by Jennifer Ouellette

Quantum Cascade Lasers Turn Commercial

Quantum cascade (QC) lasers are poised to enter the commercial market less than a decade after their creation. Their initial applications will be as compact, portable sensors for a broad range of industrial markets, including the automotive, oil-and-gas, medical-diagnostics, and environmental-monitoring industries. And Lucent Technologies' Bell Laboratories has its eye on adapting the QC laser for the lucrative telecommunications market, which now relies on tiny semiconductor diode lasers to transmit signals for distances of thousands of kilometers along optical fibers.

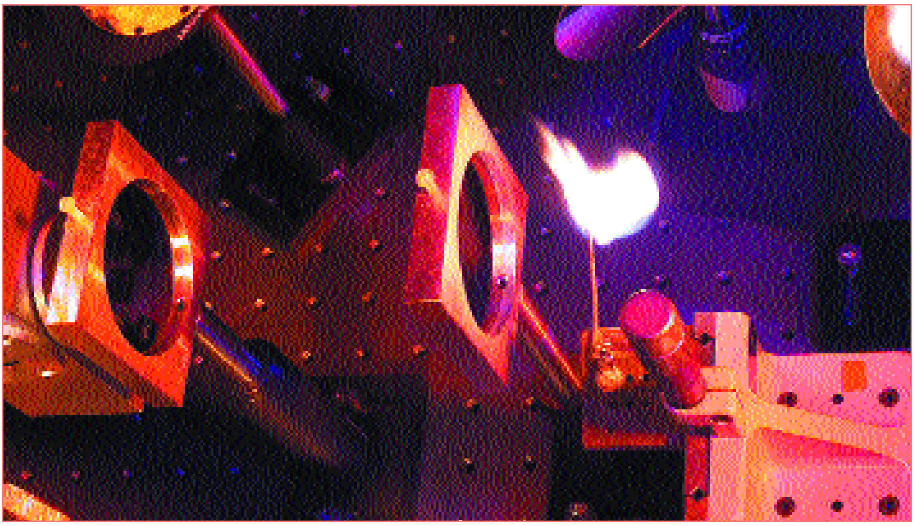


Figure 1. A quantum cascade laser, not visible because it is in the infrared, lights a match in its path as a test of its presence.

Lucent Technologies' Bell Labs

Since its invention in 1994 by physicist Federico Capasso and his colleagues at Bell Labs, the QC laser has won widespread praise, including kudos from Nobel laureate Charles Townes, the inventor of the maser. The QC laser "represents a remarkable combination of excellent solid-state and laser physics with new solid-state technology," Townes said when the device was introduced. "It opens the door to very important new laser possibilities, ones I hope will be pursued and achieved."

His hope is near fulfillment.

How it works

"A semiconductor absorbs light when electrons are excited from the valence band into the conduction band by photons, which leaves a positive 'hole' [or absence of electrons] in the valence band," Capasso explains. "Light is emitted in the opposite process, when electrons drop into the valence band and neutralize the holes." In conventional semiconductor lasers, the so-called active region consists of a sandwich of two different semiconductor materials arranged in a double heterostructure, essentially forming a p-n junction. The electrons and holes are injected into the active region, where they recombine and create photons.

A separate layer serves as a waveguide to direct the photon beam to the desired target. Two cladding layers on opposite sides of the active regions and of lower refractive index material guide the laser light parallel to the layers. This makes it possible for the radiation to bounce back and forth between two cleaved crystalline facets that serve as built-in laser mirrors.

