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Quantum Cascade Lasers (QCLs) for Standoff Explosives Detection: LDRD 138733 Final Report

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Quantum Cascade Lasers (QCLs) for Standoff Explosives Detection: LDRD 138733 Final Report

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Abstract

Continued acts of terrorism using explosive materials throughout the world have led to great interest in explosives detection technology, especially technologies that have a potential for remote or standoff detection. This LDRD was undertaken to investigate the benefit of the possible use of quantum cascade lasers (QCLs) in standoff explosives detection equipment.

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Acronyms

IED	Improvised explosive device
IR	infrared
MIR	mid-infrared
QCL	quantum cascade laser
RDX	cyclotrimethylenetrinitramine
TNT	2,4,6 trinitrotoluene
VBIED	vehicle-borne improvised explosive device
μm	micrometer

Executive Summary

Standoff detection of explosives is currently one of the most difficult problems facing the explosives detection community. Increased domestic and troop security could be achieved through the remote detection of explosives. An effective remote or standoff explosives detection capability would save lives and prevent losses of mission-critical resources by increasing the distance between the explosives and the intended targets and/or security forces. Many sectors of the US government are urgently attempting to obtain useful equipment to deploy to our troops currently serving in hostile environments.

This LDRD was undertaken to investigate the potential benefits of utilizing quantum cascade lasers (QCLs) in standoff detection systems. This report documents the potential opportunities that Sandia National Laboratories can contribute to the field of QCL development. The following is a list of areas where SNL can contribute:

- Determine optimal wavelengths for standoff explosives detection utilizing QCLs
- Optimize the photon collection and detection efficiency of a detection system for optical spectroscopy
- Develop QCLs with broader wavelength tunability (current technology is a 10% change in wavelength) while maintaining high efficiency
- Perform system engineering in the design of a complete detection system and not just the laser head
- Perform real-world testing with explosive materials with commercial prototype detection systems

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1. Introduction

1.1 Background

Increased domestic and troop security could be achieved through standoff detection of improvised explosive devices (IEDs), and vehicle-borne improvised explosive devices (VBIEDs). An effective standoff explosives detection capability would save lives and prevent losses of mission-critical resources by increasing the distance between the explosives and the intended targets and/or security forces. Many sectors of the US government are urgently attempting to obtain useful equipment to deploy to our troops currently serving in hostile environments.

Recent developments in optoelectronics have enabled significant advances in quantum cascade lasers (QCLs). QCL system size has been reduced from large laboratory laser table size to small rugged field-size units. QCLs have increased their power output to Watts, which enable long-distance applications. QCL wavelengths are dependent on fabrication design and can be tailored to specific wavelengths.

1.2 Overview

LDRD project 138733, conducted from April 2009 to September 2009, investigated the possible use of quantum cascade lasers (QCLs) in standoff explosives detection equipment. Personnel in the Contraband Detection department at SNL participated in the project.

1.3 Purpose

The purpose of this project was to investigate any potential benefits of using QCLs for standoff explosives detection.

1.4 Objectives

To achieve the purpose, the following objectives were defined:

- Investigate the technical readiness of current QCL technologies
- Investigate the possible use of QCLs for explosives detection

2. Discussion

2.1 Basic Laser-Based Optical Stand-off Spectroscopy

Laser-based optical stand-off spectroscopy is a simple concept. The laser provides a radiation source that interacts with a chemical substance, which in this case is an explosive vapor. The interaction of the radiation and vapor results in an optical signature the can be detected and analyzed using an optical receiver and computational analysis for the spectroscopy. Figure 1 shows a schematic of the system and subsystems.

