The Quantum Cascade LASER:

A Versatile and Powerful Tool

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Many important applications in the infrared are awaiting the right laser source. Advances in quantum cascade lasers will enable powerful new technologies to become commercial realities.

The diode laser has been around for more than 40 years. In the beginning, it was a scientific novelty. Later, it became a strategic technology, due to its small size, low power consumption and long lifetime. Now, thanks to mass production, millions of laser diodes are manufactured each month and appear in products ranging from telecommunications transmitters to DVD players to laser pointers. In fact, diode lasers made up roughly 55 percent of a $6.9 billion worldwide laser market in 2007.

Lasers have always been a technology in search of an application. Like the chicken and the egg, the laser application usually does not come about until the laser itself is available.

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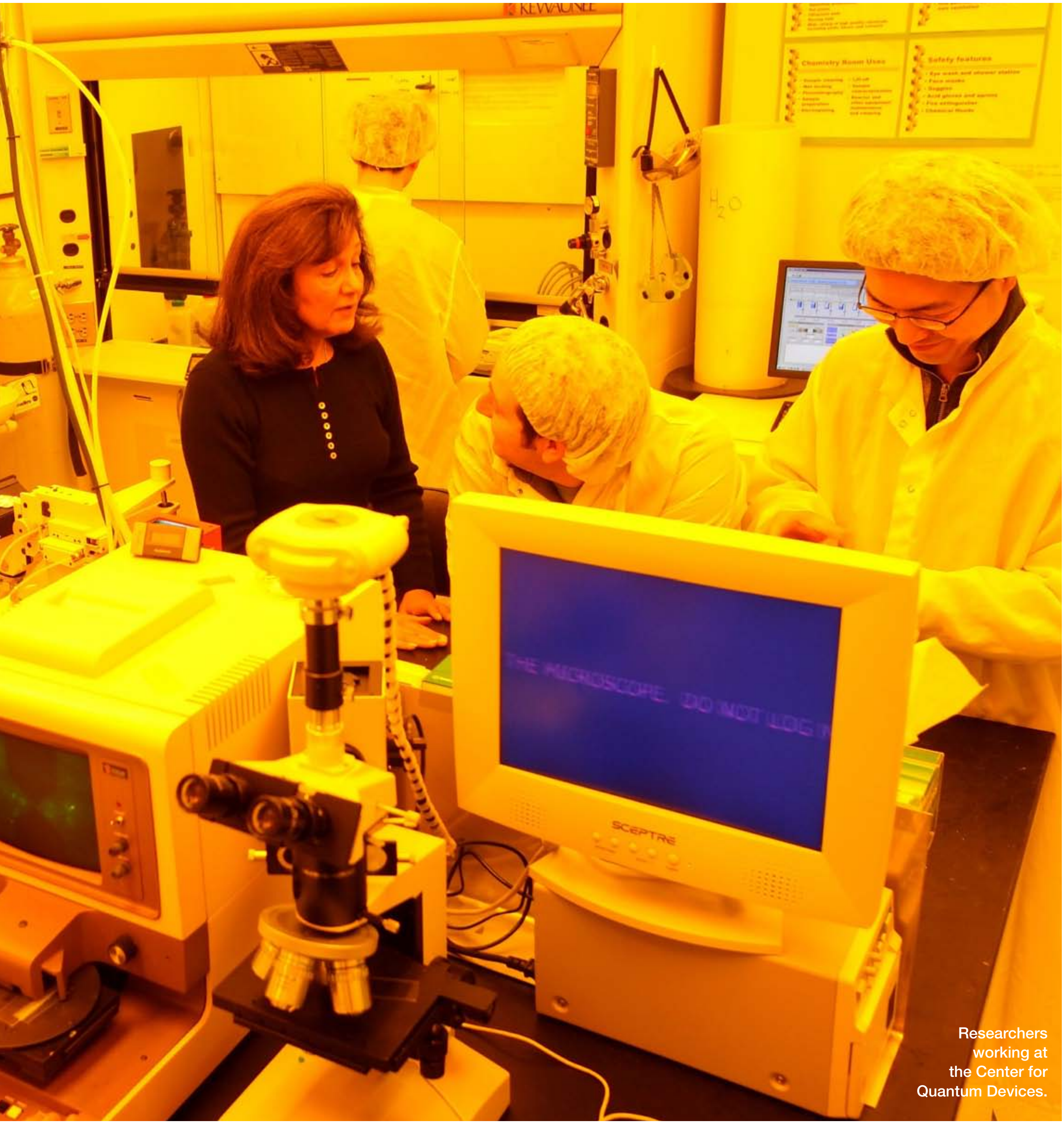

