Photonic bandgap fiber optical correlation spectroscopy gas sensor

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ABSTRACT

We present results obtained from the first all-fiber, lensless, optical correlation spectroscopy gas sensor for acetylene (C_2H_2). In the reported sensing configuration, hollow-core photonic bandgap fiber (PBGF) is employed to contain all gas samples required for optical absorption measurements. This sensor relies upon comparison of the absorption spectrum of acetylene held in a 'reference gas cell' to that of a gas sample under test, which is contained in the 'measurement gas cell'. Ingress of the test gas mixture into the measurement cell is achieved via femtosecond laser-machined micro-channels running from the surface of the PBGF to its hollow core. Stable, lensless optical interrogation of the measurement cell is guaranteed by means of arc fusion splices to standard (solid-core) single-mode fiber (SMF). The reference cell is filled with acetylene at atmospheric pressure, and is permanently sealed at both ends by splices to SMF. Therefore, being constructed entirely from optical fiber, both the reference and measurement gas cells are inherently compact and coilable, and dispense with the need for lenses or other free-space optics for connection to the correlation spectroscopy system. We quantify the acetylene concentration of various test gas mixtures and compare our sensor's measured results with computer simulations.

Keywords: Optical fiber gas sensor, photonic bandgap fiber, micro-machined fiber, gas absorption sensing.

1. INTRODUCTION

It is of great practical importance to develop gas sensing techniques that are selective, quantitative, fast-acting and not susceptible to poisoning – attributes normally associated with spectroscopic optical gas sensors[1]. The demand for high sensitivity measurements usually requires gas cells with long interaction path lengths. Hollow-core photonic bandgap fibers (PBGFs) provide the potential for combining long interaction lengths with compactness (the fiber can be coiled). Moreover, PBGFs provide a platform for highly localized interaction between the fundamental guided mode and the gas under test[2,3]. As much as 95 % of the optical power is confined to the fiber's hollow core region, which can be filled with the test gas mixture. Traditional optical interrogation systems have relied on bulk gas cells for enclosing linear optical path lengths – requiring free-space optics and careful alignment. The use of PBGF cells for the containment of both fixed and variable concentration gas samples would allow construction of compact, low-loss, all-fiber sensing systems.

Successful demonstration of gas-filled PBGFs as *reference* cells (in which the fixed volume of gas at a known concentration acts as spectral reference for wavelength calibration) has already been reported[4]. However, practical solutions for utilizing PBGFs as *measurement* cells, in which the gas sample's concentration may be varied at will, have usually relied on filling of the fiber from one or both ends[5,6]. This poses practical difficulties in that a compact solution providing stable optical coupling and simultaneous gaseous access to the PBGF core may not be possible – free-space optics would still be required. Recently, femtosecond laser irradiation at 800 nm wavelength has been used to fabricate micro-engineered ports for gaseous access from the surface of the PBGF to the hollow core, with negligible losses incurred in fiber transmission[7,8]. Such micro-channels may be located along the length of the PBGF cell, thus 'freeing up' the fiber end-faces for permanent splicing to SMF. Additionally, the use of multiple micro-channels of sufficiently large diameters[7] in a PBGF measurement cell would aid the rate of atmospheric pressure in-diffusion of the gas sample into the hollow core – thereby yielding improved sensor response times.

We report a novel optical correlation spectroscopy gas sensor, in which both the reference and measurement cells are constructed from PBGFs. Such a sensing configuration combines the advantages characteristic of correlation spectroscopy (high selectivity, broadband, potentially low-cost) with those of an all-fiber system. By employing photonic bandgap fiber as a replacement for unwieldy, linear-path gas cells relying on free-space optics, a significantly more

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compact sensor may be constructed that uses relatively inexpensive optical components and still retains good target gas selectivity.

2. METHOD

2.1 Interrogation system

Our correlation spectroscopy gas sensor operates on the complementary optical source modulation (COSM) principle[9], and its layout is shown schematically in Fig. 1. The source consists of erbium-doped SMF that is pumped by a 150 mW laser diode at 980 nm, thus producing broadband ASE light in the 1500 to 1570 nm wavelength range. An optical fiber switch (*JDSU SC-Series*, switching frequency: 0.25 Hz) is used to direct light from the source alternately along two optical paths: one containing the reference cell (switch position 1), and the other consisting of an approximately spectrally uniform optical attenuator (switch position 2). This attenuator (*OZ Optics*) can be adjusted to provide a static optical transmission loss roughly equal to that of the reference cell. The two optical paths recombine via a 50:50 SMF coupler (*Laser 2000*) to produce the so-called 'probe light'. One coupler output arm directs a proportion of this probe light to the 'feedback' detector (InGaAs, *Laser 2000*), while the second arm directs a proportion of similar probe light through the PBGF measurement gas cell, and then to an identical 'measurement' detector. When the fiber switch is set to position 1, proportionally less light enters the measurement cell at acetylene absorption wavelengths than when the switch is in position 2. Hence when acetylene is present in the measurement gas cell, the probe light is attenuated to a lesser degree in position 1 then in position 2. However, when no acetylene is present, or a gas with an altogether different absorption spectrum is present in the measurement cell, the attenuation remains the same – irrespective of the switch position. This proportionate difference in attenuation – the 'transmission arm ratio' – indicates the concentration of acetylene present in the measurement cell. In contrast to the COSM system reported previously[9], the current configuration no longer requires on-line adjustment of the source or attenuator.

