

# Highly sensitive and stable all-fiber photothermal spectroscopic gas sensor

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**Abstract:** We demonstrated a highly sensitive and stable all-fiber photothermal spectroscopic gas sensor with hollow-core photonic bandgap fibers and achieved noise equivalent concentration of 356 p.p.b. and long term stability of 0.87 dB over 6 hours.

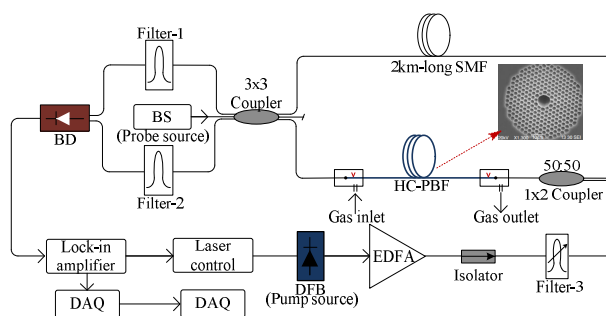
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## 1. Introduction:

Photothermal interferometry (PTI) is an ultra-sensitive spectroscopic method for trace analysis in gas- and liquid-phase materials [1]. Optical absorption of trace molecules induces localized heating, resulting in temperature, density and pressure changes, which modulate the refractive index (RI) of the material under test. Previous PTI systems used free-space optics and have limitations in efficiency of light-matter interaction, compactness, optical alignment and integration. Recently, we proposed an all-fiber photothermal spectroscopy with hollow-core photonic bandgap fibers (HC-PBFs) and demonstrated gas detection with ultra-sensitivity down to ppb level and unprecedented dynamic range of nearly six orders of magnitude [2]. The detection system used a fiber Mach-Zehnder interferometer which is intrinsically non-stable and requires active servo-control to maintain operation at the quadrature point. Here we demonstrate the use of a fiber Sagnac interferometer with a 3x3 directional coupler to achieve stable demodulation passively while maintain the high sensitivity of the PTI sensor.

## 2. Experiment

The basic experimental set-up for the photothermal (PT) based gas sensor is shown in Fig.1. We adopted a pump-probe detection configuration. A distributed feedback (DFB) laser is utilized as a pump source and its wavelength/intensity is modulated sinusoidally at 25 kHz via injection current modulation. The nominal wavelength of the DFB is simultaneously ramped across (via thermal tuning) the P(9) absorption line of C<sub>2</sub>H<sub>2</sub> at 1530.371nm with a repetition rate of 0.005 Hz. The peak acetylene gas absorption coefficient at this wavelength is 1.165 cm<sup>-1</sup> under ambient conditions.



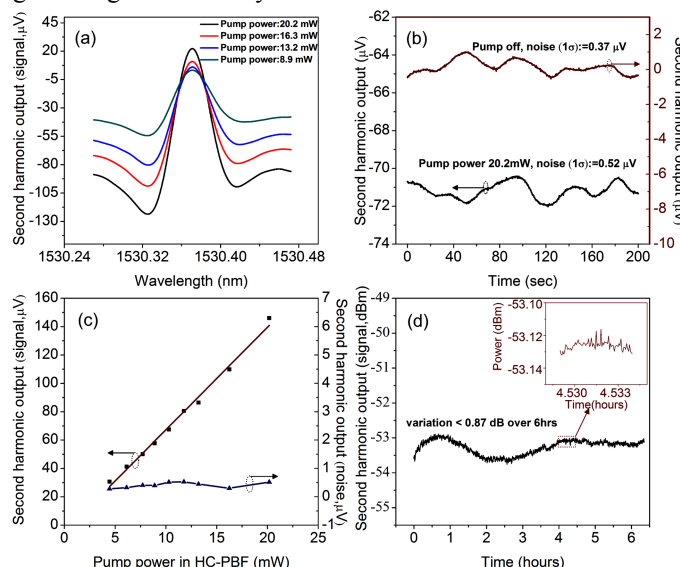
**Fig.1.** Experimental set-up for gas detection with 0.62-m-long HC-PBF. A broadband source (BS) is used as the probe source. Tunable filter-3 filters out the noise accompanying the EDFA. The two fixed wavelength filters (filter-1 and filter-2) are used to filter out the residual pump. A data acquisition card (DAQ) and a personal computer (PC) are used for data collection. The inset figure is the cross-section image of the sensing fiber (NKT Photonics' HC-1550-02 fiber) with a core diameter of ~11 μm.