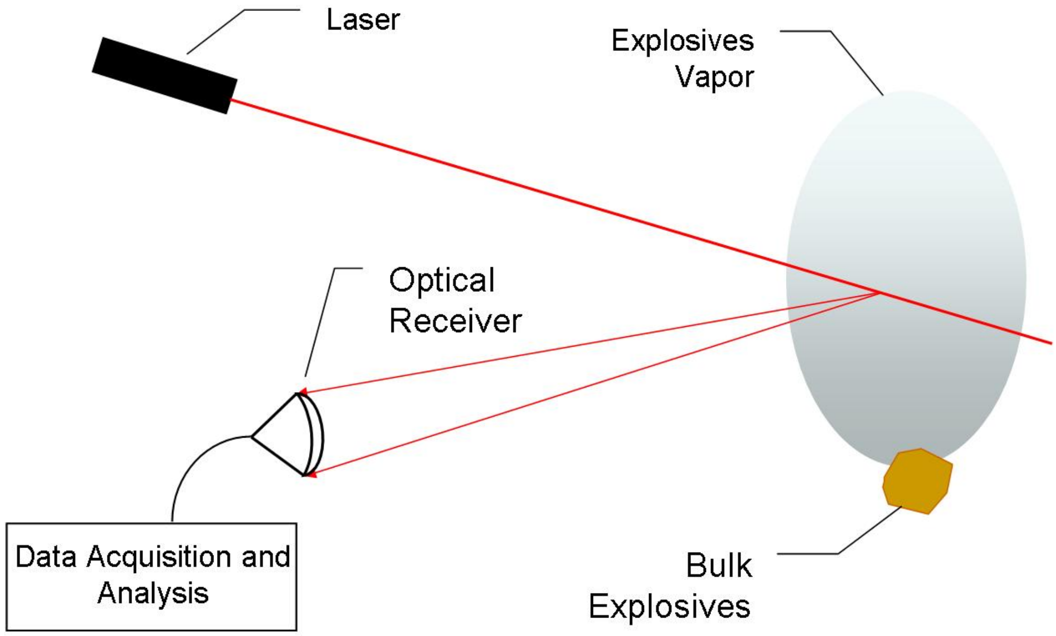

Figure 1. Laser-based Stand-off Explosives Detection Schematic

From a system perspective, Figure 1 shows a relatively simple idea. But, in fact, it is complex when all of the factors that influence a laser-based optical spectroscopy system are considered. These factors include:

1. Power-laser radiation
2. Atmospheric adsorption
3. Concentration of the chemical (in this case explosive vapor)
4. Laser characteristics
5. Interaction of the laser radiation and the chemical
6. Collection of scattered radiation after interaction
7. Receiving optics
8. Detector sensitivity

Combining these factors provides a mathematical model for a laser-based optical spectroscopy stand-off detection system. The equation in Figure 2 shows how each factor is interdependent in the entire system.

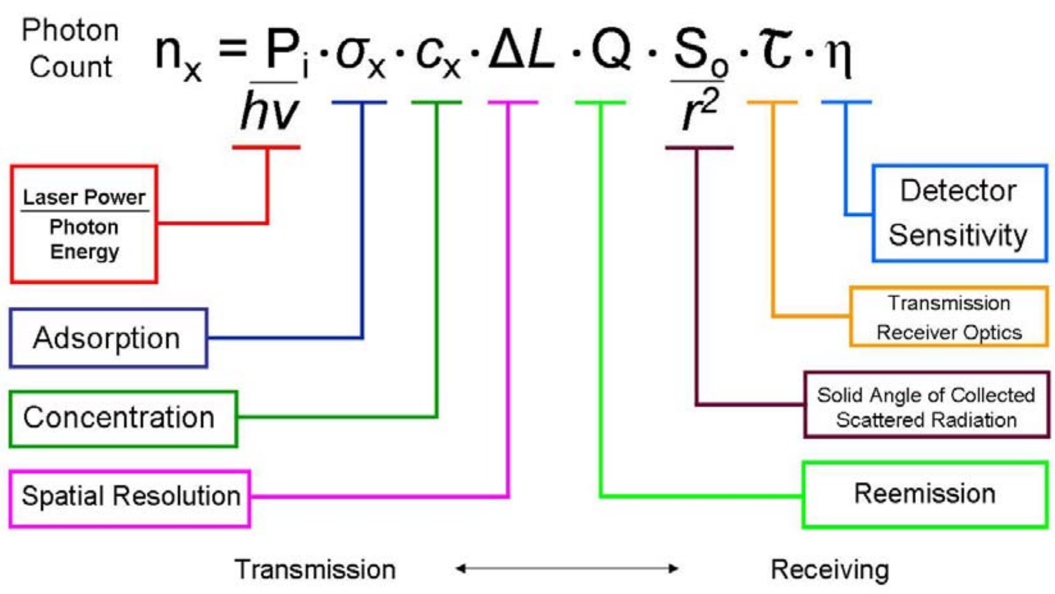

Figure 2. Mathematical Model depicting laser-based detection.

