Powerful QCLs eye remote sensing

QCLs are ideal sources for remote chemical sensors that identify gases by infrared spectroscopy. High powers are essential, and new multiwatt designs from Northwestern University are nearing this target.

Our eyes tell us a great deal about our environment. However, they can't spot the numerous invisible threats to our health and safety; threats that also evade detection by conventional imaging systems. They include harmful pollution released from industrial accidents, and some types of terrorist activity, such as the discharging of nerve agents. We have little protection against these kinds of chemical-based threats, and even governments are ill-equipped to constantly monitor their entire homeland.

What's needed is a low-cost remote chemical sensor. This would eliminate arduous, time-consuming surveys with hand-held detectors, and replace them with faster, cheaper surveys by longer-range ground or air-based detection systems.

Optical detection schemes are ideal for this task because they can quickly cover vast areas with high-power lasers that are directed far from the detection system. The low-flying aircraft ITT Angel Service, for example, covers 1000 miles per day searching for natural gas leaks from pipelines.

This search employs differential absorption spectroscopy – one of several techniques for remote optical chemical sensing. The most promising of these operate in the mid-infrared wavelength range (3–12 µm) that overlaps the so-called "molecular fingerprint" region and allows specific chemicals to be identified by characteristic absorption signatures.

The best results are obtained by scanning over a wide wavelength range because this improves the quantitative detection of trace chemicals against a background of strong absorbers. Infrared spectroscopy's specificity gives it an edge over other techniques, such as laser-induced breakdown spectroscopy.

The most promising source for remote mid-infrared spectroscopy is the quantum cascade laser (QCL), an inherently small and robust device suitable for mass production. QCL characteristics are improving all the time, with progress aided by efforts such as the Defense Advanced Research Projects Agency (DARPA) Laser Photoacoustic Spectroscopy program, which started in 2005. The primary goal is to detect trace amounts of hazardous chemicals and explosives, which requires the development of QCLs for photoacoustic spectroscopy.

Our research team at the Center for Quantum Devices, Northwestern University, IL, is involved in this project. It was given the task of developing room-temperature QCLs operating over many wavelengths with a continuous-wave (CW) output power of at least 100 mW. We have now exceeded these criteria with a portfolio of QCLs spanning 3.8–11.5 µm.

Gas leaks from an underground pipe have been detected by differential absorption, using an instrument mounted in the low-flying aircraft ITT Angel Service. This approach is far quicker than the traditional methods involving hand-held instruments and it can cover 1000 miles per day.

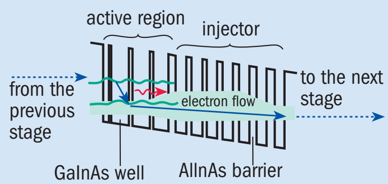
While these lasers' output powers are impressive, they are insufficient for some remote applications that demand 10 W or more. To reach these higher powers requires improvements to the QCL's overall power conversion efficiency, which until recently has languished at less than 5%. DARPA is now trying to address this issue by funding an Efficient Mid-wave Infrared Lasers (EMIL) program that aims to develop more-efficient sources for infrared countermeasures, and for remote chemical and biological threat detection. We have been chasing one of the project's goals – a room-temperature 3.8–4.8 µm QCL with a power efficiency of 50% and an output power of at least 1 W.

QCLs were chosen over competing semiconductor technologies, including nascent interband cascade lasers, which are less-developed devices that need an increase in room-temperature output power of two orders of magnitude to meet DARPA's goal. QCLs also promise to deliver significant energy savings over current sources, such as nonlinear optical parametric oscillators and gas lasers, while employing a tiny active volume comparable to existing diode lasers. What's more, these devices are built on InP, which means that they can draw on mature epitaxial and fabrication technologies that have been honed by the telecommunications industry.

