SAND2012-3928C
SAND2012-3928 C

Integrated THz Quantum Cascade Laser Technology

Mike C. Wanke

Sandia National Labs

SUNY Buffalo - April 13, 2012

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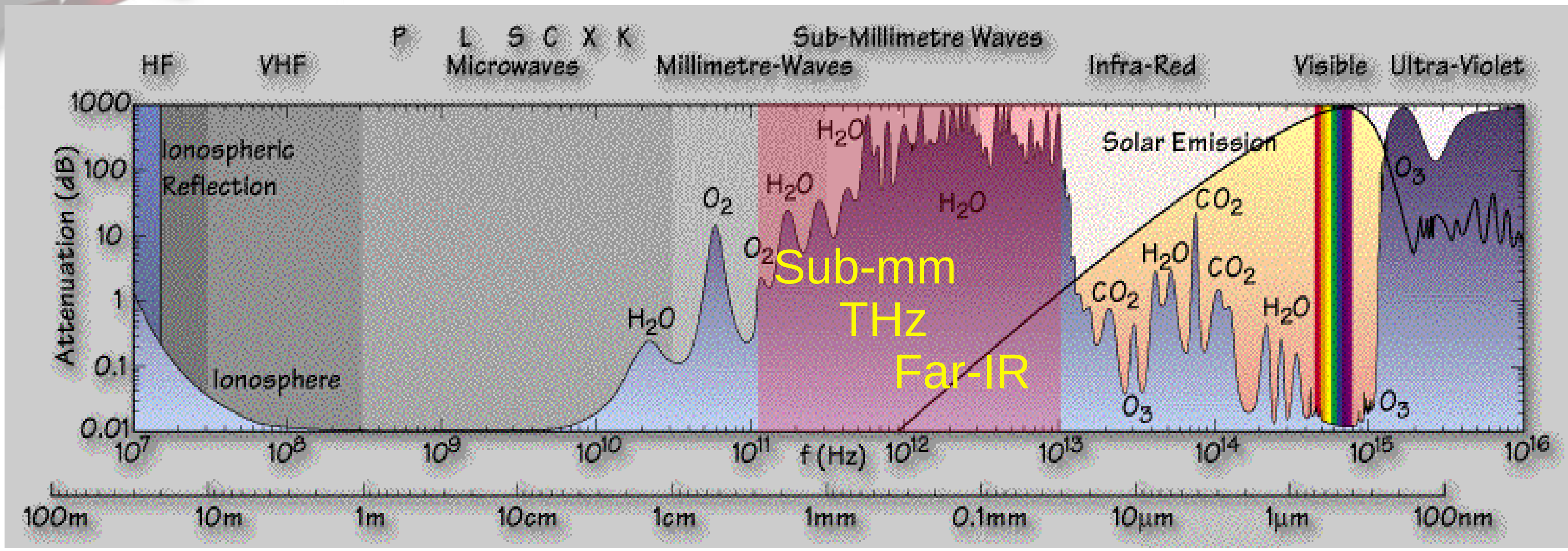
Outline

- **My definitions of “THz” and “THz gap”**

- **THz integrated circuits**
  - why replace quasi-optics
  - rectangular waveguides
  - integrated transceivers

- **What transceivers can show us about QCLs**
  - current tuning
  - feedback

The THz Spectrum



Attenuation in dB/km horizontal at sea level, 20° C, 70% r.h. (NASA)

Electronics

Undeveloped Regime

Photonics

Between Microwave and Infrared

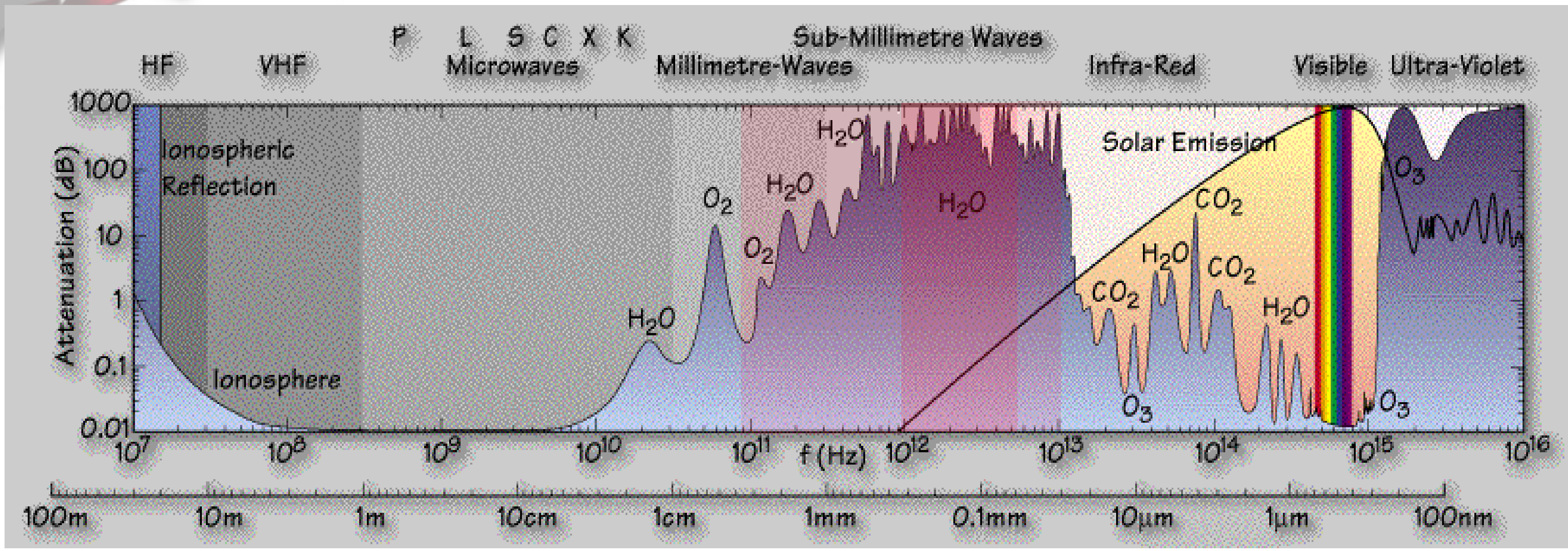
ν : $10^{11} – 10^{13}$ Hz

λ : 3000 - 30 µm

k : 3.3 - 333 cm^{-1}

E : 0.4 – 40 meV

The THz Spectrum



Attenuation in dB/km horizontal at sea level, 20° C, 70% r.h. (NASA)

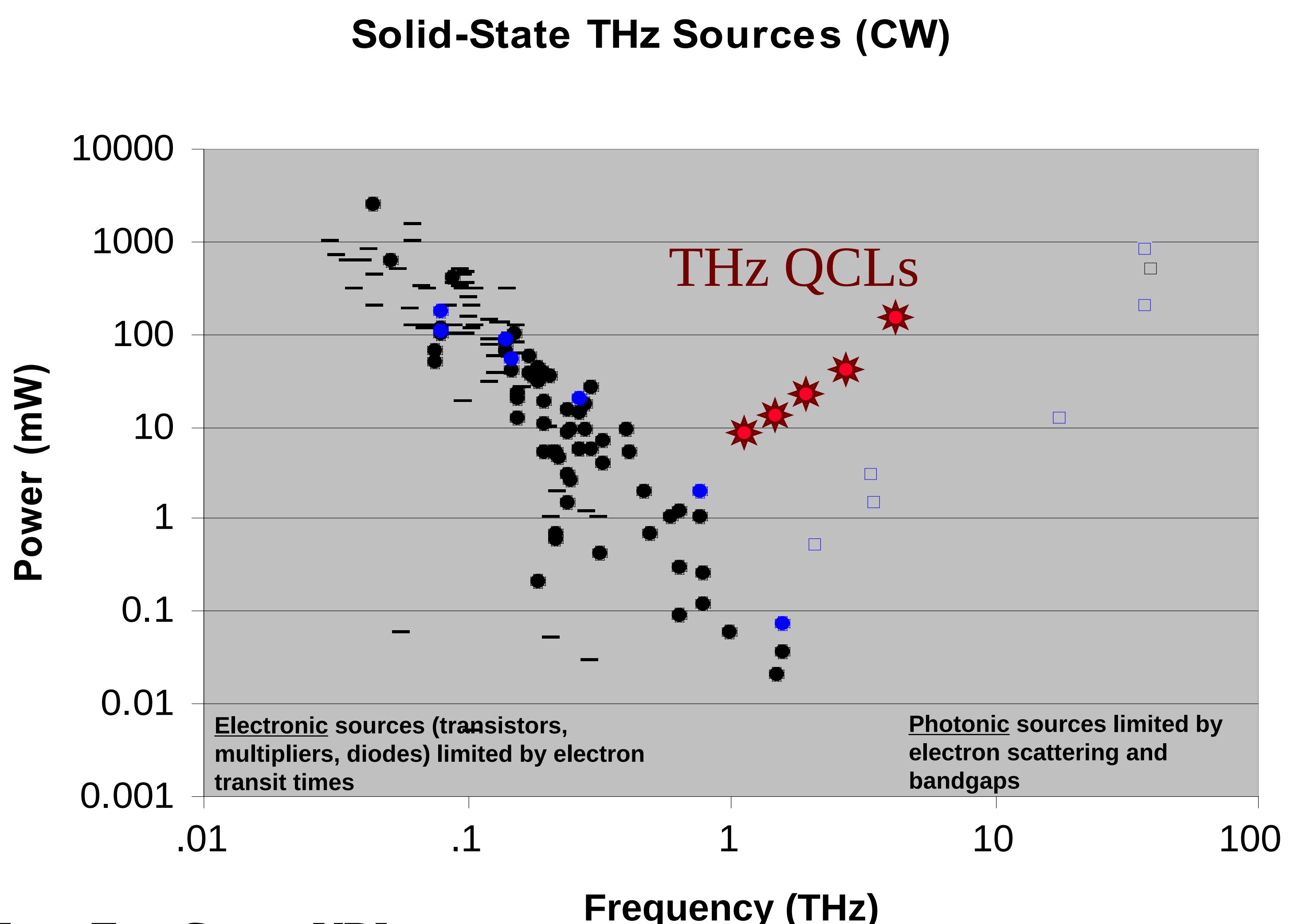
This Talk

<u>QCLs</u>

ν : 1 - 5 THz

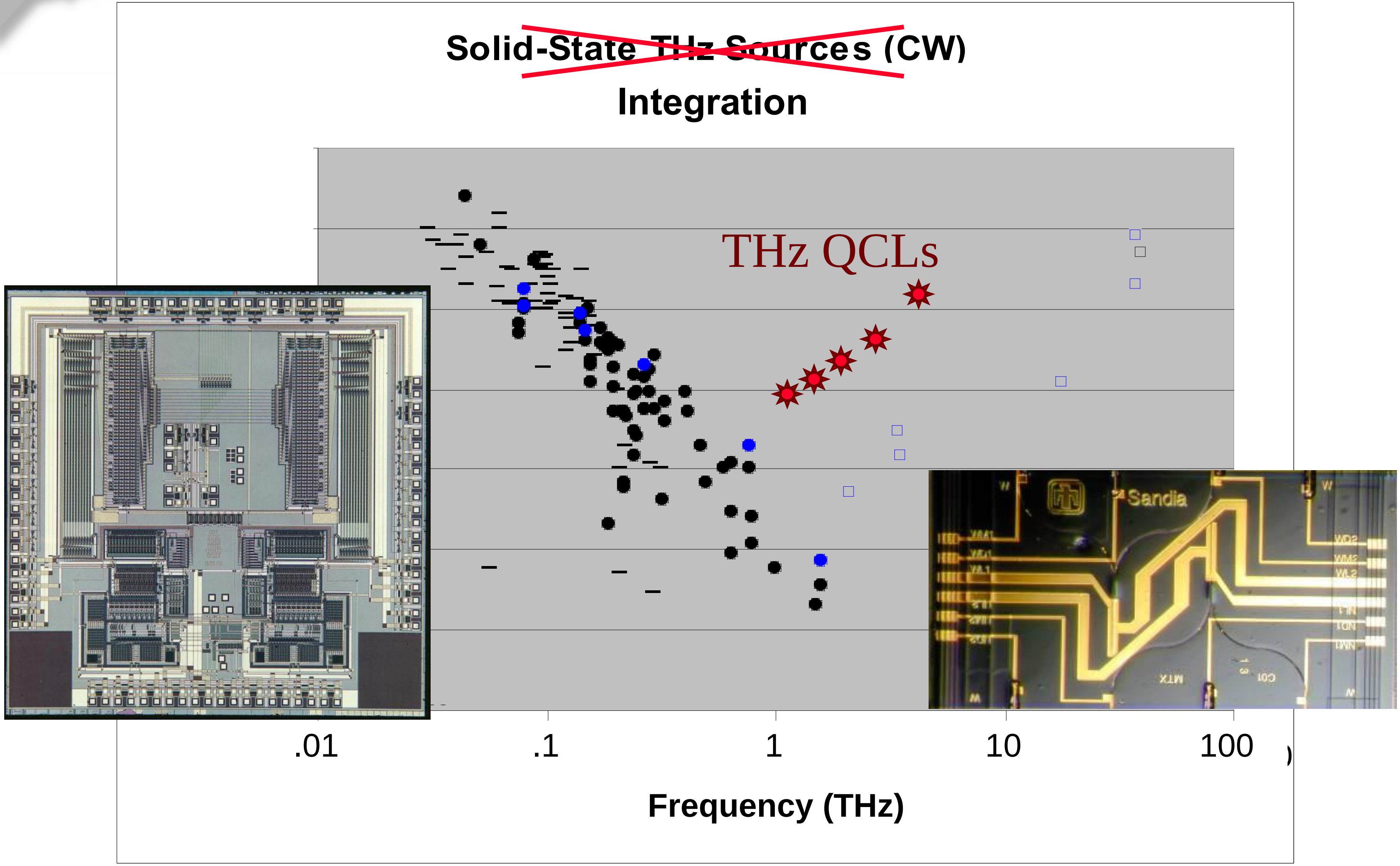
λ : 300 - 60 µm

The "Shrinking" THz Gap



From Tom Crowe, VDI

The THz Gap



~~Solid-State THz Sources~~ (CW)
Integration
THz QCLs
Sandia
.01
.1
1
10
100
Frequency (THz)

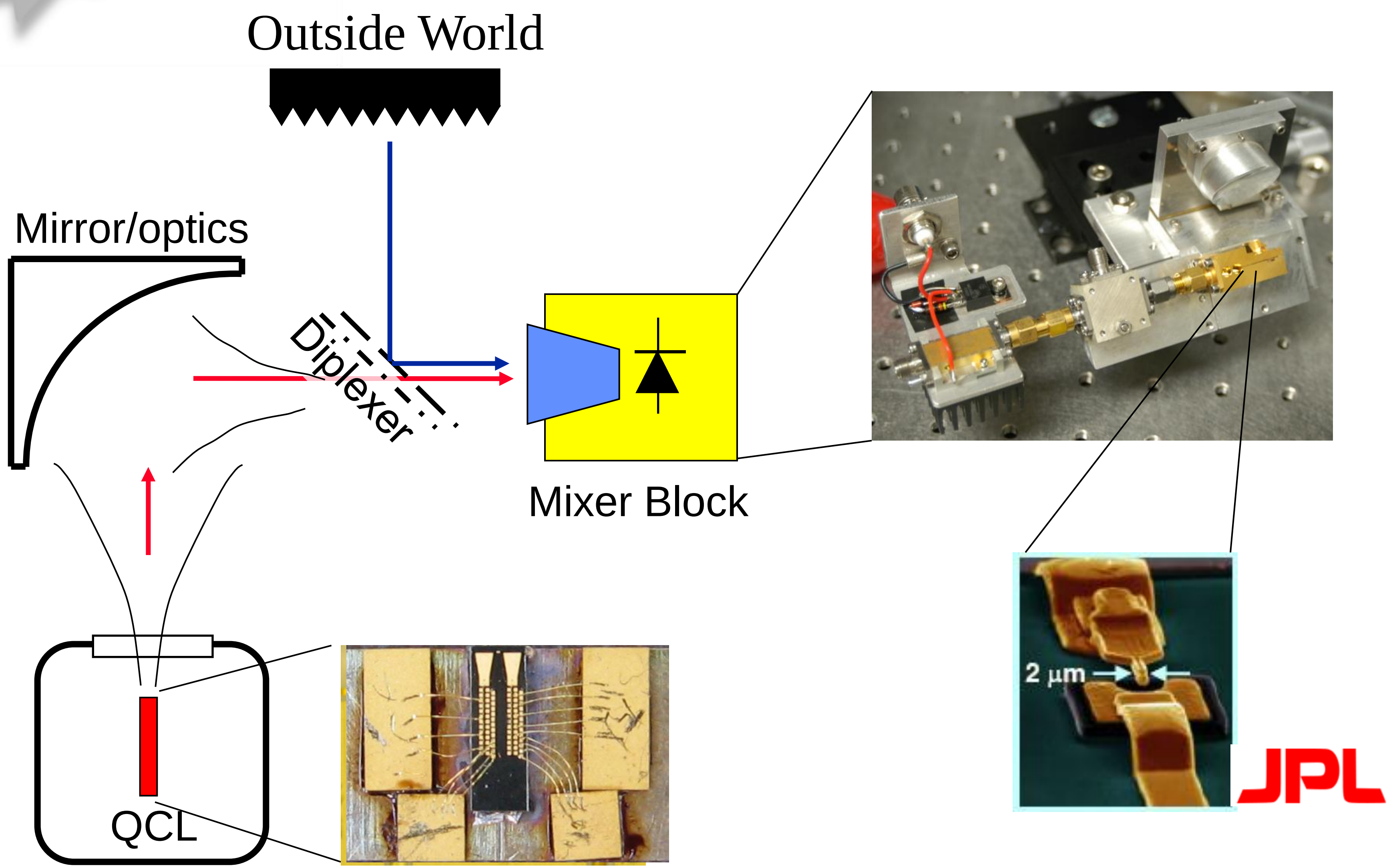
Outline

- My definitions of "THz" and "THz gap"

- **THz integrated circuits**
  - starting simple – heterodyne receiver
  - why replace quasi-optics
  - rectangular waveguides
  - integrated transceivers

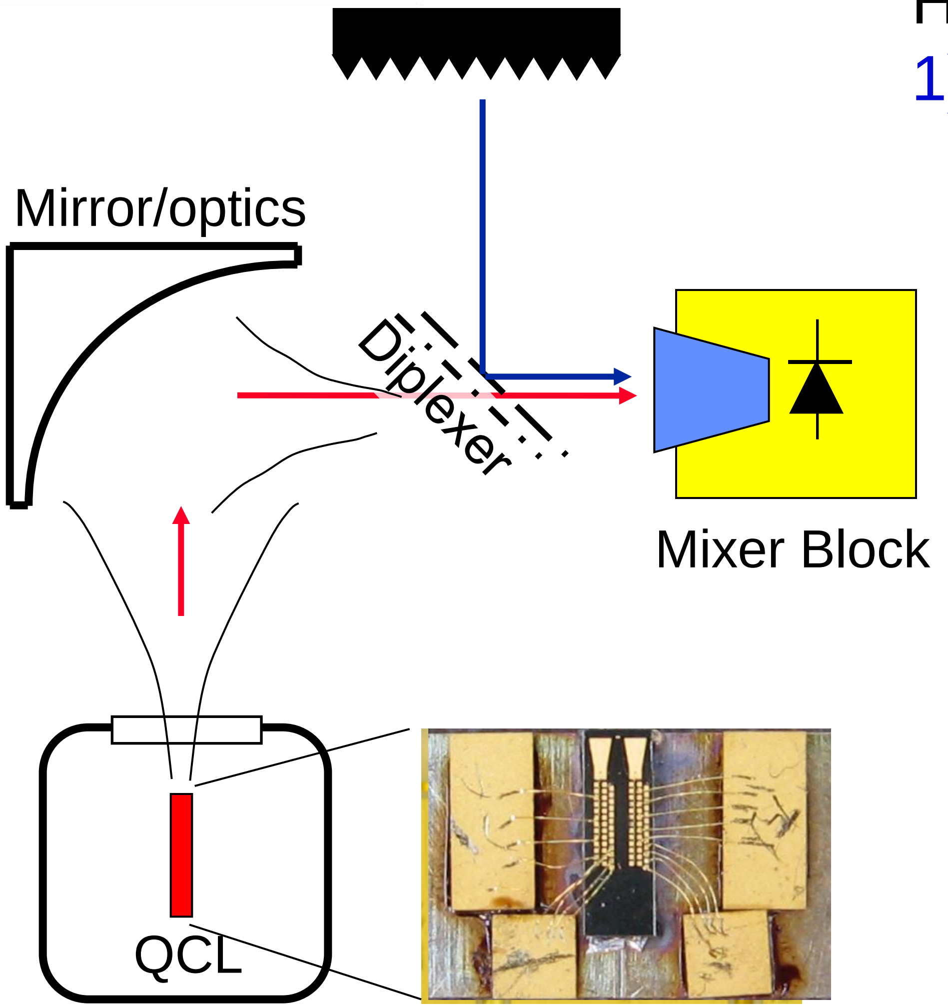
- What transceivers can show us about QCLs

Simple THz system: THz receiver



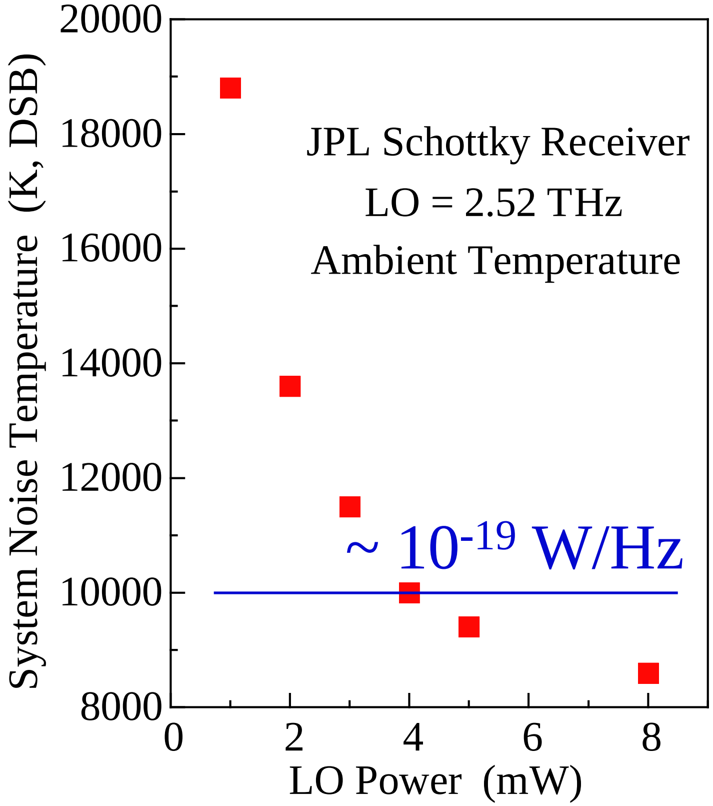
$$P \propto E_1E_2\cos(\omega_1-\omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1+\omega_2)$$

Coherent Detector: THz receiver



Heterodyne receivers enable:

1) high sensitivity detection



$$P \propto E_1E_2\cos(\omega_1-\omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1+\omega_2)$$

