QCL as a Game Changer in MWIR and LWIR Military and Homeland Security Applications

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ABSTRACT

QCLs represent an important advance in MWIR and LWIR laser technology. With the demonstration of CW/RT QCLs, large number applications for QCLs have opened up, some of which represent replacement of currently used laser sources such as OPOs and OPSELs, and others being new uses which were not possible using earlier MWIR/LWIR laser sources, namely OPOs, OPSELs and CO_2 lasers.

Pranalytica has made significant advances in CW/RT power and WPE of QCLs and through its invention of a new QCL structure design, the non-resonant extraction, has demonstrated single emitter power of >4.7 W and WPE of >17% in the 4.4µm-5.0µm region. Pranalytica has also been commercially supplying the highest power MWIR QCLs with high WPEs. The NRE design concept now has been extended to the shorter wavelengths (3.8µm-4.2µm) with multiwatt power outputs and to longer wavelengths (7µm–10µm) with >1 W output powers. The high WPE of the QCLs permits RT operation of QCLs without using TECs in quasi-CW mode where multiwatt average powers are obtained even in ambient T>70°C. The QCW uncooled operation is particularly attractive for handheld, battery-operated applications where electrical power is limited.

This paper describes the advances in QCL technology and applications of the high power MWIR and LWIR QCLs for defense applications, including protection of aircraft from MANPADS, standoff detection of IEDs, in-situ detection of CWAs and explosives, infrared IFF beacons and target designators. We see that the SWaP advantages of QCLs are game changers.

Keywords: Quantum cascade lasers, infrared lasers, high power lasers, tunable infrared lasers, sensitive detection of CWAs, TICs and explosives, standoff detection of explosives

1. INTRODUCTION

Considerable progress continues to be made in the areas of laser sources at all wavelengths. But, the progress in the infrared laser sources has been phenomenal in the last few years because of new concepts that are proving to be very necessary for the advances and because of the tremendous pull from the user community that has continued to provide the impetus for continual improvements. In particular the quantum cascade lasers, unipolar semiconductor lasers, were first experimentally demonstrated [1] in 1994 with the first demonstration of CW operation of the QCLs at room temperature [2] occurring in 2002. Since then the progress has been extremely rapid with two groups that have provided much of the leadership in new designs and demonstrations of high power, continuous wave/room temperature (CW/RT) QCLs in the MWIR and LWIR regions [3,4]. At present, the highest power that has been reported in the MWIR region [5,6] is about 5 W with device electrical power input to optical power output conversion efficiency (wall plug efficiency, WPE) of about 20% for TEC cooled devices with operation at ~ 20°C. Under similar operating conditions, CW/RT power outputs in excess of 1.4 W and WPE of 10% have been achieved [7] at a wavelength of ~7.2 µm. Our nonresonant extraction design [4,8] for QCL structures has permitted obtaining high powers and high WPE at even longer wavelengths.

The high CW/RT powers and WPE already achieved are very suitable for operation of these QCLs under quasi-continuous wave operation [pulsed operation at high (~50%) duty cycle] where the efficient heat removal between the pulses permits high power, high WPE performance without the use of thermoelectric coolers. Such operation has allowed us to significantly miniaturize the high power QCLs, producing average

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power of over 2.5 W in QCW operation. Such total systems, including the hermetically sealed butterfly package with beam collimating optics and the associated pulsed drivers, weigh no more than 2 oz. and are very suitable for handheld applications where high MWIR and LWIR powers are needed but with size, weight and power (SWaP) limitations.

The high powers and high WPE achieved with QCLs, are drivers making the QCLs ideal lasers for a broad range of defense and homeland security applications. The MWIR and LWIR QCLs are becoming game changers for a broad range of these applications because of their SWaP superiority over almost all other laser sources (as we shall see a bit later in this paper) in this region.

