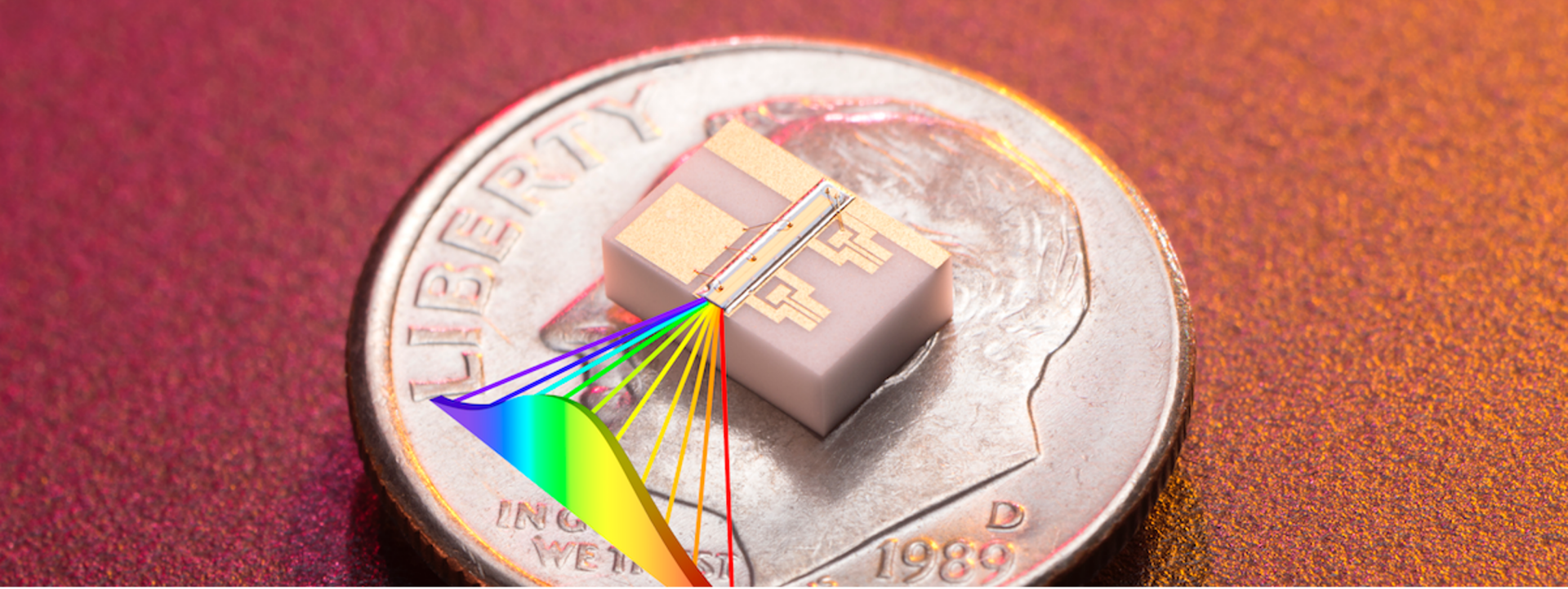


Interband Cascade (IC) Frequency Comb Devices

M. Bagheri , L. A. Sterczewski, C. Frez, I. Vurgaftman, J. Westberg,, M. Fradet, I. Grudinin, C. L. Canedy, W. W. Bewley, C. S. Kim, C. D. Merritt, J. R. Meyer, G. Wysocki

Jet Propulsion Laboratory, California Institute of Technology
Naval Research Laboratory
Princeton University

Jet Propulsion Laboratory
California Institute of Technology

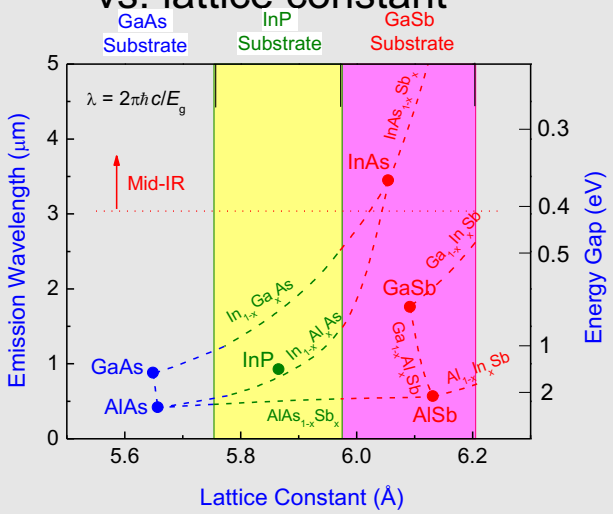
Outline

- ❑ Interband Cascade Lasers: Overview
- ❑ Optical frequency comb
- ❑ Mode-locked lasers
- ❑ Interband cascade mode-locked lasers
- ❑ Injection locked ICL devices
- ❑ Dual frequency comb spectroscopy
- ❑ Second harmonic generation in ICL devices

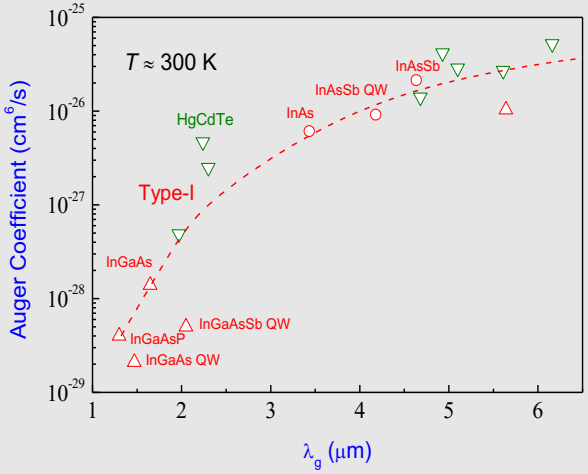
Interband Cascade Laser: Overview

Semiconductor optical sources between 3-4 μm

Semiconductor emission wavelength vs. lattice constant



Dominant decay in mid-IR semiconductors

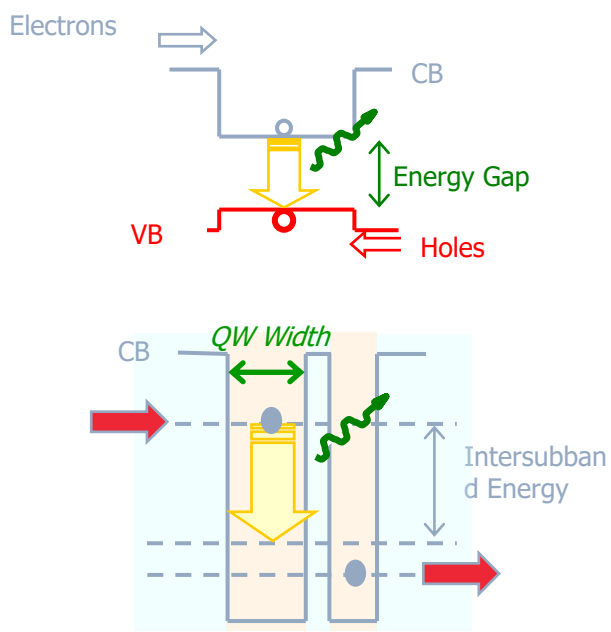


- Stubborn materials: GaSb growth & fab intrinsically harder
- High loss: Free carrier absorption scales as λ^2 to λ^3
- Short upper-state lifetime: Rapid Auger decay of upper lasing level

Interband Cascade Laser: Overview

Quantum Cascade Lasers (QCL)

ABANDON THE DIODE!

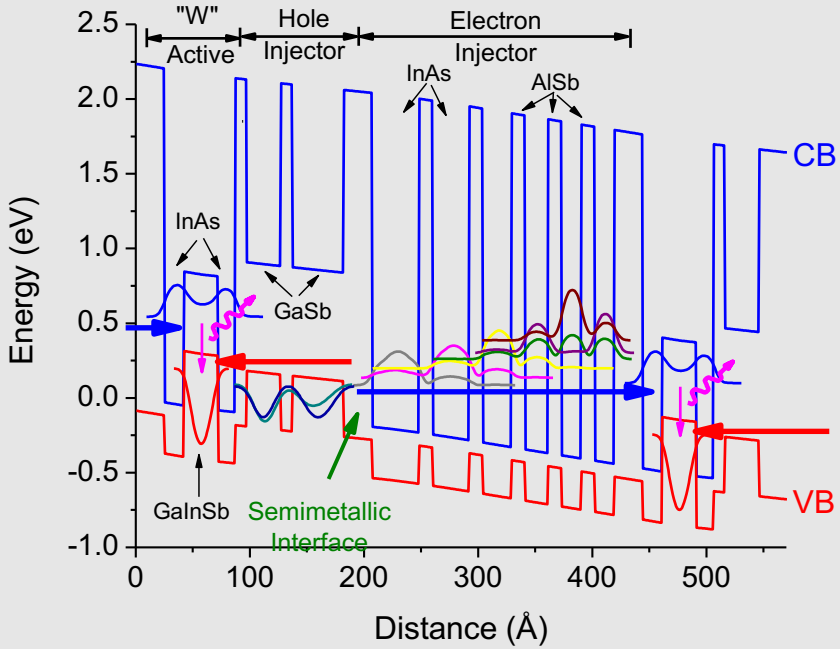


- QCL exploits optical transitions between *electron subbands in a QW – No holes, so not a diode*
- Very different regime from diodes – Upper lasing level lifetime ≈ 1 ps rather than ≈ 1 ns
- Tune λ with QW width (2.6 - 700 μm!)
- With cascade staircase, 1 electron in can yield 30-40 photons out!

Interband Cascade Laser: Overview

Semiconductor optical sources between 3-4 μm

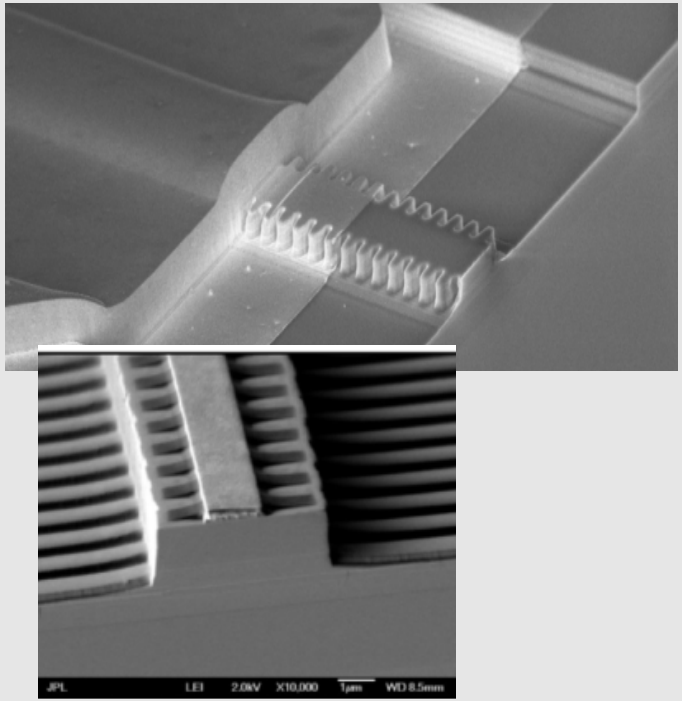
ICL active medium

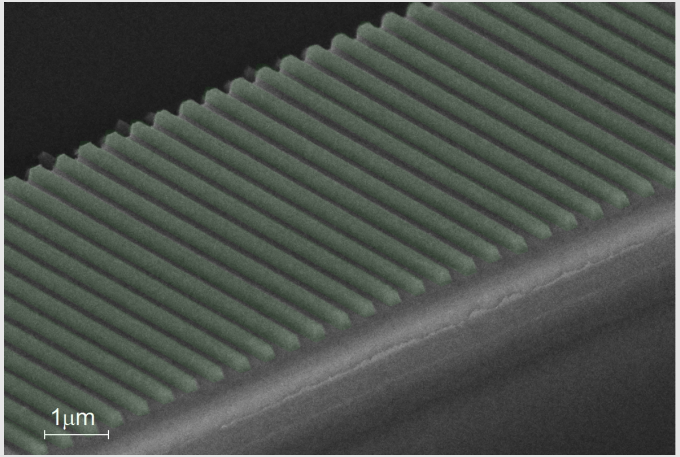


- High output powers possible
  - Wallplug efficiency > 10%
- Low power consumption (~ 100 mW)
  - Battery operated & small footprint
- Broad spectral accessibility
  - λ = 2.9-10.0 μm
- Passive mode-locking allowed!
  - Interband transitions have long gain recovery time (~ ns)

Interband Cascade Laser: Overview

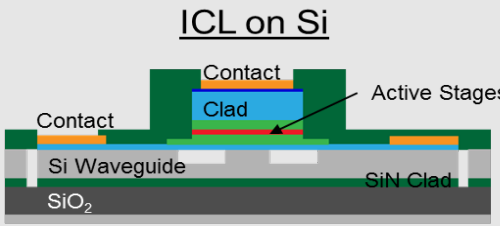
ICL progress (DFBs)

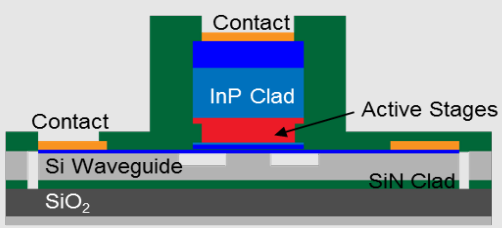


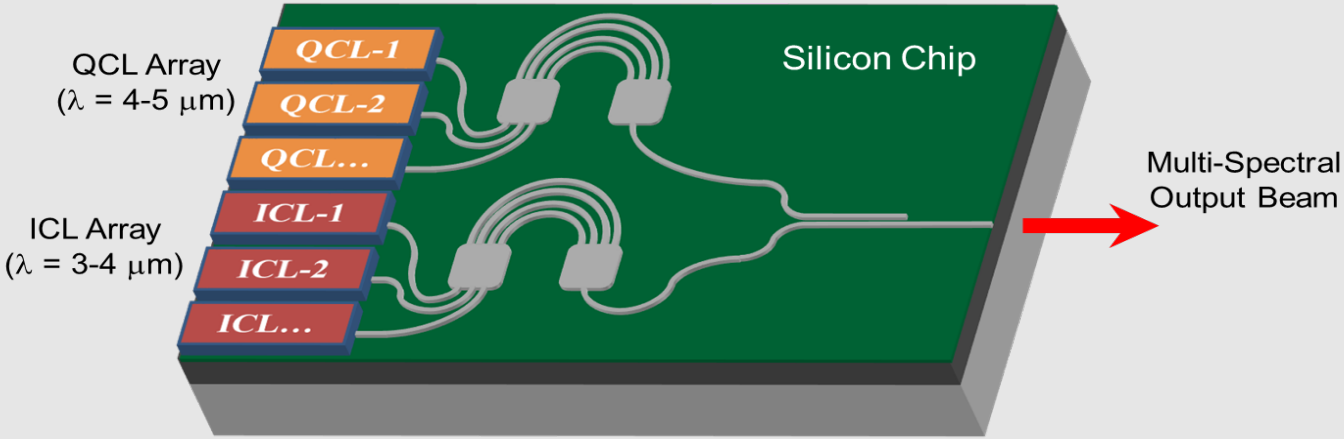


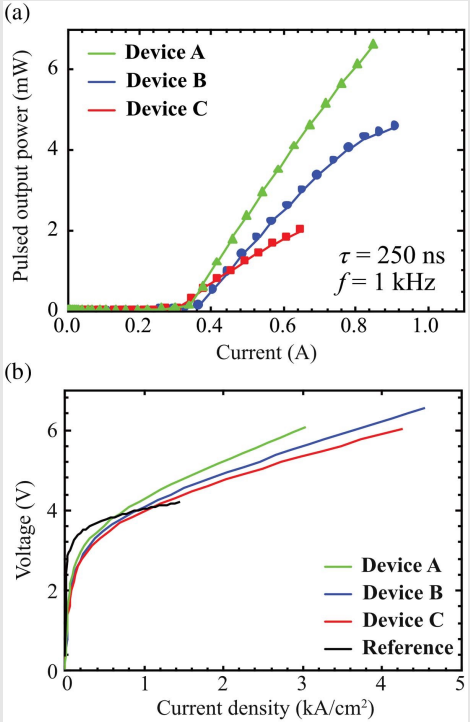
Interband Cascade Laser: Overview

ICL progress (laser on silicon)





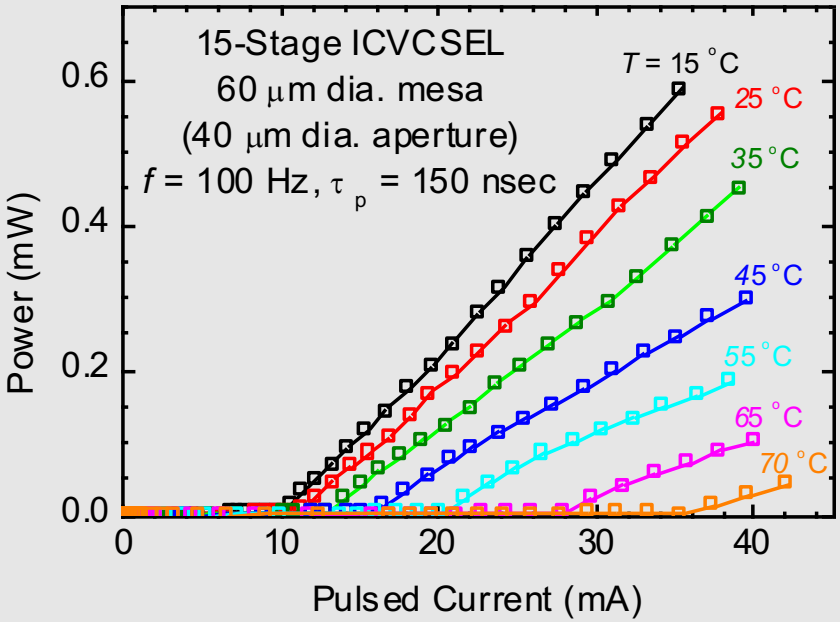


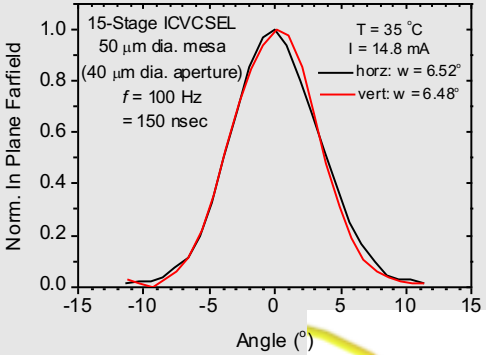


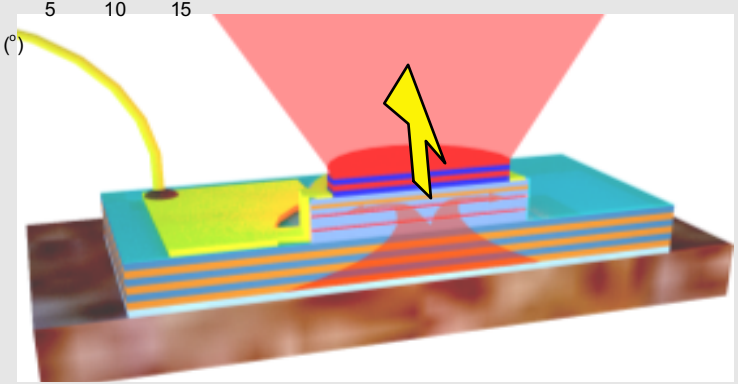
Alexander Spott et al., Optica 5, (2018)

