electron–phonon interaction rate must exceed the spontaneous-emission rate. In all laser cooling systems, the cooling efficiency reduces as the temperature decreases. This results from the depletion of thermal energy in the reservoir, which provides the vibrational or translational energy needed to enable the anti-Stokes fluorescence. Furthermore, as the system cools and/or the density increases, the mean fluorescence energy red-shifts because the mean interatomic separation between the atoms reduces. Consequently, this narrows the spectral regime in which cooling can occur at a reasonable pump absorption (laser power). The Vogl and Weitz experiment maintains high cooling efficiency by heating the gas mixture to an initial temperature of 620 K, thus allowing an ample amount of fast Rb atoms to participate in the cooling. This results in net cooling by almost 70 K at a significant cooling power of around 90 mW — four to five orders of magnitude larger than Doppler cooling.

These results, however, do not indicate the lowest attainable temperature of this method. In their 1978 paper, Berman and Stenholm described a set of constraints, such as the gas mixture and wavelength, that will eventually limit such a technique[2]. It will be interesting to put these constraints to the test and investigate any fundamental limitations involved. For example, it is worth investigating the effects of photo-association at low temperatures, and of multiple collisions due to the high densities involved. Aside from the diminishing efficiency at low temperatures, it will be essential to understand whether the only limitation in achievable temperature is set by the parasitic absorption from unwanted impurities in the gas mixture. This absorption is the key limiting factor in solid-state laser cooling, but one hopes that gaseous media are less prone to such contamination.

The pioneering research of Vogl and Weitz has proved the validity and potential of this new laser cooling approach. The road ahead will certainly be challenging and exciting; many other gas mixtures are being investigated under various conditions, with the aim of attaining much lower cooling temperatures. ❐

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TERAHERTZ TECHNOLOGY

An ultrafast amplifier

The integration of an optically pumped switch in a quantum cascade laser device yields a semiconductor terahertz amplifier that promises to extend the capabilities of time-domain spectroscopy.

Alessandro Tredicucci and Aldo Di Carlo

Terahertz (THz) photonics is attracting ever-growing attention in applications that deal with chemical recognition and detection. Areas of interest include security and customs control, non-destructive testing in the pharmaceutical industry and biomolecular diagnostics and communications[1]. Since its development in the 1980s, the workhorse of THz spectroscopy has been the coherent time-domain technique[2,3], in which picosecond pulses of THz radiation are used to investigate a sample. These pulses are typically generated using short (~100 fs) visible-wavelength laser pulses to generate electric charges in a photoconductive material, which are then accelerated (and thus emit THz radiation) by two antenna-like electrodes. The THz pulse shape is reconstructed in both amplitude and phase using the same visible-wavelength laser pulses as a time gate for the detection. Spectroscopic information is recovered by creating a Fourier transform of the temporal profile of the THz pulse, yielding a broadband signal that typically spans from a few hundred gigahertz to a few THz. Despite the low average THz powers typically used — generally in the nanowatt range — this coherent detection scheme still allows for spectroscopy with high signal-to-noise ratios of up to 70 dB. In many cases, however, its applications are being hampered by the low power delivered by existing THz sources, making the development of a convenient and practical THz amplifier highly desirable.

One potential candidate is presented on page 715 of this issue[4] by Jukam *et al.*, who demonstrate that a cleverly modified quantum cascade laser can amplify the intensity of these ultrafast THz pulses to achieve gains of over 20 dB. This result is likely to open up new prospects for THz time-domain spectroscopy, particularly in fields where strong signal attenuation is currently the limiting factor. For example, in stand-off detection and sensing, atmospheric absorption due to water vapour is restricting distances to around ten metres.

A THz-emitting semiconductor injection laser based on the quantum cascade (QC) scheme was first reported in 2002[5]. Such lasers rely on electronic transitions between sub-bands in the conduction band of a carefully engineered heterostructure, an alternating-layer sequence of two different semiconductor compounds.

The laser transition energy (and thus the operation wavelength) therefore does not depend on the particular semiconductor material used, but instead is mostly determined by the thickness of the layers. This concept can in principle also be used to create a gain medium to amplify THz waves.

When designing any kind of optical amplifier, an important issue is to eliminate the presence of any optical cavities that could establish a feedback process, for two reasons: first, to prevent the device from reaching a lasing condition, which limits the gain to its threshold value for self-oscillation and therefore limits the achievable amplification; and second, to minimize resonant enhancement at specific frequencies to avoid unwanted ripples in the gain spectrum.

In the case of a THz QC amplifier, preventing the device from reaching a lasing condition is particularly relevant because the net material gain achievable is small and restricted to a narrow bandwidth[6]. However, anti-reflection coatings to suppress feedback from the device facets are very difficult to realize in the THz frequency range because of the required thickness and stability of the coatings. In the past, an integrated master-oscillator power-amplifier based on THz QC technology, which uses a tapered geometry with an angled front facet to avoid feedback, has been used[7]. This solution, however, is far from ideal — particularly for amplifying ultrafast pulses — as it deforms the wavefront and thus deteriorates beam quality.

The elegant solution devised by Jukam and co-workers is to exploit gain switching[4]. In essence, high gain in a THz QC laser is temporarily 'switched on' using drive current pulses of duration shorter than the cavity's build-up time for laser oscillation.

