

Long distance, distributed gas sensing based on micro-nano fiber evanescent wave quartz-enhanced photoacoustic spectroscopy

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A long distance, distributed gas sensing using the micro-nano fiber evanescent wave (FEW) quartz enhanced photoacoustic spectroscopy technique was demonstrated. Such a sensor scheme has the advantages of higher detection sensitivity, distributed gas sensing ability, lower cost, and a simpler fabrication procedure compared to conventional FEW gas sensors using a photonic crystal fiber or a tapered fiber with chemical sputtering. A 3 km single mode fiber with multiple tapers and an erbium doped fiber amplifier with an output optical power of 700 mW were employed to perform long distance, distributed gas measurements. *Published by AIP Publishing.*

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Optical fiber gas sensors offer a sensitive and selective gas detection method, which has attracted considerable interest for sensing applications.^{1–4} With the merits of compact, immunity to electromagnetic interruptions, flexibility in sensor design, and on-line measurements,^{5,6} the use of a fiber evanescent wave (FEW) technique for gas detection is wide-ranging. However, the fabrication of the core component in a FEW gas sensor, usually a photonic crystal fiber (PCF) or tapered fiber, is complicated since the tapered fiber must be precisely processed with a chemical sputtered coating. Furthermore, the PCF evanescent wave sensor performance is related to the hole size or the index of the PCF, which makes the sensing parameters difficult to control.^{7,8}

In recent years, a gas sensor based on quartz-enhanced photoacoustic spectroscopy (QEPAS) was invented and developed.⁹ QEPAS has several unique properties, such as the high detection sensitivity and immunity to external interference effects, which make it ideal for trace gas detection.^{10–19} The FEW technique opens an opportunity for exploiting the properties of the combination of optical fibers and QEPAS technologies, resulting in FEW-QEPAS. Compared with the traditional QEPAS system, FEW-QEPAS can reduce the sensor system size and improve the stability of the optical system, which means that precise optical alignment is no longer needed. Compared with a FEW gas sensor, FEW-QEPAS is more sensitive with a lower minimum detection limit (MDL). In addition, a FEW-QEPAS sensor system does not require an expensive spectrometer or involved chemical processing. Particularly, since optical fibers have low transmission losses and can easily be handled, FEW-QEPAS has the potential of long distance gas sensing combined with good spatial resolution.

In this paper, a long distance, distributed fiber evanescent wave gas sensor based on QEPAS is reported. A 3 km fiber with multiple tapered detection units in a FEW-QEPAS

sensor system was used to investigate long distance and distributed gas sensing, based on multi-point, spatially resolved trace gas concentration measurements. To enhance the fiber evanescent wave field, an erbium doped fiber amplifier (EDFA) with an output power of 700 mW was utilized to amplify the laser output power. As a result, the detection system of the reported optical gas sensing technology is based on an all-fiber structure.

The experimental configuration of long distance, distributed gas sensing based on a FEW-QEPAS technique is shown in Fig. 1. Acetylene (C_2H_2) was chosen as the target analyte. Wavelength modulation spectroscopy (WMS) with 2nd harmonic detection was employed for sensitive concentration measurements. The modulation of the laser current was controlled by applying a sinusoidal dither to the direct current ramp at half of the quartz tuning fork (QTF) resonant frequency (f_0). A 1.53 μm continuous wave, distributed feedback (CW-DFB) fiber-coupled diode laser was used as the

