Quantum Cascade Lasers: A Game Changer for Defense and Homeland Security IR Photonics

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Abstract

I will describe recent developments of continuous wave, room temperature (CW/RT) high power QCLs at wavelengths < 3.8 μm to > 12 μm. QCLs now provide, on a commercial basis, CW/RT power of over 3 W at 4.6 μm, with a wall plug efficiency of over 15%, over 2 W at 4.0 μm, and over 1.2 W at 7.1 μm, with a wallplug efficiency >8%. I will describe insertion of QCLs into applications including MWIR countermeasures (IRCM), MWIR and LWIR target illuminators and designators, MWIR beacons (IFF), test equipment for measuring the efficacy of IRCM and sources for MWIR and LWIR radiation for detection of chemical warfare agents and explosives.

Keywords: Quantum cascade lasers, Infrared countermeasures, Target designators, IR beacons, Standoff detection of IEDs

I. Introduction

Quantum cascade lasers (QCL) were first demonstrated (1) in 1994. However, it took nearly eight years before the first continuous wave, room temperature (CW/RT) operation was successful, brought about by an improved design for rapidly depopulating the lower laser level thorough the use of two phonon resonance design (2). The progress since 2002 has been remarkable in improving the power output and wallplug efficiency. Furthermore, a newer structure design idea (the nonresonant extraction, NRE, principle for rapid depopulation of the lower laser level without the use of two phonon resonance) has emerged (3), which increases the structure design flexibility for simultaneous improvements in various operating parameters of QCLs. At present, CW/RT power outputs of >3 W and wall plug efficiency in excess of 15 % have been demonstrated at 4.6 μm in the midwave infrared (MWIR) region (4). Using the NRE structure design ideas we have demonstrated CW/RT power output in excess of 2 W at 4.0 μm (5) and have extended QCL operation up to 3.6 μm, where average power output of more than 300 mW has been obtained for room temperature operation (6). The NRE design principle is also applicable to longwave infrared (LWIR) regions leading to improvements in power output and wallplug efficiency similar to those attained in the MWIR region. Over all CW/RT operation of QCLs now covers a wavelength region from 3.6 μm to longer than 12 μm. Pranalytica, being a vertically integrated (from fundamental design of the structure to final customer usable product, *albeit* fabless) manufacturer of QCLs, has been supplying high power CW/RT QCLs as well as cryogenically cooled QCLs producing substantially higher power output (>7 W, CW) at very high wallplug efficiency (>30%) to military, homeland security and civilian customers.

In addition to the scientific advance of NRE design, Pranalytica pioneered the use of epi-down mounting of the QCLs using Au:Sn hard solder on CTE matched AlN substrates, which improves the thermal management considerably and makes the QCLs appropriate as reliable, robust sources of MWIR and LWIR radiation (7). Because the emitting region is quite small, the QCL output needs to be collimated using appropriate optics placed very close to the exit facet of the laser. We package the QCLs in hermetically sealed butterfly packages (Figure 1) that include a thermoelectric cooler for maintaining the QCL for efficient thermal management and appropriate optics for collimating the laser output. These butterfly packages are robust and rugged and satisfactorily pass the MIL-STD environmental tests for vibration/shock and temperature.

The high wallpug efficiency also makes it possible to operate the QCLs in an uncooled mode, i.e., without TECs, for incorporation into handheld, battery operated

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applications such as target illuminators and designators and IFF beacons. In the uncooled mode, we have demonstrated QCW (high duty cycle, pulsed mode operation) average power output of >2 W at 4.6 µm and >1.5W at 4.0 µm (8, 9). Similar performance is also expected in the LWIR region.

The performance improvements in QCL operation have allowed MWIR and LWIR QCLs to make significant inroads into applications areas where a number of alternate laser technologies have already been extensively deployed in the MWIR and LWIR regions. These applications include laser sources for MWIR countermeasures for protection of aircraft from shoulder fired missiles (MANPADS), MWIR and LWIR battlefield target illuminators and designators, MWIR identify-friend-or-foe (IFF) beacons, test equipment for measuring the efficacy of infrared countermeasures and sources of MWIR and LWIR radiation for high sensitivity in-situ and standoff spectroscopic measurements of chemical warfare agents and explosives. The drivers are the small size, reduced weight and high wallplug efficiency, which make the overall systems more attractive.