Interband Cascade Laser: Overview

Interband Cascade VCSELs



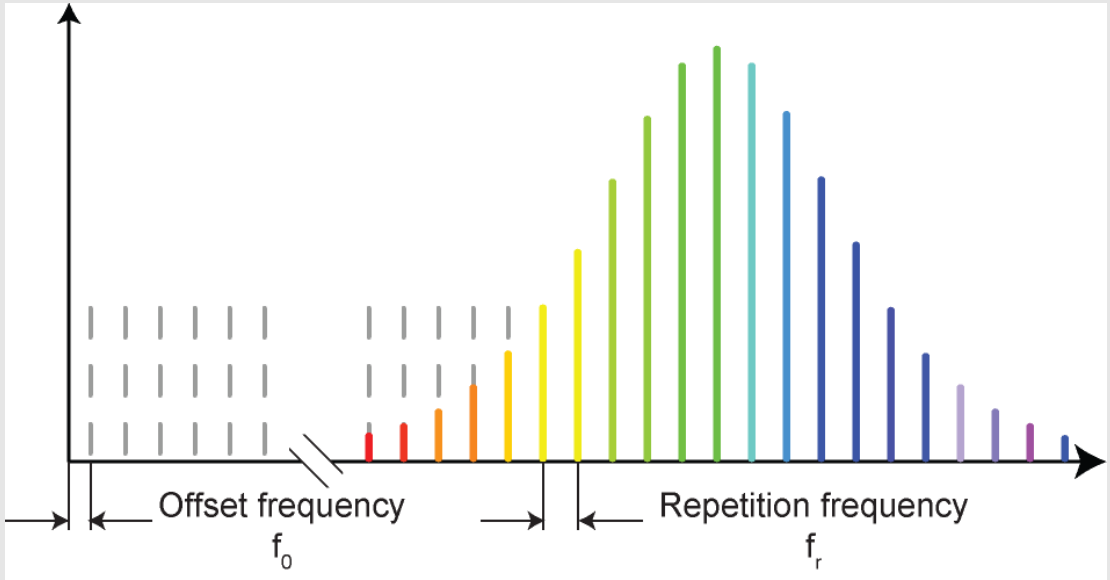




ICVCSEL

Optical Frequency Comb

What is an optical comb?

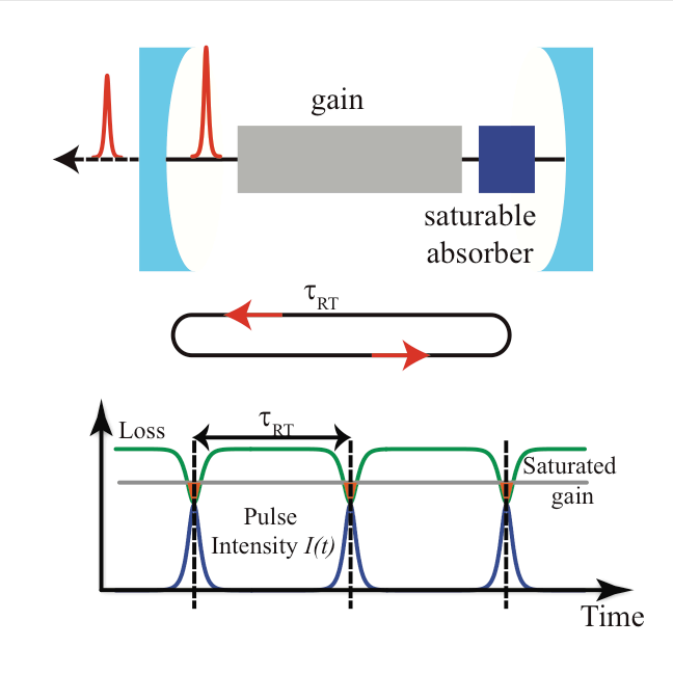


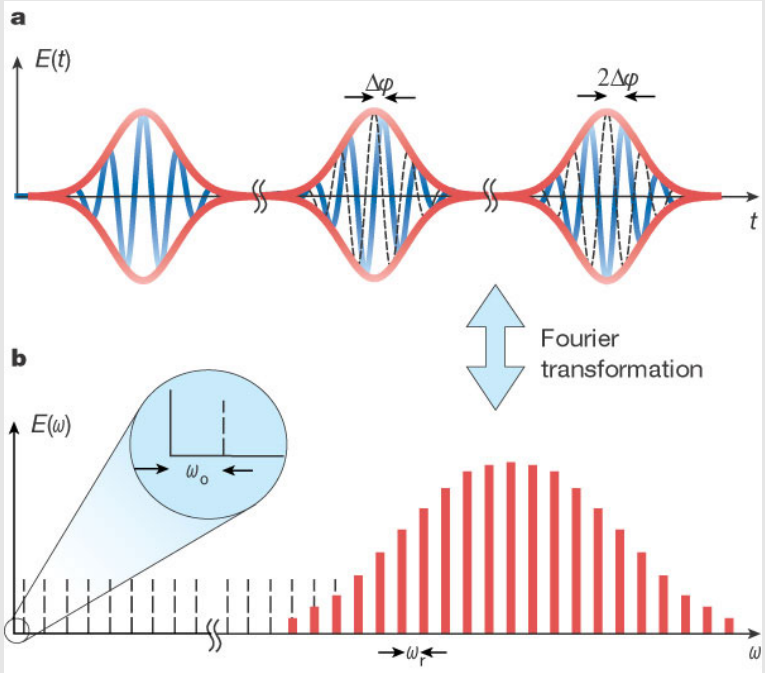
A frequency spectrum that consists of a discrete, regularly spaced series of sharp lines

$$f_m = f_0 + mf_r$$

Optical Frequency Comb

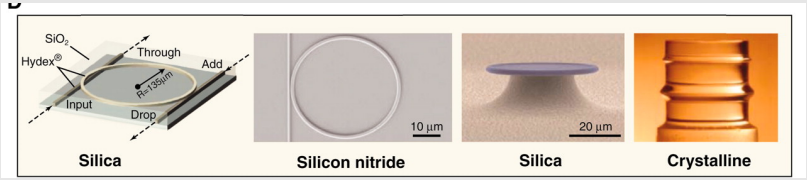
Generation: mode-locked laser

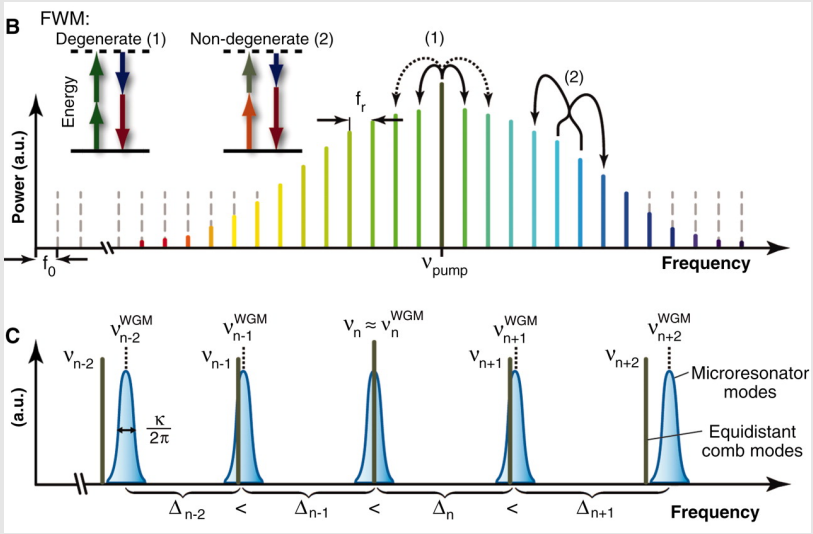


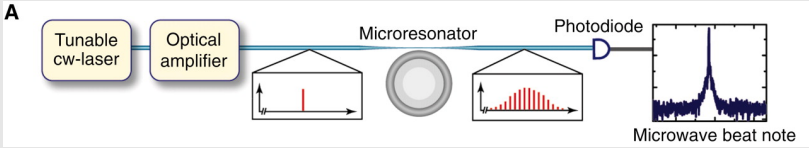


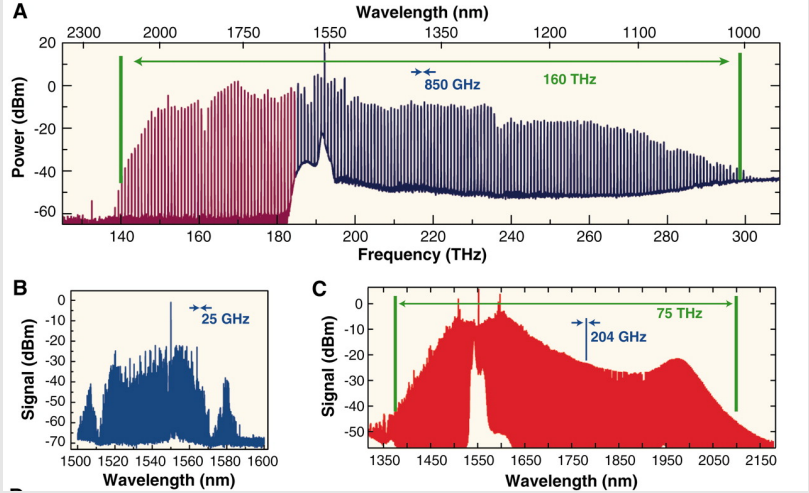
Optical Frequency Comb

Generation: Kerr comb (FWM in optical resonators)





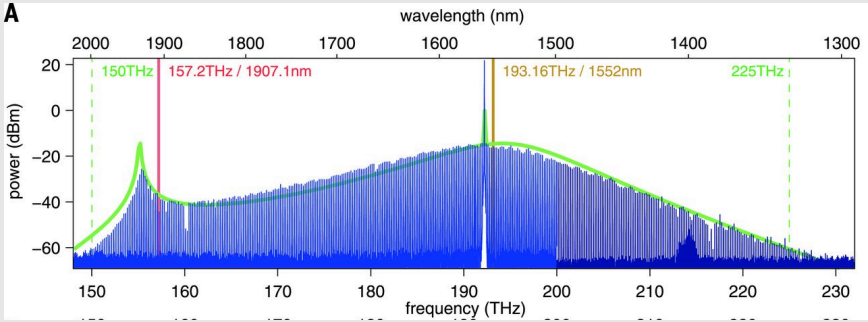


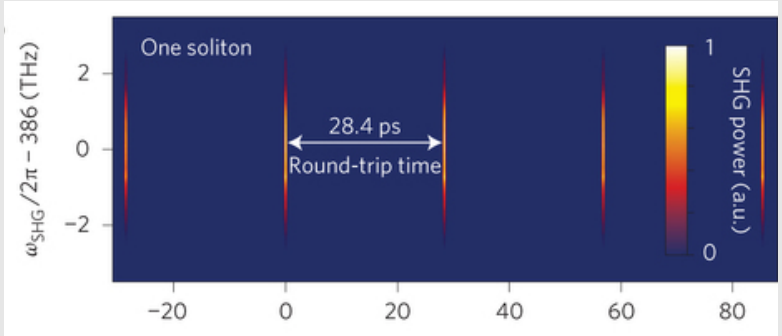


T. J. Kippenberg et al. Science (2011)

Optical Frequency Comb

Generation: Soliton comb



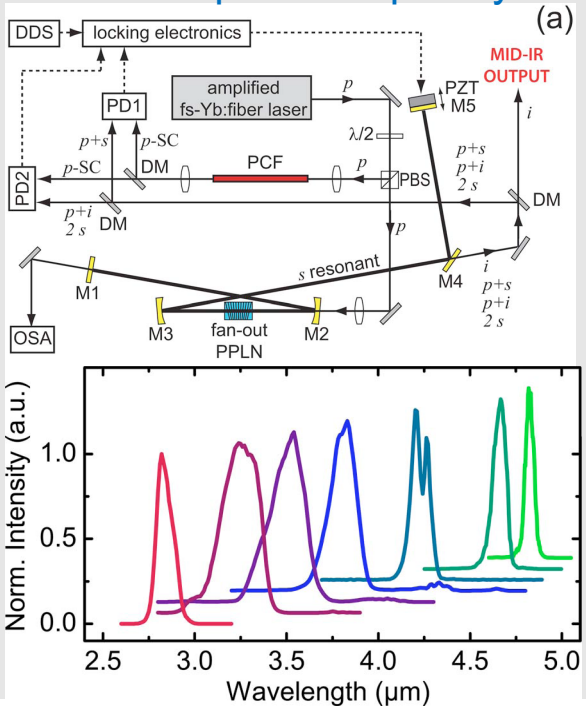


T. Kippenberg lab, EPFL

Optical Frequency Comb

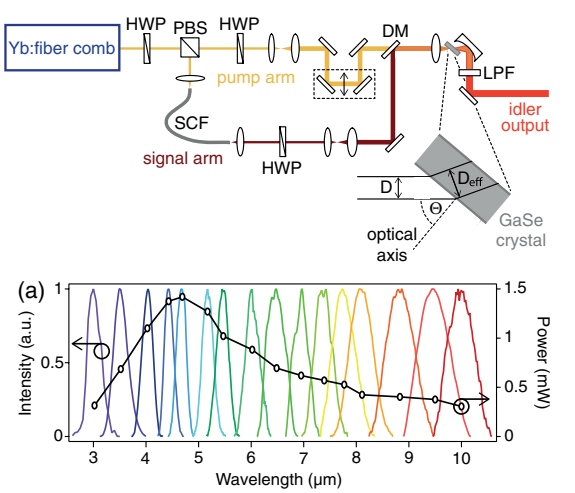
Nonlinear optical processes

OPO-based optical frequency comb



F. Adler et al., Optics Letters 34 (2009)

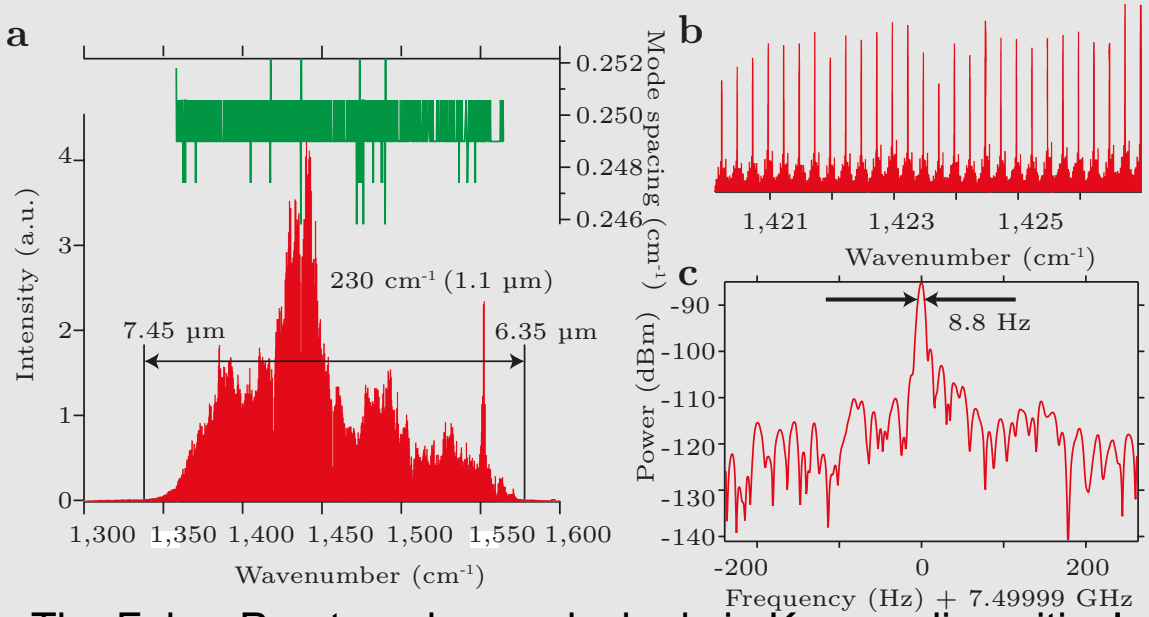
Difference frequency generated optical frequency comb



A. Ruehl et al., Optics Letters 37 (2012)

Optical Frequency Comb

Quantum Cascade Lasers



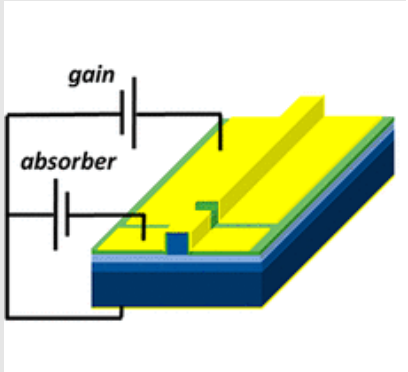
The Fabry-Perot modes are locked via Kerr nonlinearities!