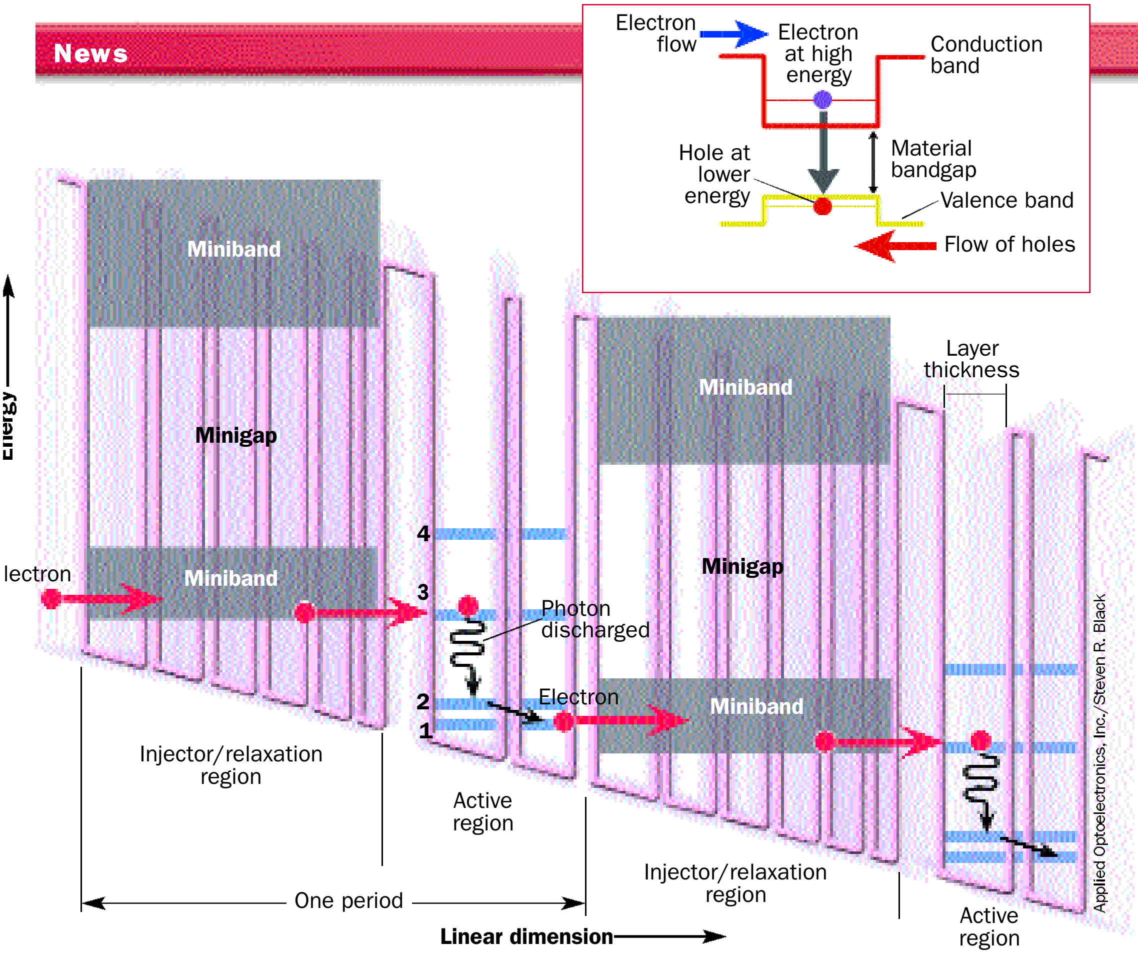
Because radiation is created by the recombination of electrons in the conduction band with holes in the valence band, the wavelength is determined by the minimum energy difference between the two bands—the energy gap—a fundamental property of a semiconductor that controls its optical properties. As a result, if one wants to substantially change the wavelength of a conventional semiconductor laser one must choose different materials.

QC lasers rely instead on one type of charge carrier, electrons, and are often called unipolar lasers. Photon emission therefore depends on an entirely different mechanism, which consists of electrons jumping from a higher to a lower energy level of a quantum well within the conduction band. Quantum wells are ultrathin sandwiches of two different semiconductors; the thickness is typically a few nanometers, and electrons are confined primarily to the center part of the sandwich.

