TUNABLE TERAHERTZ LASERS

A wrench of wavelength

Mechanically manipulating the lateral size of the lasing mode of a single-mode terahertz quantum cascade laser provides a new and robust method for widely and continuously tuning its emission wavelength.

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Tuning the emission wavelength of quantum cascade lasers (QCLs) that operate in the terahertz region is notoriously difficult, but has great importance for lasers in applications such as spectroscopy and sensing. On page 732 of this issue[1], Qi Qin *et al.* present an elegant mechanical solution to this problem that shows great promise for wide single-mode tuning. Their initial calculations suggest that a tuning range of >10% of the centre wavelength should be possible, and they demonstrate an experimental value close to 4%.

Free-running simple semiconductor lasers that use the two cleaved end-facets of the semiconductor laser crystal as cavity mirrors typically show laser action on multiple longitudinal modes. The problem is that the precise position and relative intensity of these modes is usually unstable and therefore highly unpredictable, making such lasers unsuitable for applications in spectroscopy or high-speed communication. There are two main problems: first, a single, unique and stable mode from among all the possible lasing modes is required; and second, this mode must be frequency-tuned in a predictable and reversible manner. The breadth of possible solutions to achieving these tasks is enormous, ranging from the use of macroscopic external cavities to miniature vertical cavities, but only a very few schemes dominate the field.

A popular way of turning a semiconductor laser ridge into a single-mode laser is arguably to achieve distributed feedback (DFB). A periodic grating is applied all along the laser cavity; if properly applied, it can be used to select a unique mode very close to the grating's Bragg wavelength $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} is the effective refractive index of the mode (akin to an average refractive index weighted by the overlap that the mode has with the various layers of different material refractive indices) and Λ is the grating period. Because the grating period is hard-written into the laser and a good semiconductor laser crystal has low elasticity, tuning the grating periodicity — and thus the emission wavelength — is difficult. As such, the wavelength tuning of a single-mode DFB laser typically relies on changing the effective refractive index by varying the temperature, electric current or voltage, but this tuning range is often very limited. A sturdy, mechanical solution with a broader tuning range would therefore be extremely beneficial.

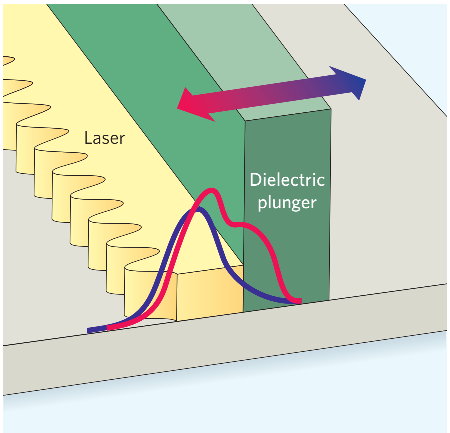

Figure 1 | Schematic of how bringing a dielectric 'plunger' (green) into close proximity with a laser ridge waveguide can 'pull' the laser mode from its initial state (blue) to a new state (red) and therefore alter the laser's emission wavelength.

Semiconductor lasers show their greatest relative change of mode size and overlap when changes of confinement and size are around or slightly below the wavelength scale. Changes on a much larger physical scale (such as the length of the cavity) do not greatly affect the actual laser mode, and changes on a much smaller scale are not sensed by the mode.

Terahertz QCLs[2] are semiconductor lasers of a special kind. Their gain is derived from an intersubband optical transition in coupled GaAs/AlGaAs quantum wells, yet it is still broad enough to support lasing over >10% of their centre wavelength[3], with the possibility of artificially broadening the gain curve[4]. They are also special because their emission wavelength is very long, from tens of micrometres to a few hundred micrometres — a length scale where a mechanical tuning solution has the potential to work well. A physical change of 1–10 µm — around the wavelength scale — is well-suited to control by fine mechanics, piezo drivers or even micro-electromechanical systems[5].

Qi Qin *et al.* implement such a mechanical solution to tune their ~80-µm-wavelength terahertz QC laser. First, they turn their QCL into a single-mode DFB laser by making it a very narrow strip double-metal clad ridge laser[6] with a strong sinusoidal first-order Bragg grating etched into one side (Fig. 1). The narrowness of the ridge and the design of the grating select the laser's single mode; they also allow the mode to sense the environment around the laser. By mechanically bringing other materials — silicon or gold — close to the flat side of the laser ridge, the mode is influenced by these 'plungers'. Bringing an undoped silicon dielectric plunger into close proximity pulls the mode from the laser ridge into the terahertz-transparent silicon (Fig. 1) — the closer the plunger to the laser, the stronger the effect. Conversely, a metal (gold) plunger pushes the mode away and sideways through the laser cavity. A small mechanical change can have a very strong optical influence because the effect is highly nonlinear.