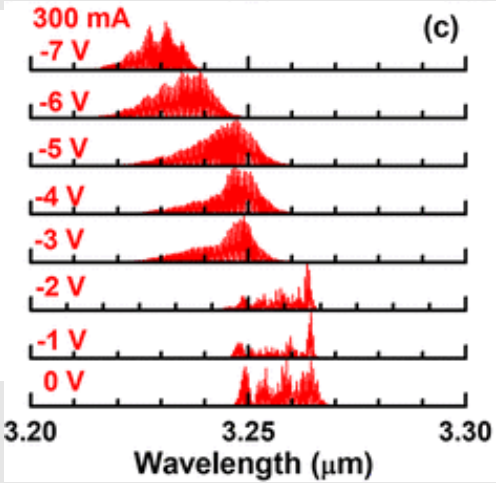
A. Hugi et al., Nature, 4 9 2, (2012),

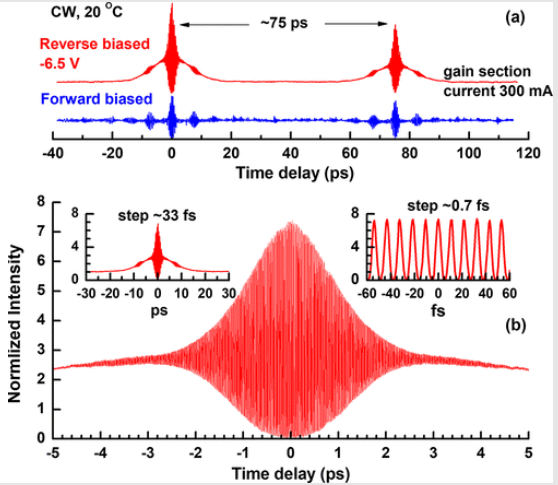
A. Hugi (2013) (Doctoral dissertation)

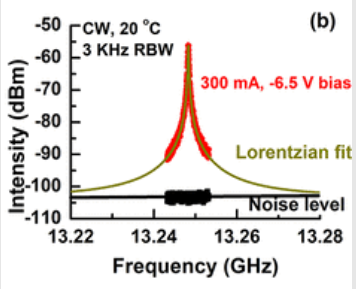
Optical Frequency Comb

GaSb-Based cascade diode lasers





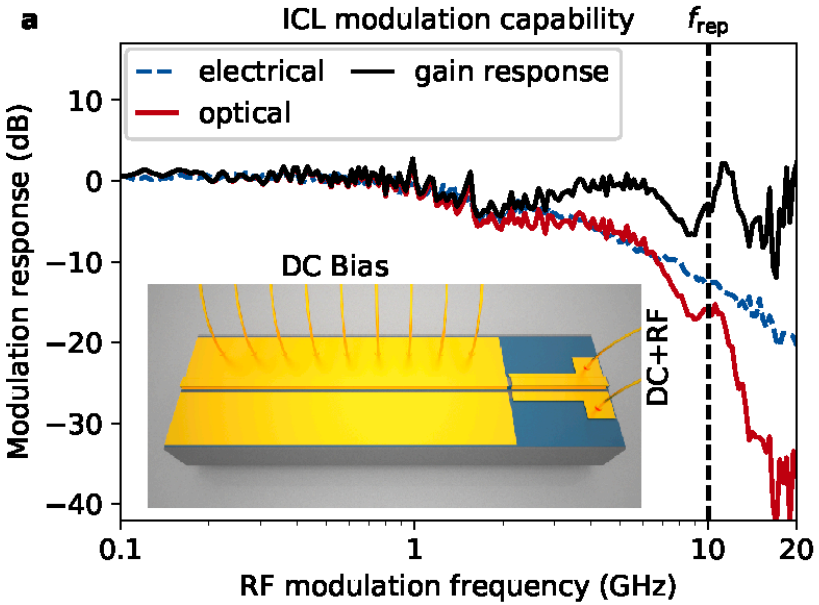


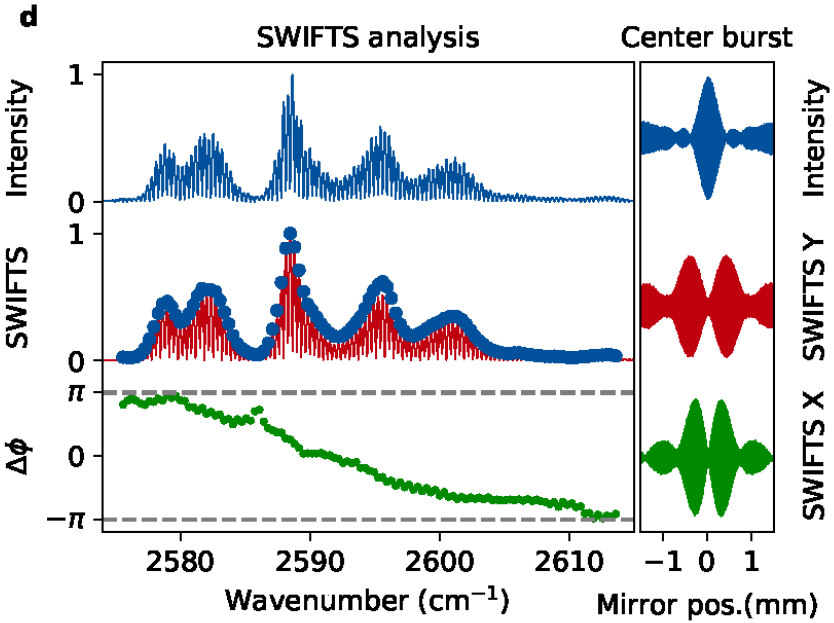


Tao Feng, et al., *ACS Photonics* **2018** *5* (12), 4978-4985

Optical Frequency Comb

ICL frequency comb

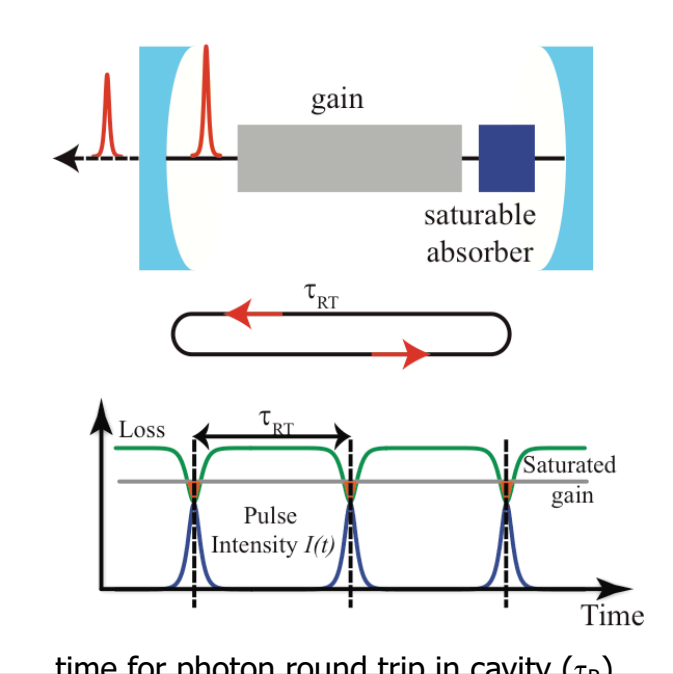




Benedikt Schwarz, et al., arXiv:1812.03879 [physics.optics]

Passively Mode-Locked Lasers

Principles of passive mode-locking



time for photon round trip in cavity (τ_R)
gain recovery time (τ_g)

Gain dynamics for mode-locking

- $\tau_g << \tau_R$
  the gain reacts nearly instantaneously to the intensity of the pulse; suppresses mode-locking (cw)
- $\tau_g < \tau_R$
  multiple pulses can propagate in the cavity, separated approximately by the gain recovery time
- $\tau_g > \tau_R$
  a single laser pulse oscillating in the cavity depletes the gain and prevents the formation of other pulses

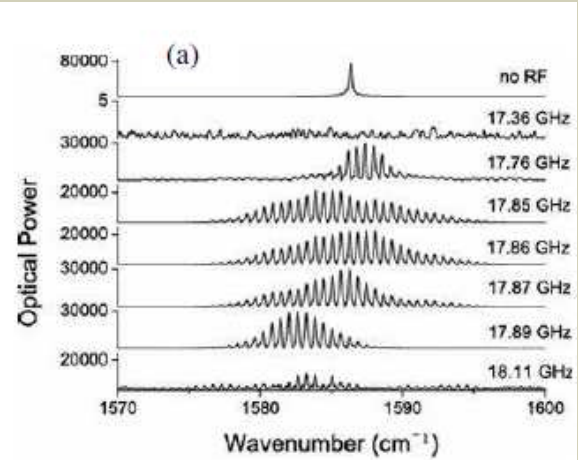
Passively Mode-Locked Lasers

Principles of passive mode-locking

Impediment to mode-locking a QCL

- Gain recovery time: $\tau_g < 1$ ps
- *vs.* $\tau_R > 50$ ps for a 2 mm long cavity
- Thus passive mode-locking is inherently inhibited
- This condition also impedes the formation of high-intensity pulses through active mode-locking

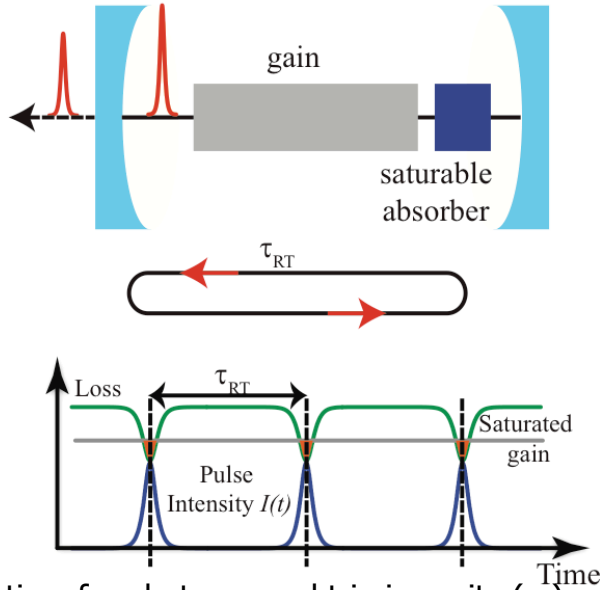
Actively-mode-locked QCL



C. Y. Wang et al. "Mode-locked pulses from mid-infrared Quantum Cascade Lasers", OPTICS EXPRESS 17, 12929 (2009).

Passively Mode-Locked Lasers

Principles of passive mode-locking



time for photon round trip in cavity (τ_R)
gain recovery time (τ_g)

Saturable absorber requirements

- Small saturation energy
  - $E_s = \frac{\hbar\omega A}{\frac{\partial g}{\partial N}}$
  - Saturable absorber length
- Fast saturable absorber recovery
  - The SA must recover before to its initial state before the pulse makes its round-trip
  - The recovery due to spontaneous emission is not enough (~ns)
    - Create defects
    - Reverse bias

Passively Mode-Locked ICLs

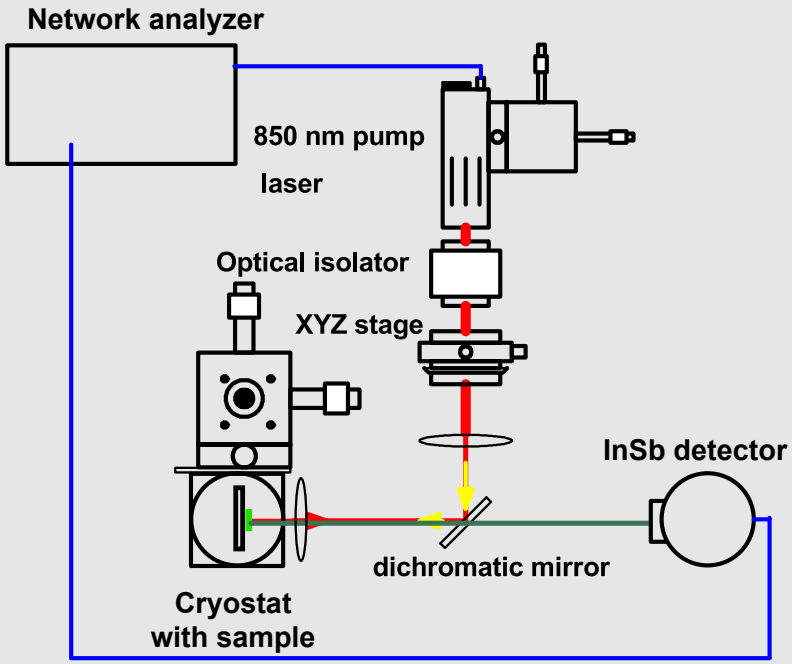
Carrier Lifetime

Carrier lifetime measurement using optical modulation response technique

$$\frac{d}{dt}(\Delta n) = G_0 + G_1 cos(\omega t) - \frac{\Delta n}{\tau}$$

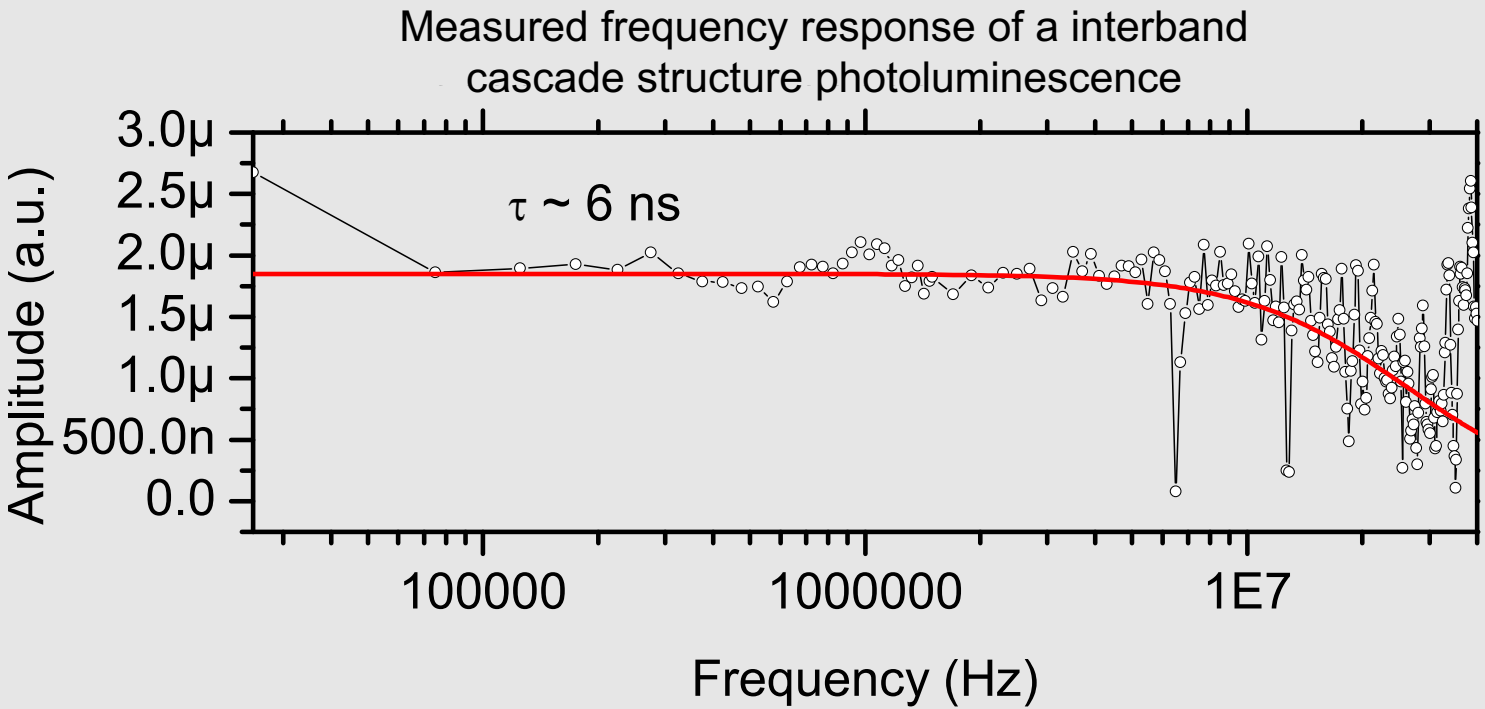
$$\Delta n(\mathrm{t}) = G_0\tau + \frac{G_1\tau}{\sqrt{1+(\omega\tau)^2}} cos(\omega t - \phi)$$

