The following publication Yanzhen Tan, Wei Jin, Fan Yang, Hoi Lut Ho, "High finesse hollow-core fiber resonating cavity for high sensitivity gas sensing application," Proc. SPIE 10323, 25th International Conference on Optical Fiber Sensors, 103230A (23 April 2017) is available at https://doi.org/10.1117/12.2265484.

High finesse hollow-core fiber resonating cavity for high sensitivity gas sensing application

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ABSTRACT

We present all-fiber resonating Fabry-Perot gas cells made with a piece of hollow-core photonic bandgap fiber (HC-PBF) sandwiched by two single mode fibers with mirrored ends. A HC-PBF cavity made of 6.75-cm-long HC-1550-06 fiber achieved a cavity finesse of 128, corresponding to an effective optical path length of 5.5 m. Such HC-PBF cavities can be used as absorption cells for high sensitivity gas detection with fast response. Preliminary experiment with a 9.4-cm-long resonating gas cell with a finesse of 68 demonstrated a detection limit better than 7.5 p.p.m. acetylene.

Keywords: Optical fiber sensor, hollow-core fiber, Fabry-Perot cavity, cavity enhancement, gas detection

1. INTRODUCTION

Conventional direct absorption optical fiber gas sensors use free-space or open-path (bulk or micro-optic) absorption cells [1, 2], and the absorption signal is small due to the weak gas absorption within the transmission window of the silica optical fiber and difficulty in fabricating cost-effective long-path-length absorption cells with compact size. Hollow-core photonic bandgap fibers (HC-PBFs) have most of the optical power (>95%) propagating in the central hollow-cores and are ideal platforms for strong light-gas interaction inside the fibre cores [3]. HC-PBFs can be coiled into small diameters with low-loss and used to construct long-path-length absorption cells with compact size. The use of HC-PBFs for gas detection has been experimentally investigated by a number of research groups [4-6] and achieved parts-per-million (p.p.m.) level gas detection by using 13 meters of HC-PBF [7]. However, the response of such HC-PBF sensors is slow due to time taken for gas filling into the hollow-core, and it is difficult to achieve long-absorption-path length (and hence higher sensitivity) and fast response simultaneously.

Here we present a novel HC-PBF-based high-finesse Fabry-Perot cavity or resonator absorption cell for high performance gas detection applications. The Fabry-Perot absorption cell is made by jointing a piece of HC-PBF with single mode fibers (SMFs) with mirrored ends, and light travels back and forth through the absorber within the resonator and the effective absorption path length is enhanced by a factor proportional to the cavity finesse. Such a resonating gas cell allows the use of a shorter HC-PBF (e.g., a few to tens of centimeters) to achieve high sensitivity, overcoming the problem of slow response associated with the use of long HC-PBF. The reduced cavity volume also minimizes the consumption of gas sample, which could be important for some applications.

2. PRINCIPLE OF CAVITY ENHANCEMENT

The principle of cavity enhancement with a high finesse Fabry-Perot resonator is shown in Fig.1. For a Fabry-Perot cavity made of two identical mirrors separated by a distance of L, assume that the transmission coefficient of the mirrors is t and the loss of the mirrors is l_{loss}, the round-trip cavity loss is then $L_{\mathrm{cav}}=2(t+l_{\mathrm{loss}})$, and the cavity finesse F may then be expressed as [8]

$$F = \frac{2\pi}{L_{cav}} = \frac{\pi}{t + l_{loss}} \tag{1}$$

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If the cavity is filled with a weakly absorbing gas sample with an absorption coefficient α and concentration C, under the condition of $\alpha CL << t+l_{loss}$, the relative change in the transmitted light signal through the cavity may be related to gas concentration by [8]

$$S_{absorption} = \frac{\Delta P_t}{P_t} = \frac{2\alpha CL}{t + l_{loss}} = \frac{2F}{\pi} \cdot \alpha CL \tag{2}$$

Comparing this with a single-path non-resonating gas cell of the same length L, the use of a Fabry-Perot cavity with finesse of F enhances the signal change by a factor of $2F/\pi$, giving an effective absorption path length of $(2F/\pi)L$.

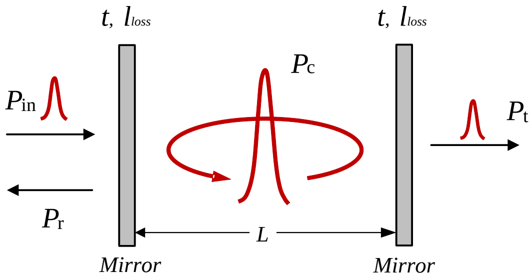

Figure 1. Principle of cavity enhancement. P_{in} , P_r and P_t are respectively the cavity input, reflected and transmitted light powers. P_c is intracavity buildup power.

