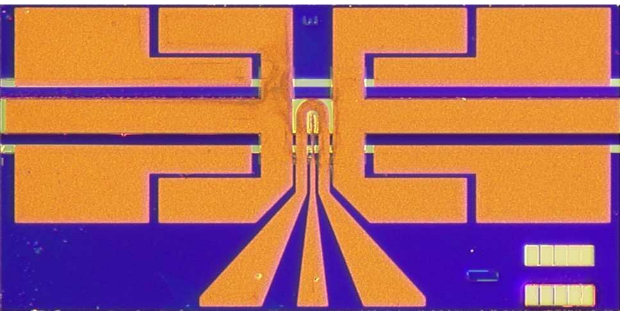
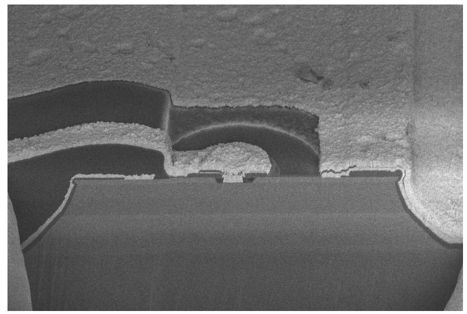
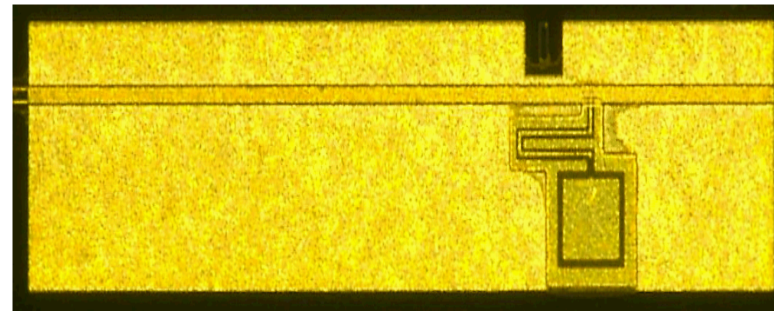
Exceptional service in the national interest

SAND2013-10206C

Integrated THz Quantum Cascade Laser Technology

Mike Wanke

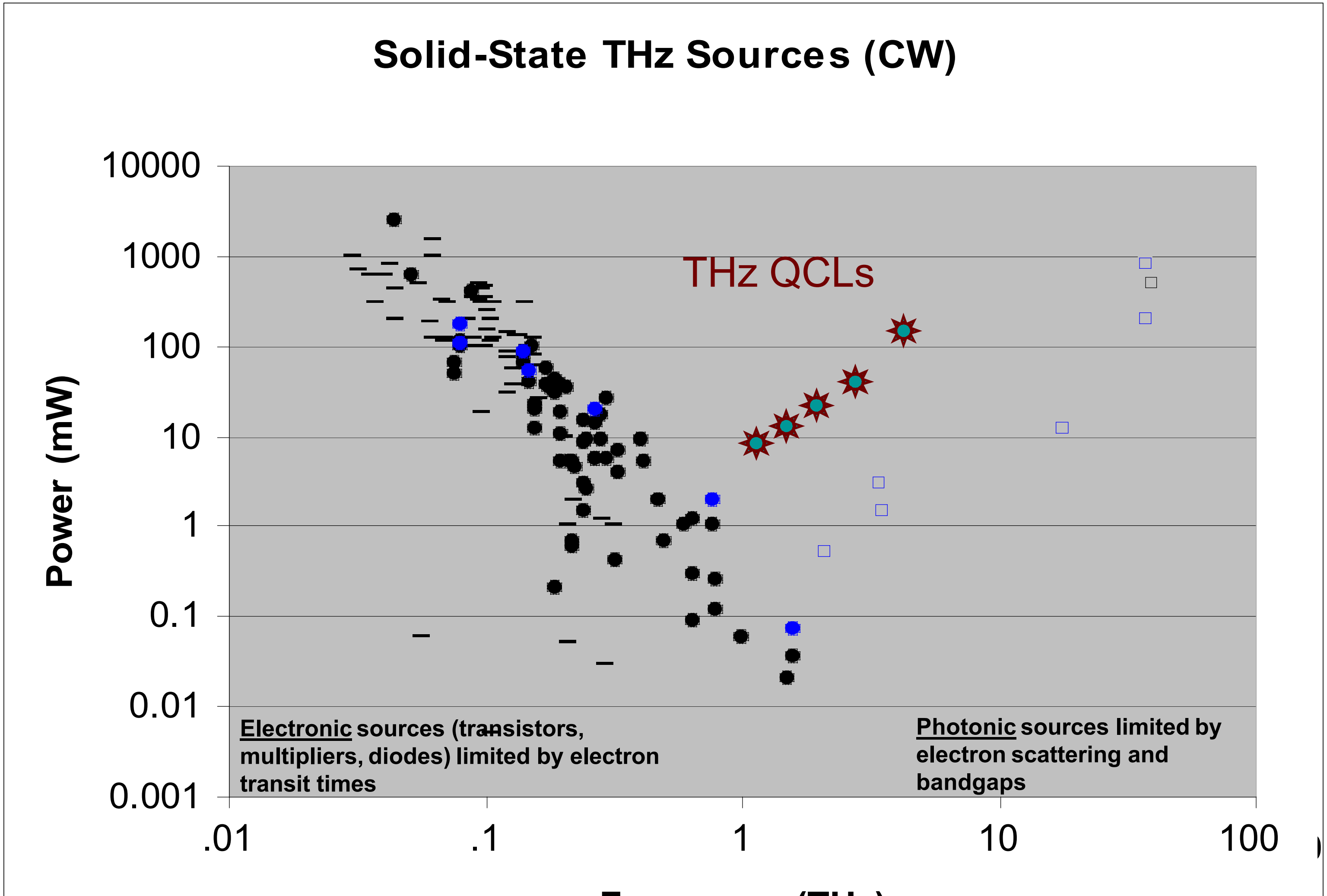
Rice University

Oct. 24, 2013

Outline

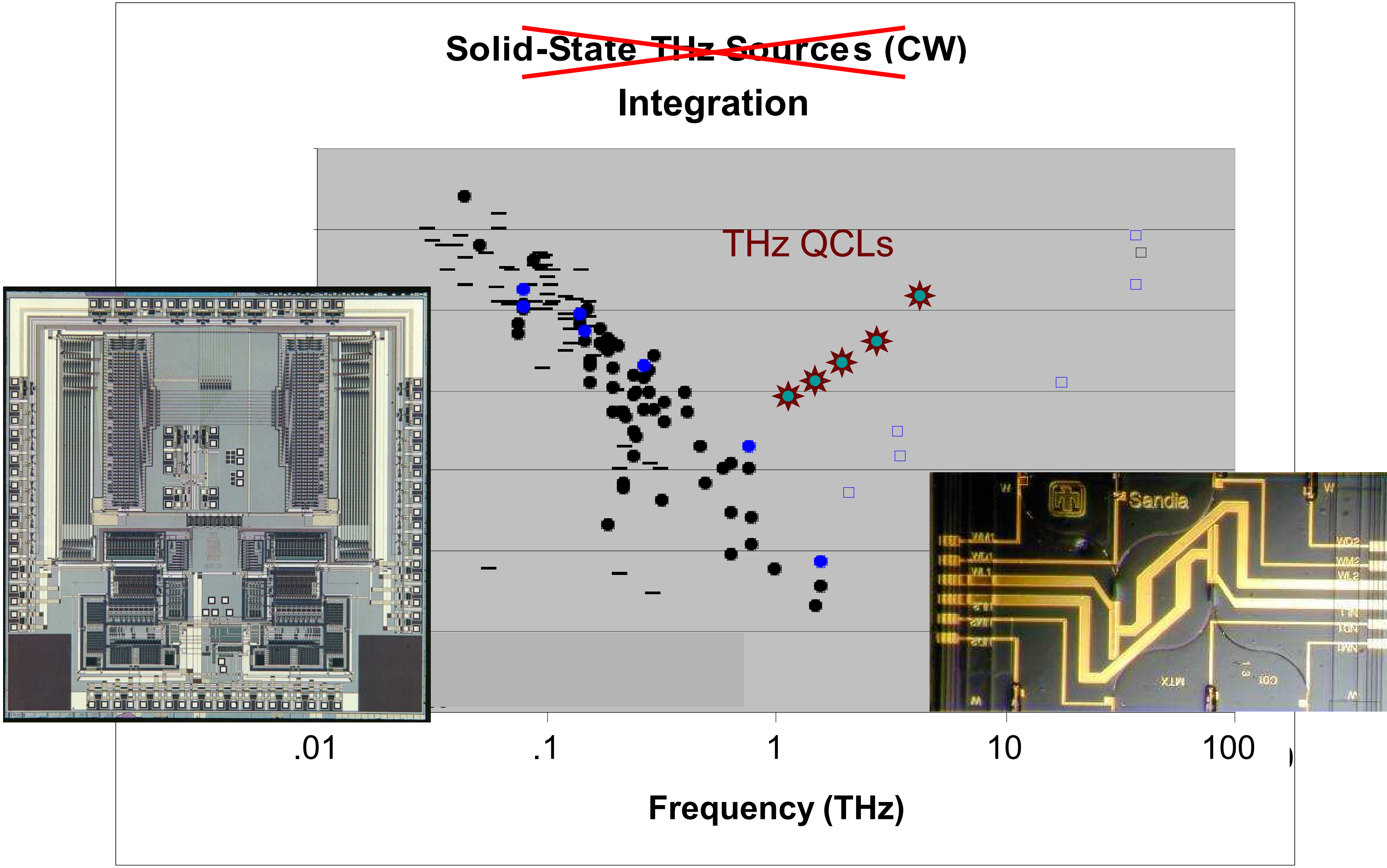
- Integration Motivation
  - Background
  - Heterodyne receiver example
- Integrated Schottky diodes and THz QCLs
  - Schottky diode review
  - Integration description
  - Diode response to internal laser fields
  - Receiver operation
  - Using the transceiver
- Integrated Schottky diodes and MIR QCLs

The “Shrinking” THz Gap



From Tom Crowe, VDI

The THz Gap

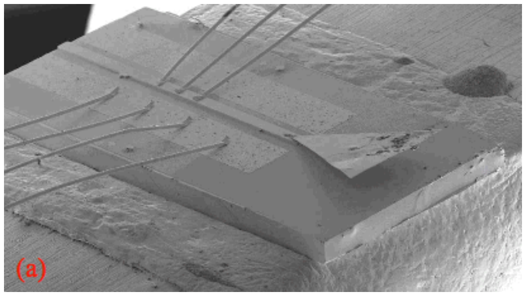


~~Solid-State THz Sources~~ (CW)
Integration
THz QCLs
.01
.1
1
10
100
Frequency (THz)
Sandia

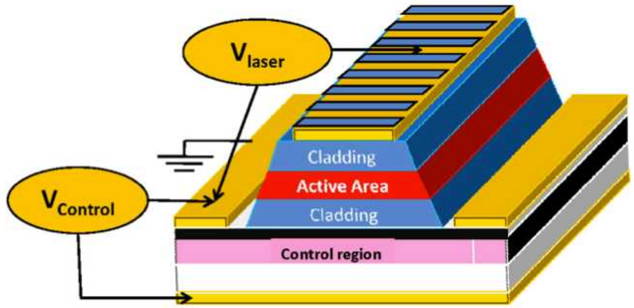
“Monolithic” Integration examples

Sandia National Laboratories

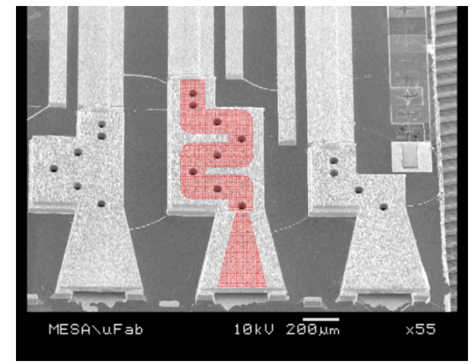
Antenna Coupling
(IEMN/CNRS)

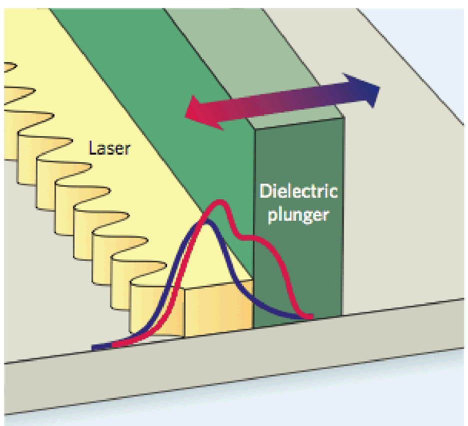


Modulator
(U. Paris 7)

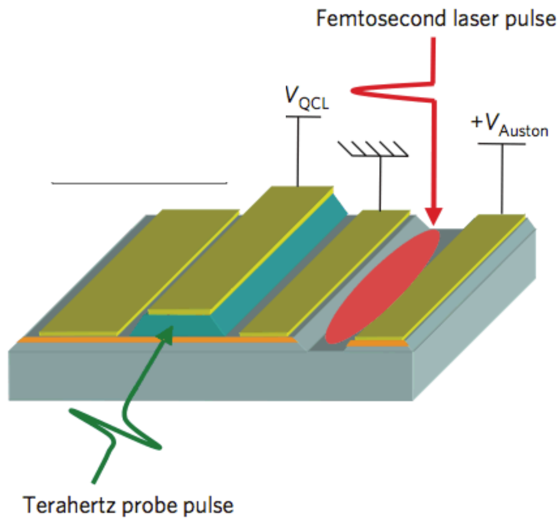


Integrated Waveguide
(Sandia)

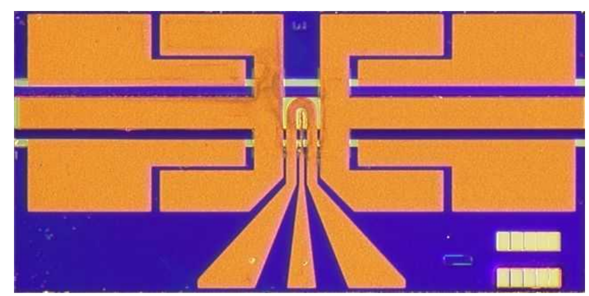




Mechanical Tuning
(MIT)

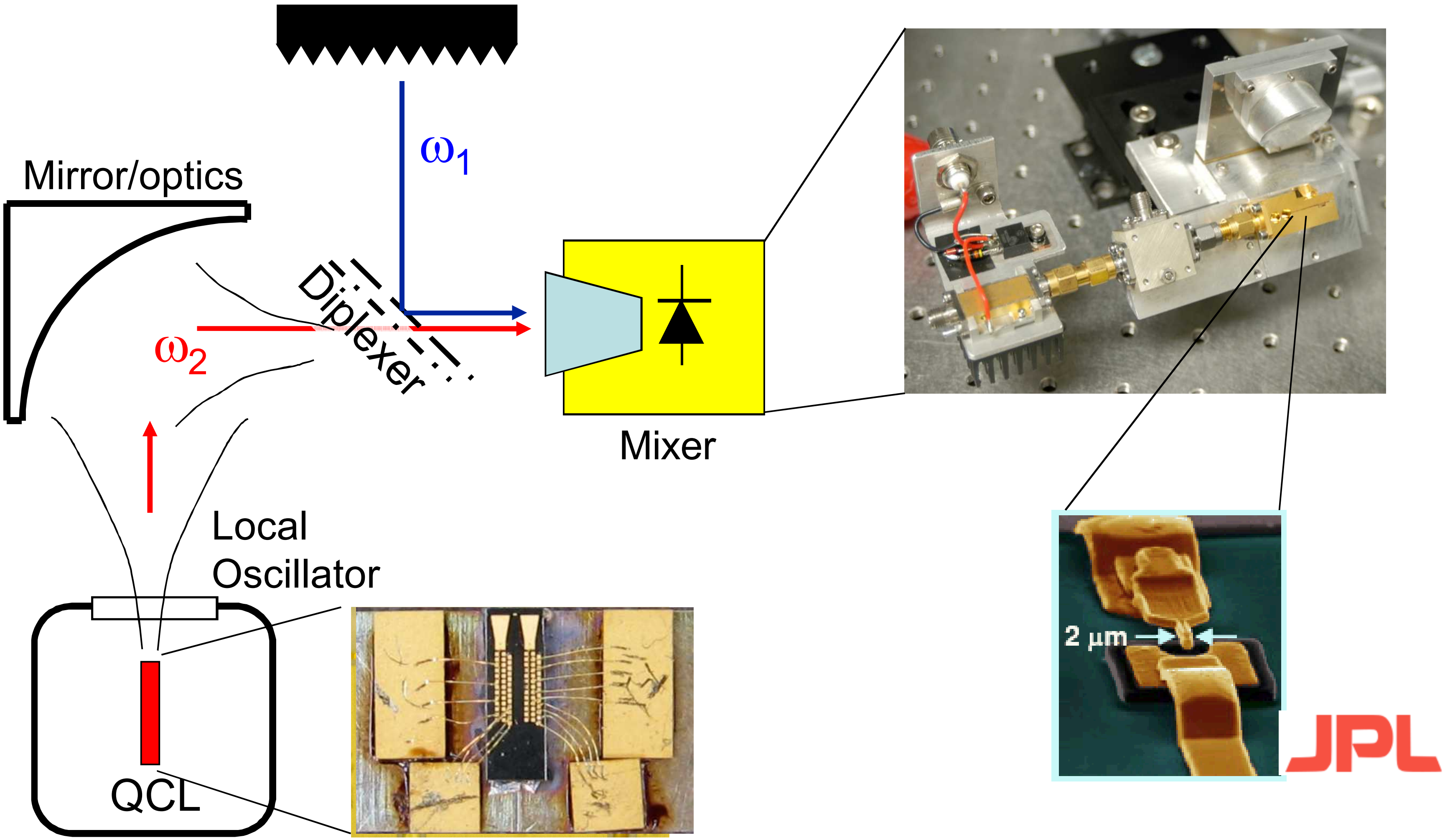


Pulse Amplifier
(Ecole Normale Sup.)