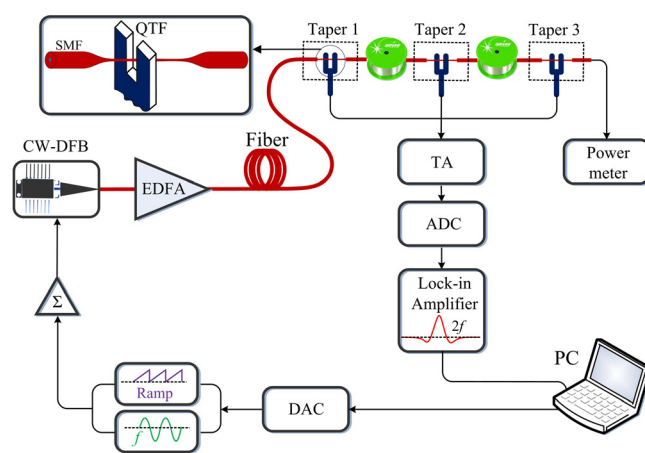


FIG. 1. Schematic configuration of a FEW-QEPAS sensor system. SMF, single mode fiber; QTF, quartz tuning fork; EDFA, erbium doped fiber amplifier; and TA, transimpedance amplifier.

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laser excitation source. The diode laser output was amplified by an EDFA with a gain of 40 dB and transmitted by a 3 km single mode fiber (SMF) with 3 tapers. The fiber length was 1 km between Tapers 1, 2, and 3. A portion of the tapered fiber was directed to an optical power meter (PS19Q, Coherent) for monitoring the tapered fiber transmission losses and alignment verification of the tapered fiber sensor. The tapered fibers were placed into the gap between QTF prongs, which resulted in 3 sensing units. The target gas was excited by the fiber evanescent field and produced an acoustic wave at a specific frequency, which was equal to twice the laser modulation frequency as a result of the QTFs' prong resonance and generated piezoelectric signals. Subsequently, a low-noise transimpedance amplifier (TA) with a $10\text{ M}\Omega$ feedback resistor and a lock-in amplifier were employed to increase and demodulate the piezoelectric signal into a $2f$ signal. The data acquired by the FEW-QEPAS sensor system were processed by a laptop computer using Labview software.

In order to determine the optical field distribution of the fiber evanescent field and calculate the optical power output from the tapered fiber sensor system, a theoretical simulation of the fiber evanescent wave based on the commercial finite element method (FEM) simulation tool COMSOL multiphysics 5.1 was developed. The calculated results of the fiber evanescent wave power ratio in air and the optical field distribution are shown in Fig. 2. As expected, the power of the evanescent field decreased with an increasing diameter of the micro-nano fiber. The power ratio was below 10% when the taper is greater than $2\text{ }\mu\text{m}$ in diameter. Therefore, in order to obtain a strong evanescent field, the diameter of tapered fibers should be $<2\text{ }\mu\text{m}$. The tapered fibers were fabricated by the flame-brushing technique from standard SMFs (Corning SMF-28e⁺).^{20,21} The diameter of the tapered fibers can be at the sub-wavelength scale by controlling the location of the flame and fiber stretching speed, which resulted in micro-nano fibers. The scanning electron micrograph images of fiber tapers are shown in Fig. 3. The measured diameters were $\sim 1.67\text{ }\mu\text{m}$, $1.77\text{ }\mu\text{m}$, and $1.12\text{ }\mu\text{m}$ for Taper 1, Taper 2, and Taper 3, respectively. Combining the measured results of tapers' diameter with the calculation results shown

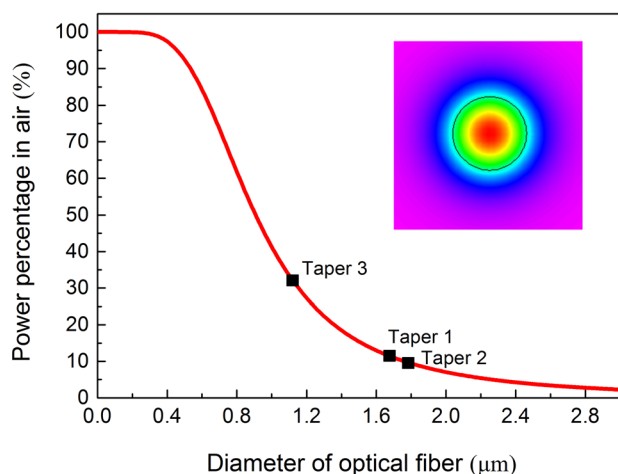


FIG. 2. Evanescent wave power as a function of the fiber diameter and its optical field distribution.

