Terahertz quantum cascade lasers – the past, present, and potential future

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***Abstract*—Since their first demonstration in 2002, the development of terahertz frequency quantum cascade lasers has been extremely rapid. We overview some of the advances that have taken place and which have made the terahertz quantum cascade laser such a ubiquitous source. We also consider potential future directions for terahertz quantum cascade laser technology, including its use in satellite-borne instrumentation for future Earth observation and planetary science missions.**

I. INTRODUCTION

The last 20 years have witnessed a remarkable growth in terahertz (THz) frequency science and engineering (300 GHz – 10 THz), which is maturing into a vibrant international research area. A wide range of organic and inorganic crystalline materials and gases exhibit characteristic vibrational/rotational modes in the THz frequency range [1], which have been exploited using current technology to create new methodologies for process monitoring and non-destructive testing in the pharmaceutical and electronics sectors, *inter alia*. These THz frequency spectroscopy techniques have also opened the way to a range of new and fundamental scientific investigations including, for example, the determination of time-resolved carrier dynamics in condensed matter systems such as semiconductors, conducting polymers, organic crystals, and superconductors.

However, despite the current success and future potential of THz spectroscopy, even a cursory comparison between what is currently possible in this part of the spectrum with that in the neighbouring microwave and optical regions reveals THz frequency science and technology to be still very much in its infancy. The principal reason for this is the lack of compact, convenient, semiconductor-based THz sources, capable of operation at room temperature or even with a Peltier cooler. The work discussed above principally exploits THz sources that although operational at room temperature, nonetheless require expensive, bulky and power hungry femtosecond pulsed near-infrared lasers.

To date, one of the most promising, high power, compact source of THz radiation is the quantum cascade laser (QCL) – an inter-subband semiconductor laser based on a sophisticated layered superlattice. The THz frequency QCL was first demonstrated in 2002, and can provide intense, precisely controlled, monochromatic radiation [2].

II. THz QCL DEVELOPMENTS

Since their first demonstration, progress in developing THz QCLs has been rapid. They have been shown to have a unique and desirable set of source characteristics including a narrow, quantum-limited linewidth (~200 Hz) [3], high output powers (>1 W) [4], pulsed operation up to a temperature of 200 K [5], and a frequency coverage from ~1 – 5 THz.

The long wavelength of the emitted radiation has readily allowed THz QCLs to be photonically engineered, leading to the engineering of the emitted beam profile, frequency and output power including using, for example, photonic crystal lasers [6,7], graded photonic heterostructures [8], and 'spoof' surface plasmons [9, 10]. And, with these developments has also arisen electronic control, including the demonstration of THz pulse amplifiers based on QCL cavities [10], and active mode-locking of THz QCLs, leading to the first measurement of sampling coherence in a QCL [11].

Concurrent with this development in source technology, there has been a strong incentive to incorporate THz QCLs into imaging systems to address the plethora of proposed applications in the THz range. Initial research focused on techniques based on bolometric detection using room temperature, or cryogenically cooled, single-pixel or array detectors. But, more recently, it has been shown that the emitting QCL cavity itself can be used as a radiation self-detector, providing system miniaturization, and absorption-coefficient-sensitive reflection imaging (for a review, see [13]). This 'self-mixing' approach has been highly successful, and it has been possible to demonstrate: displacement sensing interferometry [14]; two-dimensional imaging [15], imaging over distances exceeding 10 m [16]; and, swept frequency coherent imaging, enabling the measurement of porcine tissue [17], *inter alia*.

III. THE FUTURE

Progress over the last decade has been extremely high, with an increasing number of researchers investigating THz QCLs year-on-year. This looks set to continue as the devices themselves, and the resulting systems, become increasingly more engineered, and the potential applications for THz QCLs continue to grow.

But, the question remains – what is the long-term prospect for THz QCL technology being translated into applications outside the laboratory? And here, despite the recent development of a broad range of compact and cryogen-free cryostats, the current maximum operating temperature for THz QCLs remains a barrier. Researchers have sought to overcome this by investigating alternatives to the GaAs-AlGaAs materials system, which has become the standard for THz QCL research, including using InGaAs-InAlAs, InGaAs-AlInGaAs, and InGaAs-GaAsSb. However, progress has been limited, and the maximum (pulsed) operating temperature of 200 K attained in the GaAs-AlGaAs system has yet to be surpassed. A new technological approach thus seems needed in order for THz QCL technology to supplant the THz time-domain spectroscopy systems, which are currently used commercially.

Yet, there is one application area where the THz QCL appears the only solution, and where THz QCLs are suitable for uptake now – satellite-based instrumentation for Earth-observation and planetary science. This can be exemplified by studies of the mesosphere and lower thermosphere (MLT) region of the Earth's atmosphere (between 55 and 150 km).

The MLT forms the gateway to our near space environment, and is considered to be a key indicator of global climate change. Its exotic chemistry is driven by high-energy atomic O and OH radicals, and is characterized by strong spectral features within the THz band, including O (4.7 THz), and OH (4.7 THz and 3.5 THz), together with O_3 (4.7 THz), CO (3.5 THz) and HO_2 (3.5 THz). But, measurements of these important atmospheric species have yet to be made directly in satellite missions owing to the lack of suitable THz instrumentation, and in particular high power, compact, local oscillators for heterodyne spectrometry. The THz QCL has sufficient continuous-wave output power (~mW) to address this need, and space-qualified cryocoolers have the cooling power necessary for THz QCL operation at cryogenic temperatures (e.g. <100 K). The opportunity exists, but the technology readiness levels need to be increased to achieve the strict specifications required for space flight. This includes the need to integrate THz QCLs into robust sub-components, for example using the approach in [18]. Should sufficiently high technology readiness levels be attained, then the possibility is opened up for satellite-borne Earth-observation missions, as well as for future planetary science missions (for example, to Jupiter and the Jovian moons). This access to the supra-THz frequency range (2–5 THz) has simply not been possible before, and the prospects indeed look extremely bright.

IV. CONCLUSIONS

The first demonstration of a THz frequency QCL in 2002 led to the emergence of a new research field, which has blossomed and grown over the last decade. It has underpinned a broad range of fundamental science, as well as leading to the development of new imaging modalities. Yet, the limitations in the maximum operating temperature of THz QCLs has restricted the translation of this promising source to industry, and hence its ability to address the broad range of potential applications at THz frequencies. In particular, it has yet to displace THz time domain spectroscopy systems, based on ultra-fast laser technologies. But, one potential application, for which compact, high power sources are essential is the development of satellite instrumentation for Earth observation and planetary science missions in the supra-THz range. Here, there is no alternative technology, and immediate take-up of the THz QCL should be possible, provided the necessary technology readiness levels can be attained.

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VI. REFERENCES

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