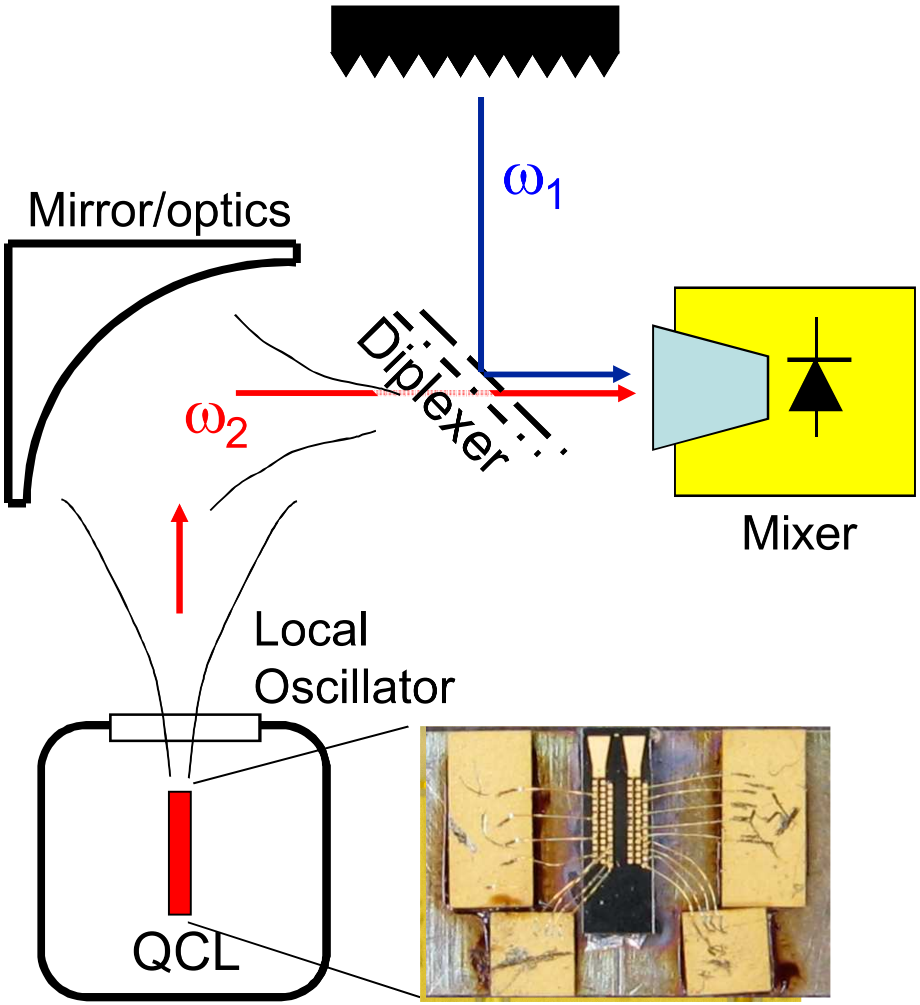
THz Transceiver
(Sandia)

Basic Heterodyne Receiver



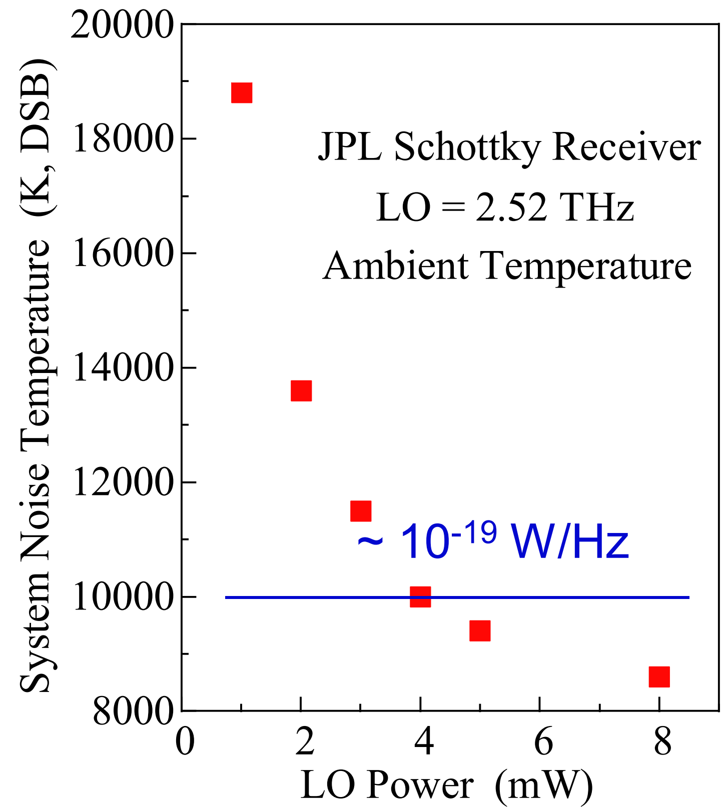
$$P \propto E_1E_2\cos(\omega_1-\omega_2) + f(\omega_1) + f(\omega_2)+ f(\omega_1+\omega_2)$$

Coherent Detector: THz receiver



Heterodyne receivers enable:

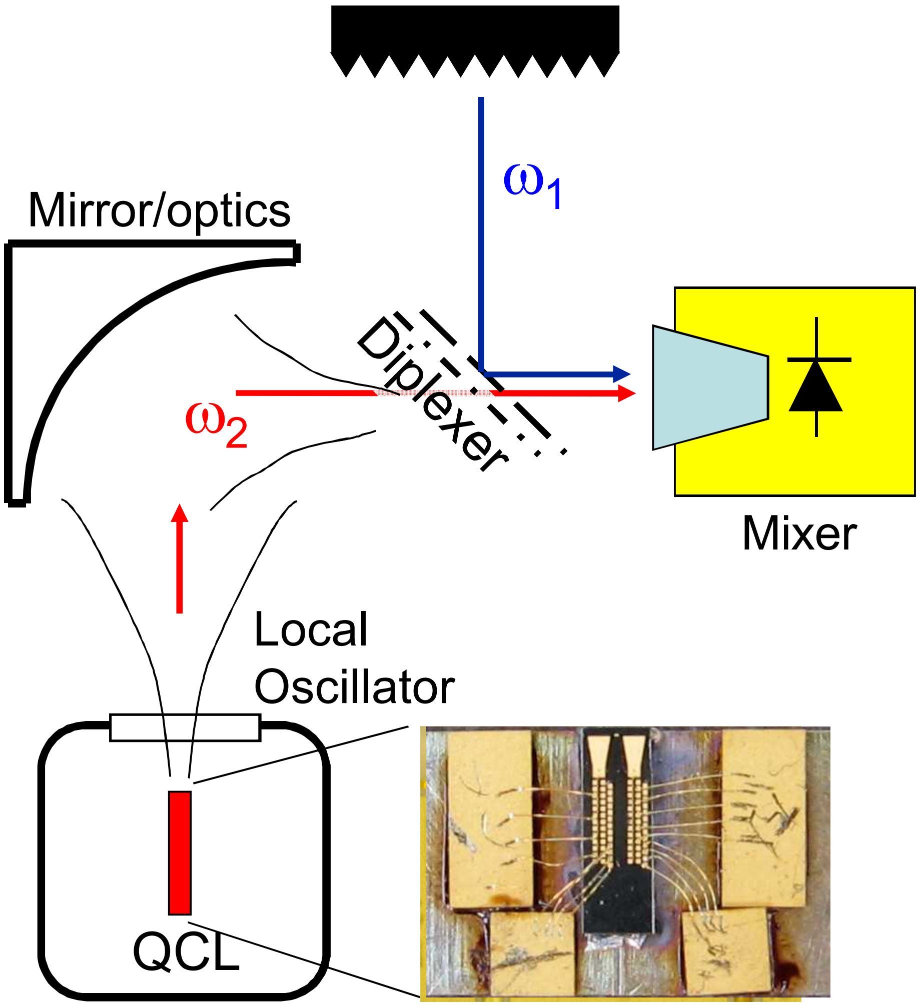
1) high sensitivity detection



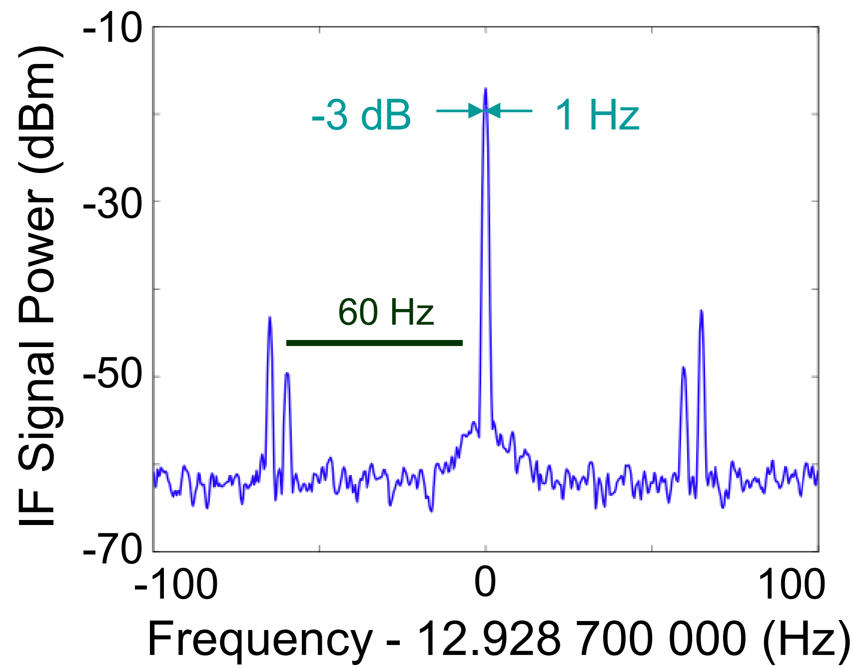
$$P \propto E_1 E_2 \cos(\omega_1 - \omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1 + \omega_2)$$

Coherent Detector: THz receiver

Sandia National Laboratories



Heterodyne receivers enable:
1) high sensitivity detection
2) high spectral resolution



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

Lee, IEEE JSTQE, **14**, 370, (2008)

Outline

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  - Heterodyne receiver example

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  - Schottky diode review
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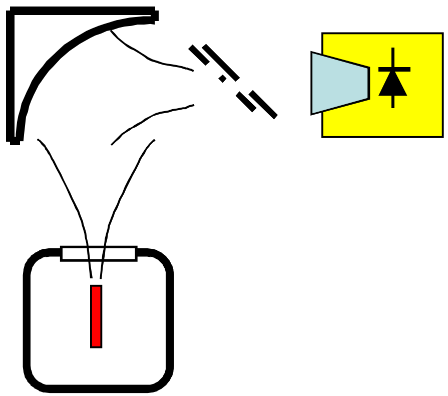
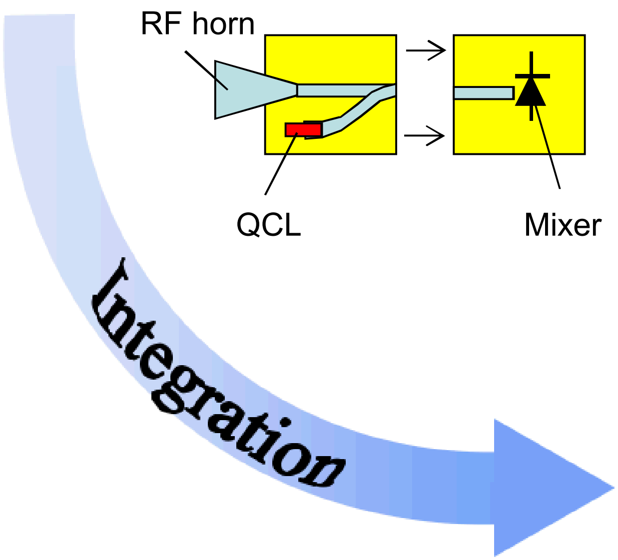
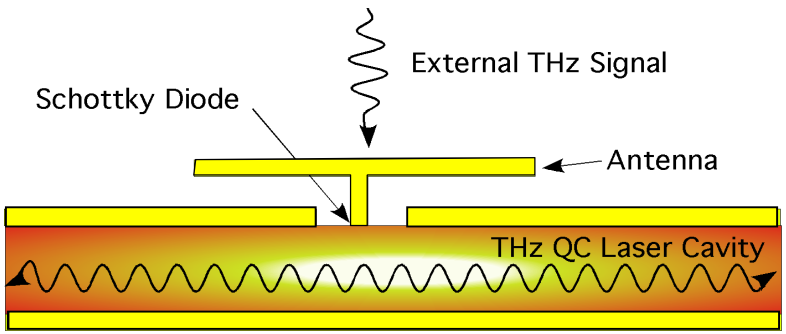
- Integrated Schottky diodes and MIR QCLs

Integration Roadmap

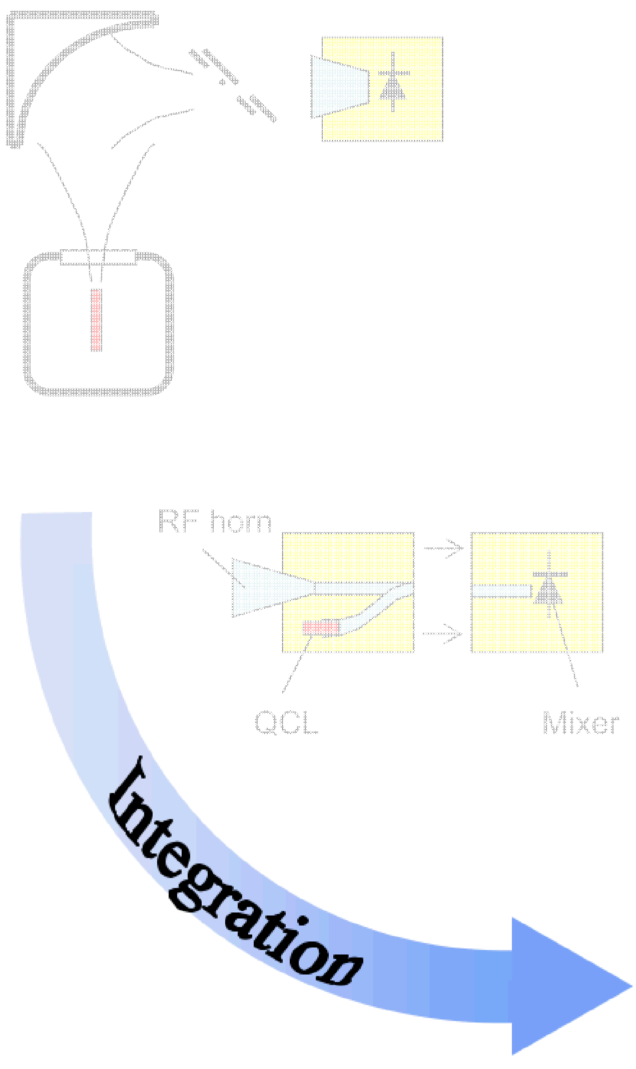


- Quasi-Optical Receiver
- Rectangular Waveguide Integration
- Monolithic Integration

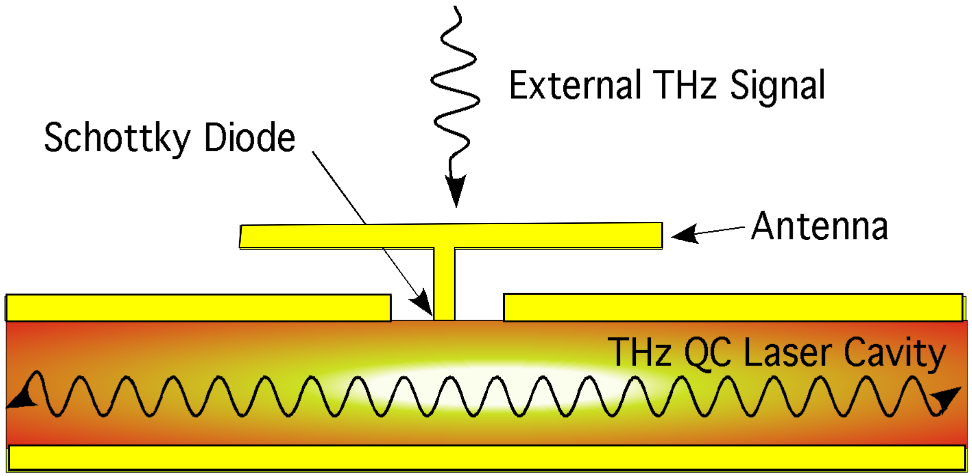




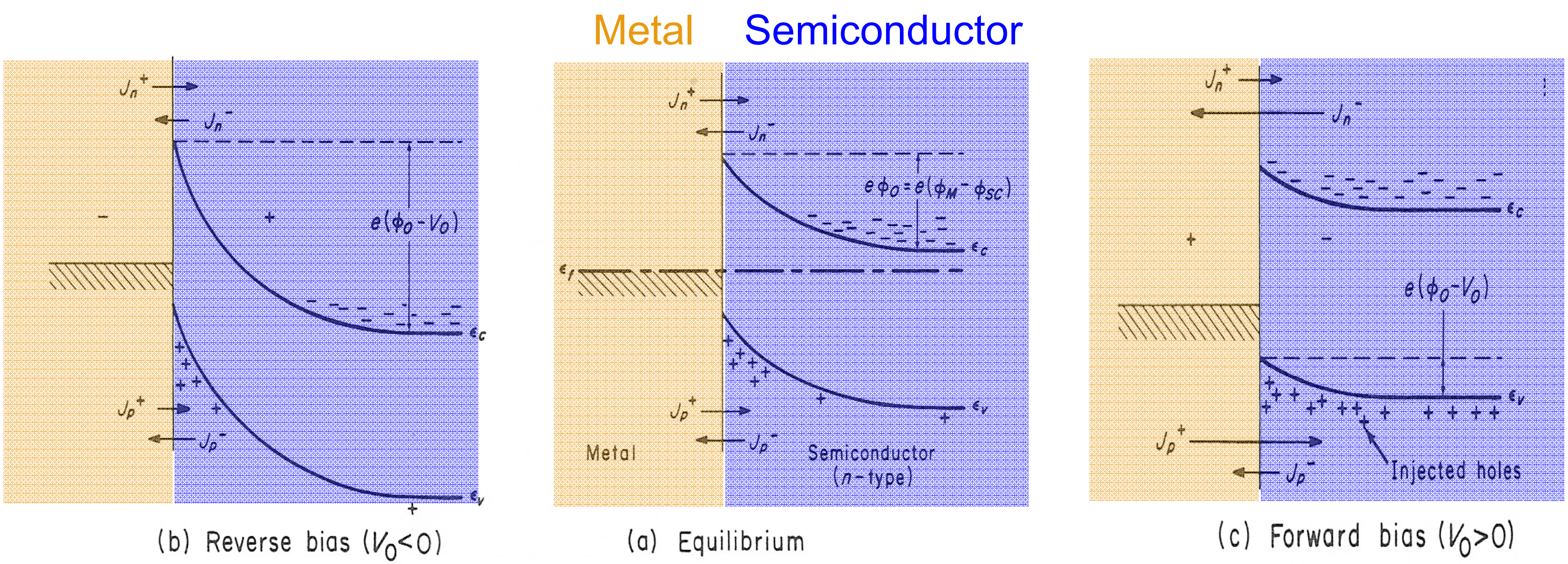
Today's Topic



- Quasi-Optical Receiver
- Rectangular Waveguide Integration
- Monolithic Integration
  - Schottky diode with THz QCL