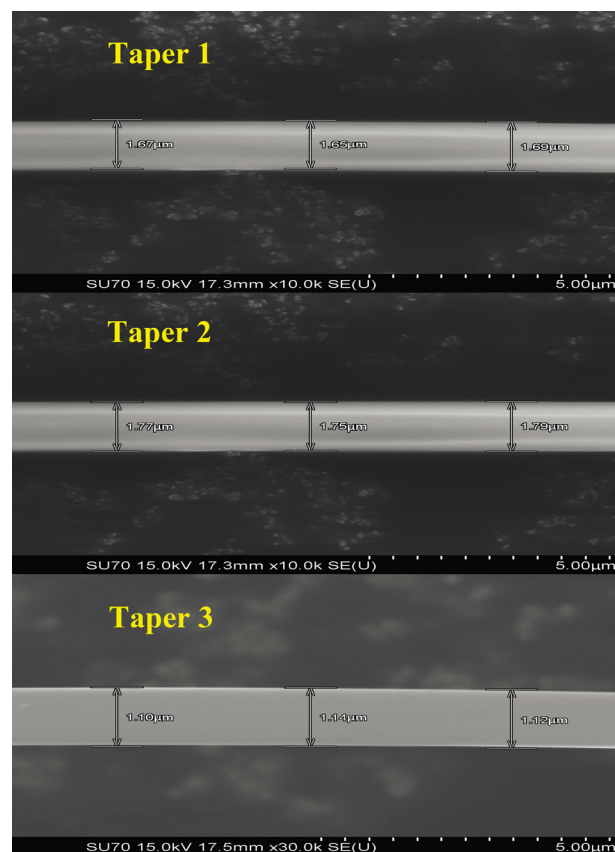
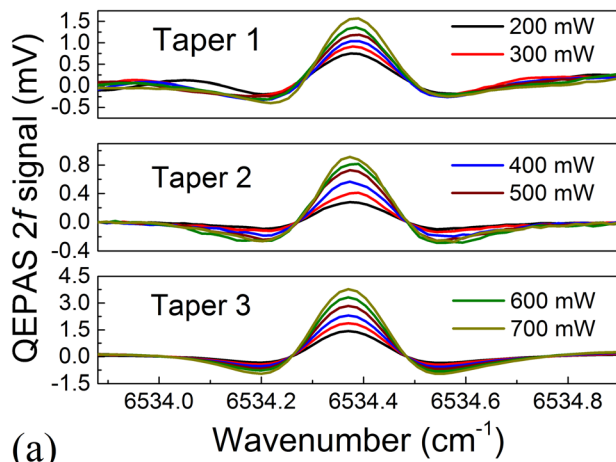


FIG. 3. SEM image of fiber tapers. SEM: scanning electron microscope.

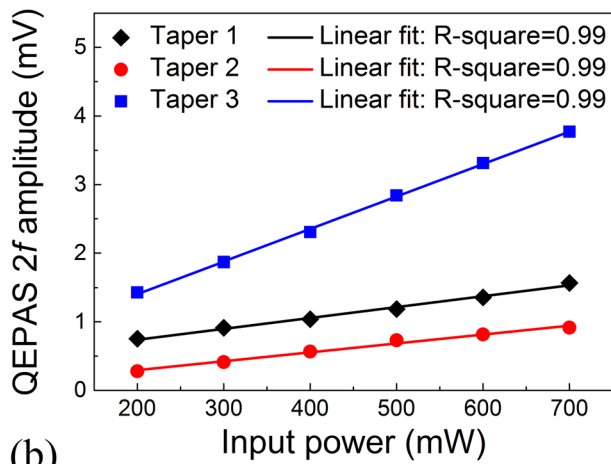
in Fig. 2, we can obtain evanescent wave power ratio of the three tapered fibers.

