Research Article
Volume 10:5, 2023

Journal of Lasers, Optics & Photonics

ISSN: 2469-410X
Open Access

Quantum Laser Sensor for Defence and Security

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Abstract

In present scenario, there is an urgent need to develop technologies and devices for Defense and Security applications to not just maintain the sovereignty of international boarders but also to safeguard the countrymen from hostile terror forces within the homeland. In the present paper, results of detection studies for Improvised Explosive Devices (homemade explosive), Chemical Warfare Agents, (CWA) and drugs have been presented. Quantum Cascade Laser having wavelength in mid-IR region (wave number region ~ 900 to 1400 cm^{-1}) has been utilized in the study as explosives and CWA have strong absorption in the region. The Quantum Cascade Laser has advantages of compact size and relatively smaller weight in comparison to other sources working in the same wavelength region. The detection limit of the setup has been measured. The detection technique presented here is immune to the interferences by sonic or other electromagnetic waves present in the surrounding atmosphere making the technology suitable for Defence, Security and forensic purposes.

Keywords: Quantum cascade laser • Photoacoustic spectroscopy • Mid-IR • Chemicals • Explosive detection • Defence and security

Introduction

The frequent use of IEDs (Improvised Explosive Devices) by terror outfits have propelled the research and developments being put in detecting the substances used to produce them. The potential use of chemical weapons is another area of concern as a small amount of these can be lethal to large populations and then come the drugs which are not only destroying the young generation but also leaving permanent scar on their families. Detection/identification of these substances is the first step towards neutralization or minimization of the impact that may be caused. Therefore, researchers are coming up with different kinds of solutions to detect the threat. Laser Photoacoustic Spectroscopy is one of the prominent and sensitive tools being utilized for detection and identification of these substances (explosive, chemical and drugs) [1-15]. Depending upon the application scenarios, several approaches in photoacoustic spectroscopy have been adopted for instance if the sample of the material to be examined is available by any means (i.e. samples collected after the blast) the resonant photoacoustic cavity is utilized for enhancing the signal [10]. The design of resonant cavity that can be utilized has been discussed at length by Miklós A, et al. [10] and Baumann B, et al. [11]. For other application such as scanning a surface from short distance for presence of any suspicious substance, cylindrical resonant tube is utilized to enhance the photoacoustic signal [13]. In this configuration, the detection range is enhanced by utilizing a photoacoustic reflector in conjunction with the resonant tube coupled detector [14]. In both the configurations, the detector used is a sensitive microphone having resonance frequency in the range of interest. A modified version of photoacoustic spectroscopy, popularly known as Quartz Enhanced Laser Photo acoustic Spectroscopy (QE-LPAS) is also emerging as a powerful tool for standoff detection and identification of hazardous substances [15,16]. In the QE-LPAS, the detector is Quartz Tuning Fork which is very sensitive. It works at particular resonant frequency making it immune to the surrounding disturbances. The system consisting of this detector is very sensitive to the alignment of transmitted light and the received one. Therefore, it is only best suitable for the places where the system is kept stationary and a pre-aligned retro-reflector is installed. In this scenario, any hazardous fumes or aerosol coming in the path of laser beam will get detected and identified. Thus each approach/configuration of photoacoustic spectroscopy has some advantages and disadvantages making them suit to different application scenario [16].

In this paper, some results of photoacoustic cell based and resonant tube based bench-top experimental configurations are being reported. Samples taken in the experiments are Acetone (precursor of TATP), DMMP (stimulant of Sarin) and Morphine (drug). Spectra have been recorded on oscilloscope as well as through the data acquisition software.

Methodology

The experiments have been conducted in two stages corresponding. First, the experiments with PA cell configuration were carried out followed by resonant tube based configuration.