Many factors influence the number of photons that can be ultimately detected, including:

1. The laser power
2. The interaction of the laser radiation and the chemical in question
3. The amount of scattered radiation that can be collected
4. The efficiency of the receiver optics and detector

From these factors, only items 1, 3, and 4 (laser power, collecting scattered radiation, and receiver optical efficiency and detector efficiency) can be addressed through technology. Other factors such as environmental conditions, properties of the chemical substance, and physics cannot be controlled by technology.

2.2 QCL Basics

Conventional semiconductor lasers emit electromagnetic radiation (a single photon emitted) when a high-energy electron in the conduction band combines with a hole in the valence band. This interband transition is determined by the energy gap between the valence and conduction bands. Quantum cascade lasers are a special kind of semiconductor laser, where the laser transitions are not between different electronic bands (valence and conduction) but on intersubband transitions of the semiconductor structure. The device is designed to have a superlattice where the probability of electrons are in varying energy locations that lead to the splitting of a band into multiple permitted energies. In this process, a single electron can cause the emission of multiple photons. Thus, QCLs can have higher output powers than other semiconductor lasers. The transition energies of the laser are defined not by fixed material properties (band gap), but rather by design parameters such as the thickness of the device’s quantum wells. QCLs can be designed for operating wavelengths ranging from a few micrometers (μm) to well above 10 μm and into the terahertz region, but usually are designed to emit in the mid-infrared (IR) region (3 to 24 μm). QCLs can operate in a broad temperature range, but most applications are at room temperature. At room temperature, the peak power level can be as much as 5 watts when pulsed.

Table 1 includes current QCL manufacturers with their contact information. Some of the manufacturers sell lasers only and not complete detection systems. From the websites, several manufacturers claim that IR detection using QCLs are many orders more sensitive than performing traditional Fourier Transform Infrared (FTIR) detection.

Table 1. Vendor list for Commercially Available Quantum Cascade Lasers (QCLs)

Company	Phone number	Web address (URL)	Mailing address
Pranalytica, Inc.	310-458-0808	www.pranalytica.com	1101 Colorado Avenue Santa Monica, CA 90401
Daylight Solutions, Inc.	858-413-1208	www.daylightsolutions.com	13029 Danielson St. Poway, CA 92064
Cascade Technologies	+ 44-1786-447721	www.cascade-technologies.com	Unit A, Logie Court, Stirling Innovation Park, KF(4NF, Scotland, UK
AdTech Optics	626-956-1000	www.atoptics.com	18007 Cortney Court City of Industry, CA 91748
Alpes Lasers SA	+41-327299510	www.alpeslasers.com	1-3 Max.-de-Meuron C.P. 1766 CH-2001 Neuchatel Switzerland

2.3 Stand-off Explosives Detection Requirements

A variety of methods are used to detect explosives when the detector and sampling scheme are either in direct contact with or relatively close to (< 10 centimeters) the explosive. These methods usually involve trace detection (where an actual sample of the explosive is acquired) or bulk detection using X rays (where the actual explosive is detected.) There are instances in an outdoor environment, for example, where detection beyond ten centimeters is possible utilizing trace. This distance, however, is not always dependable because of environmental conditions such as wind speed and direction or temperature. For true stand-off detection (> 10 meters) an optical analysis of the chemical signature is the only method that is plausible. Laser-based detection has been demonstrated for chemical detection, but often in a laboratory environment. For a QCL stand-off explosives detection to be a field-ready system, additional factors are needed. The field-ready system would require high laser power output (abundance of photons), low power consumption, ambient temperature operation, and small size for portability. Finally, chemicals, i.e., explosives, are best detected when the wavelength of radiation falls in the mid-infrared (MIR) region (3 to 30 μm) of the electromagnetic spectrum. This is because small molecules exhibit the strongest absorption of radiation between these wavelengths for spectroscopy detection. The absorption of light provides a means for detecting and quantifying chemicals, though reflection of light can also be used for detection. Figure 3 shows the electromagnetic spectrum versus the various laser types and typical operating wavelengths. For the 3 to 30 μm wavelength, Quantum Cascade Lasers (QCLs) potentially offer the broadest wavelengths for mid-infrared spectroscopy. Also, QCLs offer high laser output versus power input, the laser can operate at room temperatures, and QCLs are solid-state devices so small packaging is possible for portability.

