Quantum Cascade Lasers for Defense & Security

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ABSTRACT

Quantum cascade laser (QCL) systems are mature and at the vanguard of a new generation of products that support military applications such as Infrared Countermeasures (IRCM) and targeting. The demanding product requirements for aircraft platforms that include reduced size, weight, power consumption and cost (SWaP-C) extends to portable, battery powered handheld products. QCL technology operates throughout the mid-wave (MWIR) and long-wave (LWIR) infrared to provide new capabilities that leverage existing thermal imaging cameras. In addition to their suitability for aircraft platforms, QCL products are a natural fit to meet operator demands for small, lightweight pointer and beacon capabilities. Field-testing of high power, lightweight, battery operated devices has demonstrated their utility across a range of air and ground applications. This talk will present an overview of QCL technology and the Defense and Security products and capabilities that are enabled by it. This talk will also provide an overview of the extensive environmental and performance testing associated with products based on QCL technology.

Keywords: External-cavity, quantum cascade laser, IRCM, mid-IR, MWIR, LWIR, QCL

1. INTRODUCTION

Quantum cascade laser (QCL) technology has been demonstrated in many different applications in the defense and security market. These sources now provide enabling capabilities for illumination and sensing applications and can be configured for operation in many system geometries.

Following a brief description of technical capabilities and applications that QCLs can address, several example embodiments will be described. High power, multi-wavelength laser systems, portable, battery-operated products, and explosives residue applications will be discussed.

2. SPECTROSCOPY

Many, if not most molecular species of interest for military and homeland security applications, such as explosives, precursors and chemical agents possess distinctive, fundamental absorption features in the mid-IR. This “fingerprint” region is of particular interest because almost every compound produces its own unique pattern in this area. The combination of these absorption fingerprints along with pattern recognition algorithms allows for these targets to be unambiguously identified in a very robust way against a strongly interfering background matrix.

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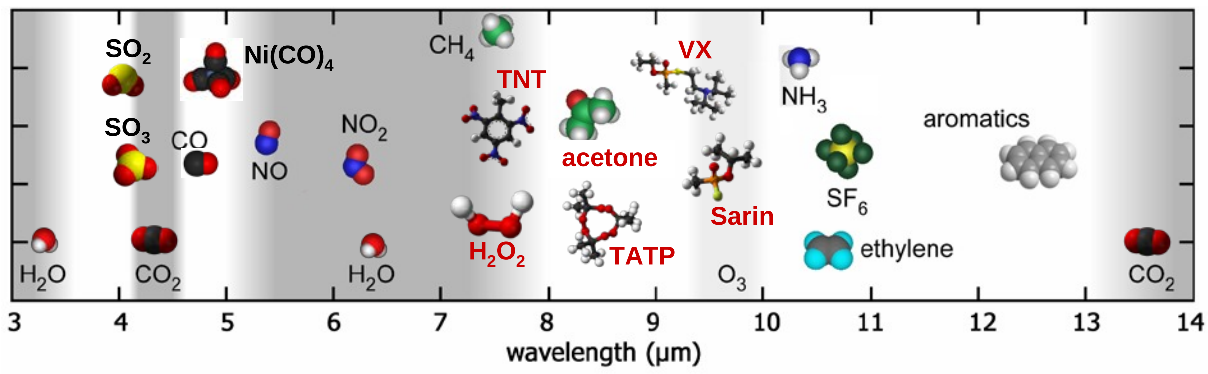

Figure 1. Example molecules with mid-IR "fingerprint" signatures. Examples of explosives, precursors and chemical agents with features in the 7-10 micron region also provided.

Traditional techniques such as cavity ring down spectroscopy[1], photoacoustic spectroscopy[2] and multipass cavities[3] have been employed as a means for optically detecting molecular concentrations. With these techniques, sensitivity down to ppb or ng/L levels has been demonstrated. However, these systems remain relatively large and complex, including in some cases the need for cryogenic cooling, which has limited their practical use in military and homeland security applications.