2. NEW QCL STRUCTURE DESIGNS

Many if not all QCL structure designs aim to facilitate rapid depopulation of the lower laser level of the QCL using mechanisms that take advantage of rapid nonradiative relaxation of a level in a semiconductor when the energy spacings involved in energy relaxations match a longitudinal optical phonon energy of the semiconductor material. In the InGaAs/InAlAs system (currently successful QCL materials system), the first QCL operation was demonstrated using single phonon resonance scheme (where on transition energy from the lower laser level to the next lower level equals the LO phonon energy, E_{LO} of ~35 meV). However, single phonon resonance relaxation QCLs did not achieve continuous wave operation at room temperature (CW/RT operation). Faist's group showed that using a two phonon relaxation scheme (where two consecutive lower levels starting with the lower laser level are each separated by E_{LO}) one could achieve CW/RT operation. The first CW/RT operation of QCLs was achieved with the 2-phonon resonance design, which has been successful in producing QCLs with power levels approaching 5 W and WPE of~ 20%. However, the 2-phonon design is overconstrained and imposes limitation on ways by which one can manipulate other levels for efficient pumping of electrons in the upper levels. Pranalytica scientists recognized that it is possible to retain the rapid depopulation of the lower laser level without the 2-phonon resonance, by modifying the overall design that permits an increase in the spacings of levels below the lower laser level and an increase in the number of levels below the lower laser level. This increased multiplicity of levels below the lower laser level compensates for reduced nonradiative depopulation transition probability by having multiple paths for depopulation. Pranalytica has named this scheme the nonresonant extraction (NRE) design [8]. Using NRE design, Pranalytica has become one of the two key groups worldwide to produce the highest power/highest WPE MWIR QCLs at or near 4.6 µm. Furthermore, the NRE design has made it possible to fabricate QCLs at shorter and longer wavelengths with improved performance [7].

3. QCLS FROM LABORATORY TO APPLICATIONS

Until about 2004, QCLs were primarily laboratory curiosities, with very few insertions into real experiments and applications. Pranalytica led the way by introducing a number of critical engineering innovations in packaging QCLs for reliable and long life usefulness. These innovations included the first epi-side mounting using Au:Sn hard solder for much improved thermal management as well as high performance over a long lifetime of operation, mounting the QCLs on AlN submounts which provide good thermal transport with excellent coefficient of thermal expansion (CTE) match between the submount and the QCL material system and the use of telecom grade materials and packaging procedures [9]. Recent advances include the use of AlN:SiC submounts [10] which provide greater thermal conductivity than AlN submounts without sacrificing the CTE match necessary for long term reliability of devices. For insertion into applications without any additional effort by the user, Pranalytica packages the high power QCLs in hermetically sealed butterfly packages which include the QCL on an appropriate submount, associated TEC in case of true CW operation (if needed), and QCL laser output collimating optics for providing a well collimated beam to the user.

Figure 1 provides a summary of various fully packaged QCLs that are now available.

