Self-Detecting Dual-Comb Spectroscopy with Injection-Locked QCLs

ABSTRACT

Researchers from Beijing, China and Evanston, IL, have developed a self-detecting mid-infrared dual-comb spectroscopy system based on high-speed, injection-locked quantum cascade lasers (QCLs). The innovative setup integrates laser generation and detection within the same semiconductor device, eliminating the need for external photodetectors. This compact and robust design simplifies alignment and enables broadband, high-resolution molecular spectroscopy. The design minimizes optical feedback and enables high-bandwidth self-detection with the effective radio frequency injection-locked QCLs. Researchers observed a spectral range of 68 cm^{-1} and a narrow comb tooth linewidth of ~10 kHz without an external detector or numerical process. The result is a breakthrough in mid-infrared sensing, achieving broadband spectral coverage and ultra-stable operation for molecular sensing and spectroscopy applications.

INFRARED & FREQUENCY COMBS

Mid-infrared spectroscopy is a cornerstone of modern molecular analysis because many gases and organic compounds exhibit strong fundamental vibrational transitions in this wavelength range. These transitions produce distinct absorption features that act as optical fingerprints, enabling precise identification and quantification of chemical species. The high sensitivity and selectivity of mid-IR spectroscopy make it essential for detecting trace gases, monitoring emissions, and analyzing complex mixtures across a wide range of scientific and industrial applications.

This spectral region is particularly valuable because it contains the strongest absorption lines for key molecules such as carbon dioxide, methane, ammonia, and sulfur compounds. Accessing these features allows exceptionally accurate chemical sensing, supporting applications in environmental monitoring, industrial process optimization, atmospheric research, and medical diagnostics. Quantum cascade lasers (QCLs), a leading mid-IR source, offer high power, tunability, and narrow linewidths, enabling precise targeting of molecular absorption features. Even at very low concentrations, small spectral shifts reveal subtle changes in gas composition, making mid-infrared light a powerful probe for both static and dynamic systems.

The development of optical frequency comb technology has further expanded the capabilities of infrared spectroscopy. Frequency combs generate a precise, evenly spaced set of optical lines that act as an ultra-stable reference grid across a wide spectral range. When implemented in the mid-infrared with QCLs, they enable broadband molecular detection with unmatched spectral accuracy, temporal resolution, and sensitivity. This combination of mid-IR light and comb precision has established dual-comb spectroscopy as a leading technique for rapid, high-fidelity molecular sensing, advancing both research and industrial applications where reliability and precision are critical.

PROBLEMS AND GOALS

Conventional mid-infrared dual-comb spectroscopy (DCS) systems face several major challenges that limit their practicality outside laboratory environments. Traditional designs rely on large, high-speed external photodetectors to capture the multi-heterodyne beat signals from free-running QCLs, which increases system size, alignment complexity, and cost. These free-space optical configurations are highly sensitive to mechanical vibrations and feedback, often resulting in unstable operation and degraded signal quality. Additionally, maintaining coherence between the two frequency combs is difficult, leading to limited radio-frequency bandwidth and reduced spectral resolution.

Overcoming these obstacles requires a platform that integrates both laser emission and detection within a single QCL-based chip. Broad spectral coverage, high stability, and narrow comb linewidths are essential for precise molecular spectroscopy and can be achieved through injection locking the lasers. QCLs are well known for their fast gain medium due to their sub-ps gain recovery time, which makes them a suitable photodetector alternative.[1]

In addition to simplifying instrumentation, long-term stability and scalability are critical for DCS systems. Minimizing the number of optical components and leveraging the intrinsic detection capability of QCLs enhances both operational robustness and manufacturability. The combination of compact integration, phase coherence, and environmental resilience positions self-detecting DCS as a next-generation solution for real-world spectroscopy systems.

METHOD

To overcome these challenges, researchers from Beijing, China and Evanston, IL developed a self-detecting dual-comb spectroscopy system that combines both light emission and detection within a single QCL chip at λ ≈ 4.6µm (**Figure 1**). This integration eliminates the need for external photodetectors and reduces system size, cost, and sensitivity to feedback or vibration. By embedding the detection function directly within the laser structure, the design simplifies the optical layout while improving measurement reliability and noise immunity.