Researchers working at the Center for Quantum Devices.

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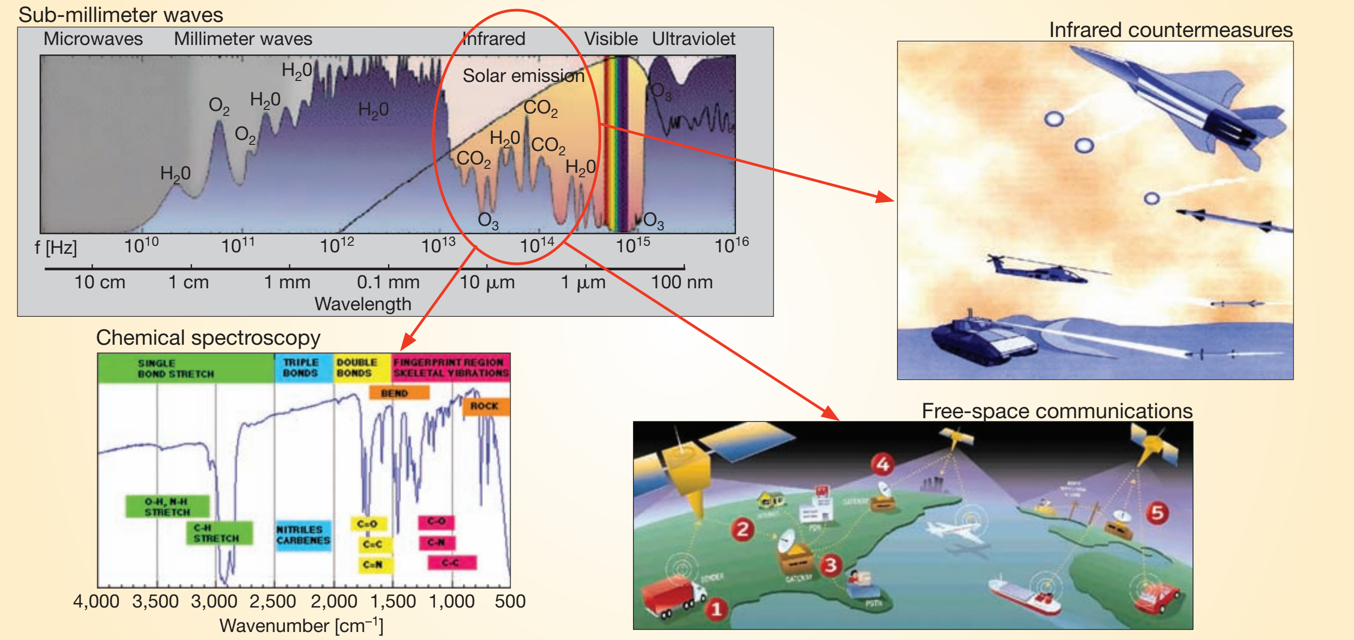
Further, the application does not become widespread until the system becomes mass-producible.

For traditional laser diodes, applications are often dictated by which part of the electromagnetic spectrum is accessible. For example, telecommunications lasers operate in a region of the infrared, where silica optical fiber has minimum dispersion or transmission loss. Laser-based displays, on the other hand, require red, green and blue lasers to make a visible image. A biological fluorescence system will often require an ultraviolet source to function correctly.