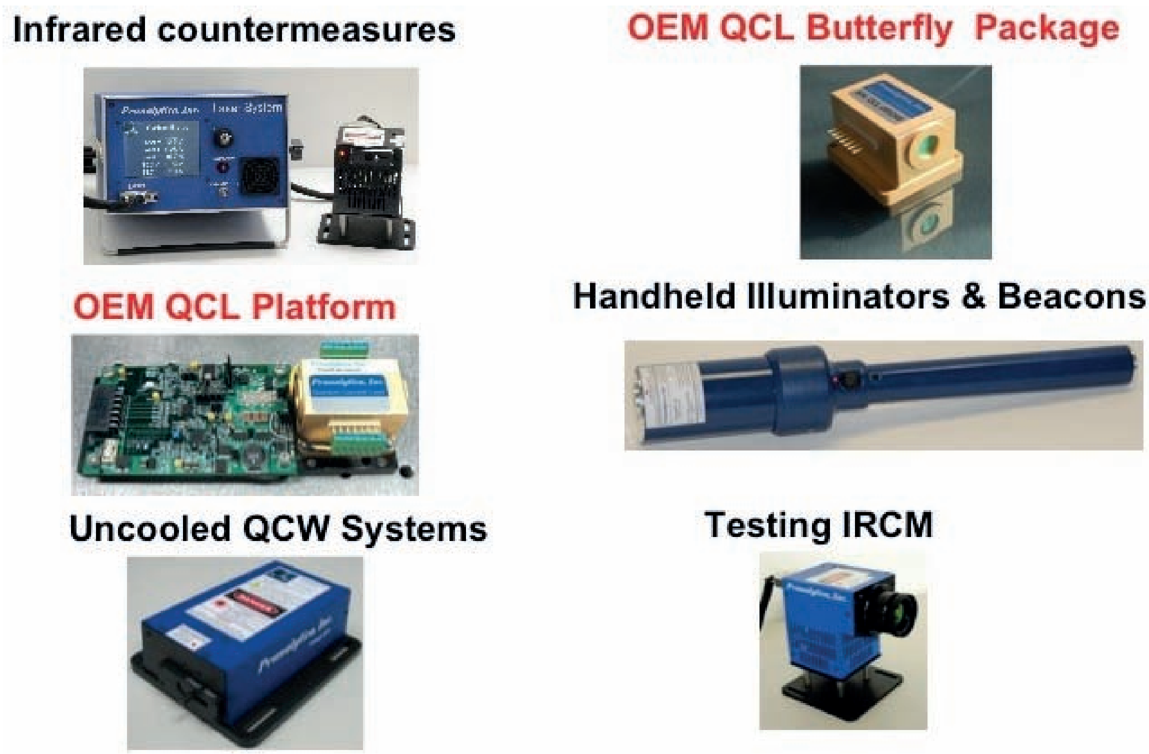

Figure 1. Fully packaged QCL systems for various applications. Note that the OEM QCL butterfly package and the OEM QCL platform meet MIL-STD vibration/shock & temperature requirements (Test protocols derived from MIL-STD-810G).

The scientific advances described in Section 2 above and the engineering advances have permitted us to provide high power, high reliability fully packaged QCLs for a broad range of applications. Tables 1 and 2 provide sample data on high performance QCLs operated in CW/RT and QCW/RT modes.

Table 1. Typical CW/RT performance of fully packaged QCLs, ready for installation in applications

BEST CW/RT LASER PERFORMANCE (w/TEC)		
Wavelength	Power Output (W)	WPE
~4.6 μm	> 4.7 W	> 16%
~4.0 μm	> 2.5 W	~ 10%
~7.1 μm	> 1.4 W	~ 10 %

Table 2. Typical QCW/RT performance of fully packaged QCLs, ready for installation in applications

BEST QCW/RT LASER PERFORMANCE (No TEC)		
Wavelength	Power Output (W)	WPE
~4.6 μm	> 3 W	> 10%
~4.0 μm	> 2 W	~ 7%
~7.1 μm	> 1.5 W	~ 12 %

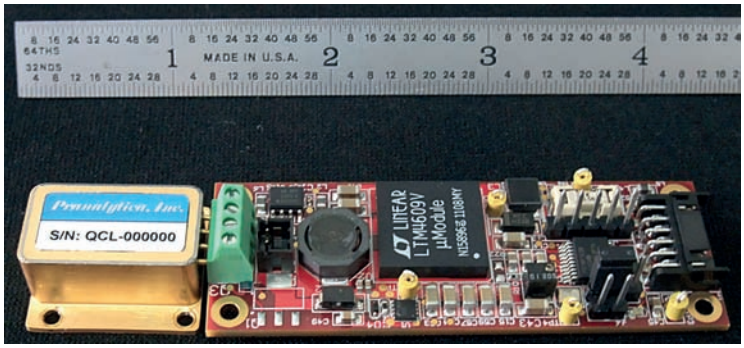

Figure 2. Miniature QCL package delivering >2.5 W of average power at 4.6 μm weighs only 2 oz and will operate from 12-20 VDC battery supply

In recent months, we have been able to accomplish significant miniaturization of QCLs, especially suited for handheld and portable applications. Figure 2 shows a photograph of a QCL package that is able to provide an average power output of >2.5 W in QCW operation at a wavelength of 4.6 μm. The entire laser, including the hermetically sealed butterfly package containing the high power QCL and beam collimating optics and the pulse electronics driver weigh only 2 oz and operate from battery supply of 12-20 VDC.