2.1 Spectral Tunability

As mentioned previously, spectral "fingerprint" analysis is a powerful method for identifying multiple species within a common sample. In order to capture the fingerprint from one or several compounds, a broad wavelength span must be generated. Figure 2 illustrates an example composite spectrum that was captured with a broadly tuned external-cavity QCL. By covering such a broad range, the spectral fingerprints from individual compounds can be identified using simple pattern recognition algorithms.

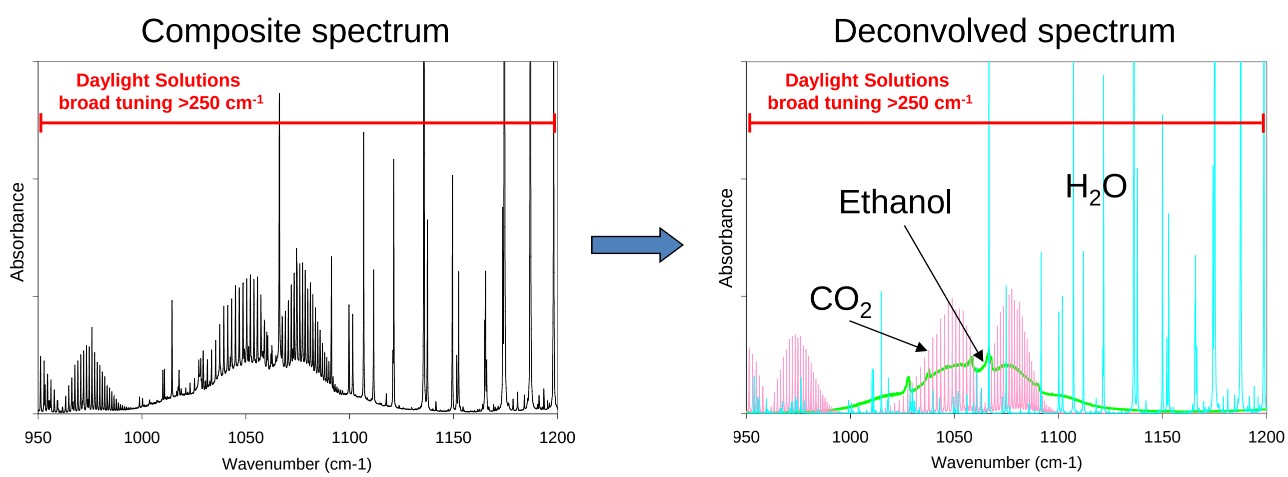

Figure 2. Example mid-infrared absorption spectrum for composite sample.

3. DEFENSE & SECURITY APPLICATIONS

There are many applications within the defense and security market that require operation in the mid-wave infrared (MWIR) and/or long-wave infrared (LWIR). These include infrared countermeasures (IRCM), targeting, marking, aiming, beacons (combat identification), explosives detection, and free-space optical communications.

The MWIR and LWIR are critical for military imaging applications. Here, the ability to image through battlefield conditions such as smoke, dust and fog provide enabling capabilities.

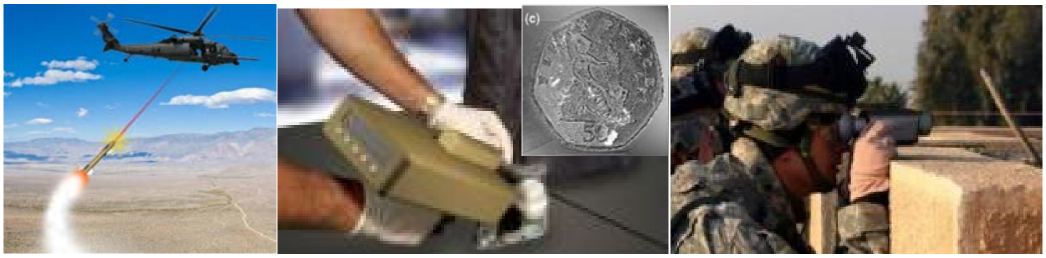

Figure 3. There are several applications that benefit from QCL technology, including IRCM (left), residue detection (center) and free-space optical communications (right).