Many people do not realize that a large part of the electromagnetic spectrum is still not fully utilized commercially.

[Applications of quantum cascade lasers]



The wavelength region accessible with quantum cascade lasers and the developing applications of this technology.

This includes the bulk of the infrared region. Though the scientific community has been exploring it for some time, the research systems are usually too bulky, expensive and hard-to-understand to become large-scale commercial products. Then again, optical storage technologies such as the CD player were also underutilized until diode lasers were tapped to enable their operation.

Applications for mid- and long-wave infrared lasers

There are three main advantages of the mid- and long-wave wavelength region. Perhaps the most important feature, and one of the major forces driving development of the quantum cascade laser (QCL), is that all molecules can be absorbed in the infrared. The atoms in a molecule can bend, stretch and rotate with respect to one another, and these excitations are, to a large extent, optically active.

Most molecules, ranging from the simple to the moderately complex, have a characteristic absorption spectrum, from 3 to 14 µm, in which they can be identified and quantified in real time. Infrared spectroscopy has been used for this purpose for many years, although industrial systems are typically not sensitive enough to detect trace amounts. The benefit of the optical technique—as opposed to chemical sensors or chromatography—is that the detection mechanism requires minimal sample pre-treatment; it is also reusable and very fast.

For hazardous chemicals, such as explosives or nerve agents, applications are needed that can detect even the smallest amount—which is why laser systems are necessary. Laser systems allow for both direct, long-path-length absorption measurements as well as the indirect monitoring of chemicals through high-power excitation (photoacoustic and photothermal detection). These systems can be built in many ways, but can quantify specific chemicals down to part-per-billion concentrations. The main challenge today is to develop systems of reasonable size, cost and complexity. Researchers who are part of the Defense Advanced Research Projects Agency's (DARPA) recent program on lasers and photoacoustic spectroscopy are working to address those issues.

Because they can directly absorb specific molecules, mid- and long-wave infrared laser systems also lend themselves to potentially useful medical technologies. Breath analysis, for example, has already been used to monitor people's health by checking for byproducts of abnormal cell metabolism. In the future, it may also be possible to target or cauterize specific types of cells by their chemical or protein content for selective surgery.

A second appeal of this wavelength range is related to atmospheric transmission. We've already discussed applications based on the presence of absorbing species, so now let's turn to those that address their absence. There are a couple of broad wavelength ranges (3 to 5 µm and 8 to 12 µm) that have minimal absorption by typical atmospheric gases. In the near-infrared, there has been a lot of research into free-space optical links to complete the "last-mile" connectivity problem for high-speed Internet. These systems have good bandwidth and are cheaper to install than fiber-optic cable.

One downside to these systems is that they are sensitive to weather. Scattering by rain and fog severely attenuates the

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signal, thereby reducing the bandwidth, distance and/or availability of the data link. At longer wavelengths, scattering by fog is dramatically reduced. An inexpensive mid- or long-wave laser source could replace the near-infrared laser and lead to better range and availability for these systems. At the same time, if the power can be increased without adding significantly to cost or causing eye safety issues, the link distance will be proportionally longer as well.

The final appeal of the mid- or long-wave laser is not related to what it interacts with, but rather to what it resembles. All objects at a finite temperature emit blackbody radiation. Colder objects emit primarily at longer wavelengths (long-wave infrared), and hotter objects (like the sun) emit predominantly at shorter wavelengths (visible). A room-temperature object (298 K) has a peak emission wavelength of 9.72 µm. Jet engines have a peak emission in the 2 to 5 µm range.

