

Gas detection with micro and nano-engineered optical fibers

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Abstract: The prospects for realization of all-fiber gas sensors with hollow-core photonic bandgap fibers and tapered micro/nano optical fibers are investigated. Issues such as high background level and slow response time are discussed.

OCIS codes: (060.2370) Fiber optics sensors; (060.4005) Microstructured fibers.

1. Introduction

Optical-fiber sensors have a number of advantages over conventional sensors, such as immunity to electromagnetic interference, remote access to hazardous areas, and possibility for distributed or quasi-distributed systems. Many gases such as methane, acetylene, carbon monoxide and carbon dioxide, possess overtone and combination absorption lines in the low-loss transmission window of silica fibers and can then be addressed by these fibers. Earlier work makes use of fiber-pigtailed micro-optic gas cells to achieve multi-point or quasi-distributed measurement [1]. Recently, there are efforts in developing distributed and quasi-distributed all-fiber gas detection systems with microstructured optical fibers or photonic crystal fibers [2, 3]. In this paper, we investigate the prospects for all-fiber gas sensors with hollow-core photonic bandgap fibers (HC-PBFs) and tapered micro/nano fibers, and address issues such as high background level from interference effect, slow response due to gas loading dynamics and potential for distributed/quasi-distributed measurement along a single optical fiber.

2. Hollow-core fiber sensor

HC-PBFs allow the confinement of an optical mode and gas phase materials simultaneously within the hollow-core. This provides an excellent platform for strong light/gas interaction inside the fiber core over a long distance. Long HC-PBFs can be coiled to very small diameters (e.g., 1cm) without introducing significant loss, allowing highly sensitive and compact “point” sensors to be developed. A typical HC-PBF designed to operate at 1550 nm have a transmission window of >200 nm, covering the absorption bands of some important gases such as CO, CO₂, CH₄ and C₂H₂, and can in principle be used to detect these gases simultaneously along the same fiber. In combination with optical time domain reflectometry technique, HC-PBFs would also allow distributed sensing of gas concentrations along a single optical fiber.

However, several obstacles need to be addressed in order to develop practical and highly sensitive sensors. One issue is the relatively high background level of the current HC-PBF sensors, as compared with open-path sensors. The background level changes with time and is believed largely caused by the coherence mixing of the propagating modes, since the commercial 7-cell HC-1550-02 fiber from NKT photonics is actually not a true single mode fiber. It guides both fundamental and second order modes, as well as other high order modes. This issue may be partially addressed by using a smaller core 3-cell fiber [4], which is believed to guide only the fundamental mode. The polarization effect may also need to be considered since the HC-PBFs are not perfect and the residual birefringence would result in light intensity fluctuation from the coherence mixing of polarization modes at, for example, a HC-PBF/single mode fiber (SMF) joint. Developing highly birefringent HC-PBFs may help to reduce the polarization related signal fluctuations. Alternatively, advanced signal processing may be used to minimize the background fluctuation, since the absorption features are different from the interference effects and might then be separated from the background through appropriate signal processing.

The other issue is the slow response due to time taken for gas to fill the hollow-core. This may be overcome by introducing openings from the side of the sensing fiber. However, introducing side-openings may cause additional transmission loss and compromise the mechanical strength of the fibers, which need to be examined carefully. Figs. 1a and 1b show a typical micro-channel made on a HC-PBF, fabricated with a femtosecond infrared laser. The loss of such channels can be made very small, and the average loss for a 30 cm long HC-PBF with 20 micro-channels evenly distributed along the HC-PBF was measured to be ~1 dB, corresponding to ~0.05 dB per channel.

