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# Portable detection system for standoff sensing of explosives and hazardous materials

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ABSTRACT

Standoff Quartz Enhanced Laser Photoacoustic Spectroscopy (QE-LPAS) technique is emerging as a powerful technique for detection of hazardous chemicals, biological and explosive agents. Experimentally, we have recorded standoff photoacoustic spectrum of hazardous molecules adsorbed at diffused surfaces from a distance of up to 25 m. Tunable mid infrared quantum cascade lasers (MIR-QCL) in the wavelength range 7.0–12.0 μm are being used as optical source. Samples of Dinitrotoluene (DNT), Pentaerythritoltetranitrate (PETN) having adsorbed concentration of approximately 5.0 μg/cm$^2$ were detected. Acetone and nitrobenzene samples in liquid having concentration 200 nl approximately sealed in polythene sachet were detected from a standoff distance of up to 25 m. All the above measurements are reported for a Signal to Noise Ratio (SNR) of 10, optimized for maintaining very less false alarm rates for field measurements. A portable trolley mounted system has been developed for field applications.


## 1. Introduction

The inventiveness and creativity of those, that would harm the civilized world is apparently boundless. The threat of terrorist activities against civilian population in crowded environment such as airports, markets and buildings etc. is increasing day by day. This threat appears in potential release of hazardous chemicals, biological warfare agents and explosives. Minimizing the impact of such threats requires early detection of the presence of these hazardous agents from a standoff safe distance. Out of many available techniques, Quartz Enhanced Laser Photoacoustic Spectroscopic (QE-LPAS) Technology has recently emerged as one of the most powerful standoff technique for homeland security in Defense as well environmental sciences and medical sciences. The technique is a modified version of conventional photoacoustic spectroscopy (PAS) [1,2]. Two main features of QE-LPAS technique are the use of tunable quantum cascade laser (QCL) and a resonant Quartz Crystal Tuning Fork (QCTF) detector. In this technique, QCL source is modulated at the resonant frequency of QCTF enabling a very high SNR for the detection set-up and having total insensitivity to ambient CW radiations. Details of the technique are explained in Refs. [1,2].

Availability of low cost QCTF detector and advent of reasonably high power QC lasers has significantly boosted the potential of this technique. The large Q-factor of the QCTF detector enables high sensitivity, low noise detection of explosive signatures even for low concentrations of the explosive material and large standoff distances. QE-LPAS technique can detect trace gaseous species; traces of surface adsorbed solids and vapors [3,4]. The QE-LPAS technique has shown detection capability of a variety of chemicals at ppb level concentration with very low false alarm rates [1]. LPAS and photothermal spectroscopy based studies have been used for environmental monitoring and homeland security [5–10]. Emerging application of the QE-LPAS technology is the standoff molecular detection of explosives, chemical and biological materials in gas, vapor, liquid, and solid phase and absorbed materials on the surface or any kind of hazardous material.

This paper presents standoff QE-LPAS spectrum of explosive simulants/molecules adsorbed at diffused aluminum plate and wood surfaces from a distance of up to 25 m in solid and liquid forms. Theoretical calculation of QCTF detector parameters has been carried out. Theoretically, standoff QE-LPAS signal is calculated considering laser and receiver parameters, target distance and target type. Experimentally, we have developed a trolley mounted portable system for detection of explosives. In future with the increase in the power of QCL Laser due to technology advancements, the system can be upgraded to detect the hazardous chemicals from safe standoff distances of approximately hundreds of meters.

### 1.1. Quartz crystal tuning fork: signal consideration

A commercially available quartz tuning fork detector (Citizen CFS308, frequency 32.768 kHz) having dimensions ~1.5 mm × 0.25 mm × 6 mm is being used. A small periodic force generated due to modulated light incident on the prongs of QCTF detector at a

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repetition rate which matches its resonance frequency ($f_0$) drives it into oscillation. Due to the piezoelectric properties of the quartz material this force gives rise to a periodic electrical current signal proportional to the deflection of the prongs [11,12]. Since the modulation of the driving force is done at the resonance frequency of the tuning fork a significant enhancement in the signal is achieved. The resonance frequency of the tuning fork depends on the ambient temperature and pressure and is to be determined experimentally before measurements.

#### 1.1.1. *QCTF characteristics parameters*

For the standoff detection, the detector parameters like noise current, responsivity, detectivity ($D^*$) and Noise Equivalent Power (NEP) needs to be evaluated. The current ($I$) per deflection ($X_L$) of tuning fork is given by [11]

$$\frac{I}{X_L} = 2\pi f_0 3 d_{12} E\left(\frac{TW}{L}\right) \quad (1)$$

With thickness ($T$), width ($W$), and length ($L$) of the tuning fork (piezo-electric coupling constant), $d_{12}=2:31\times10^{-12}$ C/N and (Young's modulus) $E=7:87\times10^{10}$ N/m$^2$ for quartz and a resonant frequency $f_0=32:8$ kHz, a current per deflection of 4.5 A/m is theoretically determined for the QCTF. The mean-square amplitude of the tuning fork tine vibration in thermal equilibrium is calculated from the equipartition theorem:

$$\frac{1}{2}k\langle x_{rms}\rangle^2 = \frac{1}{2}k_B T \quad (2)$$

where $k$ is the spring constant, $x_{\mathrm{rms}}$ the root mean deflection, $k_B$ Boltzmann's constant and $T$ the absolute temperature. At room temperature ($T=300$ K), $x_{rms}=2.94$ pm, the noise current spectral density ($I=I_N$) is current generated per unit bandwidth per unit $x_{\mathrm{rms}}$ equals to $I_N=1.32\times10^{-11}$ A/Hz$^{1/2}$, as derived from Eq. (1).

