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Comment

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30 years of the quantum cascade laser

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It was January 1994, when the first quantum cascade laser (QCL) displayed laser action in Bell Laboratories. During these 30 years the QCL evolved incessantly, from a lab curiosity to the main on-chip source of coherent radiation in the Mid-IR and THz ranges. The journey has seen an impressive development of the QCL in several fields of laser physics and its applications, with a steady growth of research groups and companies worldwide.

In a Quantum Cascade Laser (QCL) the photon emission is obtained via quantum jumps among electronic states created by quantum confinement in ultrathin alternating semiconductor layers forming quantum wells. The photon energy can be tailored at will changing the widths of the wells and barriers, enabling the control of the emission wavelength over a wide frequency range. As such, the QCL approach completely differs from traditional diode lasers in semiconductors, where the tuning of the emission wavelength requires engineering the bandgap of the constituent materials. 30 years have now passed since the first quantum cascade laser (QCL) displayed laser action in Bell Laboratories[1], and the quantum cascade lasers are entering their fourth decade. This Comment shall not be intended as an in-depth review of the many achievements in the field, and we point the interested reader to other sources, for example[2] for this purpose. Instead, we retrace the main achievements in the development and some selected applications of QCL (Fig. 1) to briefly discuss the expectations for the fourth decade of this technology.

The first 10 years were marked by landmark achievements that contributed to the establishment of the QCL technology: the first distributed feedback QCL at room temperature[3], the demonstration of the first room temperature continuous wave Mid-IR device[4], the extension of the QCLs to the THz range[5] and the first applications to sensing[6], high-resolution spectroscopy[7] and free-space communications[8]. Soon after its discovery, it was clear that the symmetric optical joint density of states of intersubband transition was the key to actual gain-shape engineering, allowing the creation of arbitrarily-shaped, ultra-broadband gain spectra[9], fully exploited in the following years in the context of external cavity lasers and lasers arrays. After this first exploratory phase, the second decade was dedicated at optimizing the operative conditions of QCLs and broadening their applications. The years 2000's saw the development of high power, high performance QCLs both in Mid-IR and in THz spectral regions. Output powers largely exceeding watt-level and wall-plug efficiency larger than 25% were reported using optimized material growth and processing[10]. Advancements in high precision spectroscopy and sensing were as well reported[11]. THz QCLs operating at 200K based on double-metal waveguides were demonstrated; THz devices emitting more than 2 W of peak power at low temperatures where also achieved. Among the applications of THz QCLs, it is important to underline their central role as local oscillators for heterodyne spectroscopy in the context of astronomical observations[12], real-time THz imaging[13], bio-medical imaging[14] and the first demonstration of active mode locking with the resolution of the time-dependent field amplitude[15].

The last 10 years have seen the definitive affirmation of the QCL as a mature technology, with some of the major laser commercial providers offering multi-mode, single mode, widely tunable and high-power QCLs in the 4–12 μm range. The academic research on QCLs has transitioned to supporting the development of several applications. Especially the field of frequency combs has seen a great surge. Active mode-locking in Mid-IR QCLs was demonstrated in 2009[16], but the widespread effort on QCL combs was ignited by the first demonstration of self-starting frequency modulated (FM) combs in the Mid-IR in 2012[17]. With the successive extension to the THz range[18], the QCL comb research took several interesting directions, from the application to dual-comb spectroscopy[19,20], to the observation of self-starting optical solitons in a variety of circular resonators (Nozaki-Bekki solitons and dissipative Kerr solitons). Recently, the THz devices also reached thermoelectric cooler operation[21,22], showing impressive bandwidth coverage emitting over one octave from a single device[23].

Particularly in this last decade, the QCL technology empowered several fields of research. As as example, the field of Mid-IR and THz nanoscopy greatly benefits from the presence of QCLs at different wavelengths. QCL sources, combined with near-field scanning microscopes at room and low temperatures, enabled the production of significant results in the MId-IR[24] as well as with THz QCLs by using an interesting self-detection technique. Furthermore, the progressive integration of III-V onto silicon platforms in the telecom community finds a successful counterpart as well in QCL research. Recent reports of QCLs[25] and Interband Cascade Lasers (ICL) growth on Si substrates with very good performance open several possibilities for Mid-IR (and eventually THz) integration on silicon photonics and CMOS platforms.

In August 2024, a symposium was held in Zürich[26] to celebrate the 30th QCL anniversary, bringing together 3 different generations of scientists, from the founding fathers of the field to the last wave of scientists pushing the boundaries of what can be achieved with this extremely powerful concept. One of the most discussed topics was the nature and the description of self-starting Frequency Modulated combs in QCLs. The ultrafast nature of the QCL gain turns out to play a central role in the achievement of new regimes of active mode locking like the quantum walk comb. The newest achievements in the field of QCL frequency combs led to a re-visit of mode locking and coherence buildup in semiconductor lasers, highlighting some general features that go well beyond the intersubband case, bringing new life to a field that was considered well understood and exploited from the theoretical and experimental point of view. Another (re)-emerging topic discussed is the possibility to develop high speed devices (e.g. detectors and modulators) based on intersubband transitions eventually coupled to cavity resonances, that can be used in combination with high performance QCL and integrated in a variety of applications from sensing and spectroscopy to free-space telecommunications Probably one of the most striking aspect of the quantum cascade laser is the fact that this device operates despite

