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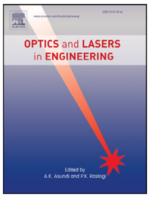

100-m standoff detection of a QCL-induced photo-vibrational signal on explosives using a laser vibrometer

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ABSTRACT

Laser Doppler vibrometry is a key technology in the field of photomechanics. It allows pointwise noncontact measurements of dynamic effects. In recent years, it has been applied as a sensor in photoacoustic/photothermal spectroscopy to detect hazardous chemicals or explosive substances in an open environment. In photoacoustic spectroscopy, normally the analysis has to be conducted in a sealed space to enable signal detection, either through a high-sensitivity microphone, or a piezo-sensor coupled with a lock-in amplifier. In addition, the requirement for sample preparation prior to analysis is an impediment preventing practical adoption of the technique in real-time, standoff chemical detection deployments in an open environment. The research team has previously demonstrated the feasible use of a laser interferometric technique to detect photo-vibrational signals of trace chemicals because it was excited by an intensity-modulated quantum cascade laser (QCL). In this study, our long distance laser Doppler vibrometer developed in house was demonstrated to be able to detect the vibration amplitude and frequency of trace explosives at long standoff distances of 100 m in an open environment. Three explosives of 10 µg/mm^2 concentration were tested, and the photo-vibrational spectrum obtained by scanning the output wavelength of the QCL through the mid-IR range, coincides well with the corresponding spectrum obtained using typical FTIR equipment. The experiment demonstrated that the detection of hazardous chemicals or explosive substances at a safe standoff distance can be realized through a system utilizing capable interferometric sensors like the laser Doppler vibrometer, coupled with a QCL excitation source.

1. Introduction

The ability to detect and differentiate trace amounts of explosive substances is of considerable interest for applications in defense and national security, and photoacoustic spectroscopy (PAS) has been identified as a suitable technique for these applications. Since the photoacoustic effect was discovered in the late nineteenth century [1], it has been developed into a sensitive spectroscopic technique for the evaluation of chemicals in solid [2], liquid and gaseous [3] states. Conventional PAS requires minimal sample preparation; however, the analysis must be conducted in a highly controlled environment such as a well-isolated photoacoustic cell. The response signal can be captured by either a highly sensitive microphone, or any other form of vibration sensor located in close proximity or even in direct contact with the sample. Hence, commercial PAS equipment does not fulfill the situational requirements for in situ standoff screening and detection of hazardous chemicals and explosive substances in high security areas such as airports.

Current trends in research and development focus on technology enablers to perform remote sensing of explosives in the open environment without any sample preparation. Progress in standoff detection of surface-bound chemicals or explosives residue using photoacoustic/photothermal (PA/PT) spectroscopy and quantum cascade lasers (QCLs) has been reported recently. QCL systems have been adopted as the excitation source due to their high power, broadly tunable wavelength in the mid-IR range and compact size over other light sources such as optical parametric oscillators (OPOs) [4]. Chen and colleagues reported the detection of a QCL-excited photoacoustic signal on explosives in an open environment using a highly sensitive microphone with a large sound reflector [5,6], and in order to improve upon the detection efficiency, Choa and coworkers applied a microphone array together with a sound reflector array [7]. However, it is extremely challenging to perform PAS in an open environment at a standoff distance, due to the tremendous transmission loss of acoustic waves in air. The maximum reported standoff distance was only around 12 m based on acoustic detection techniques.

In order to overcome the acoustic detection limit, noncontact optical detection techniques, such as thermal imaging and laser interferometry

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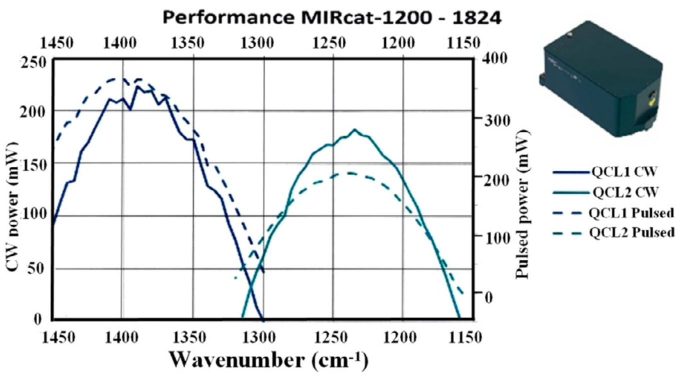


Fig. 1. MIRcat QCL system from Daylight Solutions and its output power in CW and pulsed mode.

became a more feasible approach toward achieving standoff detection of PA/PT signals [8,9] in an open environment. Cho et al. reported an excellent research work utilizing QCL as the excitation source placed at a distance of 0.5 m away from an explosive target, coupled with a coherent detection system using a CW probe laser of 1550 nm wavelength, and realized a 5-m detection range [10]. Among optical detection techniques, the technological advances in laser Doppler vibrometry [11] have enabled its use as a probing method due to its high-sensitivity and possible long measurement distance when the excitation laser is intensity-modulated at certain frequencies. Marcus and colleagues demonstrated the noncontact detection of a photo-vibrational signal on a PTFE tape [12]. Previous research has also established the ability of the photo-vibrational technique to detect chemicals in powder form and liquid state in the near field [13]. The technique has also been preliminarily tested at long standoff distances [14,15].