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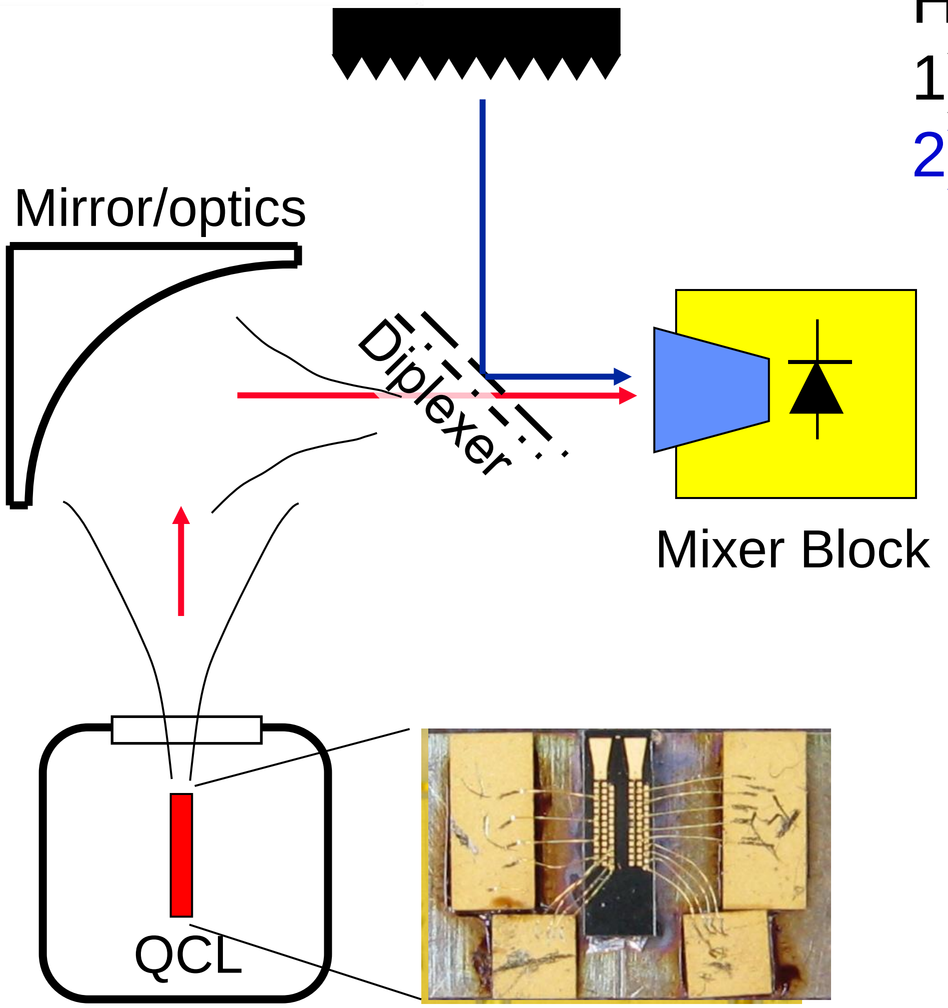
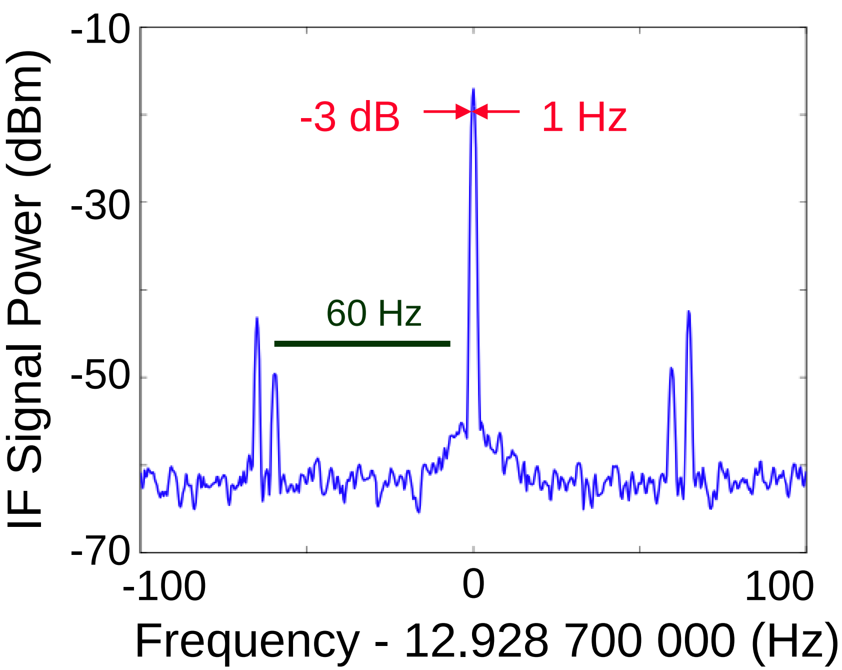
Coherent Detector: THz receiver



Heterodyne transceivers enable:

1) high sensitivity detection
2) high spectral resolution



$$P \propto E_1E_2\cos(\omega_1-\omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1+\omega_2)$$

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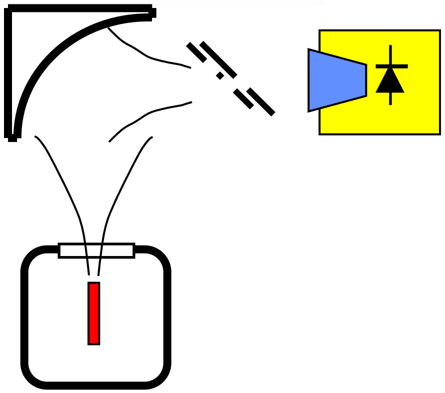
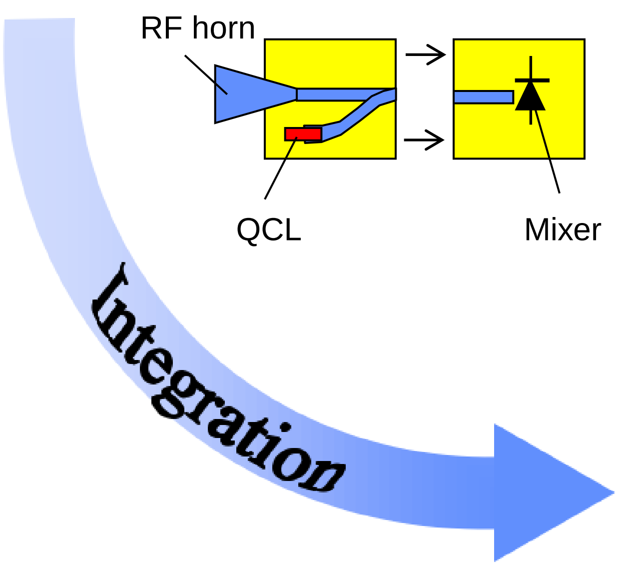
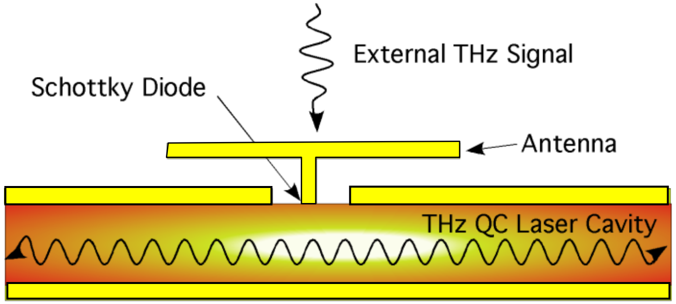
Integration Roadmap



- **Why Replace Quasi-Optical Receiver**
- **Rectangular Waveguide Integration**
- **Monolithic Integration**

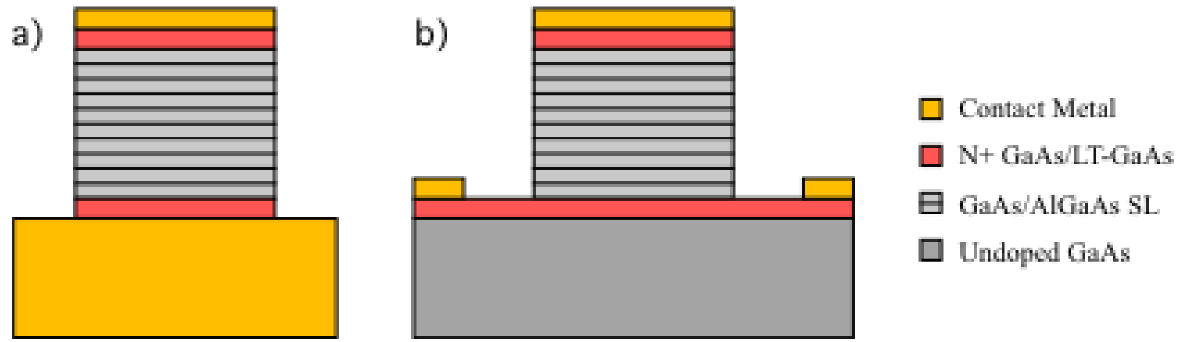


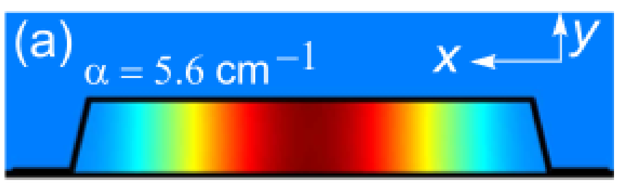


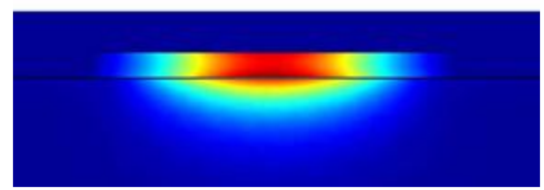
Two THz Waveguides

Metal-Metal Waveguide

Surface Plasmon Waveguide







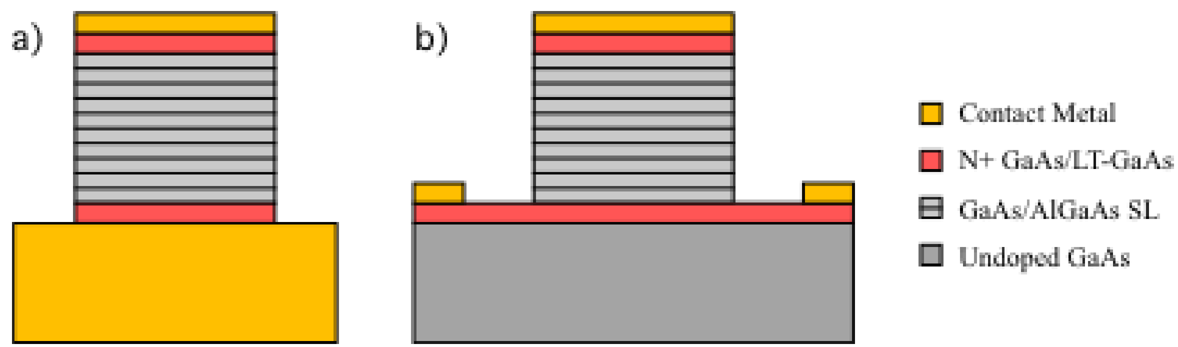
Kumar, *Opt. Exp.*, **15**, 113, 2007

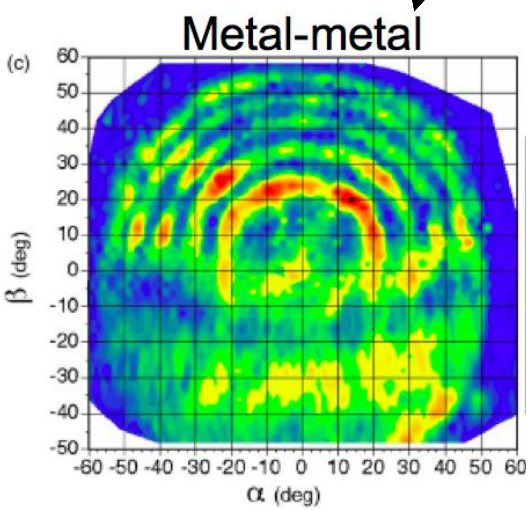
Demichel, *Opt. Exp.*, **14**, 5335, 2006

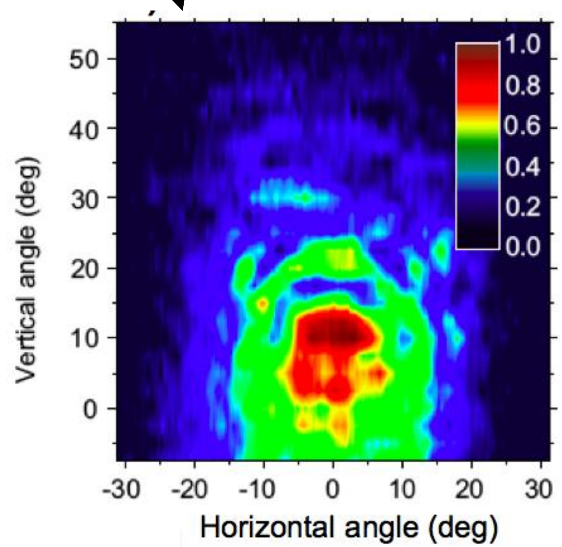
QCL Far Field Issues

Metal-Metal Waveguide

Surface Plasmon Waveguide



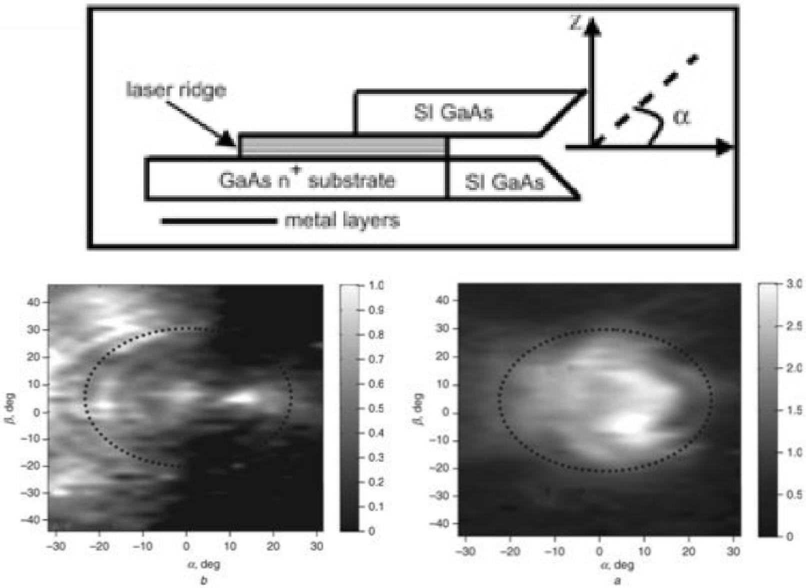




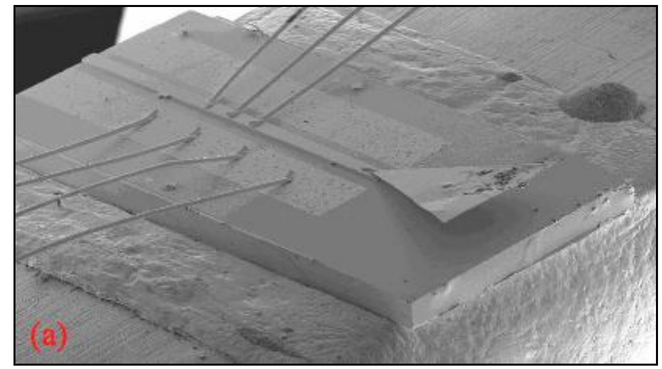
(Courtesy J. R. Gao, TU Delft)

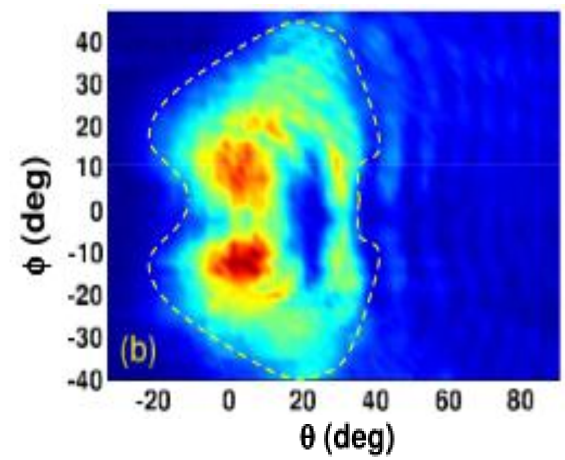
Fixing the beam pattern

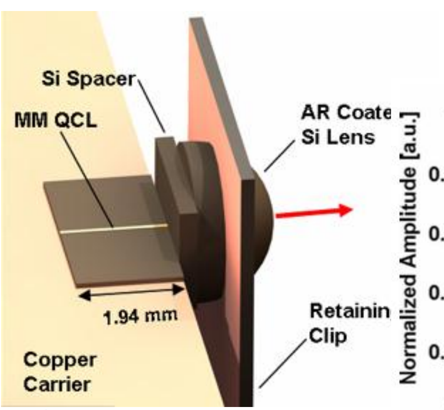
Amanti, *Elec. Lett.*, **43**, p573, 2007



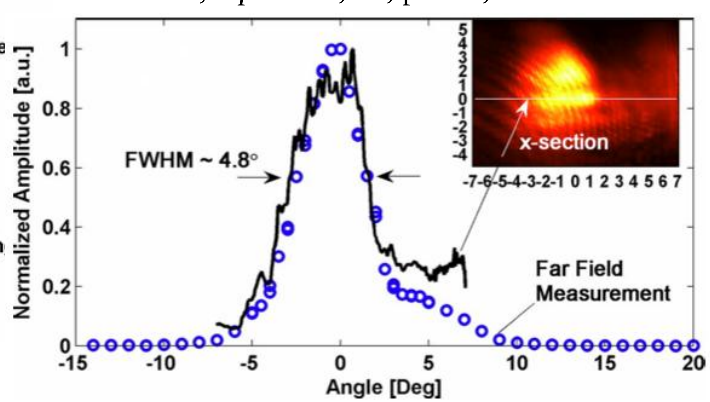
Maineult, Appl. Phys. Lett. 93, 183508 (2008)





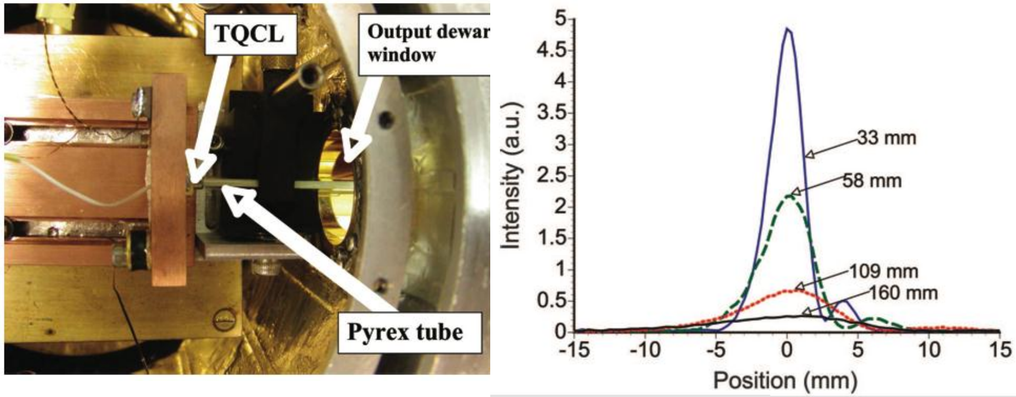


Lee, *Opt. Lett.*, **32**, p2840, 2007

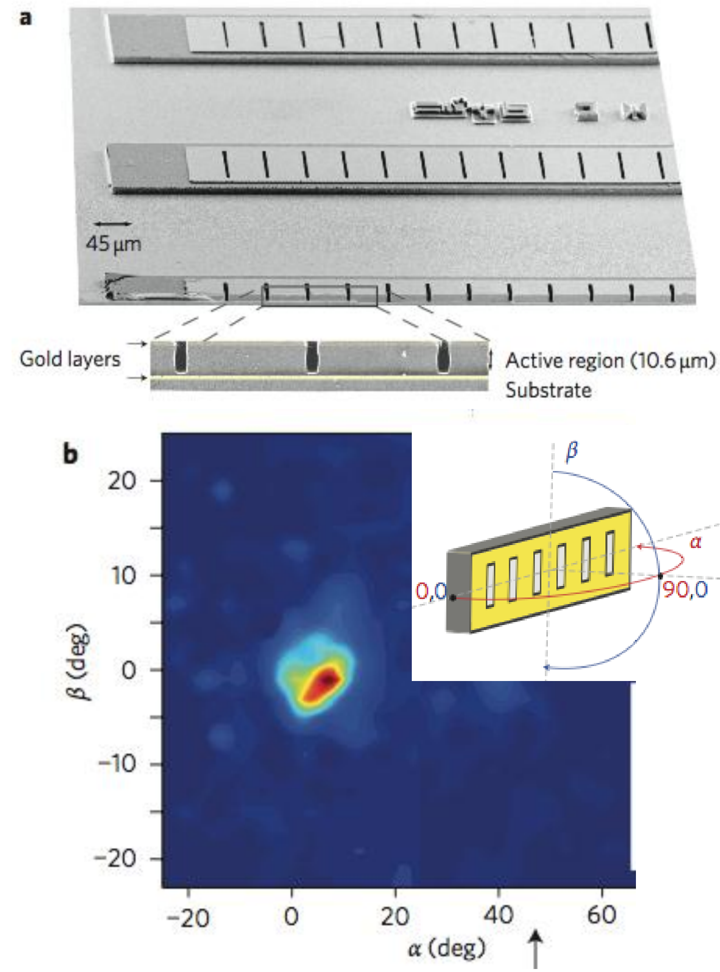


Controlling the Beampattern

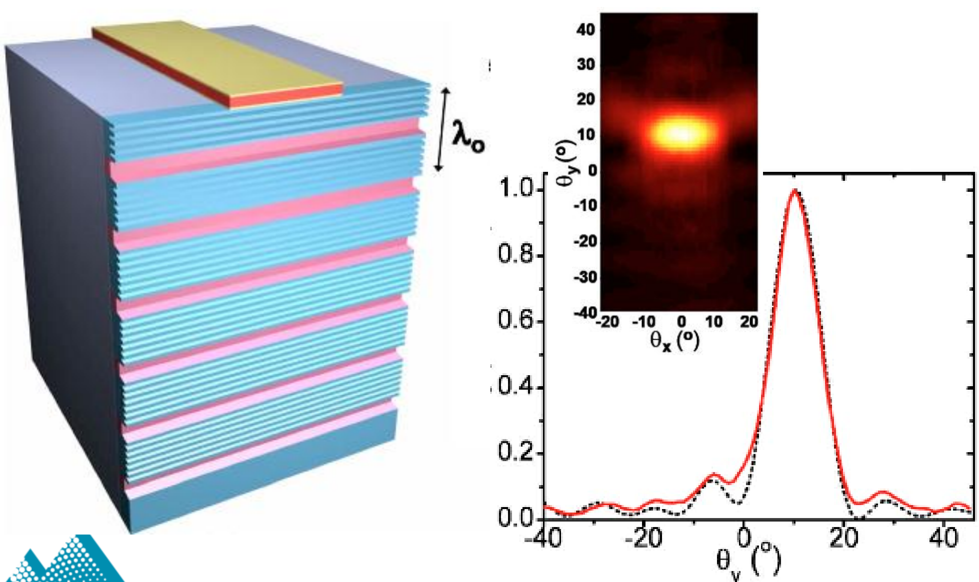
Danylov, Appl. Opt. 46, 5051 (2007)



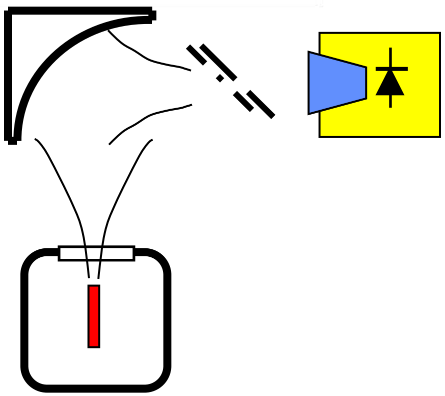
Amanti, Nat. Phot..3, 586 (2009)



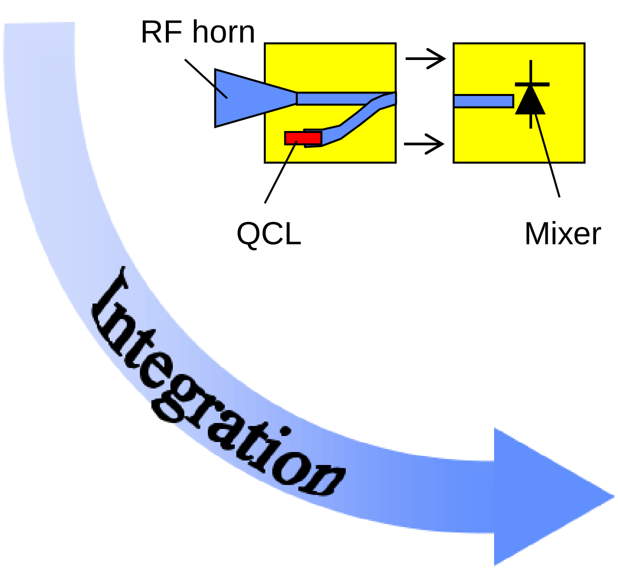
Yu, J. Opt. Soc. Am. B, 27, B30, 2010



Integration Roadmap

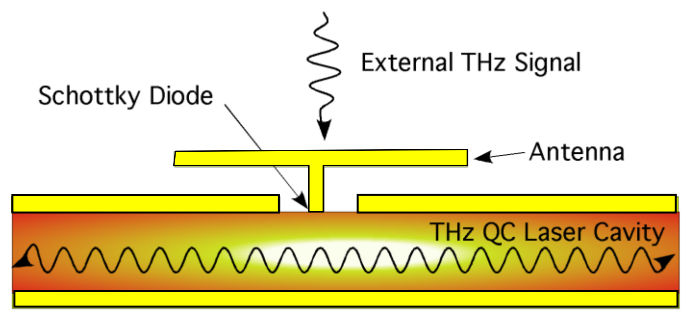


- **Why Replace Quasi-Optical Receiver**
  - **Poor coupling**
  - **Bulky**
  - **Alignment sensitivity**

