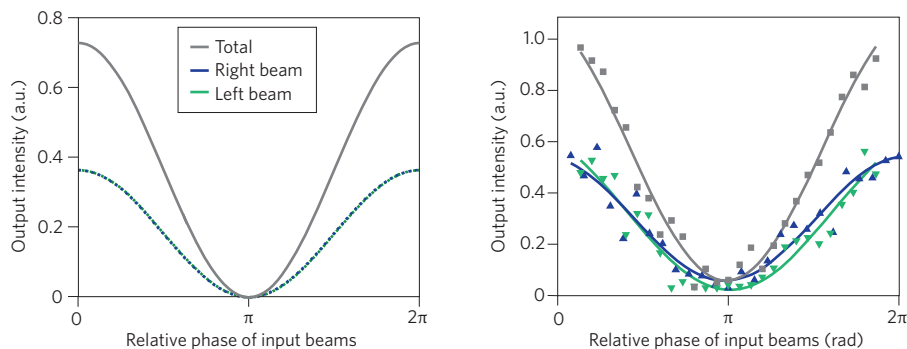


The laser wavelength was chosen to be as close as possible to the coherent absorption resonance condition (about 998 nm). The theoretical enhancement factor of  $10^4$  was not obtained because of (foreseen) laser coherence and resolution limitations. Perfect absorption could be obtained if two experimental parameters are varied instead of just one, as in the present experiment.

The observations can be thought of in a number of different ways. For instance, one could say that combining coherent beams in this way leads to a much longer path length (or residence time) inside the cavity due to interference. Alternatively, one could say that the beams leaving the cavity are reduced in intensity because of destructive interference.

Wan *et al.* have demonstrated superabsorption for a simple two-mode cavity, but this phenomenon might also be possible in higher-dimensional systems. One difficulty in attaining perfect absorption in such systems would be producing the many interfering excitation modes required by more complex phase patterns. Despite this, there are many reasons to be optimistic. First, the time-reversed counterpart of perfect absorption — lasing — can already be achieved in more complex systems. Second, the recent invention of wavefront-shaping allows for incredible flexibility in controlling excitation wave patterns, and its efficacy for enhancing absorption has already been demonstrated<sup>3</sup>.

Sources are universally considered to be an important ingredient of wave equations, and investigations into their fundamental power balance continue to reveal surprising features<sup>4</sup>. Research into their time-



**Figure 2** | Phase modulation of beam absorption. Theoretical (left) and experimental (right) normalized output intensity as a function of relative phase between the two (right- and left-incident) input beams. The wavelength was in this case chosen to be as close as possible to a perfect absorption resonance. The intensity minimum at a relative phase of  $\pi$  corresponds to an absorption enhancement of two orders of magnitude.

reversed counterparts — sinks — has been delayed for far too long. The seeming lack of interest in light absorption is unjustified, not only because applications such as photovoltaics and medical therapies depend on optimizing the absorption process, but also because it is a fundamental phenomenon. All treatments of absorption are essentially based on an incoherent, mean-field approach, in which a local time-dependent absorption process is approximated by a homogeneous amplitude that decays exponentially in time and space. Unfortunately, however, this simplistic treatment neglects all types of coherence effects and absorption-induced correlations.

Wan *et al.* have demonstrated the controllable nature of absorption, a result that promises to uncover many new surprising properties of sinks. From this

work we learn that optical properties such as absorption can be controlled not only by structuring the material system, but also by structuring the incident light. Whether absorption is desired or not, the work of Wan *et al.* is one step towards gaining control. □

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## TERAHERTZ QUANTUM CASCADE LASERS

# Going ultrafast

A new asynchronous coherent optical sampling method allows for the direct visualization of actively mode-locked quantum cascade laser pulses at terahertz wavelengths.