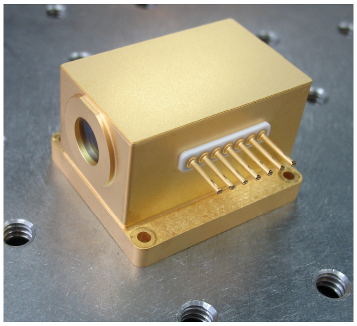

Figure 1. Hermetically sealed QCL butterfly package (volume ~ 50 cm^3, weight < 100 gm) *that meets the MIL-STD specifications for vibration, shock and temperature.*

While the above applications do not require QCL output to be single frequency and therefore lasers in Fabry-Perot (F-P) geometry are employed, there are other classes of applications that need single frequency output power from the QCL that is also widely tunable for the detection of chemical warfare agents (CWA), toxic industrial chemicals (TICs) and explosives, LADAR, differential absorption lidar (DIAL) and free space optical (FSO) communications. With the developments in the QCL technology, the deployment of QCLs in a host of these applications is taking place very rapidly. In some case, the QCLs are replacing older generation of bulky, inefficient, low power sources while some new applications are being enabled by the availability of the high power, high efficiency QCLs.

II. Progress in Extending High Performance QCL to Shorter and Longer Wavelengths

With Pranalytica's in-house QCL structure design capability, we have been able to extend the high performance operation of the QCLs to wavelengths as short at 3.6 µm to as long as >12 µm. For infrared countermeasures applications, there is a need for CW/RT QCLs operating in the 3.8 µm-4.2 µm window. We have extended the NRE design to this wavelength region (5) to obtain CW/RT power output in excess of 2 W at 4.0 µm (Figure 2).

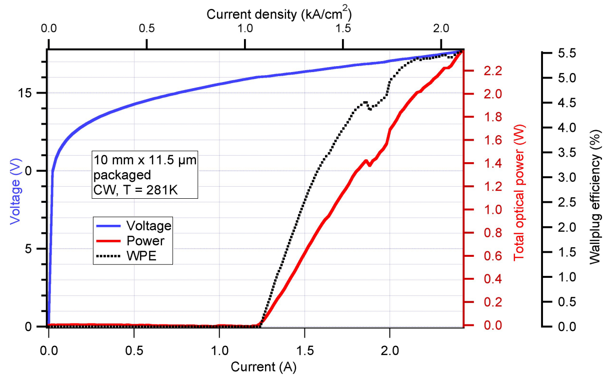

Fig. 2. CW/RT performance of a 2 W QCL at 4.0 µm.

We have recently extended (6) the short wavelength operation to 3.6 µm, where we have obtained CW/RT power nearly 50 mW and quasi-CW (high duty cycle pulsed operation) output power of nearly 300 mW (Figure 3). Figure 4 shows spectral analysis of the output form the 3.6 µm QCL.

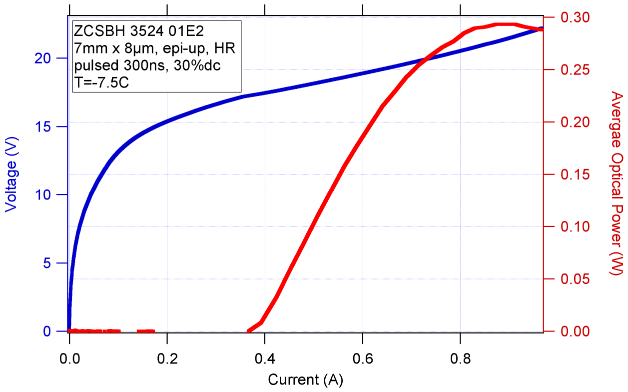

Fig. 3. QCW/RT performance of a QCL at 3.6 µm

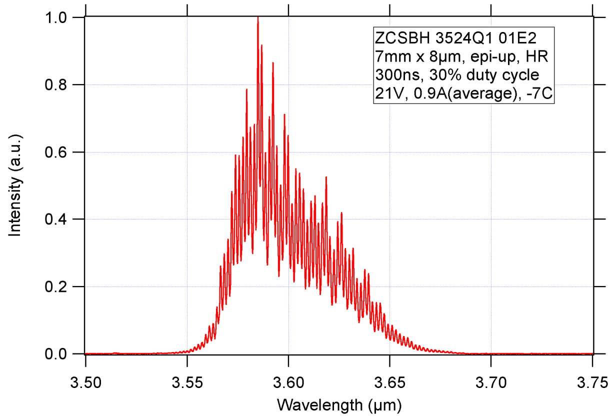

Fig. 4. Output spectrum from the QCL described in Figure 3.