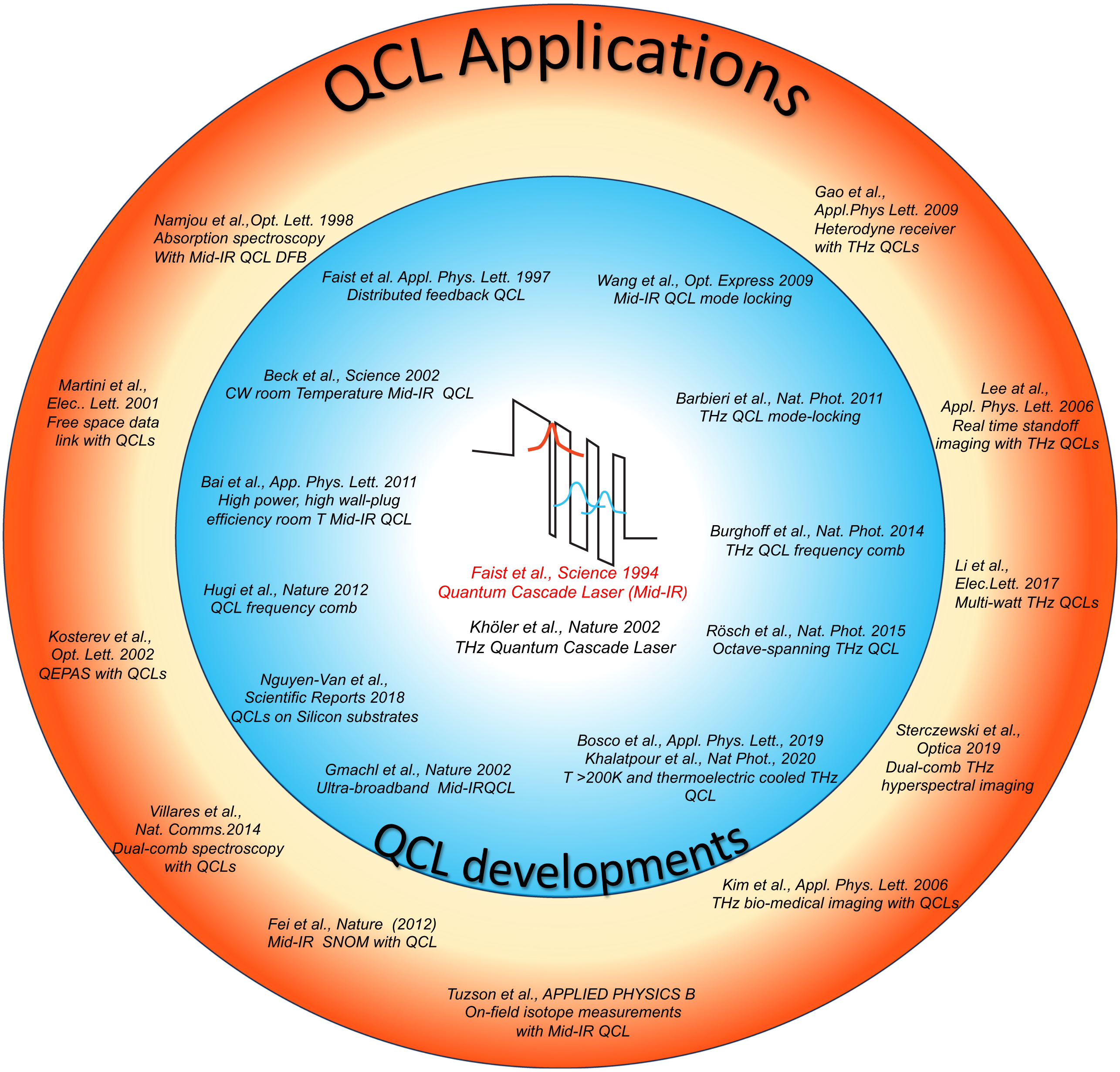

Fig. 1 | Landmarks in QCL development and applications over the last 30 years. Selection and visual depiction of the major contributions to the development (blue) and applications (red) of QCLs.

an extremely short upper state lifetime. Indeed, the prevalent understanding at the time of its first demonstration was that a proper laser system required a transition from a metastable state to operate, and intersubband transitions with sub-picosecond recovery time certainly do not qualify as metastable!

Instead, the success of the QCL stressed that achieving very low waveguide loss and tight optical confinement in a system with large optical dipole elements could go a long way in mitigating the problem of the very short upper state lifetime. Even more, being able to achieve a structure where a population inversion is maintained despite this short upper state lifetime meant also that the device is able to operate with the very short optical stimulated time arising when large optical power densities and therefore high powers are extracted from the device. In this respect, the high power capabilities of the device directly arise from the physics of the device itself.

In addition, as is pointed out above, the very short upper state lifetime enables the stabilization of very broad comb state in an actively mode-locked device. We expect therefore the quantum cascade laser, beyond its obvious applications in the mid-infrared and terahertz spectral region, to continue to inspire new avenues in laser physics in other semiconductor material systems as well.

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Competing interests

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