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A single-mode all-fiber QEPAS sensor

GANG HUANG[a,b], YING HE[c,*], ZHUO XU[b]
[a]*Electronic Materials Research Laboratory, Key Laboratory of the Ministry of Education & International Center for Dielectric Research, Xi'an Jiaotong University, Xi'an 710049, China*
[b]*National Key Laboratory of Human Factors Engineering, China Astronaut Research and Training Center, Beijing 10094, China*
[c]*National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150001, China*

A quartz-enhanced photoacoustic spectroscopy (QEPAS) system based on common single-mode fiber, which has more stable and flexible configuration, has been developed. A 1.395 μm continuous wave (CW), distributed feedback diode laser was used as the excitation source and the H_2O was selected as the target analysis. Quartz tuning fork (QTF) with a resonance frequency of 30.72 kHz was employed as the acoustic transducer. The location of laser between the QTF prongs in the vertical direction has been investigated. After optimizing the modulation depth, a minimum detection limit of 104.6 ppm was achieved.

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1. Introduction

Trace gas sensor based on laser spectroscopy demonstrate an effective method for measuring tiny quantities of specific molecules. This technology is widely used in many fields, such as atmospheric chemistry [1, 2], medical diagnostics [3] and so on. Among these laser methods, quartz-enhanced photoacoustic spectroscopy (QEPAS) technique, which was first reported in 2002 [4], holds many advantages such as low cost, small size, high detection sensitivity [5,6]. In the QEPAS system, a small size quartz tuning fork (QTF) with low cost, immunity to ambient acoustic noise and extremely high Q factor is utilized as an acoustic transducer. Due to its advantages of high sensitivity, selectivity and compactness, QEPAS has been widely used for trace gases detection [7-13].

In QEPAS technology, typically, the laser was focused on the middle of the QTF prongs. As a consequence, the collimating and focusing optical system would require align precisely. In this paper, we used optical fiber to replace this optical system. The optical fiber has many advantages such as low transmission loss, excellent flexibility, and low price. Thus, the structure would save many optical devices, and the whole system of the QEPSA will be more pithy, stable and cheaper. Besides, the size of the entire QEPAS system can be reduced dramatically due to the outstanding property of the fiber structure.

In this work, a QEPAS system based on common single-mode fiber, which has more stable and flexible configuration, has been studied. To reduce the sensor background noise, we used wavelength modulation spectroscopy (WMS) and a 2nd harmonic detection technique. To obtain high QEPAS signal amplitude, a QTF with a low resonance frequency f_0 of 30.72 kHz was employed as an acoustic transducer. Meanwhile, the location of laser in the vertical direction between QTF prongs has been investigated.

2. Experimental setup

The experimental configuration of QEPAS system based on common single-mode fiber was shown in Fig. 1. A 1.395 μm continuous wave distributed feedback (CW-DFB), fiber-coupled diode laser was used as the excitation source. The output laser was transmitted by using a common single-mode fiber. In this research, the single-mode fiber has a core diameter of 8.2 μm and a numerical aperture (NA) of 0.14. Subsequently, the end of fiber was placed on the plat which close to QTF prongs. The plat can be adjusted in the vertical direction. After the output laser passing through the QTF prongs, the remainder of the laser beam was directed to an optical power meter and used for alignment verification of the QEPAS system. Wavelength modulation spectroscopy (WMS) with 2nd harmonic detection was employed for sensitive concentration measurement. Modulation of the laser current was adjusted by applying a sinusoidal dither to the direct current ramp of the diode laser at a half of the QTF resonance frequency ($f=f_0/2$). The measured f_0 was 30718 Hz. The piezoelectric signal, which generated by the QTF was detected by a low-noise transimpedance amplifier with a 10 MΩ feedback resistor and converted into a voltage. Then this voltage signal was sent to a lock-in amplifier for the measurement of 2*f* component generated by the QTF.

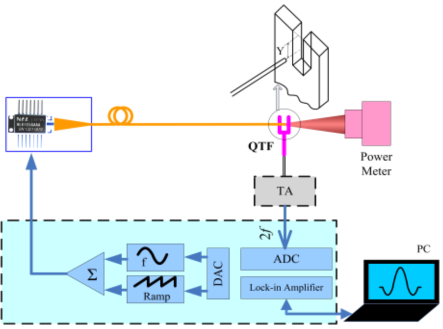

Fig. 1. The experimental configuration of QEPAS based on common single-mode fiber

The optical power which emitted by the diode laser operating with 120 mA drive current was ~30 mW (see Fig. 2(a)). The experimentally determined temperature and current tuning coefficients were -0.51 cm^{-1}/°C and -0.0246 cm^{-1}/mA, respectively. The DFB diode laser can be currently tuned to target the H_2O vapor absorption line at 7168.4 cm^{-1} (see Fig. 2(b)), which is free from spectral interference by other molecular trace gas species in the air. The optimum temperature for the highest diode laser power at the absorption line was 21°C.