The miniature QCL package (together with its electronics driver) as well as all of our packaged QCLs have been ruggedized to meet mechanical vibration and shock requirements dictated by MIL-STD-810G Method 514.6, and thermal endurance and thermal shock requirements dictated by MIL-STD-810G Method 503.5. We are confident that these packages will withstand even much higher vibration and shock requirements.

High power QCLs have been tested for long term reliability and have demonstrated capabilities for operation for more than 10,000 hours.

4. COMPARISON OF QCLS WITH OTHER MWIR AND LWIR LASER SOURCES

The spectral region from ~2 μm to >12 μm has been extensively explored for a broad range of laser sources because of the importance of the MWIR and the LWIR regions for spectroscopy, air pollution detection, detection of chemical warfare agents (CWAs), toxic industrial chemicals (TICs) and explosives, protection of aircraft from shoulder-fired missiles (MANPADS), target illuminators and designators and IFF beacons. These sources, in addition to the recently developed QCLs, include optical parametric oscillators (OPOs), optically pumped semiconductor lasers (OPSLs), optically pumped doped ZnSe lasers and CO_2 and other molecular lasers. While many of these, such as the CO_2 lasers, have yet to find alternative laser sources in their specific wavelength range and power capability, others are likely to be replaced in the near future by QCLs for a broad range of applications. Table 3 provides an overall comparison of the capabilities of these sources.

Table 3. An overall comparison of some of the MWIR and LWIR laser sources

Source	**Type**	**Wavelengths Available**	**CW/RT Power**	**WPE**
Optical parametric Oscillators (OPOs)	Solid/optically pumped (requires another pump laser)	400 nm - ~10 μm	~ 1 W	Low
Optically pumped semiconductors	Solid/optically pumped (may have to be cooled below RT and requires another pump laser)	<5 μm	~ 1 W	Low
Optically Pumped Doped ZnSe	Solid/optically pumped (requires another pump laser)	~ 1.8 μm to ~ 5 μm	~ 3 W	Low

Source	Type	Wavelengths Available	CW/RT Power	WPE
CO_2 lasers	Gas/RT	Discrete wavelengths from ~9 μm to 11 μm	> 100 W	~10 %
CO lasers	Gas/RT	Discrete wavelengths from ~ 5 μm to ~ 7 μm	~ 10 W	~10 %
QCLs	Solid/RT/Direct electrical pumping	3.5 μm to >12 μm	> 4 W	~15-20 %

From the consideration of power available and the WPE achieved, together with the significant advantage of size, weight and power, QCLs have rapidly begun to replace many of the earlier generation laser sources in defense and homeland security applications.

5. QCL SYSTEMS FOR CRITICAL APPLICATIONS

As QCLs have begun to penetrate the MWIR and LWIR laser aaplications, it has become clear that for many applications, a single QCL will not suffice. Recently, we have succeeded in offering a range of complex QCL systems that incorporate multiple QCLs and sometimes also other types of lasers for covering wavelength requirements below about 3.5 μm. These systems include a multiple laser system providing very high quality (low M^2) output that includes a Band 1, Band 4a and Band 4b lasers for infrared counter measures, multiple tunable QCL system designed for *in-situ* measurement of CWAs, TICs and explosives and a laser system designed for standoff detection of explosives (IEDs) and CWAs. The following is a brief description of these systems.

