Battery-operated mid-infrared diode laser frequency combs

Lukasz A. Sterczewski, ¹,²

¹Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland
²Previously: Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
Contributors

Mahmood Bagheri, Clifford Frez, Siamak Forouhar

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
Molecular sensing – need for broadband measurements
Broadband sources for spectroscopy
Why frequency combs if single-mode lasers work well?

Single-mode laser is sufficient – single line can be isolated (a few cm\(^{-1}\) tunability)

Comb becomes necessary – broad features would be difficult to probe with ~cm\(^{-1}\) tunability

298.1 K, atmospheric pressure, HITRAN ABS 2019 database
Novel sources for comb spectroscopy

**Type-I quantum well diode laser combs**

- Up to 20 mW of CW power at <1 W of power consumption
- \(\sim 1 \text{ THz}\) spectral coverage, 10 GHz repetition rate
- Self-starting comb emission without any microwave generators
- Native emission in the 1.5-3 µm wavelength region
- Lockable to frequency standards

**Inclusive frequency comb definition**

Frequency of each line defined by two parameters: global offset and repetition rate
Diode laser combs - LIV
Diode laser combs – spectral characterization

![Graph of diode laser combs with spectral characterization. The graph shows the power (dBm) + offset (50 dB/div.) vs. wavelength (nm) at different currents (120 mA, 40 mA increment, 800 mA). There is also a Frequency (MHz) graph with +10.05 GHz offset.](image)
Comb operation enabled by multimode operation (spatial hole burning) + nonlinearity (four-wave mixing)
Linearly swept FM source - approximation
Linearly swept FM source – more accurate picture
Original SWIFTS characteristics
A pair of devices

- $I=291$ mA, $V_b=1.2$ V, $T=17^\circ$C
- $I=289$ mA, $V_b=1.2$ V, $T=20^\circ$C
Dual-comb spectroscopy

Signal comb (SIG)

Local oscillator (LO)

Absorber

Optical multi-heterodyne
Dual-comb spectroscopy

Optical domain

RF domain

LO

SIG
Optical multi-heterodyne

Optical spectrum

Wavenumber (cm$^{-1}$)

Wavenumber (cm$^{-1}$)
Optical multi-heterodyne
Optical multi-heterodyne

Optical spectrum

Including absorber

RF spectrum

Wavenumber (cm\(^{-1}\))

Frequency (MHz)

Mid-IR QCLs: Villares et al. Nat. Comm. 5 (2014)
Battery-operated MIR dual-comb source

Detector

Diode combs

ISO

3310 3300 3290 3280 3270
Wavenumber (cm\(^{-1}\))

3020 3030 3040 3050 3060
Frequency (MHz)

Amplitude (V)

0 200 400 600 800 1000
Time (ns)

-40 -30 -20 -10 0
Relative power (dBm)

3310 3300 3290 3280 3270
Wavenumber (cm\(^{-1}\))

0.5 1.0 1.5 2.0
-40 -20 0
Norm. power (dB)

Frequency (GHz)

0.45 THz of optical coverage

L. A. Sterczewski, et al., "Battery-operated mid-infrared diode laser frequency combs," Laser & Photonics Reviews 17, 2200224 (2023).
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Multi-wavelength tunable laser spectroscopy

Pure CH$_4$. HITRAN simulation parameters $T$: 293 K, $P$: 0.1 atm (76 Torr) – for display visualization purposes.
Tuning over a full free spectral range

Parasitic external cavity
Multi-wavelength tunable laser spectroscopy

Pure CH$_4$, HITRAN simulation parameters $T$: 293 K, $P$: 0.1 atm (76 Torr) – for display visualization purposes
High resolution spectroscopy at 3 µm – $^{12}$C$_2$H$_2$

$^{12}$C$_2$H$_2$, 10 Torr

(a) Absorbance ($-\log_{10}[I/I_0]$) vs. Wavenumber (cm$^{-1}$)

(b) $R(0)$, $\nu_2+(\nu_4+\nu_5)^0$

(c) $P(4)$, $\nu_3$

Dynamic range limit (−20 dB)

340 MHz FWHM
Summary

► First mid-infrared (3 µm) diode laser frequency combs. Ultra-low power consumption enables battery-operated dual-comb spectrometers.

► Suitability for mechanical high-resolution Fourier transform spectrometers.

► Future exploitation of intracavity nonlinearities for frequency conversion.
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New chapter

TeraERC

Chip-based room-temperature terahertz frequency comb spectrometers (1 500 000 EUR).

lukasz.sterczewski@pwr.edu.pl

We are hiring!
Modal leakage – well known challenge for GaSb devices

Amplified spontaneous emission
Gain and dispersion

- Gain and dispersion
- Combined coverage
- Weak modal leakage acts as vertical dispersion compensation (local)
- Net modal gain (cm⁻¹)
- Wavenumber (cm⁻¹)
- Frequency (MHz)
- Power (dBm)
- Relative power (dBm)
- Wavelength (nm)
- SIG RBW
- LO SIG
- 3 kHz
- 38.3 MHz
- 20°C
- 17°C
- 358 mA
- 365 mA