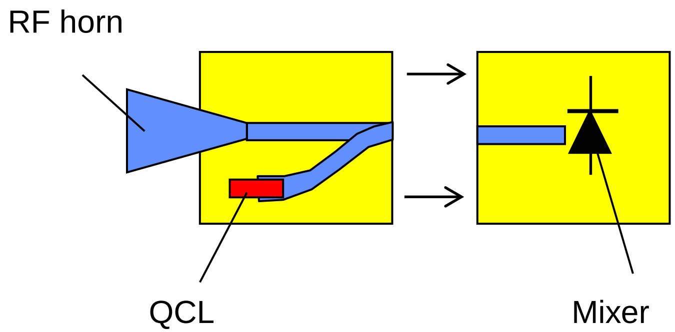


- **Rectangular Waveguide Integration**
  - Background
  - Micromachined rectangular waveguides
  - QCL / RWG integration

- **Monolithic Integration**



Hybrid Integration: QCLs in rectangular waveguides



- **Why Rectangular Waveguides**
  - RWG is a widely used standard
  - Propagation mode structure in RWG known
  - Horns should improve beampatterns and coupling
  - Waveguide elements (couplers, splitters, ...) exist
  - Can mate directly to mixers in existing RWG (no optics)
- **Problems with Existing Waveguides**
  - Conventional machined split-block RWG doesn't work well with QCLs
  - $$$ / labor intensive**

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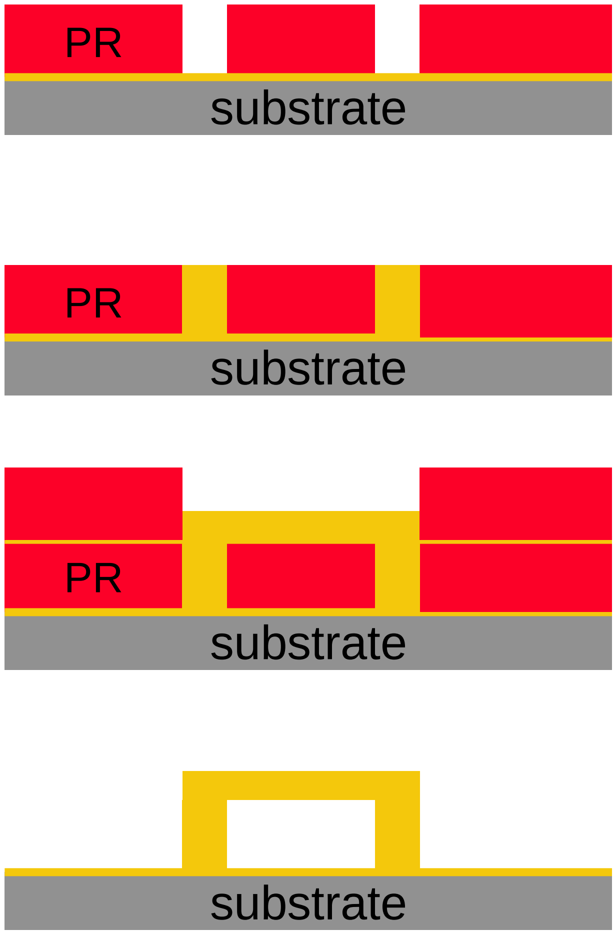
Micromachining Rectangular Waveguides

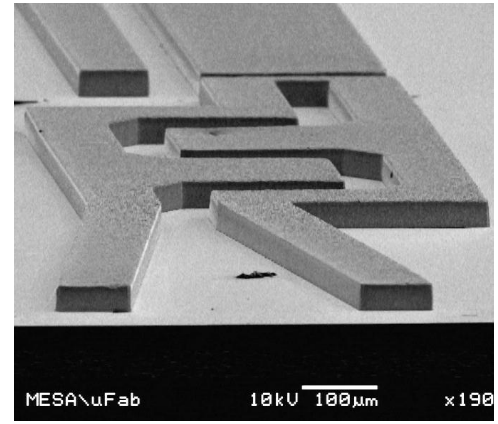
1. Deposit seed metal and pattern photoresist

2. Electoplate Au in photoresist openings

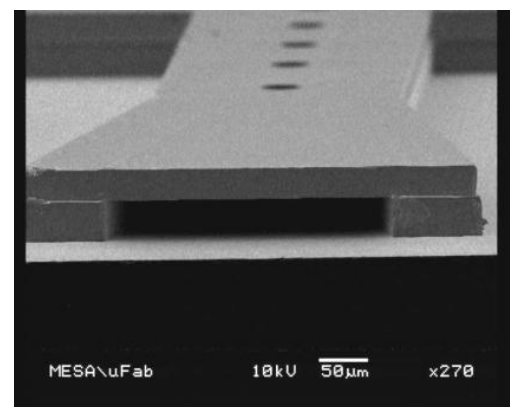
3. Deposit 2nd seed, pattern 2nd PR, and plate lids

4. Remove photoresist and 2nd seed metal





- **Additive electroplating technique suitable for various substrates**
  - *Allows waveguide fabrication on QCLs or other devices*



Rowen, Proc. SPIE, **7590**, 2010

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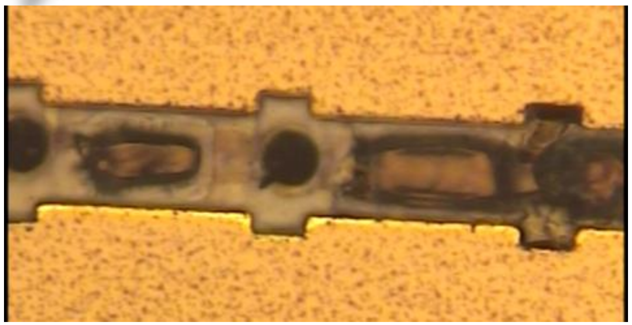
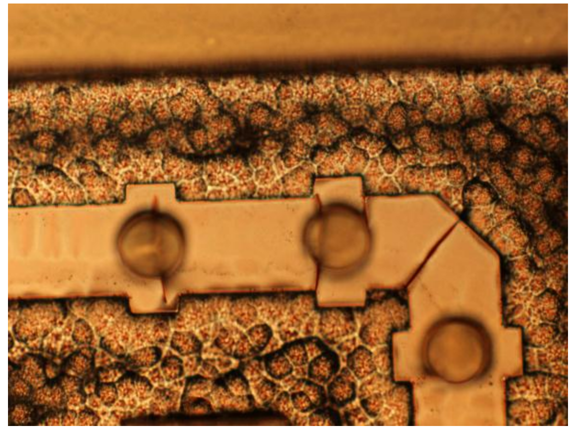
The dirty little secret...

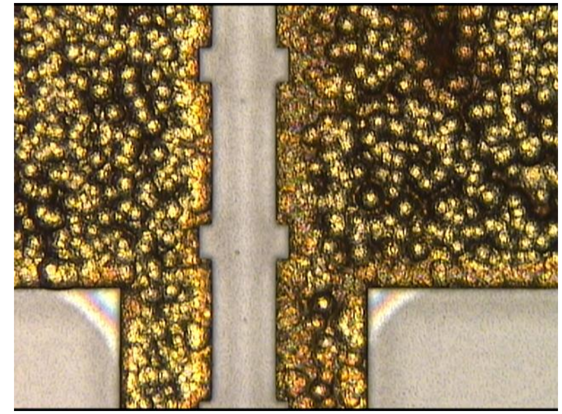
Removing Photoresist



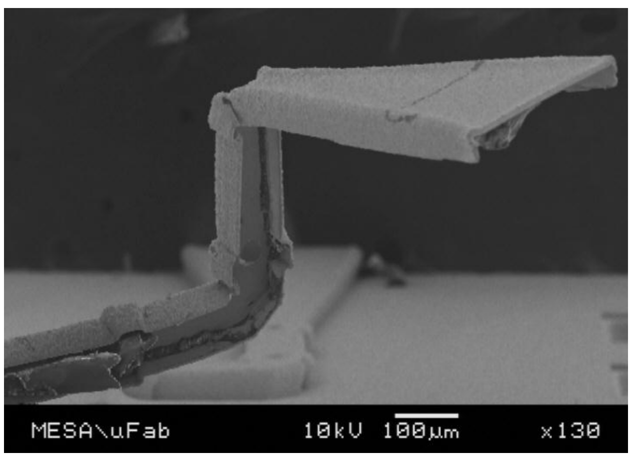
Alignment



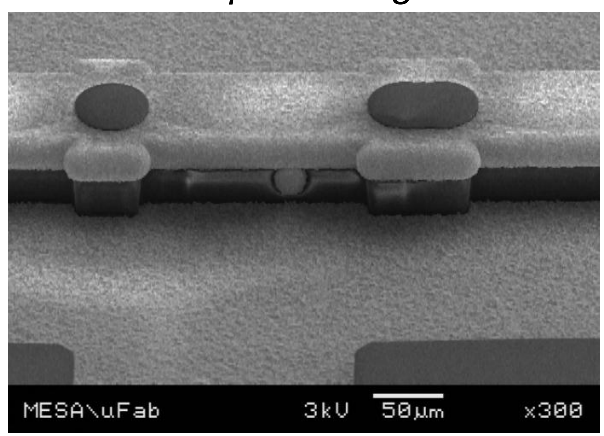
Nonuniform Electroplating



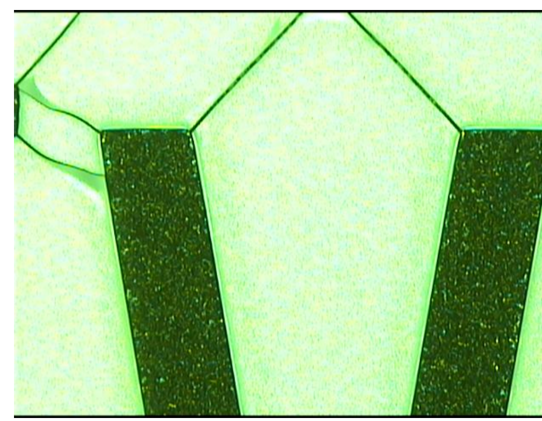
Delamination



Step Coverage

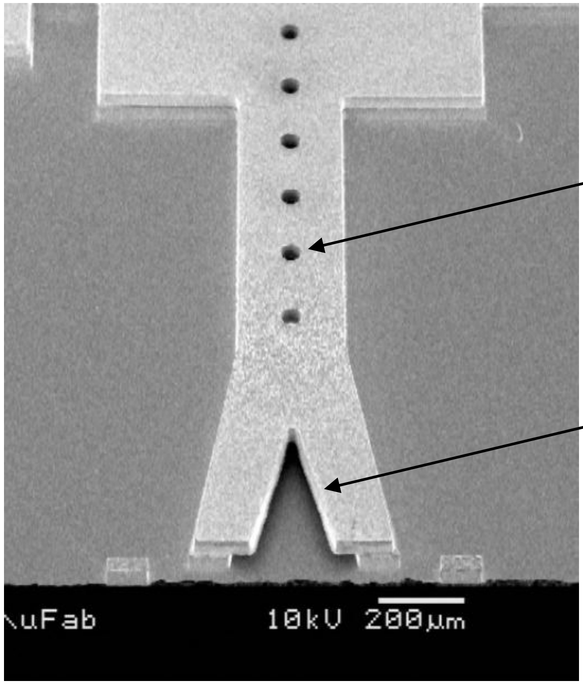


Photoresist Cracking



...simple processes are never simple

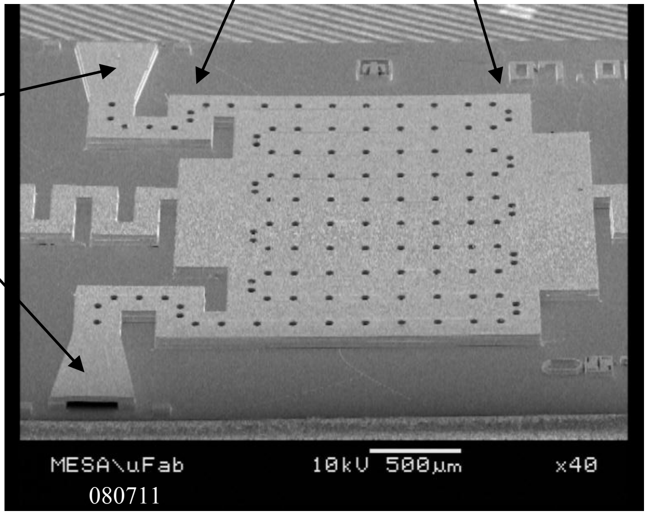
Micromachined THz Waveguides

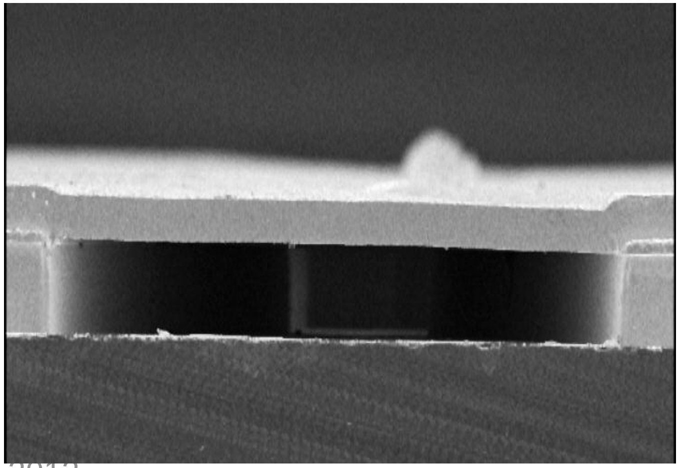


Photoresist removal holes

Horn antenna

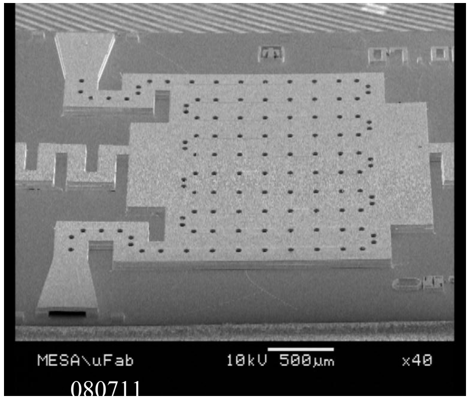
H-Plane Bends

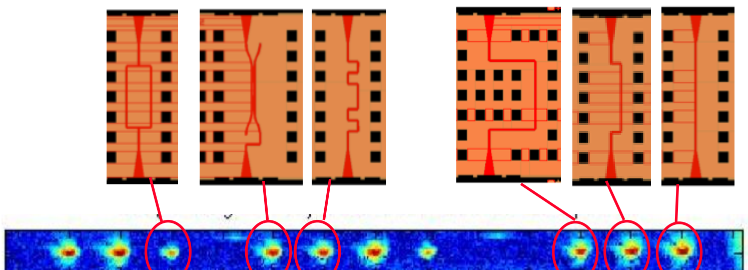




End view of waveguide horn antenna

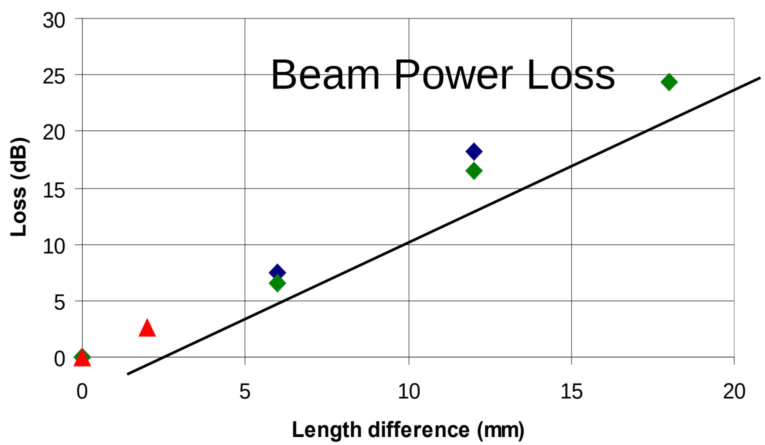
THz Micromachined Waveguide Components



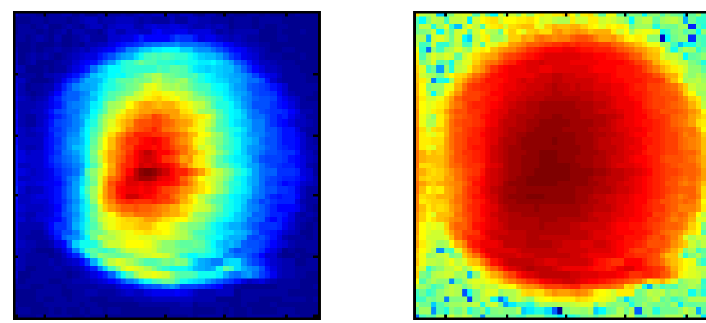


Transmission through various components

- Demonstrated THz components (waveguides, bends, tees, and couplers) needed for THz integrated circuits.
- Achieved low propagation and bend losses (at 2.9 THz).
  - 1.4 +/- 0.15 dB / mm (.15 dB / λ)
  - 0.15 +/- 0.15 dB / bend
- Observed good far-field beam patterns.



Antenna Beam Pattern



Linear Scale   Log Scale

Nordquist, JSTQE, **17**, 130, (2011)

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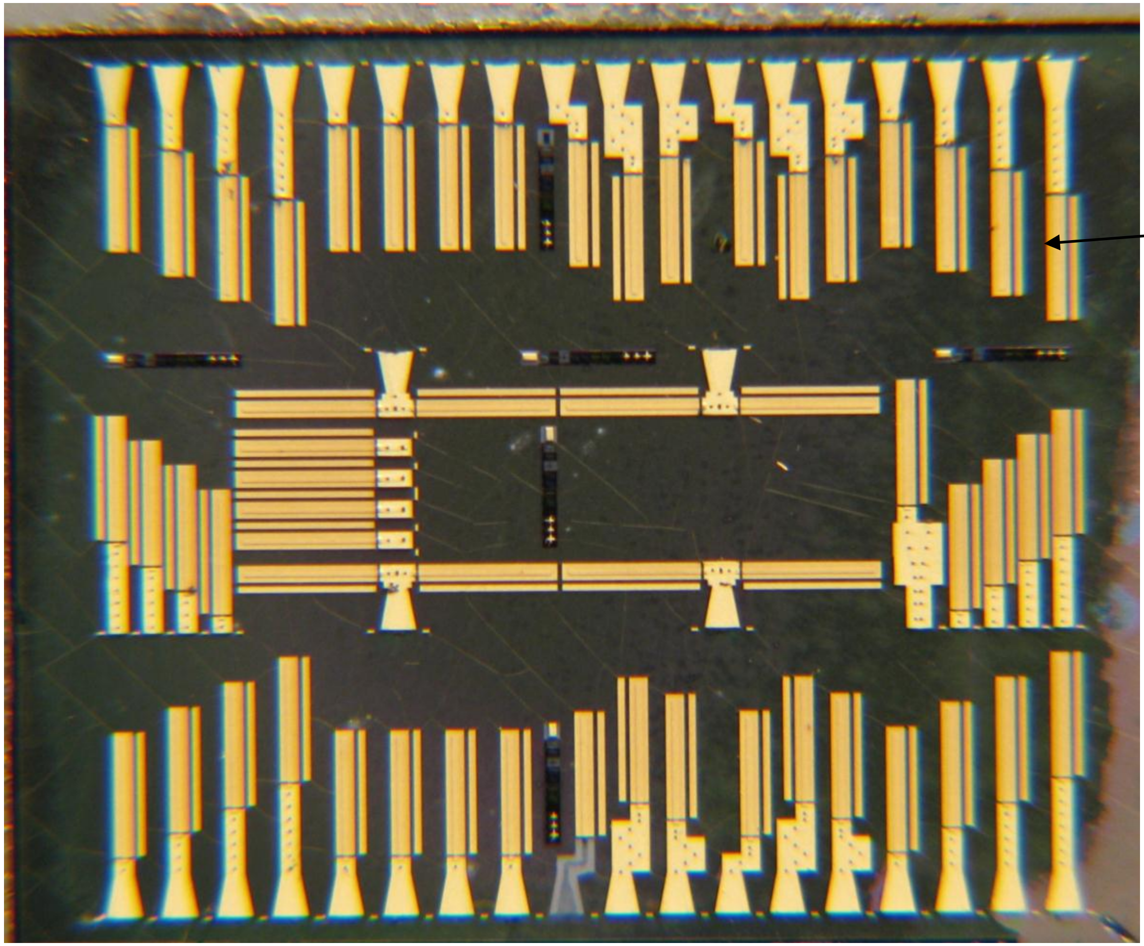
Integrated Lasers with Waveguides



Built waveguides on top of lasers

<u>Chip Tests</u>

- H-plane bends
- E-plane bends
- Magic-Tees
- Combiners
- Horns
- Insertion position
- WG length

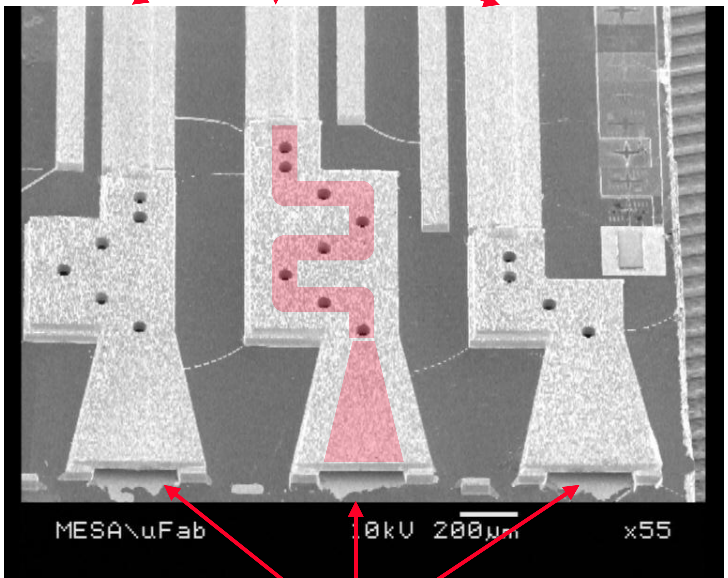
Note: parallel assembly advantage

Wanke, Proc SPIE, **7215**, (2009)

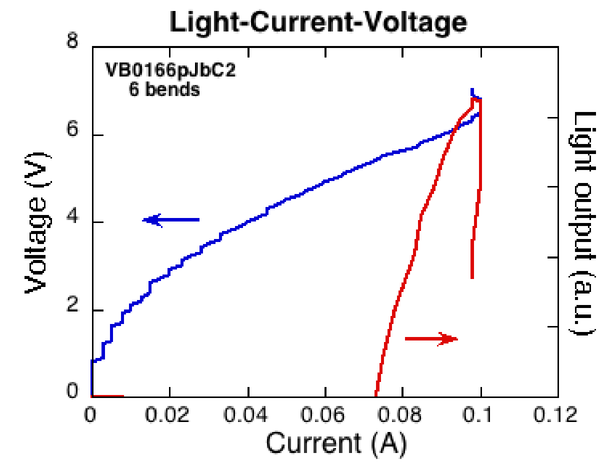
Integrated Waveguide Performance

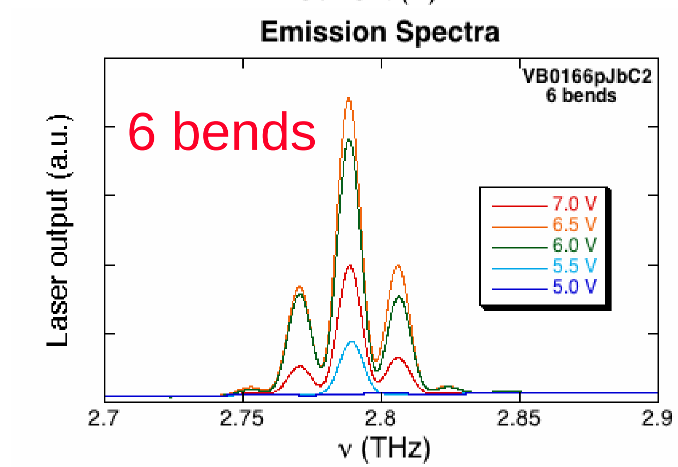
- Merges microwave and optical technology
- Output beam pattern defined by horn
- Emission can be moved around on the chip