Three interrelated effects result from this pulling and pushing of the mode: the mode size and its overlap with the laser ridge change; the mode 'sees' new materials and their refractive indices; and the overlap of the mode with the Bragg grating changes, which in turn moves the preferred Bragg mode. As a result, the effective refractive index of the mode changes and the mode is tuned. The authors do not use the 'effective index' terminology for the tuning, owing to the more complex effects that occur together as the plungers move. It is a useful concept however, especially when describing DFB lasers, because it highlights an important strength of the opto–mechanical tuning mechanism (the continuous change of the optical constants of the mode). All the modes of the cavity — the lasing and non-lasing ones — are affected, thus eliminating mode competition or mode hopping. The mechanism broadly tunes the entire lasing mode until its spectral or spatial overlap with the gain material becomes too weak, in which case the most favoured Fabry-Pérot modes will take over.

Pulling or pushing the plungers by ~25 μm achieves red and blue shifts, respectively, which together give a total tuning range of ~137 GHz (3.6%) of the centre wavelength. Theory estimates that 430 GHz (11%) of the centre wavelength is possible. This is achieved without using any other tuning mechanisms such as temperature, current or voltage; these could also be added to the scheme to complement the mechanical tuning as they are fundamentally unrelated to it.

The advantage of this new tuning concept, demonstrated here for terahertz QCLs, is that it exploits the fact that the large wavelength is similar to the length scales of fine mechanics, piezo-electric drives and micro-electromechanical systems. Furthermore, it is continuous and broad enough to cover the laser's entire gain spectrum. When a more sturdy (stick-slipfree) mechanical assembly is found and implemented, opportunities abound to provide more varied and more rapidly changing optical environments for the mechanical tuning of these lasers. Hence, broader tuning ranges should be possible in a relatively simple manner. ❐

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PHOTOVOLTAICS

Solar success for Sharp

Sharp's activities in photovoltaics have recently provided the company with two pieces of good news. The first is that its research labs in Japan have fabricated a triple-junction solar cell with a record-breaking power conversion efficiency of 35.8% — the highest value reported for any cell illuminated with unconcentrated sunlight. The second is that a solar-powered vehicle covered with Sharp's compound solar cells triumphed in the Global Green Challenge solar-car race across Australia at the end of October. The 3,000-km race from Darwin to Adelaide was won by a team from Tokai University in Japan. Their 'Tokai Challenger' vehicle completed the course with an average speed of approximately 100 km h^{-1}.

GLOBAL GREEN CHALLENGE

Sharp's record-breaking 35.8%-efficiency cells consist of three vertically stacked p–n junctions that are each made from a different compound semiconductor (the top, middle and bottom layers are InGaP, GaAs and InGaAs, respectively). Each junction is designed to absorb light at a different wavelength band of the solar spectrum, which maximizes power generation. Such multijunction cells have been a popular design for many years and are often used in space to help power satellites, and in solar farms, which use reflectors to concentrate the intensity of sunlight. Indeed, when used with concentrated sunlight, triple-junction cells — developed independently at Sharp, the Fraunhofer Institute for Solar Energy in Germany and the US firm Spectrolab — all achieved efficiencies of over 40%, but this figure is usually much lower for unconcentrated sunlight.

According to Sharp, the key to achieving these latest results for unconcentrated light was to form the bottom junction of the cell from InGaAs rather than germanium — a challenge only recently solved through considerable improvements in semiconductor fabrication technology. The research that enabled this development took place under a solar-cell initiative organized by Japan's New Energy and Industrial Technology Development Organization.

Unfortunately, it was not all good news in October for Sharp. The firm's biannual business results for the six months ending 30 September 2009 showed a year-on-year drop of 17.5% in net sales to 1,288 billion yen. Worse still, operating income declined 96.9% from 50.8 billion yen in 2008 to 1.5 billion yen in 2009 for the same biannual period, only narrowly avoiding a net loss. Sales of LCDs (down 33%) and other electronic items (down 27%) were particularly hard hit owing to the global recession, but the firm saw sales rise from June onwards and is now benefiting from a cost-reduction programme that it implemented earlier in the year.

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