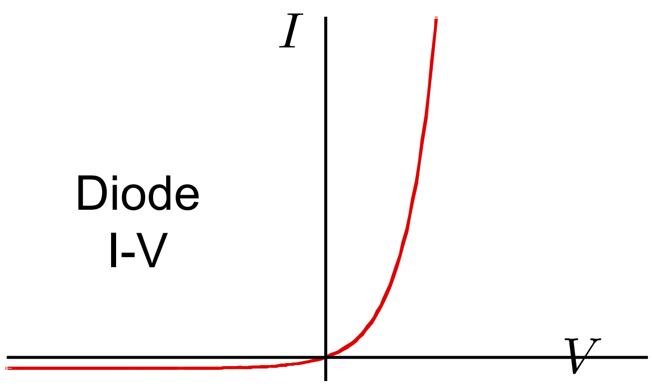


Schottky Diode Essentials



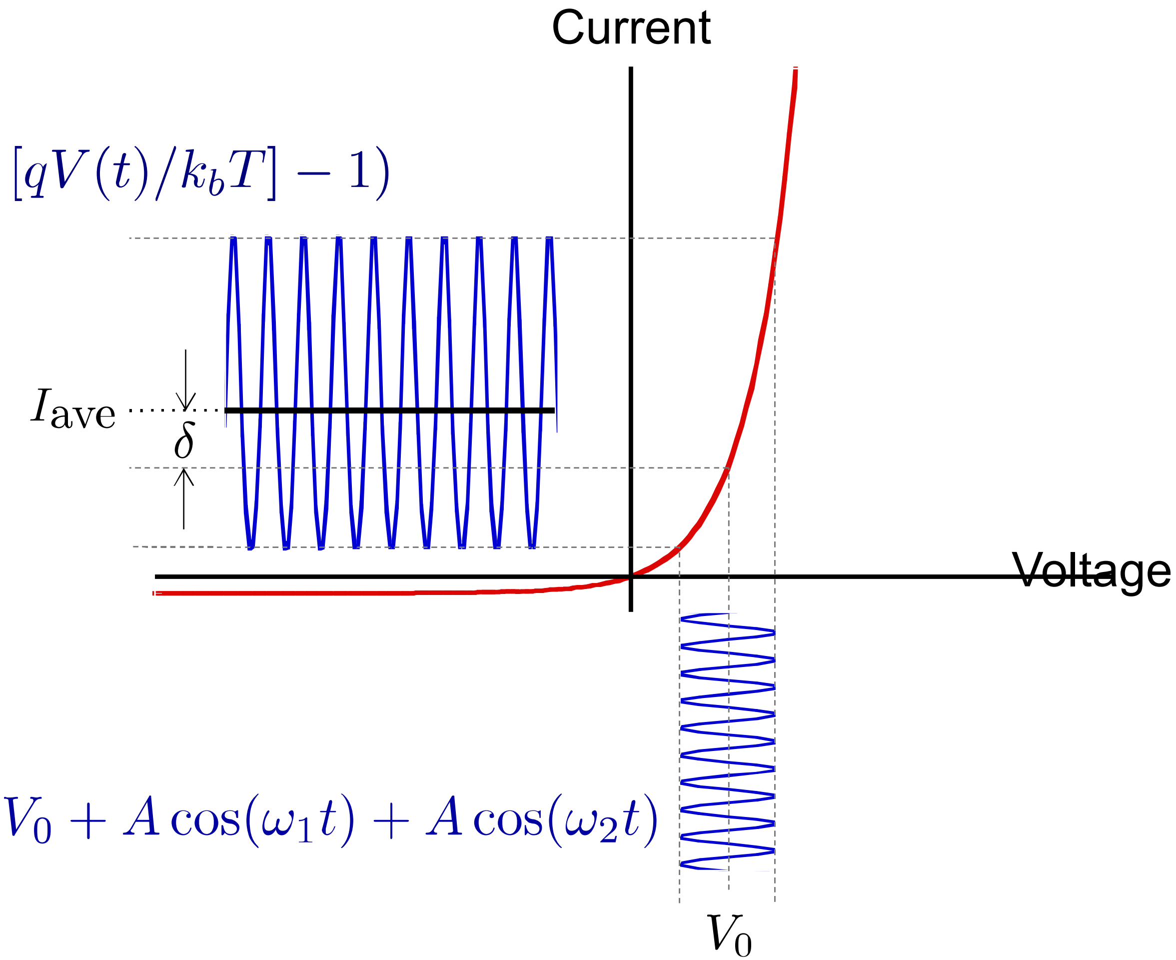
Important Point:
Need the potential drop near the interface.

Diode I-V



Diode Video (Rectified) Response

$$I(t) = I_0 \left(\exp\left[qV(t)/k_b T\right] - 1\right)$$

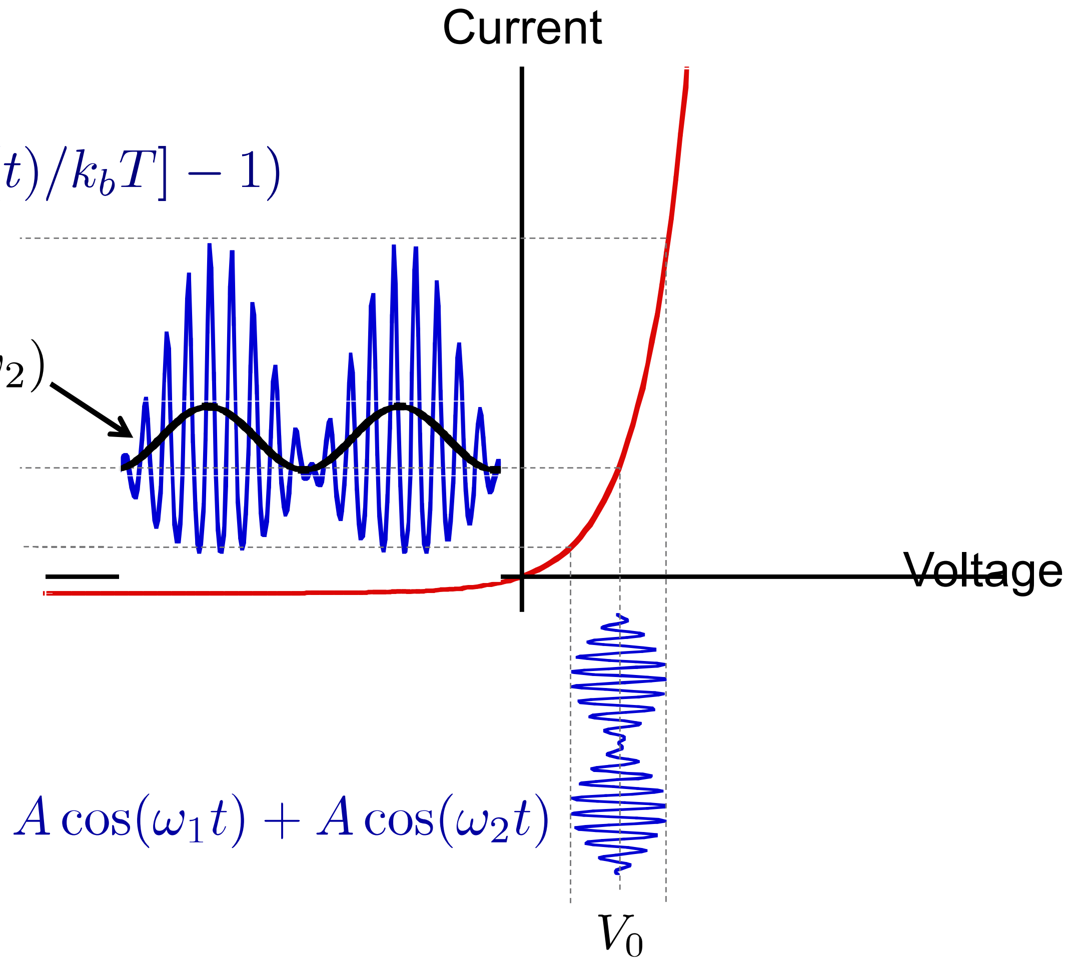


$$V(t) = V_0 + A\cos(\omega_1 t) + A\cos(\omega_2 t)$$

Diode Heterodyne Response

$$I(t) = I_0 \left(\exp\left[qV(t)/k_b T\right] - 1\right)$$

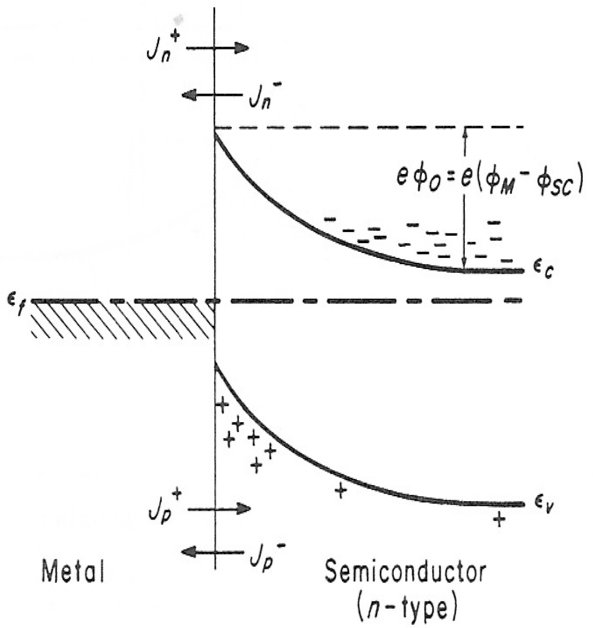
$\delta_{\mathrm{RF}}\left(\omega_1 - \omega_2\right)$



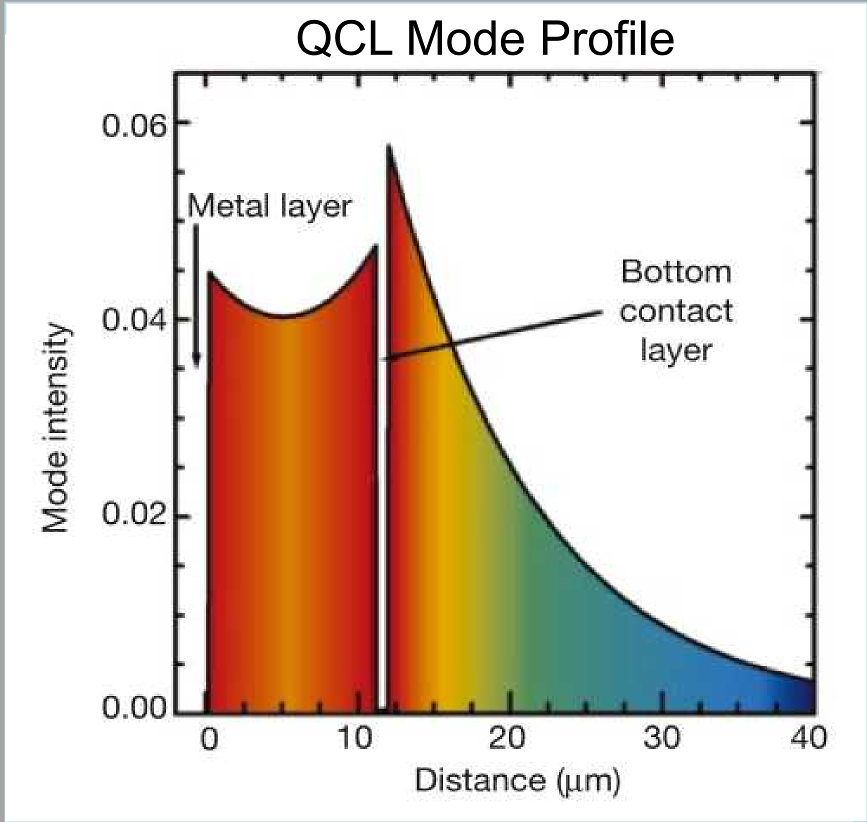
$$V(t) = V_0 + A\cos(\omega_1 t) + A\cos(\omega_2 t)$$

Schottky Diodes meet THz QCLs

Reminder:
Need the potential drop near the interface.