4. QUANTUM CASCADE LASERS

Originally predicted (theoretically) by Kazarinov, etal., in the early 1970's[4], and first demonstrated in 1994[5], the quantum cascade (QC) laser operates on a fundamentally different principle than the conventional near-infrared semiconductor diode laser. Essentially, the operation of lasers based upon the QC effect can be thought of as an electronic waterfall occurring within a stack of alternating semiconductor materials, with electrons cascading down a series of energy steps, each cascade resulting in an emitted photon. In practice, since lasers based on QC operation can be designed to have a large number of such cascades, many photons can be generated by a single electron, providing very high electrical-to-optical efficiencies with very high output power. Moreover, they can be operated at high powers without significant cooling requirements; i.e. can be run either uncooled or with simple thermoelectric cooling depending upon the application.

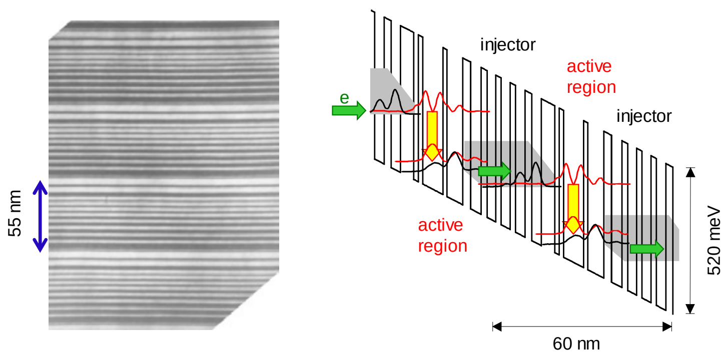

Figure 4. The epitaxial growth process of QCL technology is similar to that of conventional diode lasers. However, QCLs typically possess many more layers. Left: SEM photograph of epitaxial layers. Right: Bandgap diagram of QCL. Courtesy: MIRTHE.

One characteristic of QC based lasers is that the wavelength of the emitted photons is determined by the physical design of the semiconductor stack and not by the bandgap of the material as with traditional semiconductor diode lasers. As such, this provides a significant manufacturing advantage in that lasers based on QC structures can be designed to emit at any wavelength within the mid-IR using a common material system (such as InP/InGaAs/InGaAlAs).

Technical approaches that employ QCL components can offer several advantages in military applications. Considering other laser technologies such as the optical parametric oscillator (OPO), QCLs compare favorably in several ways. The simple laser architecture provides inherent reliability and cost advantages in military applications. This simplicity also lends itself to rapid time-to-market, shortening development cycles and minimizing cost.

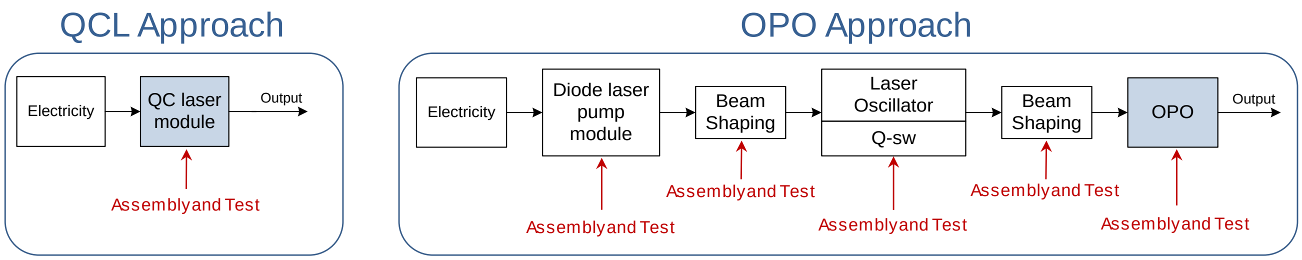

Figure 5. Comparison of technical approaches between QCL and OPO illustrate the inherent advantages in reliability and cost.