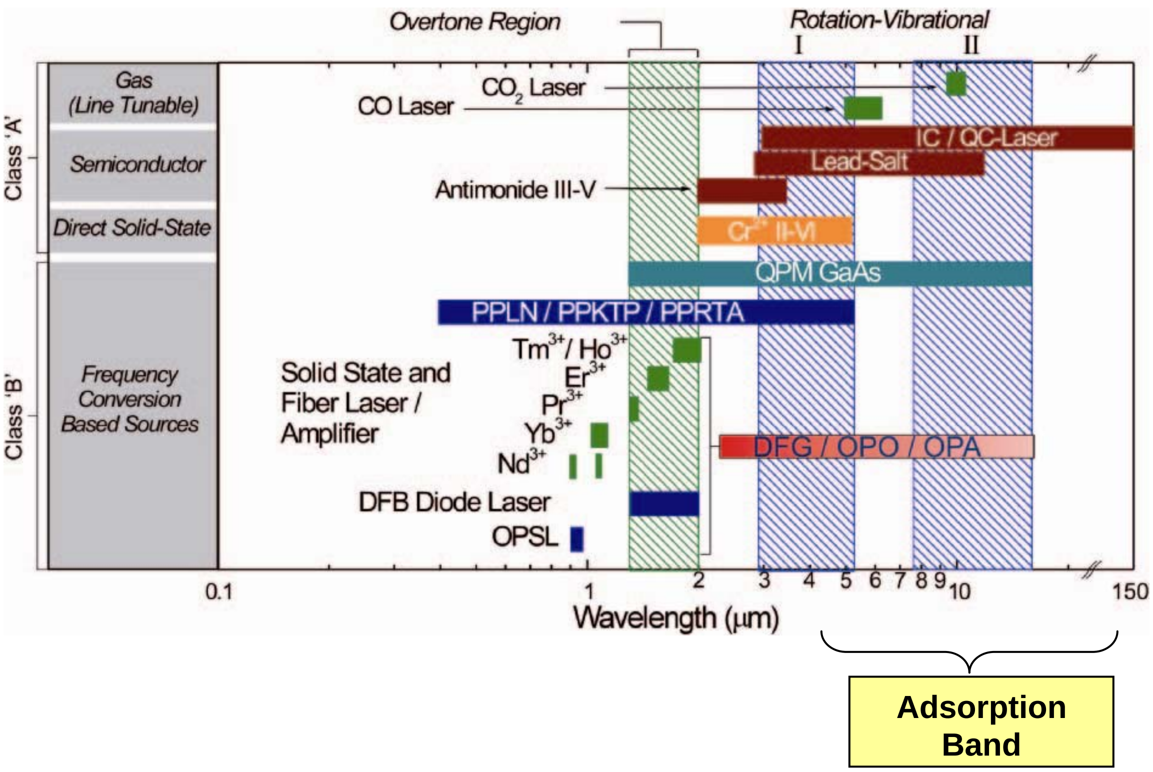

Figure 3: Infrared Laser Sources and Spectral Coverage (Figure source: Tittel, et al.)

2.4 QCLs Applied to Standoff Detection

For the application of atmospheric remote sensing, the wavelength windows must be chosen where the atmosphere is transparent. Figure 4 shows an MIR transmission spectrum for humid air, TNT, and RDX. The wavelength window located at 6.25 μm region is noted with a red line as it is located at a narrow band where humid air is transparent, which would allow propagation over distances and where both TNT and RDX have a unique signature.

