# Injection locking of interband cascade laser frequency combs

**Lukasz A. Sterczewski[1], Mahmood Bagheri[1,*], Clifford Frez[1], Igor Vurgaftman[2], Jerry R. Meyer[2]**

[1]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[2]*Naval Research Laboratory, Washington, DC 20375, USA*

**Contact Email: Mahmood.bagheri@jpl.nasa.gov*

**Short Abstract** We report on injection locking of the roundtrip frequency of an interband cascade laser emitting at 3.25 µm. An external microwave source with milliwatt power levels modulates the absorber section of a device in a split-contact geometry, thus enabling locking over a MHz frequency range. For optical characterization of the locking properties, we exploit the bifunctional operation of the ICL, which serves as a fast photodetector with microwave electrical bandwidth.

## 1. Introduction

Interband cascade laser (ICL) frequency combs are excellent light sources for portable mid-infrared dual-comb spectrometers with low power consumption [1]. While state-of-the-art ICL combs develop optical spectra with more than a terahertz of coverage accompanied by sub-kilohertz intermode beat note linewidths [1], [2], they are susceptible to environmental factors such as current noise or temperature fluctuations, which may cause the repetition rate $f_{rep}$ to become unstable and drift. Injection locking to a stable oscillator or a frequency standard is a possible remedy to this issue [3]. We study the injection locking properties of an ICL comb with $f_{rep} \approx 9.6$ GHz whose center wavelength (3.25 µm) was tailored for high-sensitivity spectroscopy of hydrocarbons.

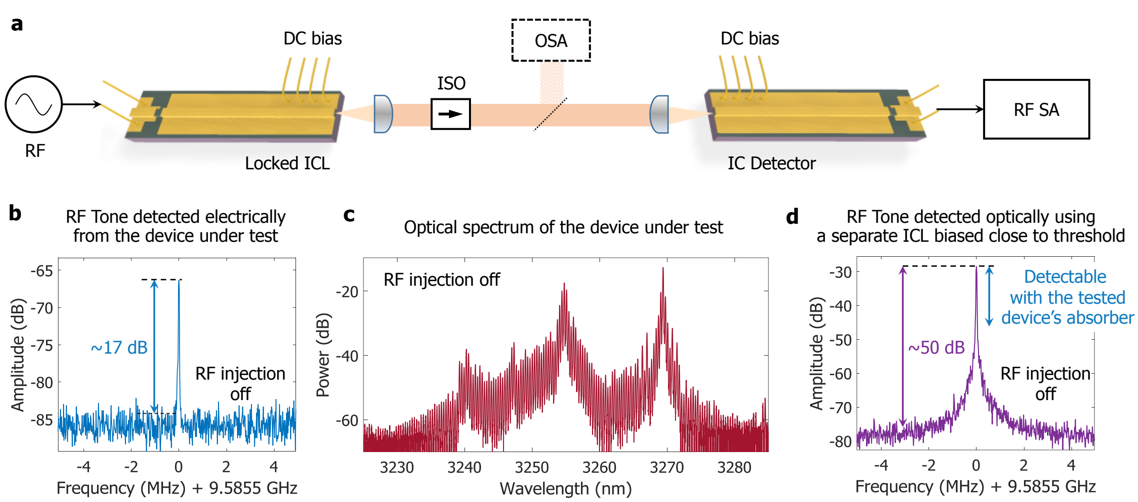


**Figure 1:** Electrical and optical characterization of a free-running and injection-locked ICL comb ($I$=214 mA, $U$=4.3 V, $t$=12°C). **a** Schematic of the characterization setup, wherein one device is biased above threshold in a frequency comb regime, while a second device cleaved from the same wafer operates close to threshold as a fast room-temperature IC photodetector. The isolator (ISO) helps to minimize optical feedback corrupting frequency comb generation. **b** Kilohertz-range intermode beat note (RF tone) in free-running mode probed from the absorber section of the device under test. **c** Optical spectrum of the tested ICL comb centered at ~3.25 µm spanning more than 50 nm. **d** RF tone measured with a second ICL serving as a fast photodetector with enhanced sensitivity compared to (**b**), which allows to see a MHz noise pedestal previously buried in noise. The optical power illuminating the IC photodetector (after ISO) was 4.5 mW.