THz QCLs

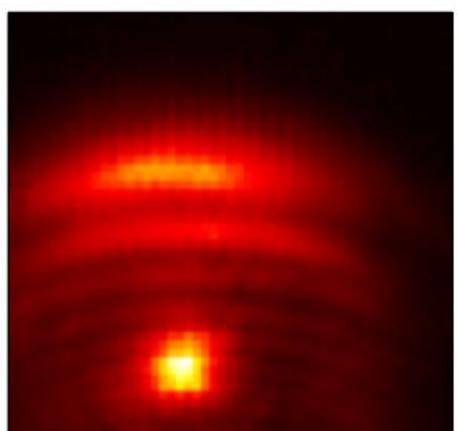


Horn Antennae





Beam Pattern



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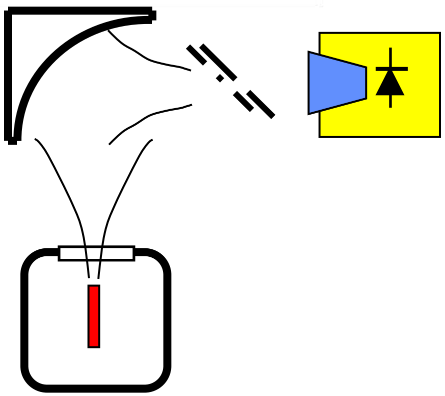
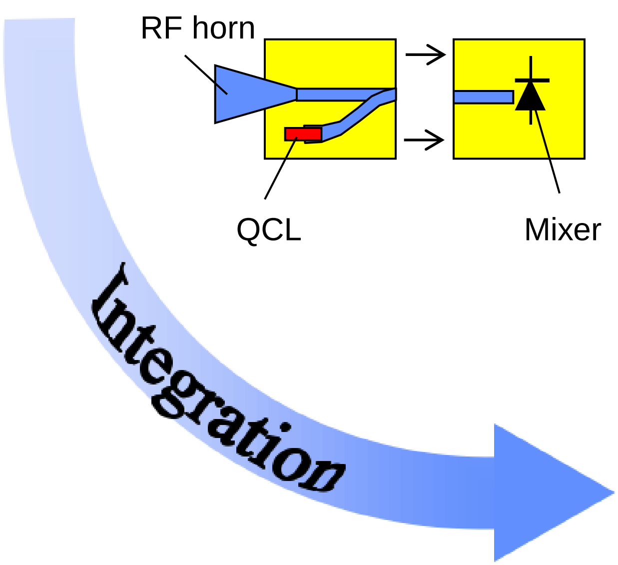
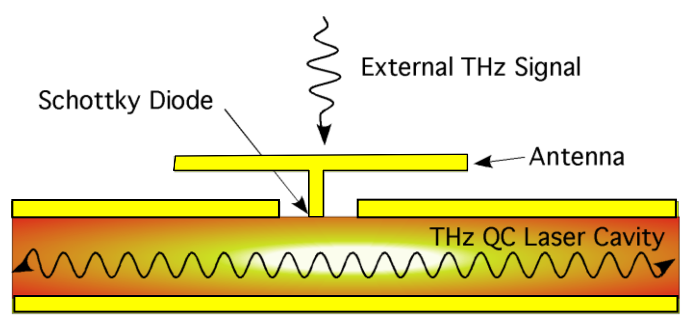
Integration Roadmap



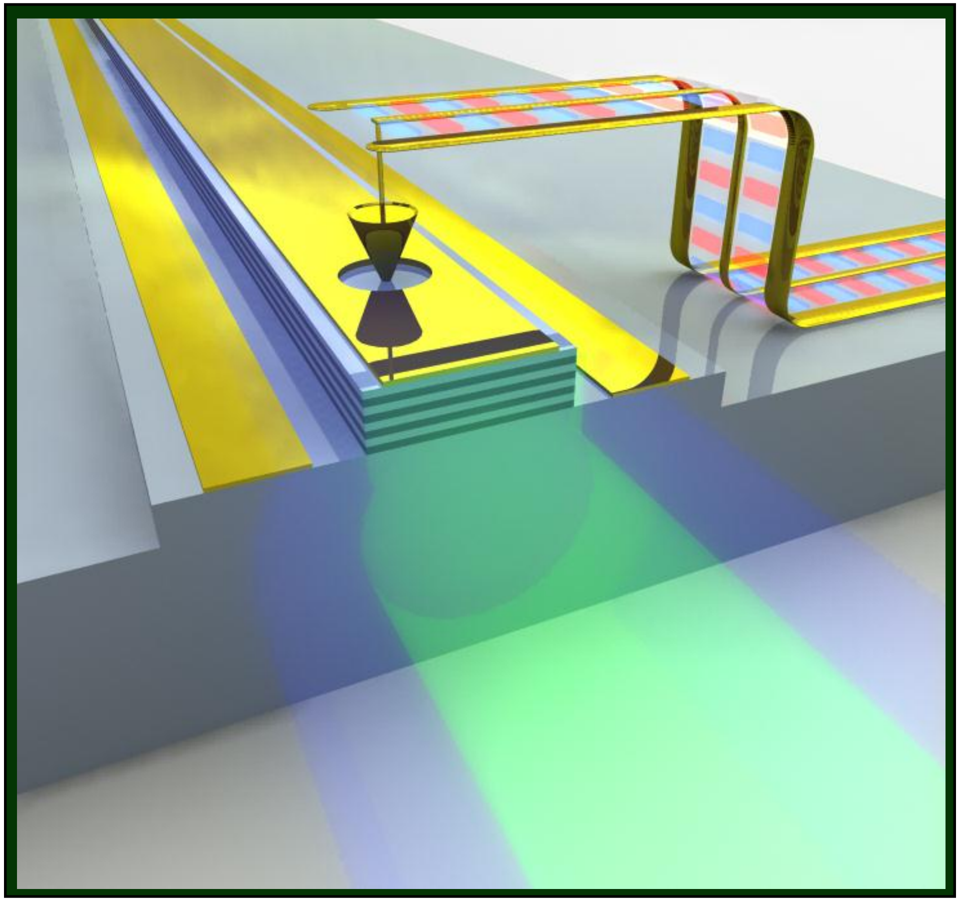
- Why Replace Quasi-Optical Receiver
- Rectangular Waveguide Integration
- **Monolithic Integration**
  - – Background
  - – Rectified DC response
  - – Mixing response



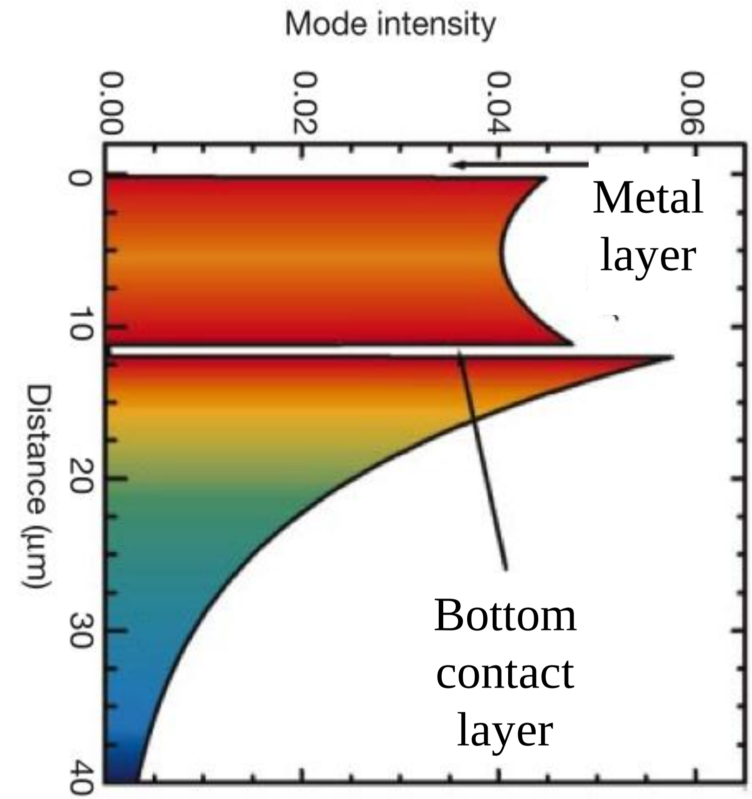


Monolithically Integrated Transciever

Insert diode directly into laser core



Wanke, Nat. Phot., **4,** 565, (2010)



Kohler et al. , Nature, **417**, 2002

Monolithically Integrated Transciever

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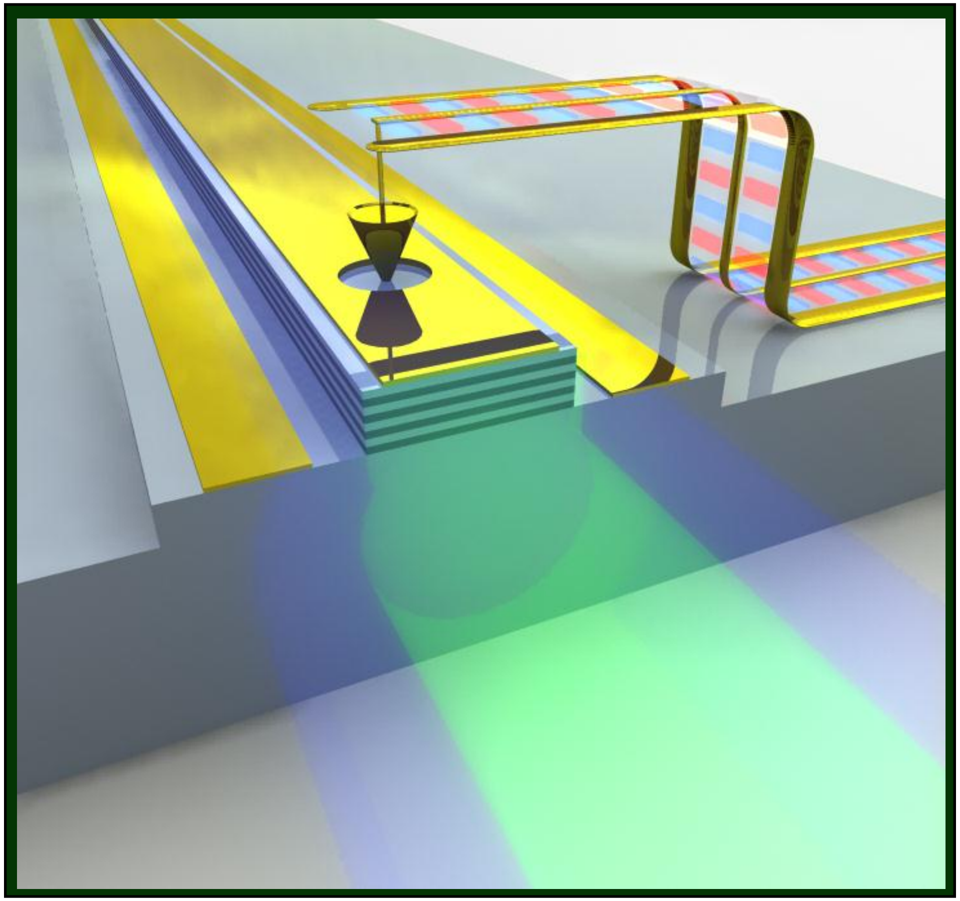


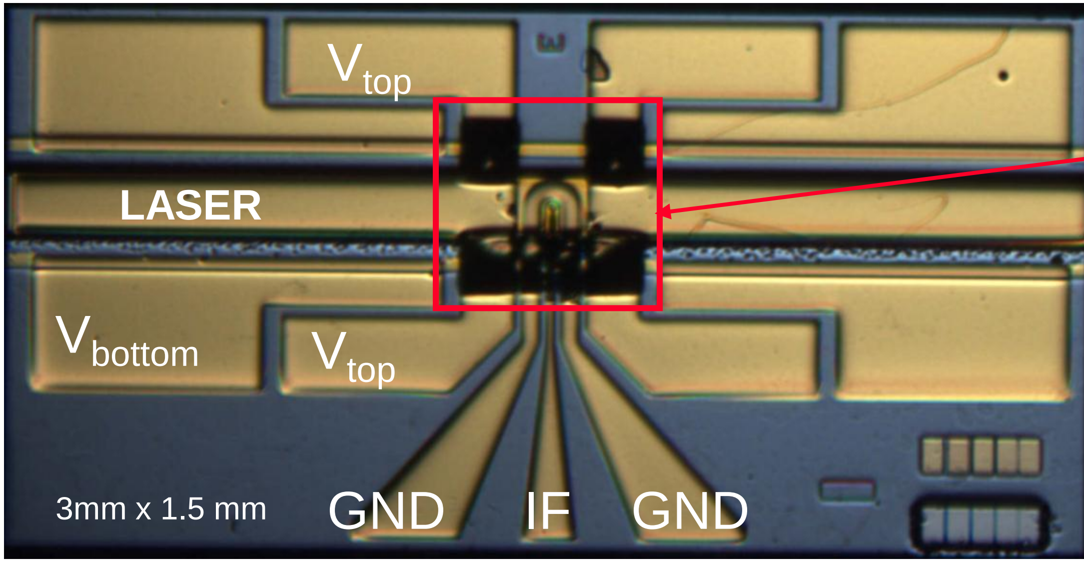
Wanke, Nat. Phot., **4,** 565, (2010)

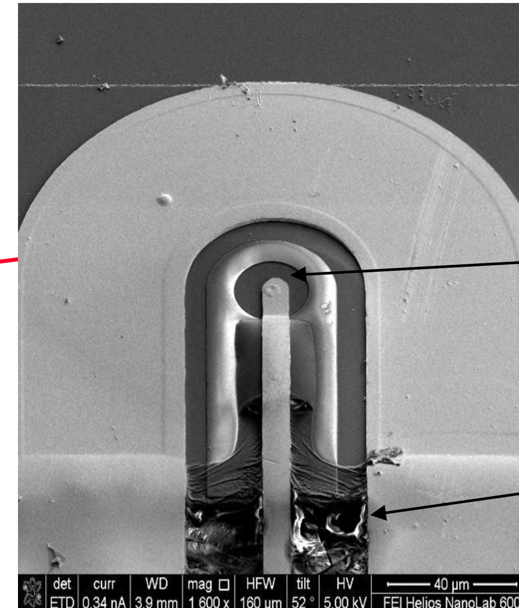
Benefits

- Reduces size
- Eliminate components
- Ensures constant 'alignment'
- Enhances laser/diode coupling
- Bonus : laser diagnostic tool