As such, to complement the thermal imaging cameras that have become so prevalent, a laser source targeting a similar wavelength range can be used to simulate a hot object, or project an image of a hot object, while itself remaining at room temperature. While the base use of this technology could simply be to test and calibrate thermal cameras, there are also larger motivations. Military and commercial aircraft, unfortunately, are in danger due to heat-seeking, shoulder-fired missiles. A properly designed infrared laser system could be used as a decoy, or, preferably, to confuse or damage an incoming missile attack. Assuming the system can be made cost-effectively, all commercial aircraft could someday be protected with this technology.

The principle of the quantum cascade laser

All semiconductors have a characteristic band gap. By varying material composition, typical III-V semiconductors—which are made of elements from columns III and V from the periodic table—have band gaps that can span a very large energy range. This range includes the III-Nitrides, which can reach into the ultraviolet, as well as InSb and near semi-metal compounds, which reach deep into the infrared. While the band gap of some of these semiconductors is appropriate for mid- and long-wave emitters, solid-state physics does not allow these materials to be very optically active as emitters.

For near-infrared lasers, when electrons from the conduction band relax to the valence band (across the band gap), the energy is typically transferred to a photon. At longer wavelengths, depending on band structure and temperature, this energy is often re-absorbed by another charge carrier and eventually transferred to heat. As such, standard semiconductor laser technology (based on interband lasers) has a fundamental hurdle to overcome for wavelengths longer than about 3 µm.

This brings us to non-standard semiconductor laser technology that utilizes band-structure engineering. While there are many variations, the most successful technique for room-temperature operation over the mid- or long-wave regions is the intersubband laser—a subset of which are the quantum cascade lasers (QCLs).

The interband structure utilizes that natural band gap for electron transitions. Thus, the material composition mainly controls the emission energy. In an intersubband emitter, a new "band gap" between quantum-well subbands is created for this purpose. Since the spacing between subbands is controlled by the quantum-well thickness, the emission energy or wavelength can be tuned over a very wide range without changing the material composition.

This has two major benefits. First, as the emission is independent of material, we can use the most mature and robust material technology available as the basis of our device (no exotic materials). Second, because the curvature of the bands is the same, the efficiency of photon emission has a much weaker dependence on wavelength and temperature—which allows easier realization of mid- and long-wave lasers at room temperature.

[Interband vs. intersubband laser diodes]

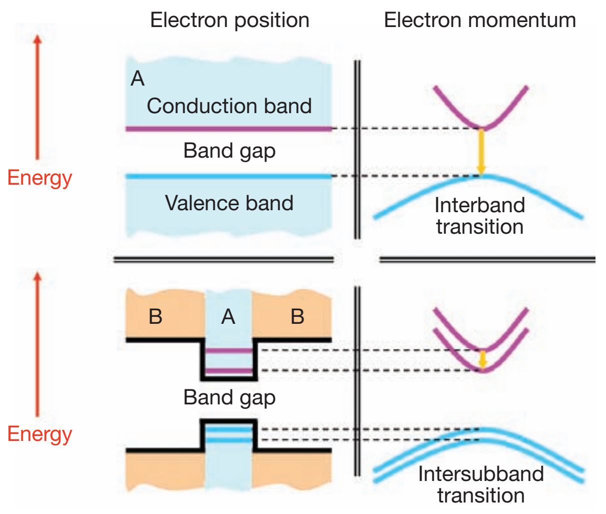
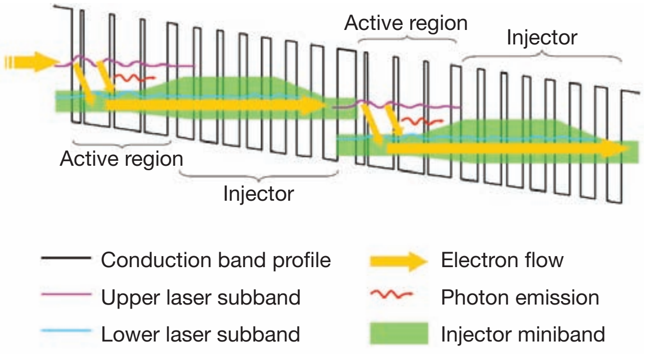