$$I_{PL}(\omega) \propto \frac{G_1\tau}{\sqrt{1+(\omega\tau)^2}}$$



Passively Mode-Locked ICLs

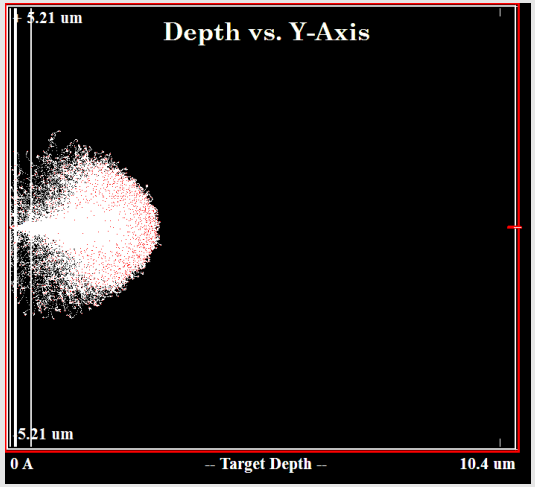
Carrier Lifetime



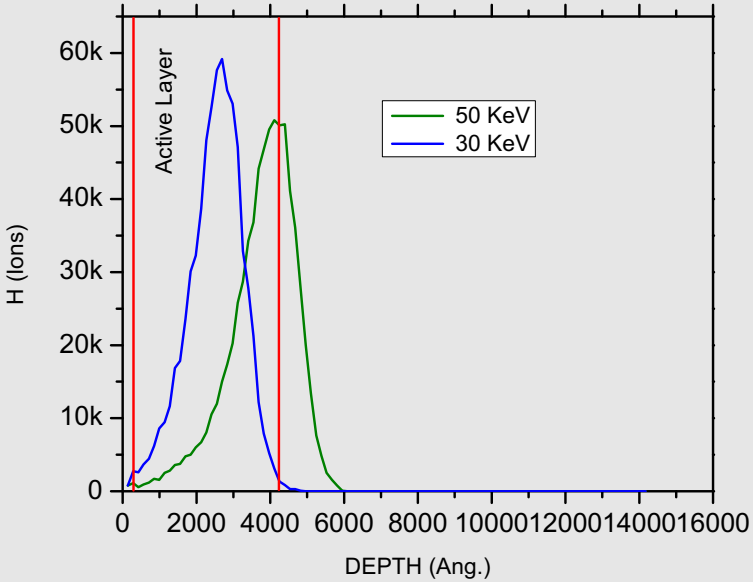
Passively Mode-Locked ICLs

Carrier Lifetime: H+ bombardment

H^+ penetration in InSb compounds @300 keV



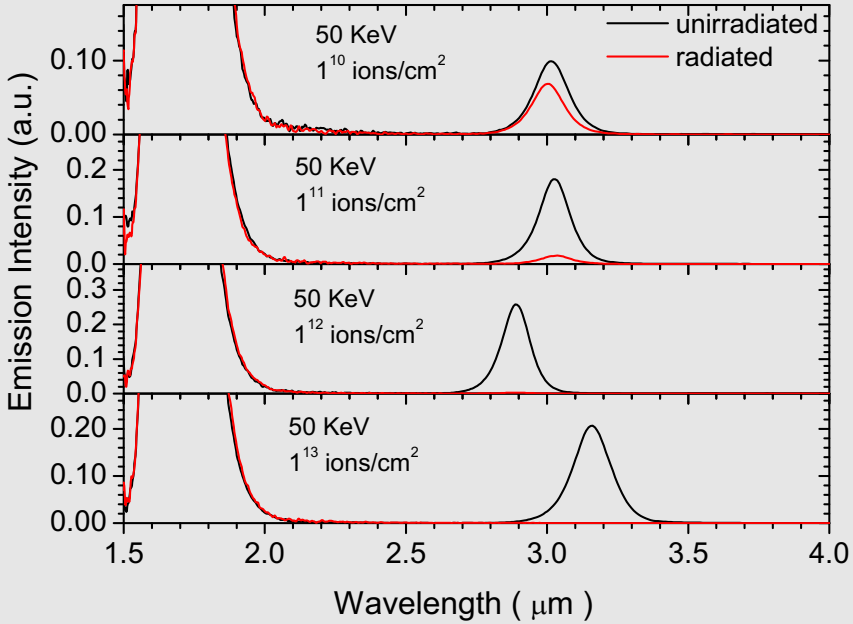
H^+ penetration profile in IC PL structure



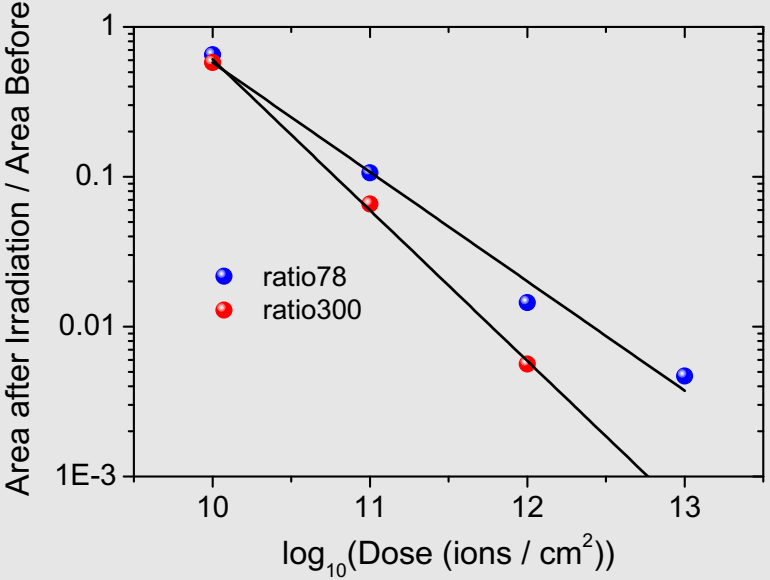
Passively Mode-Locked ICLs

Carrier Lifetime: H+ bombardment

Measured PL spectra for the as-grown PL structures (black) and the irradiated samples



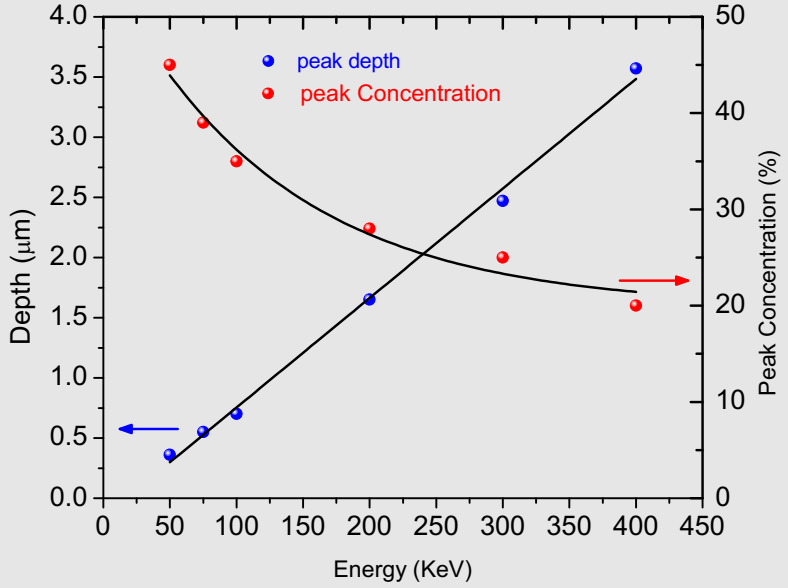
PL intensity drop ratio as a function of ion dose



Passively Mode-Locked ICLs

Carrier Lifetime: H+ bombardment

H+ penetration depth and concentration

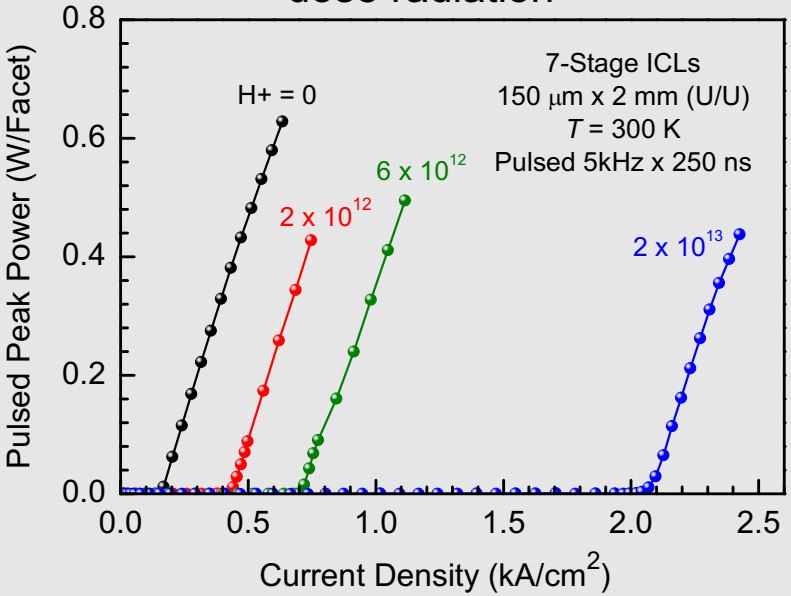


- Intrinsic carrier lifetime
  - ~ 6 ns
- Required ion dose for PL structure
  - ~ 8×10^{12} ions/cm^2
- Required ion dose for full ICL
  - ~ 2×10^{13} ions/cm^2
- Required ion energy for full ICL
  - ~ 300 KeV

Passively Mode-Locked ICLs

Carrier Lifetime: H+ bombardment

LI characteristics of ICLs under different H+ dose radiation

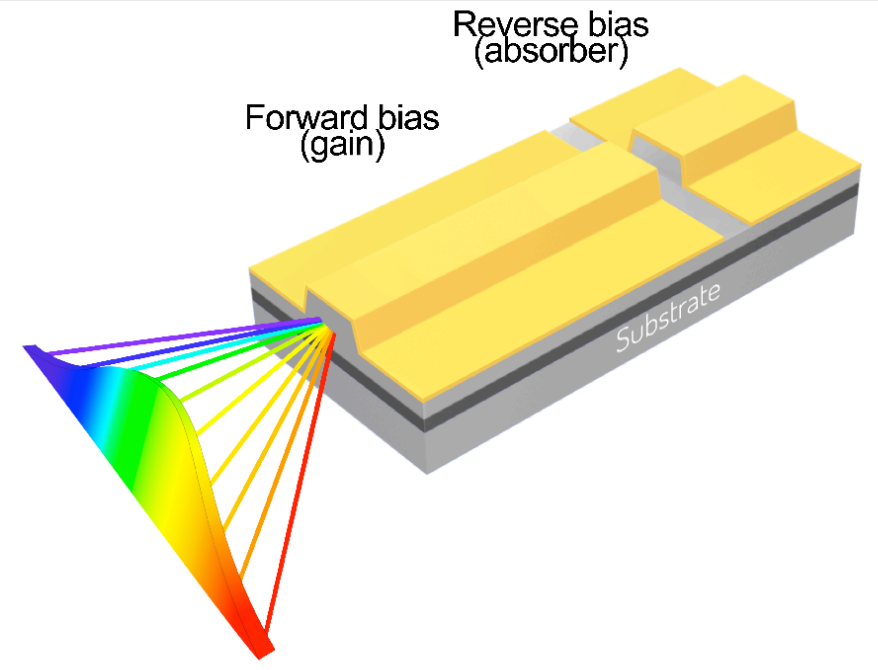


- Threshold increases with IB dose
  - 15x increase in threshold from H^+ $0 \rightarrow 2x10^{13}$
  - lifetime variation from 1 ns → 60 ps
- $6 \times 10^{13}/cm^2$ did not lase

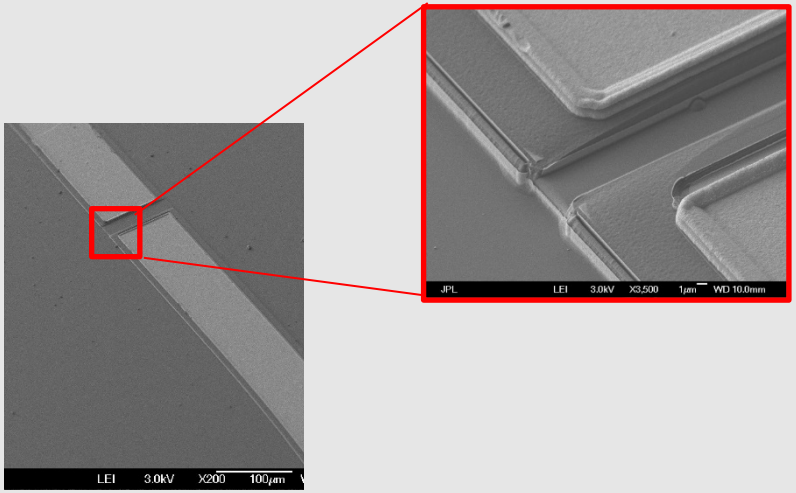
$8 \times 10^{13} – 4 \times 10^{14}/cm^2$ desired to induce carrier lifetime of 10-50 ps

ICL combs

ICL comb devices: split contact geometry



SEM image of an isolation slot

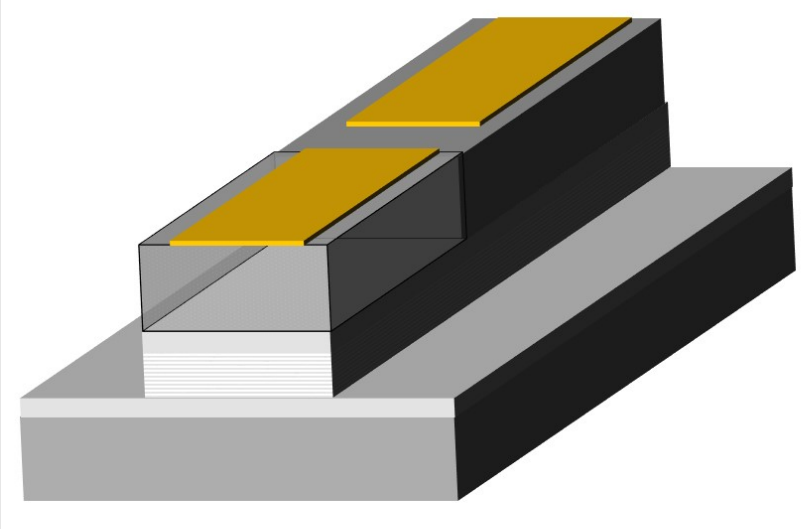


Due to ICLs low lateral resistance, this design does not provide enough electrical isolation between the two contacts (separation <50 μm)

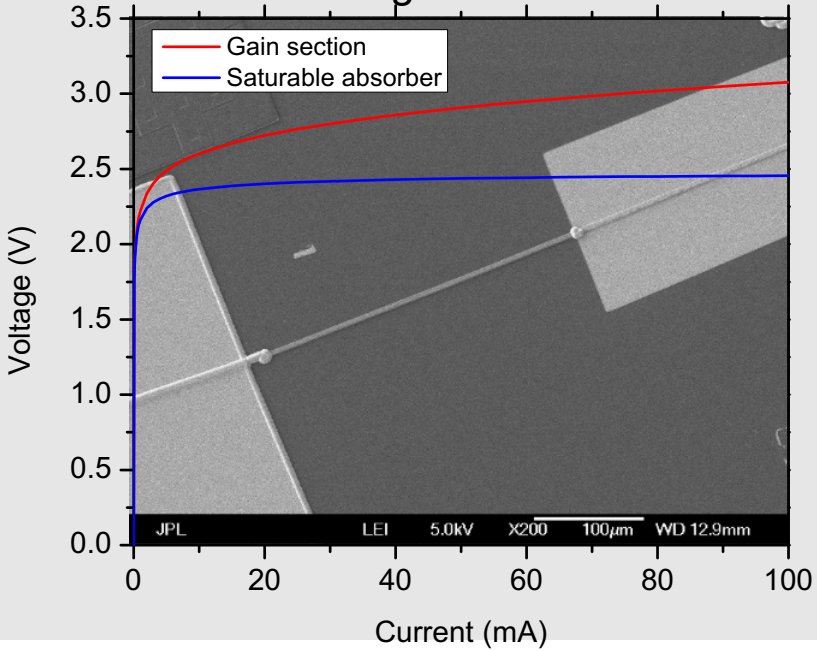
ICL combs

ICL comb devices: split contact geometry

Gain/SA isolation via carrier diffusion



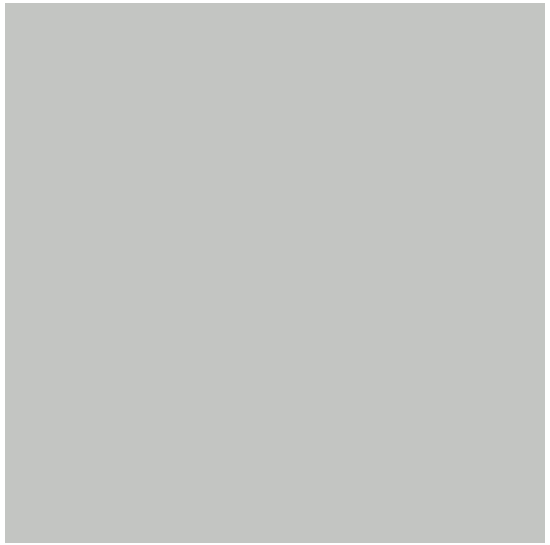
Measure voltage across contacts when gain section is biased



