In situ gas sensing using a remotely detectable probe with replaceable insert

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Abstract: We demonstrate a spectroscopic gas sensor using an optical fiber probe with a replaceable insert. The probe consists of a hollow-core photonic bandgap fiber (HC-PBGF) with a core diameter of 10.9 μm and a glass tube where a 2-μm hollow core fiber (HCF) with a gold coated end facet can be inserted. The HCF is designed to function as both a gate where gases can enter the HC-PBGF and a mirror reflecting the guided light back to the HC-PBGF. The opposite distal end of the probe is also designed to be able to regulate the gas pressure within the HC-PBGF for a high gas flow rate, while still transmitting the reflected light to the analysis instrument. The remote sensing probe, we believe, has much potential for detecting gases in hazardous environments.

OCIS codes: (060.2370) Fiber optics sensors; (060.5295) Photonic crystal fibers.

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1. Introduction

The ability to detect harmful gases that are remotely located is important for various fields such as environmental monitoring, ecology, defense, and antiterrorism. Many different types of sensors have been developed for detecting hazardous gases, and remote and passive detection are prerequisites for these sensors. The spectroscopic sensing of gases is not a new technique but is the most promising method for noxious gas detection. It has been applied by optical fiber based absorption spectroscopy and has gained much interest due to the possibility of long-distance remote measurement over such guided links. The main limitation imposed by the use of optical fibers is associated with restrictions imposed by the use of long-path or multi-pass absorption cells at the sensing location. Recently, the presence of hollow core photonic bandgap fiber (HC-PBGF) has opened up the possibility of using the fiber itself as a compact gas cell [1–9] since the fiber is very bend insensitive [10] and guides light in the hollow core where target gases can be filled [11, 12]. Although the HC-PBGF can be utilized as a compact gas cell instead of a relatively bulky gas chamber, the difficulty in the use of the fiber still remains because the sensing technique is typically based on single-path transmission for spectral analysis.

In this work, we propose and demonstrate a gas sensing probe that functions as not only a gas chamber but also a waveguide with a reflector that allows remote gas detection with double-path transmission. The probe is designed to be able to simply change the insert if it gets contaminated. The insert is a few centimeter-long section of hollow core fiber (HCF) with a gold coated distal end that can reflect light back into the core of HC-PBGF where gas is filled. We also present the results of in situ gas detection using the probe associated with the pressure driven gas filling method. Acetylene (C_2H_2) was used as a gas sample for the remote detection.

2. Gas sensing probe with replaceable insert

The gas sensing probe that we propose consists of a HC-PBGF (HC-1550-02, Crystal Fiber A/S) and a glass tube where a HCF can be inserted. A schematic structure of the probe is illustrated in Fig. 1.

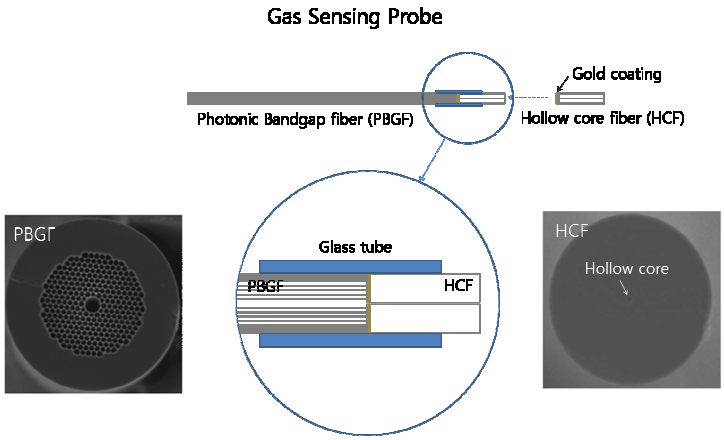

Fig. 1. Schematic structure of gas sensing probe with replaceable insert.

The HC-PBGF used in the experiment had a hollow core with a diameter of 10.9 μm in a 120-μm diameter cladding. The HCF that was fabricated via a well-known drawing technique [13, 14] in our laboratory had a core with a diameter of about 2 μm in a 120-μm diameter cladding. The distal end of HCF where it comes into physical contact with the HC-PBGF in a glass tube was gold coated to reflect light back into the core of PBGF as a mirror. Also, the glass tube was made to have an inner diameter of 130 μm, so that the two fibers could be

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inserted. The process for assembling the probe was as follows. The HC-PBGF was inserted into the middle of the glass tube. In this case, there was a gap between the HC-PGBF and the tube due to the difference in diameters between the outer cladding of the HC-PBGF and the inner hole of the glass tube. The gap was removed by applying heat to the glass tube (only to the side of HC-PBGF). The glass tube slightly shrunk and its diameter changed, creating a trumpet shape. The inside diameters of the glass tube varied adiabatically from 120 to 130 μm. We found that the HCF was tightly held by the glass tube when was near the HC-PBGF. The total length of the HC-PBGF used in the experiment was about 5 m. The few centimeter-long section of the HCF as an insert was used and the reflection rate of the gold coated facet was found to be about 30% in the NIR range. The insert was easily replaced if the end tip of the probe (HCF) got contaminated.