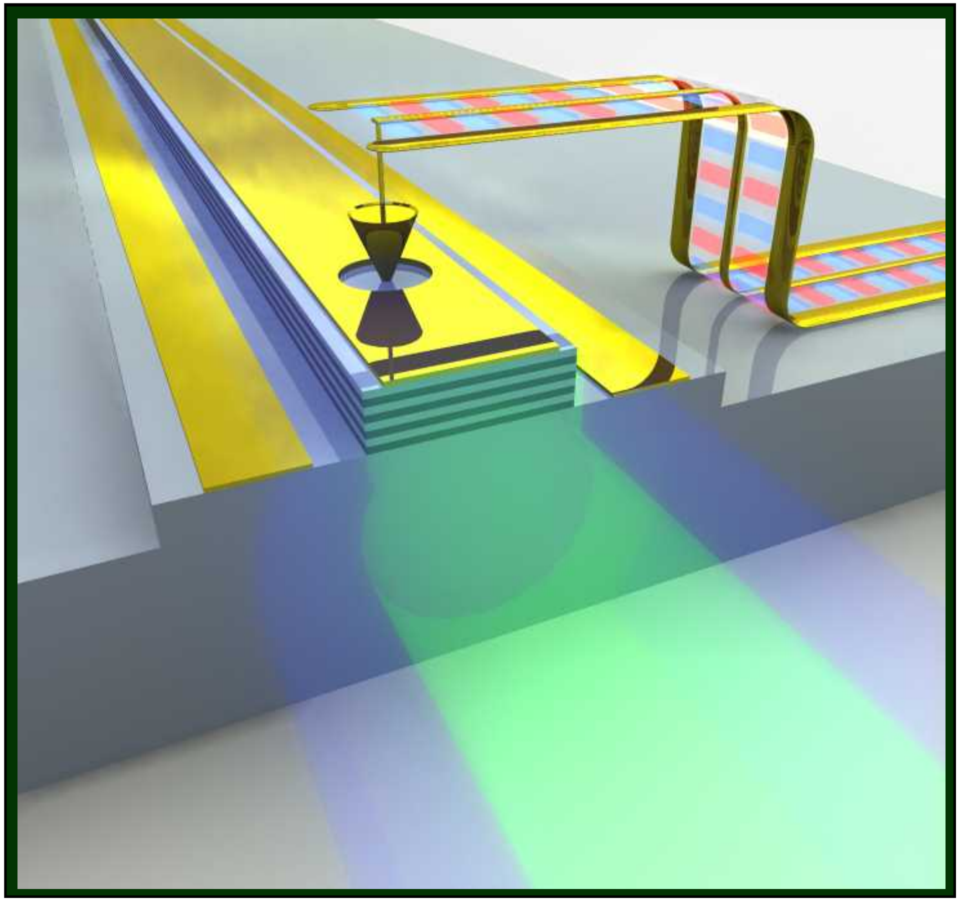
(a) Equilibrium



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

Monolithically Integrated Transceiver

Inserts diode directly into laser core

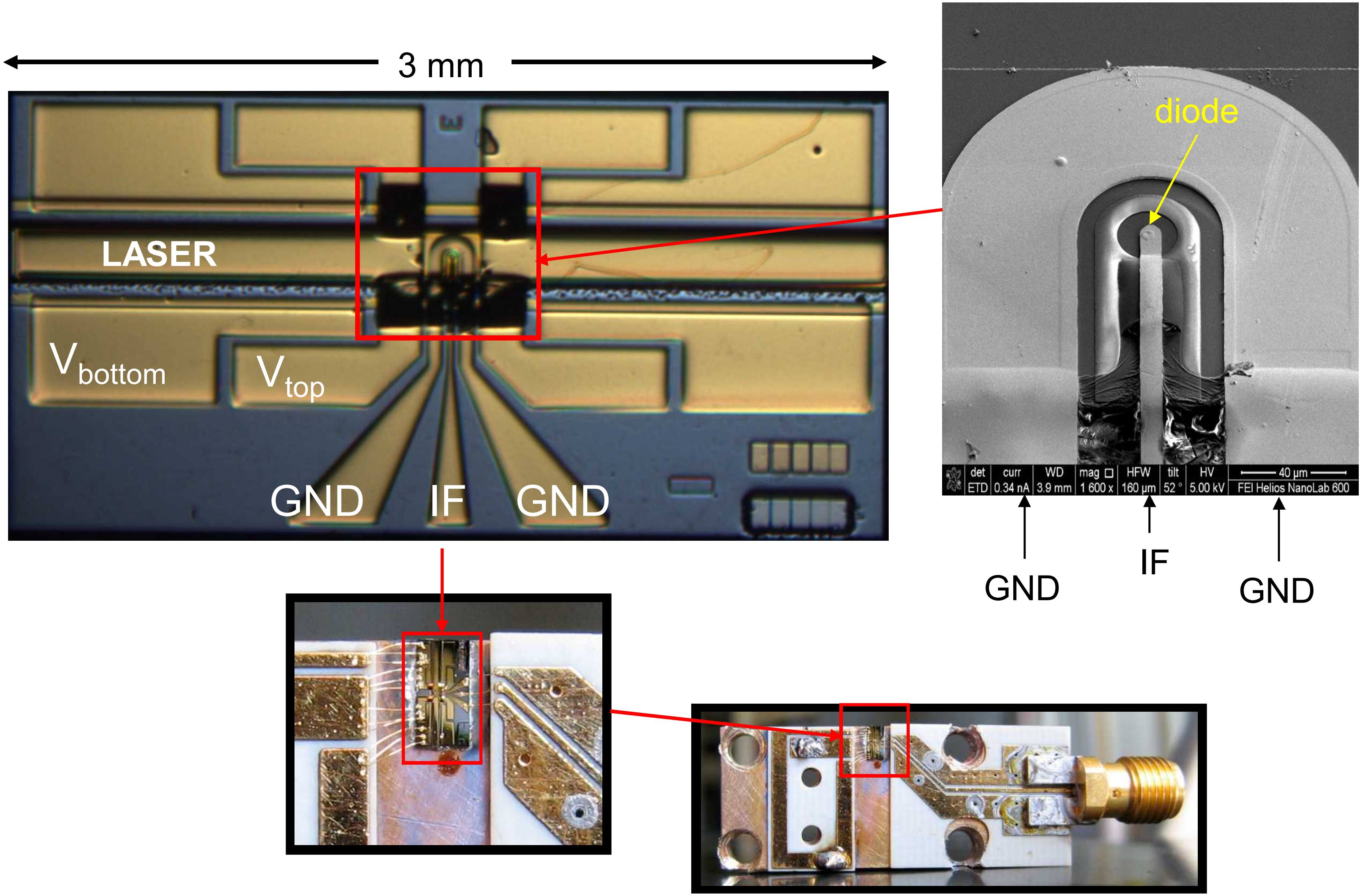


Benefits

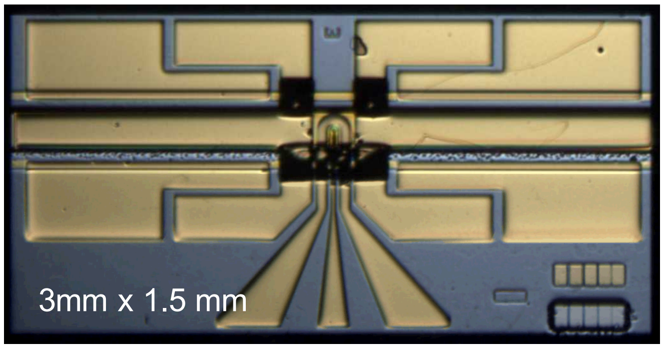
- Reduces size
- Eliminate components
- Ensures constant 'alignment'
- Enhances laser/diode coupling
- Enables probing of laser dynamics

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

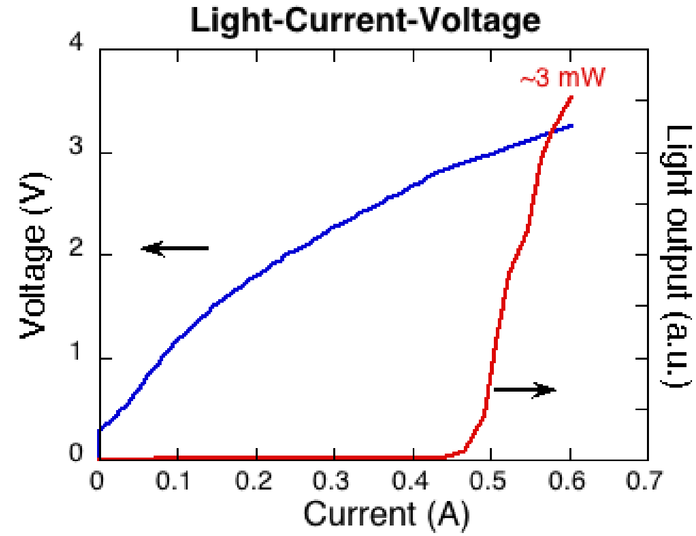
Fabricated Device



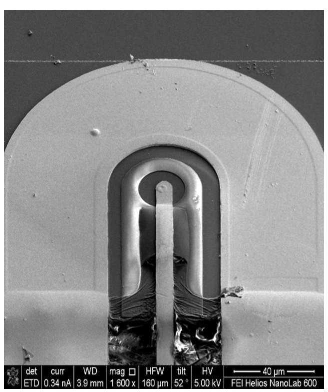
Diode and THz Laser DC Properties

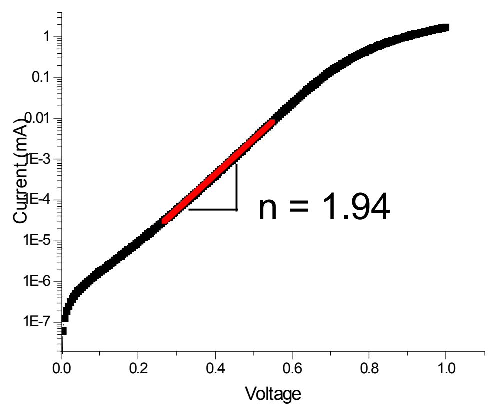


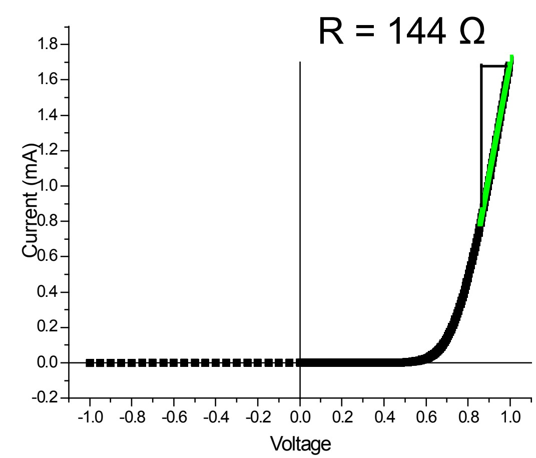
Typical QCL L-I-V Properties



Typicial Diode DC I-V Properties

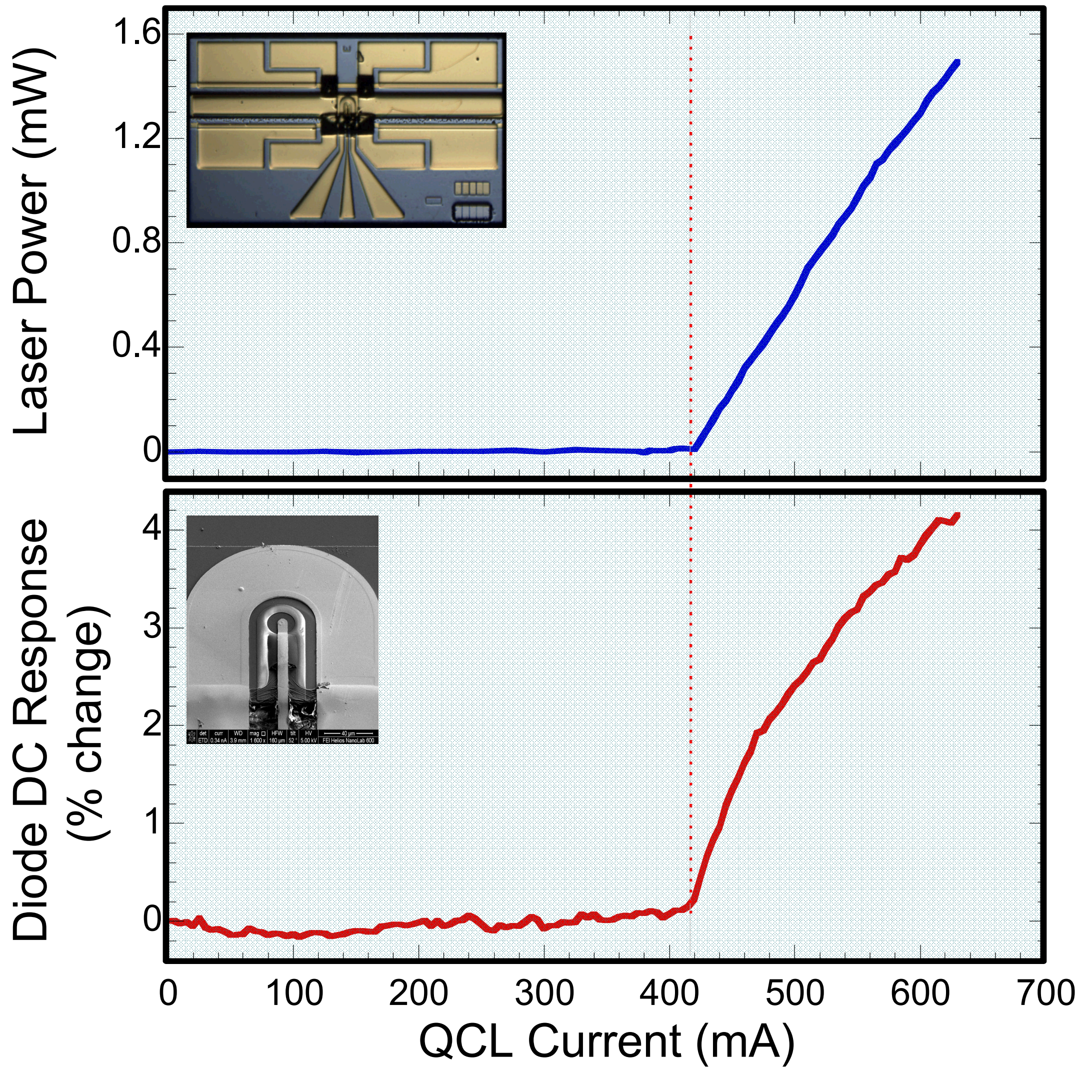






Does the diode sense the laser fields?

Diode Video (rectified) Response

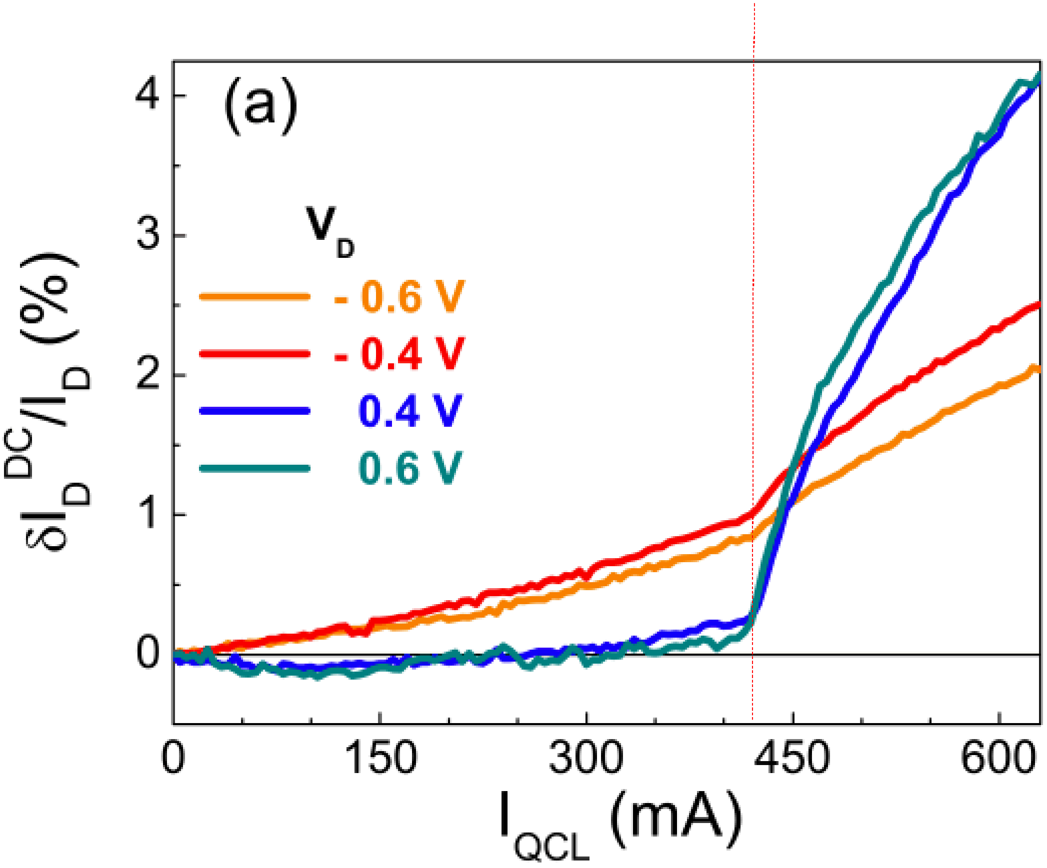


- **Diode responds to QCL power**
- **Non-linearity due to difference in spatial overlap of diode with different laser modes**

But, something is strange....

Why is there a rectified response below threshold for negative bias?

Laser Threshold



Dyer, Optics Exp., 21, 3996, (2013)

Looking a little closer ...

Diode responds depends on both laser power and laser temperature.

Simple Diode Equation

$$I_D\left(V,T\right) = I_0\left(\exp\left[qV/kT\right] - 1\right)$$

Expression for current change

$$\delta I = I(V_D + \Delta V, T + \Delta T) - I(V_D, T)$$

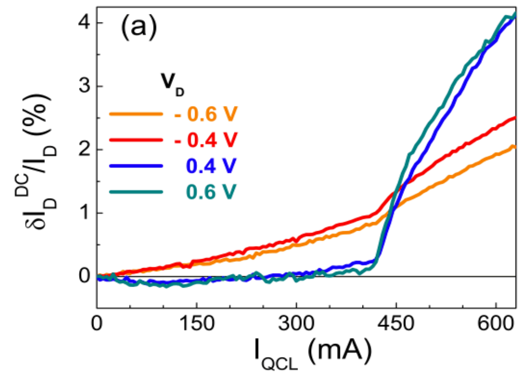
Keeping only lowest order terms in Taylor Series expansion

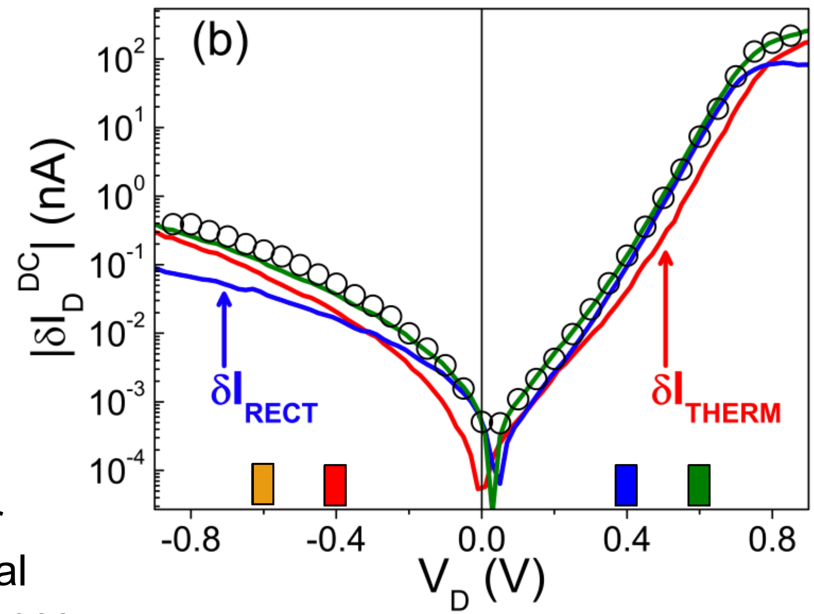
$$\delta I_D^{DC} = \frac{1}{4}\frac{\partial^2 I_D}{\partial V_D^2}\delta V_{THz}^2 + \frac{\partial I_D}{\partial T}\overbrace{\delta P_{QCL}\Theta_T}^{\Delta T}$$

Laser Power

Laser Joule Heating

Laser Thermal Conductance

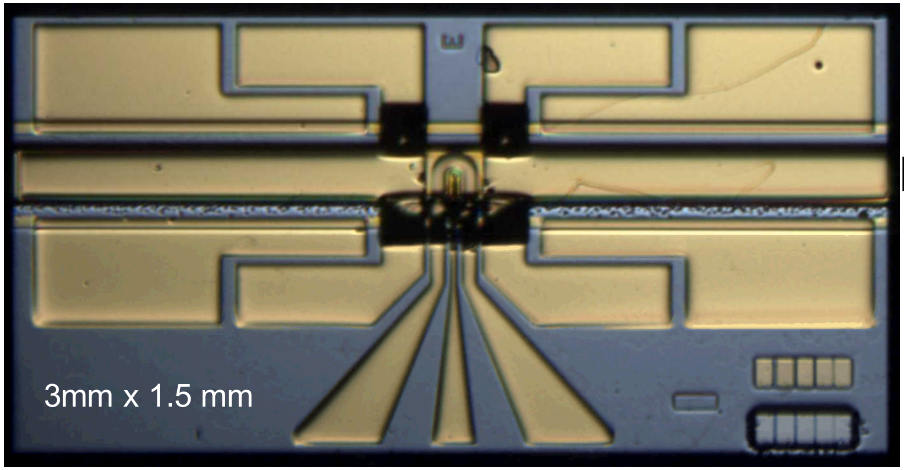


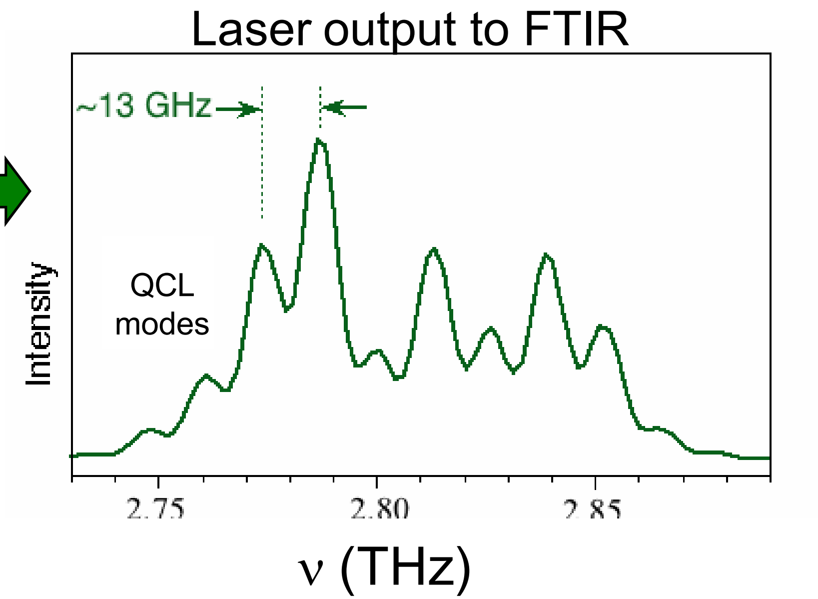


Dyer, Optics Exp., 21, 3996, (2013)

Can the diode mix multiple laser modes?