MultiLux (High Brightness Multiple Laser System)

For IRCM applications, one needs a multiple wavelength illumination source to disable the tracking sensor in MANPADS. There are several ways by which one can combine, for example, Band 1, Band 4a and Band 4b laser sources. Very often, the beam combination provides high powers at the expense of overall brightness of the source. We have paid special attention to the need for retaining brightness in a system that contains multiple Band 4a and Band 4b QCLs together with a Band 1 laser (a fiber laser at ~2.0 μm). Figure 3 shows a photograph of the system, MultiLux, that has been deployed for several initial evaluations. This system is designed to provide a power output of up to 10 W at ~2.0 μm (Band 1), a power output of up to 4 W at ~4.0 μm (Band 4a) and a power output of up to 6 W at ~4.6 μm (Band 4b). The three beams emerge collinear, overlapping and collimated with overall divergence of less than 3 mrad and a M^2 <1.3. The three laser beam diameters are ~ 3mm with less than 10% difference between them. The turn key system is air cooled and requires only AC line power or DC 28 V for its operations. In spite of the complexity, the system has shown to be rugged against normal vibrations and shocks encountered in practical usage. This ultra high brightness system can eventually be scaled up to provide combined MWIR power outputs in excess of 30 W as the performance of individual QCLs continues improve.

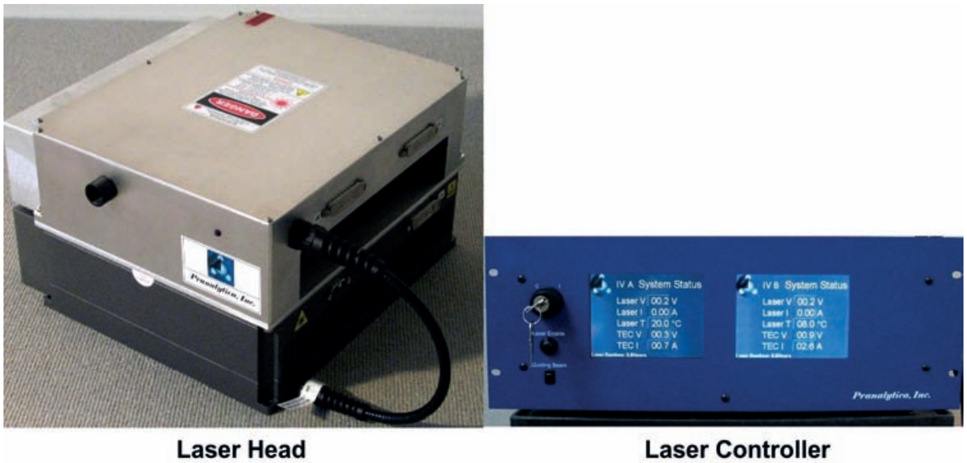

Figure 3. High brightness multiple QCL system capable of delivering a combined laser output at Band 1, Band 4a and Band 4b wavelengths with total power output of > 20 W

FREEDOM (Sensor for *in-situ* Detection of CWAs, TICs and Explosives)

For the detection of a broad range of chemical warfare agents, toxic industrial chemicals and explosives, one needs a tunable laser system that covers a wavelength range from about 7 μm to 10 μm with reasonably high power of > 100 mW over the entire range. Over the years, we have developed a laser based photoacoustic spectroscopy system [11] that has demonstrated a capability of detection of many CWA surrogates, TICs and explosives at a concentration of ~1-10 ppb with a probability of false alarm (PFA) of less than $1:10^6$. Low minimum detection capability is important for providing an early warning of potential danger and low PFA is necessary to assure that a announced alarm is real. False alarms cause unnecessary economic damage and social disruptions.

The system called FREEDOM (Fast Response Explosives and Environmental Detection Optical Monitor) uses four tunable QCLs that are multiplexed to provide a continuously tunable radiation from ~7 μm to ~10 μm. The multiplexing scheme and the photoacoustic sensor are sown in Figure 4. The digitally controlled galvanometer mirror selects radiation from each of the four QCLs sequentially to provide an absorption spectrum of the constituents in the photoacoustic (PA) cell. The library of absorption features, resident in the computer, converts the measured absorption features into concentrations of the constituents and also provides a reliability figure for each measurement. Figure 5 shows a photograph of FREEDOM sensor.