3. Regulation of gas pressure within the core of PBGF

We composed a gas sensor system based on a pressure-driven gas filling method for fast response time. With the present method, the filling gas enters the core of PBGF as a result of the higher pressure at the inlet of the fiber relative to the outlet pressure at the evacuation port.

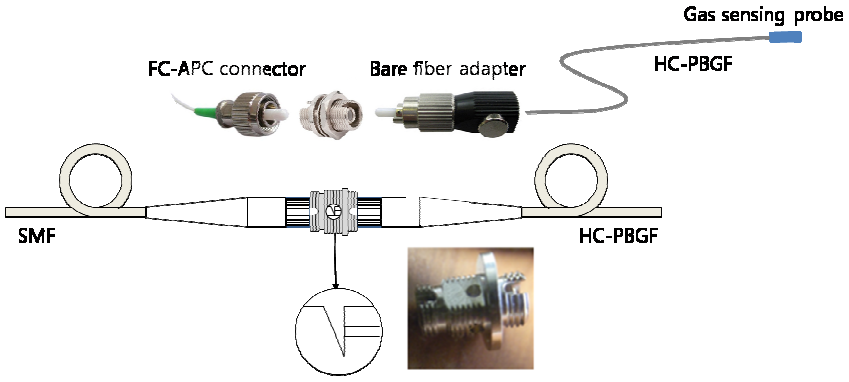

Fig. 2. A schematic diagram of processed connector for suctioning gas at the outlet.

For that purpose, an optical fiber connector was drilled for controlling the gas pressure within the core of PBGF through the hole. The HC-PBGF was butt-coupled to the SMF connecting to the circulator. To reduce the Fresnel back reflection from the end of SMF, we prepared an SMF with an 8° angle. Also, the angle-cleaved end made it possible to flow gases out of the core of PBGF as shown in the inset in Fig. 2. The average loss from the butt-coupling (Direction was considered) was found to be about 1 dB. For efficient gas-pressure regulation, the connecting part including fiber ferrules was hermetically sealed with metal housing.

With the assumption of the laminar flow during the filling process, the characteristic time T for the filling of the fiber can be expressed as [7]

$$T = \frac{32}{\Delta P}\left(\frac{L}{D}\right)^2 \mu \qquad (1)$$

where ΔP is the pressure difference between inlet and outlet, L is the length of the fiber, D is the diameter of the hollow core in the fiber, and μ is the viscosity of the gas (~10^{-5} N s m^{-2} for C_2H_2). This indicates that the filling time is inversely dependent on the pressure difference between the inlet and the outlet for the given fiber parameters.

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4. Gas sensor system using the probe

An optical fiber gas sensor system using the probe is demonstrated. The schematic diagram is shown in Fig. 3.

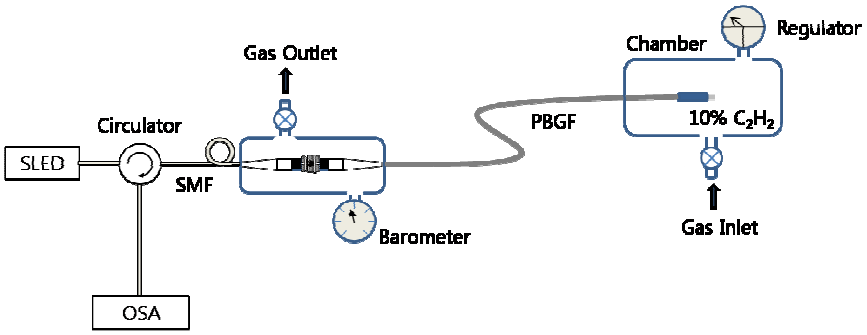

Fig. 3. Remote gas sensing system using the PBGF probe with a replaceable insert (SLED: super-luminescent light-emitting diode, SMF: single-mode fiber, OSA: optical spectrum analyzer, PBGF: photonic bandgap fiber.)

A super-luminescent light-emitting diode (SLED) centered at 1550-nm wavelength was used as a light source. Light from the source entered through the processed fiber connector where a pressure control device was installed (described in the previous section in detail) and propagated through the core of PBGF. Then, the light reflected back to the core of PBGF at the gold coated end facet of HCF, extending the optical path length through the gas sample, and returned to the fiber optic circulator. The light was interrogated using an optical spectrum analyzer (OSA, Ando AQ 6315B). The experiment was conducted in a temperature-stabilized environment at 23°C. The gas detection using the proposed probe was carried out for 10% C_2H_2 gas at different outlet pressures. C_2H_2 gas is renowned for having strong absorption in the NIR region ranging from 1510 to 1540 nm. In the experiment, the PBGF that has transmission windows covering the range was utilized.