Electrons have wavelike properties, and because their wavelength is comparable to the quantum-well thickness, their motion perpendicular to the layers is quantized. This, in turn, gives rise to a series of discrete energy levels, whose separation can be directly controlled by changing the thickness of the quantum-well layers. In QC lasers, the wavelength can be tailored over a wide spectral region, essentially the entire midinfrared and into the far-infrared.

Using this radically different principle, Capasso's group at Bell Labs has demonstrated that QC lasers emit at any wavelength between 4 and 24 μm, using the same combination of materials (aluminum indium arsenide and gallium indium arsenide) by varying the thickness of the quantum wells in the active regions. This aspect of the QC laser is unique because the chemical properties or composition of the laser material determines the wavelength of all other solid-state, atomic, and molecular lasers.

The reliance on electrons alone for laser action entails another radical departure from conventional semiconductor lasers. In traditional devices, one laser photon is created for each electron and hole that recombine in the active region (Figure 2). In QC lasers, once an electron has emitted a laser photon by jumping from the upper to the lower energy level, it remains in the conducting band. From there, it is recycled by injection into an adjacent identical stage, where a second photon is emitted, and so forth, which creates as many laser photons



Applied Optoelectronics, Inc./Steven R. Black

Figure 2. In a diode laser (top inset), a photon is emitted when an electron combines with a hole. In a quantum cascade laser, a photon is emitted every time an electron moves from a higher to a lower energy level as it cascades down an energy staircase created by the applied voltage.

as there are stages. Thus, photons are emitted by an electron cascading down the energy staircase created by the voltage applied to the device.

Capasso likens the effect to an "electronic waterfall." Claire Gmachl, a colleague of Capasso at Bell Labs, describes it as an avalanche effect because the initial laser photon is multiplied, leading to a large number of photons for each injected electron. This unique cascading effect is responsible for the high optical power of QC lasers (up to 1 W or more, depending on the number of stages) compared with a conventional semiconductor laser operating at the same wavelength

In practice, the cascading effect and the ability to carry large currents have led to QC lasers with 1,000 times the power of diode lasers operating at the same wavelength. "The materials used in QC lasers have wide energy gaps, which allows them to carry currents that would damage devices built from narrow-gap materials," Capasso says.

The concept of quantum wells originated in the mid-1960s, but constructing one took time. Only in 1974 did two groups—one at IBM in Yorktown Heights, New York, and the other at Bell Labs—report the first growth of quantum wells and the observation of discrete energy levels.

A film-manufacturing technique known as molecular beam epitaxy (MBE) made this feat possible. MBE was developed to grow layers of thin films at the atomic level efficiently and inexpensively with unprecedented precision and control. Bell Labs physicist Alfred Cho pioneered the technique in the 1960s. At the time, his colleagues were convinced that MBE would never find manufacturing applications because Cho was working on the angstrom scale, while most thin films then produced were on the order of tens of micrometers or millimeters. "No one foresaw how much computer technology would shrink," says Cho. Today, MBE is used worldwide for roughly 85% of all thin-film growth.

The marked improvements in precision and control that Cho achieved in ensuing years proved critical to constructing the first working QC laser. The crystal structure of a QC laser contains up to 1,000 alternating layers of different types of crystalline material, some only one-billionth of an inch thick, and all layers must fall within a few percent of the target composition and thickness if the device is to operate properly.

"The quantum cascade laser is probably the most complicated semiconductor structure ever commercially produced, in terms of the number of atomic layers and the precision control required to produce working devices," says James Baillargeon, one of the developers of the device at Bell Labs and now vice president for laser development at Applied Optoelectronics, Inc. (AOI), in Sugarland, Texas. With MBE, not just one but many quantum wells, all of the same size, can now be fabricated onto a substrate.