Experiments with PA cell based configuration

The schematic of experimental setup is shown in Figure 1. The actual photograph of the photoacoustic cell is shown in inset of Figure 1. During the experiments, samples were kept in the PA cell having opening at the top and the detector (microphone) was couples to the horizontal arm of the PA cell which also acts as resonant cell. The design methodology of the PA cell has been discussed in detail elsewhere [10]. In the present setup, the resonant frequency of the cell was around 40 kHz. A pulsed tunable Quantum Cascade Laser having wavelength in desired range (900 to 1400 cm-1) was used. A 40 kHz quartz microphone was used as a detector. The laser (modulated at the resonant frequency of the detector) is allowed to interact with the sample as per the schematic diagram. Due to the interaction of the modulated laser with the sample; absorption and subsequent pulsating heat generation takes place resulting in the generation of acoustic wave in the sample which propagates through the boundary layer and coupling media to the microphone. The acoustic wave intensity is amplified by the PA cell. The PA signal received by microphone is converted to electrical signal and amplified further by a pre-amplifier and routed to Lock-in-amplifier. A reference signal from the function generator at the frequency matching with the modulation frequency of the laser driven by the same function generator is fed to the Lock-in amplifier. The laser is then tuned in the desired wavelength to get photoacoustic signal as a function of wavelength. The output of the Lock-in amplifier is monitored on the oscilloscope (signal as a function of time) and also recorded as a function of wavelength using a Lab view based Graphical User Interface (GUI) based software. The hardware of the experimental setup is shown

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Received: 01 September, 2023, Manuscript No. JLOP-23-115012; **Editor Assigned:** 04 September, 2023, PreQC No. P-115012 **Reviewed:** 16 September, 2023, QC No. Q-115012; **Revised:** 22 September, 2023, Manuscript No. R-115012; **Published:** 29 September, 2023, DOI: 10.37421/2469-410X.2023.10.96

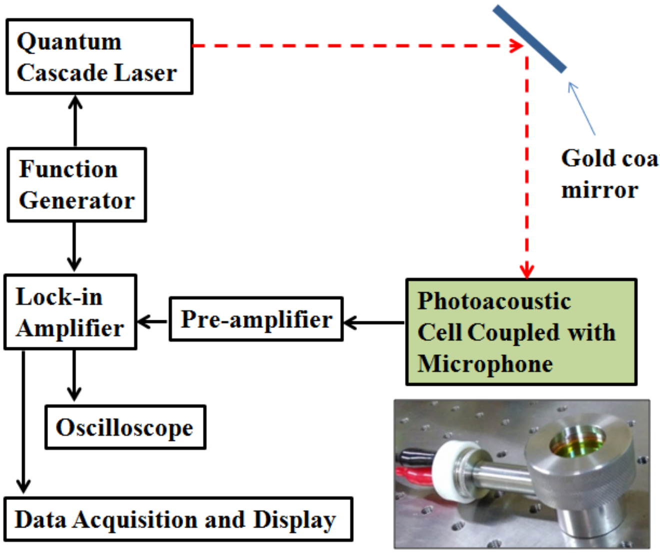

Figure 1. Schematic arrangement of the experimental setup. In the inset photograph of PA cell coupled with microphone is shown.