Completed QCL/Schottky THz IC

3 mm





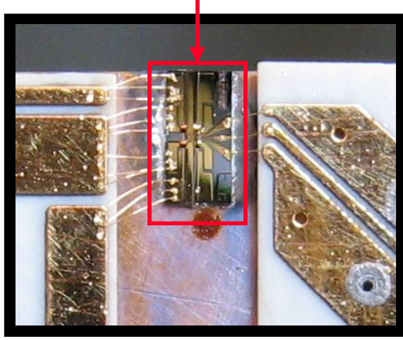
diode

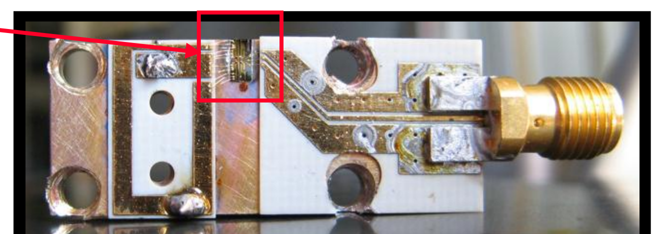
air bridges

GND

IF

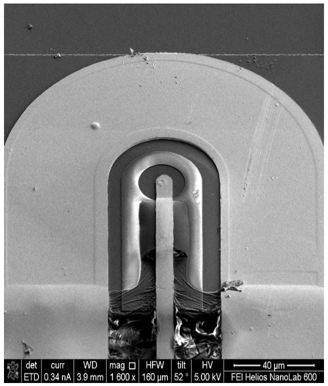
GND

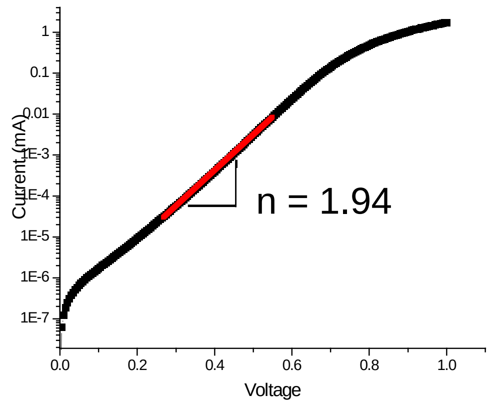


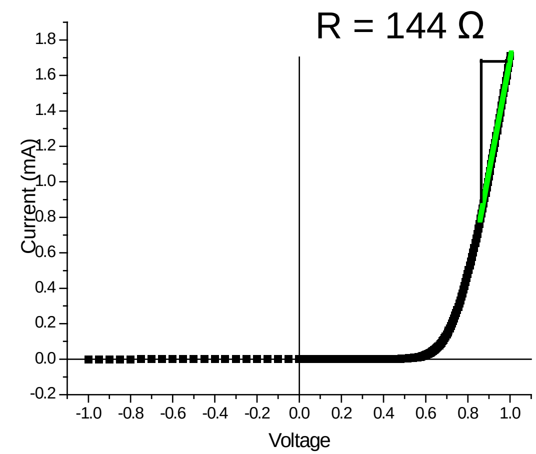


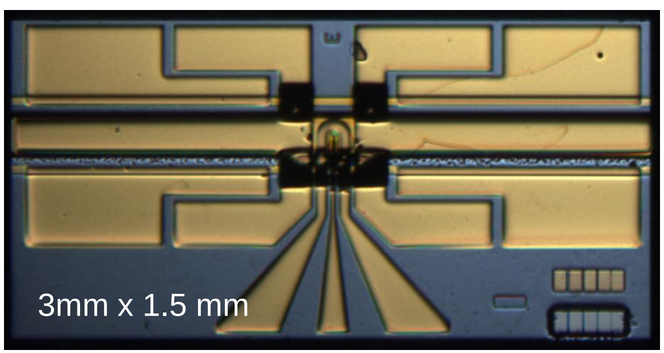
Diode and Laser DC Properties

Typicial Diode DC I-V Properties

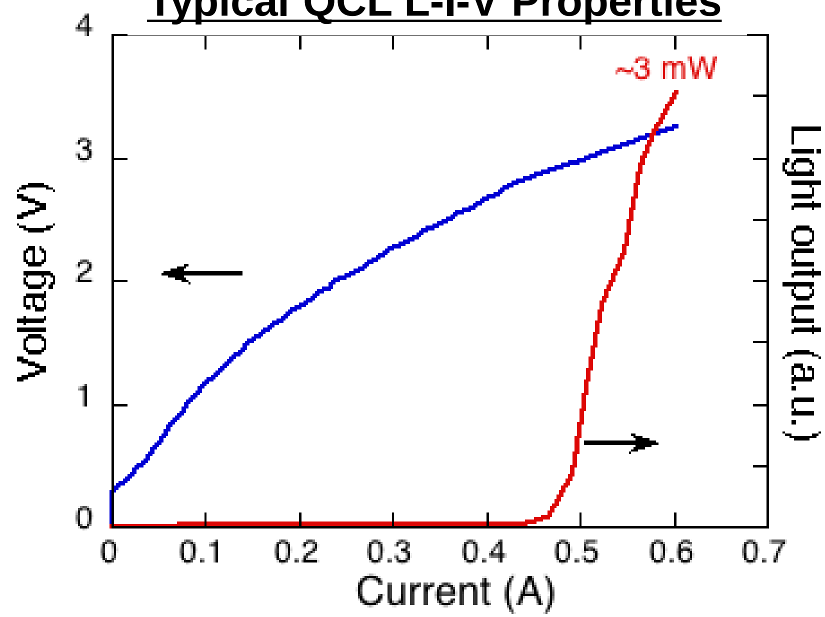




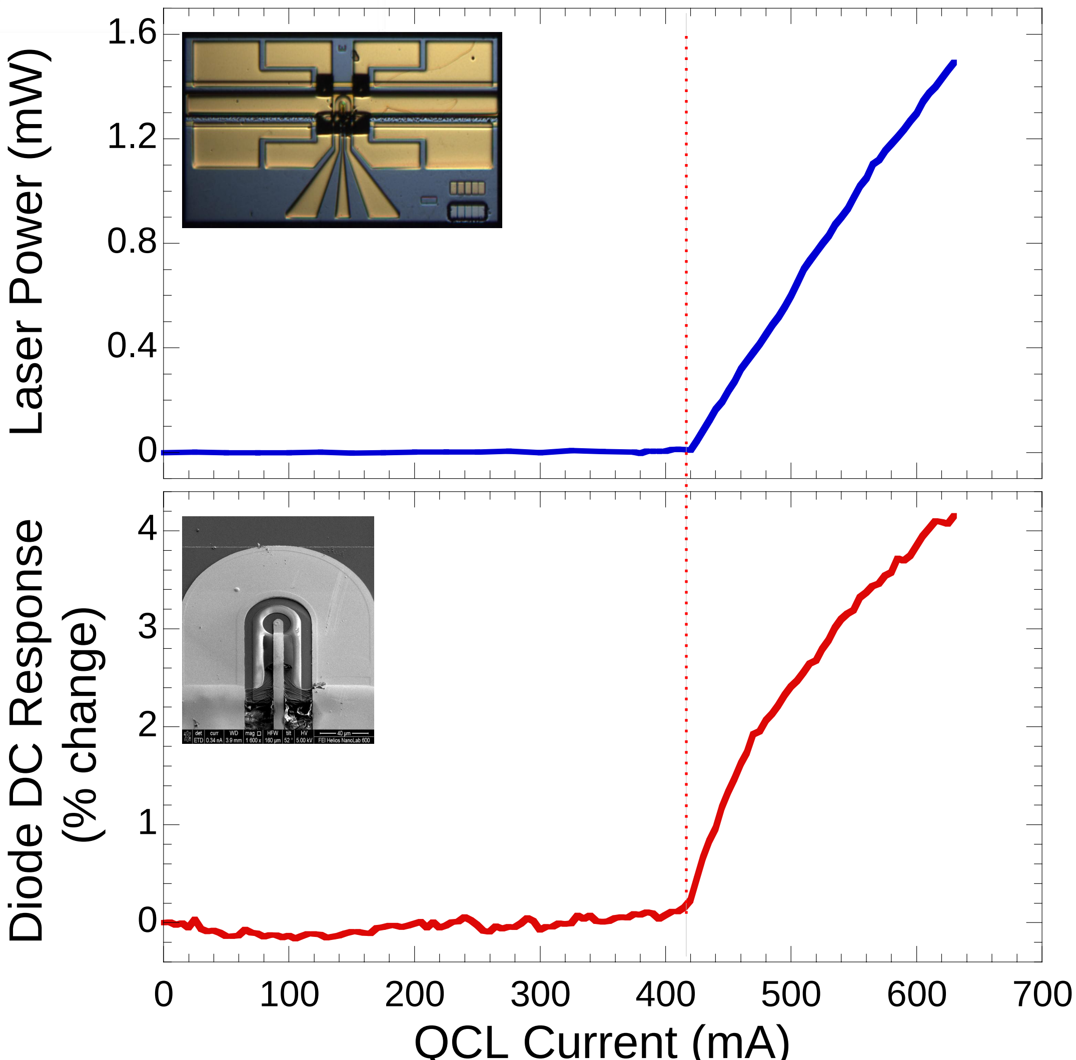




Typical QCL L-I-V Properties

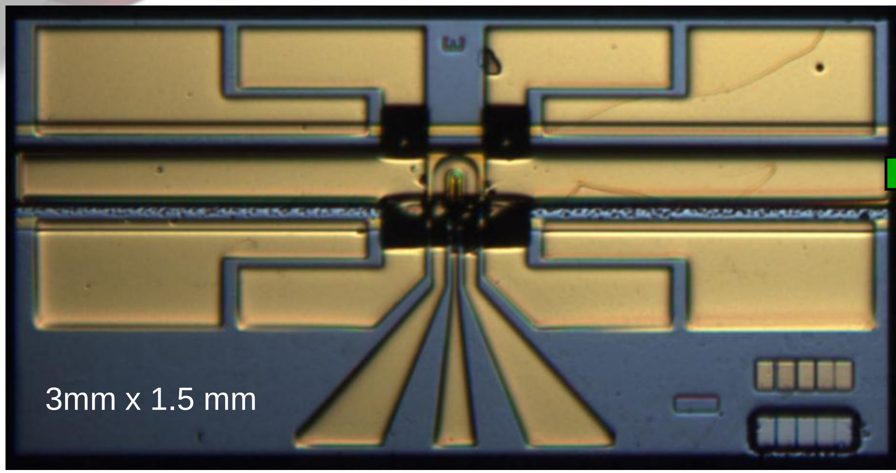


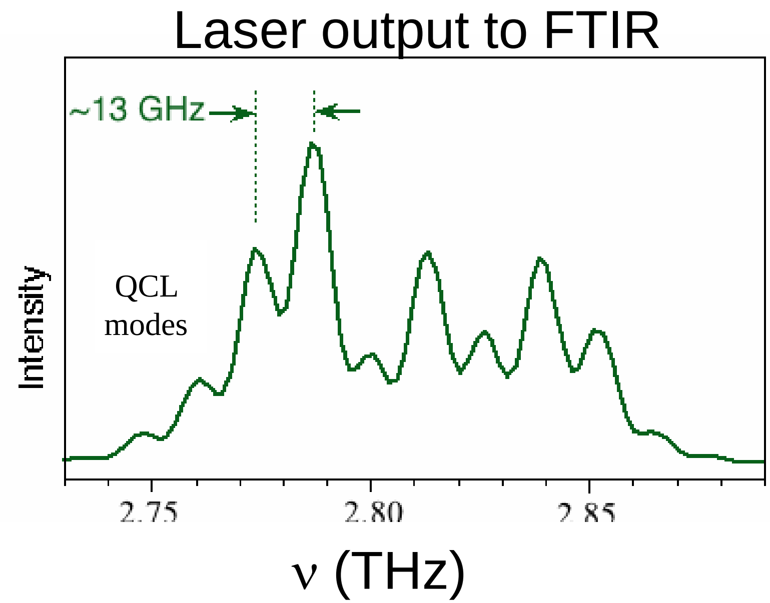
Diode Rectified (D.C.) Response



- Diode responds to QCL power
- But not linear in power

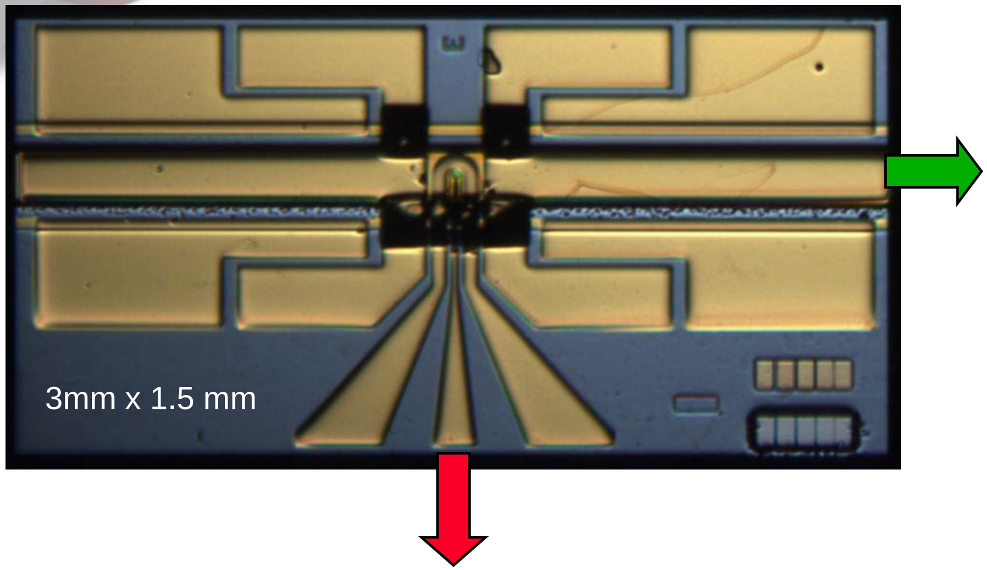
Integrated Diode THz Mixer



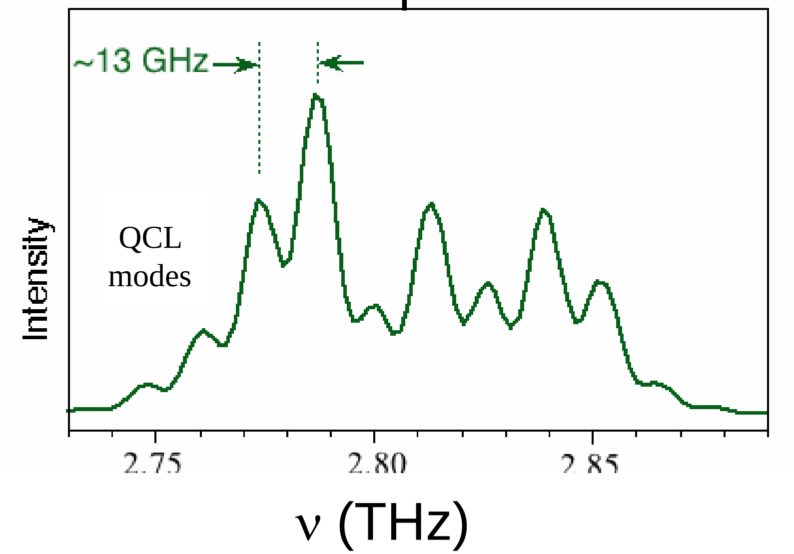


- **Purposely built a multimoded QCL centered on 2.81 THz**
  - **QCL emission (FTIR) spectra show Fabry-Perot modes spaced by ~13 GHz**

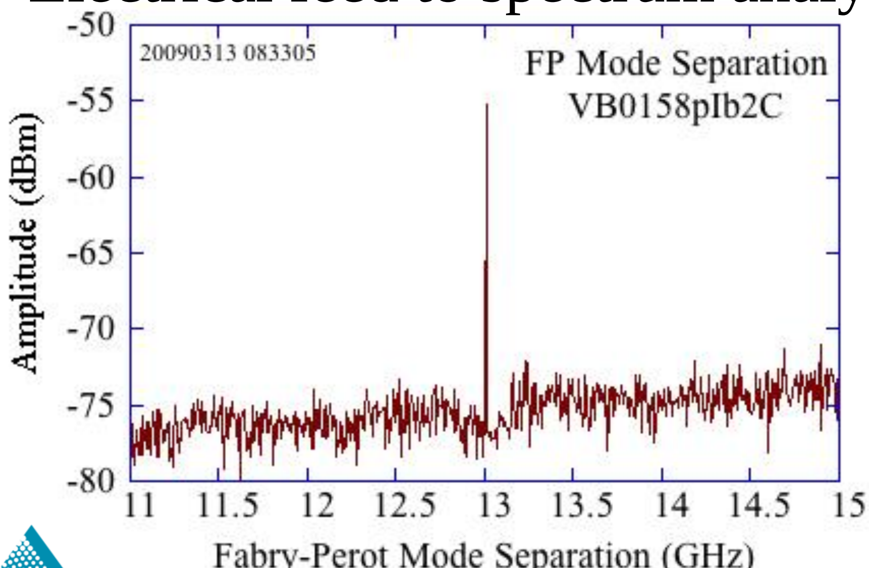
Integrated Diode THz Mixer



Laser output to FTIR

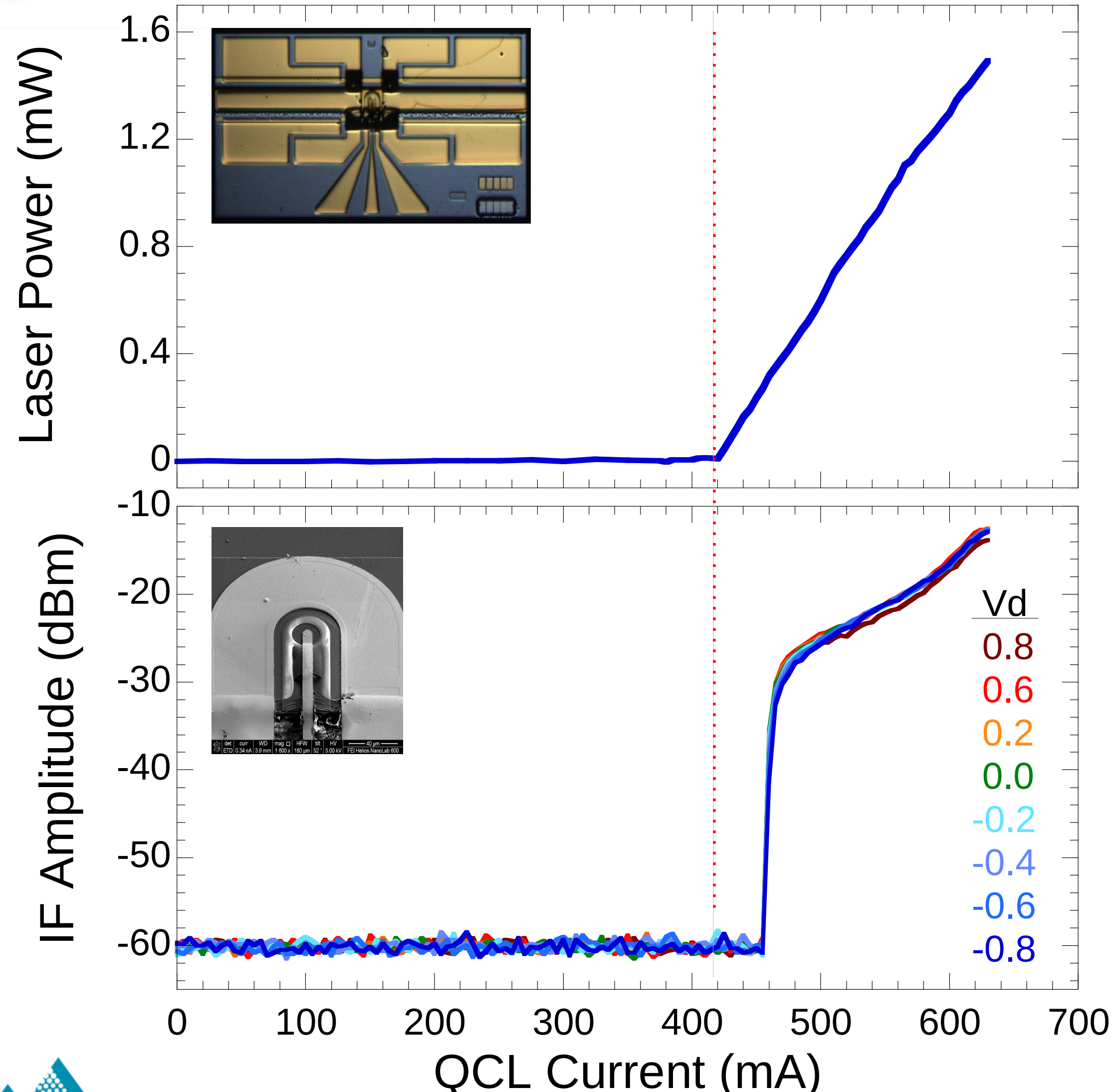


Electrical feed to spectrum analyzer



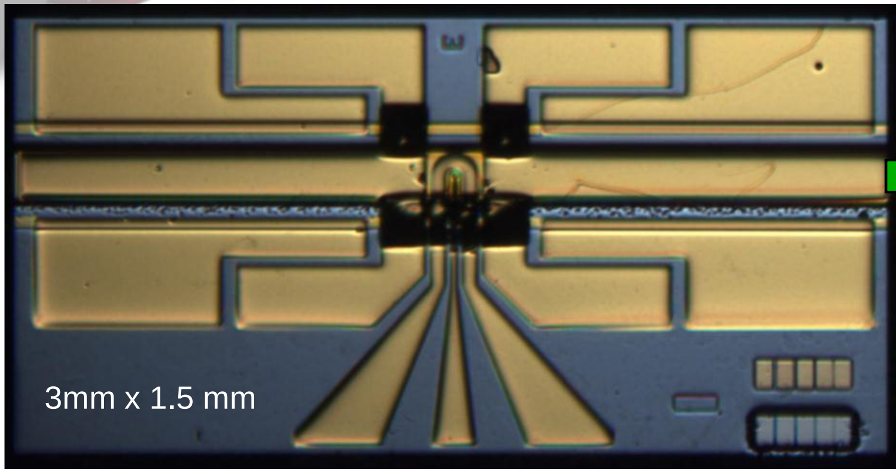
- **Diode outputs IF signal at spacing between QCL modes**

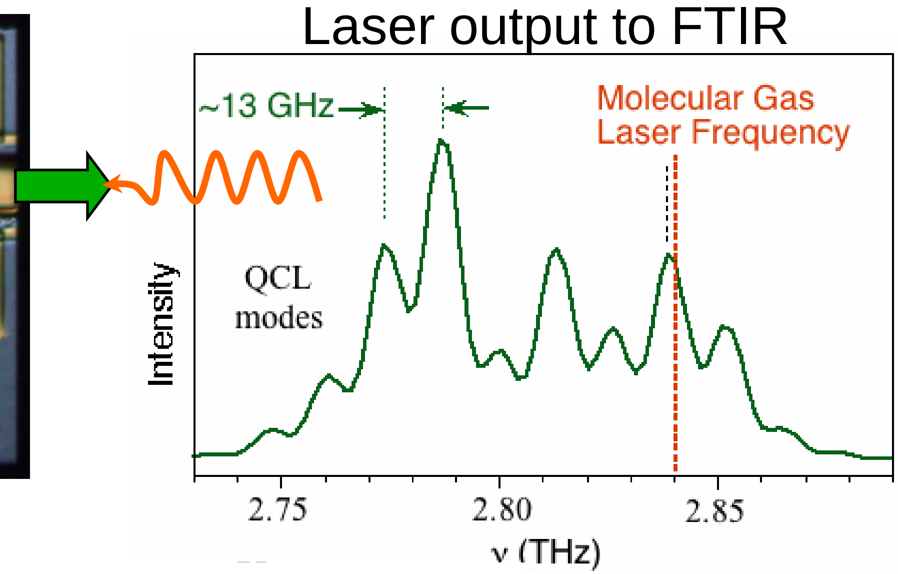
I.F. dependence on laser power

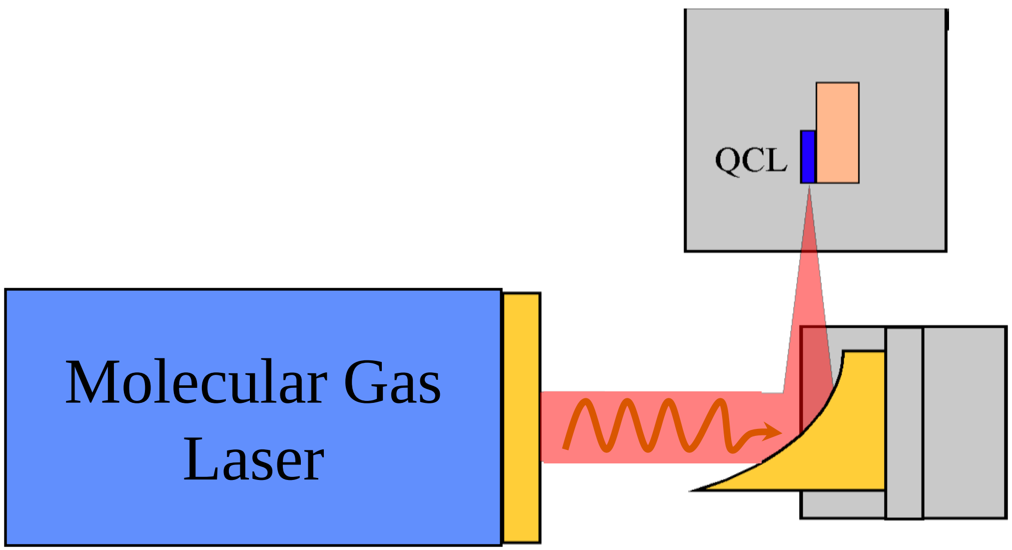


- I.F. indicates when laser turns multimoded.
- I.F. amplitude is fairly independent of diode bias.

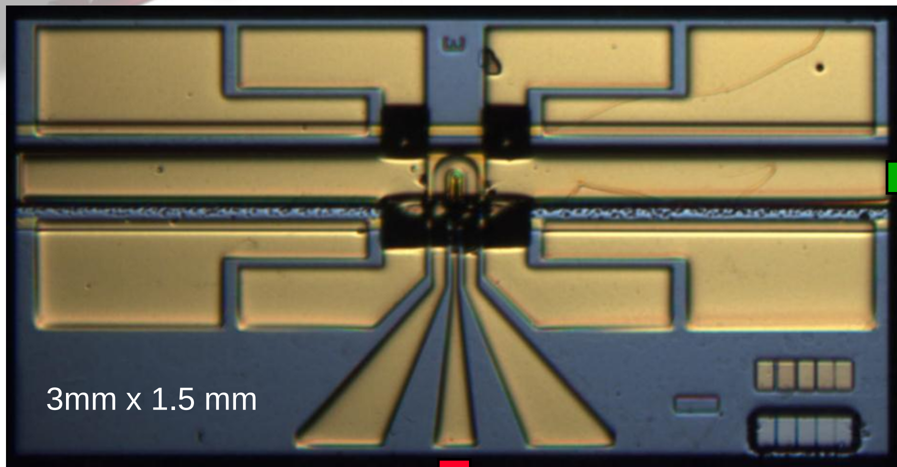
Integrated THz Receiver



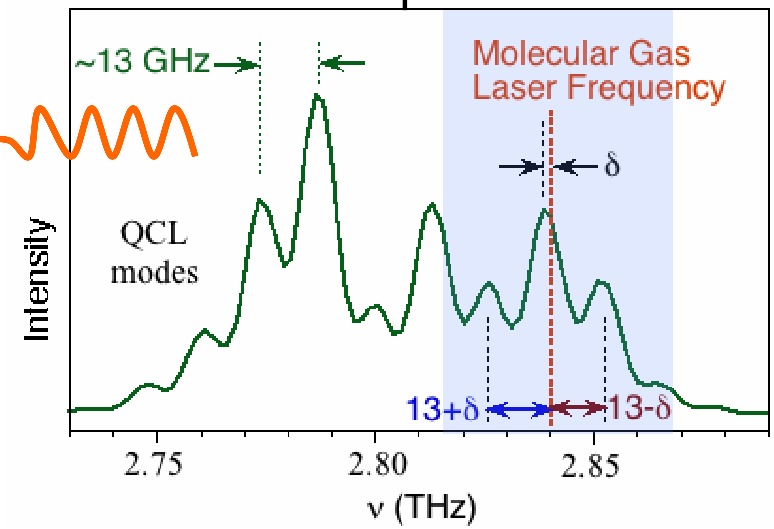




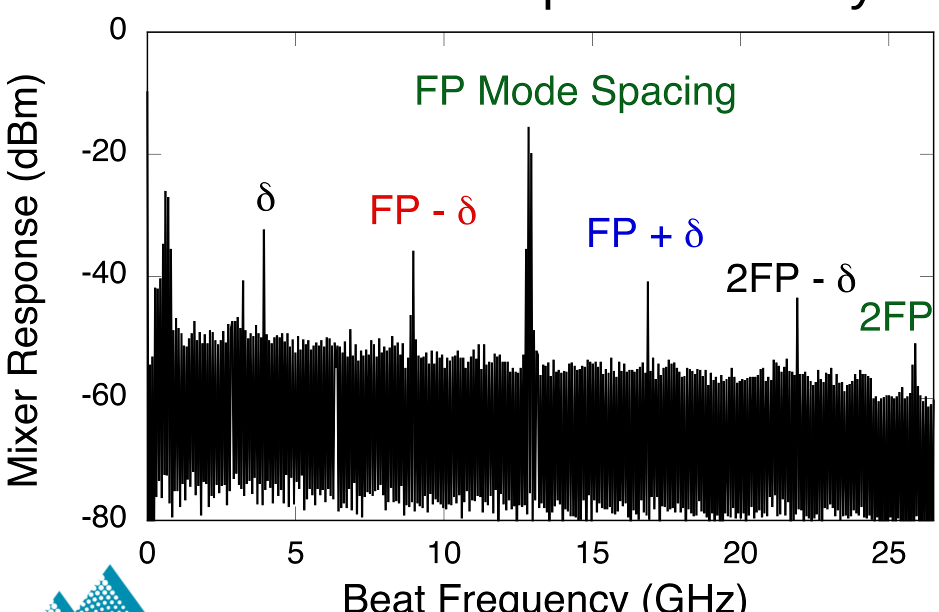
Integrated THz Receiver



Laser output to FTIR



Electrical feed to spectrum analyzer



High-resolution coherent reciever

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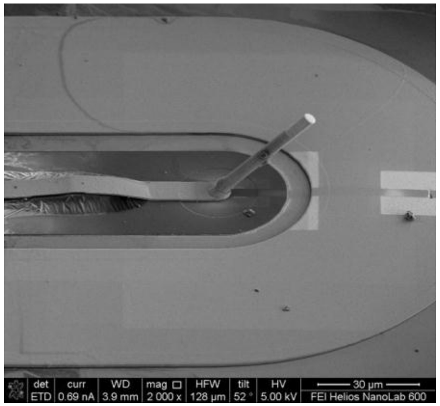
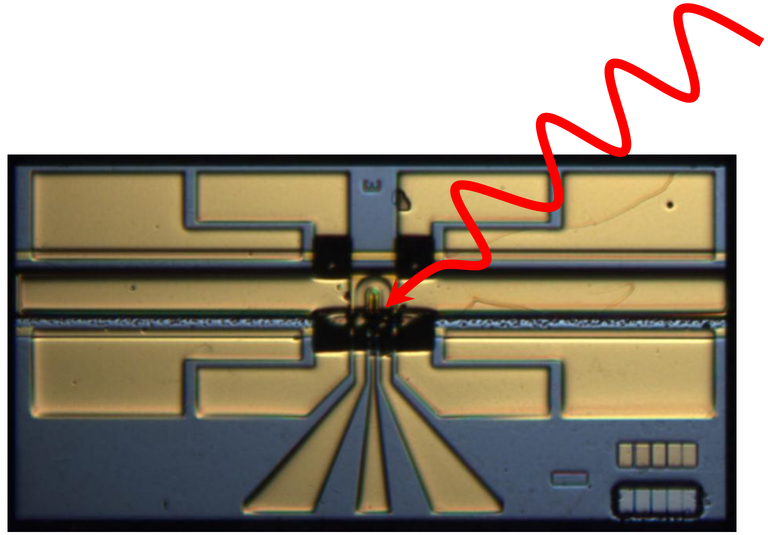
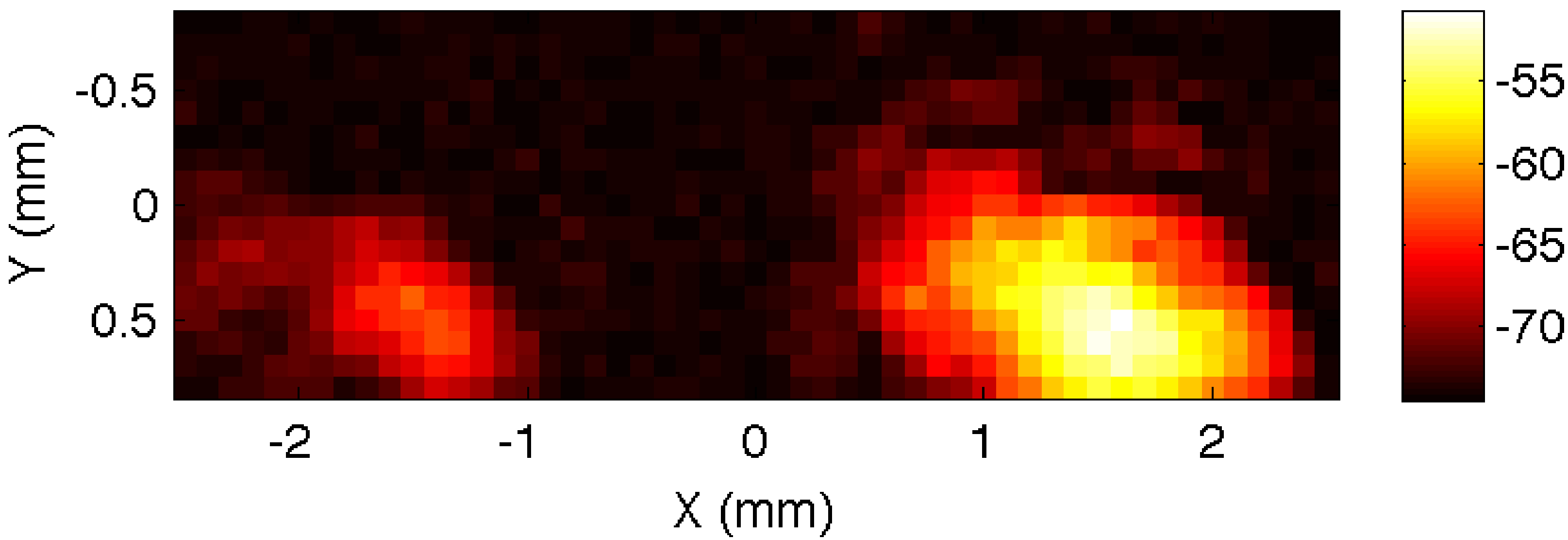
External Coupling to Receiver