3. THE HC-PBF FABRY-PEROT ABSORPTION CELL

3.1 Construction of the HC-PBF Fabry-Perot cell

A schematic of the HC-PBF Fabry-Perot gas cell is shown in Fig. 2(a). It is formed by sandwiching a length of HC-PBF in-between two mirrors made at the ends of two SMFs. Fig. 2(b) shows the scanning electronic microscope (SEM) image of HC-1550-06 fiber from NKT Photonics, which was used in our study. The dielectric mirrors have reflectivity of ~99% and are made by coating the ends of SMFs with alternating layers of dielectrics [9]. For the purpose of gas filling into the hollow-core, a small gap (~1μm) can be left at one or both of the HC-PBF/SMF joints. Alternatively, low-loss micro-channels may be made from the side of the HC-PBF to achieve faster gas filling into the hollow-core [10].

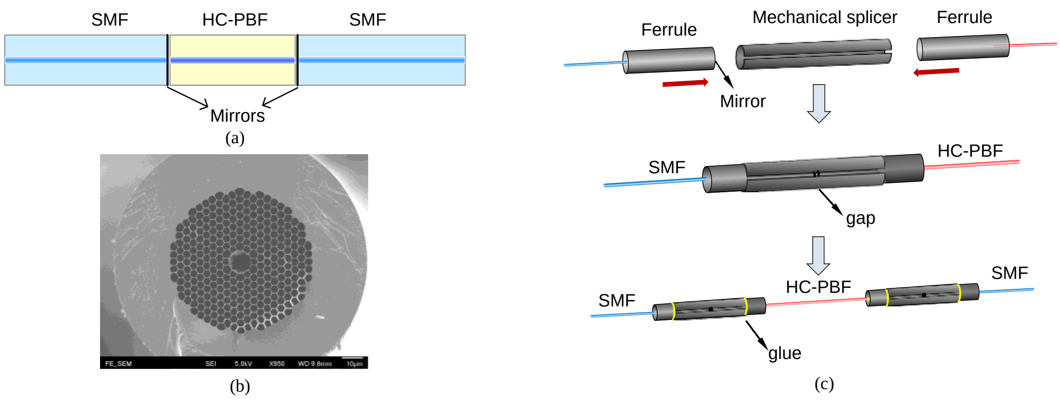

Figure 2. (a) The schematic of a HC-PBF Fabry-Perot cavity gas cell. (b) The scanning electron microscopy (SEM) image of HC-1550-06 fiber's cross-section. (c) Fabrication process of a HC-PBF Fabry-Perot cavity gas cell.

The HC-PBF Fabry-Perot cavity gas cell was made by following the procedures illustrated in Fig. 2(c): (i) a SMF fiber is inserted and fixed into a standard fiber ferrule with an inner diameter of 125 μm and an outer diameter of 2.5 mm, the assembly is then end-polished and coated with a dielectric mirror with reflectivity of ~99%, a HC-PBF is inserted and fixed into another fiber ferrule; (ii) the two fiber ferrules are joint together by a mechanical splicer with a side slot, the splicer aligns the two ferrules and holds them together tightly with a small gap (<1 μm) left between the endface of the HC-PBF and the mirrored end (the small gap facilities gas filling into the HC-PBF), the fibers, ferrules and mechanical splicer were then fixed together with glue; (iii) The other end of the HC-PBF was similarly connected to a SMF with a mirrored end. We have made several such absorption cells with HC-PBF ranging from 5-10 cm, and longer HC-PBF Fabry-Perot cells could also be made.

3.2 Characterization of HC-PBF-based Fabry-Perot cavity

Basic quantities characterizing a Fabry-Perot cavity are its free spectral range (FSR) and the full-width at half-maximum (FWHM: δν) of the cavity resonances. The finesse of a cavity can be calculated by using $F=FSR/\delta\nu$ [8]. FSR is related to the cavity length L by $FSR=c/2L$. Fig. 3 (a) shows the experimental setup for characterizing the HC-PBF Fabry-Perot cavities. The HC-PBF is mounted on the multilayer PZT actuator by nail enamel, and two SMF pigtails of the cavity are connected to external cavity diode laser (ECDL) and a photo-detector (PD), respectively. The wavelength of the laser is fixed to 1530.37 nm, while cavity length is modulated by applying a triangular voltage with magnitude of 10 V and frequency of 1 Hz to the PZT actuator. The scanning of the cavity length allows the observation of the cavity resonances, which are recorded by a digital oscilloscope. Fig. 3 (b) shows the measured transmission spectrum of a HC-PBF Fabry-Perot gas cell with a cavity length of 6.75 cm. The finesse of the cavity is calculated to be 128. This structure transforms a 6.75 cm long HC-PBF cavity into an effective optical path length of 5.5 m.