In this experiment, QTFs with a low resonant frequency of 30.72 kHz were utilized since the QEPAS signal amplitude is inversely proportional to the QTF resonant frequency.²² The absorption line used for C_2H_2 was 6534.37 cm^{-1} with a line intensity of $1.21 \times 10^{-20}\text{ cm}^{-1}/(\text{mol}\cdot\text{cm}^{-2})$. The measurements were performed at atmospheric pressure. A C_2H_2 concentration of 2% was employed. First, the position of the fiber taper and the QTF, as well as the laser wavelength modulation depth, were optimized. Then, a sensor system consisting of three tapers in FEW-QEPAS with EDFA performance was investigated when the optical output power of the amplified diode laser changed from 200 mW to 700 mW. FEW-QEPAS $2f$ signals as a function of the fiber tapers input power are shown in Figs. 4(a) and 4(b). It can be seen that $2f$ signal amplitude improved with increasing input power from Fig. 4(a). The peak values of the $2f$ signals and the linear fit are depicted in Fig. 4(b). The calculated R-square values of the three fiber tapers were all equal to 0.99, which indicated that all the tapers exhibited an excellent linearity response of optical powers, and the FEW-QEPAS $2f$ signals could be further enhanced by utilizing an EDFA with higher power output.

In order to investigate three tapers' optimal gas sensing properties, tapered $2f$ signals with an EDFA power of 700 mW were measured. Pure nitrogen (N_2) was used to test the three tapers' background noise, which is shown in Fig. 5. There were differences among the three tapers in the amplitude of the $2f$ signal. The signals were 1.57 mV, 0.91 mV,



(a)



(b)

FIG. 4. FEW-QEPAS $2f$ signals as a function of EDFA output power in three fiber tapers: (a) $2f$ signals and (b) linear fit of $2f$ amplitude. EDFA: erbium doped fiber amplifier.

and 3.77 mV for Taper 1, Taper 2, and Taper 3, respectively. The output power of each taper was measured to explain the differences. Table I lists the parameters of the three tapers' sensing characteristics. It can be seen that each taper has a different evanescent wave power ratio and transmission loss, which leads to a different evanescent wave power. Due to the fact that the QEPAS $2f$ signal is proportional to the laser excitation power, the signal amplitudes of the three tapers were different. According to the values of $2f$ signals and noise, the MDL of the three tapers was calculated, which were 30 ppm, 51 ppm, and 13 ppm, respectively. This implies that the taper sensing properties can be improved by reducing the diameters and the transmission losses of the fiber tapers. In addition, the calculated normalized noise equivalent absorption (NNEA), which represents the sensor

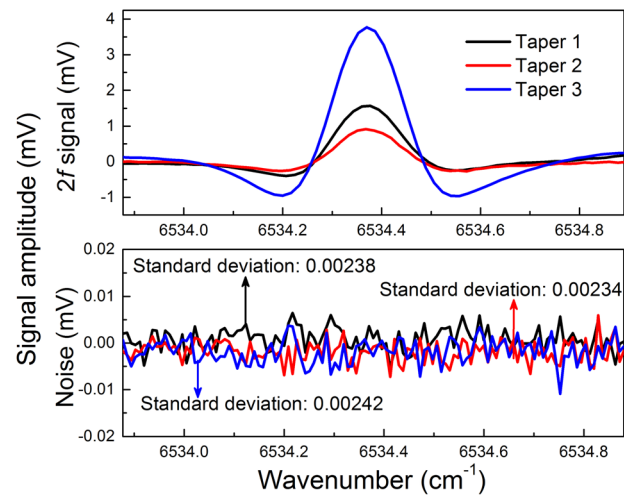


FIG. 5. FEW-QEPAS $2f$ signals and noise of three fiber tapers.

sensitivity, is also depicted in Table I. The NNEA values of each taper were almost equal, which indicated that all the tapers have the same sensitivity for gas sensing.

