which enables the realization of compact sensors with this technology. The major advantage for gas sensing is that HC-PBF can achieve long interaction pathlengths, which can compensate for the weak absorption lines of methane in the 1.3- μm band.

Hollow-core photonic bandgap fibers filled with gases have been proved to be feasible as direct absorption gas sensors [4] and optical wavelength references [5]. Saturated absorption spectroscopy has also been demonstrated using photonic bandgap fibers [6-8]. However, to our knowledge, only high concentration detection of methane (>99%) with HC-PBF has been reported [4,5]. In this paper, a methane sensor based on HC-PBF technology and capable of measuring concentrations below the LEL is described.

2. HOLLOW-CORE PHOTONIC BANDGAP FIBER

The HC-PBF used in our experiments was supplied by the Optoelectronics Research Centre from Southampton, and it is illustrated in Figure 1 (a). The fiber core diameter is 10 μm , which corresponds to seven missing unit cells from the holey region. The unbuffered overall fiber diameter is 185 μm . The length of the fiber employed in the experiment was 5.6 m. The normalized transmission of the HC-PBF is shown in Figure 1 (b). The fiber has a bandgap guidance of around 1220-1380 nm, with an estimated loss of 0.2 dB m⁻¹ in this wavelength range. This bandgap guidance makes this HC-PBF suitable for detecting methane at 1.3- μm region.

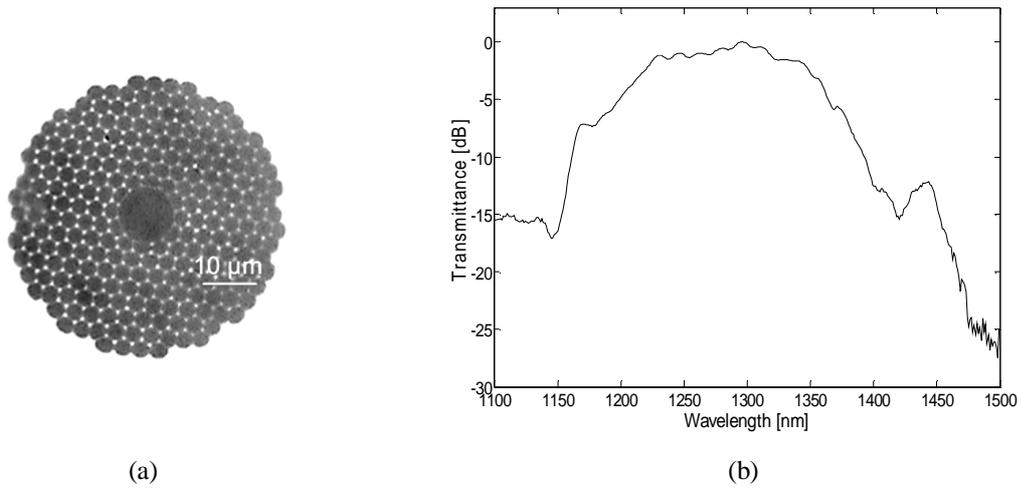


Figure 1: (a) Microscope image of the HC-PBF cross section (b) Normalized transmission of the HC-PBF employed in the experiments.

3. GAS SENSING EXPERIMENTS

3.1 Experimental setup

The experimental setup devised for methane detection measurements is shown in Figure 2. Light from a LED source (Agilent 83437A) was launched into a single-mode fiber (SMF), which was butt-coupled to the 5.6-m-long HC-PBF. To avoid Fresnel reflections, the SMF was angle cleaved, leaving a gap that allows the gas to access the hollow core, see inset of Figure 2. The other end of the HC-PBF was spliced to a SMF using an Ericsson FSU-995 electric arc fusion splicer. The splice attenuation was measured to be 1 dB. The HC-PBF, with its open end, was placed inside a vacuum chamber as illustrated in Figure 2. A pump was employed to evacuate the air from the chamber and a conventional pressure gauge was used to monitor the pressure in the chamber. This was done to ensure an efficient filling of the fiber once the gas was introduced. The transmitted power was finally recorded by an OSA (Agilent 86142A).

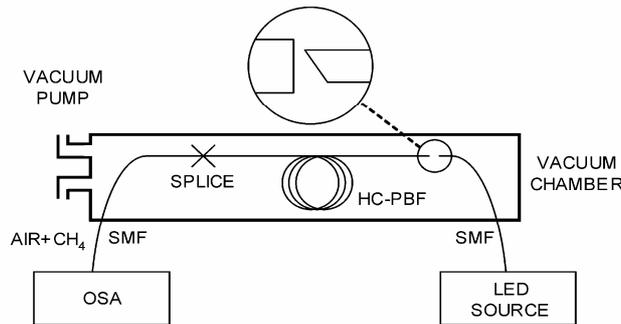


Figure 2: Experimental setup constructed for methane detection experiments.