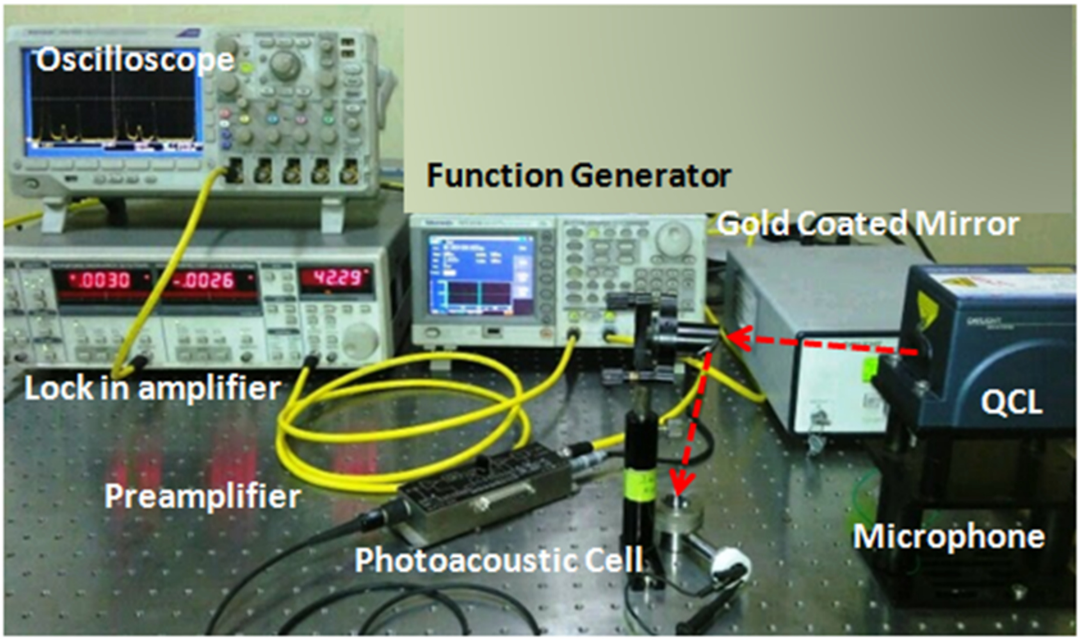

Figure 2. Hardware of the experimental setup.

in (Figures 1 and 2).

Figure 3 shows the enlarged image of the gold coated beam folding mirror and PA cell coupled with microphone detector (Figure 3).

Experiments with resonant tube based configuration

Figure 4 depicts the schematic diagram of the experimental setup. A closer view of the resonant tube coupled with microphone detector is shown in the inset. The details of the design of the resonant tube are described elsewhere [13]. In this configuration, all the components are same as those utilized for experiments in PA Cell configuration except the PA cell. The PA cell is replaced with the resonant tube which also acts as a probe for scanning the contaminated surfaces. As earlier, the modulated laser is allowed to impinge on the surface to be scanned. Acoustic wave is generated in the sample and propagates towards the probe (Figures 4 and 5)

That detects the wave and converts it in to electrical signal. The laser is then tuned in the desired range to get the photoacoustic signal as a function of wavelength/wavenumber. The recording/monitoring of signal is done as described for the previous configuration experiments. The resonant tube was designed to have resonant frequency around 40 kHz. The hardware of the setup is shown in Figure 5 where the contaminated surface shown is cloth. The distance between the probe and the surface to be scanned is 30 cm.

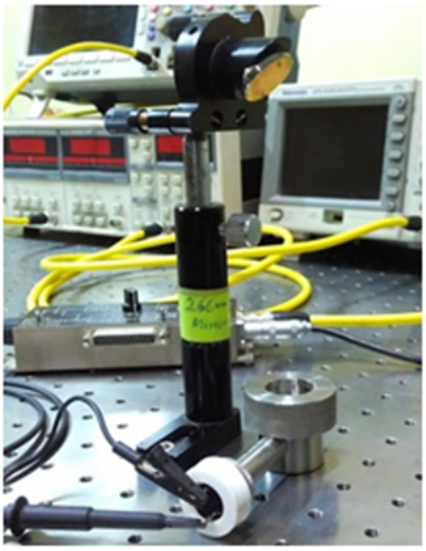

Figure 3. Close view of the gold coated beam folding mirror and PA cell coupled to microphone detector.

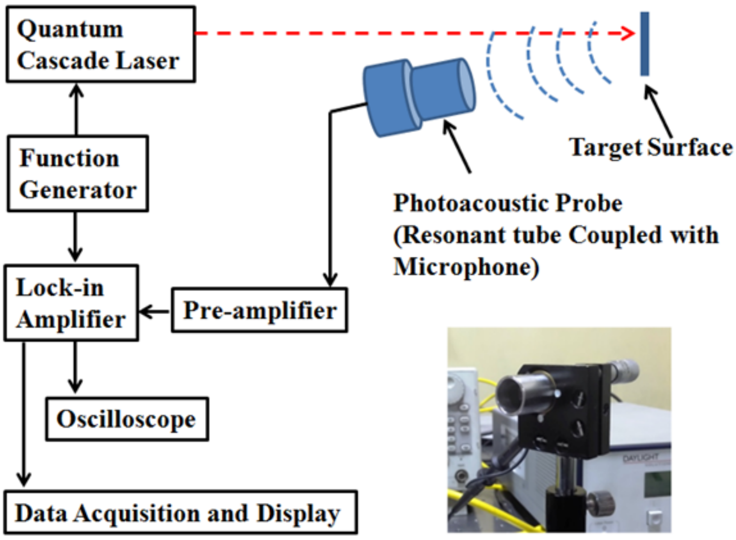

Figure 4. Experimental setup in resonant tube configuration. Image of resonant tube coupled with microphone (inset).