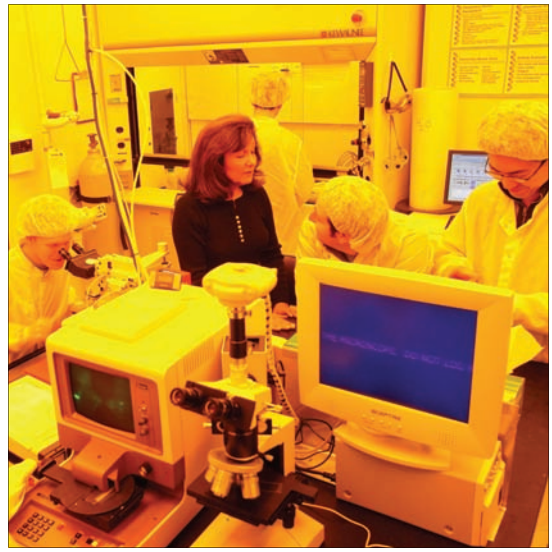
How a QCL works

QCLs are structures with a fully artificial "band gap" that is created within a given band – in our case the conduction band – through the growth of complex III-V heterostructures (see figure). The structure's emission wavelength can be tuned over a very wide wavelength range by adjustments to the thickness of the quantum well, which alters the electron's energy states. This is a major benefit because it allows the most mature and robust material technology to be employed. Building mid- and far-infrared lasers operating at room temperature is also more straightforward because the bandstructure in this type of device leads to a far weaker dependence of photon emission on wavelength and temperature.

QCLs also need to feature an efficient method for electron transport. "Injector" regions are designed to do just this, and enable a single electron to emit multiple photons during its journey across the device. The combination of quantum-based transport and cascaded emitters leads to high-power operation.



QCLs emit photons (shown in red) when electrons transfer from a high energy state to a lower one within the conduction band. Typically, 30 or more stages are stacked together to produce many photons from one electron. The shaded area (green) represents a miniband for electron conduction. The electrons are forbidden in other areas.



ANDREW CAMPBELL

Manijeh Razeghi's team at Northwestern University uses a well equipped facility that features MOCVD and MBE reactors, scanning electron and atomic force microscopes, electron-beam lithography tools, X-ray diffraction and photoluminescence systems, dicing, and life testing systems.

Obstacles to high powers

QCLs produce emission through radiative intersubband transitions (see box "How a QCL works"), and have output powers limited by electron-phonon scattering. This very fast process, which is weakly dependent on wavelength and temperature, occurs on picosecond timescales. This makes it three orders of magnitude faster than radiative recombination, which accounts for the device's incredibly low radiative efficiency and differential gain. Only one in a million electrons will recombine radiatively, and differential gain is just 10 cm/kA at most wavelengths. Neither of these key figures of merit is encouraging.

However, the radiative emission rate can draw level with the non-radiative rate when a large photon flux is employed alongside a high optical confinement factor. For modern lasers above threshold, this works so well that the internal quantum efficiency can hit 50% or more, which is a staggering improvement. Getting to these levels is a tall order though, which demands careful engineering of the wave functions within the quantum heterostructure.

The first QCLs were low-temperature devices, and it's been a massive challenge for our community to transform them to room-temperature sources. Efficiencies are governed by thermal broadening, band filling and electron leakage, and new designs have been needed to combat these effects. Fortunately, improvements have resulted from deeper reservoirs in the injector region and taller barriers that increase electron confinement.

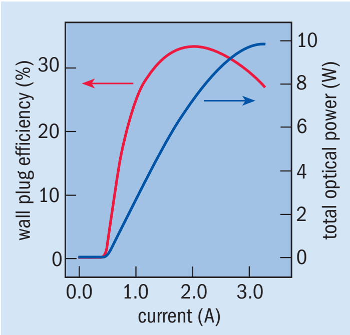
Maintaining strong electron confinement in short-wavelength devices is particularly tricky, because this structure can't be grown on InP substrates with lattice-matched $Ga_{0.47}In_{0.53}As$ and $Al_{0.48}In_{0.52}As$. But strain-balanced designs – which are still to be optimized – can address this issue and lead to the growth of dislocation-free $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ heterostructures with a band offset of up to 0.9 eV.