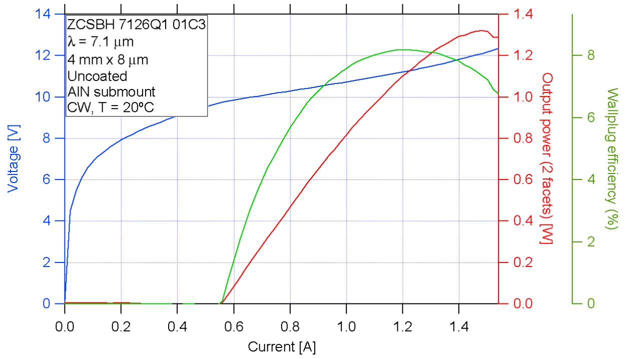

Fig. 5. QCW/RT performance of a QCL at 7.1 µm

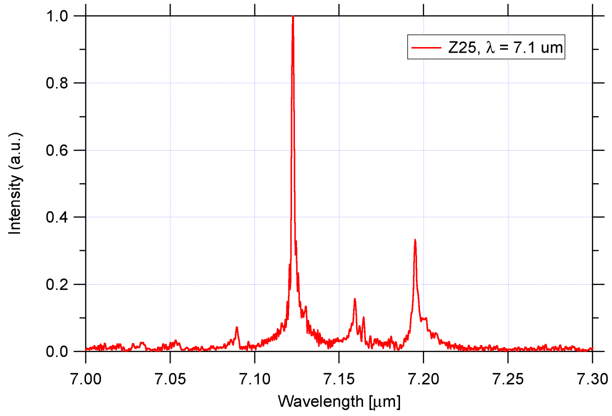

Fig. 6. Output spectrum from the QCL described in Figure 5.

Finally, for many spectroscopic applications, one needs high power (single frequency, tunable) laser radiation in the 7 µm-12 µm region. Extension of high power QCL designs to this wavelength region has led to QCLs at 7.1 µm with CW/RT power output in excess of 1.2 W (10) at a wallplug efficiency of nearly 8% (Figure 5). Figure 6 shows the spectrum of output from this QCL.

III. Multiple Wavelength Lasers in a Single Module

For many applications, including infrared countermeasures for protecting aircraft from MANPADS, one often needs multiple wavelength package that provides three or more wavelengths including one in the short wavelength infrared (SWIR) region and two wavelengths in the MWIR region (a true turnkey operation for a systems integrator) with the three laser outputs perfectly collimated and aligned to provide a single output beam with low divergence. Furthermore, the three wavelengths need to have individually controllable amplitudes and potentially switchable with arbitrary pulse sequences. We have taken up this challenge and have recently developed (11) a multiple wavelength laser system (Figure 7) which optically combines a 2.1 µm OEM fiber laser output with MWIR laser outputs form two air-cooled CW/RT QCLs operating at 4.0 µm and 4.6 µm, respectively. The three beams exit collinearly with a divergence of less than 5 milliradians and with optical collinearity better than 1 milliradian. Power outputs at 4.6 µm, 4.0 µm and 2.1 µm are 2.0 W, 1.5 W and 3 W respectively.

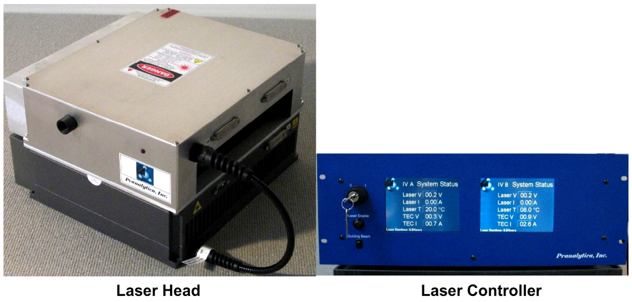

Fig. 7. Multiple wavelength laser system providing one SWIR and two MWIR wavelengths

IV. Uncooled High Power Operation of MWIR and LWIR QCLs

The high power QCL operation, in the Fabry-Perot geometry, described above involved mounting the QCL on a thermoelectric cooler (TEC) for efficient thermal management and has proven to be very successful. However, TECs are very power hungry devices that generate as much as three to five times the heat they remove from the QCL. Thus the total electrical power consumption can be quite substantial for high power QCLs in spite of the high (as much as >15%) electrical power to optical output conversion efficiency. For many applications such as aircraft mounted directional infrared countermeasure systems, this is not seen to be a problem. However, there are other classes of operations where electrical power is supplied form batteries and the additional power consumed by the TECs is not acceptable. These applications include portable infrared target illuminators and designators and identify-friend-or-foe (IFF) beacons both for security as well as rescue missions. Here high average power laser sources are required in the MWIR and LWIR spectral regions that have high overall power conversion efficiency, which negates the use of TECs.