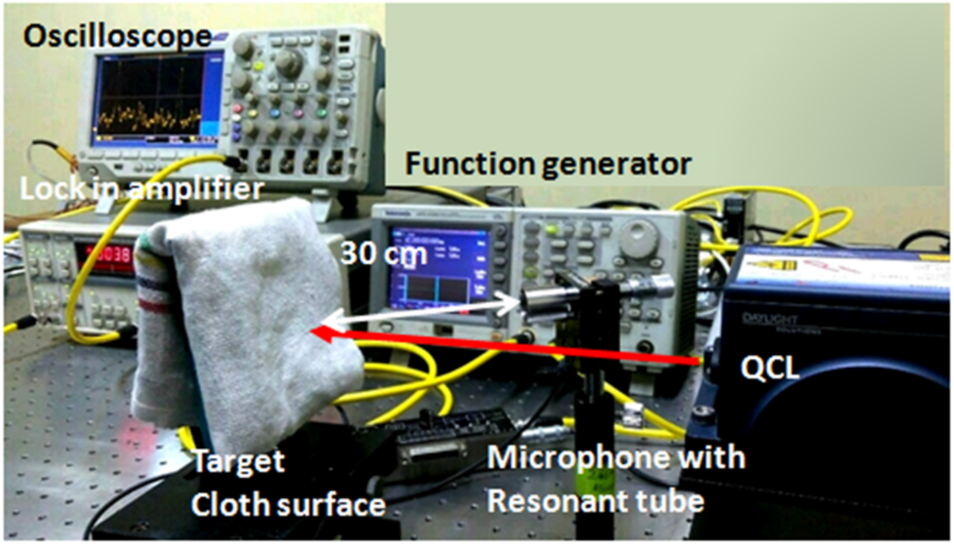

Figure 5. Hardware of the experimental setup for resonant tube configuration.

Results and Discussion

In all the experiments the laser was operated at a modulation frequency of ~ 40 kHz (ultrasonic frequency matching with the resonant frequency of PA cell and the resonant tube). The recorded spectra have been shown in Figures 6 to 9 for CWA, Explosive and Narcotics respectively. In Figure 6, a, b, c and d correspond to temporal spectra of DMMP with varied quantities of 500 ng, 300 ng, 100 ng and the background respectively, recorded on oscilloscope. The peak position of DMMP ($CH_3PO(OCH_3)_2$, stimulant of Sarin) was observed at 1275 cm^{-1}. The peak position (in terms of wave number) was estimated by utilizing the rate of tuning of Quantum cascade laser and time of the peak on the oscilloscope. The detection limit of DMMP achieved was ~100 ng. The signal to noise less than that shown in Figure, 6c was not considered as valid signal although the software can distinguish the peak with lesser signal to noise ratio to avoid the possibility of false detection/identification. Figure 7 shows the spectra of DMMP (with varied quantity) recorded using data acquisition software. Strong absorption of CH stretching in DMMP molecules is clearly visible at ~ 1275 cm^{-1}. In Figure 7, blue, red and black spectra correspond to 500 ng, 200 ng quantity of analyte (DMMP) and the background (empty PA cell) (Figures 6 and 7).

The results from the experiments based on resonant tube i.e. standoff scanning from short distance of 0.3 m are shown in Figures 8 to 10. Figure 8 shows Standoff Quantum Laser Photoacoutic Signal (a.u) of Acetone (CH3)2-C=0, Precursor of TATP) from distance of 0.3 meter. In the figure spectra (a), (b) and (c) correspond to Quantities of 600 ng, 300 ng and 100ng respectively the background spectrum (cloth surface without any analyte sample) is depicted by