The precision of the MBE manufacturing technique is also a key to another crucial feature of the QC laser: its unique ability to achieve different wavelengths for specific application requirements without the need to change the underlying semiconductor material. MBE defines wavelength by altering the depth and width of the quantum wells rather than by exploiting materials characteristics. This feature makes the QC laser more flexible. Its variations have included a QC laser that emits different wavelengths that depend on the direction of the electron current flowing through the device. “The only thing we’re limited by is our imaginations,” says Gmachl.

Sensor applications

QC lasers operate in the midinfrared spectrum and at room temperature, which is vital for their use in sensors. Many molecules—including pollutants, industrial chemicals, explosives, and medically important substances—can be sensitively detected only by using midinfrared lasers. Until quite recently, high manufacturing costs or the limited spectral or power performance of existing lasers hampered efforts to create high-performance, cost-effective laser-based sensors. The QC laser fills that gap. “By controlling the behavior of electrons on the nanometer scale, we have developed a completely new type of laser that operates in wavelength regions that are not well served by existing sources,” says Capasso.

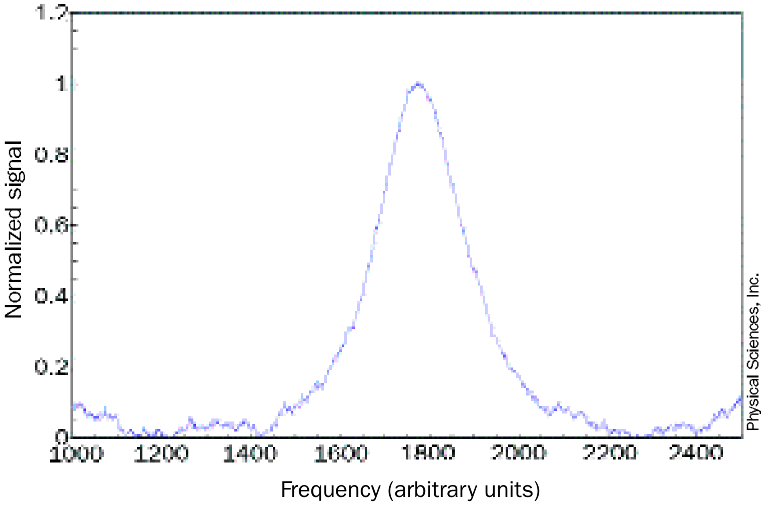


Figure 3. This absorption spectrum for 100 ppm of nitric oxide in nitrogen was obtained with a sensor whose quantum cascade laser was supplied by Lucent Technologies.

In all these applications, the laser wavelength must be extremely well defined and tuned to match that of the absorption feature or molecular fingerprint of interest. To achieve this control, a grating is incorporated near the active region. The wavelength in the QC laser’s emission spectrum that matches the period of the grating is the laser’s wavelength. By changing the laser current, the active region is heated, which produces wavelength tuning. In this way, several molecular fingerprints can be resolved with great precision.

The entire QC system, including the laser active element and the necessary cooling equipment, can be made as small as a few cubic inches at a fraction of the cost of conventional systems. “The QC laser has revolutionized the way scientists think about semiconductor lasers, and it now stands as a viable commercial product," says Thompson Lin, founder and president of AOI. The company signed a licensing agreement with Lucent last July that gives it the right to manufacture and distribute QC lasers. AOI has had a QC laser commercially available since last September.

Bell Labs has also recently signed two licensing agreements for the commercial development of its QC laser technology as part of a corporate strategy to partner with other companies in transforming some technologies outside of its core business into commercially viable products.

Physical Sciences, Inc. (PSI), based in Andover, Massachusetts, recently reached an agreement with Lucent to use QC lasers in its manufacture of sensitive gas sensors. PSI has prototype sensors already in development, and it expects to market them later this year, according to Mark Allen, vice president of photonics. "The sensor market is modest, and very fragmented across multiple industries," says Allen, who estimates, however, that the sales volume in any one sector is tens of millions of dollars. "When you add them all together, you're looking at hundreds of millions of dollars per year of sensors sold worldwide."