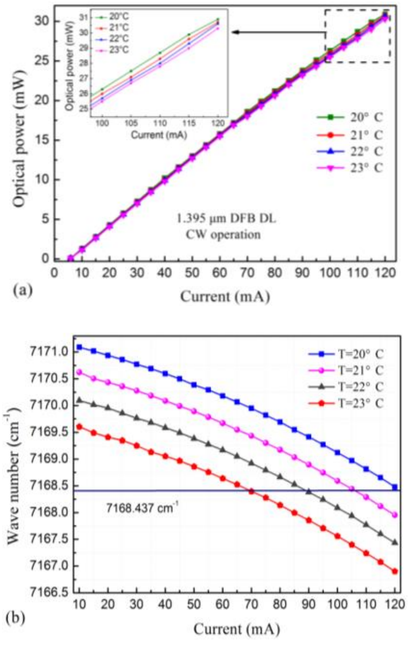

Fig. 2. Diode laser output performance at different temperature: (a) Optical power as a function of current; (b) Laser current tuning

3. Results and discussion

To obtain a high 2*f* QEPAS signal, we optimized the location of laser between the QTF prongs by adjusted the plat in the vertical direction when the laser modulation depth was 0.49 cm^{-1}. The experimental result was shown in Fig. 3. The Y-axis was set as the vertical direction, the initial point Y=0 was the top of the QTF prongs. The path length was 0~1.8 mm along the top to the root of the QTF prongs. In this work, the strongest 2*f* QEPAS signal was obtained when Y was ~0.8 mm. The existence of optimum position can be interpreted as following. The acoustic wave source can be treated as a spot. The acoustic wave spread around the spot homogeneous and force on the QTF prongs. So, the QTF would generate resonance. If the location of laser is higher than the optimal spot (close to the top of QTF prongs), there will be a part of acoustic wave that would not force on the prongs. On the contrary, when the location of laser is close to the root of QTF prongs, the equivalent torque forced on the prongs which generated by acoustic wave would reduce. Due to these two conditions, the optimal location should be the spot where QTF has large torque and less loss of acoustic wave.

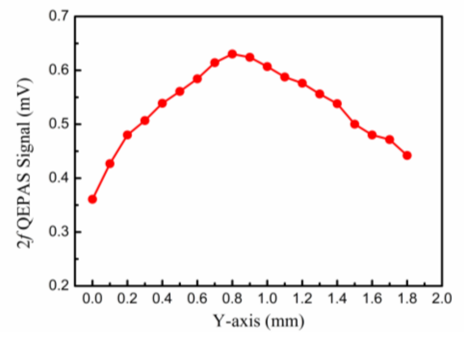

Fig. 3. 2f QEPAS signals with different laser locations between the QTF prongs in the vertical direction

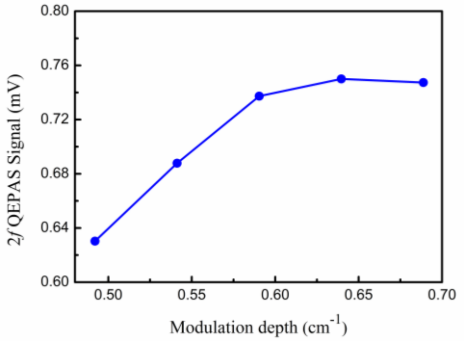

Fig. 4. The measured 2f QEPAS signal amplitude as a function of laser modulation depth

The experimental results shown in Fig. 4 illustrate the influence of the laser modulation depth on the QEPAS signal measured at the targeted 7168.4 cm^{-1} H_2O absorption line. The QEPAS signal amplitude increased with the modulation depth, but when the modulation depth was higher than 0.59 cm^{-1}, no further significant change was observed. Therefore, the optimum modulation depth was 0.59 cm^{-1}. From Fig. 5, the noise was determined from the signal far from the targeted absorption line. The signal to noise ratio (SNR) calculated from the measured results was 81 for QTF with f_0 of 30.72 kHz. The calculation normalized noise equivalent absorption (NNEA) coefficient was 4.69×10^{-7} $cm^{-1}W/\sqrt{Hz}$. The water vapor concentration was 0.85%. This resulted in a minimum detection limit (MDL) of 104.6 ppm.

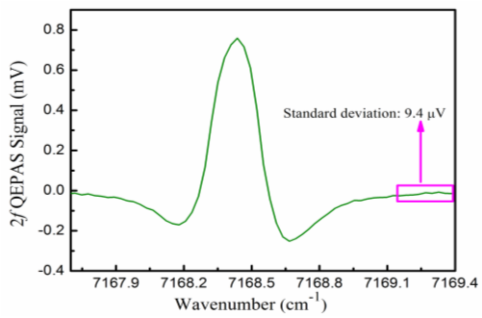

Fig. 5. Measured 2f QEPAS signal at modulation depth of 0.64 cm^{-1}

4. Conclusions

In conclusion, a QEPAS system based on common single-mode fiber was studied. A QTF with f_0 of 30.72 kHz was used as acoustic wave transducer. Wavelength modulation spectroscopy (WMS) and a 2nd harmonic detection technique were utilized to reduce the sensor background noise. The location of laser between the QTF prongs in the vertical direction was optimized to generate the strongest photoacoustic signal. In this research, a MDL of 104.6 ppm was achieved. The calculation normalized noise equivalent absorption (NNEA) coefficient was 4.69×10^{-7} $cm^{-1}W/\sqrt{Hz}$.

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[*] Corresponding author: hearkenyi@163.com