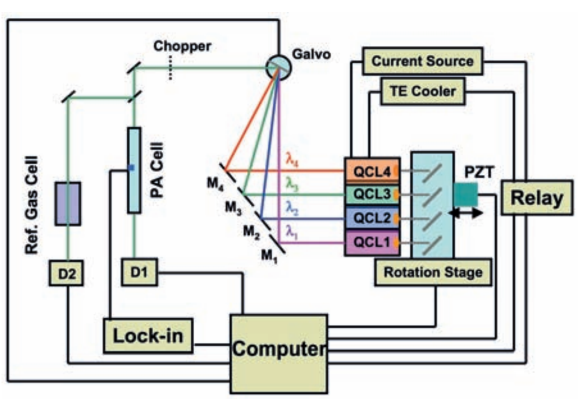

Figure 4. Schematic diagram of the FREEDOM sensor

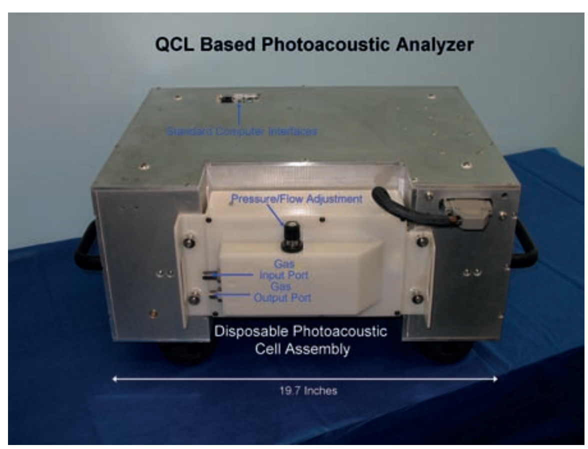

Figure 5. Photograph of the FREEDOM sensor

OmniLux (Multiple Tunable Laser System for Standoff Detection of Explosives)

For battlefield as well as many civilian applications it is not possible to locate the sensor in the near vicinity of the dangerous source. As a matter of fact personnel safety considerations dictate that the sensor should be located at a safe distance from the potential danger, such as hidden explosives and IEDs. We have developed one scheme for the standoff detection of explosives, the Remote Optical Sensor (ROSE) that remotely monitors the temperature rise of a distant target substance when illuminated, by laser radiation, at its optical absorption wavelength. Initial demonstration, carried out using a step-tuned CO_2 laser as the tunable laser source, proved that this scheme is capable of detecting trace quantities of explosives such as TNT [12] at a distance of 150 m with a signal-to-noise ratio of ~70:1 (Figure 6). From these data we estimate that ROSE should be able to detect ~10 ng cm^{-2} of TNT at a distance of 25 m. ROSE also demonstrated capability of detecting a SF_6 gas cloud [13] of concentration of 1 ppm-meter at a distance of ~ 400m (Figure 7).

A different way of standoff detection, developed by Oak Ridge National Laboratory involves detecting scattered light returned from the remote target. Spectrum of such return scattered light will be modified by the absorption properties of the surface layer of the target and/or absorption properties of the intervening path. This scheme called SDER (Standoff Detection of Explosive Residues) has already been demonstrated for the detection of a variety of explosives at distances up to 50 m.

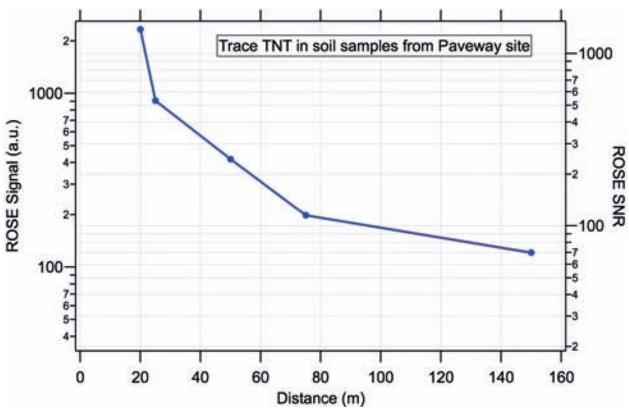

Figure 6. Detection of trace TNT in soil samples from Paveway site showing signal and signal-to-noise ratio as a function of distance

