QUANTUM CASCADE LASERS

Terahertz race heats up

The journey to realize a terahertz quantum cascade laser that operates at room temperature has taken a jump forward with news of a device that operates at –23 °C, within the reach of Peltier coolers.

Carlo Sirtori

Terahertz (THz) waves are electromagnetic radiation that lie in the portion of the frequency spectrum between the realms of optics and microwaves. The THz region shows great promise for many applications in spectroscopy and imaging since many forms of condensed matter, molecular compounds, vapours and gases possess different physical features resonant with THz waves. Many substances can thus be easily revealed or imaged using THz spectroscopy techniques. One of the early drivers of THz spectroscopy was the need for high-sensitivity instrumentation for astrophysical observation and environmental monitoring. Today, security and public safety could also benefit from artificial noses sensitive to THz, as many common explosives and illegal drugs can be identified by detecting THz spectral features. Furthermore, in biology, THz spectroscopy of DNA is attracting great interest[1].

However, the cost, complexity and portability of many THz systems is still hindered by the lack of a semiconductor source of THz waves that operates at room temperature. Quite surprisingly, the THz range still evades the extensive emission capabilities of semiconductor technology, which is already very advanced and serving other nearby frequency regions, namely the visible, infrared, radio and microwave sectors. Indeed, to date, semiconductor quantum cascade lasers (QCLs) that operate in the THz region have been limited to low temperatures that necessitate cryogenic cooling.

Now, the race for the first THz QCL operating at room temperature has been reopened by Qing Hu and colleagues at the Massachusetts Institute of Technology in the United States. As reported in this issue of *Nature Photonics*, Hu's team has demonstrated a QCL emitting at 4 THz and operating at 250 K (ref. [2]), which is equal to –23 °C.

The realization of a semiconductor laser emitting at room temperature in this frequency range is very challenging. This can be understood by considering the physics that describes the amplification of radiation in a medium. For a laser to operate, a population inversion of electrons for the desired lasing electronic transition needs to be established. In effect, the electron population needs to be higher in the excited state than the lower state — a situation out of thermodynamic equilibrium.

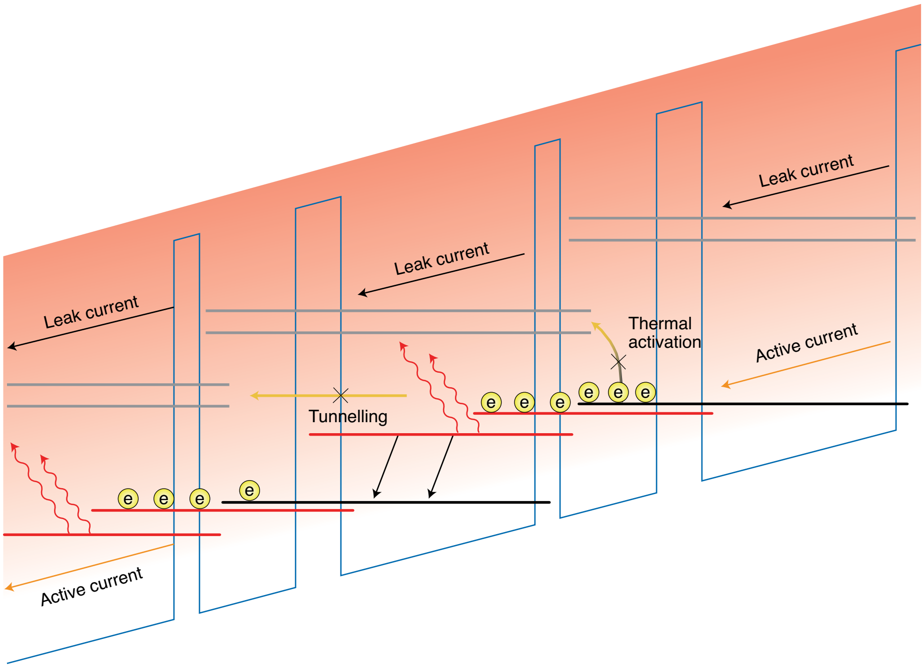

Fig. 1 | Band diagram with energy levels and schematic of the electron flows across the potential. The red solid lines show the electronic states involved in the laser transition, and the injector is in black. The red wavy arrows are the emitted photons. In the design of a QCL electrons should flow only on the lowest laying energy levels generating an active current that produces population inversion, thus gain. However, activated thermal processes and unsolicited tunnelling into high energy states (grey lines) gives rise to a leak current, which hinders laser action. The new design presented by Hu and colleagues reduces these spurious effects, preserving the active current even at high temperatures.