PSI is using QC lasers to develop a compact sensor for sulfur dioxide and sulfur trioxide, both important pollutant species emitted by aircraft engines. The company is also collaborating with scientists at Lucent to develop lidar (light detection and ranging) devices for the remote sensing of chemical vapors and for high-flying sensors deployed aboard unmanned aircraft to trace atmospheric species. Ford Motor Co. expects sensors based on QC lasers to quantify the concentration of nitric oxide (NO) in vehicle exhaust gases. Although the QC laser is not yet sensitive enough to measure concentrations of emitted NO at less than 1 part per million in real time—the Holy Grail for the automotive industry—Ford expects them to find short-term use in vehicle-certification testing.

Under federal regulations, all new vehicles must be certified to meet specific standards for unburned hydrocarbons, most notably carbon monoxide and nitrogen oxides, which are measured in grams per mile after the vehicle has gone through a specified driving cycle. Bag samples are collected for later off-line measurements, some of which have NO concentrations of tens of parts per billion, which is comparable to those found in ambient air and too low to be measured accurately by current sensors. However, "the vehicle-certification facility is an ideal environment to implement a QC laser measuring system, which has more than adequate capability to measure minute concentrations of nitric oxide in bag samples," says Willes H. Weber, a senior staff technical specialist at Ford.

Taking off

Other potential QC laser applications include spacecraft-borne probes to detect trace gases in planetary atmospheres and noninvasive medical sensors that analyze the breath of patients for real-time diagnosis of ulcers, colon cancer, and diabetes. QC lasers could also prove useful in radiocarbon dating, monitoring atmospheric methane levels, collision-avoidance radar, cruise control in automobiles, and military applications such as "blinding" the sensors in heat-seeking missiles.

Recently, QC lasers made by the Bell Labs group were flown in the stratosphere as part of a NASA mission led by Chris Webster of the Jet Propulsion Laboratory (Pasadena, CA). The laser sensors detected traces of methane and nitrous oxide, two important tracers of atmospheric circulation, down to a few parts per billion in volume. Similar methane levels were detected in a laboratory experiment by Frank Tittel, Robert Curl, and collaborators at Rice University, who also resolved its various isotopes. Even higher detection limits (a hundred parts per trillion) were achieved by Richard N. Zare and his group at Stanford University, who detected ammonia traces using a QC laser with a technique called cavity ringdown spectroscopy.

The standard QC laser technology continues to improve. In February, AOI announced that it had achieved continuous-wave operation of a QC laser at 210 K, about 35 K higher than the previous record held by Lucent. The company achieved this record through careful thermal engineering of the laser and improved material quality. AOI believes that the advance will make the QC laser an even better tool for sensitive spectroscopic chemical detection.

Capasso and his colleagues have begun extending the range of wavelengths of their QC lasers into the far-infrared region. Eventually, they hope to achieve the very short wavelengths required for telecommunications. Moving to shorter wavelengths will require deeper quantum wells and, hence, different materials. Gmachl believes that aluminum gallium nitride–gallium nitride is the most promising material system, but she expects that such a QC laser will take several years to build.

Most recently, the group announced the achievement of ultrashort pulse emission from the first self-mode-locking QC laser, a phenomenon in which the transition that provides the laser gain also produces the nonlinear refractive index absorption that is essential for the generation of pulses. The discovery is important for the study of ultrafast chemical dynamics of systems that absorb in the midinfrared, including many common pollutant gases.

Capasso emphasizes that there are many other exciting opportunities for device research in QC lasers, most notably electron-beam steering, which is not possible in diode lasers because their active region is essentially neutral. In a QC laser, however, electrostatic gates can be used to deflect electrons crossing the active region, enabling the output beam to be steered in space. Bell Labs patented such a device in 1995 and is now working on developing the concept further.

“The quantum cascade laser opens up a range of diverse potential applications, initially in environmental sensing and high-resolution spectroscopy, and many more are sure to follow,” says Capasso.