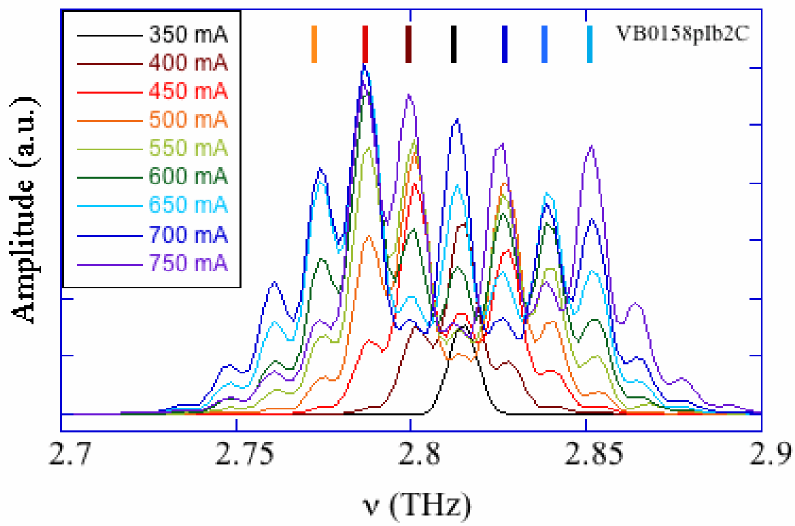


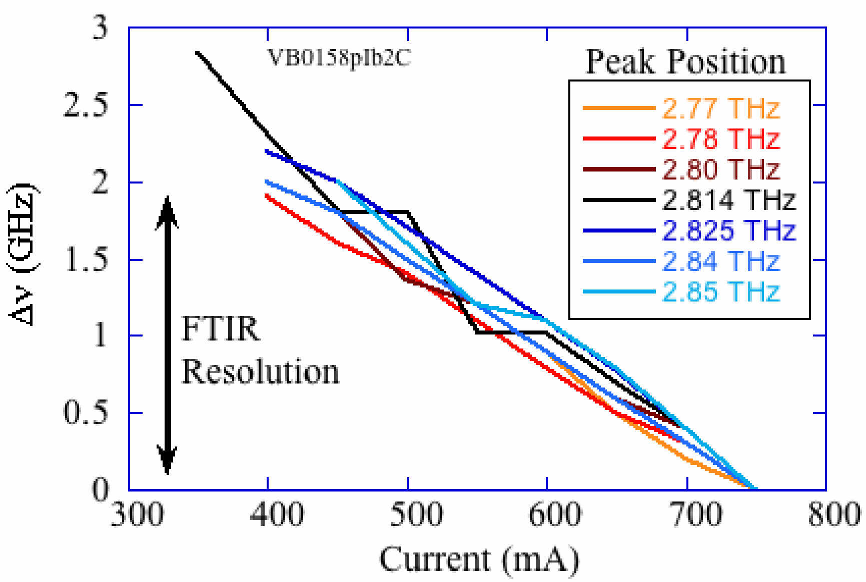


Outline

- My definitions of “THz” and “THz gap”
- **THz integrated circuits**
- **What transceivers can show us about QCLs**
  - Current Tuning
  - Feedback Sensitivity

Current Tuning

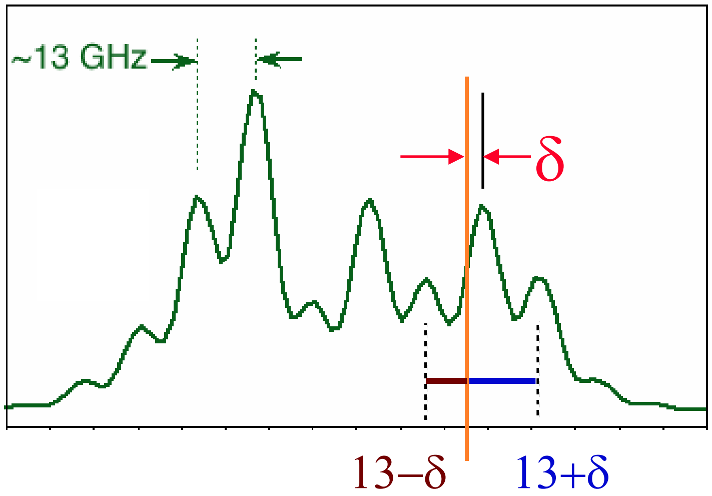


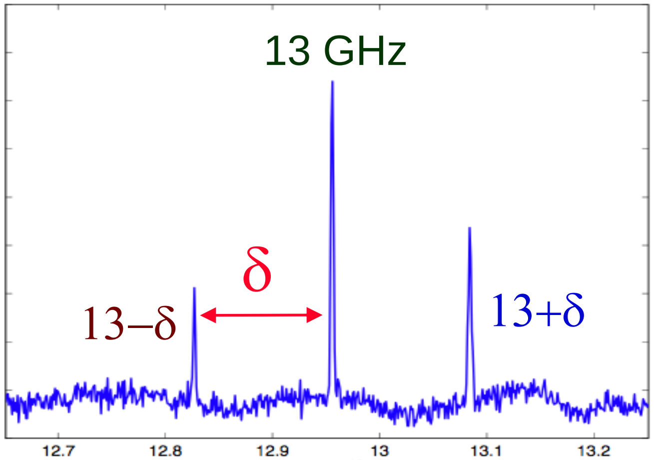


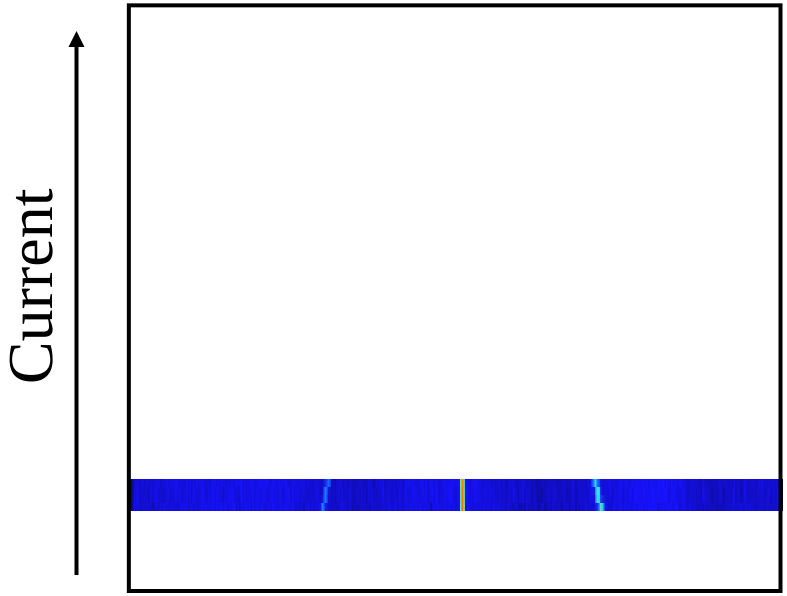
Small redshift with current

- Smaller than FTIR resolution
- Fairly noisy measurement

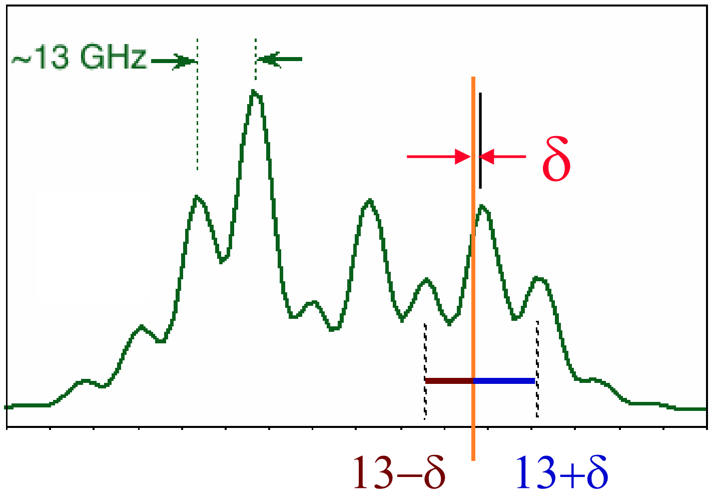
Current Tuning

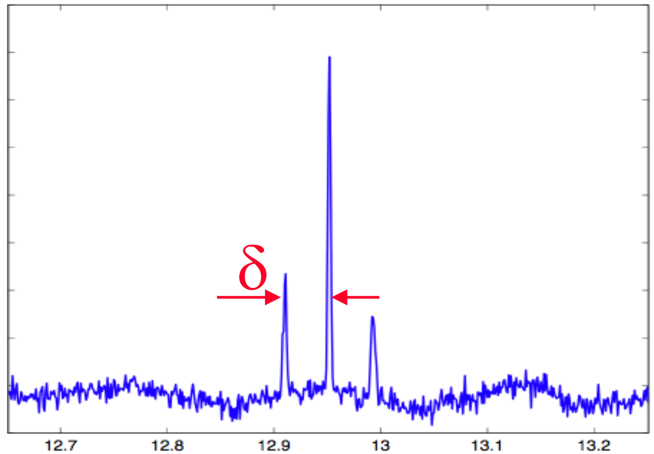


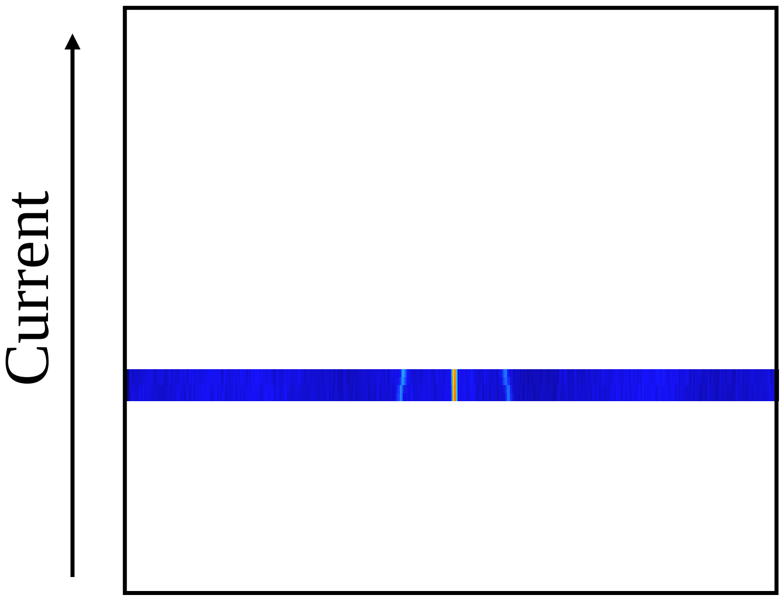




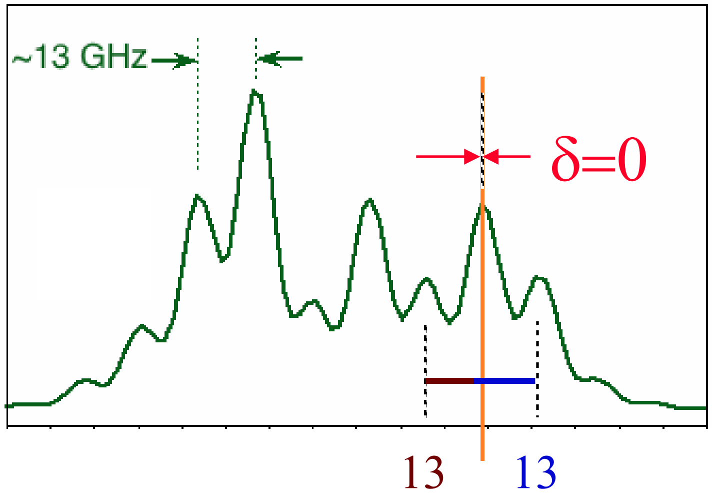
Current Tuning

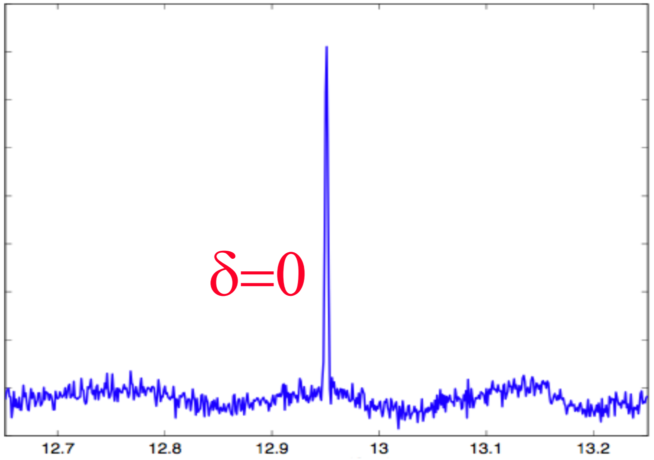


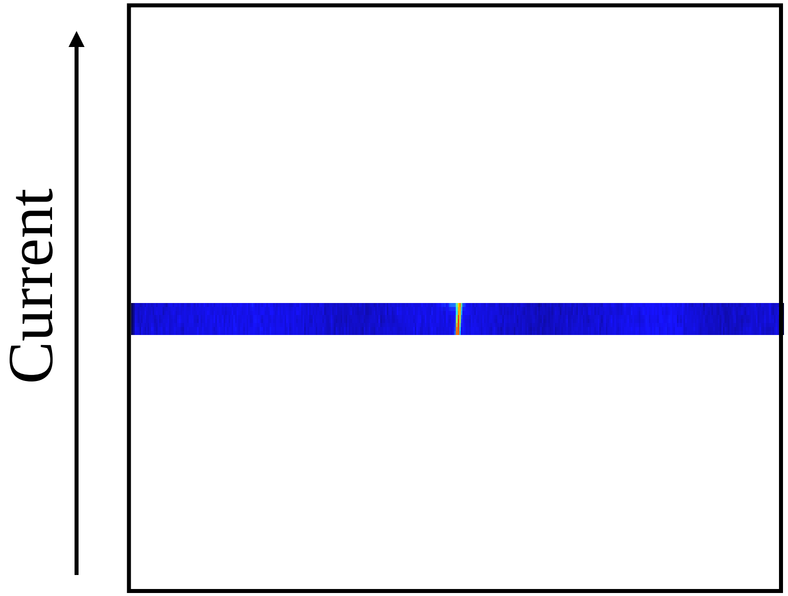




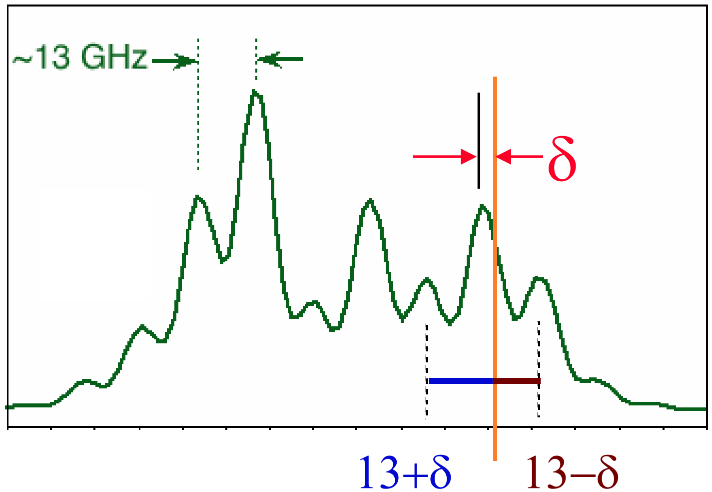
Current Tuning

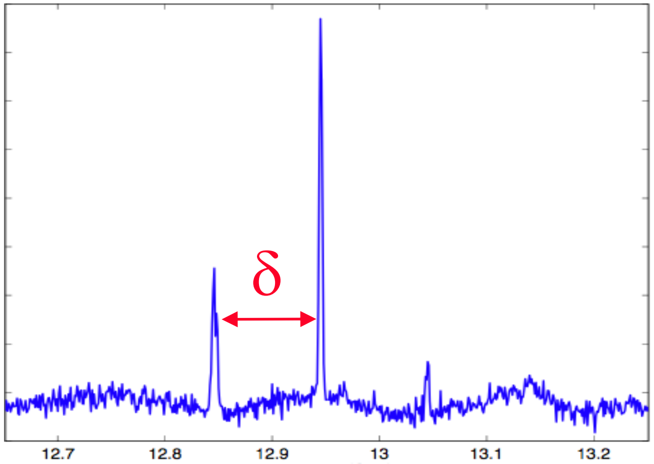


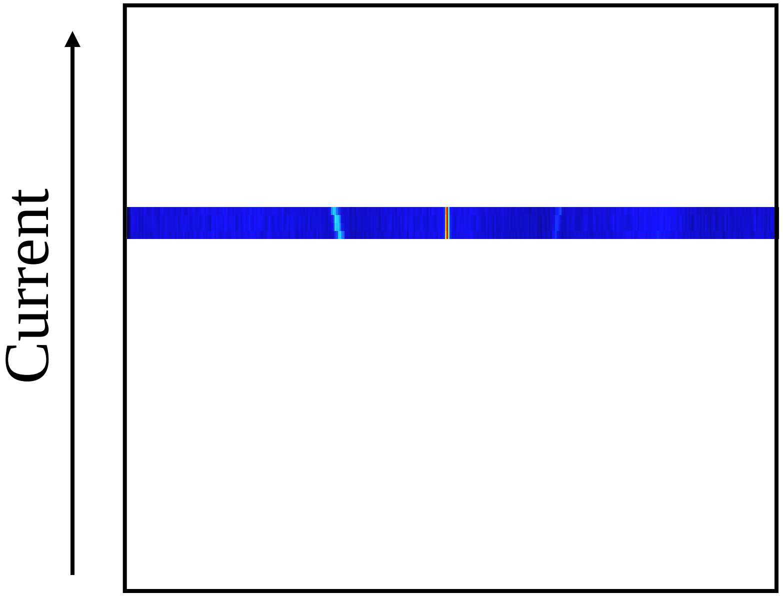




Current Tuning







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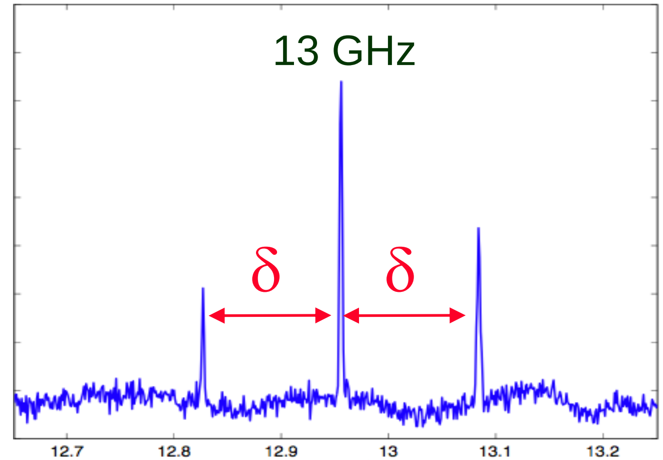
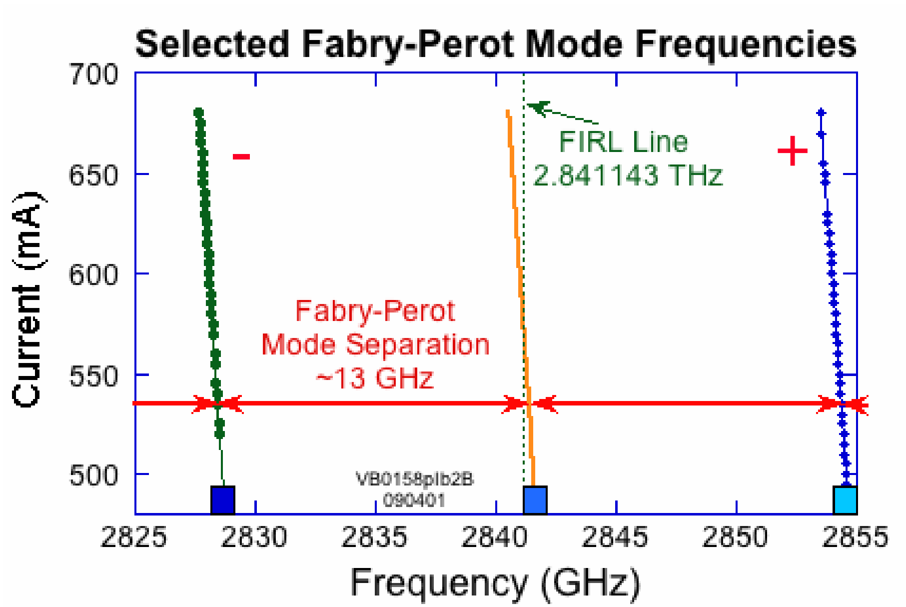
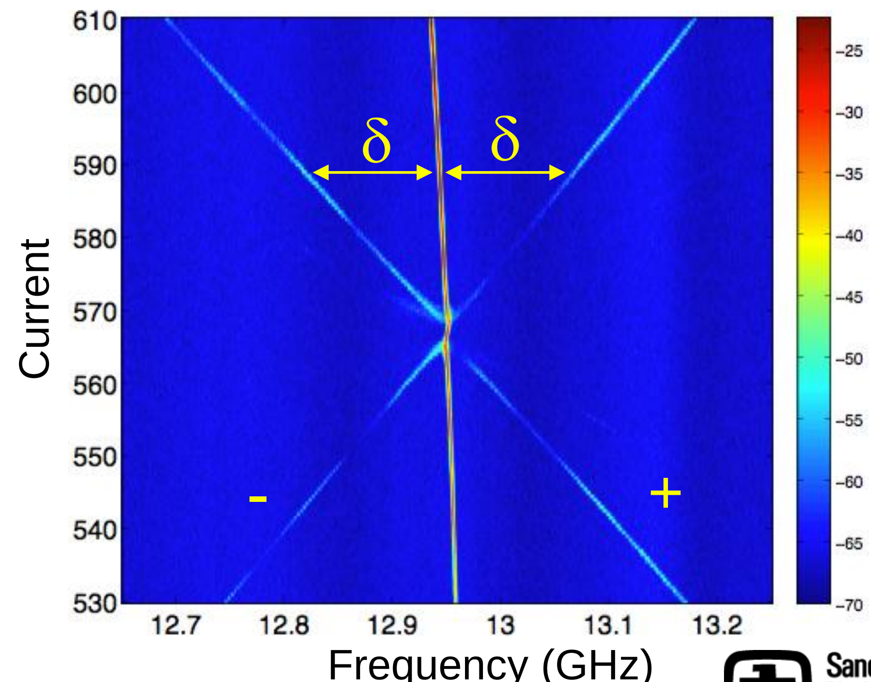
Current Tuning



~ 6 MHz / mA





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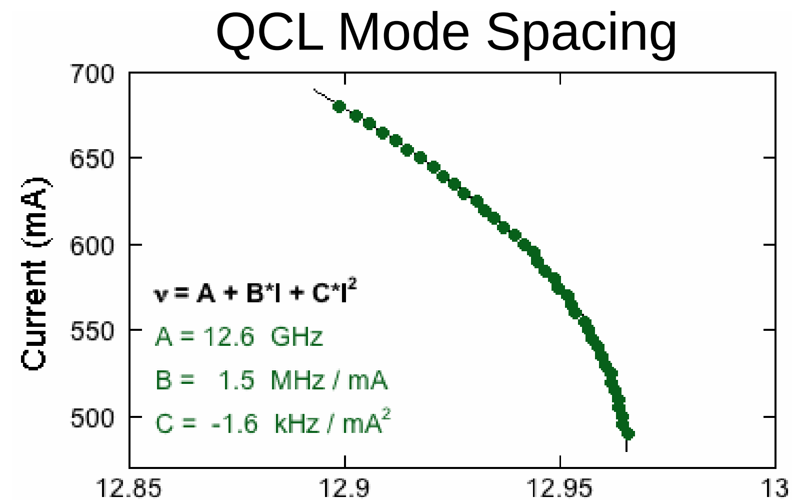
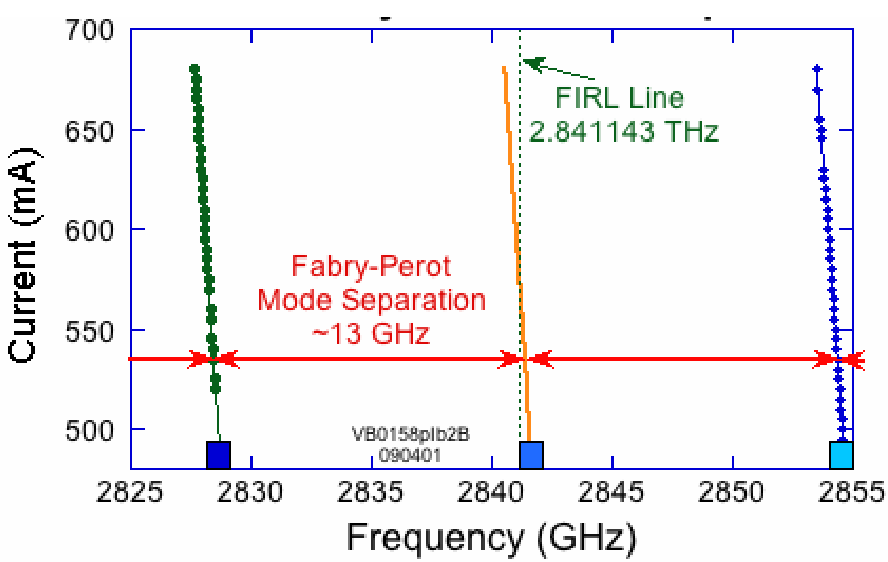
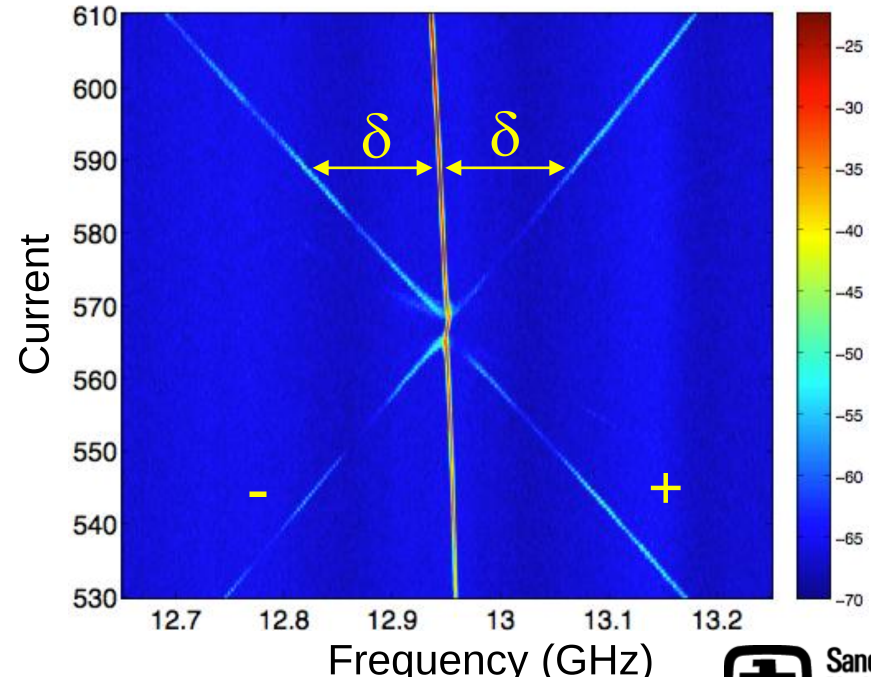
Current Tuning