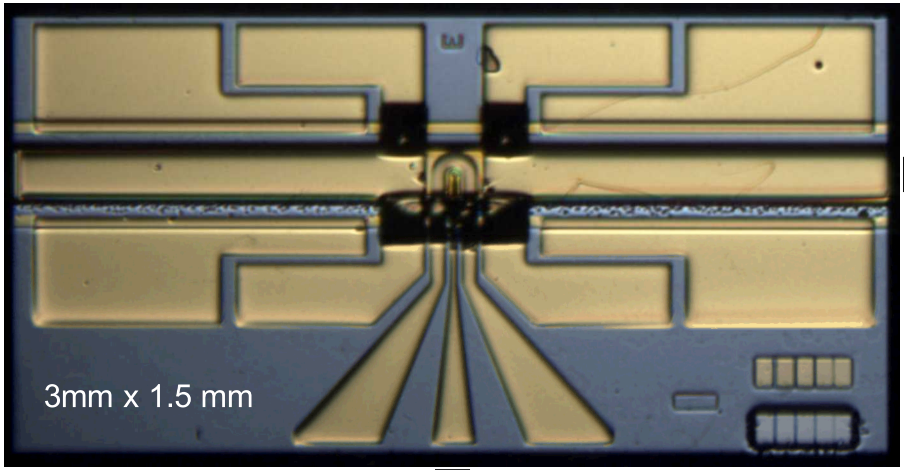
Laser Spectrum

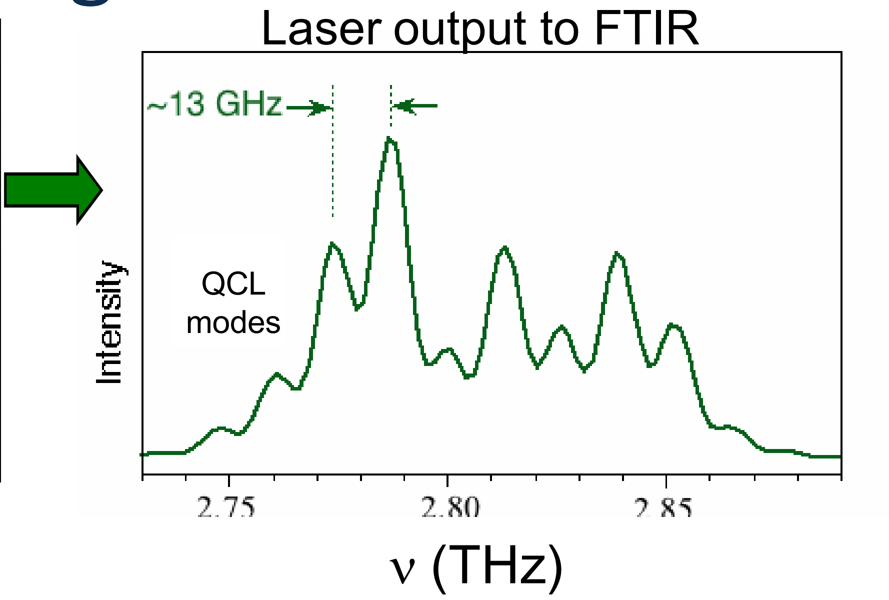


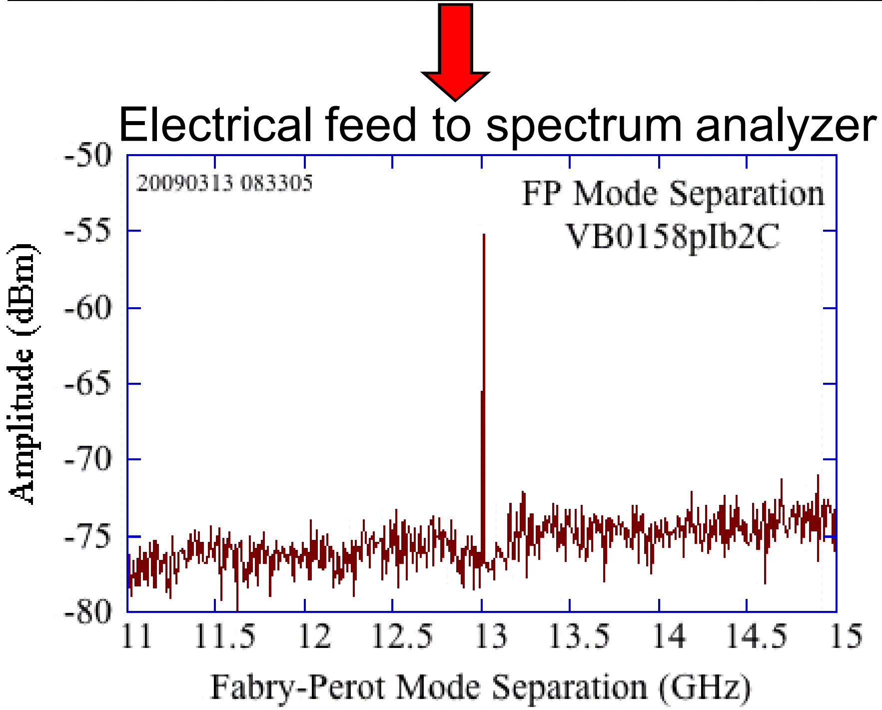


- **Multimoded QCL centered on 2.81 THz**
  - **QCL emission (FTIR) spectra show Fabry-Perot modes spaced by ~13 GHz**

Demonstration of Mixing

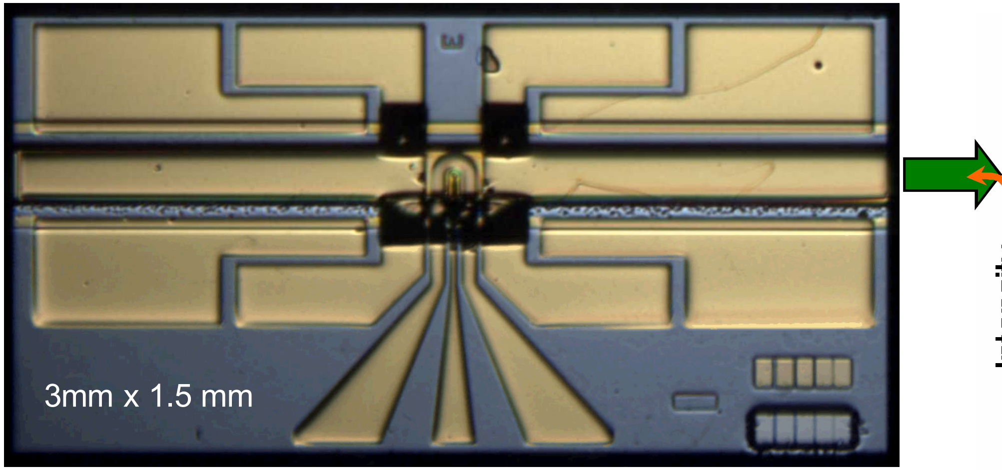


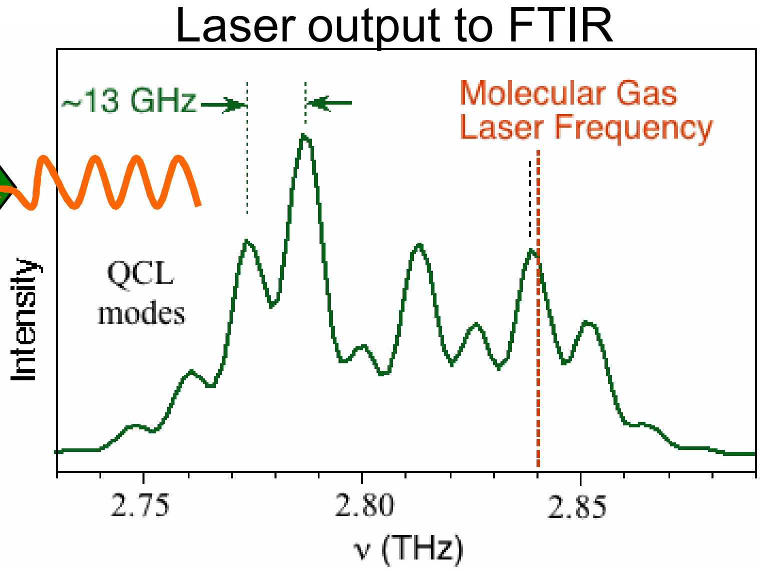


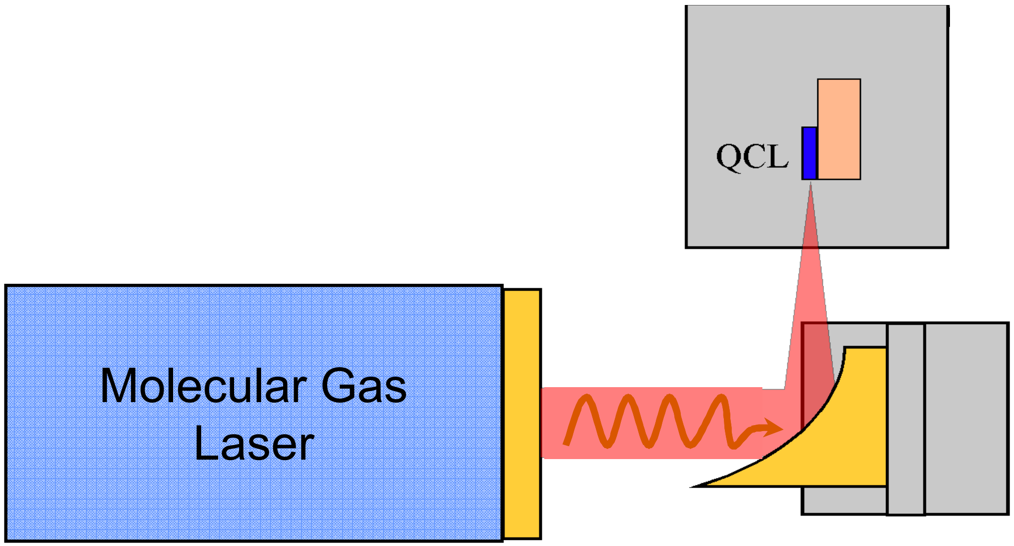


- **Diode outputs IF signal at the spacing between QCL modes**

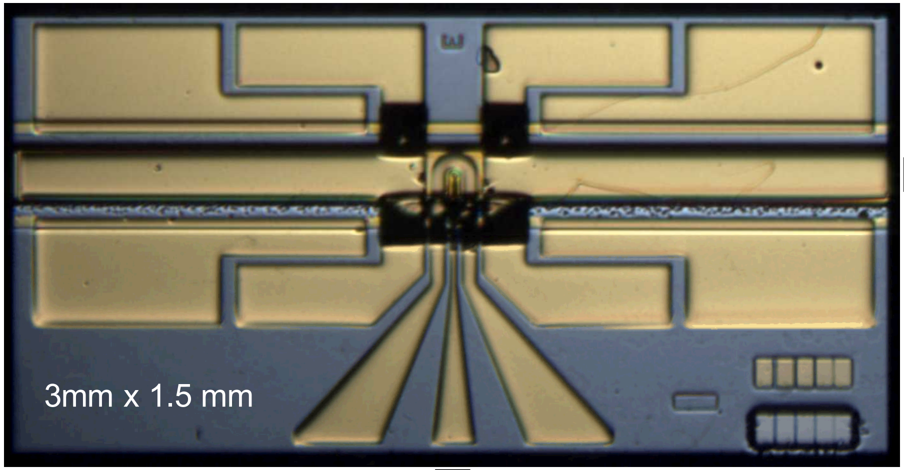
Heterodyne Receiver Demo

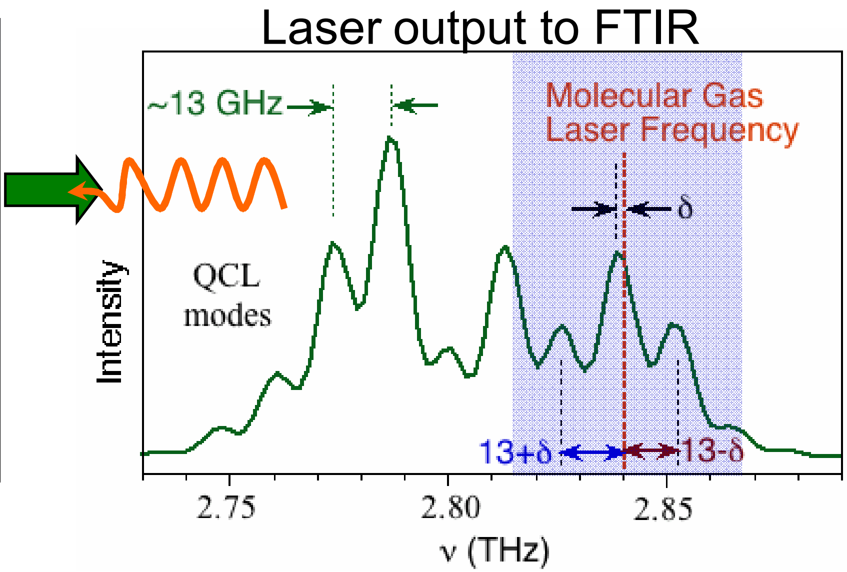


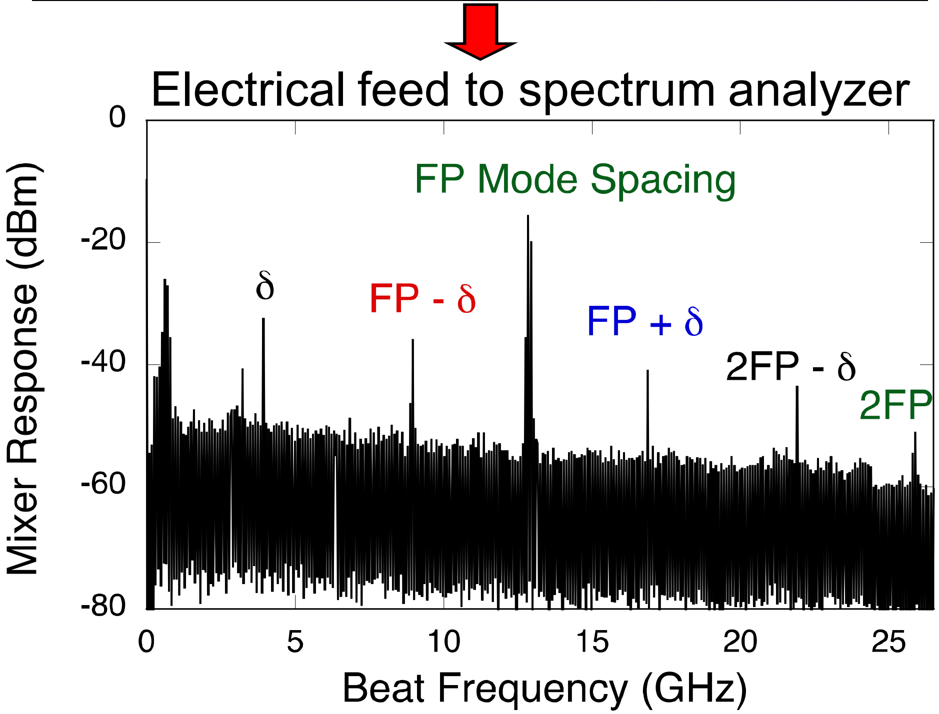




Heterodyne Receiver Demo







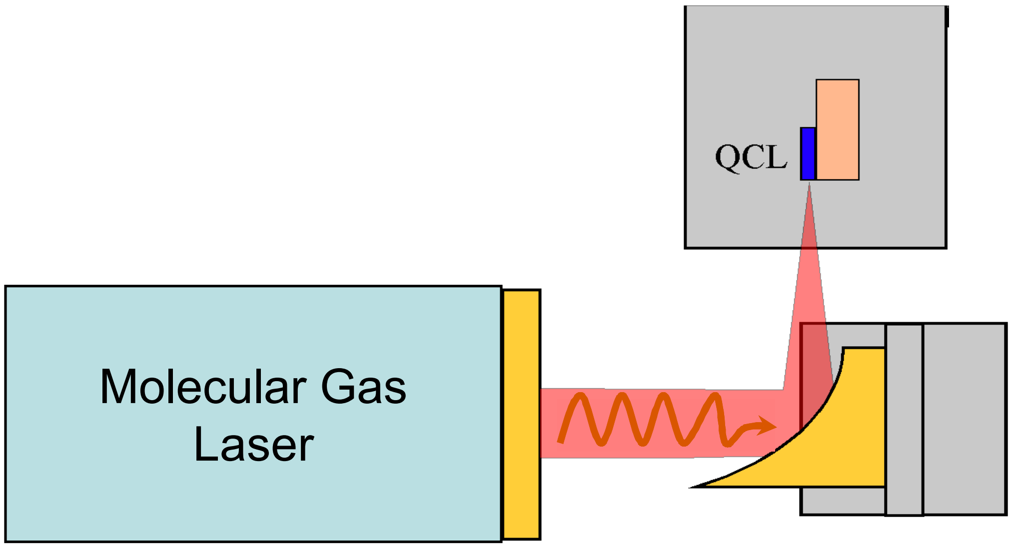
- **Detects external signals**
- **Resolves multiple mixing signals simultaneously.**

What can we learn and do with an integrated transceiver ?