Roberto Paiella

Over the past decade, quantum cascade lasers (QCLs) have firmly established themselves as the leading semiconductor laser sources for the mid-infrared and terahertz spectral regions. The light-emission mechanism of QCLs involves intersubband transitions between quantized energy states derived from

the same energy band (the conduction band), which is radically different from the electron–hole recombination mechanism of traditional interband diode lasers. As a result, QCLs feature a wealth of unique physical properties and operational characteristics that have been widely investigated over the past several

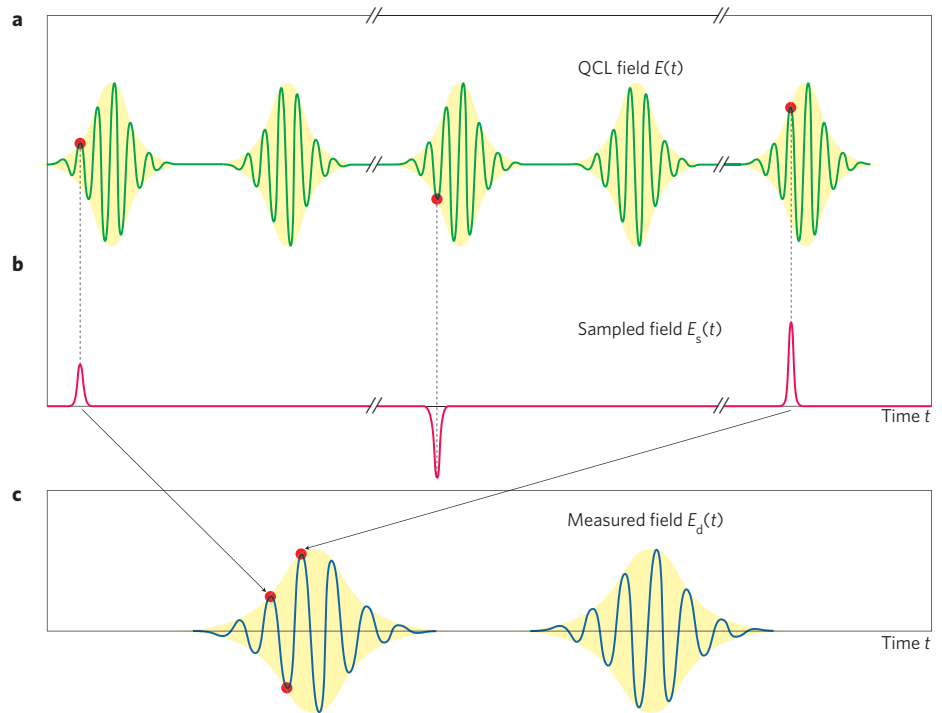
years and continue to be the subject of extensive research.

A particularly interesting example is provided by their dynamic properties<sup>1</sup>. In general, laser dynamics is controlled by three separate time constants, namely the laser-cavity roundtrip time, the photon lifetime and the relaxation lifetime of

the population inversion. In QCLs, the relaxation lifetime can be as short as 1 ps, which is orders of magnitude shorter than that of most other laser systems. Physically, this property is the result of very strong electron–phonon interactions in the polar-semiconductor gain media of QCLs, which lead to ultrafast nonradiative intersubband relaxation. In terms of laser dynamics, this has several desirable implications, including the absence of relaxation oscillations in the device transient response and the ability to achieve record-large intrinsic modulation bandwidths of many tens of gigahertz. At the same time, this short relaxation time also complicates the generation of stable ultrafast laser pulses using mode-locking, while allowing coherent instabilities to arise when the population inversion relaxes on a timescale shorter than the cavity roundtrip time<sup>2</sup>. An additional complication in this respect is the lack of suitably efficient nonlinear autocorrelation techniques for the measurement of ultrafast optical pulses at the typical mid-infrared and terahertz wavelengths of QCLs. In the case of mid-infrared devices, an important recent advance was the measurement of actively mode-locked QCL pulses through two-photon absorption autocorrelation in an intersubband quantum-well photodetector<sup>3</sup>.