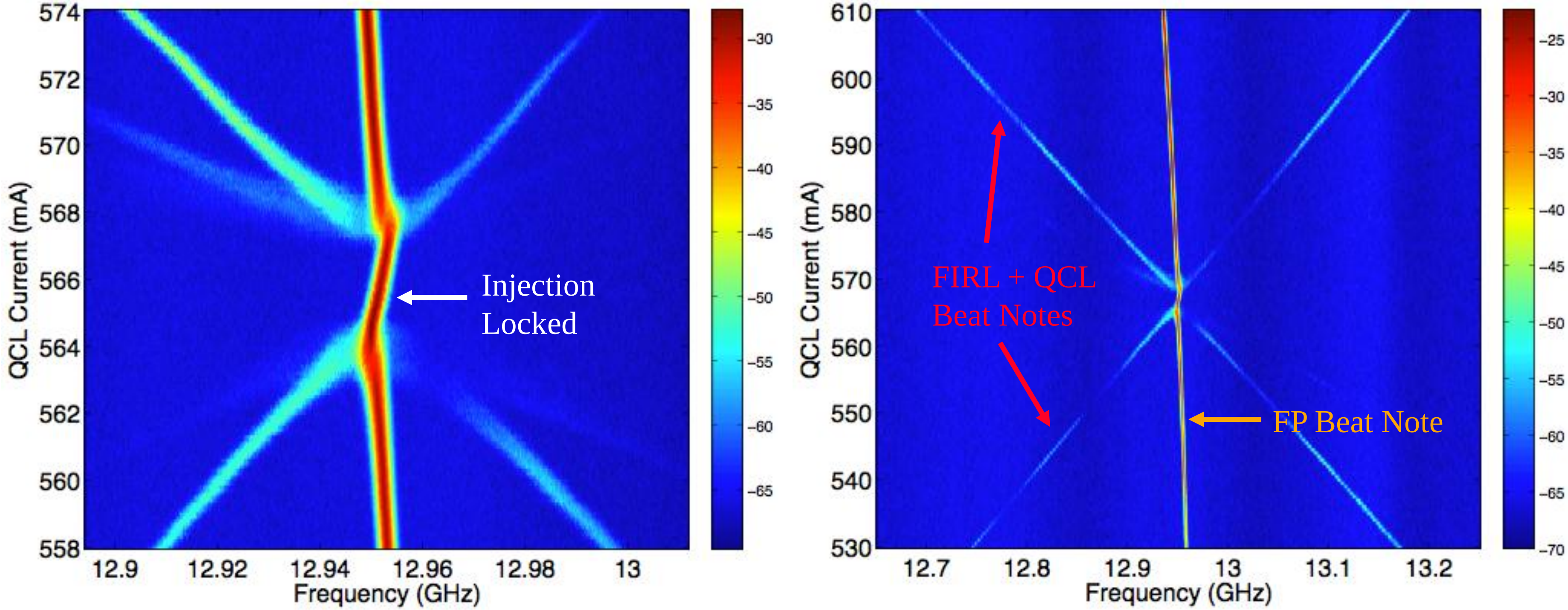






What happens when lasers cross?

- For δ < 23 MHz, the QCL is injection locked.



Wanke, Proc SPIE, **7953**, (2011)

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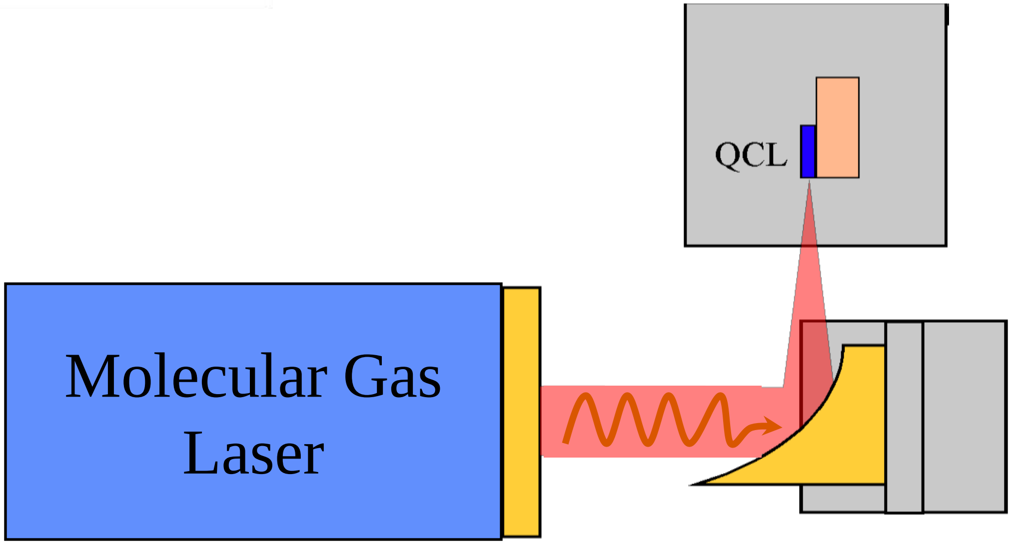
Outline

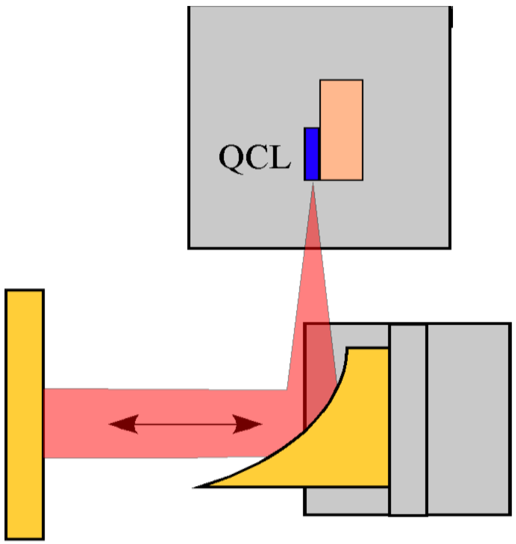
- **My definitions of “THz” and “THz gap”**
- **THz integrated circuits**
- **What transceivers can show us about QCLs**
  - Current Tuning
  - Feedback Sensitivity

Feedback Sensitivity



Some of the QCL emission retroreflects

Feedback Sensitivity



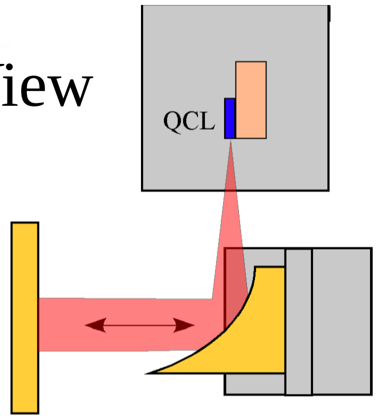
Some of the QCL emission retroreflects

- Another laser facet
- Window or lens
- External mixers

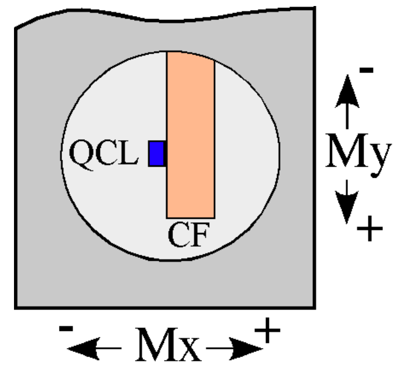
Wanke, Proc SPIE, **7953**, (2011)

Focal Position Feedback Sensitivity

Top View

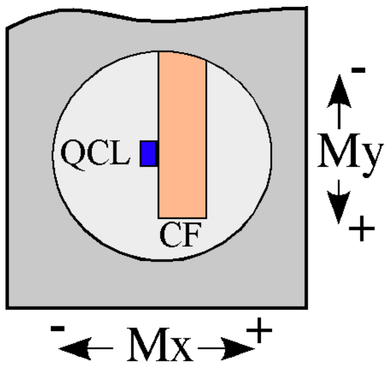


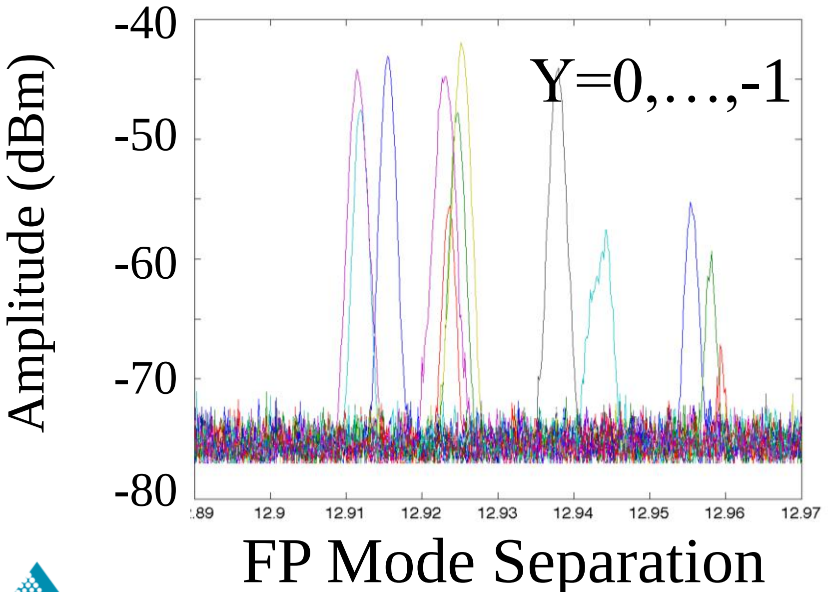
Front View

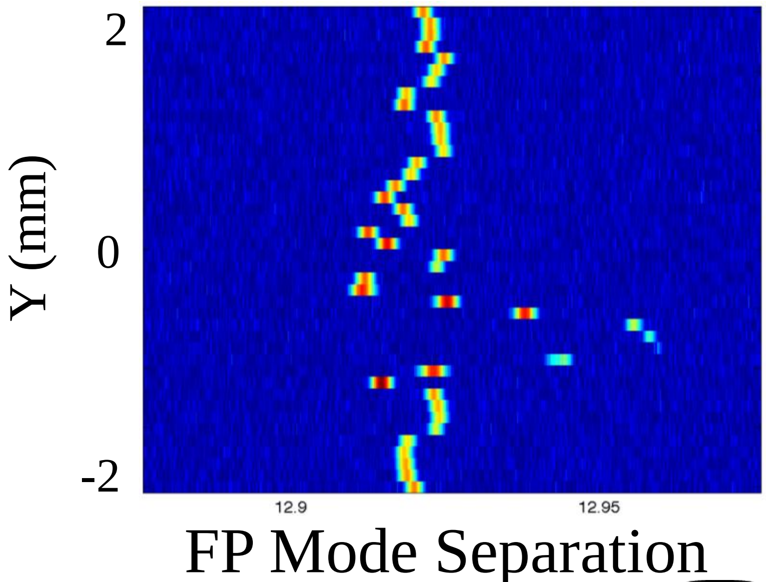


What happens when we scan the cryostat to find the FIRL beam?

Focal Position Feedback Sensitivity



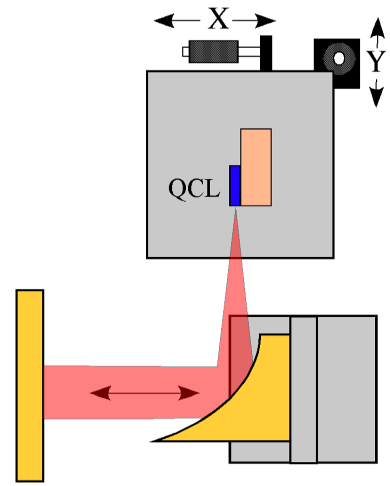


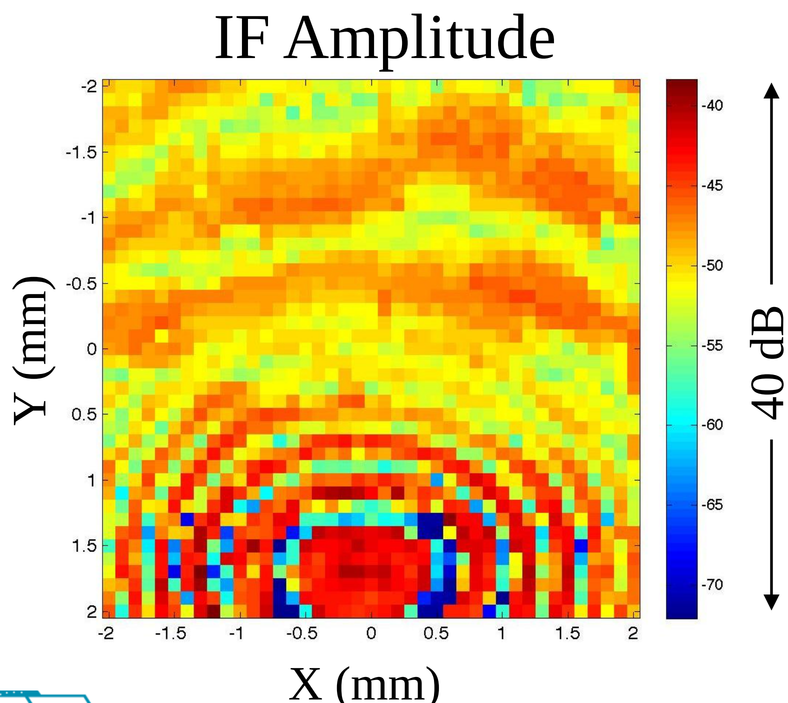


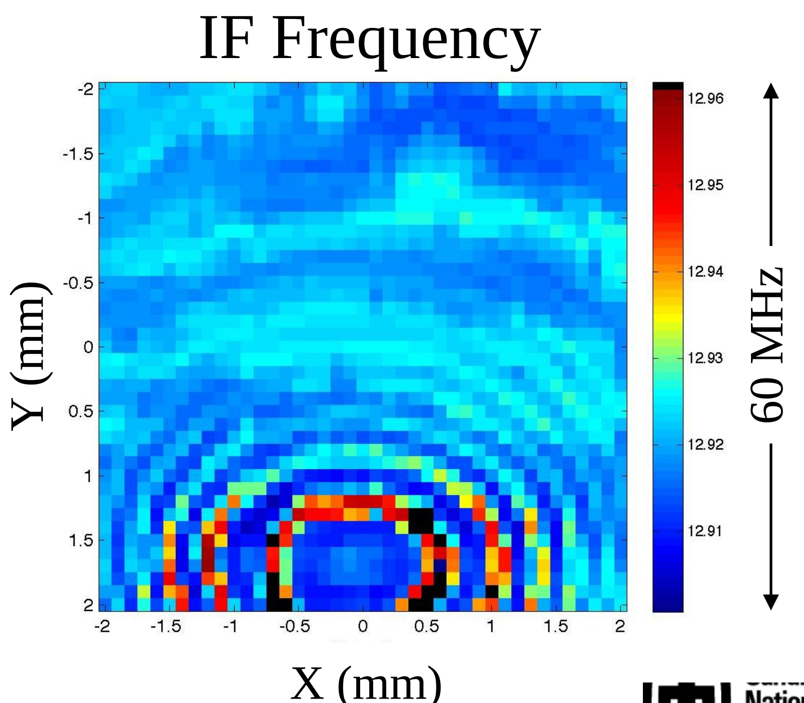
Focal Position Feedback Sensitivity

Strong frequency and amplitude pulling

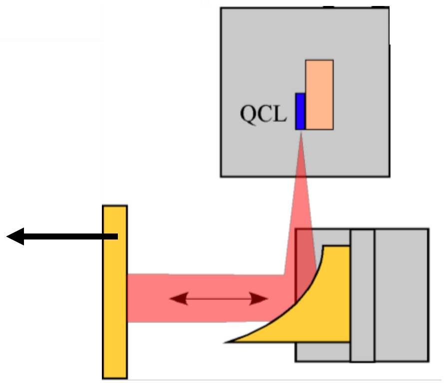
Simple demonstration of Airy diffraction pattern