What can we learn and do with an integrated transceiver ?

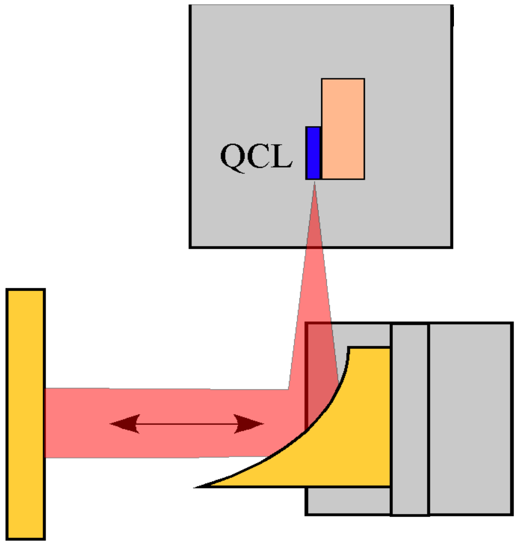
Example 1 : Feedback Effects

Feedback Sensitivity



Some of the QCL emission retroreflects

Feedback Sensitivity



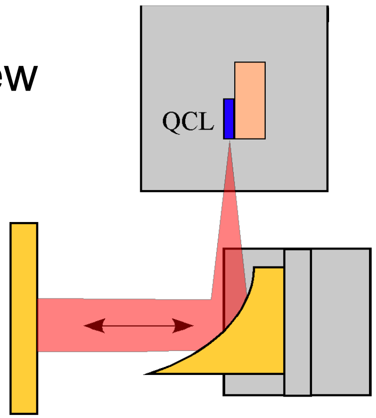
Why should we care?

There is always other components such as:

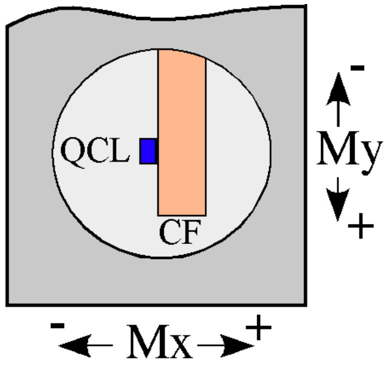
- Another laser facet
- Window or lens
- External mixers

Focal Position Feedback Sensitivity

Top View

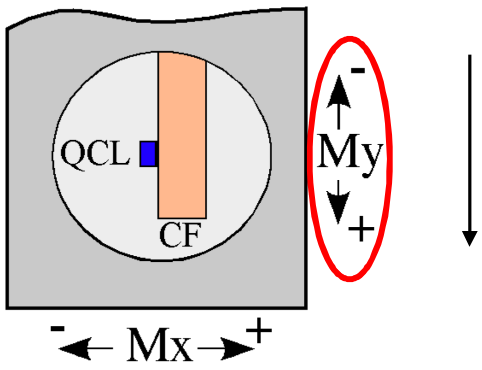


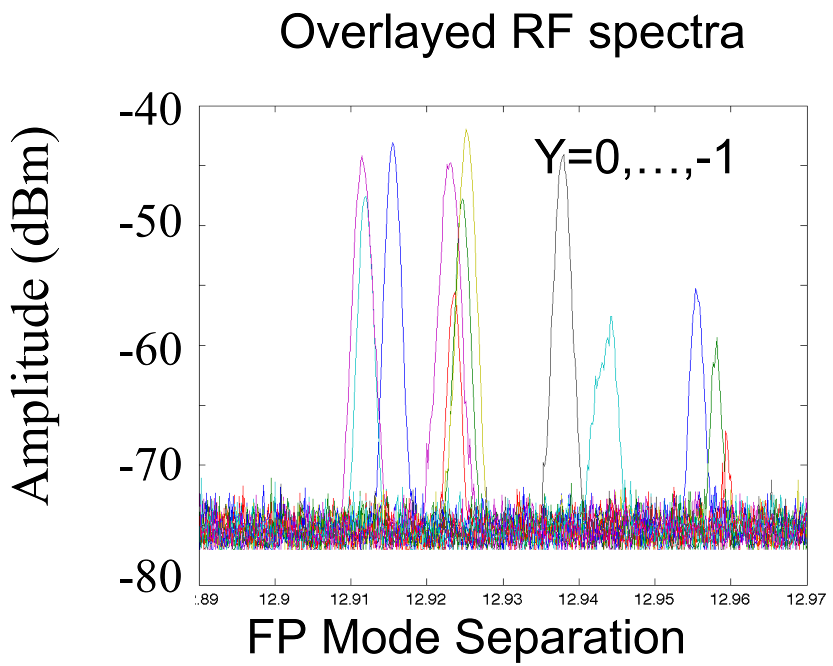
Front View

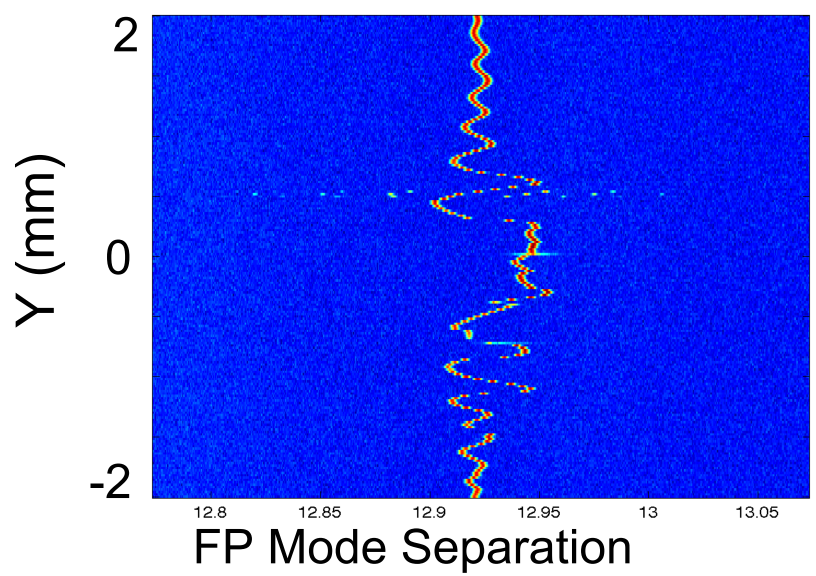


What happens when we scan the cryostat to find the FIRL beam?

Focal Position Sensitivity

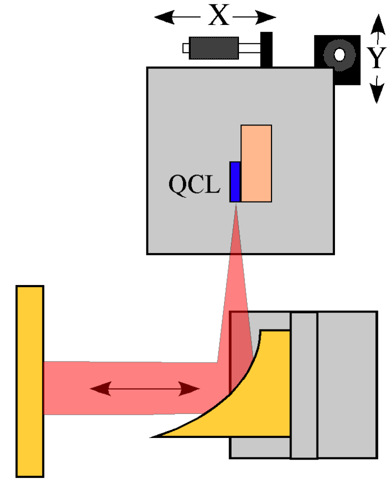




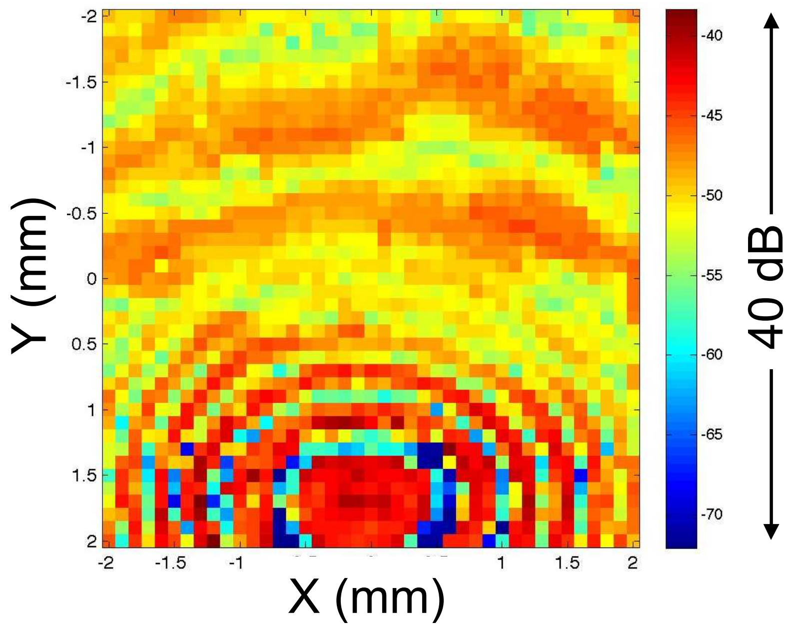


Focal Position Feedback Sensitivity

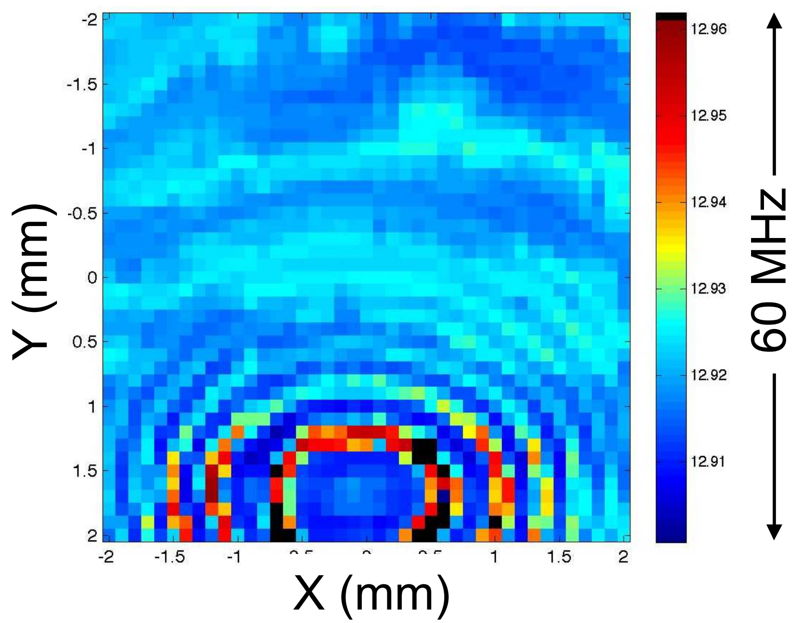
- **Strong frequency and amplitude pulling**
- **Simple demonstration of Airy diffraction pattern**
- **Phase Sensitive Detector**



IF Amplitude



IF Frequency

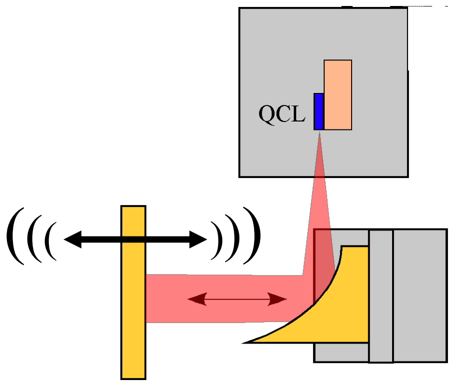


When life gives you ~~lemons~~ peaches...

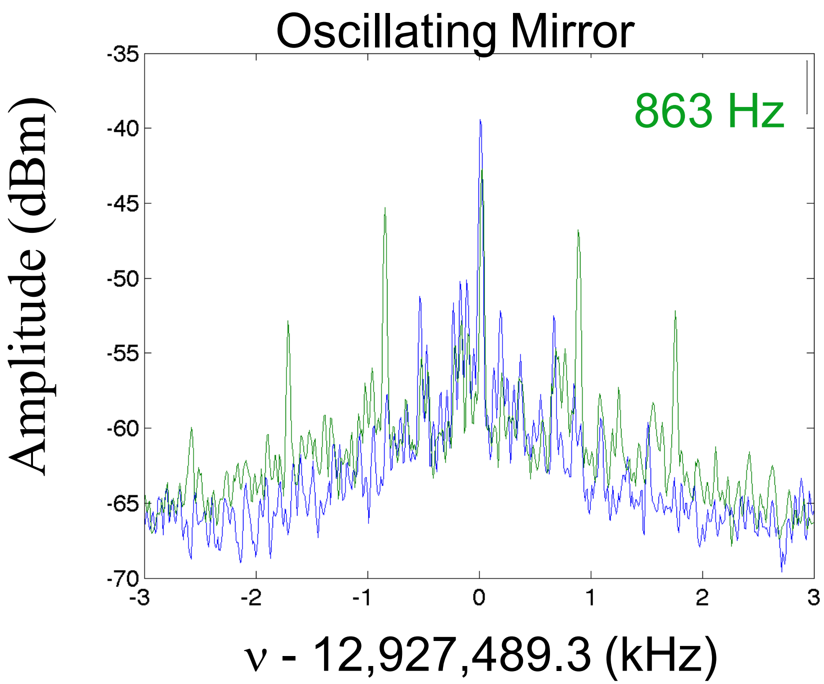
... use feedback to image the topography

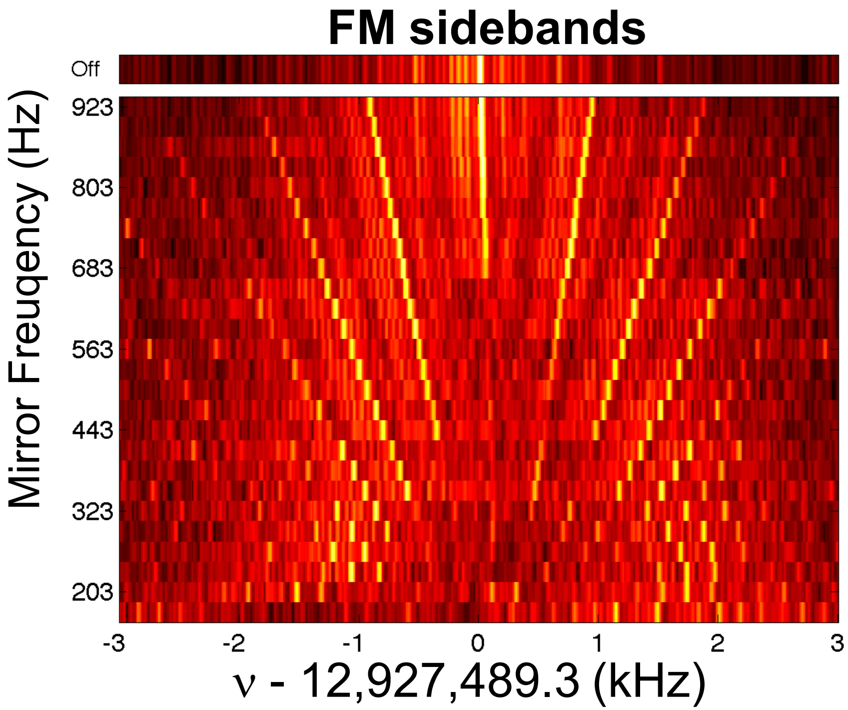
Wanke, Proc SPIE, **8031**, (2011)

Or…



… use feedback to measure vibration frequency of a reflector



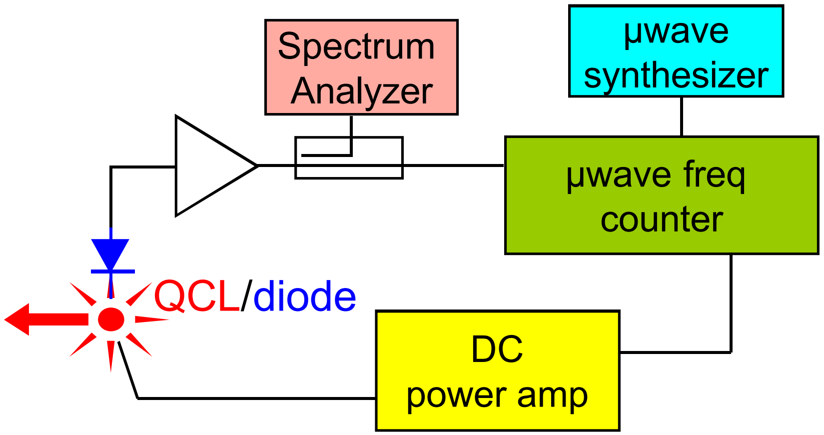


What can we learn and do with an integrated transceiver ?