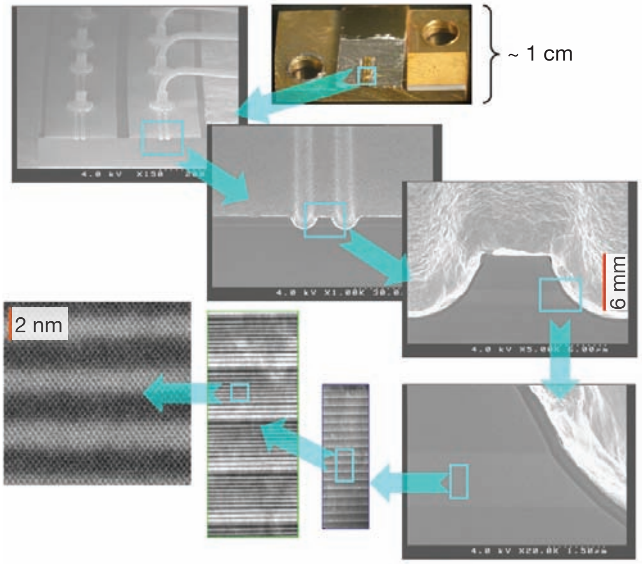
Illustration of the differences between traditional (interband) laser diodes and intersubband laser diodes such as the quantum cascade laser. Unlike the interband laser, the intersubband makes use of an electronic transition (yellow) solely within the conduction band.

[Two emitting stages of the quantum cascade laser]



This schematic shows the role of the injector region and the cascaded nature of photon emission; a single electron can emit multiple photons.

[Size scales of the QCL]



(Top) A packaged device; (Center) the waveguide cross-section as imaged by a scanning electron microscope; (Lower left) some of the individual layers of the injector region as imaged by a transmission electron microscope.

This technology can also access terahertz spectral regions (30- to 300-μm wavelengths) by making the subband spacing extremely small (< 40 meV); however, it requires cryogenic cooling to operate ($T < 178$ K). The only exception, so far, is a device that uses nonlinear conversion of two mid-wave QCLs to achieve operation at room temperature. Unfortunately, the power output is still 7 orders of magnitude lower than standalone midwave QCLs. Still, as midwave QCL performance increases, this translates to an improvement of this nonlinear technique as well. Work is continuing in this area, and if this or another laser technology can operate in the terahertz range without cryogenic cooling and significantly higher power, a whole new set of applications may emerge for the commercial sector as well.

Construction of the quantum cascade laser

The QCL is a type of general intersubband laser that specifies not only the light emission mechanism, but electron transport and power scaling as well. While the earliest intersubband emitters were optically pumped, the QCL is electrically pumped (e.g., with a battery), similar to standard laser diodes. The secret to success is to engineer the electron flow through a series of subbands and minibands (groups of subbands), which allow for a buildup of electrons within the upper laser subband, and fast extraction from the lower subbands.

This is accomplished by a special injector region, which blocks electron escape out of the upper subband while still strongly coupling to the lower subband. In addition, this injector region also serves to recycle extracted electrons by re-injecting them into the upper laser subband of a subsequent emitting stage. This quantum-based transport, combined with the cascaded emitter design, is responsible for the name of this laser.

Beyond this basic design principle, the full laser design must take into account the actual emitting wavelength, operating conditions and operating temperature. Like many devices, the QCL will experience some performance degradation with temperature (though not as much as an interband device) and requires detailed optimization for high-temperature operation, including the introduction of strategic energy barriers to minimize thermal leakage.

