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Position effects of acoustic micro-resonator in quartz enhanced photoacoustic spectroscopy

Hongpeng Wu[a], Lei Dong[a,*], Wei Ren[b], Wangbao Yin[a], Weiguang Ma[a], Lei Zhang[a], Suotang Jia[a], Frank K. Tittel[b]

[a] State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan 030006, China
[b] Department of Electrical and Computer Engineering, Rice University, Houston, TX 77004, USA

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ABSTRACT

The impact of acoustic micro-resonator (AmR) positions with respect to quartz tuning fork on signal amplitude, *Q*-factor and signal-to-noise ratio (SNR) of the quartz enhanced photoacoustic spectroscopy spectrophone was investigated. The replacement of the result plots' abscissas makes the highest signal amplitude and the lowest *Q*-factor for different AmRs appear at the two absolute positions, respectively. These positions are independent on the AmR geometrical parameters, which facilitates the assembly of the spectrophone. The noncoincidence between the positions of the two extreme values results in a flat peak of the SNR curve, which is different from previously reported results. The spectrophone designs for three different applications are discussed in detail.

1. Introduction

The real-time detection and quantification of trace chemical species in the gas phase has an important impact in diverse fields of applications, such as industrial process control, environmental monitoring, medical diagnostics, and automotive exhaust analysis [1–6]. Recently, there has been a growing interest in the quartz enhanced photoacoustic spectroscopy (QEPAS) technique which combines the main benefits of conventional photoacoustic spectroscopy (CPAS) with the characteristics of using a commercially available quartz tuning fork (QTF) as a resonant acoustic transducer. Due to the high quality factor Q (∼12,000 in air), high resonant frequency f_0 (∼32,768 Hz) and narrow resonance width (3–5 Hz) of the QTF, QEPAS is immune to ambient acoustic noise. The small size of QEPAS spectrophone as well as the cost-effectiveness is additional benefits of the QEPAS technique. In a commonly used QEPAS-based spectrophone, a so-called acoustic micro-resonator (AmR) is employed in addition to a QTF for detecting the sound signal generated by the trace gas absorbing the excitation laser beam [7–12]. With the "on-beam" configuration [7], the AmR is formed by two hypodermic, metallic thin tubes and is coupled to the QTF in order to enhance the QEPAS signal. Thus, in contrast to CPAS spectrophone including a photoacoustic cell and microphone, the optical collimating scaling requirements decrease from mms to μms, which implies that variations in the AmR position at the μm level can affect the QEPAS signal.

The performance of QEPAS spectrophone is determined by both the measurement environment and its design. The environmental parameters include electromagnetic field intensity, pressure and temperature, while the structural design includes the AmR geometrical parameters, such as shape, length, inner and outer diameters (ID and OD) and the AmR position. The influence of the electromagnetic fields on the QEPAS signal can be eliminated when an optical readout method is used, since in this case the sensor head contains no electrical components [13,14]. The pressure and temperature dependence of QEPAS spectrophone were investigated by Dong et al. [15] and Kohring et al. [16], respectively. Moreover, Dong et al. [15] studied the influence of the AmR diameter and length on the spectrophone properties. Serebryakova et al. [17] and Cao et al. [18] demonstrated that changes of the AmR length have a significant influence on QEPAS spectrophone performance. Yi et al. [19] proposed a novel T-shaped AmR to decrease the effect of viscous drag. However, the influence of the AmR position with respect to a QTF on the performance of QEPAS spectrophone has not been reported

* Corresponding author. Tel.: +86 3517018904; fax: +86 3517018927.
E-mail address: donglei@sxu.edu.cn (L. Dong).

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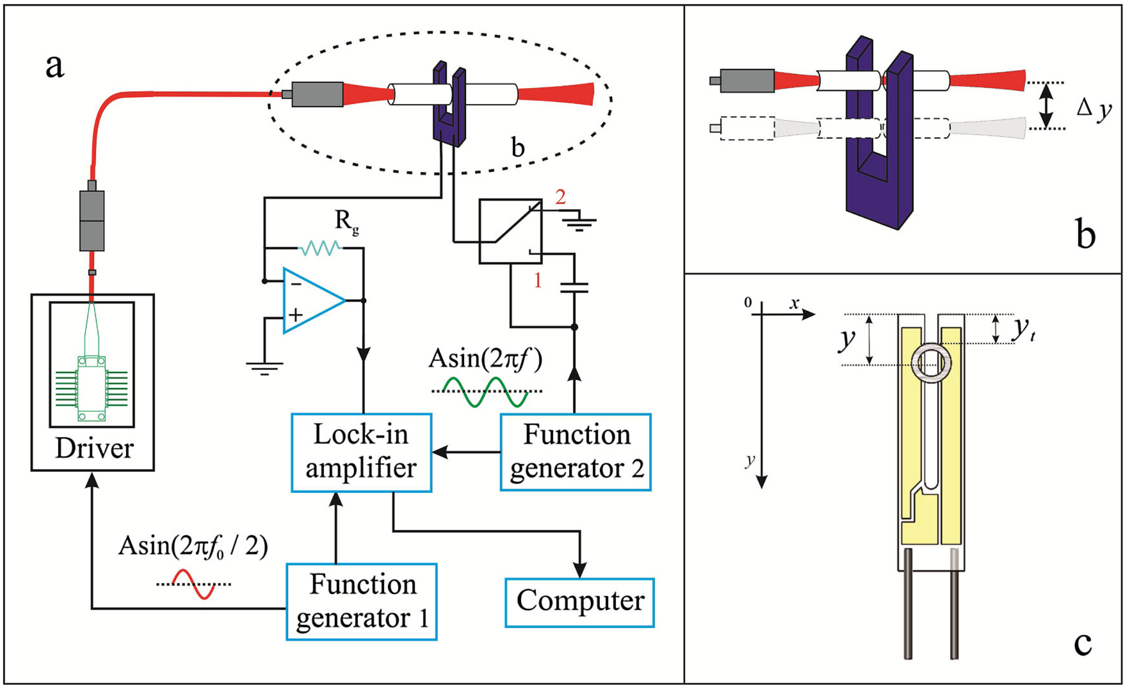