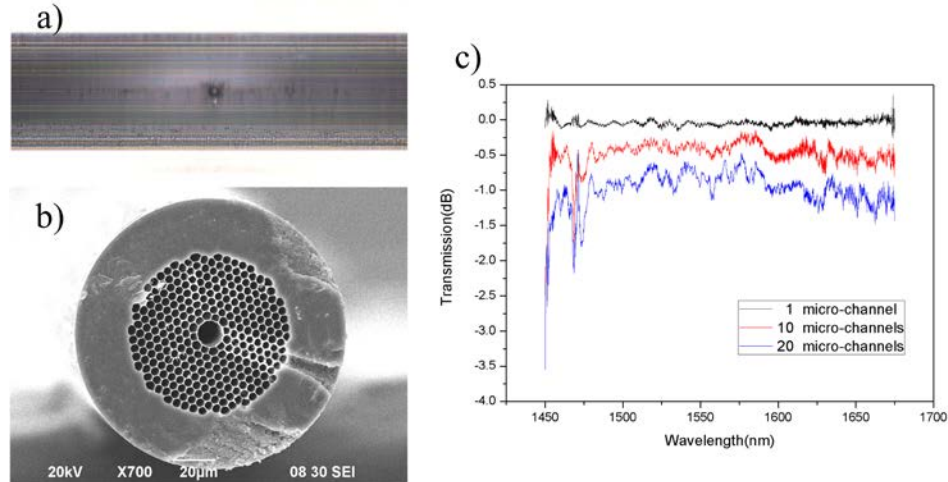


Fig. 1. (a) Side-view and (b) cross-section of a micro-channel fabricated on the HC-1550-02 fiber. (c) Loss spectrum of a 30 cm long HC-1550-02 fiber with 10 and 20 micro-channels evenly distributed along the fiber.

We carried out gas detection experiments with different lengths of HC-PBFs with micro-channels drilled from the side of the fiber. Fig. 2 shows the results of an acetylene detection experiment, conducted at atmospheric pressure and room temperature. The sensing fiber is a 3-meter long HC-1550-02 fiber with 12 micro-channels, separated by ~25 cm between the adjacent channels. At $t = 0$, 1% acetylene gas (balanced with N_2) was loaded into the gas chamber and at ~6300 s, the chamber was opened and acetylene diffuses out. The response time is ~1000 s (17 minutes). If no micro channels were introduced, the response time of a 3 meter long HC-PBF would be ~20 hours [2].

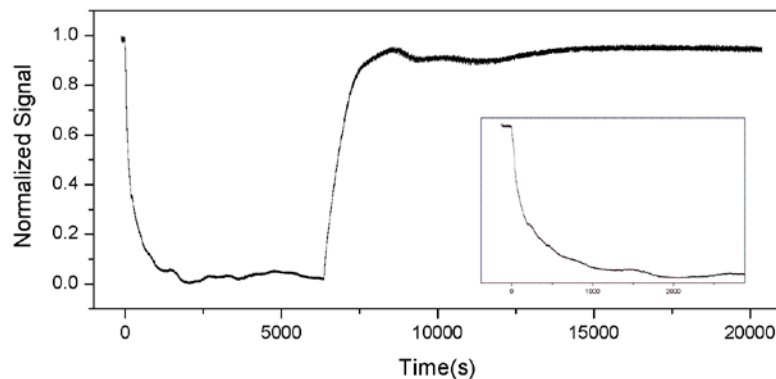


Fig. 2. Output signal measured from a 3-m long HC-1550-02 fiber with 12 micro-channels evenly distributed along the fiber. The gas acetylene concentration used is ~1%.

3. Micro/nano fiber sensor

When an optical fiber is tapered down to the scale of optical wavelength or smaller, a significant part of the optical mode power extends to the outside of the fiber as evanescent field. This part of optical field may be exploited for sensing applications. Fig. 3a shows the concept of using a tapered micro/nano fiber for photoacoustic spectroscopy (PAS). Once the tapered region is surrounded by a gas species with its absorption line near the wavelength of the laser source, the light power in the evanescent region will be absorbed and photoacoustic pressure wave generated. The localized pressure wave is then detected by an acoustic pressure transducer such as a microphone, or quartz tuning fork (QTF). The use of evanescent field associated with a tapered micro/nano fiber, instead of an open-path photoacoustic cell, would avoid collimating and alignment optics, allow compact sensors, and have potential for distributed sensing, as low-loss tapers could be made periodically along a single optical fiber.