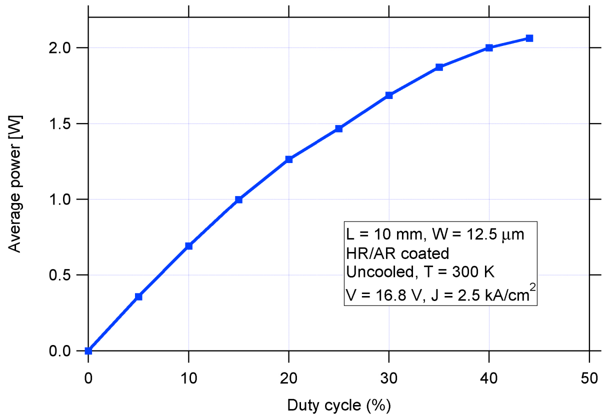

Fig. 8. Average output power as a function of duty cycle for uncooled (no TEC) operation of a 4.6 µm QCL (Ref. 9)

The high inherent power conversion efficiency of the QCLs, developed by us, can be advantageously used for producing high powers from these devices without the use of TECs for thermal management. As mentioned above, true CW operation is often not required as long as high duty cycle pulsed operation produces the required level of average power output. We have found (9) that we can operate the high performance QCLs in such a mode, ~ 200 ns pulses with a duty cycle of 50% to produce of >2 W of average power output at 4.6 µm and >1.5Wof average power output at 4.0 µm. Figure 8 shows the power output as a function of duty cycle for the 4.6 µm QCL, from where we see that >2W of average power is available for the single emitter QCL at 4.6 µm. Because no TEC is utilized, the overall efficiency of the QCL system is very close to the power conversion efficiency of the QCL chip itself. The overall efficiency as a function of the average power output is shown in Figure 9. We see that a system efficiency of >10% is achieved for average power output of 1 W and >9% is achieved for an average power output of 2 W.

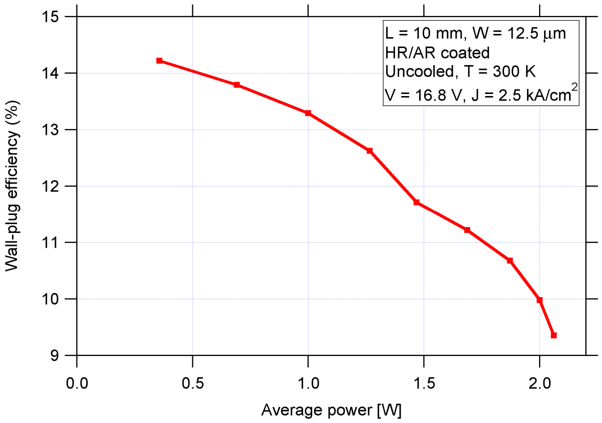

Fig. 8. Overall efficiency of the uncooled QCL system at 4.6 µm as a function of the average power output (Ref. 9).

We have also found that in the QCL, producing high average power output of 2 W at room temperature in high duty cycle pulsed operation mode, continues to provide high power output even when then QCL ambient temperature (i.e. heat sink temperature) rises to 340 K as shown in Figure 9, where average power output in excess of 1W is available at 4.6 µm. Similar results have been obtained at 4.0 µm as seen from Figure 10, where we note that an uncooled QCL operating at 4.0 µm at room temperature and providing >1.5W of average power will still provide >0.8 W of average power output at heat sink temperature of 340K (67ºC).

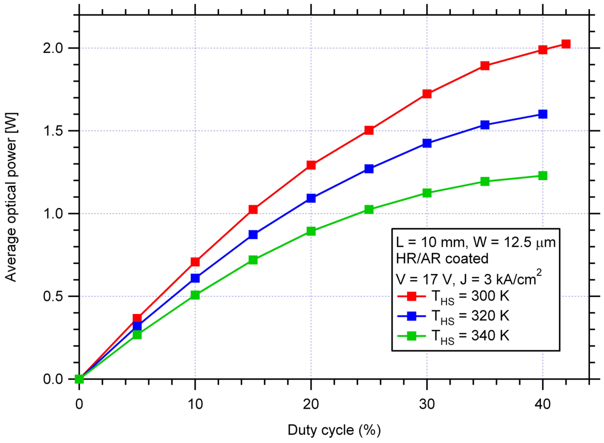

Fig. 9. Average power output vs. duty cycle for three different heat sink temperatures for QCL at λ ~ 4.6 µm (Ref. 9).