Using injection-locking to synchronize two QCL frequency combs (**Figure 2**), researchers maintained phase coherence across a broad optical bandwidth without additional stabilization optics. This compact, detector-free configuration enables fast, broadband spectral acquisition while preserving high signal-to-noise ratio and resolution, advancing mid-infrared spectroscopy toward a truly portable and industrial-ready design.

The system utilized two injection-locked distributed-feedback (DFB) quantum cascade lasers fabricated on a hybrid monolithic integrated waveguide (HMIWG) platform. The emitted laser light frequencies are combined using the injection locking to produce a self-detected multi-heterodyne signal within the same chip structure without requiring an external photodetector.

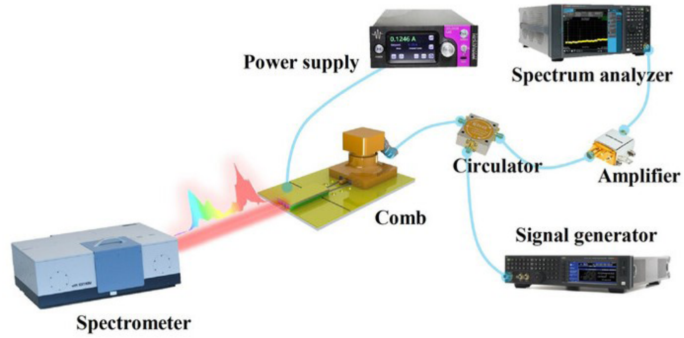

Figure 2. Fundamental and higher harmonic-state injection locking for HMIWG QCLs. The experimental setup for RF-injection-locking measurement, including spectrum analyzer, signal generator, Fourier transform infrared spectrometer, circulator, and power supply (Wavelength Electronics, QCL2000 LAB).[1]

The QCLs were powered by Wavelength Electronics' QCL2000 LAB instruments, chosen for their ultra-low noise, high modulation bandwidth, and precise current control, ensuring stable injection conditions for both lasers. The device operated near 10ºC - 45ºC with a threshold current density of 2.05 kA/cm^2 and continuous-wave output power of ~700 mW.

