QUANTUM CASCADE LASERS

A glass half full

Researchers from Princeton and Northwestern Universities have independently demonstrated, through different design strategies, mid-infrared quantum cascade lasers with wall-plug efficiencies reaching 50%. The result is a quantum cascade laser so efficient that it generates more light than heat, albeit at low temperatures of operation.

Hui Chun Liu

Since the first report of its successful operation in the mid-1990s[1], the quantum cascade laser (QCL) has evolved to become an important source of mid-infrared and terahertz radiation. However, it has historically been labelled as a device with a relatively poor efficiency of operation. This view may finally be about to change, thanks to the report in *Nature Photonics*[2,3] of two mid-infrared QCLs that both provide wall-plug efficiencies reaching 50% for the first time.

Unlike conventional semiconductor lasers, which are driven by electronic transitions between the conduction and valance bands, QCLs have a unique principle of operation[4] that instead relies on intersubband electronic transitions within the conduction band of a carefully engineered quantum well, which provides quantum confined states. However, because the confinement is only in the direction of the quantum well potential (the crystal growth direction), the electrons move freely in the other two dimensions; that is, they have an in-plane momentum and (ideally) infinite degrees of freedom, hence the term 'subband'.

This in-plane freedom causes serious issues. It means that between two subbands, a rapid non-radiative transition — in which a longitudinal optical phonon is emitted or absorbed — is always allowed. The problem is that this transition strongly competes with the optical emission of a photon as a mechanism for an excited electron to lose its energy. Usually, for the quantum wells used in mid-infrared QCLs and made of compound semiconductors (such as InGaAs and AlInAs), this non-radiative lifetime is of the order of a picosecond. However, the radiative intersubband transition spontaneous lifetime is about a microsecond. Consequently, there is a difference of the order of 10^6 in the lifetimes and transition rates, and hence there is only a one-in-a-million chance that an electron will emit a photon rather than a phonon when making the transition from an upper subband to a lower one. As a result, the very first observation of intersubband optical emission in quantum wells was viewed as a major milestone[5] when it occurred at the end of the 1980s.

However, it was not clear at that time whether an electrical injection intersubband laser could be realized. It took several years of visionary, dedicated and systematic work before the breakthrough that realized the first QCL[1] was made in 1994, beating the one-in-a-million odds.

Of course, above the lasing threshold, the stimulated radiative transition rate is the important factor for laser operation and substantially increases because it is proportional to the laser cavity photon density (which is high when lasing). Nevertheless, in the early days of QCL development, the feasibility of making a highly efficient QCL was greatly doubted.

For this reason, the mid-infrared QCLs reported in *Nature Photonics* by Claire Gmachl's group from Princeton University (in collaboration with Johns Hopkins University and AdTech Optics)[2] and by Manijeh Razeghi's group from Northwestern University[3] — which both operate with wall-plug efficiencies reaching 50% — represent an important milestone, even though operation is in pulsed mode at cryogenic temperatures.

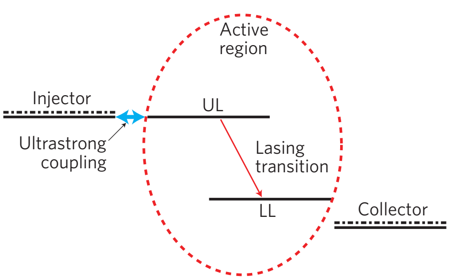

Figure 1 | Key physical process in the Gmachl study[2]. The active region includes an upper lasing state (UL) and a lower lasing state (LL). The injector state couples with the upper lasing state by tunnelling. The ultrastrong coupling regime corresponds to a narrow tunnel barrier.

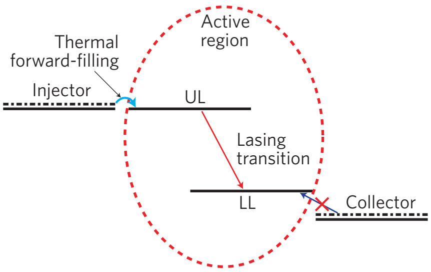

Figure 2 | Key physical process in the Razeghi study[3]. When the separation between the lower lasing state and the collector region chemical potential is small, thermal back-filling is negligible at low temperatures. Moreover, at such temperatures, thermal forward-filling is possible from the injector state to the upper lasing state. Both mechanisms favour a lower voltage defect and therefore a higher wall-plug efficiency.

A high wall-plug efficiency has a number of practical implications, such as a reduced heat-sinking requirement. Perhaps equally important is the overcoming of a psychological barrier. We now have a justifiably optimistic outlook; the glass is finally half full. The long-held opinion that QCLs are devices with intrinsically high power consumption and low efficiency is over.