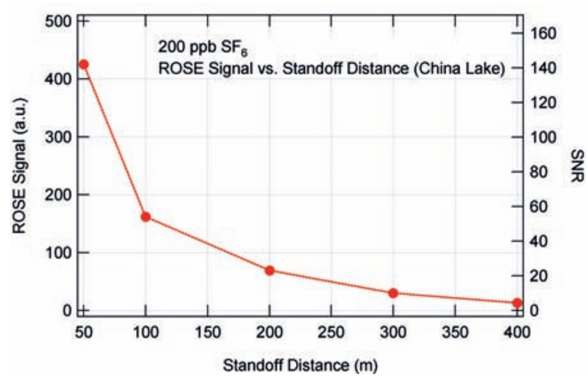

Figure 7. Detection of a column (5 m long) SF_6 at a concentration of 200 ppb showing signal and signal-to-noise ratio as a function of distance

For a sensor to detect a broad range of CWAs, TICs and explosives, we need a broadly and continuously tunable laser in place of the CO_2 laser that was used for the ROSE experiments. Following the scheme of multiple lasers used in the FREEDOM sensor, we have developed a platform for standoff detection multiple laser system called OmniLux. Figures 8 and 9 show the schematic and a photograph of OmniLux. The schematic in Figure 8 also includes the rest of the detection system that either monitors remotely the temperature of the distant object by collecting the blackbody radiation using the telescope (shown) or detects the return scattered light whose spectrum is modified by the absorption caused by trace layers of substances on the target surface. Depending on the specific application, we can use any combination of four QCLs from ~3.8μm to >12 μm to provide tunable laser radiation for detection of other target substances.

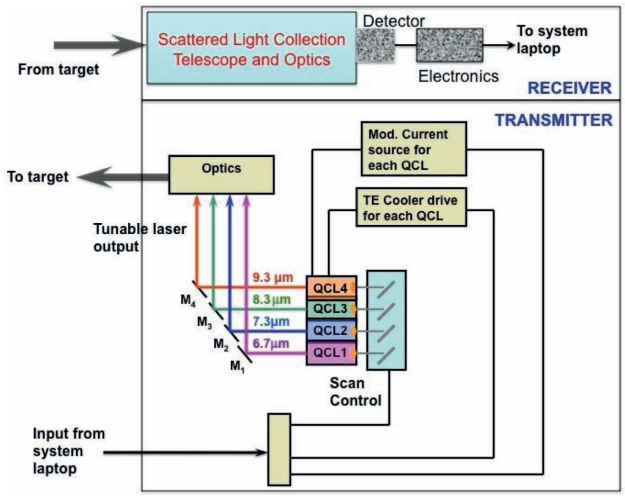

Figure 8. Schematic of OmniLux including the detection scheme for standoff detection

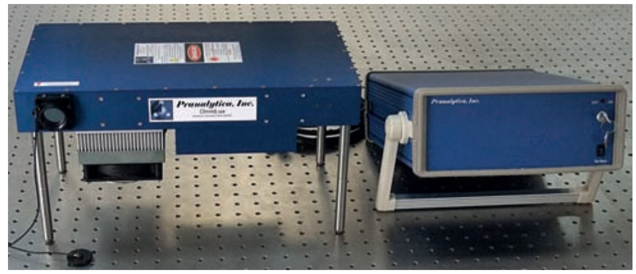

Figure 9. Photograph of the OmniLux laser system consisting four tunable QCLs covering a wavelength range from ~7 µm to 10 µm

The Omnilux and the associated telescope based detection system is compact and portable, weighing about 10 kg. Figure 10 shows the total detection system mounted on a tripod and Figure 11 shows that the system is portable for use by a single individual.

Figure 10. Photograph of standoff explosives sensor on a tripod

Figure 11. Photograph showing portability of the standoff explosives sensor

6. CONCLUDING REMARKS

In the very short period of time from the first operation of the QCLs in 1994, the QCL technology has made giant leaps and QCLs are poised to displace many of the formerly used laser sources in the MWIR and the LWIR spectral regions. Much still remains to be done in improving the performance, power and WPE, of QCLs but the path is clear.

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