Writing in *Nature Photonics*, Stefano Barbieri and co-workers now successfully address both of the aforementioned complications (related to the generation and measurement of stable mode-locked QCL pulses) for the case of terahertz devices<sup>4</sup>. Specifically, they report the observation of actively mode-locked 2.5 THz pulses using a novel asynchronous coherent optical sampling technique. The work involves directly measuring the optical field of a QCL's output in the time domain, thus providing a conclusive demonstration of mode-locked operation and accurate identification of the emitted pulses' characteristics. Active mode-locking is achieved by modulating the laser bias current with a sufficiently strong radiofrequency signal at the cavity roundtrip frequency ( $\sim 13$  GHz), which drives a large number of longitudinal modes above threshold and phase-locks them together through the modulation sidebands of their neighboring modes. The emitted pulses are found to be transform-limited and have a temporal width as short as  $\sim 10$  ps, depending on the input radiofrequency power.

To enable the formation of stable mode-locked pulses, Barbieri *et al.* use a device featuring a relatively long-lived (5–10 ps) upper laser state. In general, QCLs offer many degrees of freedom for engineering



**Figure 1** | Asynchronous coherent sampling of THz pulses. **a**, Mode-locked terahertz QCL waveform. **b**, Measured sampled signal. **c**, Down-converted QCL waveform as reconstructed by low-pass filtering the signal of **b**. As indicated by the diagonal lines between **b** and **c**, the timescales of these two traces are widely different.

the basic properties of their gain medium, including emission wavelength, oscillator strength of the laser transition and phonon-assisted intersubband relaxation lifetimes. In particular, the relaxation lifetimes of a QCL strongly depend on the energy separations and mutual wavefunction overlaps of the active-region subbands, which can be accurately tailored through the design of the gain-medium quantum wells. In the terahertz QCLs used in the work of Barbieri *et al.*, the upper laser states are energetically separated from their neighboring subbands by less than the longitudinal-optical phonon energy. As a result, phonon-assisted gain relaxation is strongly suppressed, at least at the cryogenic temperatures used in this demonstration. Incidentally, the gain relaxation lifetime can also be increased using QCL structures with reduced wavefunction-overlap between the laser subbands, as in the work of ref. 3, at the expense of decreased oscillator strength.

To address the complications associated with measuring ultrafast QCL pulses, Barbieri *et al.* use a commercial femtosecond fibre laser and a standard ZnTe-based electro-optic cell to sample the QCL electric-field amplitude directly in a novel asynchronous configuration. The mode-locked QCL waveform (Fig. 1a) is used to instantaneously modulate the

birefringence of the ZnTe crystal, thereby modulating the polarization state of the fibre laser's frequency-doubled output pulses as they propagate through the crystal. This polarization modulation is then converted using polarization optics into a proportional field-amplitude modulation, which is measured through balanced detection. Because the repetition rate of the fibre laser (96 MHz) is significantly smaller than that of the mode-locked QCL (13 GHz), the pulsed terahertz waveform is heavily undersampled in this configuration (Fig. 1b) and therefore cannot be fully reconstructed from the measured sampled field. However, analytical considerations indicate that the lowest-frequency periodic waveform consistent with the measured sampled signal (Fig. 1c) is identical to the mode-locked QCL waveform, except that it varies on a much slower timescale by a large, easily identifiable scale factor. The electric-field amplitude emitted by the QCL can therefore be directly visualized on an oscilloscope simply by filtering the measured sampled waveform with a low-pass filter of appropriate bandwidth.

This asynchronous sampling technique is extremely powerful and versatile because it can be used to measure arbitrary periodic waveforms with carrier frequencies across the terahertz spectrum and moderate field

amplitudes (owing to the relatively high sensitivity of the electro-optic detection scheme). The only fundamental limitation is provided by the pulse width of the sampling optical signal (about 100 fs in this case), which determines the measurement time resolution and therefore sets an upper limit to the carrier frequency of the measured waveform. Experimentally, the main challenge is to stabilize the carrier frequency and repetition rate of the mode-locked QCL with respect to the fibre laser's repetition rate, so that during the measurement the sampled signal accumulates coherently to produce large signal-to-noise ratios. In practice, this is achieved with three radiofrequency synthesizers sharing a common reference that, respectively, modulate the QCL at its cavity roundtrip frequency, stabilize the fibre laser's repetition rate and phase-lock the QCL carrier frequency to the nearest harmonic of the fibre laser's repetition rate (using fast servo electronics to control the QCL bias current).