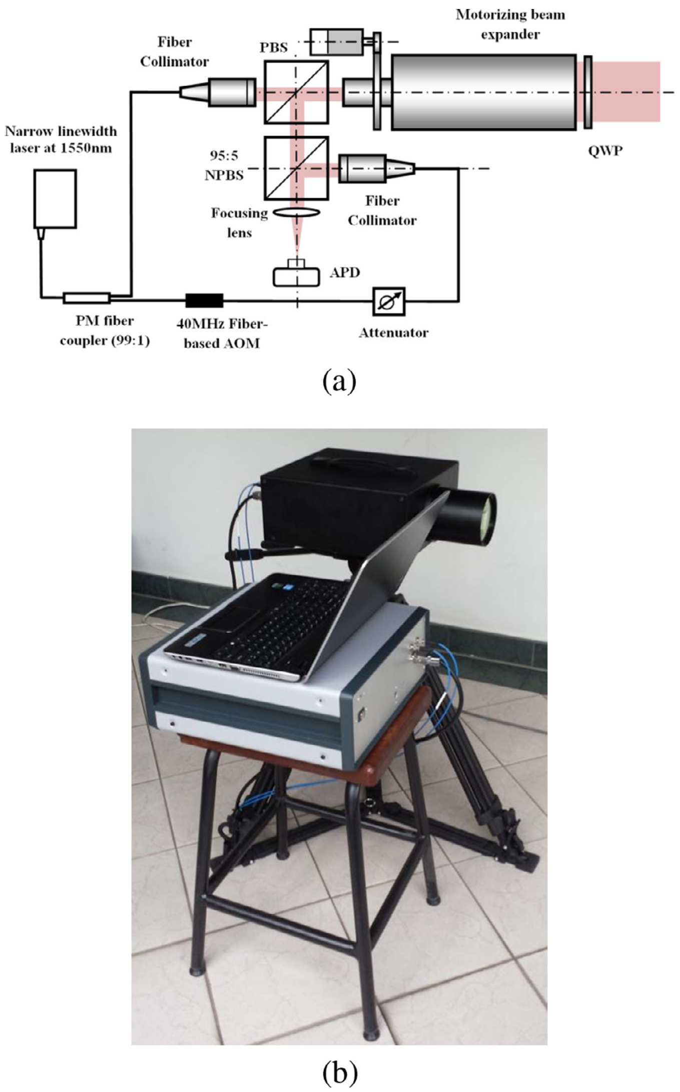
In this work, an in-house-developed laser Doppler vibrometer (LDV) was applied to detect the photo-vibrational signal of explosive residues at 100 m standoff distance in an open environment. The excitation light source was a tuneable QCL system with an optical chopper. Trace samples of three high-explosive substances were tested: (1) trinitrotoluene (TNT); (2) pentaerythritol tetranitrate (PETN); and (3) a mixture of TNT and PETN at a ratio of 50:50% by weight. The vibration amplitudes obtained by LDV at different wavelengths were normalized by the QCL power. The spectra obtained were compared with the corresponding FTIR spectra of each material, and the results demonstrate that the laser interferometer is an effective sensor for photo-vibrational spectroscopy and displays excellent potential for applications related to standoff detection of explosive substances and hazardous chemicals.

2. QCL induced photo-vibrational signal

The photo-vibrational signal is produced when a molecule transits from an excited state to the ground state after excitation by periodically modulated electromagnetic radiation. In this research, a QCL system with intensity modulation was used to excite the explosive substances, and a long-distance LDV was employed to measure the periodic change in the optical path length (OPL) at a 100 m standoff distance. The variation in OPL of the probing laser beam was then converted to the equivalent vibration amplitude in displacement, or velocity whose frequency corresponded to the modulation frequency of the excitation laser.

2.1. Excitation laser

In this study, a multiplexed broadly tunable laser system from Daylight Solutions, MIRcat-1200-1824 was employed as the excitation source. It contains two QCL modules whose tuning ranges are from 6.89 to 7.55 µm and 7.65 to 8.5 µm, respectively, together with a co-axial red aiming laser for easy alignment. The maximum CW power of these two modules is >150 mW. The working temperature of the QCL is only 17 °C, hence water cooling is necessary for operation in the CW mode. Fig. 1 shows the MIRcat system and its power distribution at various wavenumbers. In our experiment, CW mode was applied, and an optical chopper was mounted in front of the laser to modulate the intensity. However, the disadvantage of using an optical chopper is the reduction in QCL power by 50% as illuminated on the sample.



(a)

(b)

Fig. 2. (a) Schematic layout of optical design of long-distance LDV; (b) prototype of the long-distance laser Doppler vibrometer.

2.2. Photo-vibrational signal

The mathematical equations and reasonable assumptions for conventional PAS utilizing a microphone to detect pressure variations in an isolated photoacoustic cell for analysis of solid bulk chemicals is well-established [2]. However, there are other complexities involved in the mathematical expression for other forms of samples such as loose powders [16,17] or even chemical residues, as photoacoustic signal may be dependent upon many other factors related to the morphological, thermo-chemical, and transport properties of the chemicals, substrate and air mass [10]. Ref. [13] lists various factors that contribute concurrently to the change in optical path length (OPL) as detected by LDV, as well as the factors that may affect the absolute value of the vibration amplitude being measured. The authors assume the linear contribution of these various factors to be a fixed variable, which will not affect the