During this short time — typically a few hundred picoseconds — electromagnetic energy accumulates within the cavity and, before reaching steady-state operation, the cavity's gain can freely exceed its optical losses. To implement this scheme practically, Jukam *et al.* bias a THz QC laser slightly below threshold and add a third electrical contact that is separated from the QC active region by a thin undoped semiconductor area. When this area is illuminated by a visible pulse from the time-domain spectrometer it becomes electrically conductive, supplying a short burst of drive current to the QC active region and thus enhancing the gain. This current pulse can be synchronized with the incoming THz pulse, and has a duration that is determined by the time constants of the device's electrical circuit. In the study of Jukam *et al.*, the duration is long enough to allow amplification of the THz radiation for at least seven back-and-forth passes within the Fabry–Pérot QC laser cavity. In fact, as shown in Fig. 1, each THz pulse entering the QC amplifier is partly reflected at each device facet, producing a stream of pulses separated by the cavity round-trip time, with each subsequent output pulse being stronger than its predecessor. The amplitude increases along the sequence up to the fourth pulse, which has traversed the device seven times. The amplification coefficient can be deduced by making measurements of the THz output amplitude when the amplifier is turned on and off. The ratio for the fourth stream pulse (that is, seven-pass amplification) is an impressive 24 dB.

This multipass configuration is not ideal because it wastes much of the amplification by spreading the THz field energy into multiple pulses, rather than into a single strong pulse. Fortunately, this can be easily avoided in future studies by using longer-length amplifiers that have a transit time matched to the gain switch-on time.

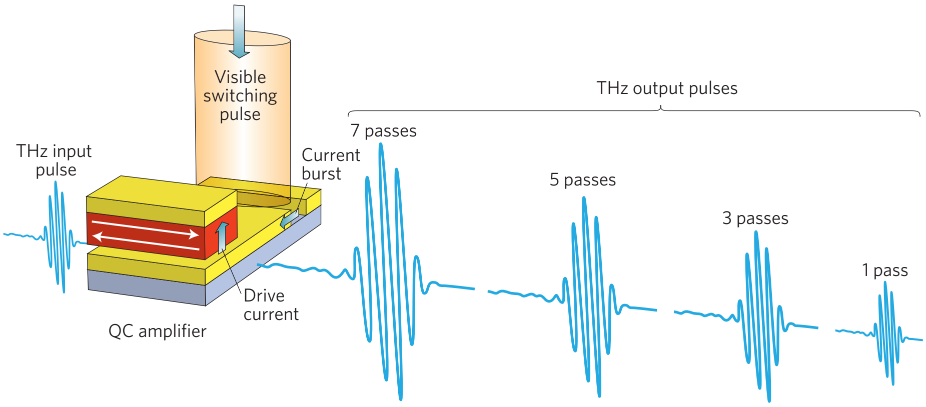

Figure 1 | Operation of the gain-switched THz amplifier. The visible light pulse from the time-domain spectrometer excites carriers in the gap between the contacts, generating a current burst that adds to the bias current. During this time the input THz pulse enters the quantum cascade (QC) device and is amplified while bouncing back and forth in the laser cavity. At each reflection from the output facet, part of the THz radiation is transmitted, creating a stream of THz pulses separated by the cavity round-trip time. At the output, the amplitude increases from pulse to pulse as it continues to pass through the QC cavity, increasing the amplification. After the fourth pulse of the stream (corresponding to seven passes) the amplitude drops because the current burst that drives the QC gain only lasts for a short period of time.

Research and development of THz amplifiers is just beginning — several other strategies have also been proposed. In particular, vacuum tubes have been recently considered as possible amplifiers for low-frequency THz radiation, and several projects in university and industry laboratories are now underway to implement this scheme[8–11]. The general working principle of a vacuum device is based on the interaction between an electromagnetic signal and an electron beam. The electromagnetic signal imposes a velocity modulation on the beam electrons, permitting energy transfer from the beam to the electromagnetic wave. For example, Calabazas Creek Research in collaboration with the University of Wisconsin, Madison, is developing a travelling-wave tube amplifier to produce peak powers of up to 360 mW at 650 GHz (ref. 12). Semiconductor transistors are also progressively extending their operation frequency towards the THz range. The Northrop Grumman group has fabricated an indium phosphide high-electron-mobility transistor with a maximum frequency greater than 1 THz and a 3-dB cut-off frequency of 0.5 THz (ref. 13). This transistor was used to fabricate a 0.34-THz amplifier with a gain of 15 dB, and this technology may allow monolithic amplifiers that operate at 600–700 GHz. Silicon technology is also targeting this frequency range. A record maximum frequency of 0.62 THz was achieved at 4.5 K (compared with 0.35 THz at 300 K) using Si/SiGe heterojunction bipolar transistors. It has also been suggested that a new scaling roadmap may push the maximum operating frequency close to 1 THz (ref. 14).

These purely electronic approaches offer characteristics that are complementary to QC devices because they cover the low-frequency range of the THz spectrum better and display wide gain bandwidths. Rapid development of both technologies will be an important driving force for further enhancing the application opportunities that THz photonics is already presenting. ❐

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