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Future pathways to quantum cascade laser technologies

The mid-infrared (MIR) spectrum is fast gaining recognition as one of the most valuable spectral windows for sensing applications due to its selectivity and specificity. It provides a rich source of high-precision, high-resolution data that can be used both qualitatively and quantitatively. Gas sensing technologies based on MIR are increasingly important across a plethora of industries ranging from healthcare to energy. They enable accurate identification and quantification of, for example, methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S), which exhibit strong, distinct absorption features – a molecular 'fingerprint' – in this region. These capabilities are proving ever more critical as industries respond to stricter safety requirements, environmental regulations, and sustainability goals. In this context, quantum cascade lasers (QCLs) – designed specifically for the MIR range – are attracting interest for their narrow emission bands, wavelength selectivity and ability to reduce interference from complex gas mixtures, making them especially valuable for gas sensing and environmental monitoring. This blog discusses some of the advantages and challenges of QCL technologies, and their potential applications.[1]

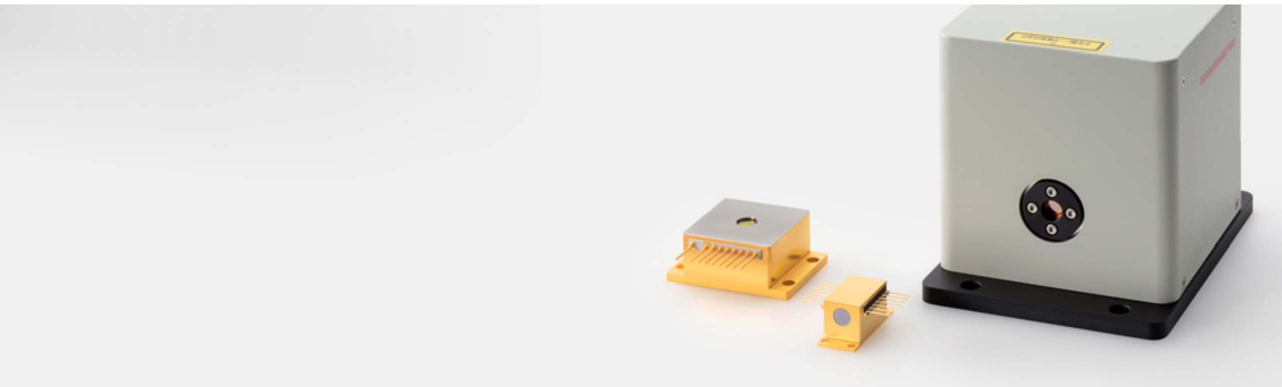
Why choose the MIR range?

Many of the gases that require industrial monitoring absorb light most strongly in the MIR region – approximately 2.5 to 25 µm. This absorption is tied to fundamental vibrational modes of chemical bonds, producing spectral features that are sharp, unique, and easily distinguished from one another. CH_4, for example, shows strong absorption at 3.3 µm, and CO^2 at around 4.2 µm. Nitrogen oxides, regulated in maritime and industrial emissions, also fall in the UV to MIR range. Similarly, highly toxic H_2S can be detected in the MIR region; although technically challenging to monitor, it can be detected using a QCL device.

In contrast, near-infrared (NIR) technologies – widely used thanks to mature telecoms-derived devices[1] – suffer from weaker absorption and overlapping bands, making it harder to distinguish between species. While NIR detectors tend to be more sensitive overall, MIR provides greater specificity and cleaner separation of gas signatures, even in complex environments. As a result, MIR sensing – particularly with QCLs – represents a significant step forward in gas monitoring, offering high selectivity and the ability to reduce interference from other gases, even in complex environments.

The rise of quantum cascade lasers

QCLs were first developed in the 1990s and marked a major step forward for MIR light sources.[2] While standard semiconductor lasers work through interband transitions, QCLs use intersubband (intraband) transitions in specially engineered quantum well stacks. This design gives them extraordinary flexibility: their emission wavelength can be engineered across much of the MIR spectrum by adjusting layer thicknesses during fabrication. Key advantages of QCLs include:



Hamamatsu's Quantum cascade lasers (QCL)

- Narrow linewidths and tunability for precise targeting of specific gas absorption peaks.
- High spectral brightness, enabling sensitivity down to ppm or even ppb.
- A compact, chip-scale design, though current cooling and power requirements mean they are most often used in laboratory, analytical, and process control systems rather than fully portable devices.

QCLs were initially adopted in the defense and security sectors,[3] but their use has expanded today to include applications in healthcare, climate strategy, process control and industrial monitoring.[1,4]

Challenges and barriers to adoption

Great strides have undoubtedly been made in QCL technologies, however, there are still some challenges to overcome.[5,6]

- **Complex, high cost manufacturing** – relatively low production yields result in high unit prices compared to alternative emitters. However, unit prices are likely to come down as demand grows and volumes increase.
- **Low wall-plug efficiency** – much of the input energy becomes heat; typically, thermoelectric cooling and stable power supplies are required, increasing both the unit size and cost.
- **Integration complexity** – operating QCLs requires careful engineering and training. Precise control electronics are required as small temperature shifts can change the emission wavelength.
- **Limited portability** – cooling and power needs make QCLs less suited to handheld or battery-powered devices, where LEDs and simpler emitters dominate.
- **Competing technologies** – cheaper and simpler light sources such as tungsten lamps or blackbody emitters, which are easier to integrate even if less precise, are often chosen instead of QCLs.
- **Adoption hurdles** – despite strong technical advantages, uptake is slower in some sectors due to cost sensitivity, the need for ruggedization, and the lack of mass-production economies of scale.