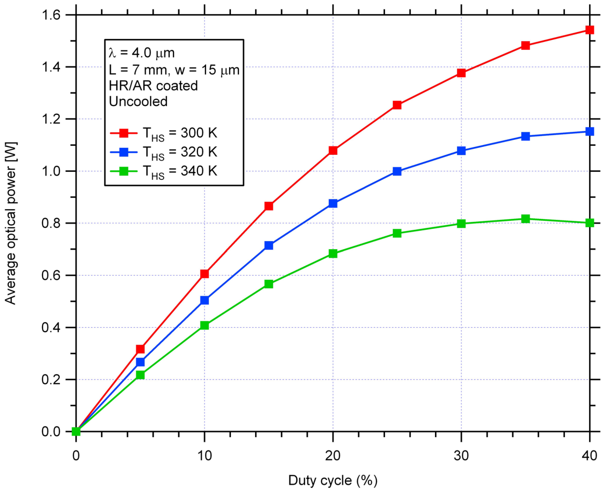

Fig. 10. Average output power as a function of duty cycle for uncooled (no TEC) operation of a 4.0 µm QCL (Ref. 9).

The uncooled non-TEC operation of high average power QCL simplifies the QCL system significantly. The entire package become smaller and lighter as would be needed for portable applications including target illuminators and designators and IFF beacons. Figure 11 shows a photograph of an OEM laser package including electronics driver that occupies a volume of ~5 cm x 12.5 cm x 2.5 cm. The system is powered form a very simple computer grade 12-24V DC power supply and produces > 2W at 4.6 µm and >1.5W at 4.0 µm.

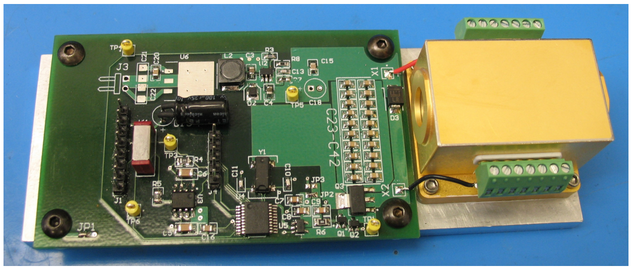

Fig. 11. An OEM uncooled (no TEC) QCL package that produces >2W at 4.6 µm and >1.5W at 4.0 µm and operates from a standard 12-24V DC computer grade power supply.

Because of the simplicity of the QCLs operating in the high average power high duty cycle pulsed mode, they can be packaged into very simple and user friendly tabletop configurations for the ease of use as shown in Figure 12.

Fig. 12. An tabletop version of uncooled (no TEC) QCL package that produces >2W at 4.6 µm and >1.5W at 4.0 µm and operates from a standard 12-24V DC computer grade power supply.

V. Ruggedization of the QCL and Electronics Drivers

For almost all of the defense and security related applications of QCLs, the laser must be able to withstand significant vibration and shock as well as survive extended storage at very low and very high temperatures. Pranalytica has, through careful engineering, ruggedized the QCL butterfly package shown in Figure 1 as well as the total pulsed high average power OEM system shown in Figure 11 to comply with relevant MIL-STD specifications. An example of the vibration tests to which we subject the butterfly package and OEM butterfly package/electronics board is shown in Figure 12 where the acceleration spectral density is plotted as a function of frequency.

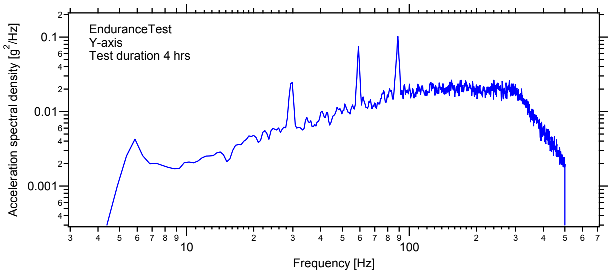

Fig. 12. Typical vibration test (derived from MIL-STD-810G Method 514.6) *that the QCL package is designed to withstand.*

Similarly, Pranalytica's QCLs are subjected the MIL-STD shock tests to assure survivability in actual field deployed systems. Figure 13 shows the g-value of the shock to which the Pranalytica's QCL packages are exposed.