Fig. 1. (a) Schematic of the QEPAS-based experimental setup for water vapor detection. (b) Enlarged image for the QEPAS spectrophone. (c) The dimensions and coordinate system of the QTF with an AmR. The tubes were centered between the tines. y and y_t are the distances from the QTF opening to the center and the top of the tubes, respectively.

to date. Most of the previous studies mentioned above were carried out in the case that the laser beam and AmR were below the QTF opening 0.7 mm and centered between the tines which corresponds to the most sensitive position for a bare QTF. This has been confirmed theoretically and experimentally by N. Petra et al. [20] and P. Patimisco et al. [21]. However, the presence of the AmR and the interaction between the AmR and QTF alter the QTF characteristics, so that the position mentioned above is no longer optimal. The new optimal position must be experimentally determined.

In this paper, we present an experimental investigation of the AmR position effects via detecting water vapor in ambient air, with the "on-beam" configuration, at normal atmosphere pressure and temperature at ~21 °C. The QEPAS spectrophone designs for three different applications are also reported in detail.

2. Experimental optimization and results of the AmR position

A schematic of the QEPAS experimental setup for water vapor detection is shown in Fig. 1a. The experiments were carried out in two operational modes—measurement mode and calibration mode. In measurement mode, the switch in Fig. 1a was set to position 2. The detection was based on a 2f wavelength-modulation spectroscopy approach [22] by dithering and scanning the laser current. A near-infrared distributed feedback (DFB) diode laser (HuaYing Inc. Model DFB-136813C1424) with a center wavelength of 1368.7 nm and an output power of ~12.6 mW was served as the QEPAS based sensor excitation source. The DFB laser was mounted onto a custom driver board for laser temperature and current control. A sine wave supplied by a function generator 1 (Agilent Model 33210A) was applied to the driver board to modulate the laser wavelength. The modulation frequency was set to one half of the QTF resonant frequency ($f_0/2$). The function generator 2 was disabled. The output laser beam was directed into a 100 μm-diameter light spot by a fiber-coupled focuser (OZ optics model LPF-01), and then passed through the AmR and between the QTF prongs without touching any surfaces. The gaps between the QTF and the tubes were 40 μm which facilitated changing the AmR position. The tubes were centered between the QTF tines as reported in previous QEPAS publications. An H_2O line at 7299.43 cm^{-1} with an intensity of 1.008×10^{-20} $cm^{-1}/(mol\,cm^{-2})$ was chosen as the target line for demonstration. The signal produced by piezoelectric effect due to the prongs anti-symmetric vibration, were demodulated at f_0 by a lock-in amplifier (Stanford model SR830).

Two different AmRs were selected as research targets. The first AmR consists of two 4.4 mm long tubes with a 0.6 mm ID and a 0.9 mm OD, marked as AmR #1, while the second AmR is composed of two 4 mm long tubes with a 0.8 mm ID and a 1.24 mm OD, marked as AmR #2. The objective of using the two sets of AmR parameters is to further improve the previous optimized results in Refs. [15,23], which shows that the AmR #1 is the optimal AmR for a near-infrared excitation laser source, whereas the AmR #2 is more suitable AmR for the mid-infrared spectral region. The AmR and the focuser were fixed on the same holder in our experimental setup. This design ensures that the position of the laser beam with respect to AmR remains the same while the AmR is moved down along the direction of the QTF prongs, as shown in Fig. 1b. The commercially available QTF has a fork structure of two tines with a resonance frequency of 32.7 kHz. The width, length and thickness of the tine are 0.6 mm, 3.8 mm and 0.3 mm, respectively. The gap between two tines is 0.3 mm. The vertical distance between the QTF opening and the tube center was defined as y and the QTF opening is defined as zero point of y as shown in Fig. 1c.

The result of H_2O QEPAS signal amplitude for AmR #1 as a function of y is plotted in Fig. 2. The data was normalized to water concentrations to eliminate the influence caused by water vapor concentration variations. The measurement originated at the position where the tangent plane of the AmR #1 bottom just touched the top surface of the QTF tines. Therefore, the initial position of the y starts from −0.45 mm, as shown in Fig. 2. At the beginning, most of the tubes were outside the QTF tines. As the tubes moved down and overlapped with the QTF section, the coupling via the sound wave between the AmR and the QTF was established. As a result, the signal amplitude of the QEPAS spectrophone rapidly