common impurity in diamond and often single emitters cannot be resolved using standard confocal microscopy techniques. Several proposals have been put forward to minimize the incorporation of silicon during growth. One promising scheme that indeed results in isolated SiV centres involves growing diamond under high-power plasma densities[5,7].

In addition, fabricating the SiV emitters close to the diamond surface — as required for many photonic devices — is yet to be demonstrated. Nevertheless, the global race to integrate the SiV emitters into scalable photonic architectures has already begun. Just recently, the SiV centres have been successfully coupled to photonic crystal cavities[9] and to microdisk cavities[10] — a crucial step for the development of integrated nanophotonic quantum circuits. Furthermore, a better understanding of the photophysical properties of the SiV — particularly the fine structure of the excited state manifold and the metastable states as well as its photochromism — will be important for harnessing it in quantum technologies. Finally, electrical, rather than optical, excitation of a single SiV defect is necessary to make the approach scalable and practical.

This long 'to do' list may seem unrealistic. However, the lessons already learned by the diamond community with respect to the NV defect serve as an excellent knowledge base from which to drive rapid progress towards understanding and controlling single SiV defects. It now transpires that silicon — undoubtedly the most important material for microelectronics — may turn out to be the answer for realizing deterministic single photon sources for practical quantum information processing[11] and optical quantum computing. ❐

Igor Aharonovich is at the University of Technology, Sydney, Ultimo, NSW 2007, Australia.
e-mail: igor.aharonovich@uts.edu.au

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VIEW FROM... IQCLSW 2014

Frequency comb cascade

Frequency combs based on quantum cascade lasers are a thriving topic of research and offer the attractive vision of more compact and higher performance comb systems for spectroscopy or metrology.

Noriaki Horiuchi

The quantum cascade laser (QCL) has evolved to become an invaluable light source for generating mid-infrared (MIR) and terahertz (THz) waves. The great advantage of the QCL is its flexibility — the emission wavelength can be arbitrarily designed by modifying the structure of quantum wells. In recent years, scientists with backgrounds in quantum mechanics, semiconductor materials and spectroscopy have been striving to improve the performance of QCLs and develop applications to exploit them. Those involved in the study of QCLs gathered at the International Quantum Cascade Lasers School and Workshop (IQCLSW) held in Policoro, Italy, over 7–12 September 2014. This year marks the 20th anniversary of the first experimental demonstration of QCL, but rather than looking back on the history of QCLs the workshop was focused on leading-edge research. It featured about 150 presentations, including both oral and poster, and attracted more than 200 researchers from 15 countries.

MS LYNDA BOTEZ AND DR MIRIAM SERENA VITIELLO

Group photograph in the court of the Hotel Marinagri in Policoro, Italy, where IQCLSW 2014 was held. More than 200 researchers from 15 countries gathered.

Keynote speaker Federico Capasso of Harvard University, USA — widely considered one of the fathers of QCL technology — provided an outlook for the field during his presentation. When asked if QCLs are on their way to finding a 'killer application' he gave an optimistic reply: "Mid-infrared photonics based on QCLs is poised to make a major impact in several applications." Capasso emphasized the affinity of QCLs with MIR light, which underpins applications such as healthcare, monitoring environmental pollution and detecting explosive materials. As for one of the potential killer applications, he mentioned the intriguing idea of an "emissive energy harvester" — a device that gathers renewable energy from the Earth's MIR emissions. He estimated that the device would be able to generate d.c. power from the large amount of MIR power emitted by the Earth, which is estimated to be as large as 10^{17} watts.

There were two main research trends discussed at IQCLSW 2014: the exploitation of the extremely high coherence of QCLs and the study and control of broadband, multi-frequency emission. Paolo De Natale of CNR-INO, Italy, explained to *Nature Photonics*: "These two trends are at first glance contradictory regimes, but their common root is the existence of broadband, highly coherent laser sources, that is, frequency combs."

In addition to inherent features of QCLs such as high spectral purity and ultranarrow linewidth, the high-optical power and broad gain of QCLs are now attracting attention and being put to good use. "With these advantages, QCL-based frequency combs can be realized," added Miriam Serena Vitiello, one of the conference chairs, from NEST-CNR NANO, Italy.