4.1 Performance

For most military applications, operation (and storage) at extreme temperature ranges is required. For high power applications, heat dissipation requirements drive the size, weight and power (SWaP) performance of practical systems. It is highly desirable, therefore, to maximize the operating temperature of the laser device, so as to minimize the thermal management and system SWaP. Daylight has significantly advanced the performance of QCL devices at elevated operating temperatures. As illustrated in Figure 6, such devices provide over 1 Watt of cw optical power while operating (device temperature) at 75 deg C.

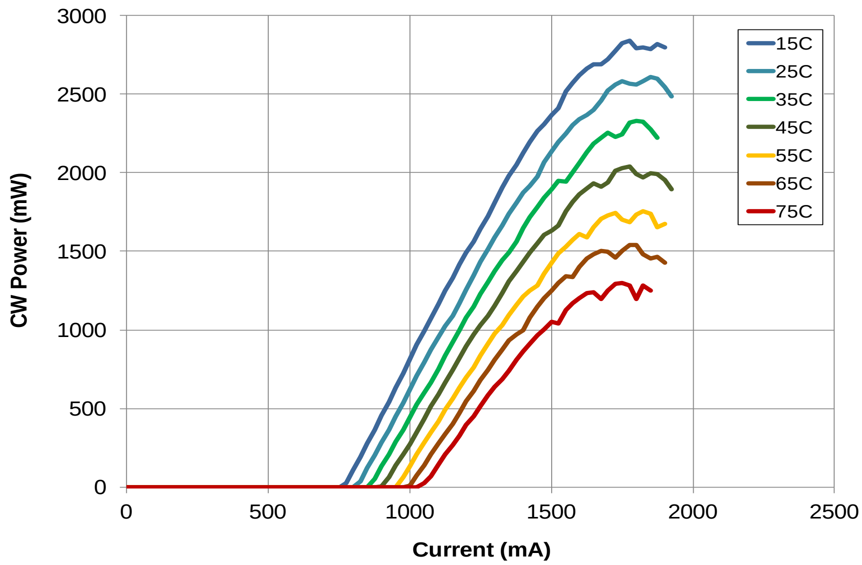

Figure 6. The operating temperature of QCL based systems drives overall SWaP. Typical system operating temperatures of ~70 deg C are required for most military-grade applications. Being able to generate over 1 Watt cw optical power with device temperatures in excess of 70 deg C is significant to minimize thermal management system requirements and SWaP.

Daylight has continued to collaborate with academia to drive bleeding edge performance. In partnership with Northwestern University, Daylight has evaluated advanced R&D results. Figure 7 illustrates the results obtained through this collaboration. Emitting ~4.9 µm, the chip-on-submount data generated at Daylight shows that cw power levels in excess of 5 Watts have been achieved at high efficiency at room temperature. This data corroborates the results obtained by Northwestern during their in-house testing. These devices are now poised to transition to slightly shorter wavelengths and into Daylight commercial modules. While this activity still requires manufacturing/technology transfer for full commercial production, these results are indicative of future capabilities.

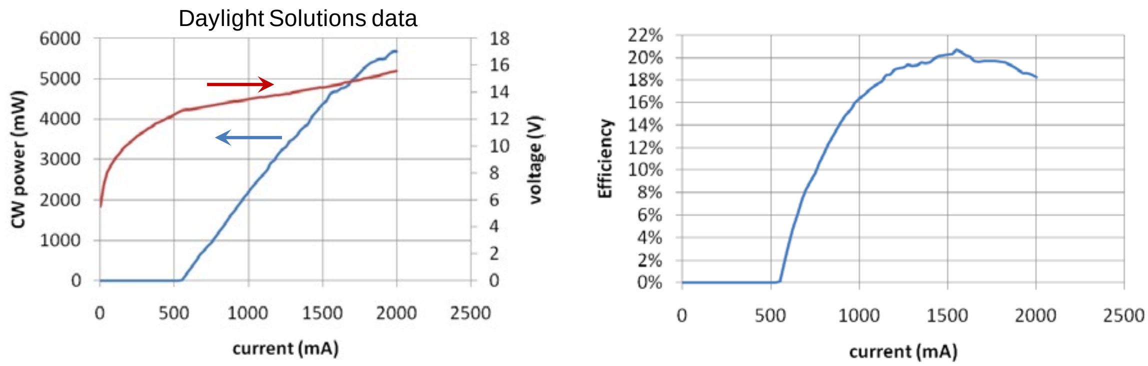

Figure 7. Advanced R&D results achieved through collaboration between Daylight and Northwestern University.