Before target gas injection, the probe needed to be purged with nitrogen gas to remove the residual gases in the PBGF and obtain the reference spectrum for comparison purposes. Absorption spectroscopic data were then collected for different outlet pressures. The target gas mixture consisted of 10% C_2H_2 with balance of nitrogen. The net pressure within the chamber with the gas mixture was set to be the same as that of the atmosphere (= 1 bar). Then, the outlet pressure was controlled to flow the gas mixture out of the chamber through the PBGF by a piston-like method. Thus, the filling time was significantly reduced by the pressure difference compared to the traditional diffusion method. The absorption spectrum was monitored as the core of PBGF was filled with the gas mixture. Figure 4 shows the absorption transmission spectra with respect to the different filling times for the pressure difference of 0.7 bar between the inlet and the outlet. The absorption spectral lines indicate the existence of C_2H_2 gas in the chamber. As predicted, the spectral lines got clear and deep as the gas was filled. In this case, complete filling is assumed when 95% absorption of reference light at the wavelength corresponding to R9 absorption line for C_2H_2 gas [15]. It is worth noting that the source power was optimized to be able to achieve more than 95% absorption at the R9 absorption line for 10% C_2H_2 gas and the given fiber probe parameters such as length and core diameter.

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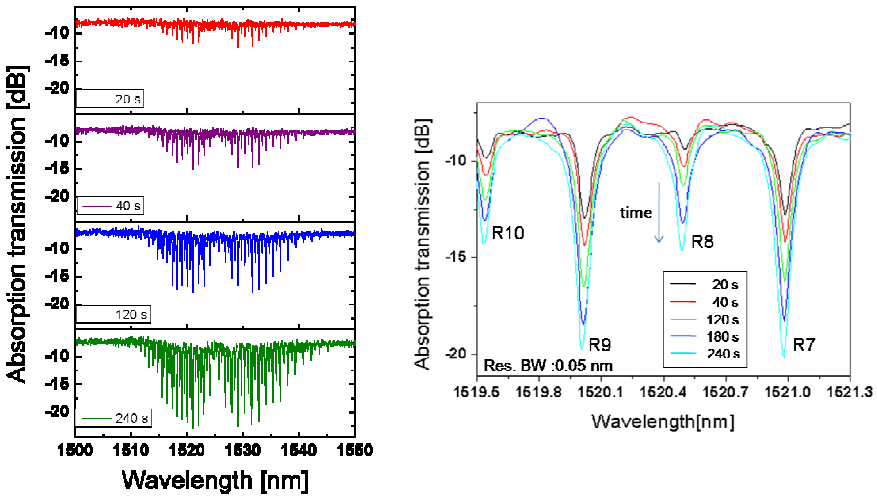

Fig. 4. Absorption transmission spectra with respect to filling time (R7, R8, R9, R10 indicate absorption spectral lines from the R branch.)

Figure 5 shows the normalized absorption transmission for 10% C_2H_2 R9 peak as a function of time for two pressure differences of 0.7 and 0.4 bar, respectively.

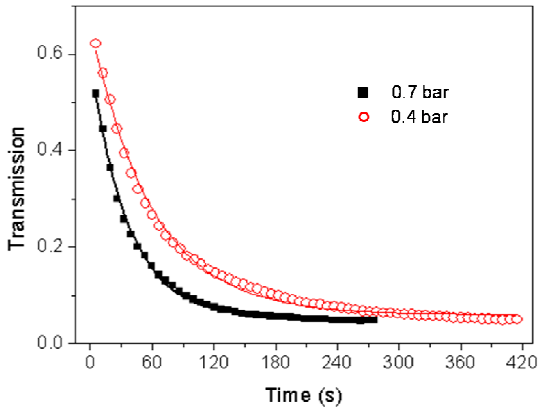

Fig. 5. Comparison of normalized absorption transmission for 10% C_2H_2 R9 peak as a function of time for two pressure differences of 0.7 and 0.4 bar, respectively.

As expected, it was found that higher pressure difference shows faster response time. The results reveal that the complete filling times are about 240 and 360 s for the pressure differences of 0.7 and 0.4 bar, respectively, which is one order of magnitude faster than that for the diffusion method. It is worth noting that the pressure difference could be maintained during the gas-filling process since the total volume of PBGF core is negligibly small compared to that of the chambers at the inlet and outlet ports. According to Eq. (1) that is based on single viscosity and laminar flow model, the filling time T can be calculated and it is about 800 s for the pressure difference of 0.7 bar. There are discrepancies between the measured filling times and the predicted values from Eq. (1), which is thought to be from complexity in our gas flow system relative to the theoretical model used for the derivation of Eq. (1).

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5. Conclusion

We demonstrated an optical fiber gas sensor using a remote sensing probe with a replaceable insert. The probe is composed of a HC-PBGF and a glass tube that can hold a HCF with a gold coated end facet as an insert. The probe can flow gases through the HCF into the core of PBGF while reflecting light from the surface of HCF. The opposite end of the sensing probe is designed to be able to control the gas pressure within the PBGF while transmitting the reflected light to an analysis instrument. The proposed gas sensor has the potential to be used for the remote detection of gases in hazardous environments.

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