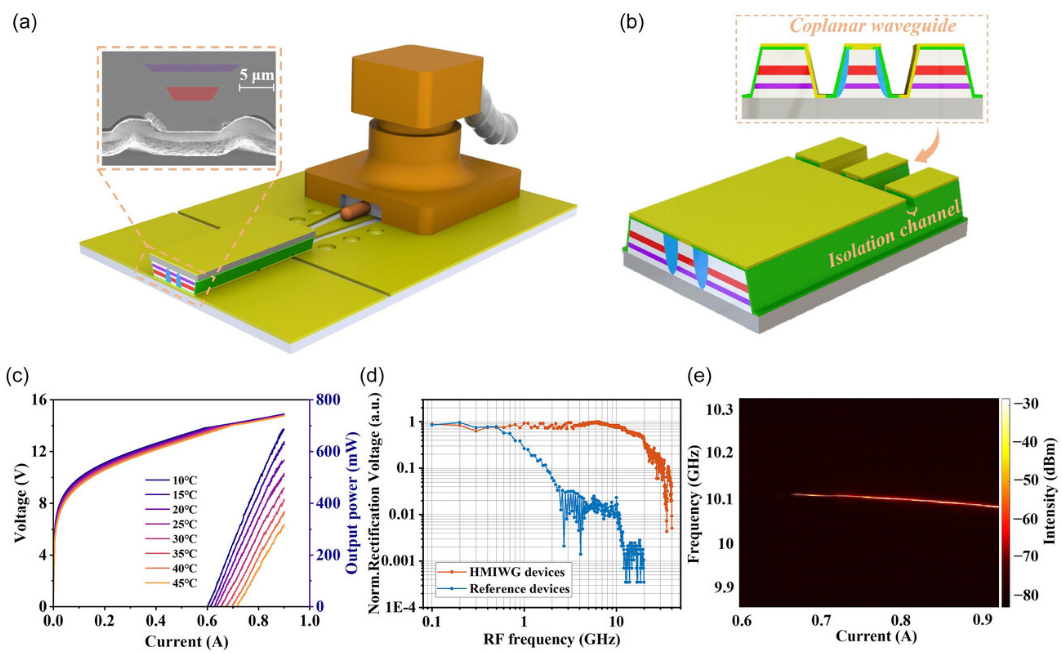

Figure 1. High-speed design and characterizations for HMIWG QCLs. a) Schematic diagram of devices based on a hybrid-monolithic-integration waveguide structure with high-speed packaging. Inset: false-colored scanning electron microscopy image (SEM) of the front facet of a device. b) Schematic diagram of a segregated-CPW structure. c) L–I–V characterization of a 4.5-mm-long high reflective coated device in continuous-wave (CW) operation at 10−45 °C. d) Normalized electrical rectification data of the HMIWG device and that of a reference device without high-speed packaging. e) Free running beatnote mapping as a function of drive current measured at 15 °C in CW mode. RBW is set as 300 kHz and VBW is 3 kHz.[1]

RESULTS

The integrated self-detecting DCS system achieved broad spectral coverage of approximately 68 cm^{-1} at 4.6 μm, with strong signal-to-noise ratios (SNRs) ranging from 25 dB to 40 dB, nearly doubling the SNRs of 10 dB to 25 dB from systems without RF injection. Injection-locking maintained excellent comb coherence and stability, even under moderate optical feedback conditions,[1] as shown in **Figure 3**. This precise synchronization between the two QCL frequency combs ensured uniform mode spacing and minimized phase noise across the entire spectral band, allowing for accurate spectral reconstruction and consistent multi-heterodyne signal generation over extended measurement periods.

Beyond stability, the team explored the system's high-speed modulation capability, successfully operating the QCL combs up to the fourth-order harmonic state with a cutoff frequency of 40 GHz.[1] This cutoff frequency at -15dB is substantially improved from a conventional device, which only achieved a 3 GHz cutoff frequency. The spectrum of the two combs exhibited a coverage of roughly 1.4 GHz, containing approximately 200 comb lines, as illustrated in **Figure 4**. This wide spectral distribution highlights the system's ability to sustain coherent emission across a dense optical bandwidth while maintaining excellent mode uniformity. Researchers achieved a broad RF comb bandwidth of 1.4 GHz and observed a narrow tooth linewidth ≈ 10 kHz.[1] The high-frequency response and dense comb structure enable precise, broadband acquisition of molecular features and enhance time-resolved measurement capability for dynamic samples.

The combination of self-detection, high-frequency performance, high-speed, RF injection, and compact design demonstrates how the integrated QCL platform bridges the gap between laboratory-grade precision and industrial practicality. With a simplified optical layout and reliable mid-infrared signal generation, the researchers demonstrated a robust, stable, high-speed spectroscopic platform capable of molecular fingerprinting and trace-gas analysis with excellent SNR and repeatability. These results highlight a major step toward field-deployable, mid-infrared, injection-locked DCS instruments for environmental monitoring, high bit-rate optical communication, multiphoton imaging, and astronomical frequency comb generation[1], offering the performance of traditional bench-top systems in a scalable, practical form.