3.2 Methane transmission spectrum

The transmission spectrum for methane at $\nu_2+2\nu_3$ band was first recorded employing the setup shown in Figure 2. After reaching a relative pressure of -500 mbar in the vacuum chamber, the system was filled with an air-methane mixture of 2.5% methane at a relative pressure of 1 bar. The obtained spectrum was normalized to the transmission spectrum when the chamber was set to vacuum. The resulting spectrum is shown in Figure 3. As can be seen, methane spectrum is very

complex and congested in this region, with many absorption lines in the band. However, the Q-branch, centered at 1331.55 nm, shows the strongest absorption in the band and a good signal-to-noise ratio (SNR). This feature is therefore chosen as it is the most suitable for monitoring methane concentration.

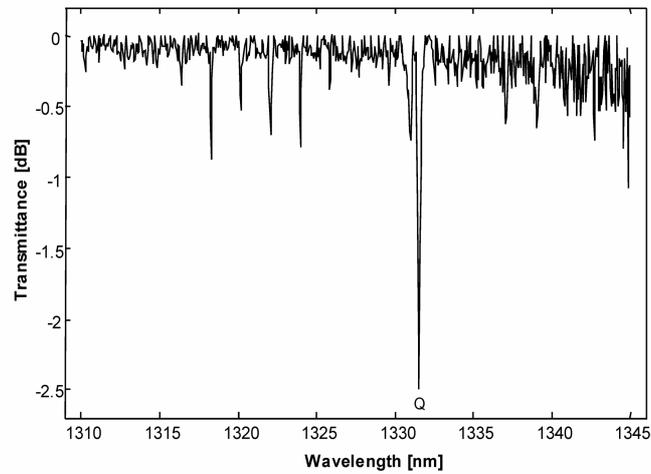


Figure 3: Transmission spectrum of methane recorded at 1 bar and 2.5% methane concentration in air. The wavelength range scanned was from 1310 to 1345 nm with a resolution of 0.05 nm. The Q-branch selected for methane absorption measurements is labeled.

3.3 Filling dynamics of the HC-PBF

In order to evaluate the performance of the methane sensor based on HC-PBF, we first investigated the filling dynamics of the fiber. The response time of the sensor strongly depends on the time needed for the gas to diffuse along the hollow core of the fiber. This time is influenced by the gas species, the length of the fiber and the pressure [2]. To evaluate the filling process, the power of the light transmitted through the HC-PBF was monitored at the Q-branch when the chamber was filled with methane at 1 bar. The filling process is depicted in Figure 4. It can be seen that the transmittance as a function of time follows an exponential decay with approximately 15 minutes required to reach a steady state.

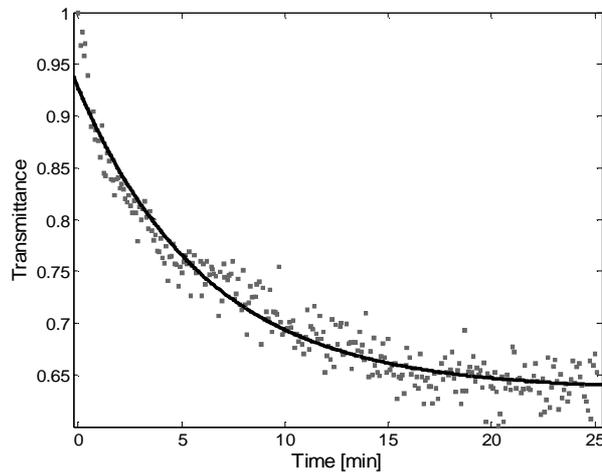


Figure 4: Measured normalized transmittance at the Q-branch as a function of time.

3.4 Absorbance measurements

The absorbance of the gas was measured for different values of methane concentration in air at the Q-branch (1331.55 nm). Calibrated concentrations of 0.1%, 0.5%, 1% and 2.5% of methane in air at a relative pressure of 1 bar were utilized and their absorbances calculated. It was found that the relationship between the absorbance of the gas and its concentration followed a linear fit (correlation coefficient >0.99), as expected from Beer-Lambert law [1]. This result demonstrates the validity of employing HC-PBF as methane sensors to measure concentrations down to 0.1% (2% of methane LEL). We also believe that an optimized setup and further data processing could yield to an increased sensitivity.

4. CONCLUSIONS

In this paper, we have demonstrated a methane sensor based on HC-PBF capable of measuring sub-% concentrations of methane in air. Methane spectroscopy in the 1.3- μm band was first investigated in order to select the appropriate feature for absorption measurements. The Q-branch (1331.55 nm) was finally chosen as it provides a good SNR with our experimental conditions. Filling dynamics of the gas diffusion through the fiber was investigated as it determines the response time of the sensor. A filling time of around 15 minutes was obtained for our experimental conditions. Absorbance measurements at the Q-branch for a range of calibrated concentrations of methane in air were taken to assess the performance of the sensor. Linear absorbance dependence with concentrations down to 0.1% methane in air was demonstrated, proving the feasibility of using HC-PBF for weak absorbing gas detection. We believe that an optimized experimental setup and an optimum selection of the fiber length could improve both the sensitivity and the response time of the sensor. Currently, further research is needed to achieve, at the same time, high-sensitive and real time methane sensors based on HC-PBF.

5. ACKNOWLEDGEMENTS

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