The set-up in Fig. 1(a) is used to evaluate experimentally the responsivity of QCTF detector. Fig. 1(b) is the plot of QE-LPAS signal vs. incident laser power on the QCTF detector.

Experimentally a responsivity $R=2\times10^{-3}$ A/W at the output of transimpedance amplifier with a feedback resistance of 1 MΩ is measured, which results in a

$$\mathrm{NEP} = \frac{I_N}{R(\mathrm{responsivity})} = 6.6\ \mathrm{nW/Hz^{1/2}} \quad (3)$$

$$\text{And detectivity}(D^*) = \frac{\sqrt{A}}{\mathrm{NEP}} = 5.37\times10^6\ \mathrm{cm\ Hz^{1/2}/W} \quad (4)$$

For the sensing area '$A$', the maximum circular spot fitting on the lateral surface of the tuning fork with a diameter of 250 μm has been used.

### 1.2. *Standoff QE-LPAS signal calculations*

Laser power at the QCTF detector for standoff set-up (as shown in Fig. 3) is calculated by using Eq. (5) [13].

$$P_{\mathrm{Detector}} = \frac{T_a^2 \rho \eta_{\mathrm{Transmitter}} \eta_{\mathrm{Receiver}} D^2}{16R^2} P_{\mathrm{Transmitter}} \quad (5)$$

$T_a$ is atmospheric transmission$=\exp(-\alpha R)$, where '$\alpha$' is the attenuation coefficient of atmosphere. The value of '$\alpha$' in mid-IR band ~$10^{-3}$ m$^{-1}$. '$\rho$' is the reflectivity of target. $\eta_{\mathrm{Transmitter}}$ and $\eta_{\mathrm{Receiver}}$ are the transmission efficiency of transmitter and receiver systems respectively. Receiver mirror is a gold coated ellipsoidal mirror (conic constant$=-0.85$) of reflectivity $>95\%$ in the spectral band 7–12 μm. Laser transmitter ($Tx$) is a 2X to 5X variable beam expander having transmission $>95\%$ in the spectral band 7–12 μm, '$D$' is the diameter of receiver mirror ($D=250$ mm), and '$R$' is the range. Keeping the assumed values of parameters in Eq. (5), $T_a=0.90$ (typical for 10 m range), $\rho=0.6$ and 0.2 for aluminum and wood, $\eta_{\mathrm{Transmitter}}=0.95$, $\eta_{\mathrm{Receiver}}=$ 0.95, $D=0.25$ m, $R=0$–100 m. Using Eq. (5) we have plotted the received power vs. range for a laser having average transmitter power of 12 mW as shown in Fig. 2. Powers received from a distance of 10 m are ~0.1 μW and 0.4 μW for wood and aluminum sample respectively. From the sensitivity as derived by using Fig. 1, a 0.1 μW signal will result in a LPAS signal of approximately 0.2 nA/Hz$^{1/2}$. Noise floor of QCTF detector was calculated as $1.32\times10^{-11}$ A/Hz$^{1/2}$ (corresponding to Johnson's noise due to mechanical dissipation in the fork). So, 10 m standoff signal can be detected corresponding to a high SNR.

### 1.3. *Standoff laser photoacoustic signal measurement of explosive simulants*

A schematic diagram of the Standoff trolley mounted experimental setup is shown in Fig. 3. The laser source and the acoustic detector are situated away from the target sample. The commercially available QCL sources from M/s. Daylight Solutions are used. Model number UT-8 (tuning range 800–1000 cm$^{-1}$) and UT-10 (tuning range 1130–1420 cm$^{-1}$) each with increment wavelength of 1 cm$^{-1}$ and total scanning time $<2$ s are employed for present experimental work.

QCL laser beam is modulated by pulses at the frequency 32.8 kHz using a function generator (Tektronics: AFG 3102) having a duty cycle of 1.62% (maximum average power 12 mW). Incident radiation is absorbed by the explosive simulant paste adsorbed at the surface of the target. The laser radiations are backscattered/reflected from the target. These backscattered laser radiations are collected by the ellipsoidal mirror and are focused on one of the

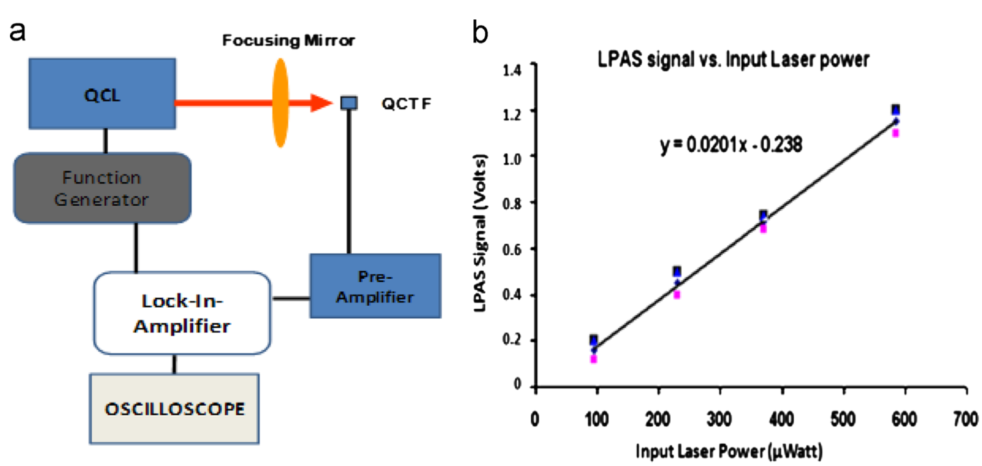


**Fig. 1.** (a) Optical set-up for QCTF characterization and (b) LPAS signal vs. Laser Power.