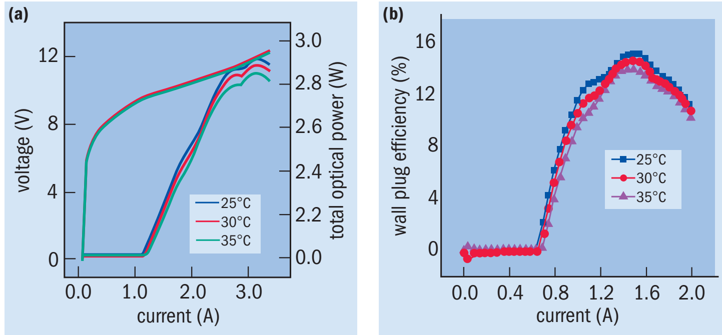
Output powers are also held back by laser cavity losses. Free carrier losses from the waveguide cladding and contact layers are far higher in the infrared than the visible, and scale as λ^2 to λ^3. We minimize this and increase the differential gain by lengthening the cavity to 3–5 mm and employing a 3–4 µm thick, low-doped cladding. This creates a QCL with low threshold gain, good power-conversion efficiency, acceptable parasitic series resistance and an external optical loss to the laser core that can be as low as 0.5 cm^{-1}.

We have taken care to avoid absorption between the other subbands in the active region and injector. This type of loss tends to scale with the doping in the injector, but it can be minimized through wave function engineering and improvements in material quality, which reduce emission linewidths.

Boosting internal efficiencies and cutting optical losses has spurred the fabrication of QCLs with outstanding characteristics. These include 4.6 µm room-temperature multimode lasers with up to 22% wall-plug efficiency and a peak output power of up to 34 W. But QCLs with a high average power are more important for us, and our recent efforts have focused on efficient, high-power CW lasers.

We are working towards DARPA's 50% efficiency target. As such, all QCLs still generate a tremendous amount of heat. This makes thermal management a key issue. We have investigated several designs, including those featuring a gold heat spreader on the chip's top surface to increase thermal conductance by 30%. We also used the well known trick of bonding the epitaxial side of the wafer directly to a high





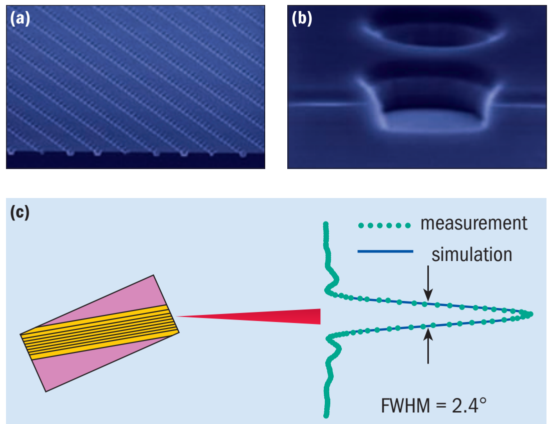


Fig. 1. (top left) Longer cavities, thicker cladding regions and a buried ridge geometry can crank up QCL continuous-wave output powers to almost 10 W at 80 K. **Fig. 2.** (top center and right) QCLs operating at close to room temperature can produce an output of several watts **(a)** at efficiencies of greater than 10% **(b)**. **Fig. 3.** (bottom) Photonic crystal distributed-feedback QCLs promise to deliver the spectrally pure emission profile needed for gas sensing. The two-dimensional grating structure **(a & b)** is tilted with respect to the laser mirrors **(c)** to improve spatial filtering of the laser's transverse mode. A single-mode output is produced by this design.

thermal conductivity submount.