The development and application of this technique in the work of Barbieri *et al.* allows for the unambiguous demonstration of QCL active mode-locking at terahertz wavelengths. The researchers observed decreasing temporal widths down to around 10 ps (resulting from the mutual phase-locking

of an increasing number of longitudinal modes) as the radiofrequency modulation power was increased. Interestingly, comparing the spectra and waveforms of the measured signals also reveals that these pulses are transform limited; that is, their time–bandwidth products are as small as physically allowed. By comparison, in the case of interband diode lasers, mode-locked pulses typically exhibit significant frequency chirping, which increases their bandwidth for a fixed pulse width<sup>5</sup>. This phenomenon is a direct consequence of the coupling between gain modulation and refractive-index modulation that exists in interband lasers, which is ultimately related to the asymmetric shape of their gain spectra. Owing to their radically different light-emission mechanism, such coupling is generally absent in QCLs, a property that seems to directly manifest itself in these measurement results.

We expect that further insight into the fundamental dynamic properties of intersubband gain media will be enabled by future applications of the same technique on a variety of terahertz QCL structures. As already mentioned, early work in this area has been hindered by the lack of direct measurement techniques for the time-domain visualization of pulsed QCL waveforms. The new method

of asynchronous coherent sampling demonstrated by Barbieri *et al.* provides just that, and therefore can be used to address fundamental questions such as the conditions under which QCLs can be stably mode-locked. For example, of particular interest is the relationship between non-radiative relaxation lifetimes, the cavity roundtrip time and stable pulse formation, which can now be directly investigated in terahertz devices based on different gain-medium designs. Finally, the development of compact, high-average-power sources of pulsed terahertz radiation based on actively mode-locked QCLs promises to have a strong technological impact in applications such as spectroscopy, sensing and imaging. □

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## OPTICAL MANIPULATION

# Tweezer app for iPad

Scientists in the UK have developed an application ('app') for Apple's iPad that allows the user to create and simultaneously control the three-dimensional positions of up to 11 independent optical traps by touch (*J. Opt.* **13**, 044002; 2011). The aptly named 'iTweezers' is the innovation of Richard Bowman and colleagues from the physics departments of the Universities of Glasgow and Bristol. Bowman told *Nature Photonics* that they soon hope to make the app available to download for free from the iTunes App Store. In the meantime, a copy can be requested directly from the authors (r.bowman@physics.gla.ac.uk). The app is designed to work with holographic optical tweezers that use a computer-controlled spatial light modulator to create and control multiple optical traps.

The app uses the iPad's screen to display the real-time video from the microscope of an optical tweezer and indicates the trap positions using circular markers. Manipulating the positions of the traps and



their trapped particles is simple: a finger drag gesture moves a trapped particle in the *x*-*y* plane, whereas a pinch gesture outwards or inwards moves it up or down along the *z* axis. Traps can be created or removed by double-tapping the screen.

"When we first got a iPad in the group, we were keen to see what could be done with it. We soon realized that it could be the perfect control platform for optical tweezers,"

explained Bowman. "The app will also work with the latest iPhone and iPod Touch."

The app works by using a WiFi connection to communicate the user's gestures to a desktop computer that uses LabVIEW software to control the trapping hardware.

A video showing the app in action can be seen on YouTube ([www.youtube.com/watch?v=qgDMcP9e5G0](http://www.youtube.com/watch?v=qgDMcP9e5G0)), where it has already received over 15,000 views.

Bowman and colleagues have also developed an app called the iHologram, which allows the user to visualize the light fields used in optical trapping but does not offer any form of trap control.

The Glasgow–Bristol collaboration are now working on developing a more general toolkit app that will allow the iPad to control any scientific equipment that can receive commands through National Instrument's LabVIEW software.

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