ICL comb

Implanted split contact ICL fabrication

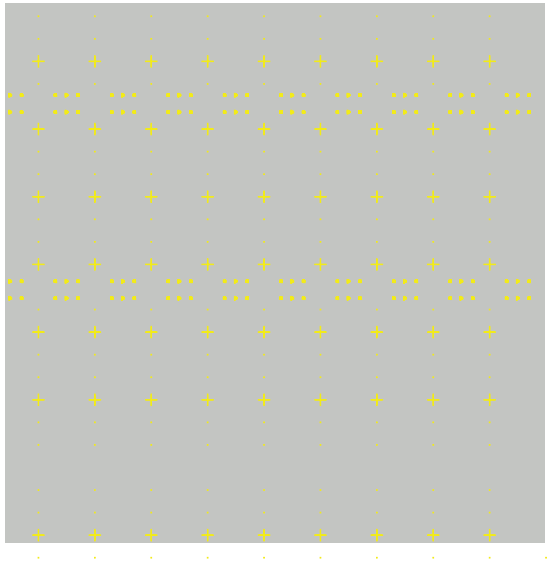
ICL Wafer



ICL comb

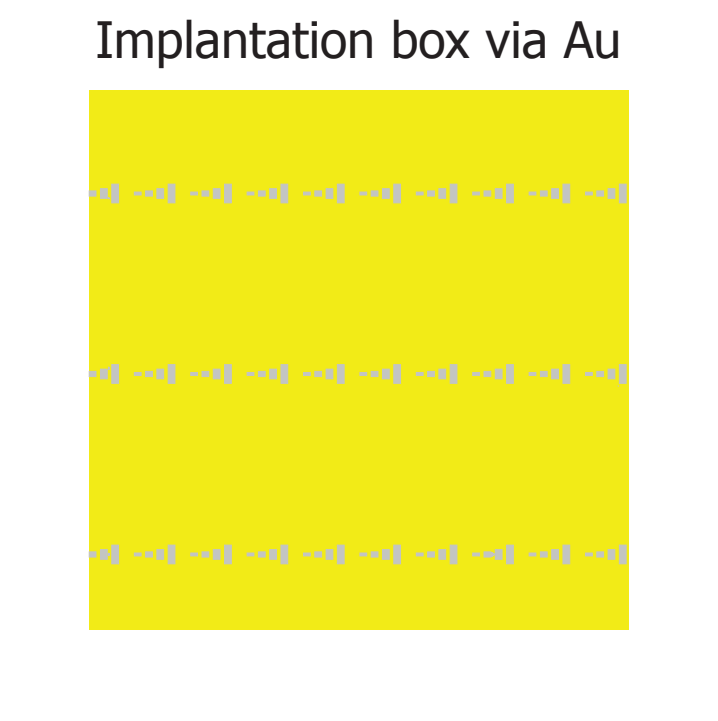
Implanted split contact ICL fabrication

Alignment marks



ICL comb

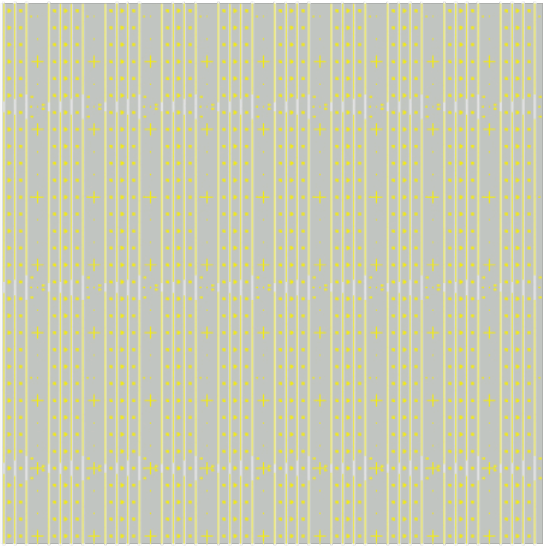
Implanted split contact ICL fabrication



ICL comb

Implanted split contact ICL fabrication

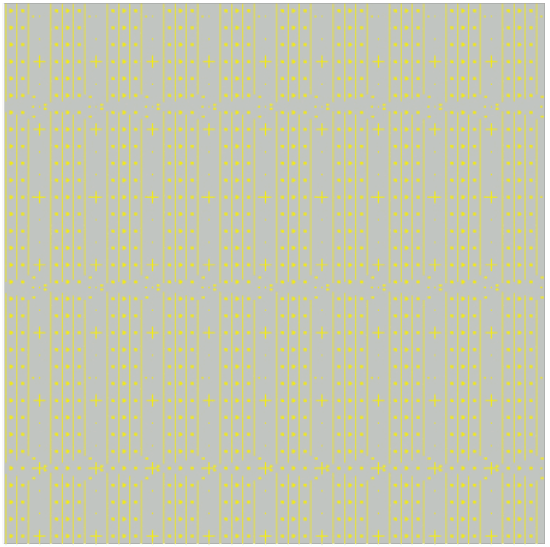
Etch waveguides



ICL comb

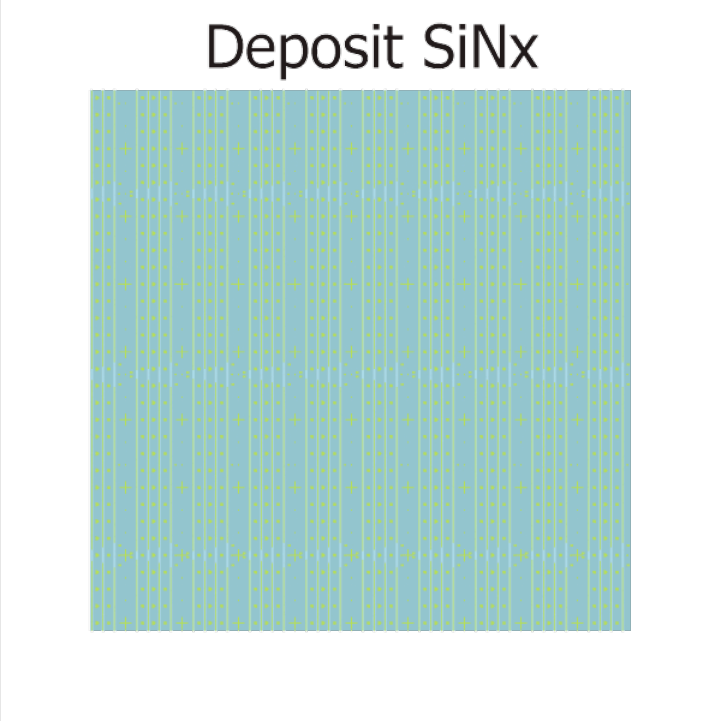
Implanted split contact ICL fabrication

Narrow metal stripes



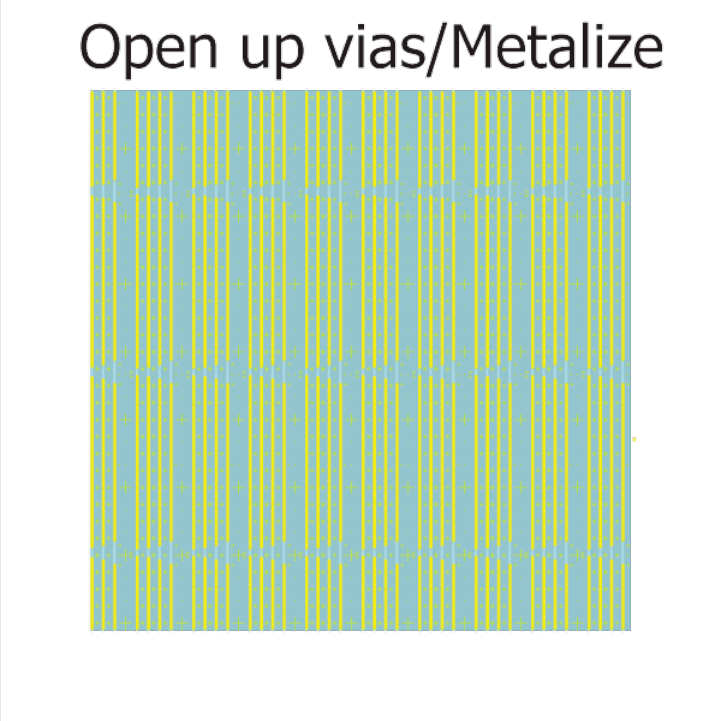
ICL comb

Implanted split contact ICL fabrication



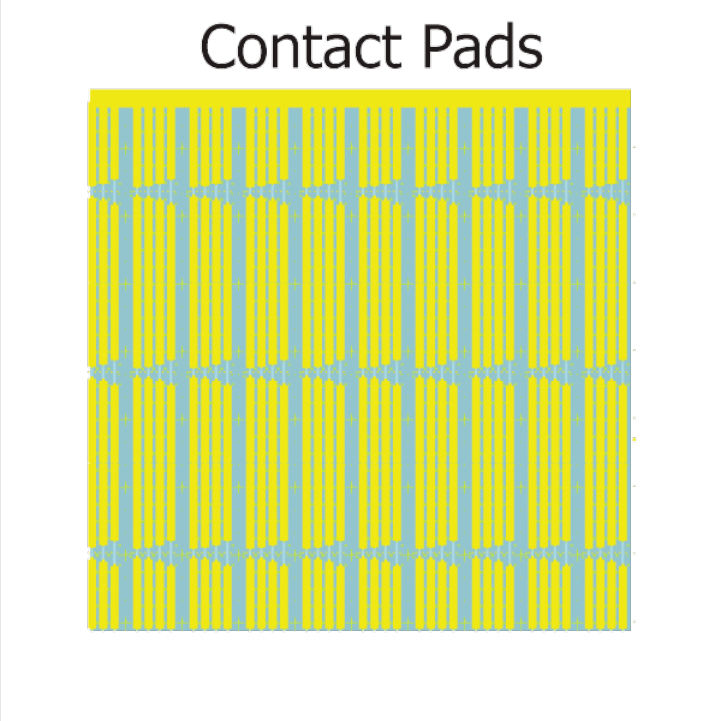
ICL comb

Implanted split contact ICL fabrication



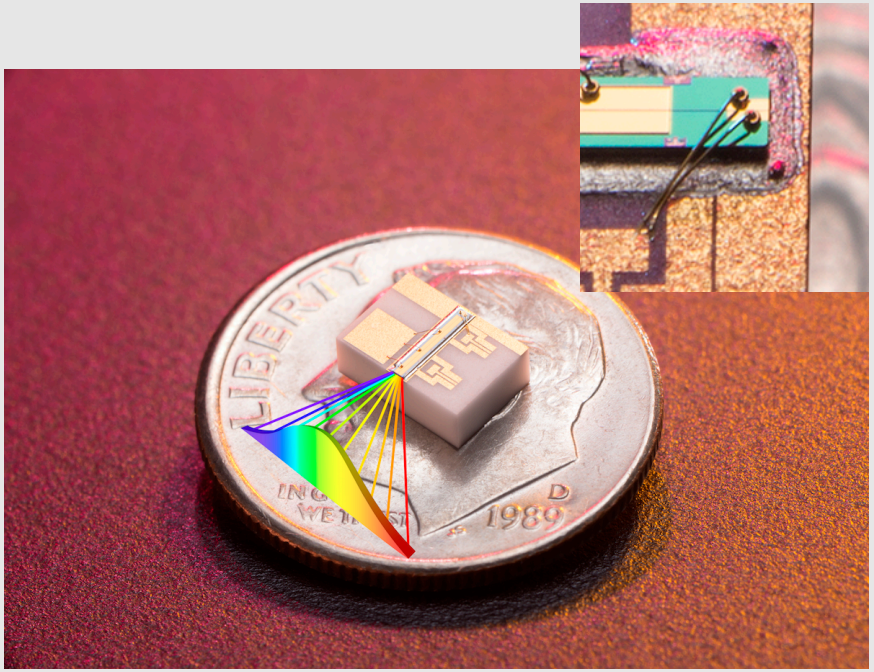
ICL comb

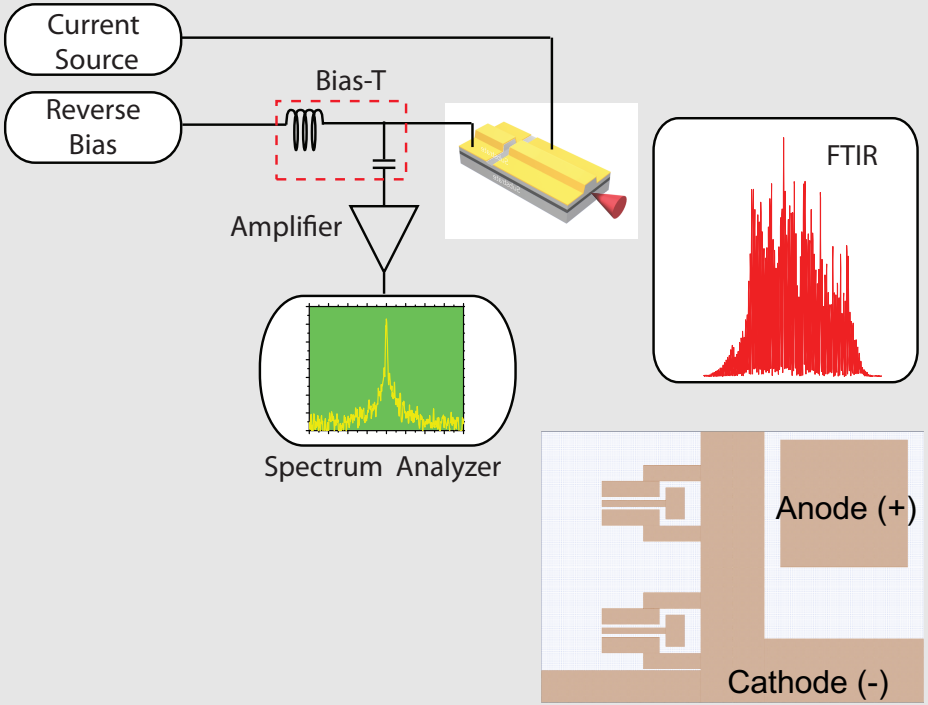
Implanted split contact ICL fabrication



ICL combs

Interband Cascade Mode-locked Lasers

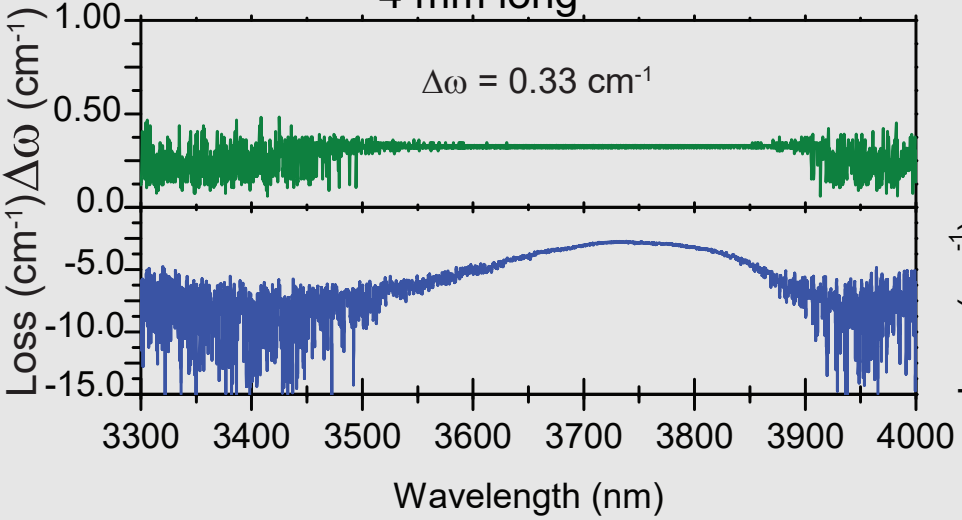




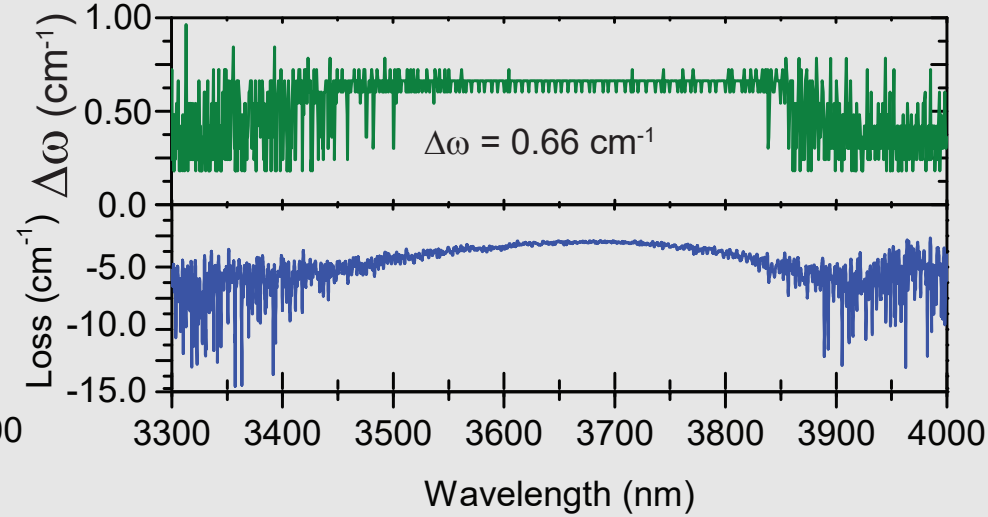
ICL combs

Interband Cascade Mode-locked Lasers

Extracted optical loss (bottom) and mode spacing (top) from a 300μm-400μm device 4 mm long



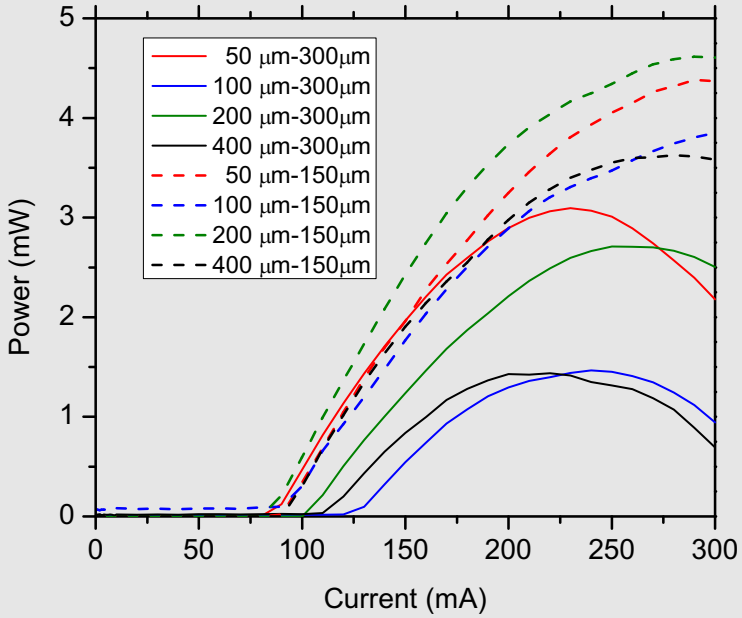
Extracted optical loss (bottom) and mode spacing (top) from a 2mm-long cavity (no SA)



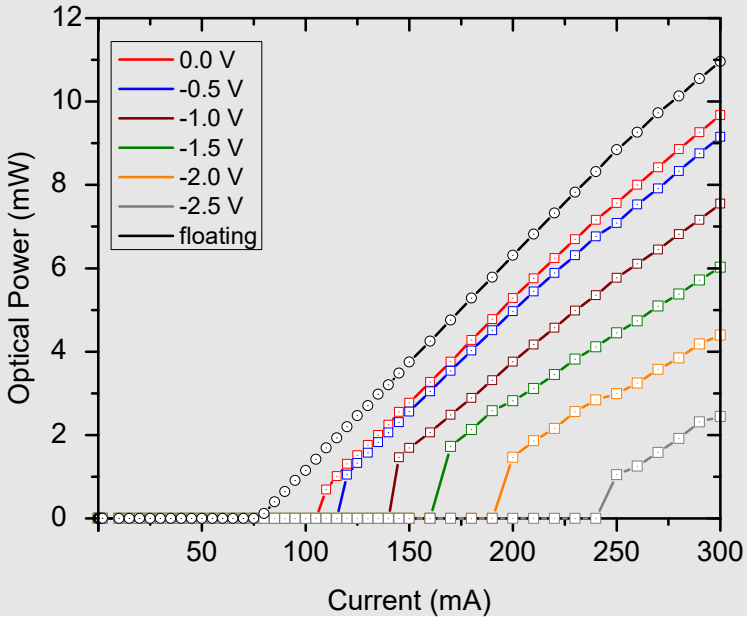
ICL combs

Interband Cascade Mode-locked Lasers

Collected LIVs for devices with 300μm (solid line) 150 μm contact separation (SA is floating)

