WAVELENGTH
ELECTRONICS

An Introduction to Quantum Cascade Lasers (QCLs)

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WHAT IS A QCL?

Quantum Cascade Lasers (QCL) are semiconductor lasers that emit in the mid- and long-wave IR bands, and are finding new applications in precision sensing, spectroscopy, medical, and military applications(1). Their wide tuning range and fast response time allow for faster and more precise compact trace element detectors and gas analyzers that are replacing slower and larger FTIR, mass spectroscopy, and photothermal microspectroscopy systems.

Since the first operational QCL emitted light in 1994 tremendous effort has been put into making them more robust, versatile, and manufacturable. Quantum cascade lasers are used in industrial exhaust sensing, safe-distance explosives detectors, light sources for infrared imaging systems, medical diagnostic breath analyzers, and a variety of other sensing and spectroscopic applications(2). The number of markets for QCLs is growing at an ever-increasing rate as scientists and manufacturers gain more experience with them.

QCLs operate in a fundamentally different way than diode lasers:

- Diode lasers depend on the process of electron-hole recombination: an electron from the conduction band recombines with a hole in the valence band, and in the process a single photon is emitted.
- Diode lasers are limited to about 2.5 μm wavelength because the wavelength is determined by the recombination energy, or bandgap, of the material system used to fabricate the device. Different material combinations result in different bandgaps, but there is a limit to the materials that can be used to make a diode laser.
- **Figure 1** illustrates the principle on which QCLs operate, which is discussed in detail in the next section.

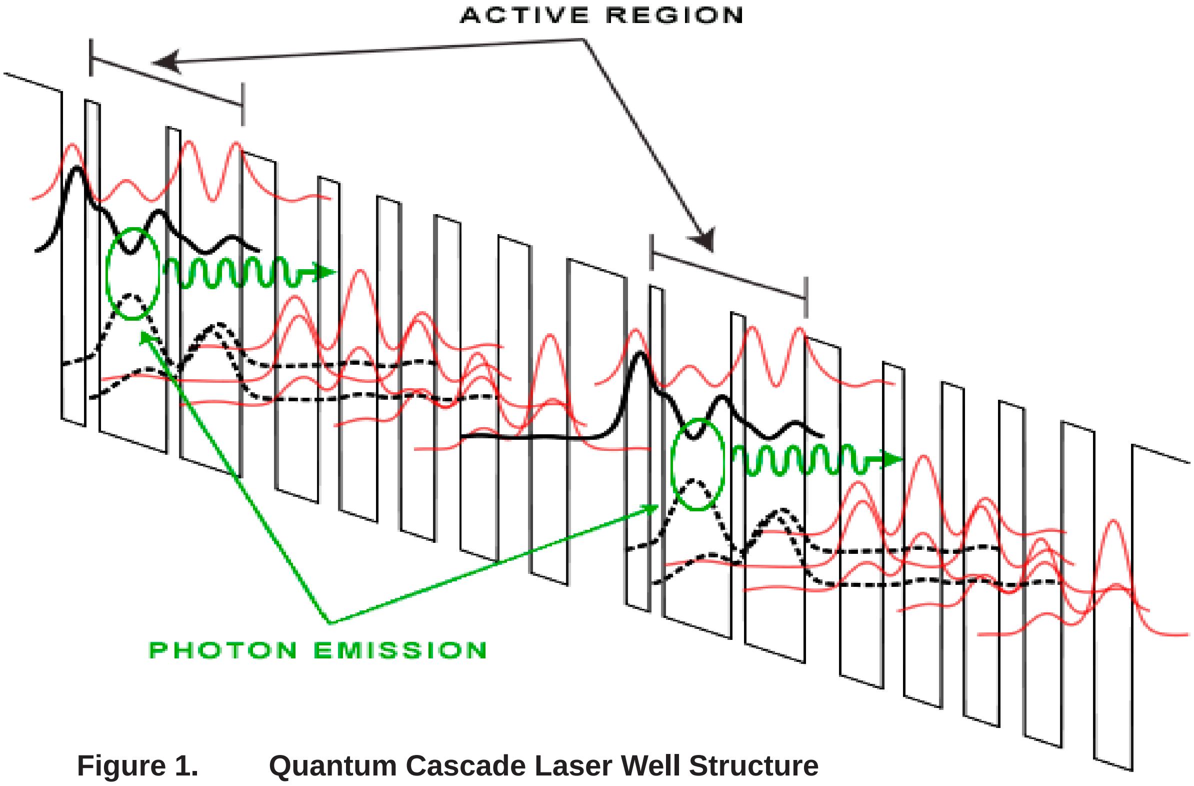

Figure 1. Quantum Cascade Laser Well Structure

THEORY OF OPERATION

Quantum cascade lasers are comprised of dozens of alternating layers of semiconductor material, forming quantum energy wells that confine the electrons to particular energy states. As each electron traverses the lasing medium it transitions from one quantum well to the next, driven by the voltage applied across the device. At precisely engineered locations, called the “active region,” the electron transitions from one valence band energy state to a lower one and in the process emits a photon. The electron continues through the structure and when it encounters the next active region it transitions again and emits another photon. The QCL may have as many as 75 active regions, and each electron generates that many photons as it traverses the structure.