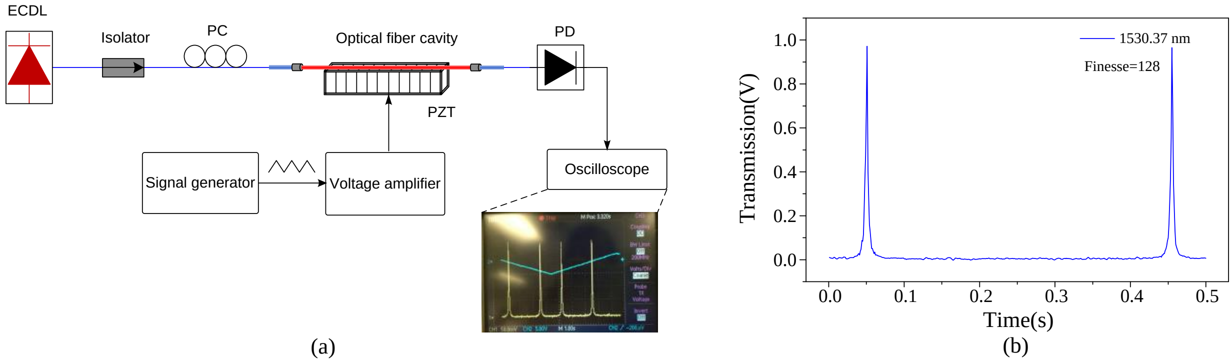

Figure 3. (a) Experimental setup. (b) transmission spectrum of a HC-PBF Fabry-Perot gas cell with 6.75 cm cavity length.

4. GAS DETECTION WITH A HC-PBF FABRY-PEROT ABSORPTION CELL

Gas (acetylene) detection experiments were conducted with the HC-PBF Fabry-Perot gas cells, by use of wavelength modulation spectroscopy and lock-in detection [2, 7]. During the experiments, a cavity resonance of the Fabry-Perot is tuned to the center of the P(13) line of acetylene at 1532.83 nm by using the PZT actuator. A distributed feedback (DFB) laser is wavelength-modulated at 22.1 kHz and at the same time it is scanned across the Fabry-Perot cavity resonance at the center of the gas absorption line. During the scanning, the second harmonics of the transmitted signal is detected by a lock-in amplifier.

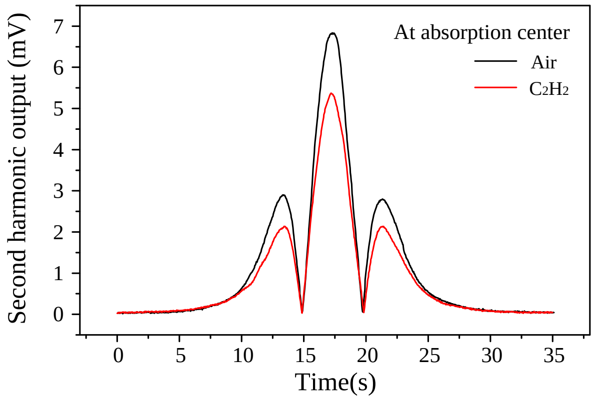

Figure 4. Second harmonic lock-in output signals when laser is tuned across a Fabry-Perot resonance at the center of the P(13) line of acetylene at 1,532.83 nm. The black and red curves are respectively for the cavity filled with air and 550 p.p.m. acetylene balanced by nitrogen (N_2).

Fig.4 shows the second harmonic lock-in outputs for a Fabry-Perot gas cell with a cavity length of 9.4 cm and finesse of 68. The red line is for the cavity filled 550 parts-per-million (p.p.m.) acetylene balanced by nitrogen (N_2), while the black line is for the cavity filled with air. The signal variation due to absorption by acetylene is 1.47 mV, corresponding to an absorbance of 1.47 mV/6.84 mV=21.5%. According to HITRAN 2004 database, the absorbance for the absorption length of 9.4 cm is 0.54% for 550 p.p.m. of acetylene [11]. This corresponds to an enhancement factor of $2F/\pi$ =21.5%/0.54%=40 or a cavity finesse of F = 62, in agreement with the measured value of 68.

We also evaluated the fluctuation of peak second harmonic signal by repeatedly scanning through the resonance over a period of 8 mins, the standard deviation of fluctuation is less than 0.02 mV, giving a lower detection limit better than 7.5 p.p.m. For comparison, we also conducted a similar experiment with a 9.5-cm-long HC-PBF (single path, without mirrors) and found the signal fluctuation is too large to conduct any meaning measurement. The large fluctuation is believed caused by modal interference noise [7], which is largely avoided in the high finesse resonating HC-PBF cavity.

5. SUMMARY

In summary, we have presented all-fiber gas cells based on HC-PBFs spliced to pigtail SMFs with mirrored ends. The high reflectivity mirrors (~99%) form high finesse Fabry-Perot cavities, which achieves long effective path length even with relatively short HC-PBG gas cells. The enhancement factor is proportional to the cavity finesse. We have made several HC-PBF Fabry-Perot gas cells with length from 5 to 10 cm and cavity finesses from 50 to well over 100, achieving effective path length of several meters. Such gas cells will enable trace-gas or liquid sensors with high sensitivity and fast response. With a cavity length of 9.4 cm and finesse of 68, we demonstrated acetylene detection with a lower detection limit better than 7.5 p.p.m..

ACKNOWLEDGMENTS

This work was supported by the Hong Kong SAR Government through a GRF grant PolyU 152229/15E, the National Natural Science Foundation of China (NSFC) through Grant Nos. 61535004 and 61290313, and the Hong Kong Polytechnic University through grants 4-BCBE, 4-BCD1 and a studentship.

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