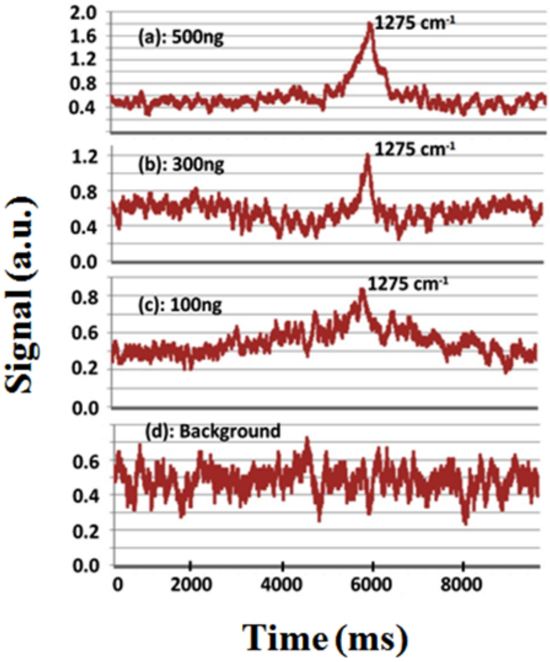

Figure 6. Photoacoustic signal (a.u.) of DMMP (Simulant of CWA) of quantity **a)** 500 ng, **b)** 300 ng, **c)** 100 ng and **d)** Background profile with time recorded on oscilloscope.

(d). In the spectra two strong peaks at (~ 1216 cm^{-1}, and 1237 cm^{-1}) corresponding to -C=0 and C-C band stretching are clearly resolved. The signal with appreciable signal to noise ratio has been achieved with ~ 50 ng quantity of Acetone. Figure 8 shows the Standoff Quantum Laser photoacoustic signal (in a.u.) of drug (Morphine) from the distance of 0.3 meter. In the Figure 9, the spectrum shown by (a) corresponds to a quantity of 500 ng of Morphine ($C_{17}H_{19}NO_3$) whereas (b) shows

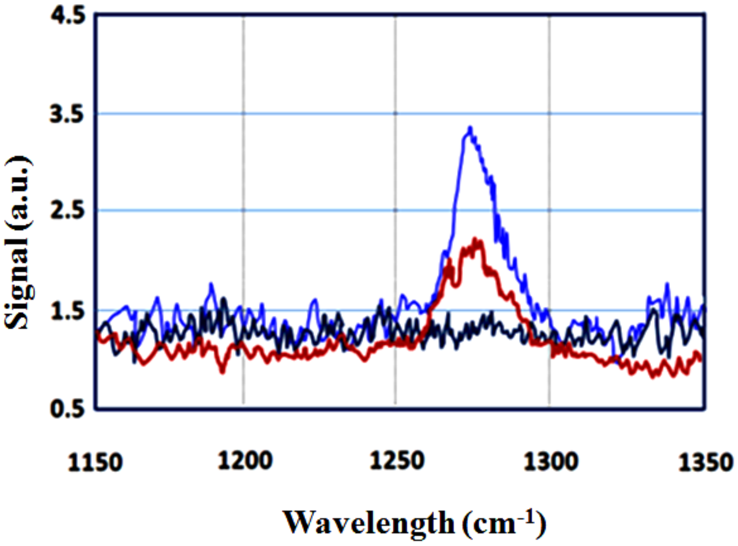

Figure 7. Quantum laser photoacoustic signal (a.u.) of DMMP (Simulant of CWA) at a distance of 30 cm of quantity 500 ng (blue colour spectrum), 200 ng (red color spectrum) and background profile (black color spectrum).

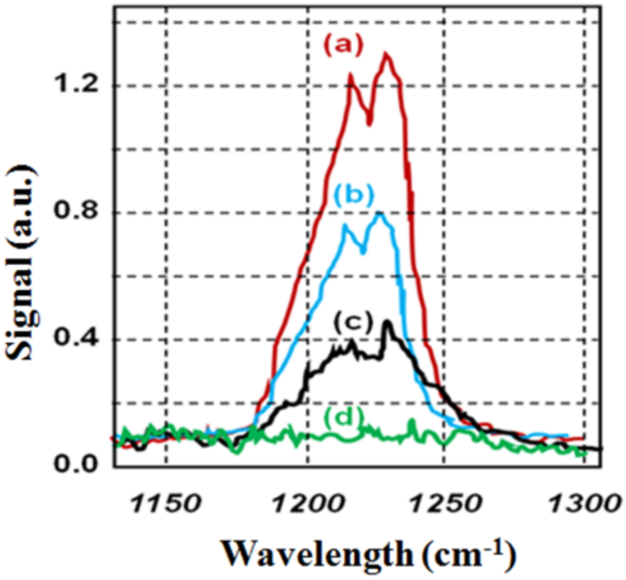

Figure 8. Standoff Quantum Laser Photoacoustic Signal (a.u.) of Acetone (Precursor of TATP utilized in IEDs) at distance 0.3 meter of quantity **a)** 600 ng, **b)** 300 ng, **c)** 80 ng and **d)** shows the background profile.