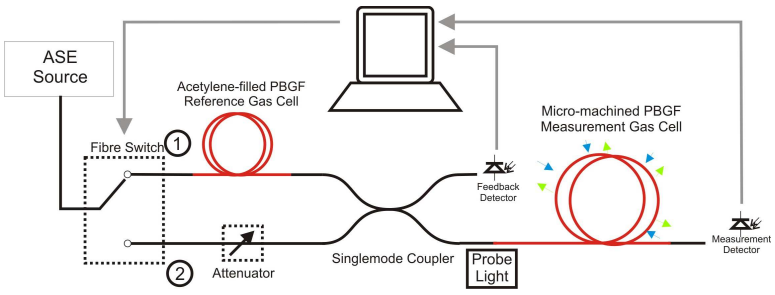

Fig. 1. Design of optical correlation spectroscopy interrogation system.

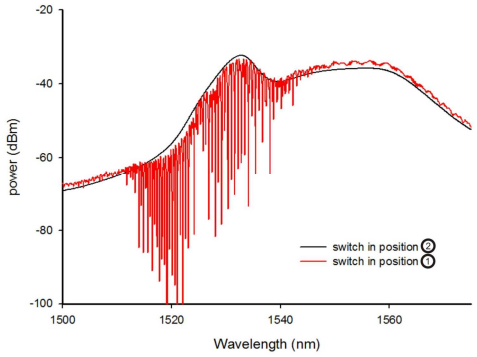

Fig. 2. Probe light spectra for different fiber switch positions: 1) ASE source spectrum; 2) ASE source followed by reference cell spectrum.

2.2 Photonic bandgap fiber and reference cell

Seven-element core defect PBGF was manufactured in our fiber fabrication facility by means of the stack-and-draw technique. The chosen fiber has an outer diameter of 205 μm, a core diameter of 14.4 μm, a cladding pitch of 4.5 μm, and an air filling factor of 94 %. As a consequence, photonic bandgap guidance is centered at 1530 nm – corresponding to the wavelength location of the near-infrared overtone absorption bands for acetylene. PBGF transmission loss was measured to be 90 dB.km^{-1} at 1530 nm by means of a white light source. A scanning electron microscope (SEM) image of the fabricated fiber's microstructured region is shown in the insert of Fig. 3.

The PBGF reference cell was constructed by first splicing one end of the hollow-core fiber to conventional SMF in an electric arc fusion splicer (following a procedure developed independently from a similar published method[6]). Next, the open end of the PBGF was placed in a sealed vessel, via a leak-tight fiber feedthrough assembly, for single-ended filling at atmospheric pressure. We allowed acetylene in-diffusion to take place for a sufficient time before removing the output end of the PBGF from the feedthrough assembly and sealing the cell by splicing to SMF (splice performed within a few minutes). The 1 m-long PBGF reference cell has a total insertion loss of 5 dB – most of which can be attributed to

the output PBGF-SMF splice. Final acetylene concentration in the sealed cell was estimated by comparing its transmission spectrum (measured with a tunable laser source near 1542 nm, at 0.3 pm resolution) with a simulated spectrum. Figure 3 displays the resulting absorption spectrum, which compares well with the spectrum modeled for 60 % acetylene in air at 25 °C, along a free-space interaction length of 1 m.

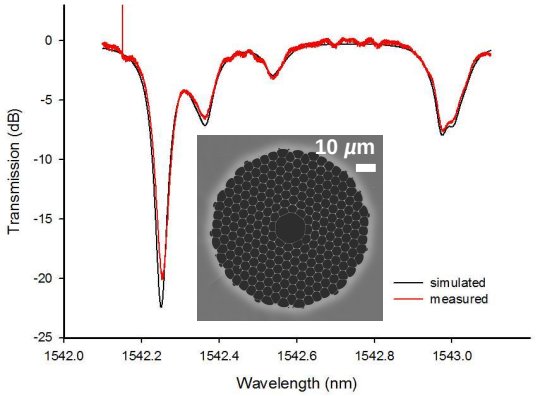

Fig. 3. Reference cell's measured and simulated transmission spectra (acetylene *P*27 and *P*28 absorption; simulation performed using data from the *HITRAN* database).

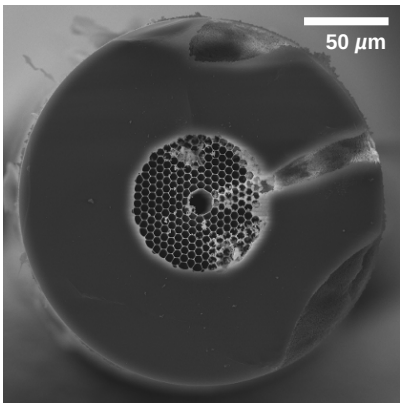

Fig. 4. SEM of typical micro-channel cross-section: the channel tapers from a diameter of 20 μm at the PBGF surface to a few microns at the core.