The output wavelength is determined by the structure of the layers rather than the lasing material, and that means device fabricators can tailor the wavelength in a way that can’t be achieved with diode lasers. While diode laser output wavelength is limited to ~2.5 µm, QCLs operate at much longer wavelengths: mid-wave infrared production devices up to 11 µm are available, and some 25 µm emitters have been made on an experimental basis. This transmission range is useful because of the large number of absorption lines exhibited by common target gases that fall within this band.

Terahertz QCLs are now being commercialized - some emitting in the range of 100 µm to 150 µm. More complex gas molecules absorb at these longer wavelengths, and greater measurement accuracy is possible with QCL-based systems than with current technologies. QCLs allow for remote sensing of these complex molecules, whereas most traditional methods require a sample of the subject material. Some technical challenges remain before these systems are commercially viable on a large scale, but the technology is advancing rapidly.

WHERE ARE QCLS USED?

Perhaps the most important application for QCLs is in gas sensing and measurement. Systems based on widely-tunable QCLs can be used to measure multiple gas species, and narrowly targeted systems can detect and measure gas concentrations in the parts-per-trillion range.

Distributed feedback QCLs (DFB QCL) are capable of wavelength tuning up to a few tens of cm-1. External cavity QCLs (EC-QCL) expand the tuning range to ~1000 cm-1, and are used for sensing and measuring multiple gas species(3),(4). These types of QCLs are used for both local and remote sensing of numerous gas species, including CO, CO_2, NH_3, CH_4, NOX, and SO_2.

Because they require relatively low power and are so small, QCL-based systems replace larger and slower FTIR and mass spectroscopy systems for both lab and field work. Ruggedized applications include continuous exhaust monitoring on an industrial basis, such as in-the-stack measurements of pollutants, or well-head detection of byproduct gases at petroleum drilling platforms.

Specific examples of applications where QCLs excel include:

- High-power 4 µm QCLs used in heat-seeking missile countermeasures
- Improvised Explosive Devices (IEDs) are often made of compounds that absorb in the terahertz range; ruggedized and portable THz QCL-based detectors could be continuously scanned ahead of a moving convoy or used to search a public gathering space for threats
- Real-time monitoring of industrial exhaust emissions for process control
- Remote sensing of industrial exhaust stacks for environmental regulation enforcement
- Compact and fast airborne instruments for monitoring and measuring trace atmospheric gases in studies relating to global climate change

QCL-based systems are also finding application in the growing field of medical diagnostics(5). Trace gases present on a patient’s breath can indicate diabetes, asthma and other respiratory issues, kidney and liver dysfunction, and other indicators are being discovered regularly. Such an application requires extremely fast sampling times, relatively small size, and accurate results in order to avoid misdiagnosis.

At present QCLs are still somewhat specialized devices. Manufacturing is difficult to optimize, and small batch sizes result in high unit cost. As the value of these devices is more widely realized and more applications are created, QCLs will become more readily available and affordable.

Implementing QCLs requires system designers to pay particular attention to the driver and temperature control electronics. Current noise from the QCL driver causes the laser linewidth to broaden, which reduces the overall system sensitivity and precision, and temperature change causes the wavelength to drift. In order to fully realize the precision made possible by QCLs it is important that they are powered by ultra-low noise drivers and highly stable temperature controllers. Refer to *AN-LD14: QCL Basics* for more information about these important components of any QCL-based system.

LINKS TO ADDITIONAL INFORMATION

The Bell Labs website is a very readable primer on quantum cascade laser physics:
http://www.bell-labs.com/org/physicalsciences/projects/qcl/qcl.html

Northwestern University's QCL physics page details the construction and reliability of QCLs:
http://cqd.eecs.northwestern.edu/research/qcl.php

RESEARCH PAPERS:
Wysocki, et. al., *Widely tunable mode-hop free external cavity quantum cascade lasers for high resolution spectroscopy and chemical sensing* (2008);
http://www.springerlink.com/content/q0p138243033555m/

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http://www.mdpi.com/journal/sensors

Soibel, et. al., *Development of mid-IR lasers for Laser Remote Sensing* (paper, 2005);
http://trs-new.jpl.nasa.gov/dspace/itstream/2014/39495/1/05-0717.pdf

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http://trs-new.jpl.nasa.gov/dspace/itstream/2014/37798/1/05-0828.pdf

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(1) Zeller, et. al., *DFB Lasers Between 760 nm and 16 µm for Sensing Applications*, (Sensors 2010, 10, ISSN 1424-8220)

(2) Tittel, Bakhirkin, Kosterev, and Wysocki, *Recent Advances in Trace Gas Detection Using Quantum and Interband Cascade Lasers* (Rice Quantum Institute, Rice University, 2006)

(3) Wysocki, et. al., *Widely tunable mode-hop free external cavity quantum cascade lasers for high resolution spectroscopy and chemical sensing,* (Applied Physics B, 2008)

(4) Soibel, Mansour, Spiersand, Forouhar, *Development of mid-IR lasers for Laser Remote Sensing*, (Jet Propulsion Laboratory, California Institute of Technology, 2005)

(5) Bakhirkin, et. al., *Mid-infrared quantum cascade laser based off-axis integrated cavity output spectroscopy for biogenic nitric oxide detection,* (Rice University, 2004)

REVISION HISTORY

REV	DATE	NOTES
A	20-Apr-13	Initial Release