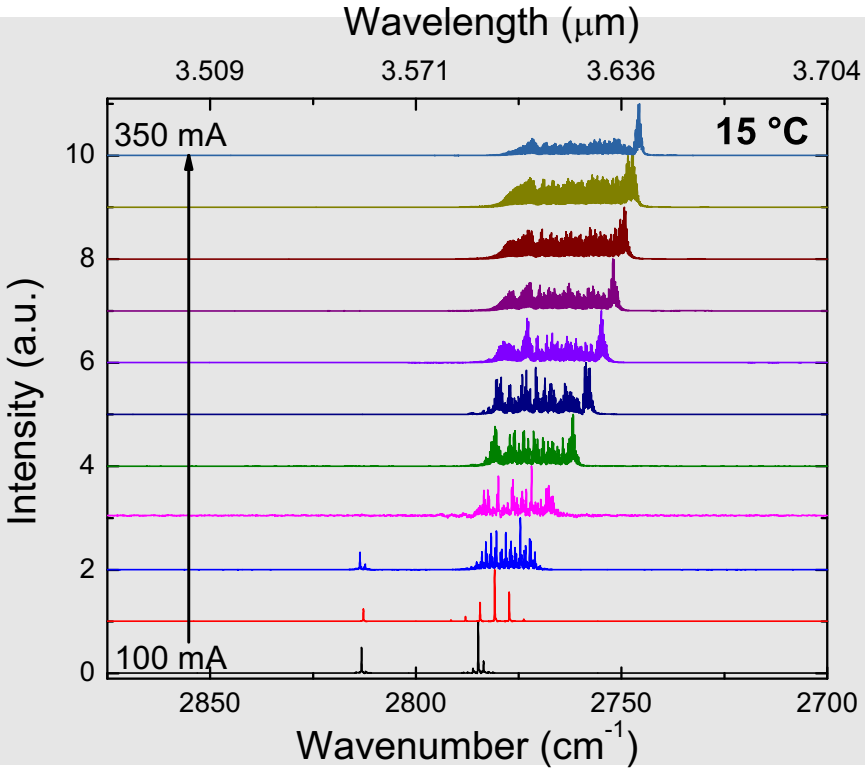


Collected LIVs at 10°C as a function of SA section reverse bias-150μm-200μm device



ICL combs

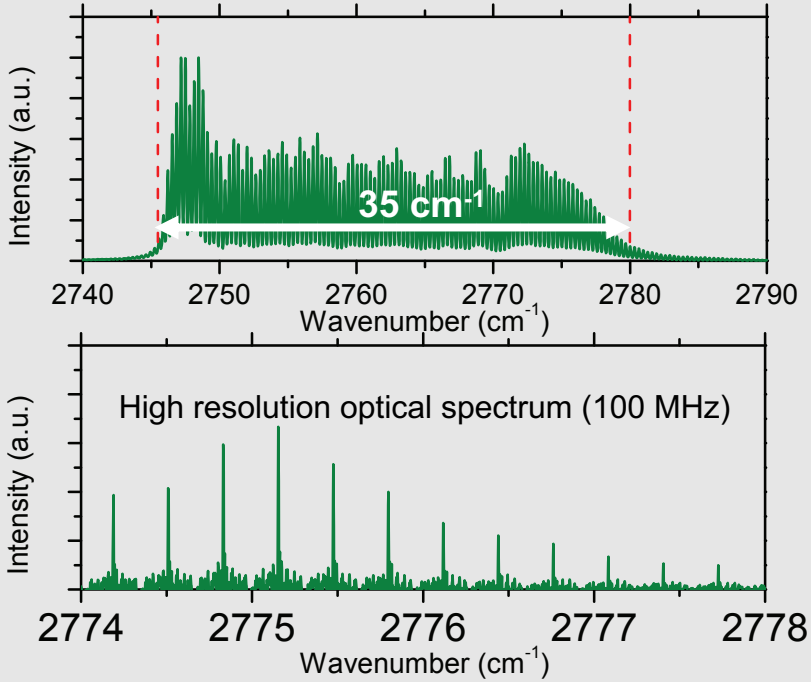
Interband Cascade Mode-locked Lasers



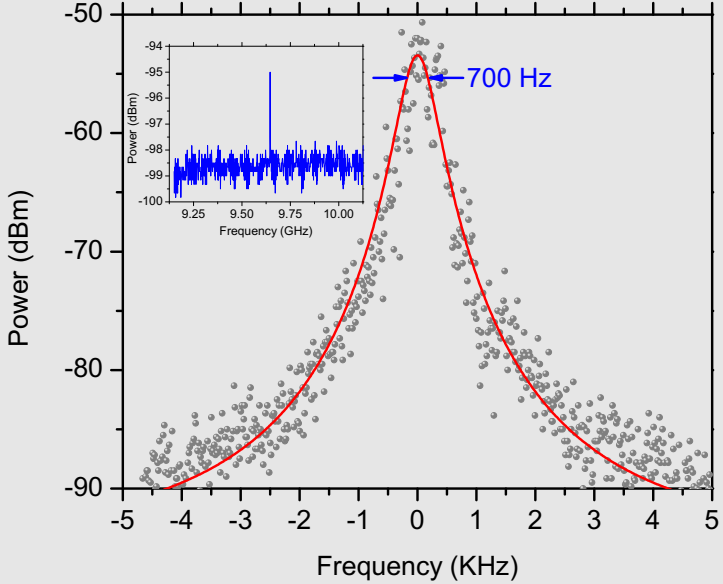
ICL combs

Interband Cascade Mode-locked Lasers

Collected lasing spectra at 15 ºC



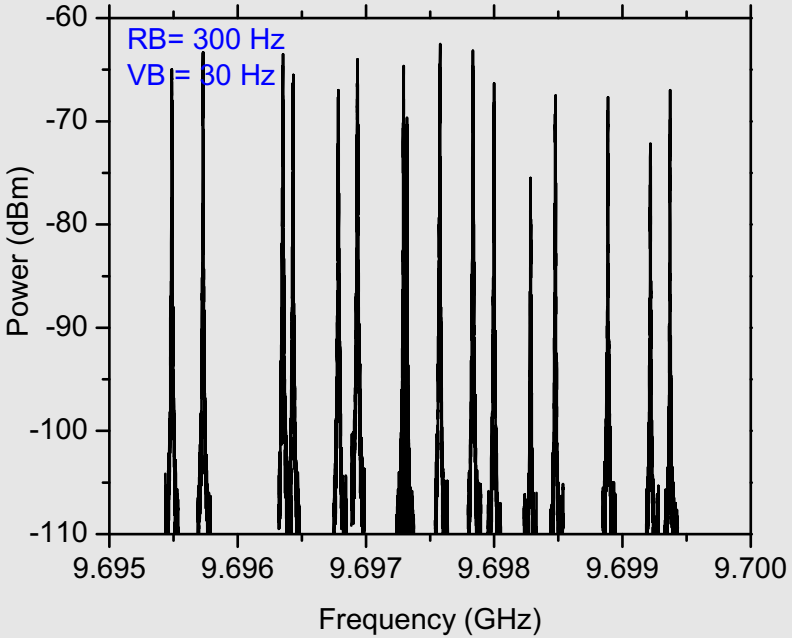
Measured RF beat-note at 9.6 GHz

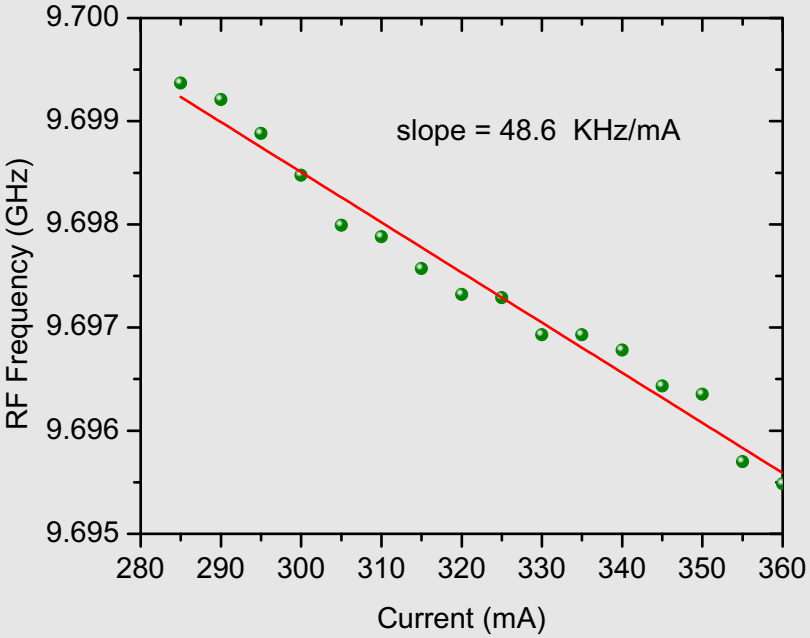


A linewidth of ~ 700Hz was extracted

ICL combs

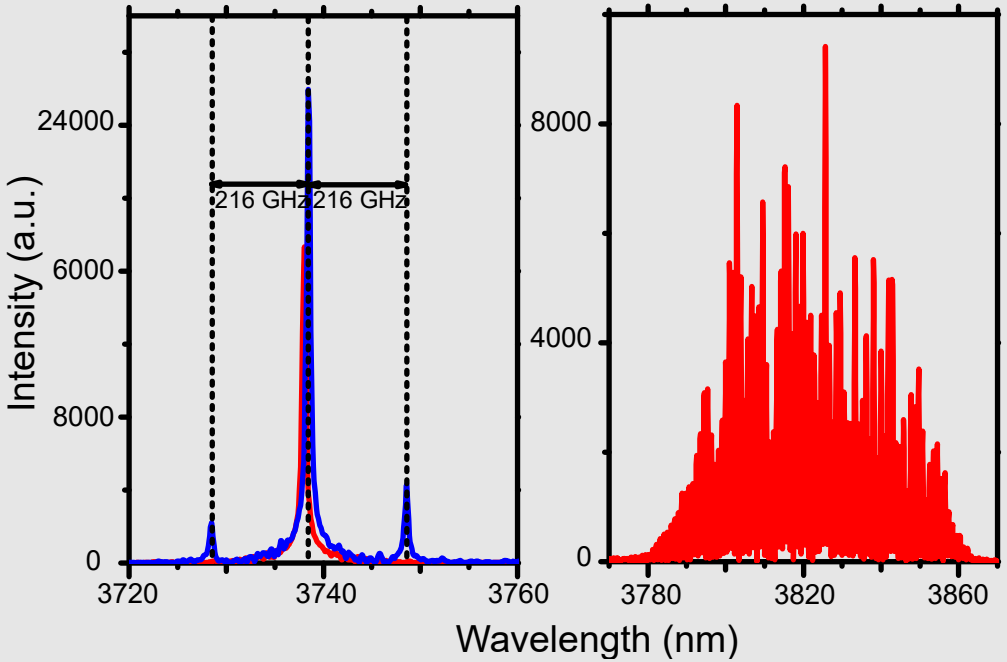
Interband Cascade Mode-locked Lasers





ICL combs

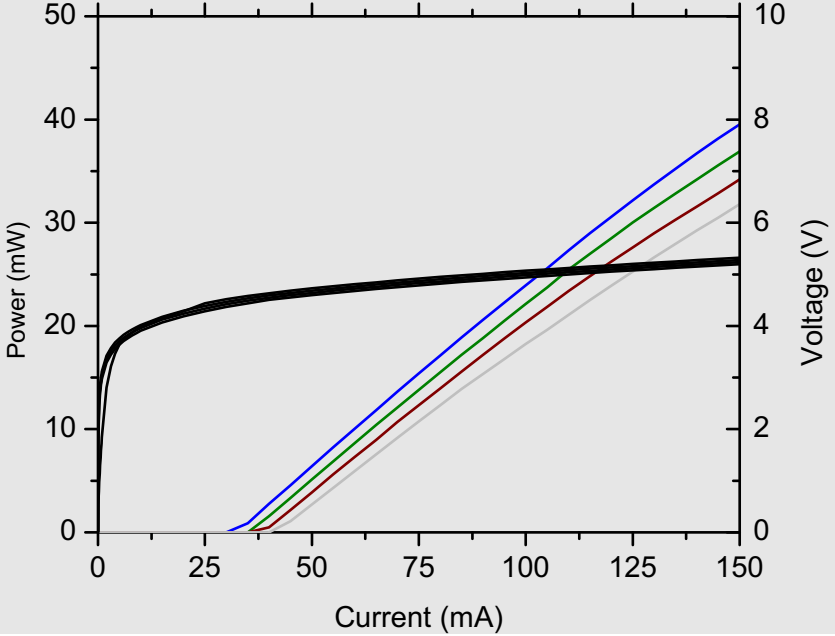
ICL FP devices



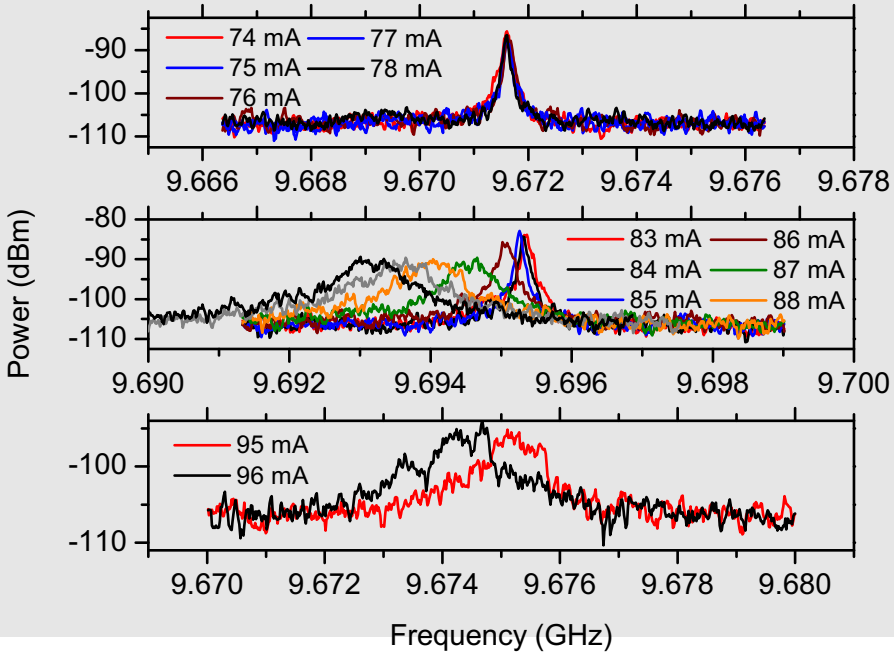
ICL combs

ICL FP devices

Collected output power (left) and junction voltage (right)

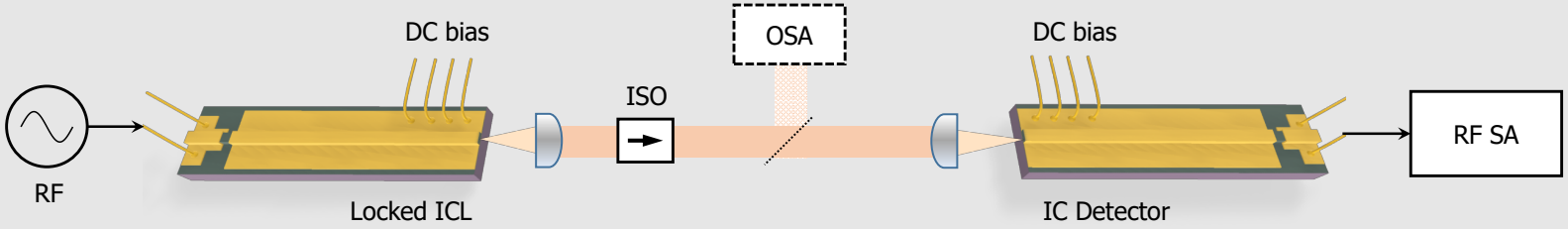


Collected RF beat-notes

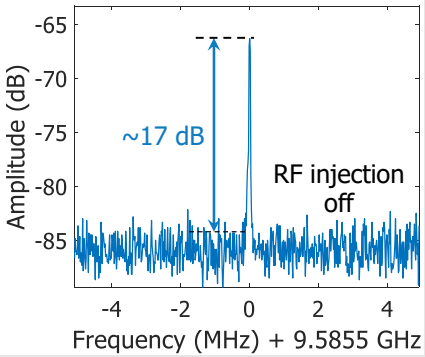


ICL combs

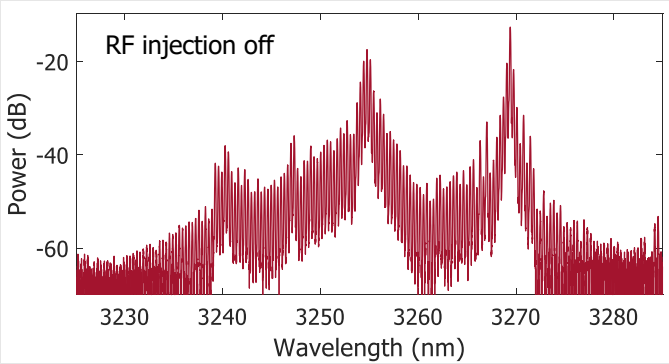
Injection locking of ICLs



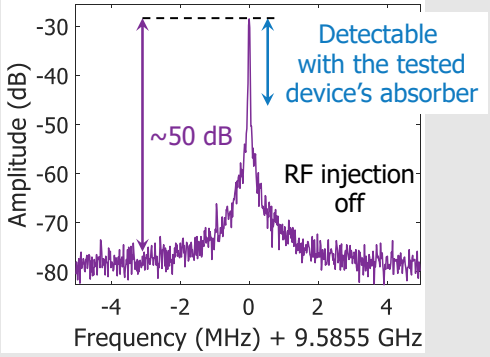
RF Tone detected electrically from the device under test