For a THz laser transition, the energy separation between the upper and lower levels is only few millielectronvolts (5–20 meV), which is well below the thermal energy ($k_B T$) that electrons acquire at room temperature (26 meV). Therefore, the ambient temperature tends to redistribute the electronic populations of the energy levels of the system, thus hindering the necessary out-of-equilibrium steady-state condition. Overcoming this situation is not a fundamental obstacle, but does further increase the complexity and requirements on how electrons cascading along the semiconductor quantum structure dissipate their energy. The history of THz lasers proves that population inversion between small energy level gaps can be maintained regardless of the temperature of the system. Indeed, the first THz laser[3], which appeared in the 1960s, was based on molecular transitions of a water vapour at ~600 K.

The latest findings presented by Hu and colleagues represent a temperature leap of 40 K over the previous best results[4]. Importantly, operation at 250 K is a range easily accessible by thermoelectric Peltier cooling elements, and thus cryogenics is not needed.

The improvement in the temperature operation of the laser is related to the design of the active region that sets the energies of the electronic levels and controls the shape of the wavefunctions, a refined work of a quantum silversmith. The authors identified that in previous THz QCL designs, when the temperature increases, electrons are thermally activated in high energy levels and create a parallel leakage current that strongly reduces the flow of electrons in the lower laying states (Fig. 1). To overcome this issue, the new active region is designed with two important modifications: the first corresponds to an increase in the barrier height and the second is the use of a thicker injection barrier. The use of higher barriers allows a greater energy separation among the electronic levels, thus suppressing thermally activated processes, while the thicker injection barrier reduces the parasitic tunnel coupling with high energy levels of the subsequent period. Finally, the new quantum potential of the active region uses the shortest possible period for a cascade laser, made of only two quantum wells. This has the merit of reducing the number of energy levels in the active region, thus avoiding electron scattering into superfluous states, and moreover it increases the total population inversion per unit length.

Remarkably, when mounted on a thermoelectric cooler operating at 230 K, the lasers can provide a peak output power of tens of milliwatts, with the beam visualized by a far-infrared room-temperature camera. The operation of THz QCLs with a thermoelectric cooler is an important step forward for the technology and its practicality and commercialization, as it simplifies the overall system and reduces its volume and cost.

These latest results are encouraging as they show that the temperature of THz QCLs can still be improved and that room-temperature operation in the future could be realistic. That said, the quantum efficiency of the laser is still too low to envision continuous-wave operation. This is an aspect that has to be tackled and improved to affirm the utility of quantum cascade THz technology.

It should also be noted that there are other means to generate THz radiation at room temperature that are rapidly improving and could become an alternative to a direct generation. For example, very interesting results have been recently obtained using tunnel diodes, or by exploiting integrated nonlinear down-conversion of mid-infrared QCLs[5–7]. In addition, quantum cascade pumped gas lasers[8], although not an integrated solution, have very low noise and could suit applications in metrology.

In closing, these latest results let us dream of the advent of a new semiconductor THz technology operating at room temperature that will eventually close the gap between the worlds of microwaves, optics, electronics and optoelectronics. For 50 years, THz lasers have been optically pumped by CO$_2$ lasers and now semiconductor technology brings us back to the future by promoting a current injected laser, as in the 1960s, when a current discharge was pumping the water vapour THz laser. The difference is that the water laser cavity was about 10 m long, whereas now a QCL with a length of few millimetres is sufficient to attain THz laser action.

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Competing interests

The author declares no competing interests.

NANOPHOTONICS

Photonic-crystal optical parametric oscillator

The first demonstration of an optical parametric oscillator using a photonic crystal microcavity is promising for the future development of on-chip light sources for applications in integrated quantum optics.

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Shrinking photonic structures such as cavities, waveguides and associated devices to the smallest size possible has always been a major goal of nanophotonics, with a recent example being the successful demonstration of strong enhancement of second-harmonic generation in a single sub-wavelength dielectric nanorod[1]. One photonic device in particular that scientists have been trying to miniaturize and put onto a chip is the optical parametric oscillator (OPO), a source of light where two beams, named the signal and idler, are generated from a pump beam by nonlinear optics. Commercial and lab-built OPOs are usually on the scale of tens of centimetres and are a common sight in optics labs around the world where they are a convenient tunable source of light. However, chip-scale OPOs are desirable as the signal and idler are correlated and so could yield an integrated light source for generating entangled photon pairs for applications in integrated quantum optics.

To date, there has been considerable success in fabricating frequency comb generators and OPOs based on semiconductor microring cavities[2–5], but this approach has some constraints in terms of device size, pump threshold power and *Q* factor. For example, a microring cavity requires a *Q* factor exceeding 10^5 and ideally an even higher value for reducing the threshold pump power[3]. A complexity is that the *Q* factor scales with the diameter of the microring[6], which makes the footprint of