Public health and safety

In hospitals, QCLs and other MIR sources are now being chosen for capnography – monitoring of exhaled CO_2 during anesthesia – delivering critical feedback on patient safety.[7] QCLs are also used to ensure the health and safety of staff employed in industrial settings, such as oil and gas environments. Rugged QCL sensors can now detect hazardous gases such as CH_4 and H_2S with ppb-to-ppm sensitivity.[8] Emerging technologies even combine gas sensing with wireless optical communication, enabling remote monitoring of gas leaks in high-risk zones.[9]

Climate strategy

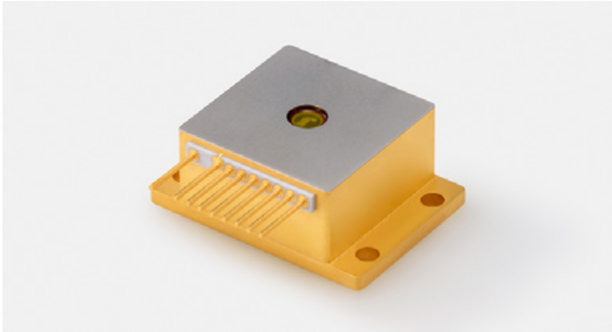
QCLs are already being applied to continuous emissions monitoring (CEMS) in industrial settings, with hybrid QCL/tunable diode laser (TDL) analyzers delivering fast, reliable detection of gases such as CO_2 and CH_4, even in hot, harsh environments.[10] Increasingly, networks of sensors are being deployed around oil and gas facilities to detect fugitive CH_4 leaks. This approach is reinforced by Regulation (EU) 2024/1787 – the EU Methane Regulation – which mandates leak detection, repair, and robust emissions reporting across oil, gas, coal, and import chains.[11,12] Drones fitted with compact QCL-based spectrometers can now detect CH_4 leaks at ppb sensitivity,[13] while portable QCL-quartz enhanced photoacoustic spectroscopy (QCL-QEPAS) sensors demonstrate detection limits of ~13 ppb for CH_4.[14]

Environmental and smart infrastructure

MIR sensing is ideal in urban air quality monitoring, able to detect a range of gases that are subject to binding limits under the EU Ambient Air Quality Directive,[15] with stricter thresholds planned for 2030. Researchers at TU Wien – the Vienna University of Technology – have successfully demonstrated ambient air monitoring and quantification of five gases – carbon monoxide, nitrogen oxide, nitrogen dioxide, nitrous oxide, and sulfur dioxide – affecting the air quality using a QCL-based sensor.[16] Elsewhere, scientists in Boston undertook a field trial of a mobile QCL dual-comb spectrometer, exploring the remote detection and quantification of airborne chemical plumes in dense urban environments.[17] In the construction sector, building standards and voluntary certifications are increasingly driving the integration of MIR sensors into smart buildings, where monitoring CO_2 helps to optimize ventilation and energy efficiency. There are applications in agriculture too, where MIR technology enables monitoring of CH_4 and ammonia (NH_3) emissions to track both environmental impact and animal welfare.[18]

Industrial process control

QCLs excel in process environments where ppm level accuracy is essential, such as real-time monitoring of chemical reactions. They also have potential for in situ reaction monitoring in pharma, where they are being tested for process analytical technology applications requiring real-time process monitoring and control to ensure quality assurance, optimized yields, and regulatory compliance, while enhancing operational efficiency and safety.[7]



Hamamatsu's CW Quantum cascade lasers L1200X series

A bright future for QCLs

QCLs have an exciting future, with a number of exciting avenues opening up. There is, for example, a need for integrated solutions where QCLs are embedded into photonic integrated circuits or coupled directly into fibers. This would simplify optical alignment and reduce optical component costs, opening up possibilities for scalable, robust modules. Another potential development is that of dual-comb QCL spectroscopy, paving the way for compact systems offering high-resolution, broadband measurements, potentially replacing bulky Fourier transform infrared spectrometers for field use. Low-cost, MIR light-emitting diodes (LEDs) and detectors also have applications in urban environments, agriculture, and industrial fence-line monitoring; hybrid networks combining high-precision QCL nodes with distributed low-cost sensors are expected to become commonplace. Simultaneously, climate and safety regulations are helping to accelerate the adoption of QCLs by creating demand for precise, reliable sensing solutions.

Summary

QCLs show promise as potential mainstream enablers of healthcare, industrial safety, and climate action due to their better wavelength selectivity, tunability, and beam quality. Looking ahead, QCLs will increasingly complement LEDs and advanced detectors in innovative sensing solutions as integration, regulatory momentum and manufacturing advances become more aligned, making a deeper impact across global markets. Hamamatsu – with a product range that includes not only QCLs, but also LEDs, indium arsenide antimonide detectors, indium gallium arsenide photodiodes, and associated electronics – is uniquely positioned to support this transformation, with solutions for high-performance QCL applications and scalable LED-based networks.

For more information, or to discuss how we can help with your gas sensing project, please visit www.hamamatsu.com or contact us at info@hamamatsu.eu

To learn more, watch our webinar[1] to hear experts in the field explore the potential of advanced MIR detection technology.

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