Optical spectrum of the device under test

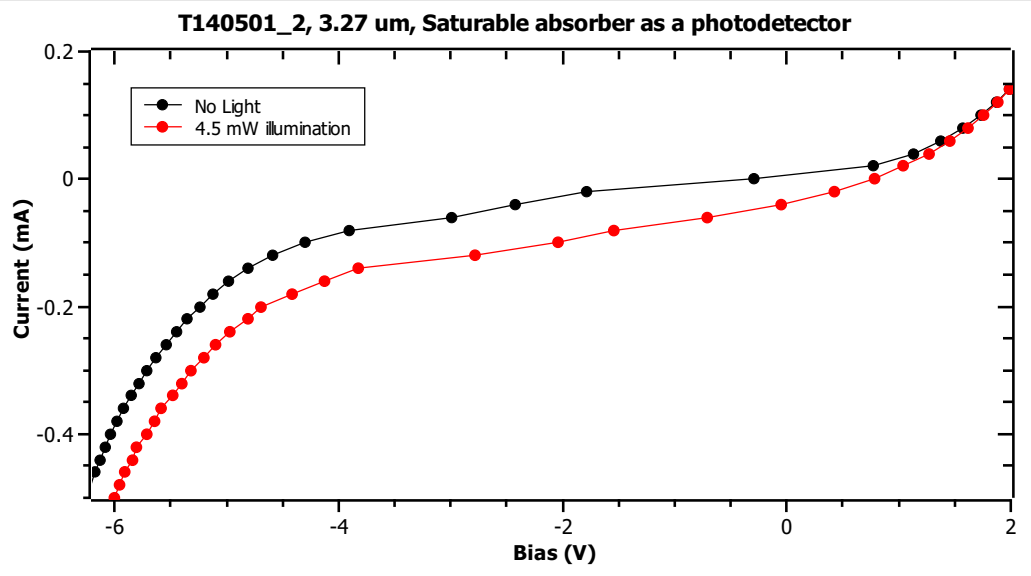


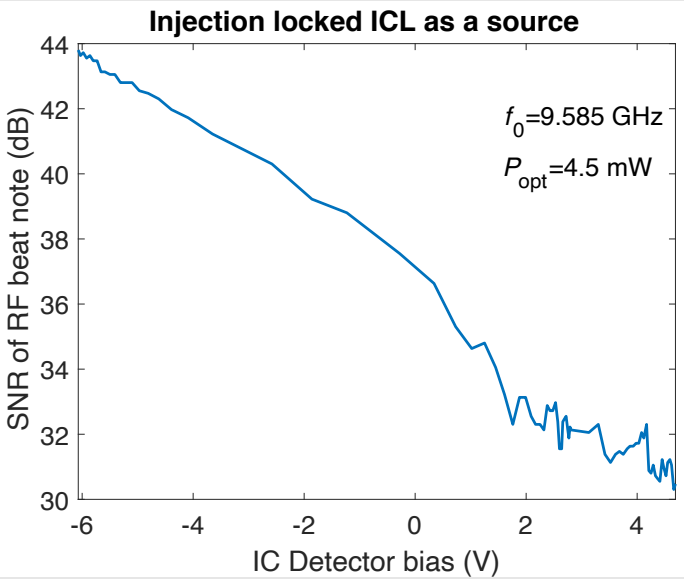
RF Tone detected optically using a separate ICL biased close to threshold



ICL combs

Injection locking of ICLs

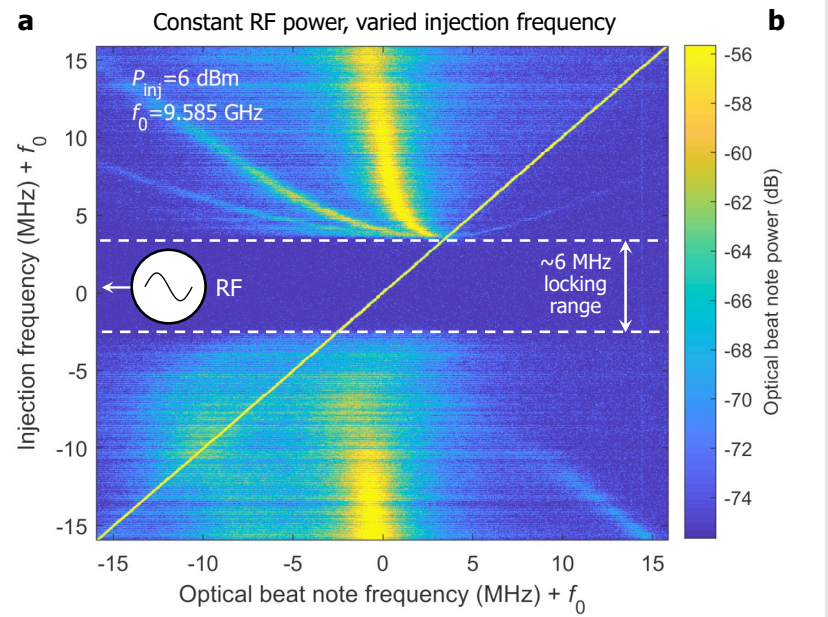


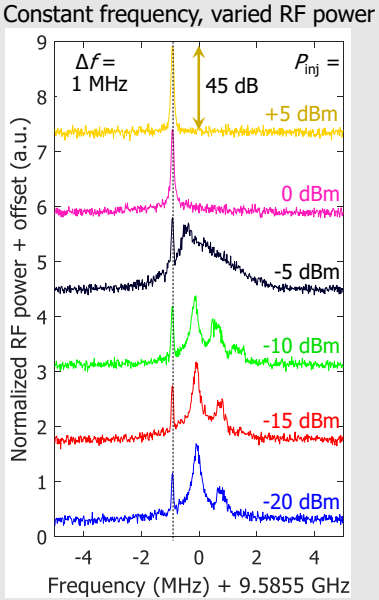


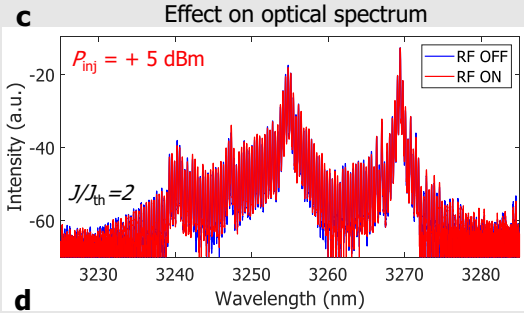
ICL combs

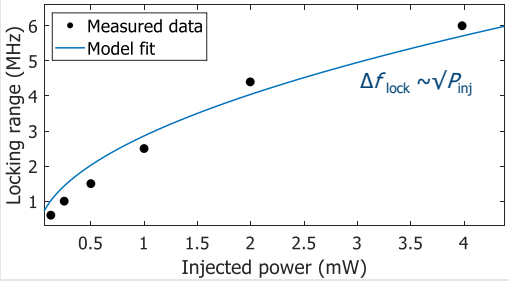
Injection locking of ICLs

RF injection of ICL frequency combs





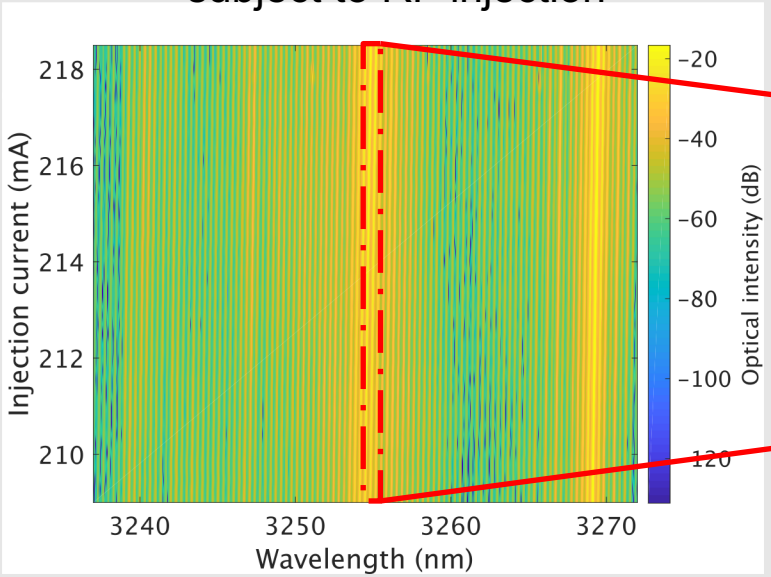




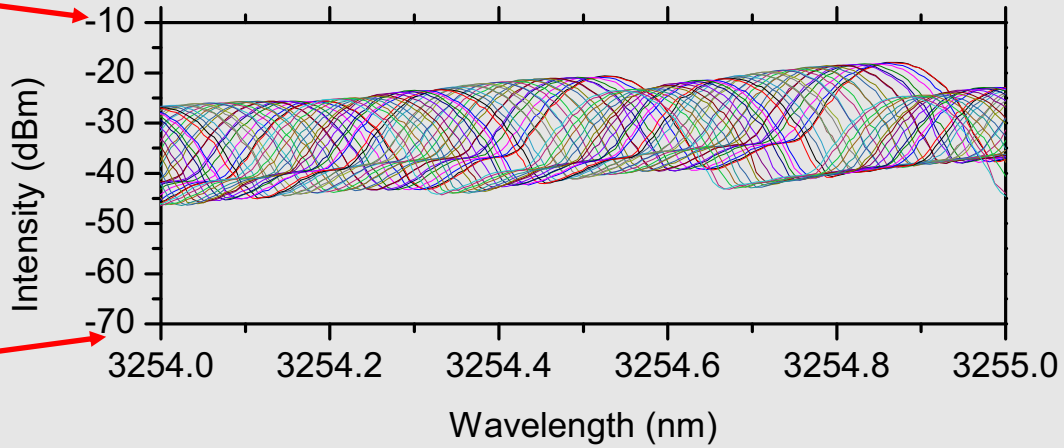
ICL combs

Injection locking of ICLs

Evolution of optical spectrum subject to RF injection

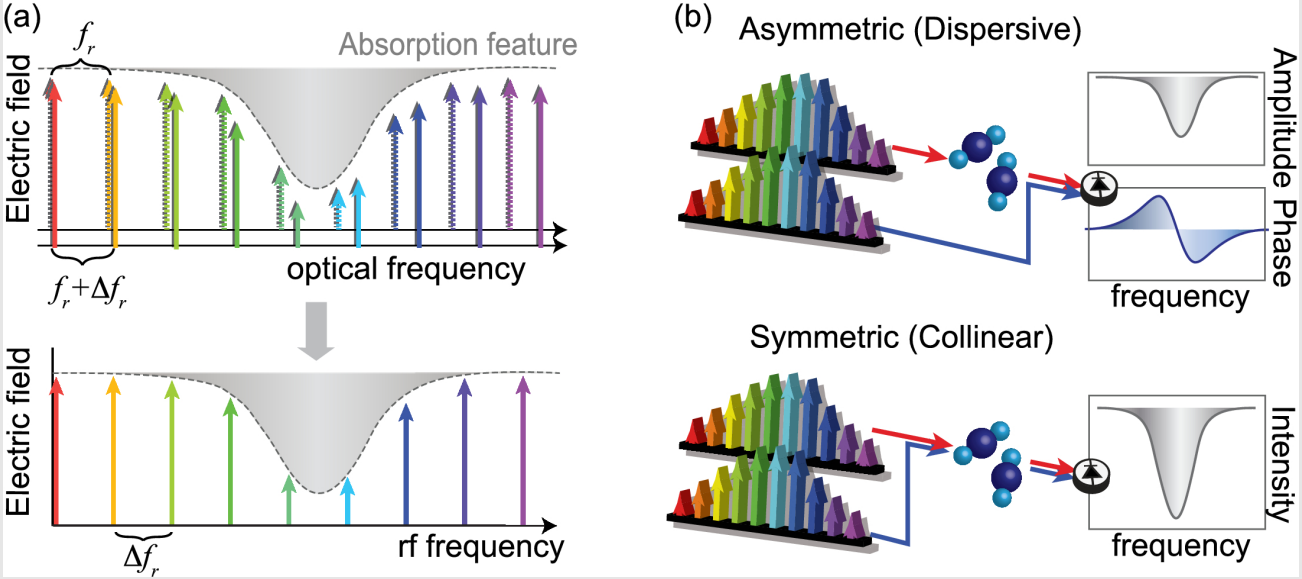


Gapless sampling of optical spectrum



Comb Spectrometers

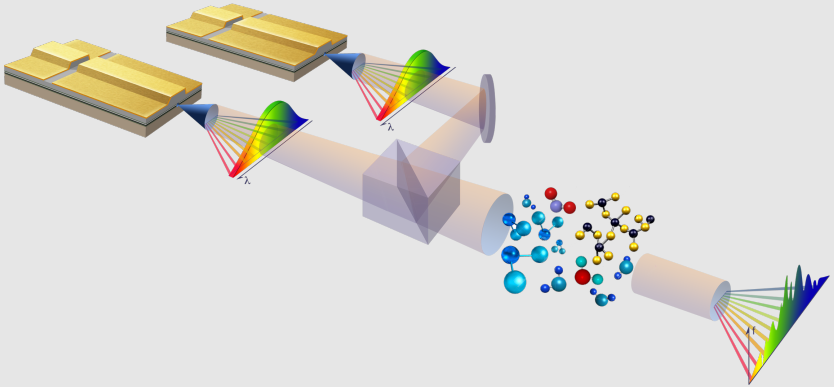
Dual frequency comb spectroscopy



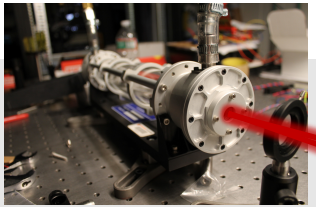
Ian Coddington, et al, Optica 3, 414-426 (2016)

Comb Spectrometers

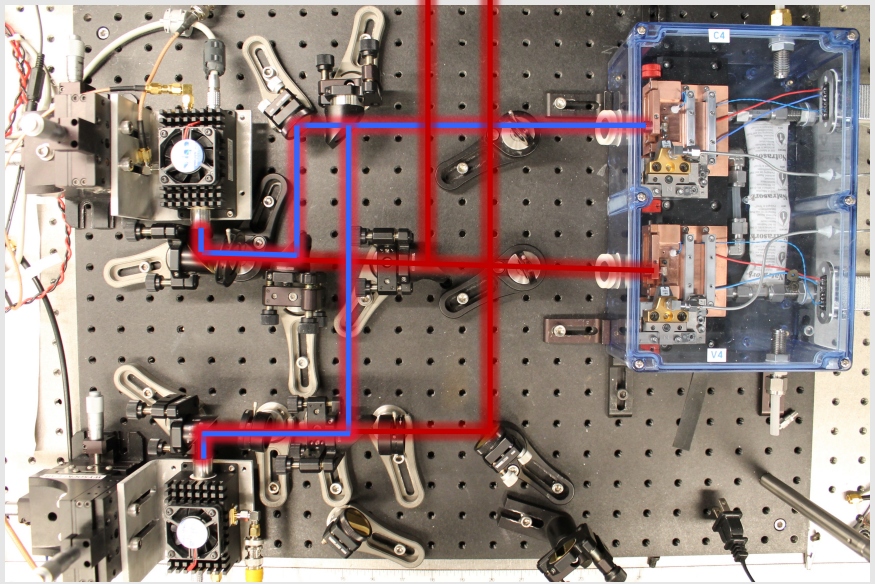
Dual frequency comb spectroscopy



Multipass cell,
76 m

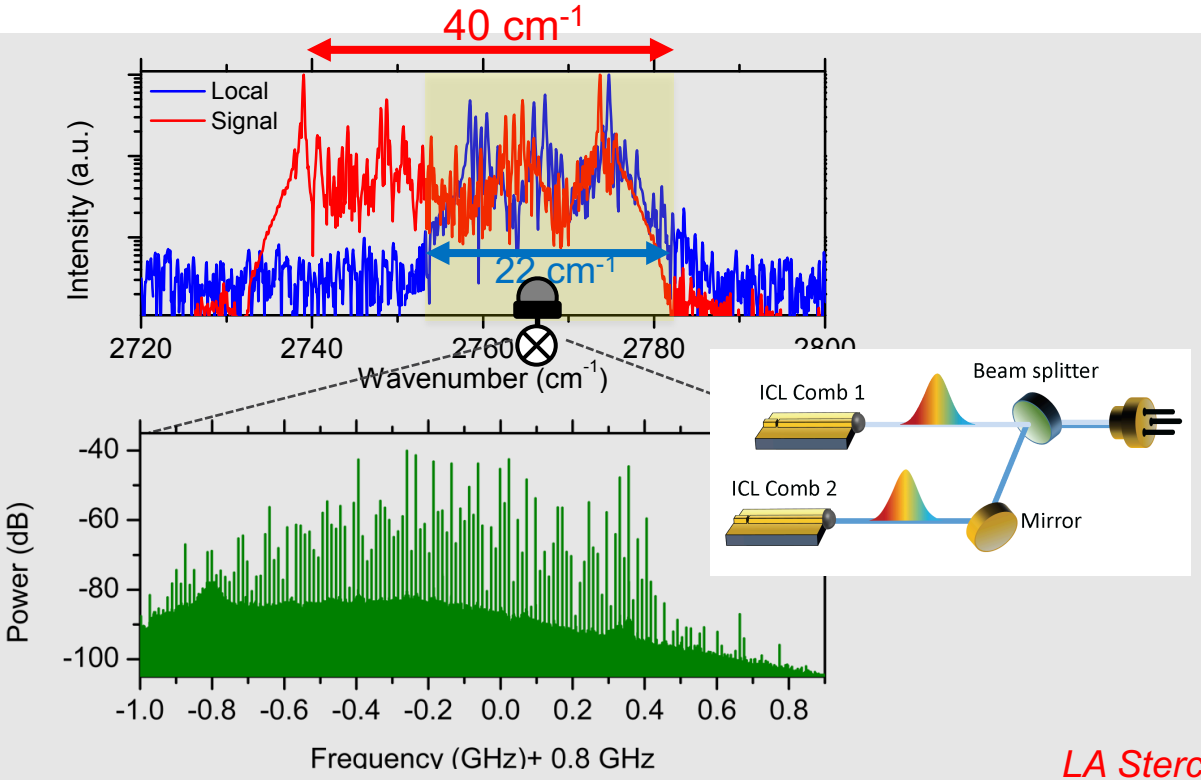


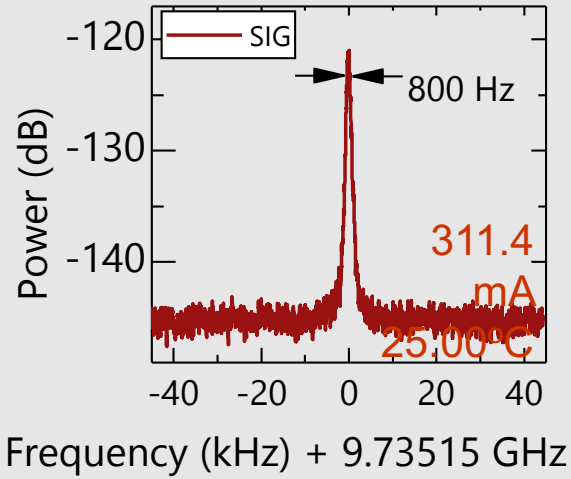
Optical breadboard
24”x 18”