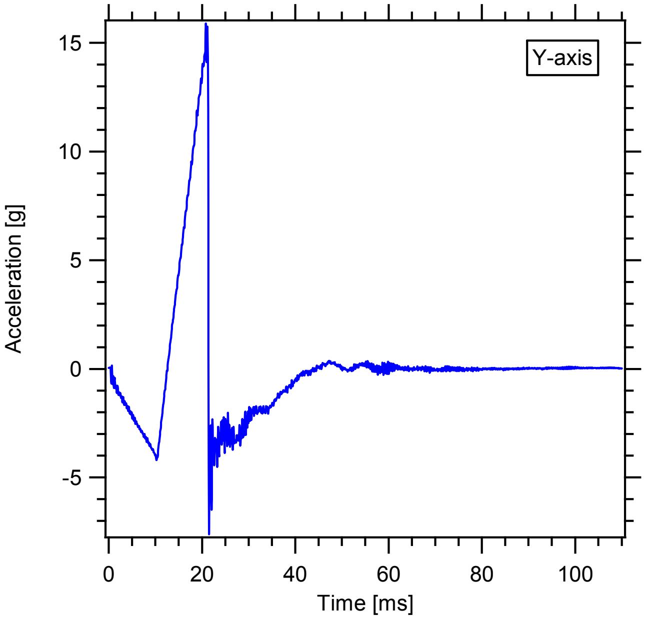

*Fig. 12. Typical shock test (*derived from MIL-STD-810G Method 516.6) *that the Pranalytica's QCL package is designed to withstand*

Finally, in actual field deployment, the QCLs must also be able to survive extended storage at temperatures of -40ºC to +68ºC and temperature shock cycle as required by MIL-STD-810G Method 503.5 specifications. A typical environmental test thermal cycling is sown in Figure 14.

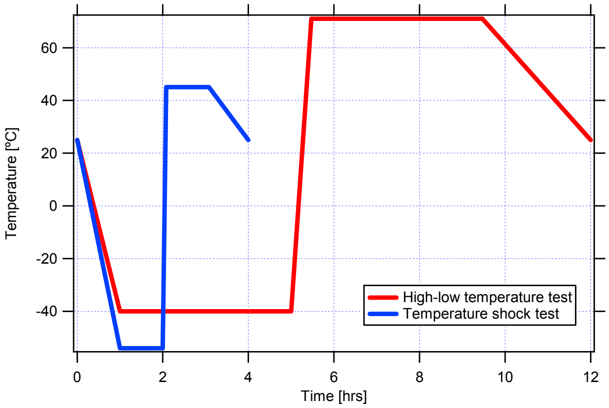

Fig. 14. Typical thermal endurance test (MIL-STD-810G Method 503.5) that the QCL package is designed to withstand.

Figure 15 shows performance data (power output vs. drive current) for a 4.0 μm QCL system that was subjected to the vibration/shock and temperature endurance tests. The data indicate that Pranalytica's QCL systems satisfy the MIL-STD described above and are ready for field deployment in very stressing environments.

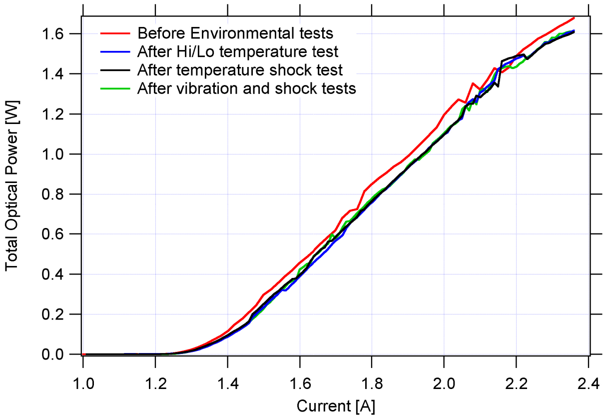

Fig. 15. An example of performance of Pranalytica's QCL system at 4.0 μm before and after various environmental stress tests.

VI. QCL Reliability

We have spent considerable effort in understanding the various failure modes of high power QCLs and as a result we have now the best data on the long term reliability of these lasers. Figure 16 shows the results of long term measurements on a 2 W QCL operating in a CW/RT mode at 4.6 μm.