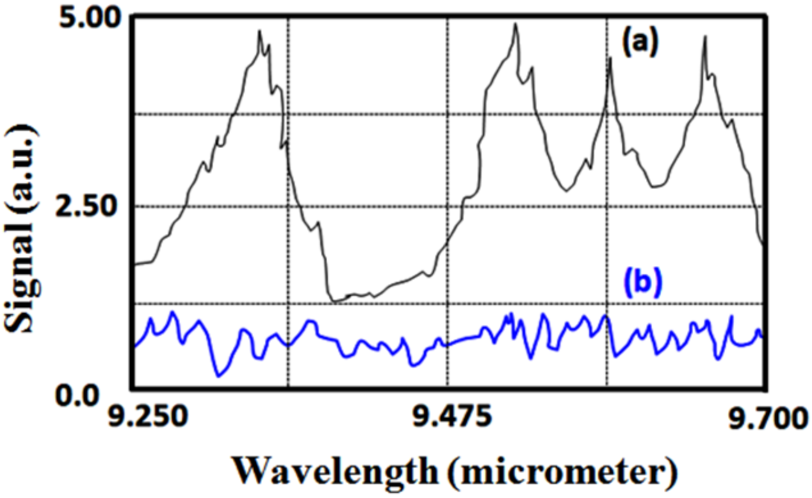

Figure 9. Standoff quantum laser photoacoustic signal (a.u.) of Drug (Morphine) at distance of 0.3 meter with quantyiyy a) 500ng and b) Meter and quantity background profile.

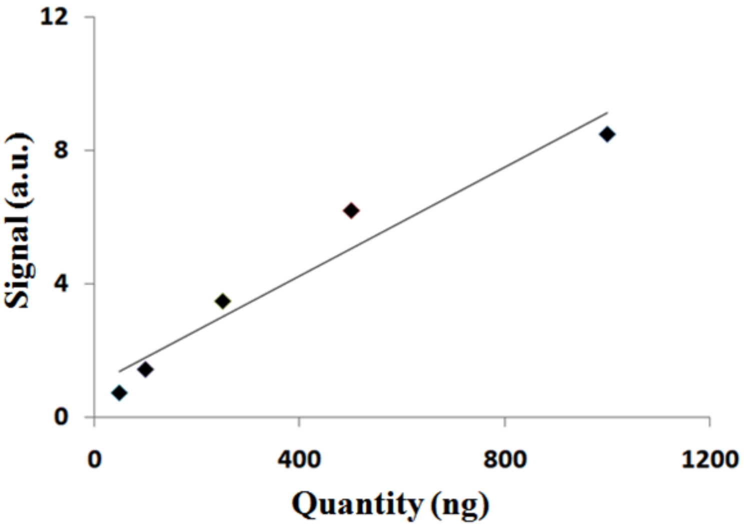

Figure 10. Standoff quantum laser photoacoustic signal (a.u.) of drug (Morphine) at distance 0.3 meter *vs.* quantity of morphine drug.

the background spectrum. The amount of Morphine from which photoacoustic signal was received successfully was of the order of 75 ng. The recorded signal strength for Morphine has been plotted with the quantity of Morphine and shown in Figure 10. There are four clearly resolved peaks of Morphine at wavelengths ~ 9.311, 9.541, 9.597 and 9.653 μm. The present technology is capable to detect any type of drugs (Figures 8-10).

Conclusion

Detection experiments with different types of analytes (CWA, Explosive and drug) have been carried out using Photoacoustic spectroscopy in two different configurations namely PA cell based for point detection of traces of these substances and resonant tube/probe based experiments for scanning kind of application. Spectra have been recorded in both the configurations successfully. The primary takeaway from these studies is that the techniques are good enough to detect the trace analytes of hazardous substances and has the potential to be converted in to compact man portable devices for defence, security and forensic applications.

Acknowledgement

Authors are thankful to Professor Kamal Singh at IISER Mohali for fruitful discussion on the experimental work.

Conflict of Interest

None.

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How to cite this article: Sharma, Ramesh C., Subodh Kumar, Abhishek Parmar and Neeraj Bhargava, et al. “Quantum Laser Sensor for Defence and Security.” *J Laser Opt Photonics* 10 (2023): 96.