Recently, we demonstrated an evanescent field quartz-enhanced (QE) PAS with a system showing in Fig. 3b. The optical micro/nano fibers used are taper-drawn from standard SMFs, and the acoustic pressure wave is detected by a QTF. The operation wavelength of the laser source is tuned to the target gas absorption line and modulated at half of the resonant frequency of the QTF, the second harmonic signal is detected and shown in Fig. 3c. It can be

seen that a smaller-diameter taper generates a larger acoustic signal because of its large evanescent field strength. A maximum second harmonic PA signal of 0.0317 mV/(W ppmv) was obtained by using a fiber taper with a waist diameter of $\sim 1.1 \mu\text{m}$ (taper 1 in Fig. 3c) for C_2H_2 gas detection at its P(9) absorption line. This corresponds to a minimum detectable concentration of ~ 178 ppmv with a laser power of 9.8 mW. The magnitude of the second harmonic signal increases linearly with the percentage light power in the evanescent field, as well as with gas concentration.

It should be mentioned that, in contrast to sensors based on direct absorption spectroscopy, the PA signal is relatively independent of the length of the tapered region. A few millimeter long taper would be sufficient to generate significant acoustic signal for high sensitivity gas detection. With the evanescent field PAS technique, a number of tapered sensors could be multiplexed along a single optical fiber to achieve quasi-distributed sensing, as shown in Fig. 3d. The photoacoustic microcell (PMC) in Fig. 3d comprises a tapered fiber section for PA generation and an acoustic transducer (a QTF) for acoustic wave detection. One issue associated with the micro/nano fiber sensors is the effect of surface contamination on the waveguide properties and the fragility of the tapered regions. Proper packaging and protection are needed to develop practically useable sensors.

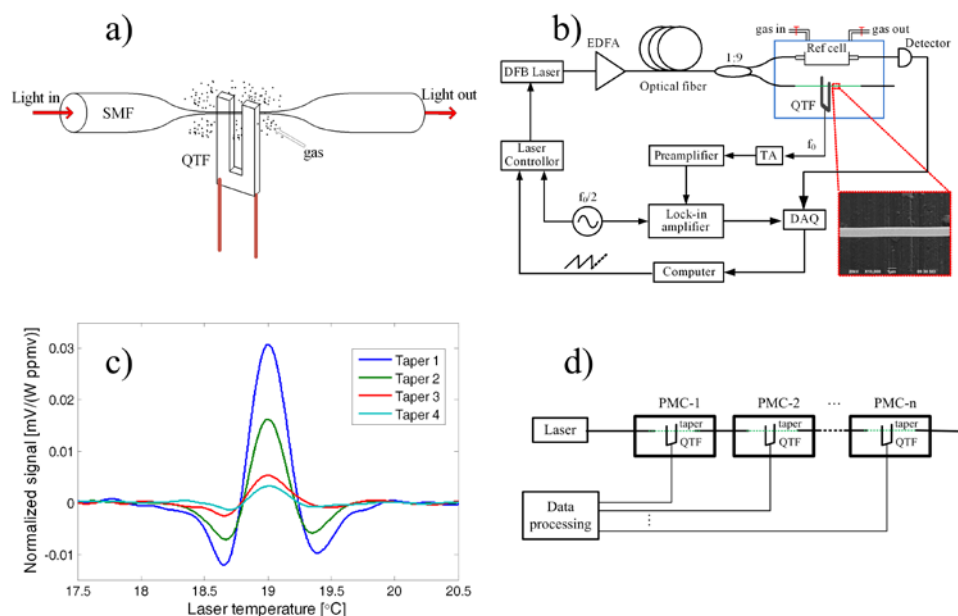


Fig. 3. Evanescent-field PAS with a tapered optical micro/nano fiber [5]. (a) Schematic of the evanescent field PAS; (b) Experimental setup; (c) Measured results for fiber tapers with 4 different waist diameters; (d) A potential quasi-distributed system by using evanescent-field QE-PAS with tapered optical fibers. QTF, quartz tuning fork; EDFA, erbium-doped fiber amplifier; TA, transimpedance amplifier; DAQ, data acquisition; PMC, photoacoustic microcell.

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6. References

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