2.3 Measurement cell

PBGF of length 1.2 m was used to construct the measurement cell. Two micro-channels were machined by femtosecond laser irradiation (110 fs pulse duration, 800 nm wavelength, 1 kHz repetition rate) using the technique previously described[7]. It should be emphasized that micro-machining was performed after the PBGF had been spliced to SMF at both ends. This allowed on-line monitoring of the PBGF cell's transmission during channel fabrication (with an ASE source and optical spectrum analyzer) to ensure that no additional fiber transmission loss was incurred. As illustrated in the SEM of Fig. 4, the micro-channels extend from the PBGF surface to its hollow core, with limited damage to the microstructured cladding region. Micro-channels in the measurement cell were located a distance of approximately 0.4 m from either end of the PBGF. To allow diffusion of the test gas mixture into the PBGF core, via the micro-channels, the measurement cell was placed in a gas-tight vessel containing inlet and outlet valves. Two mass flow controllers (*Tylan FC3900*) were used to vary the rate of acetylene and nitrogen flowing through the vessel, and hence past the PBGF measurement cell.

3. RESULTS

Test gas mixtures containing 0, 10, 20 and 30 % (± 5 %) concentrations of acetylene in nitrogen were directed through the measurement cell vessel at a rate of 0.9 litres.min^{-1} while the transmission arm ratio was recorded. The results are shown in Fig. 5 and reveal the sensor's response to varying acetylene concentrations. A computer model simulating the sensor's operation was used to predict transmission arm ratios for these concentrations, assuming a 1 m free-space path length reference cell containing 60 % acetylene in air, and a 1.2 m measurement cell length with 94 % of the optical mode travelling in free-space. Discrepancies in the modelled and measured peak values obtained for each acetylene concentration may be ascribed to the inaccuracies in flow rate control (which resulted in significant errors in test gas concentration). However, the sensor response shows good repeatability over 48 hours. Our sensor had a t-90 time of 1.6 hours (for 0 to 100 %). The noise in received transmission arm ratio was measured to be 1.34 x 10^{-4} in 4 s, which yields a projected limit of detection (LOD) of 45 ppm in 4 s.

4. CONCLUSION

We present initial results obtained from an all-fiber correlation spectroscopy sensor for the detection of acetylene. Both the reference and measurement gas cells in this sensing configuration have been manufactured from photonic bandgap fibers. For the first time to our knowledge, a fully-spliced PBGF gas cell has been implemented in a practical sensing

application. In the measurement cell, gas in- and out-diffusion via laser-machined micro-channels has been demonstrated for variable concentrations of acetylene. The sensor response has been investigated for several concentrations of acetylene in nitrogen: it exhibits a t-90 time of 1.6 hours and LOD of 45 ppm in 4s (measurement cell length: 1.2 m). Due to the all-fiber nature of the interrogation system, the sensor provides great potential for miniaturization. In addition, it utilizes relatively low-cost optics, contains non-hazardous sample volumes (of the order of micro-liters), and may easily be developed for sensing numerous other test gases with appropriate absorption bands in the near-infrared.

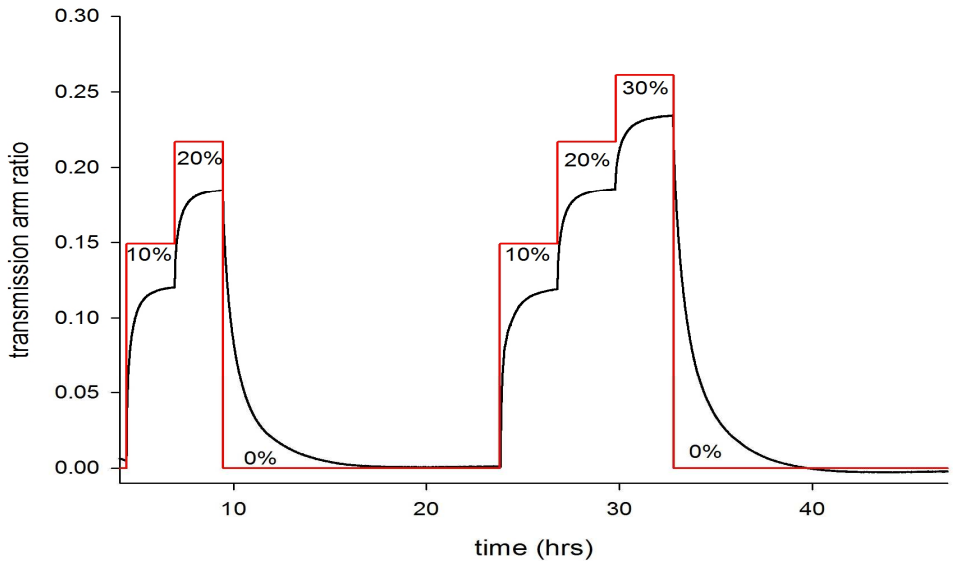

Fig. 5. Sensor response (black curve) to various concentrations of acetylene in nitrogen (simulated response appears in red).

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