The achievement of the Gmachl group[2] is made possible by the recently recognized physical insight of Khurgin *et al.*[6], who re-evaluated the effect of interface roughness on QCL performance using a density matrix model that treats transport, leakage and radiative transitions on equal footing. The main conclusion was that, due to the substantial interface roughness scattering, ultrastrong coupling between the electron injector and upper lasing states is favoured for better injection efficiency and higher optical gain. Figure 1 illustrates the device operation and coupling between the injector and the upper lasing states.

In contrast, the approach taken by the Razeghi group[3] to improve the efficiency of QCLs operating at low temperatures is to minimize the 'voltage defect' $V_{def} = V_{appl} - h\nu/e$, where V_{appl} is the applied voltage per cascade, $h\nu$ is the emission photon energy and e is the elementary charge. Because V_{appl} is proportional to the power consumption and $h\nu$ is the useful output, minimizing V_{def} is obviously advantageous. Specifically, this study uses a single-well injector design, in which the energy difference between the lower lasing state and the collector state is made small (note that the collector is simply the injector for the next cascade). This injector design also favours thermal forward-filling at finite temperatures, which further reduces V_{def}. The drawback is that this design is inherently confined to operation at cryogenic temperatures. When the temperature is increased, thermal back-filling from the collector populates the lower lasing state and decreases the population inversion (Fig. 2).

The research reported in these two papers[2,3] not only represents an important milestone but also shows that there is still plenty of room to improve the design of QCLs. This should stimulate research to further improve QCL efficiency and, more importantly, to obtain better QCL performance at room temperature. Ultimately, the success of any semiconductor device is measured by its applications. Having a high wall-plug efficiency will undoubtedly attract interest from those in application areas such as chemical and environmental sensing and biomedical diagnostics. Equally importantly, high-performance QCLs may have new applications that we have not yet envisioned. ❒

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POLITICS

Budget cuts impact photonics

Japan's new government has reversed its decision for research funding and angered many scientists in the process as budgets — including those for photonics research — get cut.

Ichiko Fuyuno

The advent of the new administration in Japan in September 2009 was initially considered good news for the local science community, as Yukio Hatoyama became Japan's first prime minister with a scientific background — a specialist of operations research, a discipline in which various complex problems are tackled through a mathematical approach. Indeed, many researchers had high expectations that Hatoyama's Democratic Party of Japan (DPJ), which took office from the long-ruling Liberal Democratic Party, would step-up government support for basic scientific research. However, one of Hatoyama's main promises — to scrutinize public spending — has come as a big disappointment to researchers over the past few months, with discussions about how to allocate research money more effectively reaching an impasse.

It seems that photonics researchers are not immune to these recent political twists and turns. For example, the budget for the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST), Japan's newly established initiative to support 30 chosen researchers, has been nearly halved. Four photonics researchers in the FIRST programme — Chihaya Adachi, Yasuhiro Koike, Yasuhiko Arakawa and Hiroshi Segawa — were set to start research on organic electroluminescence, plastic optical fibres, large-scale chip integration and photovoltaic power, respectively, but were asked to revise research proposals. The initiative had been scheduled for launch by autumn 2009, but is now set for early 2010.

"In Japan, no-one takes responsibility for decision-making. After the programme was approved, the rules can change," says one researcher in the FIRST programme. For many years, the public research budget in Japan has been considered 'sacred' as a growth engine for a rapidly ageing country that faces a falling birth rate and scarce natural resources. Even though the sluggish economy has prompted the government to cut regular subsidies to universities and other funding surrounding the research environment, the Budget for the Promotion of Science and Technology, a fundamental research budget that accounts for a third of the Japanese government's Science and Technology Budget, had been on the rise every year until fiscal 2009. Moreover, many universities and research institutes also benefited from slices of the 15-trillion-yen supplementary budget, which was set aside in May 2009 by former prime minister Taro Aso as a stimulus package.

On taking office, Hatoyama pledged to take a different approach by shifting the government money "from unnecessary public works to people," but his plan appears to have backfired in many respects. Major disputes broke out in November when the working groups of the newly established Government Revitalization Unit, which is chaired by Hatoyama, reviewed around 220 large-scale government projects and proposed drastic cutbacks or even suspension of scientific grants for fiscal 2010. According to a preliminary report released on 7 January 2010 by the Council for Science and Technology Policy, the overall Science and Technology Budget increased by 0.8% from the previous year to 3.57 trillion yen for fiscal 2010, but the fundamental research funding saw the first decline in 27 years — a drop of 3.3%.

The recent controversy has initiated active public debate over the pros and cons of research spending, and many prominent scientists have rallied against the budget cutbacks — the first research budget cuts in modern Japanese history. As a result of the protests, funding for a new 220-million-yen grant to 'create regional innovation' was revived after being ruled to be abolished. One of two projects selected to benefit from this grant is the organic electroluminescence research headed by Junji Kido, a professor at Yamagata University. In contrast, funding for the Global Center of Excellence Program, which includes the Photonics Integration-Core Electronics project run by the Tokyo