However, our highest efficiencies have been reached by switching to the more complicated "buried ridge" geometry. The laser is etched into a ridge waveguide before a semi-insulating, lattice-matched InP layer is grown selectively on the side of the ridge. This replaces an amorphous dielectric insulating layer such as SiO_2. The buried-ridge design also cuts optical loss and thermal mismatch, and enables manufacture of laser cores with good structural stability that are less than 10 µm wide.

Combining these advances delivered a dramatic improvement in our 4.6–4.8 µm QCLs. Single emitters at cryogenic temperatures emit a multimode CW output of more than 10 W at 34% wall-plug efficiency (figure 1) and at 25 °C we have produced 2.8 W QCLs with 15% wall-plug efficiency (figure 2).

Power-scaling ambitions

Simple geometrical changes offer us a route to even higher power lasers. One option is to build laser arrays, an approach that is used in near-infrared pump lasers. Alternatively, we could scale our emitter's width from around 10 µm to 100–200 µm.

Both approaches will crank up the output power, but at the expense of beam quality. Emitter width scaling, for example, will probably cause high order, double-lobed emission. However, the beam profile can be controlled to emit within a single spatial mode through additional lateral index modulation. Another way to fabricate a spectrally pure laser source is to incorporate wavelength-specific feedback inside the laser cavity.

One design that features both of these improvements is the photonic crystal distributed feedback (PCDFB) laser. This type of device – which we were inspired to investigate by Jerry Meyer at the Naval Research Laboratory – promises to deliver powerful, high-purity, single-mode emission profiles that are essential for remote infrared spectroscopy.

Our PCDFB laser, like some commercial distributed feedback (DFB) lasers, employs diffractive feedback from a buried grating near the waveguide core (figure 3). However, it differentiates itself with two-dimensional patterning, which is tilted with respect to the laser mirrors to improve the spatial filtering of the device's transverse mode.

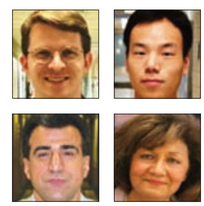
Despite its complexity, we have had some success and reported the results for a spectrally pure, broad-area QCL that emits a diffraction-limited single-lobed far-field pattern. We have only demonstrated low peak power to date, but we are confident that dramatic improvements in output power are possible through design and fabrication refinements.

The US military wouldn't be the only beneficiaries of a successful DARPA program – QCLs are promising sources for free-space communication. They have the capability to create robust links, thanks to emission wavelengths that can penetrate further through dense fog than near-infrared sources.

We believe that QCLs with an output power of up to 10 W will soon be available, providing a major boost to remote sensing. These lasers could also serve a wide variety of other applications, such as multipoint industrial monitoring and standoff detection of hazardous chemicals. Integration with infrared camera systems would even allow differential absorption imaging of chemical spills and clouds. The foundations of this technology are already under development, and several organizations are exploring active imaging with weaker laser sources and passive gas imaging with infrared cameras. ●

Further reading

A A Kosterev *et al.* 2002 *IEEE J. of Quant. Elect.* **38** 582.
Y Wang *et al.* 2005 *Optics Express* **13** 6572.
J S Yu *et al.* 2006 *Appl. Phys. Lett.* **88** 251118.
Y Bai *et al.* 2007 *Appl. Phys. Lett.* **91** 141123.
Y Bai *et al.* 2008 *Appl. Phys. Lett.* **92** 101105.



About the authors

Steven Slivken (top left) is the QCL group team leader at the Center for Quantum Devices and is responsible for epitaxial growth of QCLs. **Yanbo Bai** (top right) is a PhD student at the Center for Quantum Devices in the EECS department at Northwestern University and is working on QCL simulation, fabrication and testing. **Shaban Ramezani Darvish** (bottom left) is a research scientist at the center whose specialty is fabrication, testing and packaging of optoelectronic devices. **Manijeh Razeghi** (bottom right; razeghi@eecs.northwestern.edu) is the director of the center. She oversees all of the group's projects, including QCLs, type-II detectors and focal plane arrays, quantum-dot infrared photodetectors, UV avalanche photodiodes, and blue/green LEDs and lasers.