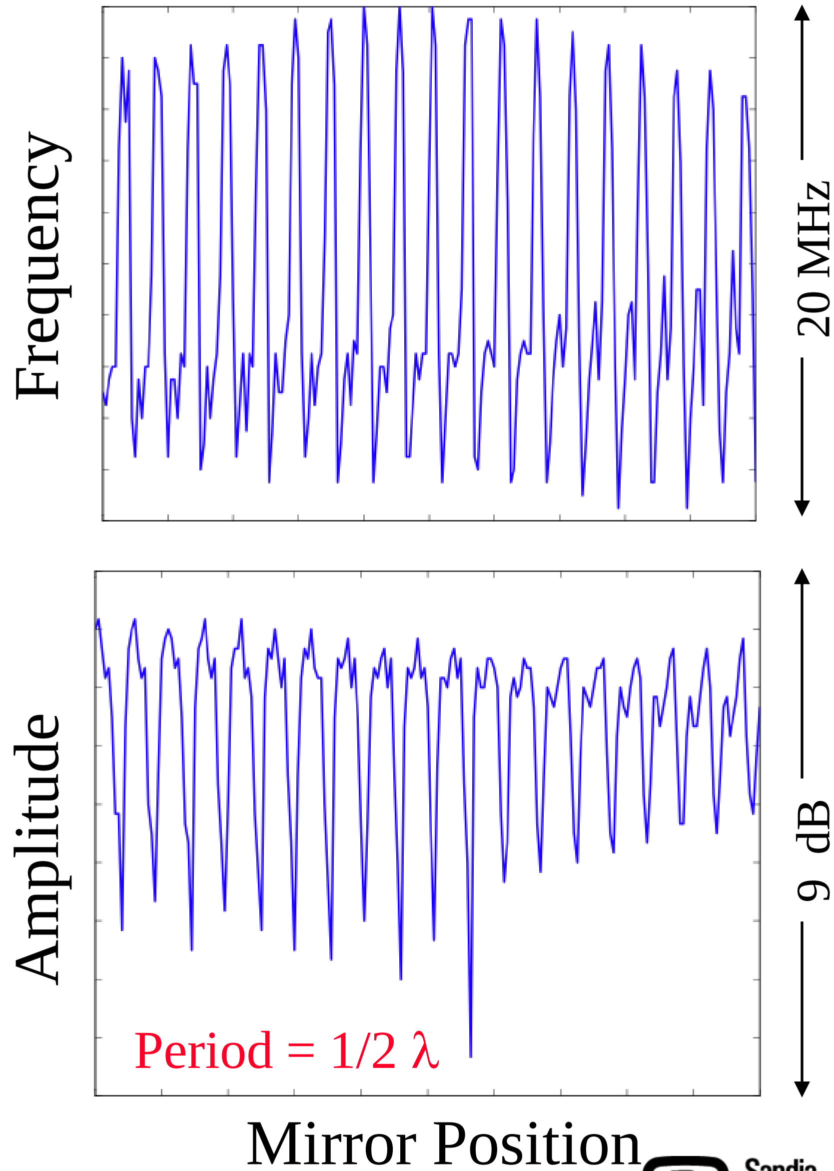


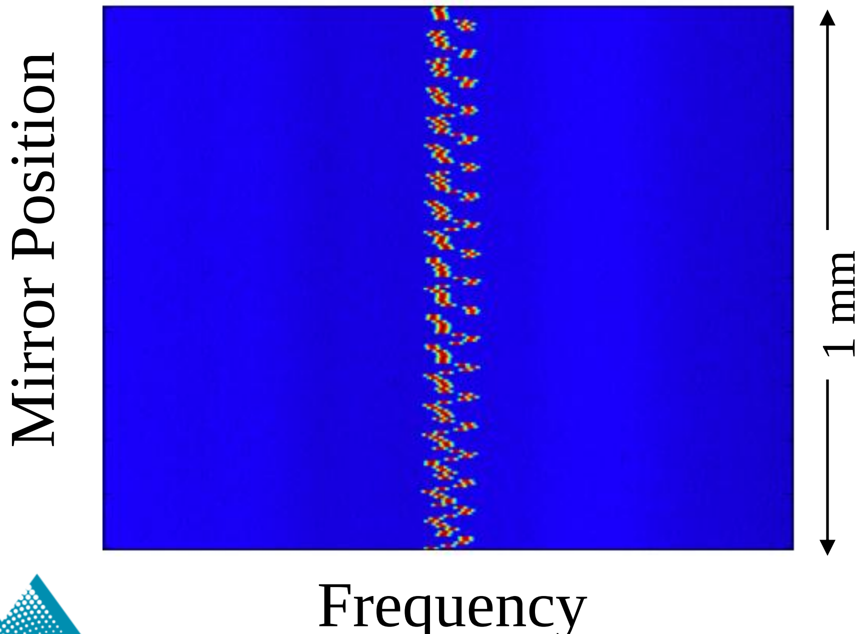




Cavity Length Sensitivity

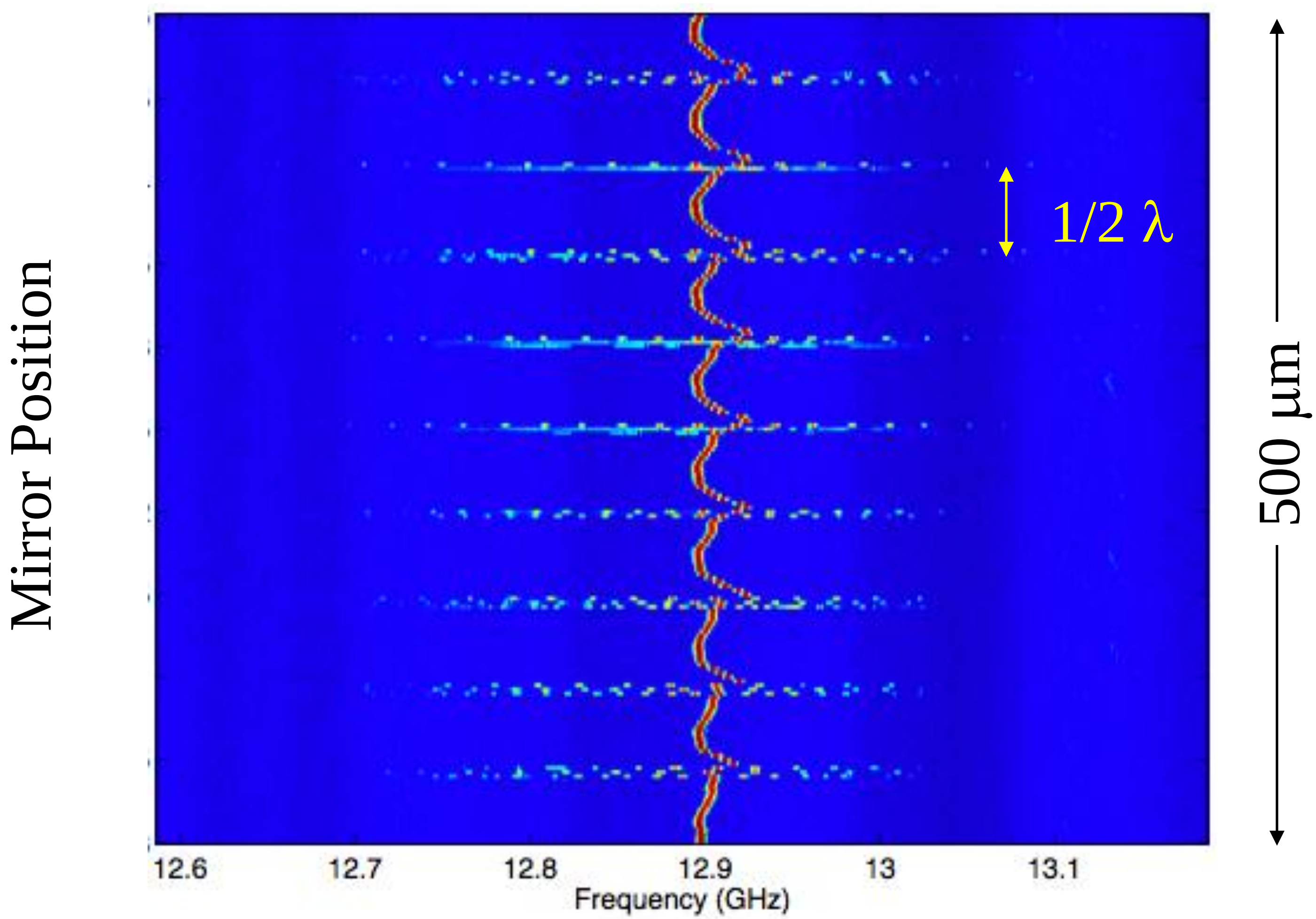




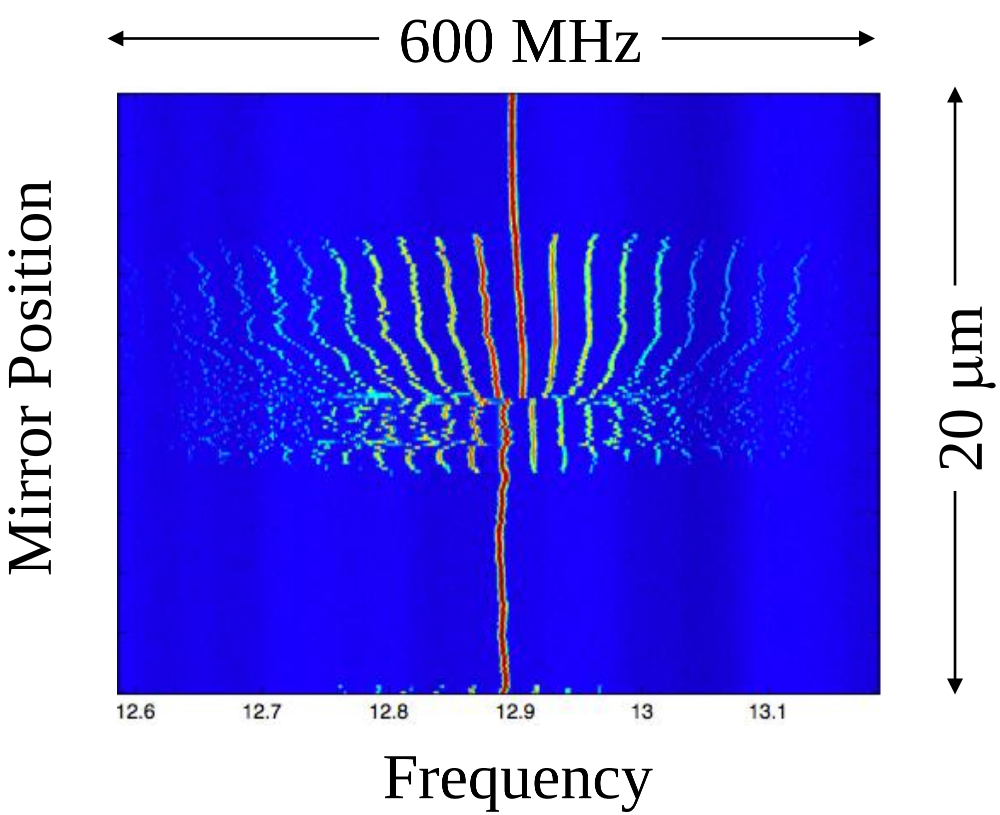


Feedback Effects on FP mode

Not always a single beat frequency



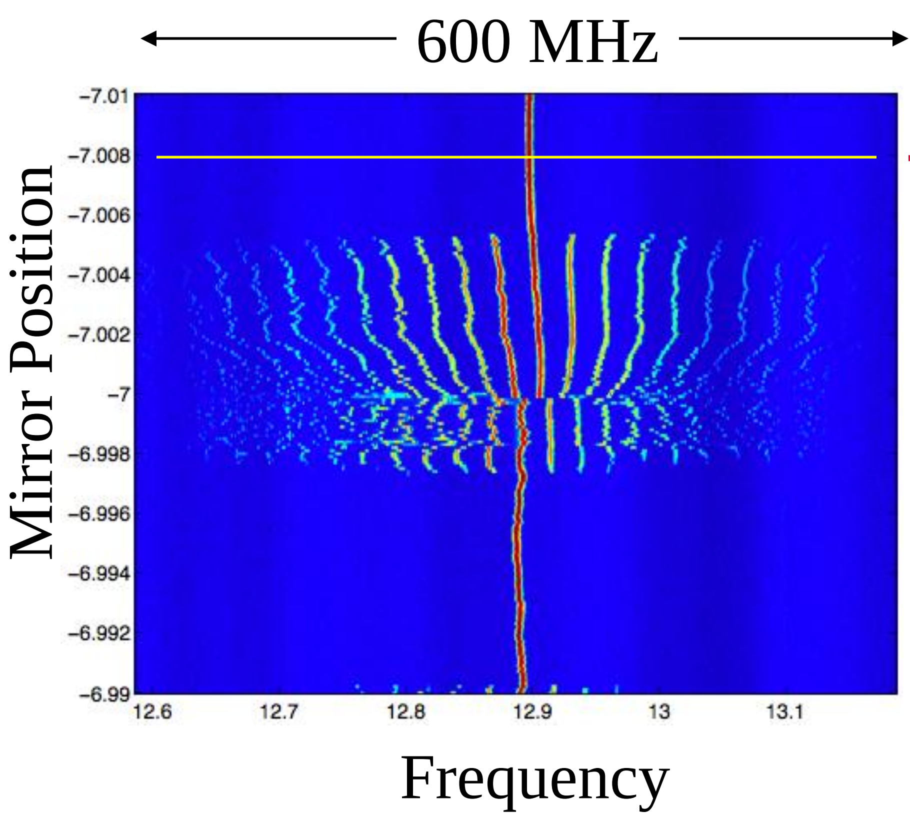
Feedback Effects on FP mode

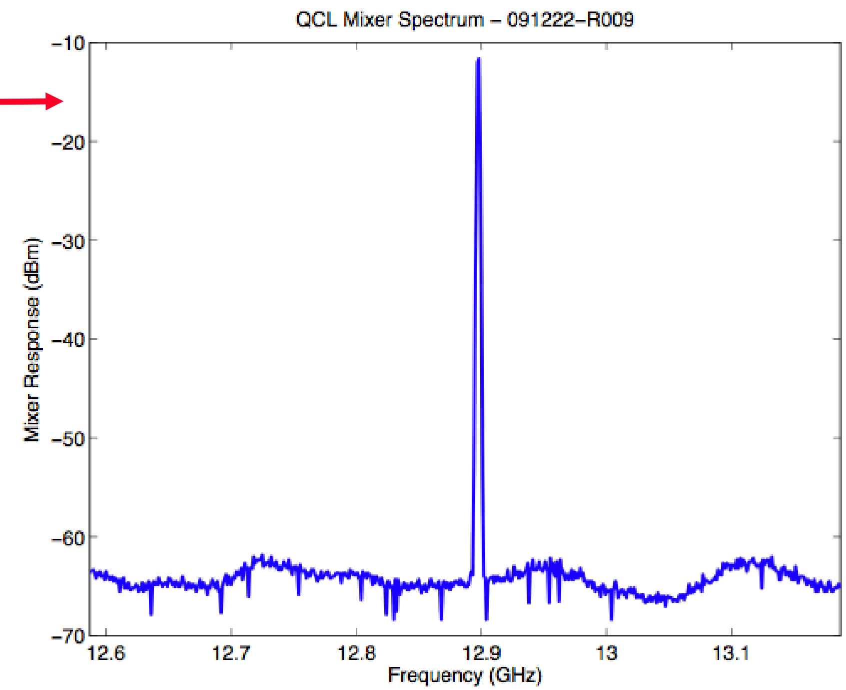


FP Modes Split into multiple lines

Feedback Effects on FP mode

Region I - Normal Fabry-Perot Modes





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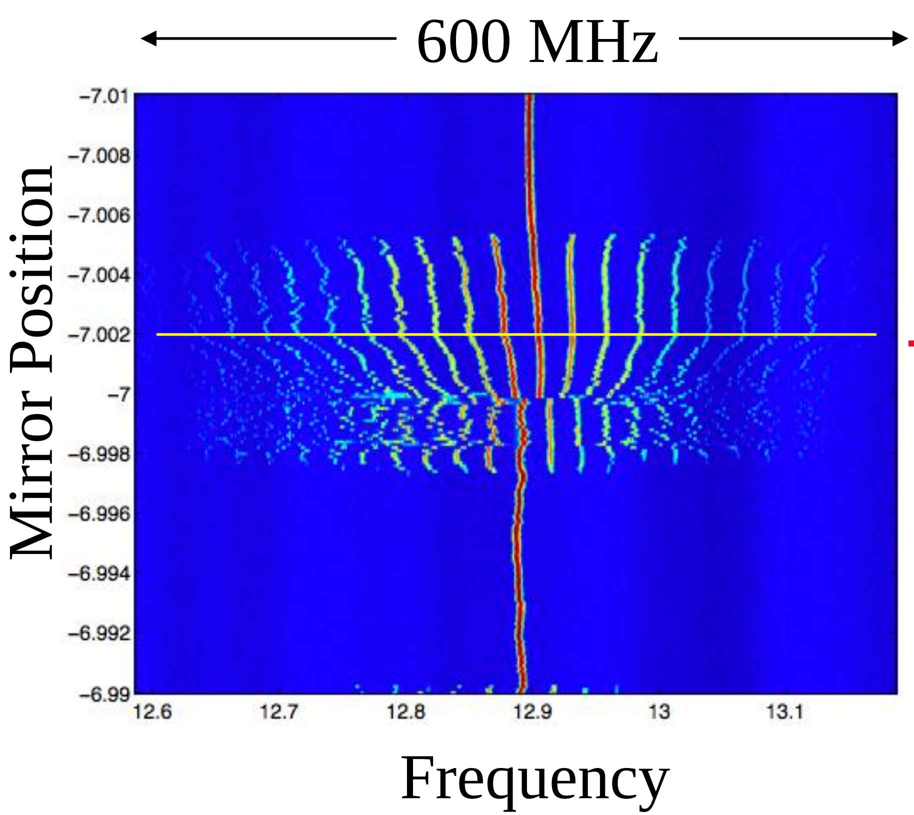
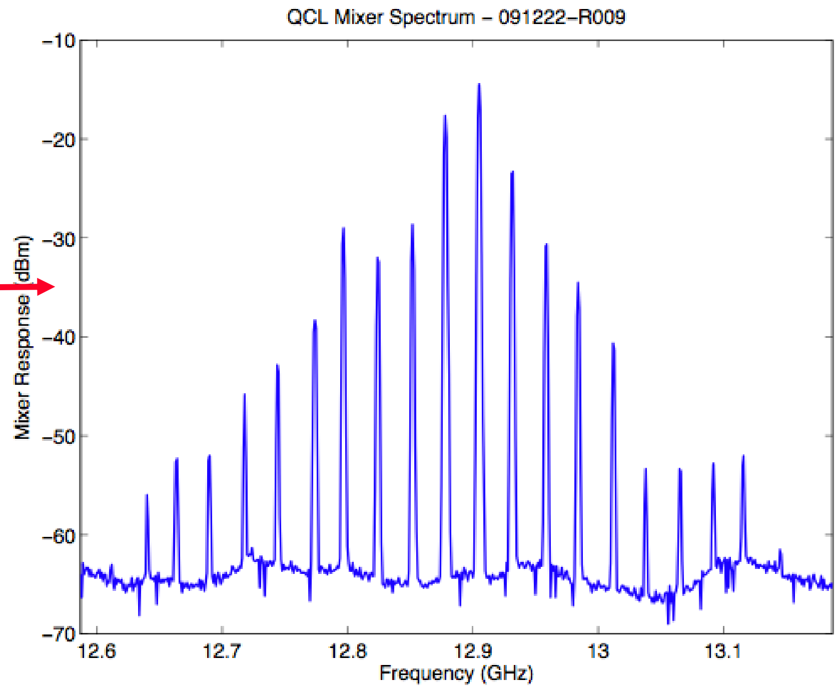
Feedback Effects on FP mode

Region II - Fabry-Perot Modes Bifurcate





Stable Spectrum

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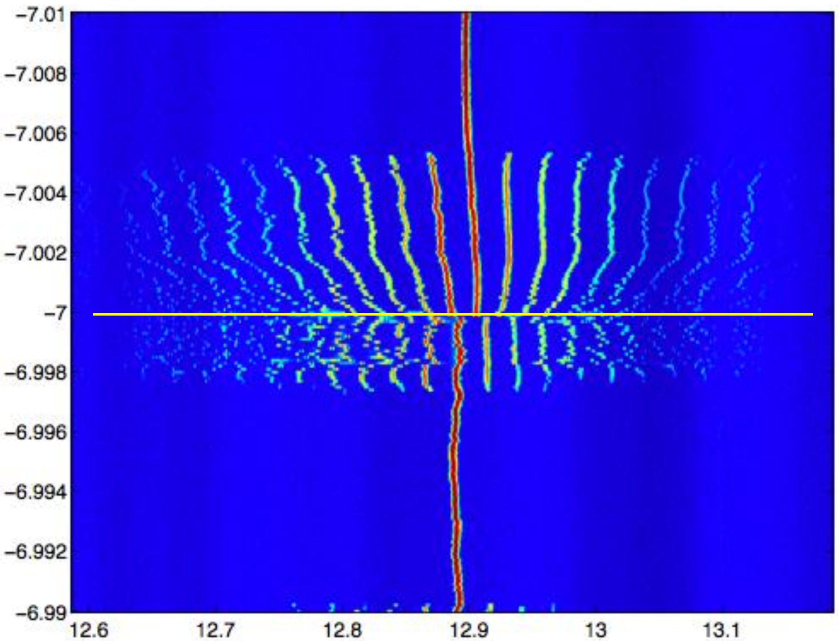
Feedback Effects on FP mode

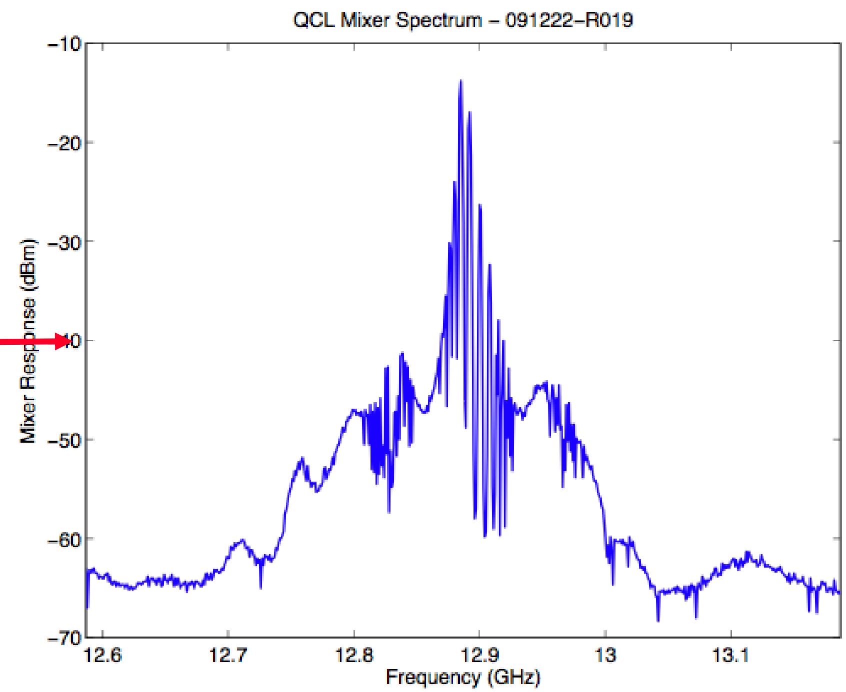
Region III - Chaos Onset

600 MHz

Mirror Position



Frequency

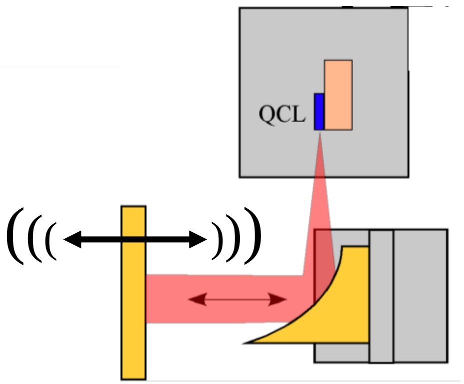


Unstable Spectrum

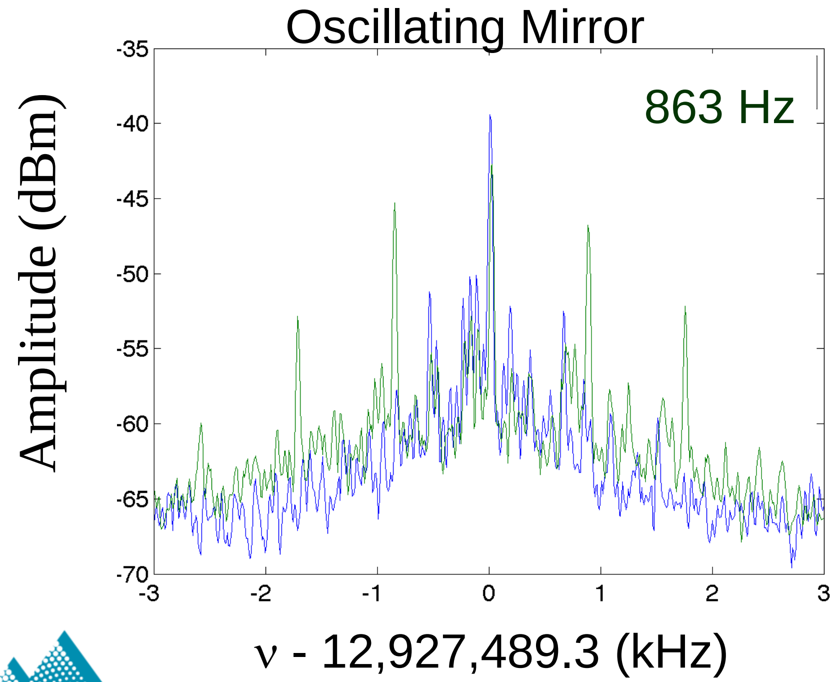
When life gives you ~~lemons~~ peaches...

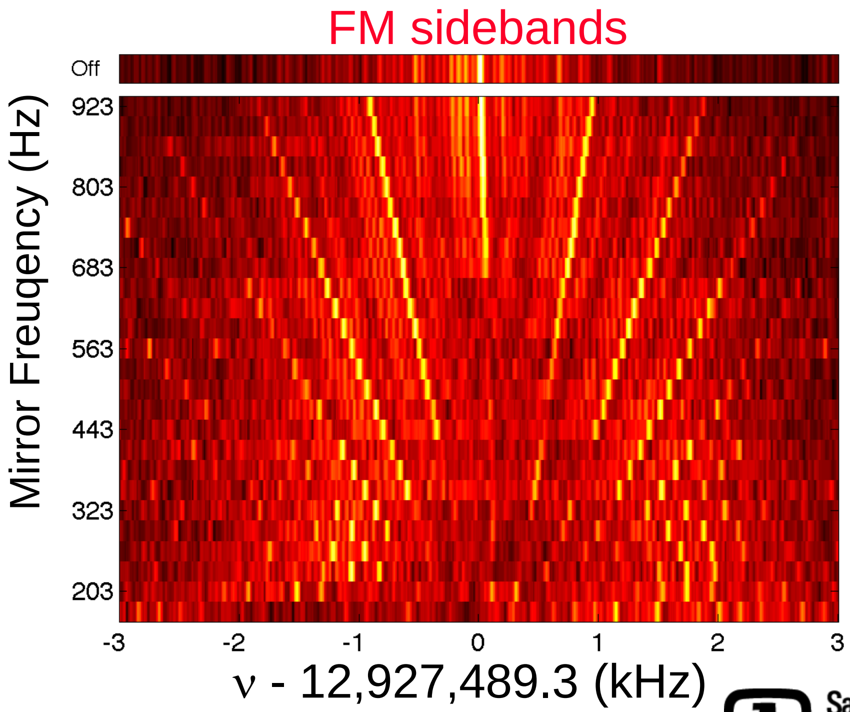
... use feedback to image the topography

Or...



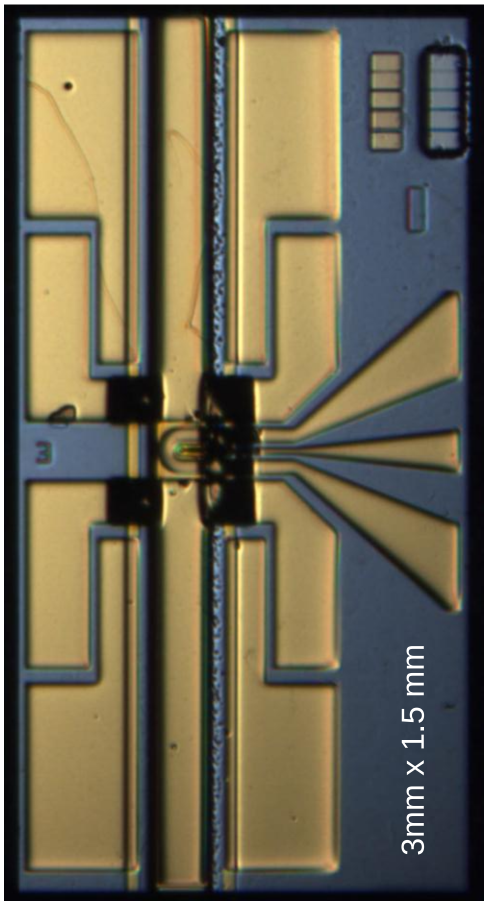
... use feedback to measure vibration frequency of a reflector



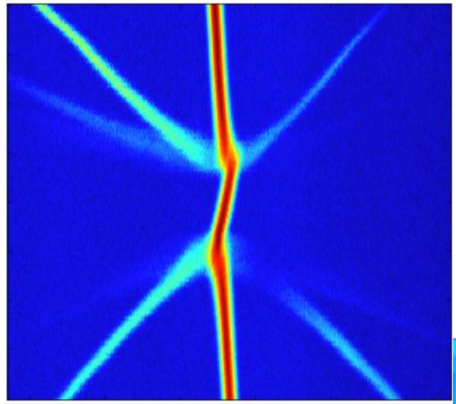


Summary

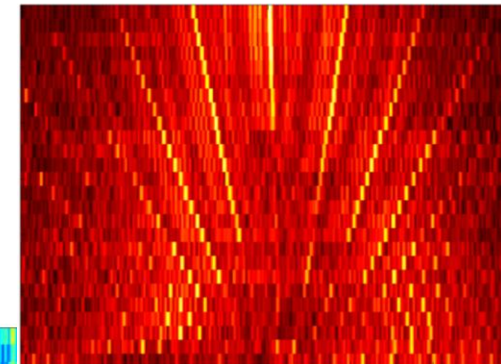
THz Integrated Transceiver



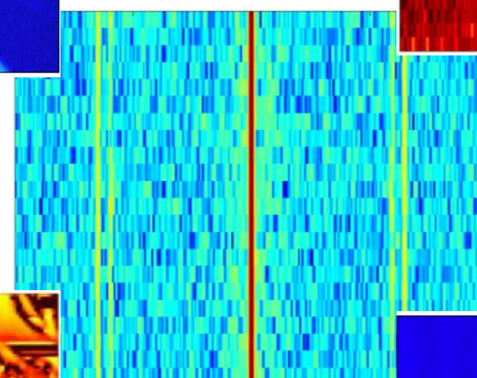
Laser Characterization
Injection Locking



Vibrometry

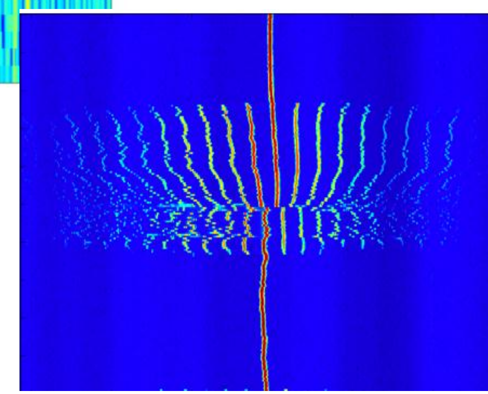


Phase Locking



Imaging

Feedback / Chaos



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