Example 2 : Phase Locking

Frequency/Phase Locked THz IC

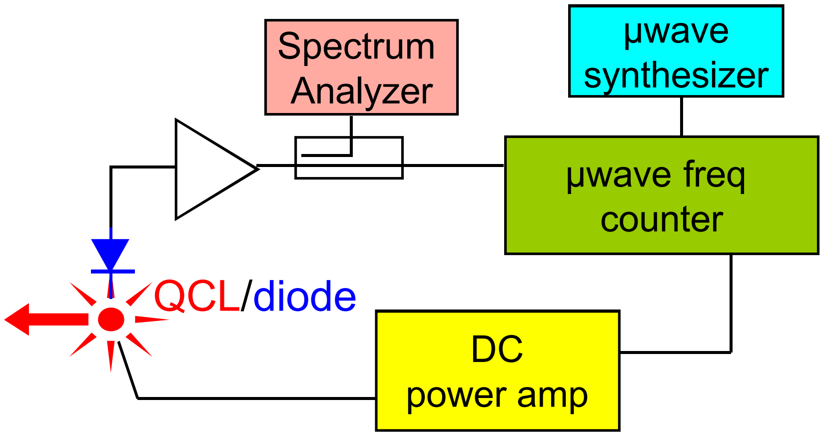
- **Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations***



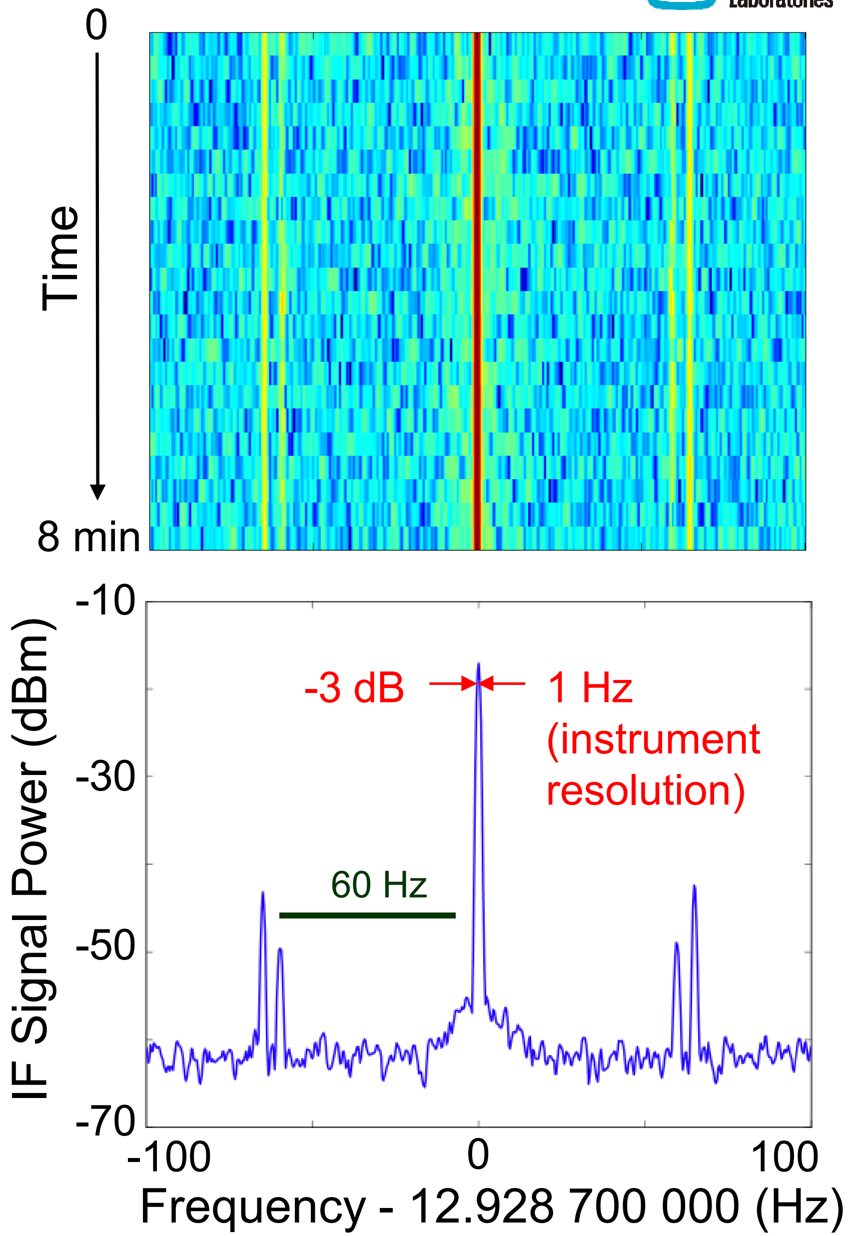
*Following Betz, Opt. Lett. **30**, 1837, (2005)
Baryshev, APL, **89**, 031115, (2006)

Phase Locked THz IC

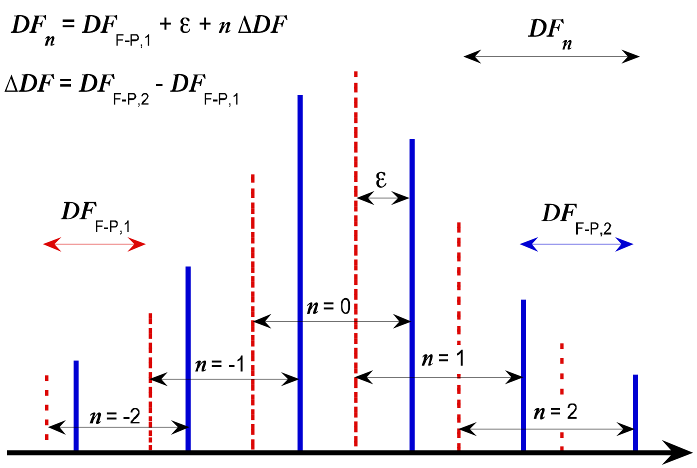
- Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations*
- **Locked IF linewidth ~1 Hz**
- **Extremely stable IF frequency and amplitude**

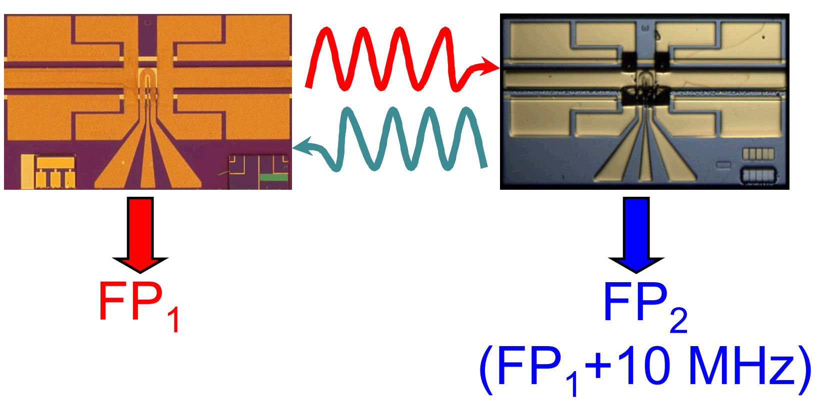


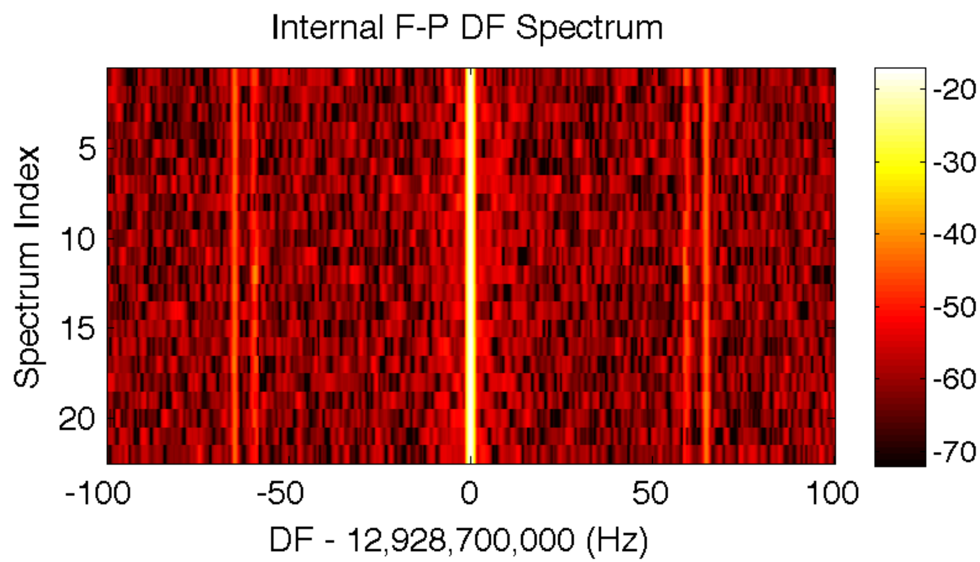
*Following Betz, Opt. Lett. **30**, 1837, (2005)
Baryshev, APL, **89**, 031115, (2006)

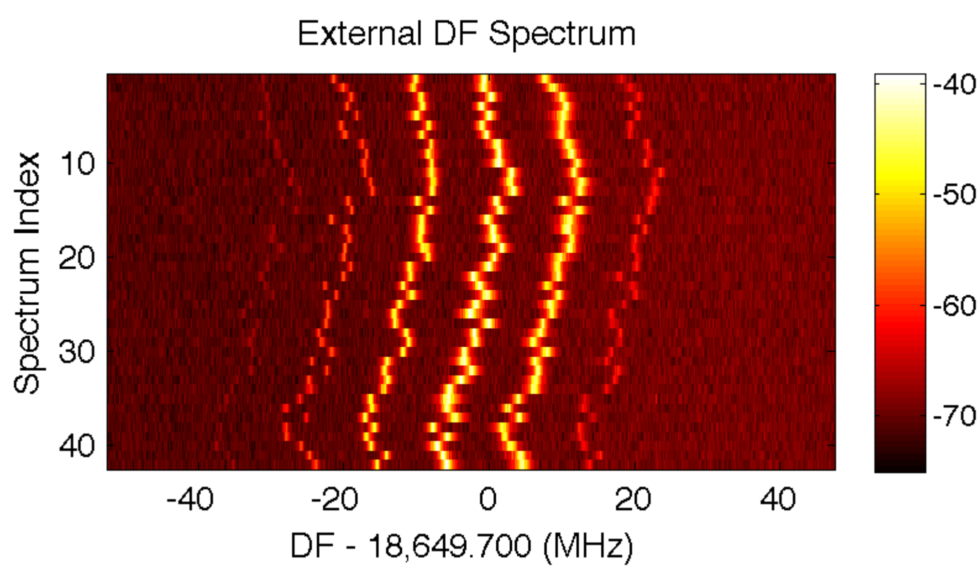


Absolute Frequency not Simultaneously Locked…



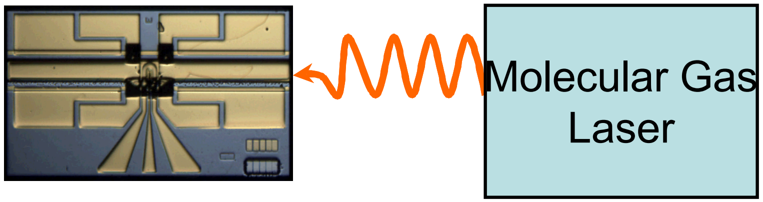


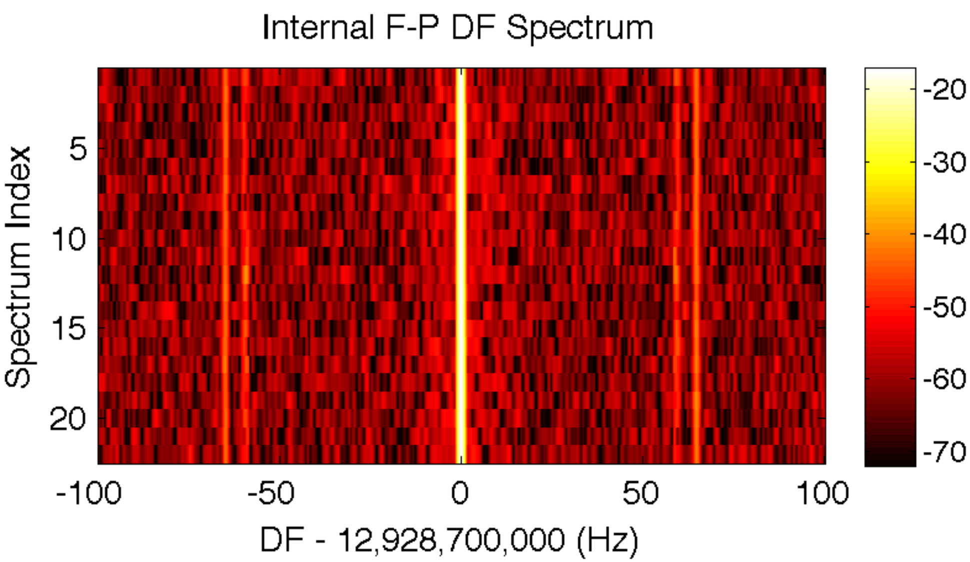


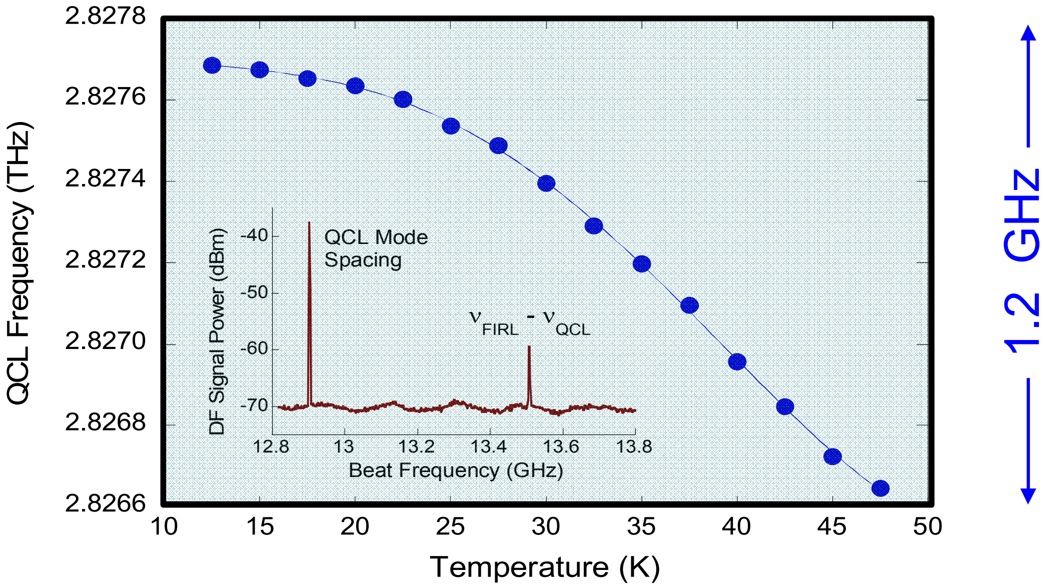


Wanke, Opt. Express, **19**, 24810 (2011)

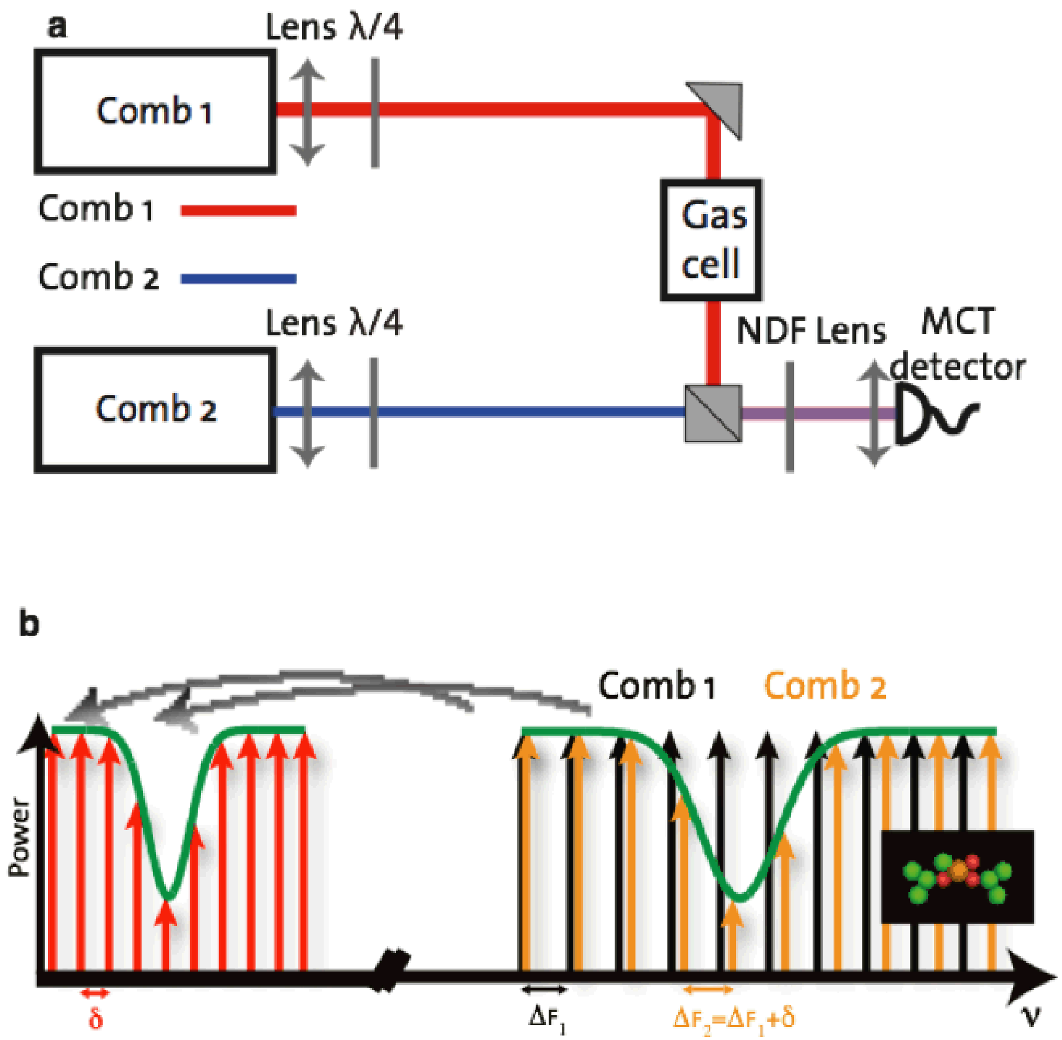
… which allows tuning of the comb…



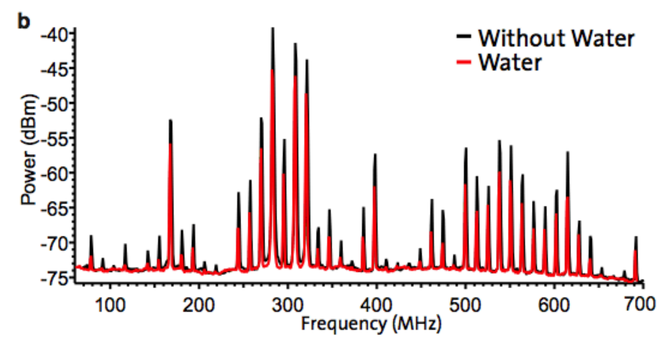




… and dual comb spectroscopy.