In addition, like all semiconductor lasers, the quality of the device is directly related to the quality of the material used to construct it. Unlike some traditional semiconductors, however, the QCL is truly a “quantum” device. The individual layer thicknesses range only from 1 to 4 nm. With 22 layers per stage, and 30-40 emitting stages within a laser core, this translates to 660-880 thin layers per device. Although that does seem like quite a lot, researchers have used both molecular beam epitaxy and metalorganic chemical vapor deposition to successfully grow high-quality QCLs. These are industry standard reactor types that do not need any special modifications. Some groups are also exploring limited mass-production, which is starting to bring the price point down for standard QCL designs.

An optical waveguide must also be grown to help confine light inside the device. As such, the full structure is often 4 to 10 μm in thickness, depending on the emission wavelength. After standard photolithography, etching and metallization to define the overall device dimensions and current injection path, the full device is only about 100 μm thick (including substrate) and takes up less than 0.001 cm^2 of area.

The first demonstration of this technology at Bell Laboratories was published in 1994 at croyogenic temperatures. Shortly

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thereafter, in 1996, room-temperature pulsed operation was demonstrated. Our group, at the Center for Quantum Devices, led by Manijeh Razeghi, began working on QCLs shortly thereafter at the request of DARPA. Within one month, we had operated our first room-temperature lasers. Since then, we have made steady progress to improve both the power, efficiency and wavelength range of mid- or long-wave QCLs.

Recent achievements in QCLs

At room temperature, researchers have demonstrated QCLs in pulsed operation spanning wavelengths from 3 to 16 µm. Many of the lasers in this wavelength range can also operate well above 400 K when necessary. Unfortunately, the overall wavelength range is limited due to technological hurdles. For example, at shorter wavelengths, very deep quantum wells are required, and they often necessitate more exotic materials. As a result, material quality becomes an issue and additional band structure elements (X and L valleys) affect electron transport. At longer wavelengths, the waveguide absorption grows very quickly and thereby influences the device efficiency. Various research groups are interested in widening this operating range, with the goal of extending the versatility of the QCL.

Of course, pulsed operation is usually only the prelude to continuous wave (CW or constant-on) operation, which gives the laser its maximum potential for various applications. CW operation allows for both high average power delivery and narrow linewidth. The main hurdles for CW operation at room temperature have always been a high-power density and a low-power efficiency. Decreasing the threshold power requirements, minimizing loss and optimizing laser packaging have all had important impacts on the road to continuous wave QCL development. Toward this goal, we have reached 22 percent pulsed power efficiency; this is a noted improvement over the less- than-5-percent efficiency that most lasers have demonstrated.

Since the first CW demonstration in 2002 (about 10 mW of power), QCLs have experienced rapid and dramatic improvements in power, efficiency and wavelength range. Our group has demonstrated CW QCLs at wavelengths from 3.8 to 11.5 µm with more than 100 mW output power. At a targeted wavelength in the range of 4 to 6 µm, we have also demonstrated well over 1 W from individual CW QCLs at room temperature. In addition, while initial power efficiencies were below 1 percent, our recent devices have CW efficiencies of more than 12 percent. CW operation for these devices is also possible above 100° C.

Conclusion

Many applications will benefit from the recent improvements in QCL wavelength range, operating temperature, power and efficiency. From a spectroscopic viewpoint, a wider wavelength range means that more chemical absorption features can be measured with this technology—which in turn translates to better discrimination, and less chance for false positive and negative responses. A higher operating temperature means more efficient cooling and the ability to operate in harsh environments. Higher power means an increased range for many applications, and allows for the possibility of remote chemical detection.

For photoacoustic spectroscopy, a higher power source leads to a better signal-to-noise ratio and potentially faster acquisition times. Finally, higher efficiency should pave the way to smaller laser-based systems that weigh less. Moreover, a more efficient device would use less input power to achieve the same output power, decreasing battery size and cooling requirements, both of which dominate current QCL packaging.

The quantum cascade laser is an excellent compact laser source that opens the door to many important applications in the infrared spectral region. Current operating deficiencies are being actively mitigated, thanks to continued funding in this area. As performance starts to approach that of standard laser diodes, and as mass production ensues, this technology is destined to have a lasting impact.

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