## 2. Results

Figure 1 shows the experimental setup wherein two identical ICL devices are used. By guiding light from one to the other, we exploit the recently demonstrated bifunctional operation of ICLs [3] enabling us to optically characterize the injection locking properties without the need for cryogenic QWIPs. The device under test was biased in a narrow beat note regime (tens of kHz, Fig. 1b) while emitting optical modes covering more than 50 nm (Fig. 1c). Unexpectedly, the beat note of a free-running device measured from the on-chip absorber section separated ~100 µm from the FP cavity is more than 30 dB weaker than that obtained from a detector device biased close to threshold (Fig. 1d). The origin of this effect may require further investigation, yet the considerable improvement in sensitivity is highly desired in context of detecting weaker optical signals with large electrical bandwidths. Figure 2 shows the optically measured locking characteristics of the device ($P_{opt}$=4.5 mW). At 6 dBm of injected RF power modulating the absorber section, the locking range reaches 6 MHz (Fig. 2a). When the injected frequency is 1 MHz away from the natural $f_{rep}$, at power levels above 0 dBm the device fully follows the injected signal with more than 45 dB of carrier-to-noise ratio (Fig. 2b). Moderate levels of injected power have almost no effect on the shape of the optical spectrum (Fig. 2c), which is consistent with results published in Ref. [3]. Comparison of the measured locking range with the square root of RF power model [4] shows good agreement (Fig. 2d), albeit slight deviations occur and will be subject to further analysis.

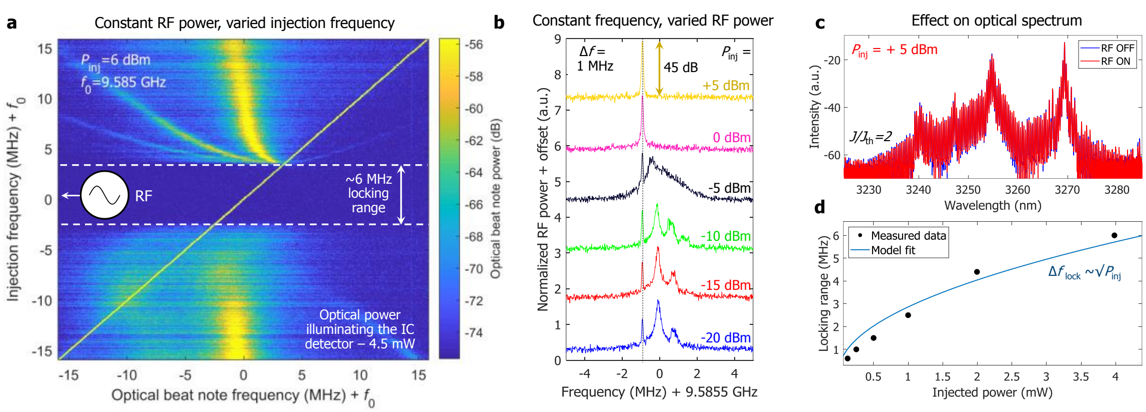


**Figure 2:** RF injection of ICL frequency combs. **a** Measurement of the RF intermode beat note spectrum for different injected frequencies. At 6 dBm the locking range reaches ~6 MHz. **b** Measurement of the RF intermode beat note spectrum for different levels of injected power (constant detuning from the natural $f_{rep}$). **c** Influence of RF injection on the optical spectrum. **d** Locking range as a function of injected power plotted together with a fitted square root model.

## Acknowledgements

This work was supported under National Aeronautics and Space Agency's (NASA) PICASSO program and was in part performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the NASA. L. A. Sterczewski's research was supported by an appointment to the NASA Postdoctoral Program at JPL, administered by Universities Space Research Association under contract with NASA.

## References

[1] L. A. Sterczewski *et al.*, "Mid-infrared dual-comb spectroscopy with interband cascade lasers," *Opt. Lett.*, vol. 44, no. 8, 2019.

[2] M. Bagheri *et al.*, "Passively mode-locked interband cascade optical frequency combs," *Sci. Rep.*, vol. 8, no. 1, p. 3322, 2018.

[3] B. Schwarz *et al.*, "A monolithic frequency comb platform based on interband cascade lasers and detectors," *ArXiv181203879 Phys.*, 2018.

[4] M. R. St- Jean *et al.*, "Injection locking of mid-infrared quantum cascade laser at 14 GHz, by direct microwave modulation," *Laser Photonics Rev.*, vol. 8, no. 3, pp. 443–449, 2014.