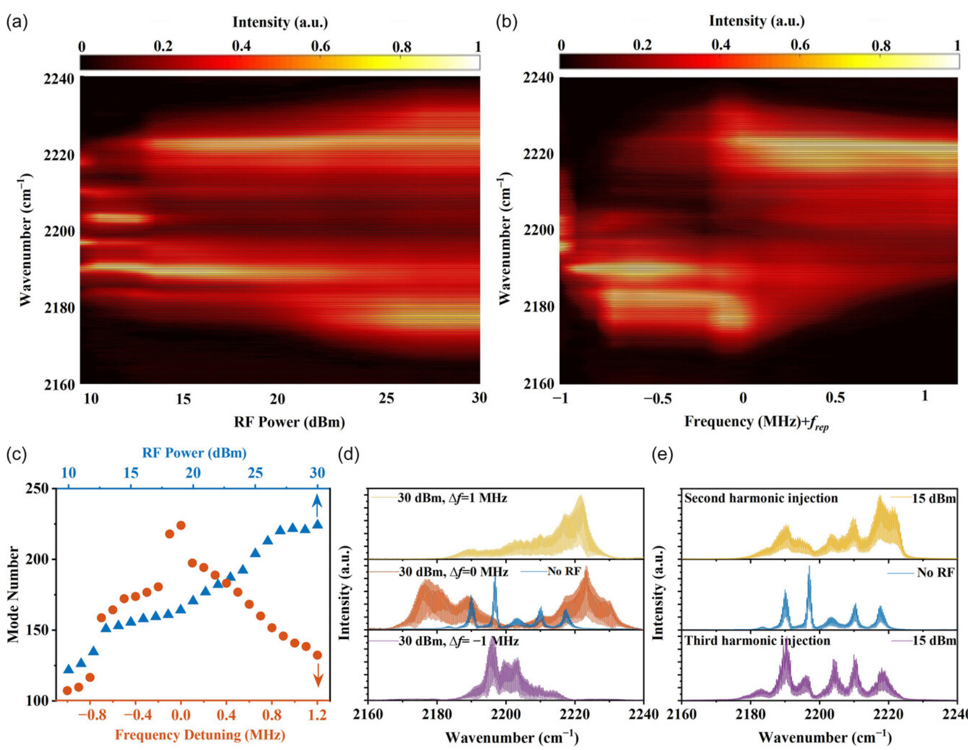

Figure 3. Spectral characterizations for HMIWG QCLs under various RF modulation conditions. a) Spectral sweeping under different RF injection power at Δf = 0 MHz. b) Spectra for sweeps of the RF injection frequency at RF power = 30 dBm. c) Mode number as a function of the injection power when Δf = 0 MHz and injection frequency at RF power = 30 dBm, respectively. d) Spectral characterizations at RF power = 30 dBm under different frequency detuning Δf = 1, 0, −1 MHz, respectively, and compared that with no RF injection. e) Spectral characterizations of second-harmonic injection and third-harmonic injection at RF power = 15 dBm and Δf = 0 MHz, respectively, and comparison with no RF injection.[1]

