High-power continuous-wave quantum-cascade lasers at room temperature

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Recent advances in the design and fabrication of mid-IR lasers pave the way for important applications such as countermeasures and remote sensing.

Quantum-cascade lasers (QCLs) are semiconductor injection devices that emit light in the mid-IR (wavelengths $\lambda = 3$–$25\mu m$) and THz regimes. Since their invention at Bell Labs in 1994, they have undergone constant development. The most interesting applications employing mid-IR light sources are currently in industrial-process monitoring, noninvasive diagnostics, and security and defense, among others. Most of these are based on spectroscopic analysis, which does not necessarily require high power levels (for instance, chemical-process monitoring or gas analysis). However, a significant number of important mid-IR applications require high-power lasers, including IR countermeasures, free-space optical-data links, and remote sensing. In all cases QCLs are the laser source of choice because of their portability, wavelength agility, robustness, and output power.

QCLs are unique in many respects. Unlike semiconductor-diode lasers, QCL lasing occurs between two subbands within the conduction band of the semiconductor heterostructure. While a single electron–hole recombination can only ever produce a single photon, an electron in a QCL can cascade down 20–100 identical stacks of quantum wells, producing a photon at each step. This significantly increases the lasing efficiency, enabling an output power of several watts. The QCL lasing wavelength is not determined by the choice of material (as for interband lasers) but by adjusting the physical thickness of the semiconductor layers.

The complex structure of a QCL’s active regions—with several hundred interfaces and layer thicknesses of only a few monolayers—poses challenges to the growth process. Until very recently, high-performance QCLs were grown by molecular-beam epitaxy (MBE). In 2006 we demonstrated QCL growth through the technologically important metal-organic vapor-phase epitaxy (MOVPE), resulting in comparable performance to their MBE-grown counterparts. The fabrication of high-performance QCLs using MOVPE reactors (widely used in the semiconductor industry) marked a milestone in their commercialization.

However, despite tremendous improvements in performance, leading, for example, to the demonstration of high-power continuous-wave operation at room temperature, the QCL power efficiency is still significantly below theoretical predictions, at $\sim 40\%$ for short-wavelength ($\sim 5 \mu m$) devices. We aimed to improve the QCL wall-plug efficiency, defined as the ratio of

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the optical output and the electrical input power. In addition, MOVPE-grown devices were designed for high-performance operation in continuous-wave mode at room temperature. This restricts the doping level and physical size because the active region’s self-heating must be kept low. In continuous-wave operation the active-region temperature can be several tens of Kelvins higher than its heat-sink temperature.

The optical waveguides were designed to suffer from low optical losses and to have a large overlap of the optical mode and the gain medium. Application of a buried heterostructure laser with a narrow width is the most effective route to achieve these goals. It also maximizes heat dissipation from the waveguide core. The active region of our structure is based on highly strained indium-gallium arsenide/aluminum-indium arsenide quantum wells and barriers. The strain is needed to achieve deeper quantum wells, allowing short-wavelength operation. Since electron backfilling and leakage currents due to hot electrons can significantly decrease device performance at high temperature, the active region was optimized to reduce these parasitic effects.\(^7\)

The QCLs were mounted episide down on aluminum-nitride submounts and operated on thermoelectric (TE) coolers for temperature stabilization. In pulsed mode we obtained 16% wallplug efficiency at room temperature (300K) and 22% at 243K, a temperature easily achievable using standard TE coolers. Figure 1 shows the input-current/output-voltage and input-current/output-peak-power characteristics at these temperatures. The peak output powers were 4 and 5.5W at 300 and 243K, respectively. Operating in continuous mode we still obtained 1.6W peak power at room temperature with a wallplug efficiency close to 10%. This was the first time watt-level continuous-wave QCL operation at room temperature was reported.\(^7\) It was subsequently also demonstrated with QCLs grown through MBE.\(^3\)

The present level of performance and device integration already permits QCL incorporation into practical applications where high-power mid-IR lasers are required, such as photoacoustic spectroscopy, free-space optical communications, and IR countermeasures.\(^5\) User-friendly, fully packaged devices exhibiting this performance level (see Figure 2) pave the way to general adoption of QCL technology. In fact, turn-key laser systems incorporating these devices are already commercially available, producing 1W at 4.6\(\mu\)m in continuous-wave mode at room temperature.

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