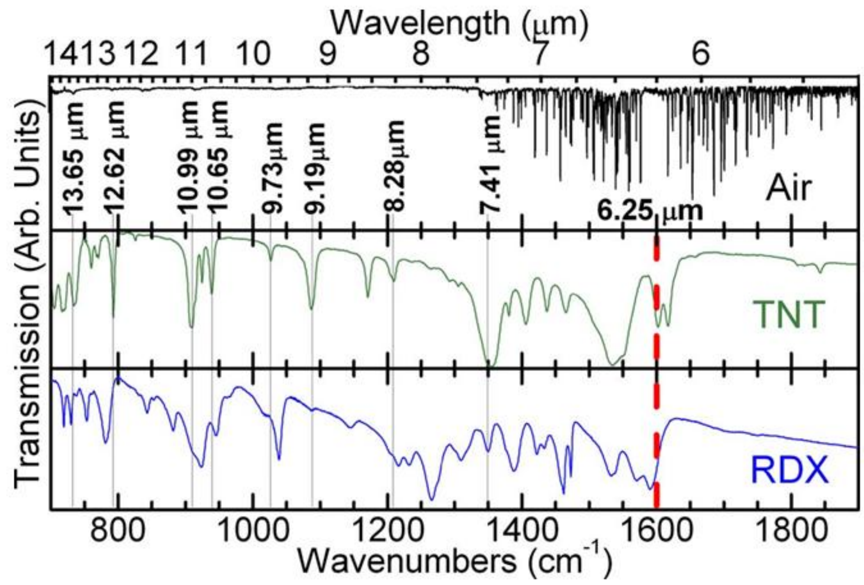

Figure 4: IR transmission spectra of humid air, TNT and RDX. Shared absorption bands are highlighted (Figure Source: Furstenberg, et al.)

QCLs are ideal for standoff applications due to their wavelength range, high laser power, narrow linewidth, tunability, and low beam divergence. Additionally, QCLs are small, compact (see Figure 5), and consume low power due to room temperature operation. QCLs are robust because they are solid-state and are very reliable.

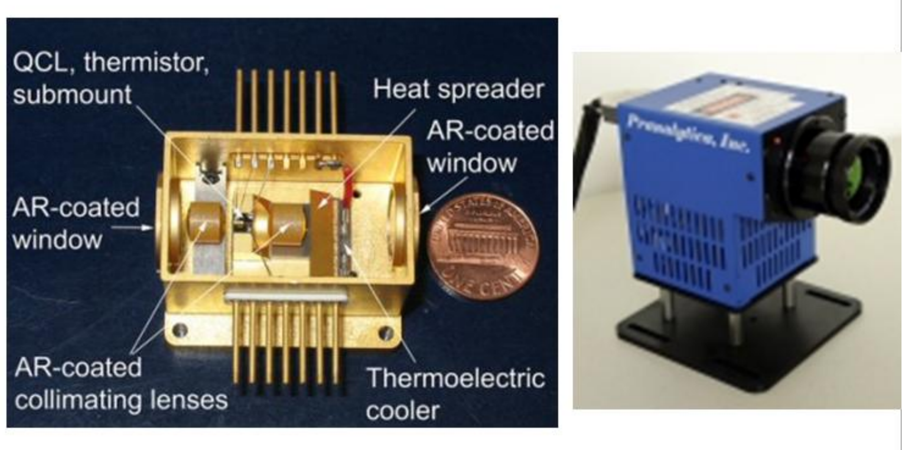

Figure 5: Photos of the Pranalytica QCL laser head. (Model 1101-46-XXXX, pulsed high power room temperature laser, taken from Pranalytica's website)

3. Opportunities for Future Work

The idea of a solid-state semiconductor laser with a superlattice was proposed in 1971, with the first demonstration of a QCL in 1994 at Bell Laboratories. The first commercialization of a QCL product was in 2004. The QCL laser optics field is a rapidly evolving field that is still in its infancy.

Sandia National Laboratories has a unique opportunity to contribute to QCL development before the field reaches full maturity. The following is a list of areas where SNL can contribute:

- Determine optimal wavelengths for standoff explosives detection utilizing QCLs
- Optimize the photon collection and detection efficiency of a detection system for optical spectroscopy
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