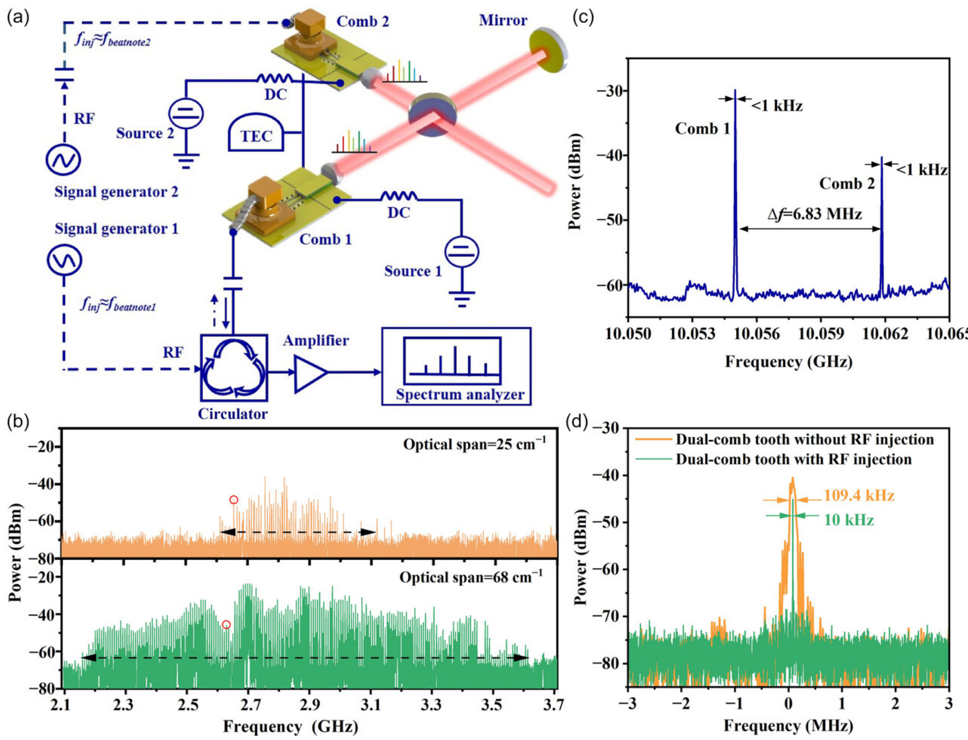

Figure 4. Self-detecting DCS based on injection-locked HMIWG QCLs. a) Experimental setup for self-detecting DCS system based on injection-locked QCLs. b) Multiheterodyne spectra (real-time acquisition) of the two combs without RF injection and with RF injection. RBW: 510 kHz, acquisition time: ≈3.35 ms. c) Beatnotes of the Comb 1 and Comb 2 measured with a spectra analyzer, both linewidths of two combs are less than 1 kHz. d) A typical dual-comb tooth under RF injection (green line, corresponding to the red circle in Figure 4b) with a FWHM of ≈10 kHz, and a typical dual-comb tooth without RF injection (orange line, corresponding to the red circle in Figure 4b) with an FWHM of 109.4 kHz. The corresponding RBWs are 7.5 and 75 kHz, respectively.[1]

WAVELENGTH'S ROLE

Stable and precise laser operation was critical to maintaining the dual-comb coherence and low phase noise required for self-detection. Wavelength Electronics' QCL2000 LAB driver provided ultra-low current noise and high dynamic response, enabling consistent laser injection-locking and stable beatnote generation. Its wide modulation bandwidth supported the system's RF operation while minimizing baseline drift and electrical interference. With current noise density below 1.3 µA RMS up to 100 kHz and modulation capability extending to 3 MHz, the driver maintained clean spectral performance and preserved the stable drive current essential for dual-comb operation.

By supplying a highly stable, low-noise drive current with precision setpoint control and integrated safety circuitry, the QCL2000 LAB ensured long-term reliability for both lasers under continuous-wave operation. Its intuitive user interface simplified system integration and allowed precise synchronization with the RF injection-locking electronics. The instrument benchtop package also includes programmable current limits, brown-out and short protections, and active and passive interlocks, features that safeguard sensitive QCLs during extended operation. This combination of protection, bandwidth, and noise performance enabled the researchers to achieve broadband spectral resolution and compact self-detection in a single, integrated mid-infrared chip for dual-comb spectroscopy.

Wavelength Electronics partners with leading researchers and high-tech developers worldwide, providing precision control electronics that empower innovation in spectroscopy, sensing, and photonic integration.

REFERENCES

1. Ma, Y., Wu, D., Huang, R., Zhang, S., Zhou, B., Ma, Z., Sun, Y., Liu, J., Zhuo, N., Zhang, J., Zhai, S., Liu, S., Liu, F., Razeghi, M. and Lu, Q., Self-Detecting Mid-Infrared Dual-Comb Spectroscopy Based on High-Speed Injection-Locked Quantum Cascade Lasers. *Adv. Photonics Res.*, 6: 2500062 (2025) **https://doi.org/10.1002/adpr.202500062**

USEFUL LINKS

- QCL2000 LAB **Product Page**

PERMISSIONS

PRODUCTS USED
QCL2000 LAB

KEYWORDS
Dual-comb spectroscopy, optical frequency comb, quantum cascade laser, radio frequency injection locking, RF, self detection, quantum cascade laser, QCL, QCL2000 LAB, laser driver

REVISION HISTORY

Document Number: CS-LD16

REVISION	DATE	NOTES
A	November 2025	Initial Release