Importantly, the performance of QCL devices in the LWIR have also advanced significantly. Figure 8 illustrates cw power in excess of 1 Watt for QCL modules operating at ~8.6 microns. These devices perform with excellent beam quality and sub-milliradian pointing stability over military relevant environmental conditions.

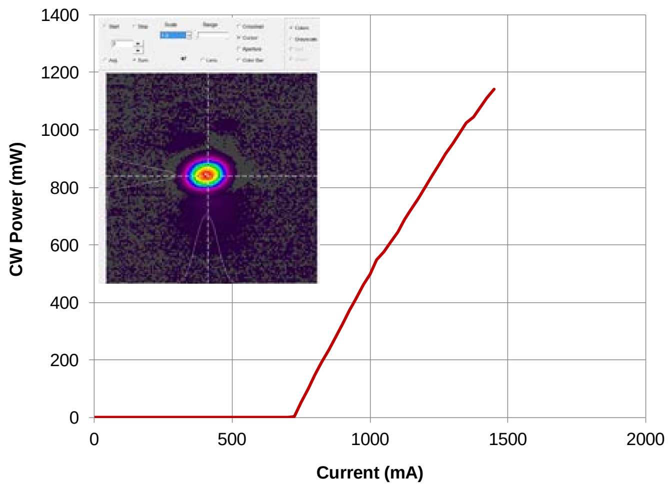

Figure 8. The cw power generated from QCL modules in the 8.6 micron regime have been demonstrated at greater than 1 Watt. This level of performance is provided with near-diffraction limited beam quality and sub-milliradian beam pointing stability.

In order to begin building statistical data samples to inform future reliability growth activities, several batches of QC devices have begun run time characterization testing. Figure 9 summarizes these characterization tests. Over 972,800 hours of data have now been collected over several devices, wafers, and operational conditions.

Number of QCL Devices	Number of Wafers Sampled	Temperature of Operation	Mode of Operation	Total Hours (each device)	Total Hours (cumulative)
9	1	20ºC	CW	32,600	293,400
4	2	20ºC	CW	24,000	95,000
20	2	60ºC	CW	24,600	482,400
12	1	60ºC	1kHz, 50% duty cycle	8,500	102,000
45					**972,800**

Figure 9. Long term reliability is critical for military products. QCL devices have been characterized by sampling several production runs and operating individual devices under various conditions to understand their behavior over long periods of time. These data will serve to inform the development of an aging model for QCL devices in the future.

5. HIGH POWER RUGGEDIZED LASER SYSTEMS

Daylight has pioneered the development of QCL technology for defense and security markets. Multi-Watt, multi-wavelength QCL-based systems have been manufactured and tested against harsh military environmental requirements. In all cases, Daylight's QCL technology and laser systems have demonstrated compliance.

Daylight has focused on transitioning QCL technology into military ruggedized products. Daylight's product family that has been established to meet requirements for airborne applications is referred to as "JammIR™". There are currently three different lines that fall within the JammIR™ family. Examples of these different embodiments are illustrated in Figure 10 along with their timeline of first deliveries.