Comb Spectrometers

Dual frequency comb spectroscopy

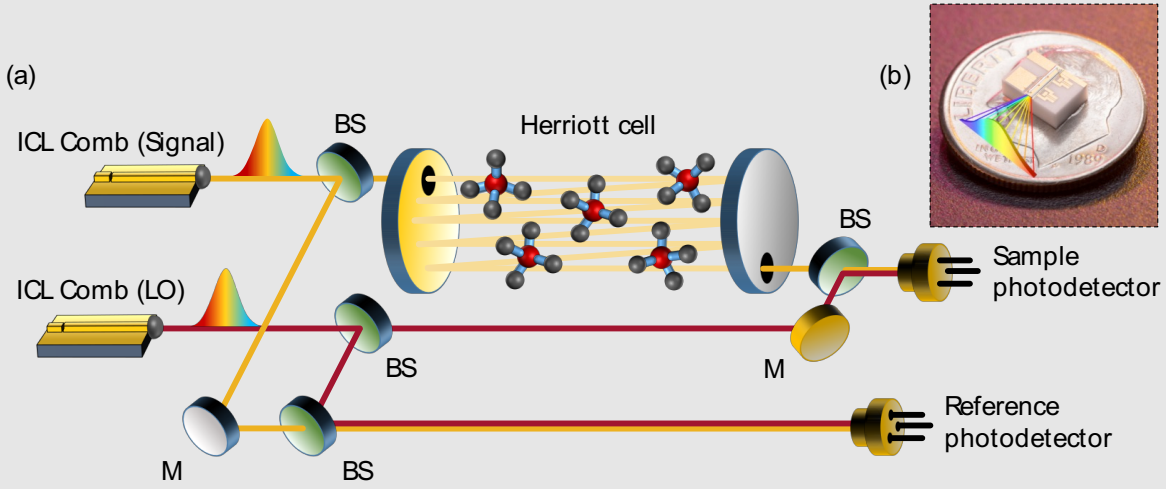


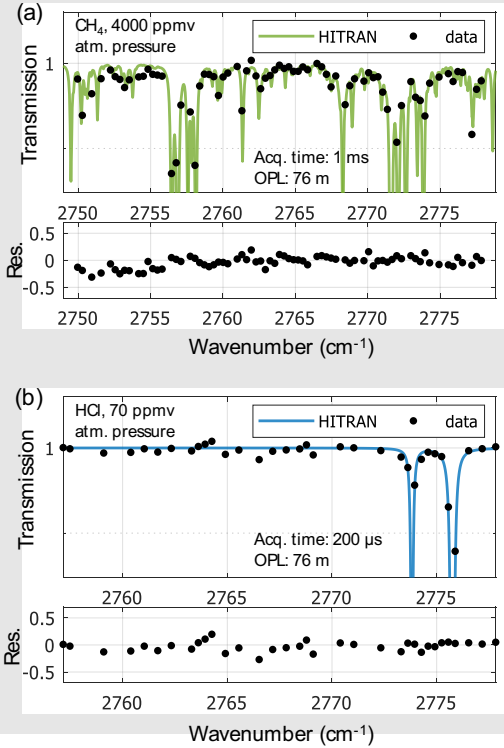


LA Sterczewski et al., Optics Letters 44 (2019)

Comb Spectrometers

Dual frequency comb spectroscopy



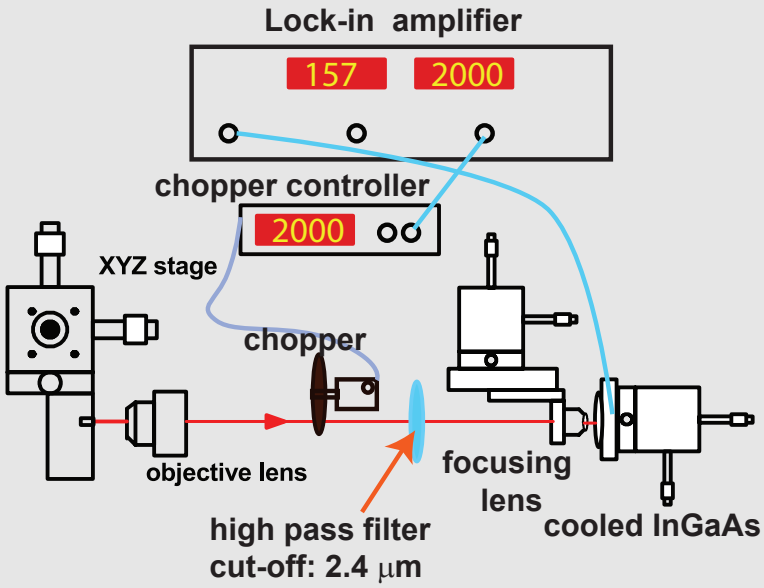


LA Sterczewski et al., Optics Letters 44 (2019)

Interband Cascade devices

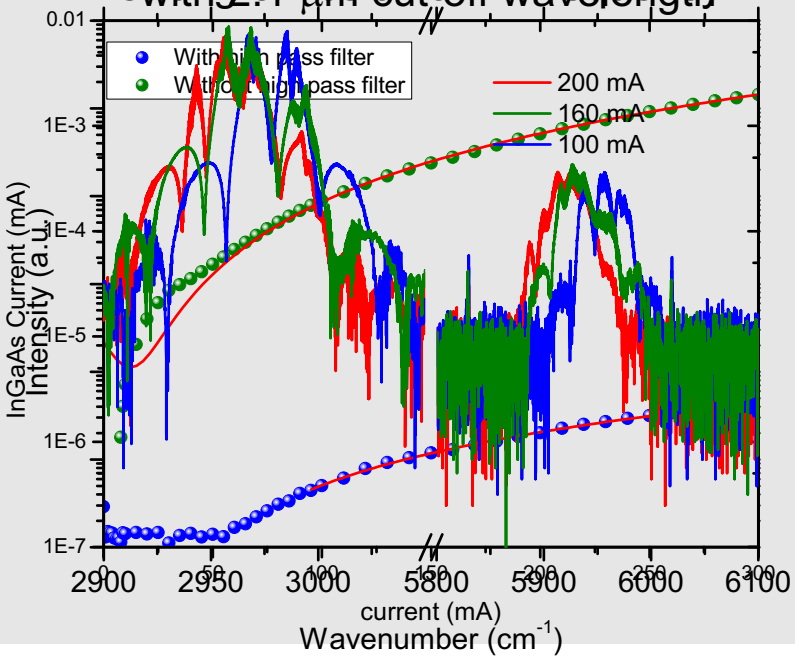
Second harmonic generation

Two photon absorption measurement setup



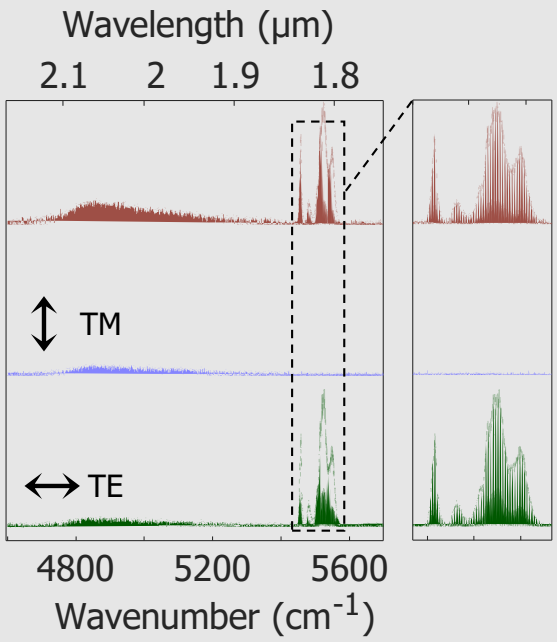
Measured optical spectrum indicates strong emission at 2x frequency

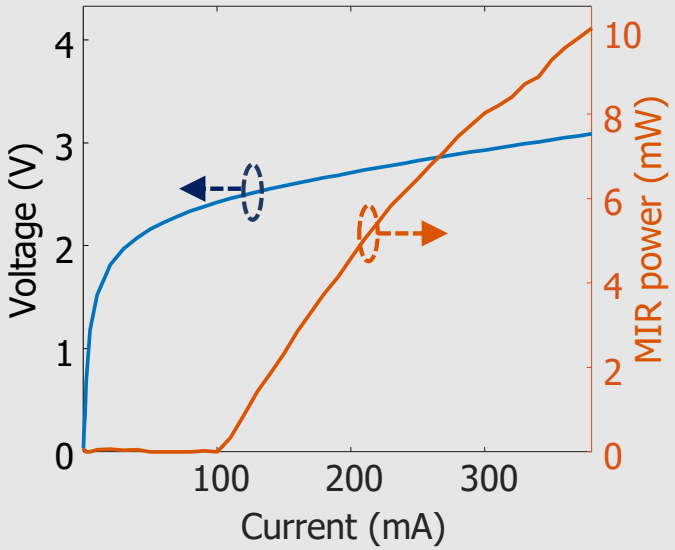
Measured photo-current on a detector with 2.1 μm cut-off wavelength

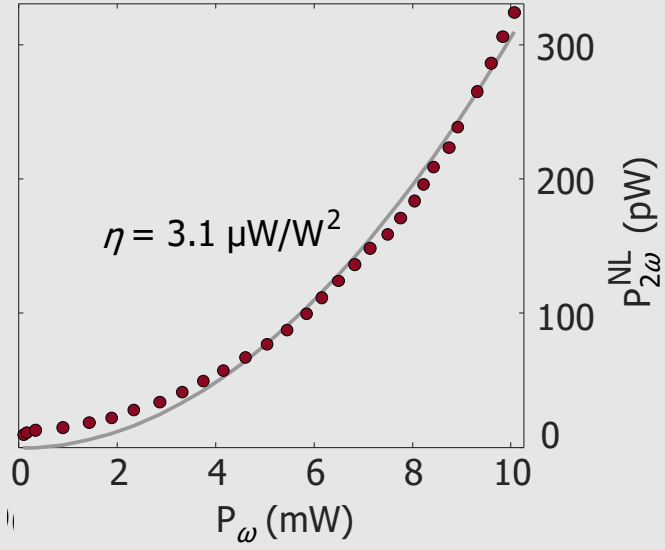


Interband Cascade devices

Second harmonic generation



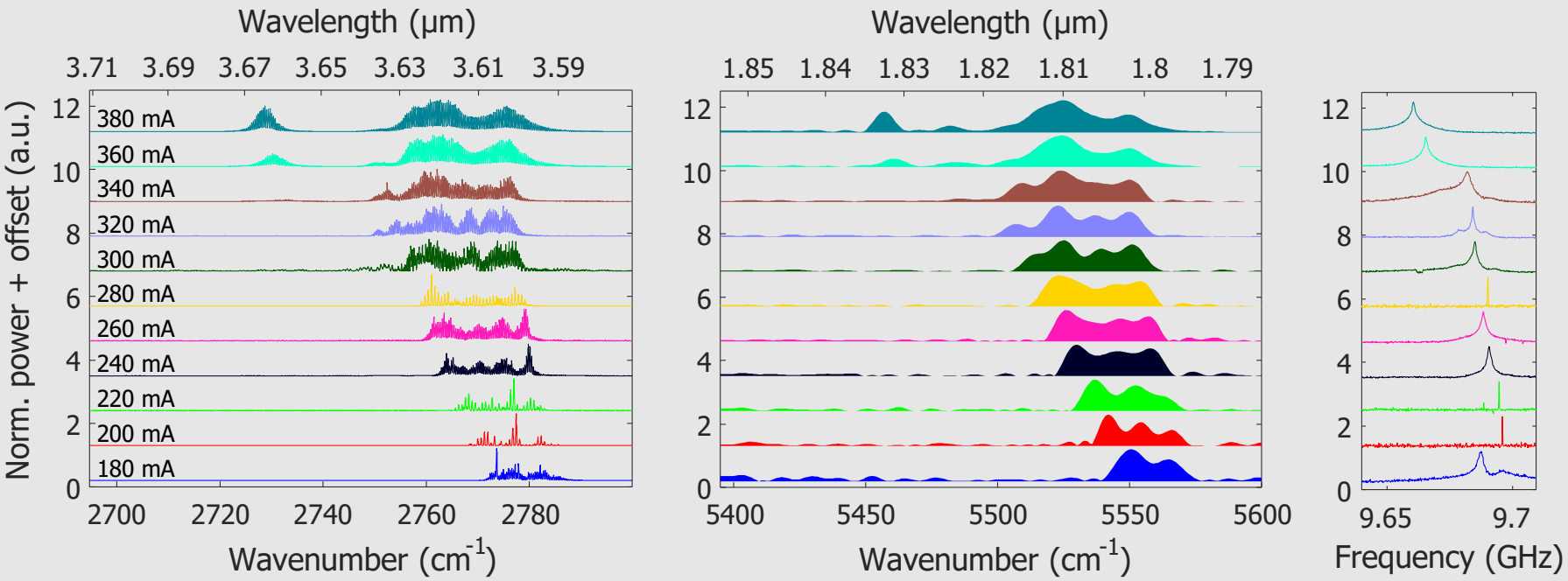




Interband Cascade devices

Second harmonic generation

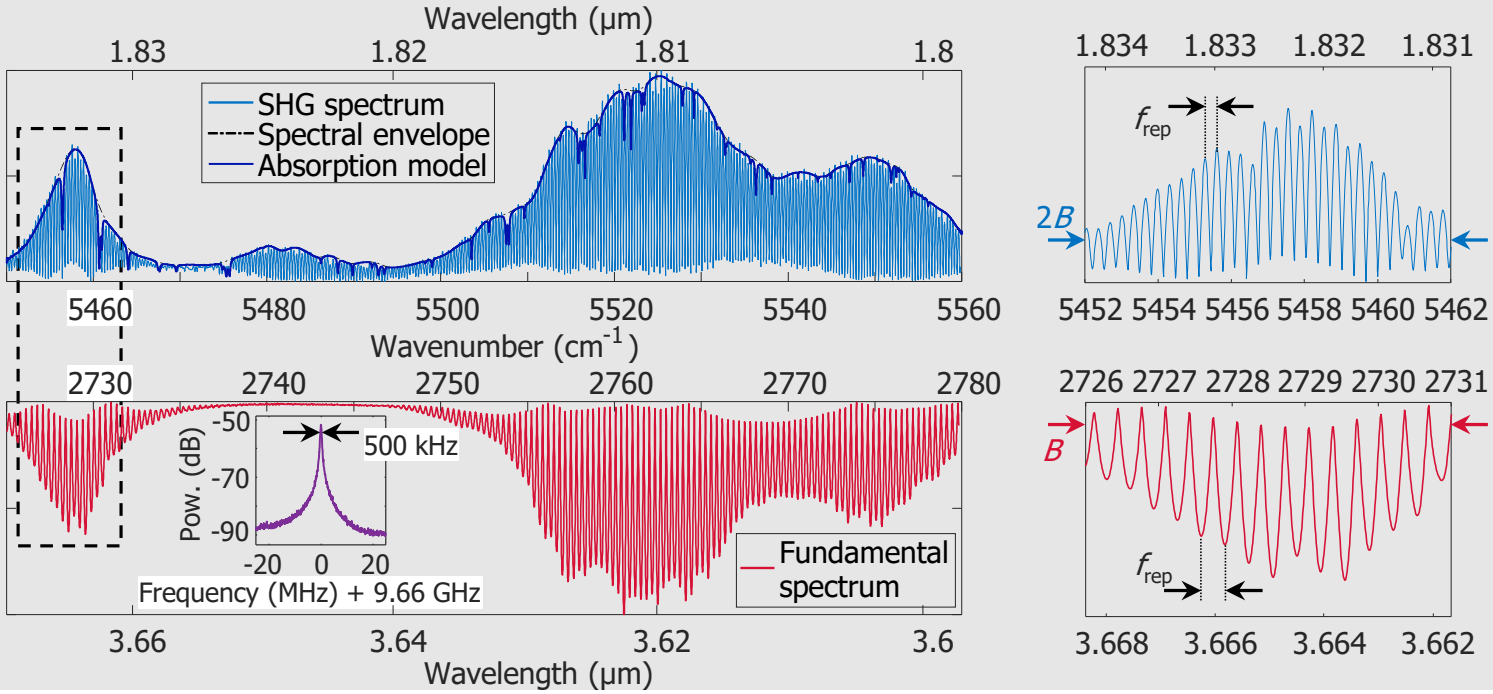
Evolution of the optical (MIR: left, NIR: middle) and radio frequency (right) spectra



Interband Cascade devices

Second harmonic generation

Preservation of the mode spacing and water vapor absorption in the near-IR



Conclusion