To verify the linear concentration response of three tapers based on the C_2H_2 sensor platform, a 2% $C_2H_2:N_2$ gas mixture was diluted with pure N_2 down to concentrations of 1.5%, 1.0%, and 0.5%, respectively. The measured $2f$ signals as a function of the C_2H_2 concentration and the linear fit of the $2f$ signal amplitude with three tapers are shown in Figs. 6(a) and 6(b). On the basis of the calculated R-square values with three fiber tapers equal to 0.99, the tapers showed an excellent linearity response of C_2H_2 concentration levels.

In conclusion, this paper demonstrated a long distance, distributed gas sensing system based on micro-nano FEW-QEPAS. The optical field distribution and optical power ratio of the fiber evanescent field were theoretically calculated. To enhance the sensors' sensitivity, an EDFA amplified diode laser with an output optical power of 700 mW was used as the tapered fiber transmitting source. A 3 km SMF with three tapers was developed to demonstrate a long distance, distributed gas sensing architecture. Compared with a FEW gas sensor and a traditional QEPAS sensor, the fabrication of tapered fibers (without chemical processing) was simplified, and the size of the optical system was reduced since it uses a small QTF and a compact tapered fiber. Furthermore, distributed measurements of gas concentration levels were obtained with three tapers. For the FEW-QEPAS sensor system operation at atmospheric pressure, the MDL of the three tapers was 30 ppm, 51 ppm, and 13 ppm, respectively. In this paper, the fiber taper transmission loss is the main loss, which can be reduced by applying an improved processing method.²³ The sensor's capability can be further improved when an EDFA with a higher output power, microresonators, and

TABLE I. The parameters of three fibers' sensing features. MDL: minimum detection limit and NNEA: normalized noise equivalent absorption.

Taper	Diameter (μm)	Evanescent wave power ratio	Transmission power (mW)	Evanescent wave power (mW)	MDL (ppm)	NNEA ($\text{cm}^{-1} \text{ W/Hz}^{-1/2}$)
1	1.67	11.8%	422	49.80	30	3.55×10^{-6}
2	1.77	9.7%	294	28.52	51	3.52×10^{-6}
3	1.12	32.3%	238	76.87	13	3.66×10^{-6}

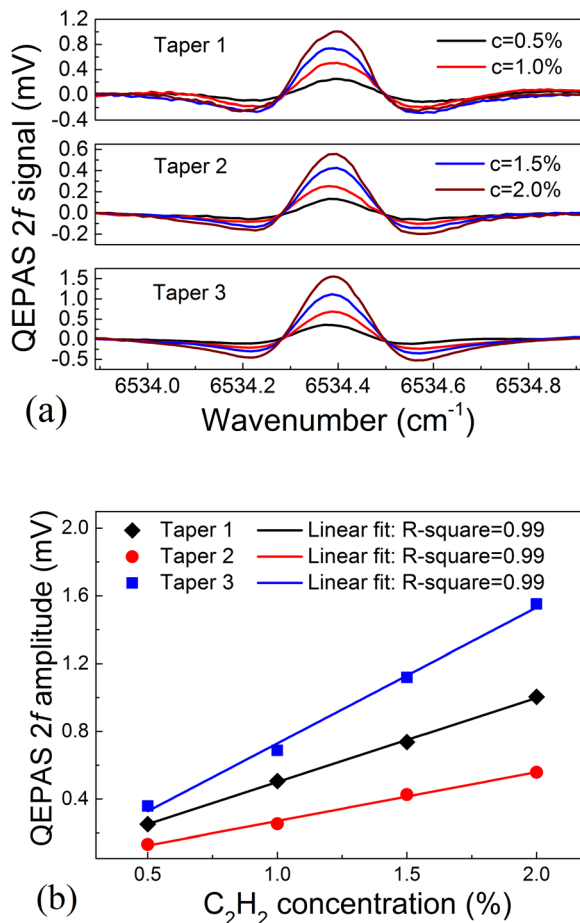


FIG. 6. FEW-QEPAS $2f$ signals as a function of the C_2H_2 concentration in three fiber tapers: (a) $2f$ signals and (b) linear fit of $2f$ amplitude.

better quality fiber tapers with a smaller diameter and lower transmission loss are used.²⁴

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