The laser frequency comb (FC) — a simple and powerful tool for precisely measuring optical frequencies — was developed by Theodor Hänsch of the Max-Planck-Institute of Quantum Optics, Germany, a Nobel laureate in physics and one of the keynote speakers of IQCLSW 2014. "The main advantage of QCL-based frequency combs is a much higher power level," explained David Burghoff from the Massachusetts Institute of Technology (MIT), USA.

QCL-based FCs can generate output powers on the order of 10 mW as opposed to typical powers of 1 μW for combs down-converted from a mode-locked laser. In addition, the repetition rate of QCL-based FCs is on the order of 10 GHz, whereas a repetition rate of only around 100 MHz can be obtained using a mode-locked laser. Another advantage of QCL is that the gain media can be designed and implemented for a much broader gain bandwidth.

"Obtaining broader bandwidth and uniform spectral intensity will be the next challenge facing the QCL-based frequency comb," Qing Hu of MIT added. "If we can achieve octave-spanning combs, then we can use the $1f$–$2f$ method, which is a highly effective and compact technique for stabilization."

Karl Unterrainer from the Vienna University of Technology, Austria, explained how phase-resolved THz spectroscopy is perfectly suited to investigate the properties of the gain media inside QCLs. This technique can provide information about processes in the laser gain medium for a wide range of operational conditions including operation above the lasing threshold. Information obtained includes the spectral gain profile, its change with the driving conditions and saturation caused by the lasing modes, the time recovery of the gain as well as the gain bandwidth for different active region designs. "The technique also allows access to the losses of waveguides typically used for THz QCLs and, very importantly, allows the determination of the dispersion. The latter is of upmost importance for the development of frequency comb or mode-locked lasers," Unterrainer stressed.

To achieve mode-locking of QCLs, microwave modulation is a commonly used technique, especially for MIR QCLs because the sub-picosecond upper-state lifetime relevant to lasing is too short for pulse formation in the cavity. Carlo Sirtori of the Université Paris-Diderot, France, said that beyond mode-locking, microwave injection is also a powerful tool to study the gain dynamics of QCLs. The gain dynamics and high photon density in a QCL cavity can lead to wideband modulation up to 100 GHz — wider than what can be obtained from a diode laser. As Sirtori explained, "such a wide band can be exploited in communication systems for high bit-rate data exchange at discrete wavelengths in the mid-infrared region."

Jérôme Faist of ETH Zurich, Switzerland, reported dual-comb spectroscopy based on the use of MIR QCL FCs. Two combs with slightly detuned repetition frequencies were heterodyned, leading to a down-converted FC in the radiofrequency domain. The system is capable of broadband (16 cm^{-1}) high resolution (0.0027 cm^{-1}) absorption spectroscopy. "We are convinced that comb operation over more than 200 cm^{-1} is completely feasible," Faist told *Nature Photonics*.

Another emerging topic of discussion at the conference was ultrabroadband tunable QCLs. Mikhail Belkin from the University of Texas at Austin, USA, reported the demonstration of tunable monolithic THz QCL sources based on difference-frequency generation. Their emission frequency could be electrically tuned from 3.44 to 4.02 THz. As for MIR QCLs, Manijeh Razeghi of Northwestern University, USA, reported broadband tuning over 5.7–9.3 μm using a heterogeneous structure. She is now trying to extend the tunability even further. "Imagine having a QCL source that is electrically tunable across the entire mid-infrared range of 3–12 μm," she said. "This would revolutionize mid-infrared spectroscopy and perhaps enable new applications as well."

In addition to upgrading the functionality of QCLs, the use of semiconductor gain materials alternative to GaAs is also an important issue, because GaAs-based QCLs are not able to lase in the 5–12 THz frequency range. With this in mind, Wataru Terashima of RIKEN, Japan, has fabricated GaN-based THz QCLs that lase at 5.5–7.0 THz. This work could kick-start the further development of GaN-based THz QCLs.

The next IQCLSW will be held in Cambridge, UK, over 4–9 September 2016. ❐

Noriaki Horiuchi is at Nature Photonics, *2-37 Ichigayatamachi, Shinjuku-ku, Tokyo 162-0843, Japan.*
e-mail: n.horiuchi@nature.com

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Correction

In the News & Views 'Frequency comb cascade' (*Nature Photonics* **8**, 819–820; 2014), the affiliation of Miriam Serena Vitiello was incorrect and should have read NEST-CNR NANO, Italy. This has now been corrected in the HTML and PDF versions after print 5 November 2014.