The wavelength/intensity modulated pump beam is coupled into the acetylene-filled HC-PBF and interacts with the absorbing gas molecules. The periodic absorption of pump beam induces periodic change of the RI of fluid in HC-PBF. Therefore the phase of a probe light beam propagating in the same HC-PBF is modulated. The probe source is a broadband super-luminescent LED with a center wavelength of ~1545 nm and a bandwidth of ~41 nm. In the presence of an optical delay line, a periodic phase difference between the clockwise and counter-clockwise probe beams is resulted. Based on the intrinsic phase bias of 3x3 coupler and with a balanced detector (BD) to perform differential detection, the output signal from the BD (under small signal approximation) is proportional to this phase difference and hence to the gas concentration within the sensing HC-PBF [3]. The output includes both first and

higher order harmonics of the pump modulation frequency, and here we use a lock-in amplifier to detect the second harmonic signal, and the amplitude of which is linearly proportional to the gas concentration.

### 3. Results and discussion

The measured results are shown in the Fig.2. The measured spectrums of  $C_2H_2$  under different pump power levels are shown in Fig.2.(a). With the pump power of 20.2 mW, the noise equivalent detection limit is about 356 p.p.b. ( $4.2 \times 10^{-7} \text{ cm}^{-1}$  in gas absorption coefficient). Such sensitivity is significantly better than the previous wavelength modulated direct absorption fiber gas sensors [4]. There is no significant change of standard deviation (s.d.) of second harmonic output when pump is off and when the pump level is 20.2 mW but pump wavelength is tuned away from the absorption line, as shown in Fig.2.(b). However, a constant bias exists due to background absorption. The second harmonic output signal has a linear relationship with the pump power levels in HC-PBF as shown in Fig.2. (c) while the noise floor show no evident increase with increasing pump power level. Hence increasing the pump power level in the HC-PBF would enhance the signal to noise ratio and further improve the detection limit. As depicted in Fig.2.(d), the system has a good long term stability of  $\sim 0.87$  dB over 6 hours under our lab environment.



**Fig.2.** Experimental results for 0.62-m-long HC-PBF. (a) Second harmonic lock-in output as functions of pump wavelength for different pump power levels. (b) Measured second harmonic output while pump wavelength is tuned away from the absorption line, red line: pump switched off, black line: pump power of 20.2mW. (c) Second harmonic output and the s.d. of the noise as functions of pump power levels. (d) Measured second harmonic output over 6 hours with pump power level of  $\sim 20$  mW and the wavelength of pump tuned to the center of the absorption line.

### 4. Conclusion

We demonstrated an all-fiber photothermal spectroscopic sensor with a hollow-core photonic bandgap fiber. A Sagnac interferometer with a 3x3 directional coupler was used to detect the PT-induced phase change and the measured minimum detectable (acetylene) gas concentration is 356 p.p.b. ( $4.2 \times 10^{-7} \text{ cm}^{-1}$  in gas absorption coefficient) with 0.62-meter-long HC-PBF and a pump power level of 20.2 mW. This result is significantly better than the previous direct-absorption fiber gas sensors. The Sagnac demodulation system is intrinsically stable and requires no active servo-control to maintain stable operation of system over a long term. Increasing the pump power level and the length of the sensing HC-PBF would further improve the lower detection limit. Our system is simple, stable while remains highly sensitive and it would have potential applications for remote and distributed sensing in real world environment. The work was supported by the Hong Kong SAR government via GRF grant PolyU 152064/14E, the NSFC of China via grant no. 61290313.

### 5. Reference

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