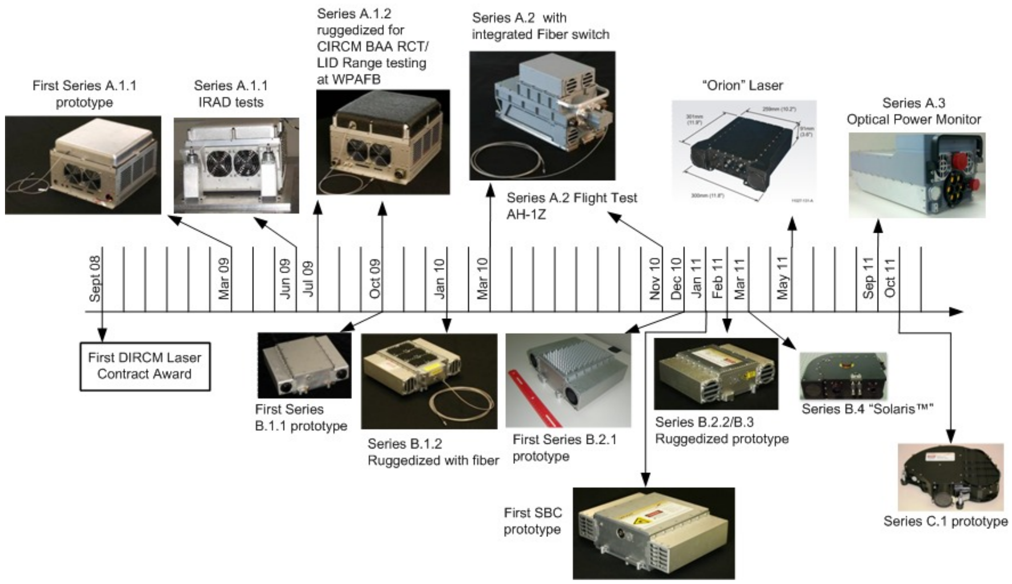

Figure 10. For airborne applications, Daylight has designed, built, tested and delivered 15 different QCL-based laser system embodiments over the past 3 years. Daylight's modular design approach has allowed for multi-Watt, multi-wavelength laser systems to be rapidly configured to optimize for different systems' performance.

6. PORTABLE LASER SYSTEMS

Compact, high brightness sources have shown their usefulness as beacon emitters when viewed by thermal cameras operating in the LWIR and MWIR spectral bands. Wavelengths throughout these bands have been demonstrated in battery-operated, handheld and wearable form factors. Figure 11 illustrates an example of a handheld beacon that can be seen at ranges in excess of 20 km, but only with non-proliferated cameras.

Figure 11. Example portable, handheld beacon product that is based on Daylight's QCL technology. These signals can be detected at ranges in excess of 20 km, but can not be seen with conventional night vision goggles (i.e., can only be viewed with non-proliferated cameras).

Daylight has also integrated QCL technology into multi-spectral, wearable beacons. Figure 12 illustrates prototypical multi-spectral beacons that have been field tested in several environmental conditions. These multi-spectral beacons integrate visible (VIS), near-infrared (NIR), short-wave infrared (SWIR), MWIR and LWIR into a single, compact package.

Figure 12. Multi-spectral beacons have been developed that integrate VIS, NIR, SWIR, MWIR and LWIR into a single package (left). These prototypes are battery operated, and are lightweight to be worn directly on a uniform or mounted to a helmet. These beacons have been field tested at several sites, including San Diego (right), where the MWIR beacon was seen clearly at ranges in excess of 18 km, over water (at sea level) with representative cameras.

7. NON-CONTACT DETECTION OF EXPLOSIVES

QCL technology has been demonstrated in several system geometries that provide non-contact detection of explosive residues[6,7,8,9]. In each of these detection methodologies, the mid-infrared light generated by QCL technology serves as the interrogation source for explosive materials of interest. Since mid-infrared light is strongly absorbed by explosive residues, it can be used as a probe for variety detection technologies.

Standoff distances in the range of 10-20 meters have been demonstrated in limited field test environments, and with breadboard hardware and software. Less than 20 micrograms per square centimeter have been detected, with below 1 microgram per square centimeter being detected in some cases.

8. SUMMARY

QCL technology has been integrated into military ruggedized laser systems for defense and security applications. Multi-Watt, multi-wavelength systems have been manufactured and tested against harsh environmental requirements. QCL technology has been integrated into wearable, battery-operated packages, and has been demonstrated in the field at tactical ranges of interest. Fingerprint identification and pattern recognition algorithms offered by QCL based sensors can allow standoff and point detection of these threats to be achieved with high sensitivity while maintaining low false alarm rates. This performance provides for several detection geometries to be considered and allows for flexibility and optimization in design depending upon the application and theater in which the system is to operate.

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