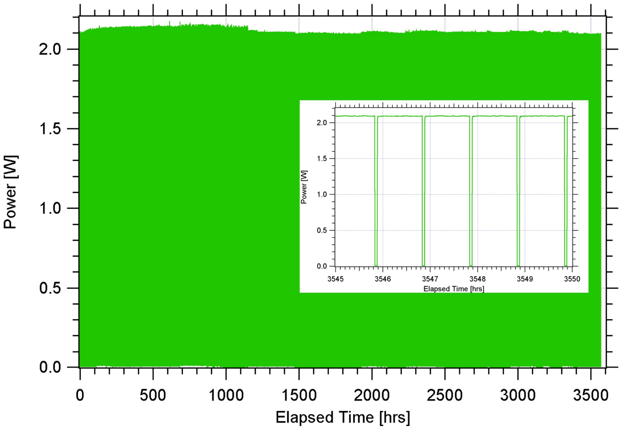

Fig. 16. Long term reliability test of a 4.6 μm QCL.

The laser is turned on full power for 57 minutes and then turned off for 3 minutes to subject the QCL to extreme temperature stress. It is clear that there no slow long term degradation in the power output from which we estimate that such QCLs will have degradation free life expectancy considerably longer than 10,000 hours. We have obtained similar data for high power QCLs at 4.0 µm.

VII. F-P QCL Applications: Directional Infrared Countermeasures

With the increase in worldwide terrorism, safety of civilian as well as military aircraft from man-portable air-defense systems (MANPADS), often called shoulder-launched surface-to-air missiles, has become an important issue for homeland security as well as the defense department. There are a number of documented cases of military and civilian aircraft being often hit by the MANPADS launched by terrorists (12).

Directional infrared countermeasures have been investigated for a number of years and have used a variety of secondary laser sources such as fiber lasers and optical parametric oscillators for illuminating the seeker on the MANPADS with radiation at ~2 µm, ~4 µm and ~4.6 µm. The QCLs in the IRCM system employing directed beams of light (at different wavelengths), independently modulated with appropriate pulse sequences, can impart false data into the seeker and therefore make missile targeting system to break its target lock and eventually cause the MANPADS miss the target. Therefore, there has been a concerted effort to move towards directional infrared countermeasures (DIRCM). With the advent of high reliability, very rugged and efficient QCLs, there is considerable activity in replacing the older laser sources with QCLs. It is clear that the QCLs have changed the rules of the game significantly.

VIII. F-P QCL Applications: MWIR and LWIR Target Illuminators

A key battlefield requirement is to illuminate and designate an enemy target using a wavelength that the enemy cannot see. The 4.6 µm and the 9.6 µm QCLs fit the requirement nicely, replacing the present sources in the near infrared (NIR) region for which viewers are widely available. Uncooled MWIR or LWIR quantum cascade lasers are beginning to replace the NIR laser sources because the infrared viewers for these wavelengths are not as widely available and permit the users of MWIR and LWIR target designators to retain the element of surprise.

IX. F-P QCL Applications: IFF Beacons

Again as with the target illuminators and designators, the current IFF beacons use NIR lasers, which are increasingly being seen as the technology of the past. The uncooled MWIR and LWIR QCLs, producing watt-level power outputs at ambient temperatures as high as 67ºC and being immune to vibration/shock and temperature changes, are natural for the next generation of beacons.

X. Single Frequency Tunable QCL Systems: Applications to Trace Gas Detection

As mentioned earlier, spectroscopy and sensing applications require tunable single frequency sources rather than the broadband sources (i.e., Fabry-Perot configuration QCLs). As we have shown in several publications in the past, the broadband source can be made to provide single frequency tunable laser output over its gain bandwidth by including a wavelength selective element such as a grating inside the laser cavity. Without going through details, wavelength tuning of over 10% of the center wavelength is possible (13) as seen from Figure 16. Such single QCL element external cavity tunable systems have been used for high sensitivity, ultra low probability false alarm detection of chemical warfare agent surrogates and various explosives (14-16

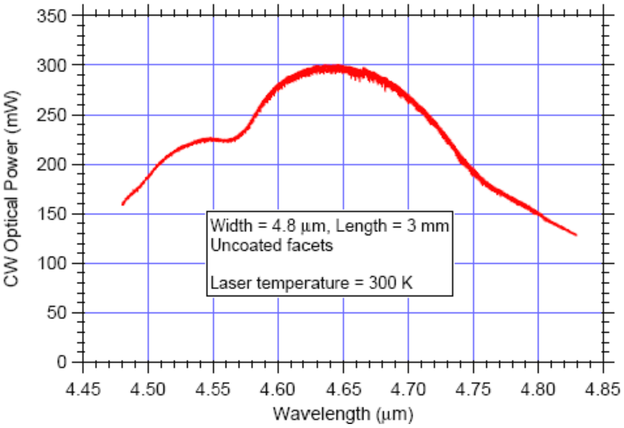

FIG. 16: Optical power as a function of wavelength of the external cavity laser operated in continuous-wave mode at room temperature.

For a broad tuning requirement, for example for covering the wavelength region from 7 µm to 12 µm, where absorption features of all the chemical warfare agents and most explosives are to be found, we will have to use multiplexed external cavity QCLs for covering all the targets (17). Typical simultaneous experimental detection of NH_3, NO_2, dimethyl methyl phosphonate (DMMP, a simulant for nerve agents), acetone and ethylene glycol in a mixture containing ~ 3 ppb of NH_3, ~8 ppb of NO_2, ~20 ppb of DMMP, ~30 ppb of acetone and ~40 ppb of ethylene glycol is shown in Figure 17.

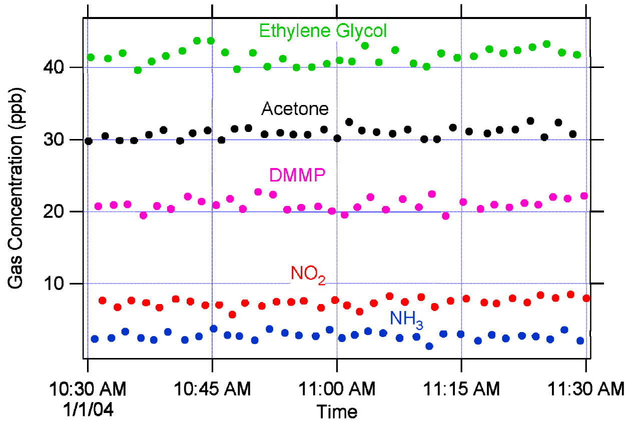

Fig. 17. Simultaneous detection of five components using a multiplexed external cavity QCLs.

Such a multiplexed spectrometer (Figure 18) is at present undergoing initial tests for final testing with live CWAs.

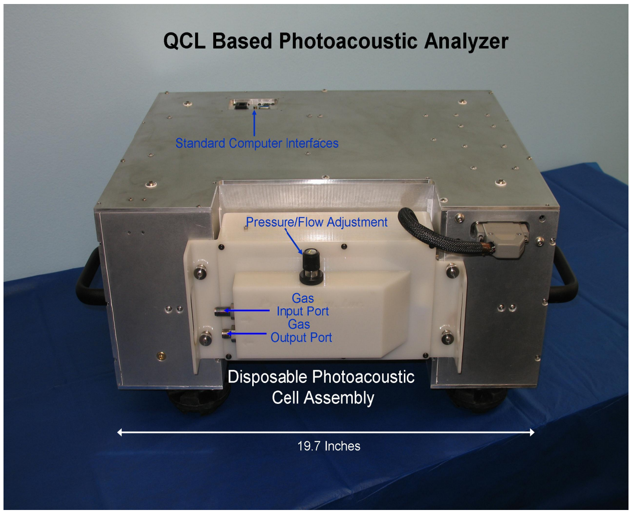

Fig. 17. QCL based photoacoustic spectrometer covering a wavelength range from 7 µm to 12 µm.

XI. Single Frequency Tunable QCL Systems Applications to Standoff Detection of Explosives

Identifying dangerous objects, such as improvised explosive devices (IEDs) from a safe distance has been an urgent issue in battlefield environments such as Iraq and Afghanistan (18). Recently we have been investigating the use of lasers for remote detection using the scattered light or other signals that can come back from an object that is being illuminated by tunable laser radiation that is absorbed by trace amounts of explosives on the surfaces of the suspicious objects. We have shown that standoff measurement of the target when illuminated by tunable laser radiation permits the detection of trace amounts of explosives at distances up to 150 meters (19). An alternate technology that analyzes the return scattered light has been utilized by the Oak Ridge National Laboratory. High power tunable lasers are needed for either of these schemes and multiplexed QCL systems fill that need. We have recently fabricated a total system combining tunable QCLs and return light collection system (Figure 19) that has a very high probability of finally providing a reliable solution to the vexing problem of standoff detection of IEDs.

Fig. 19. Multiple tunable QCL and light collection system for standoff detection of trace explosives residue.

XII. Conclusion

The very rapid technological advances in the QCL performance have resulted in the enabling of a very large number of practical applications in the civilian and military environments. As the performance continues to improve, many more applications will become possible. Don't change the channel!

Acknowledgements

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