Borrowed from Faist, et.al, ITQW 2013 Abstract

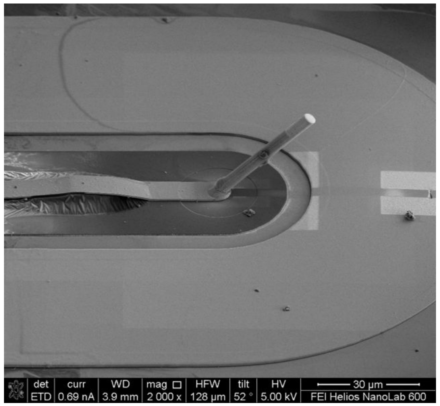


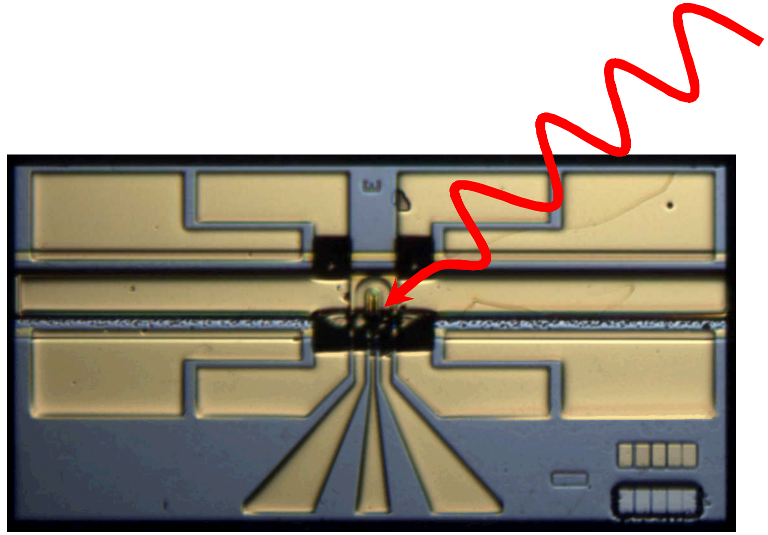
Wanke, Opt. Express, **19**, 24810 (2011)

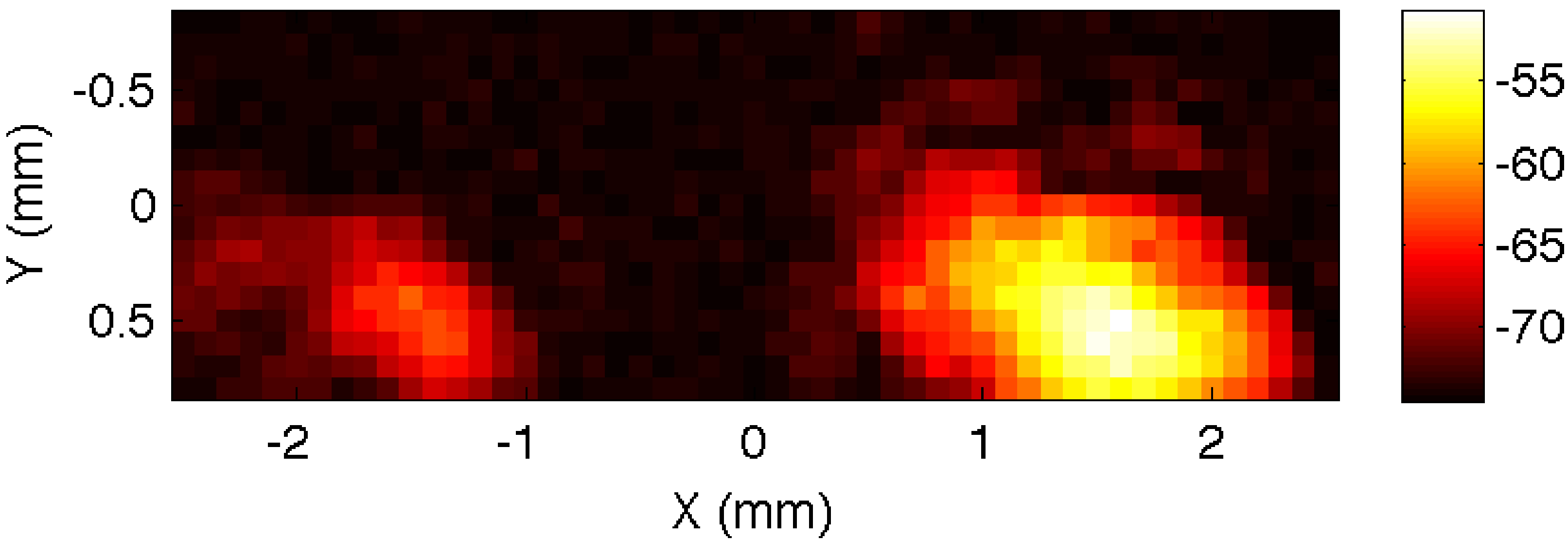
Outline

- Integration Motivation
  - Background
  - Heterodyne receiver example
- Integrated Schottky diodes and THz QCLs
  - Schottky diode review
  - Integration description
  - Diode response to internal laser fields
  - Receiver operation
  - Using the transceiver
- Integrated Schottky diodes and MIR QCLs

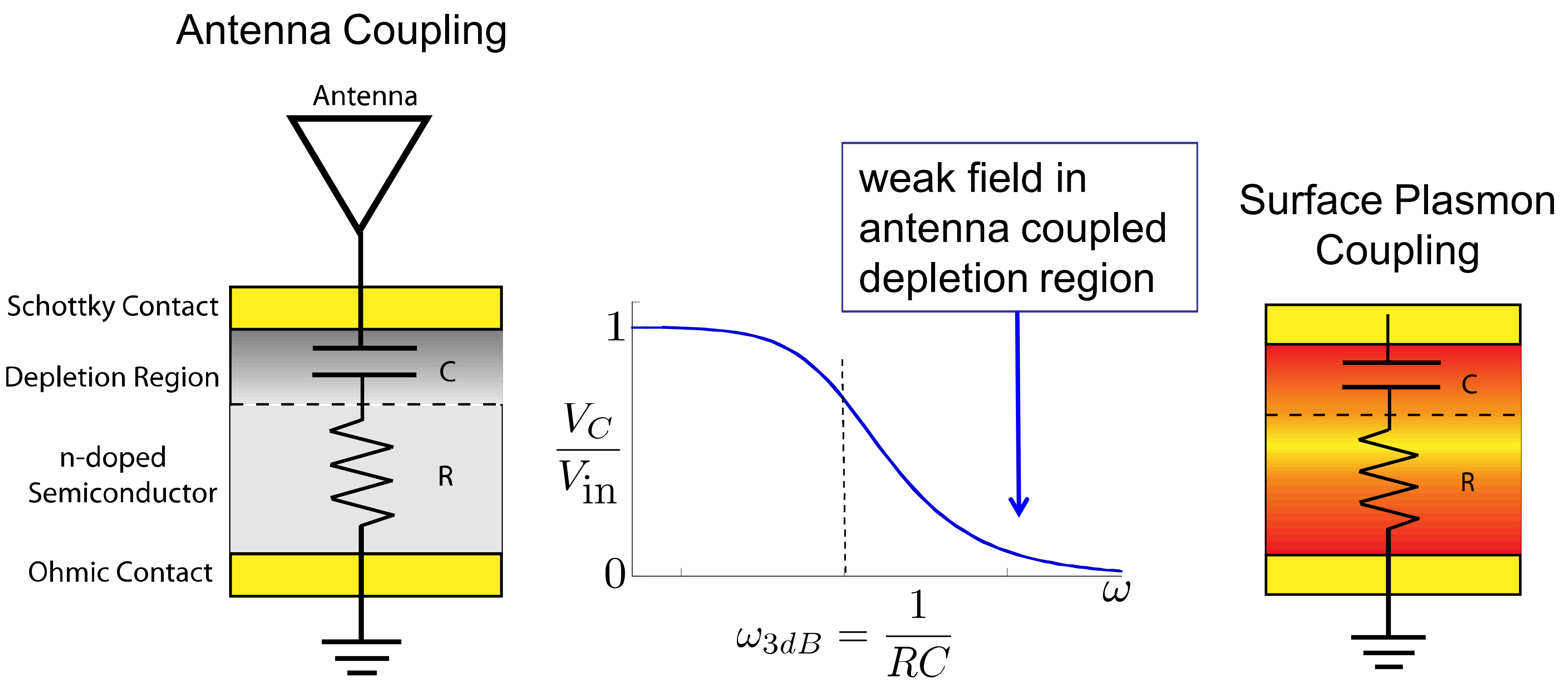
Coupling to the diode







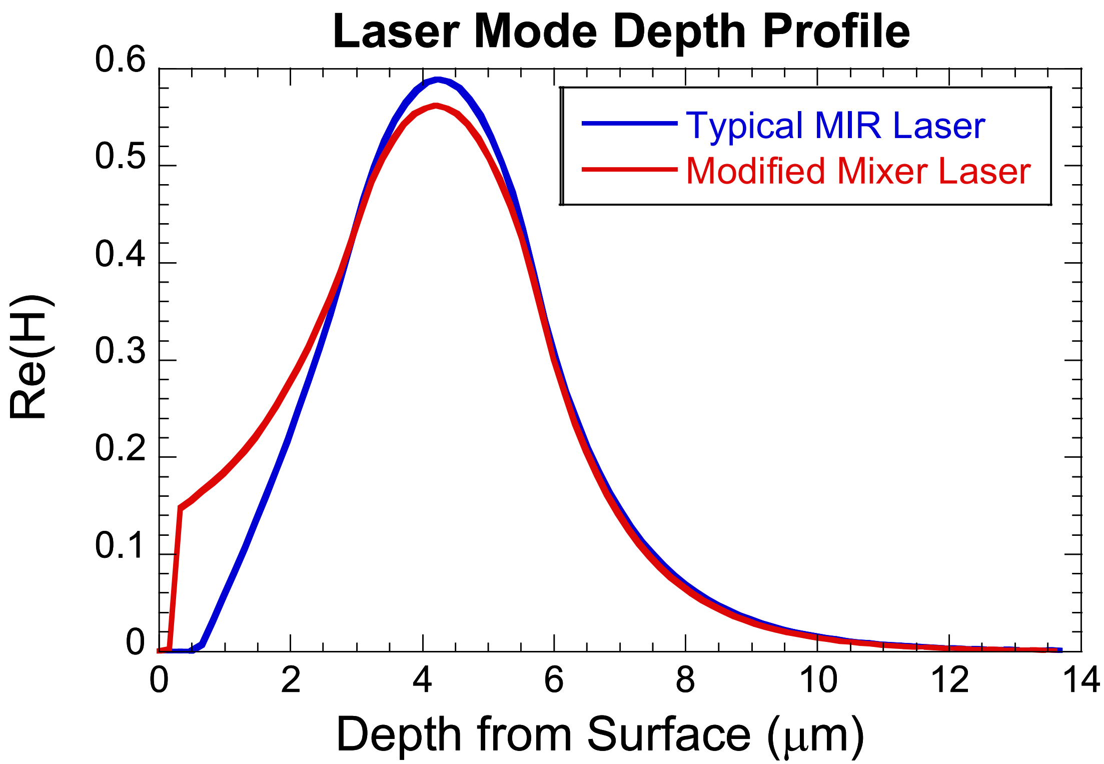
Antenna Coupling vs Surface Plasmon Coupling



Suggests possibility of MIR operation of planar Schottky diodes !

MIR mode profile

Normally no field at metal interface

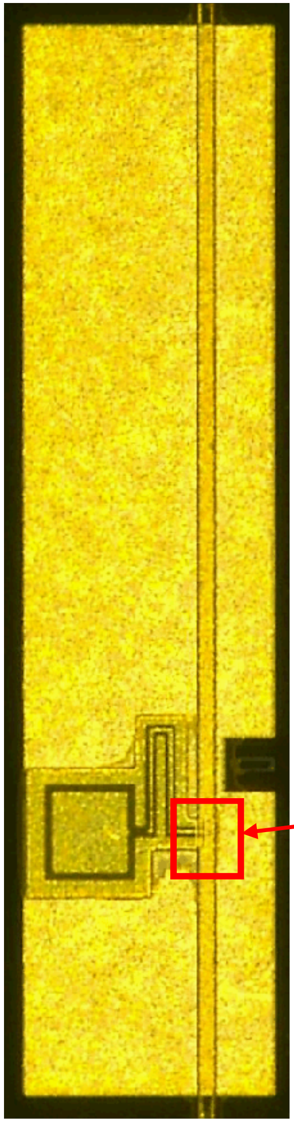


Top two layers differ:

- 100A (1E20) / 3500A (8E18)
- 500A (5E18) / 3000A (1E18)

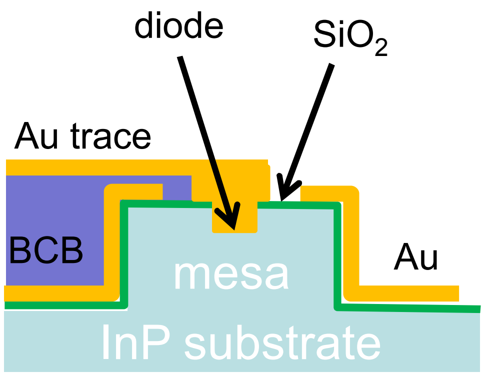
Compromise between loss and surface coupling

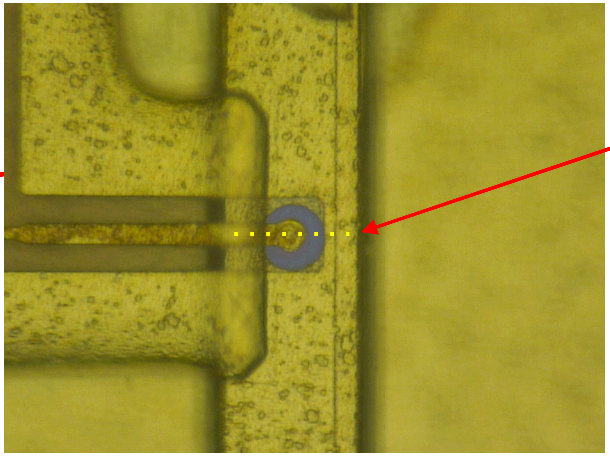
MIR device structure

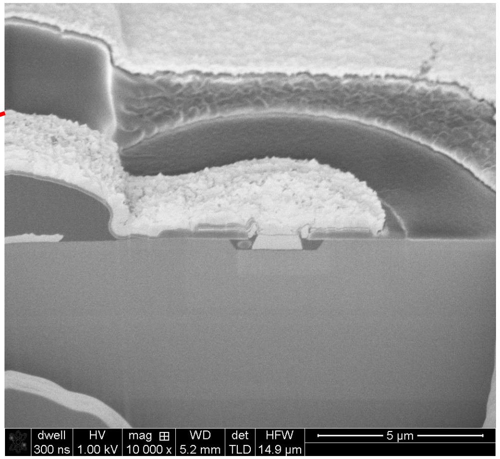


Laser
- 8 μm wavelength
  - Active region courtesy of C.Gmachl
  - Cladding courtesy of A. Belyanin
- 2 or 3 mm x 25 μm
- InGaAs/AlInAs/InP

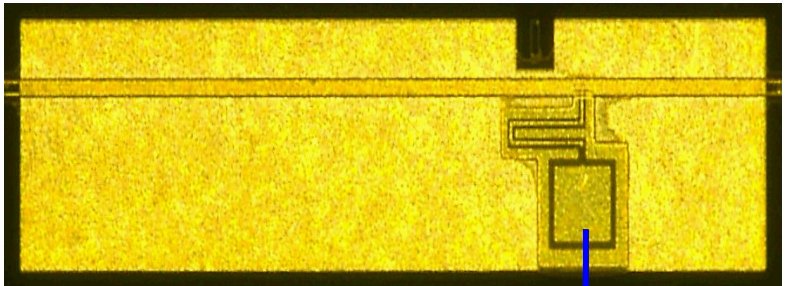
Diode
- 2 or 5 um diameter
- TiAu on InGaAs
- Recessed below n+

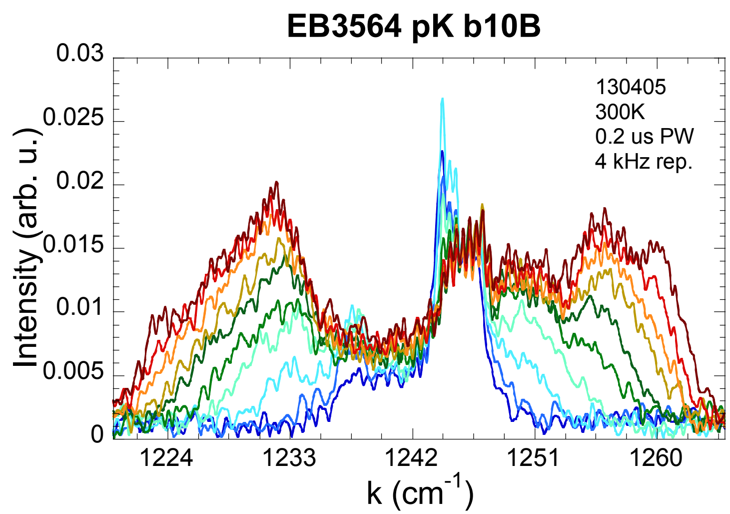


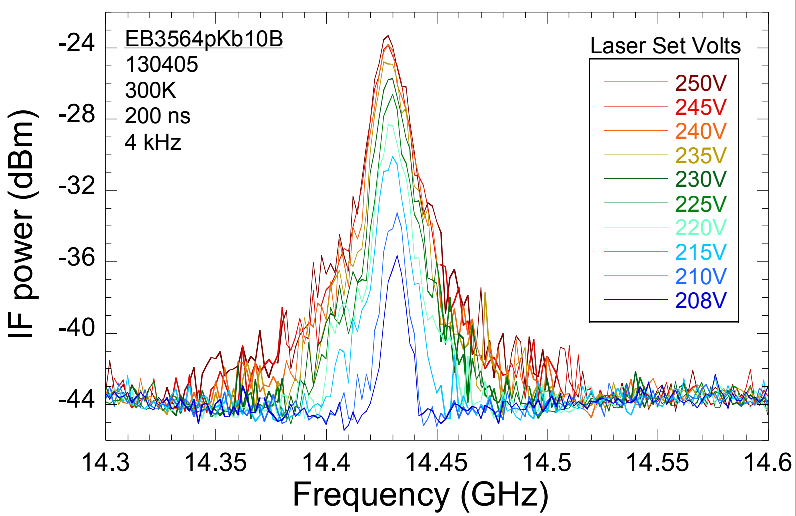




Demonstration of MIR mixing





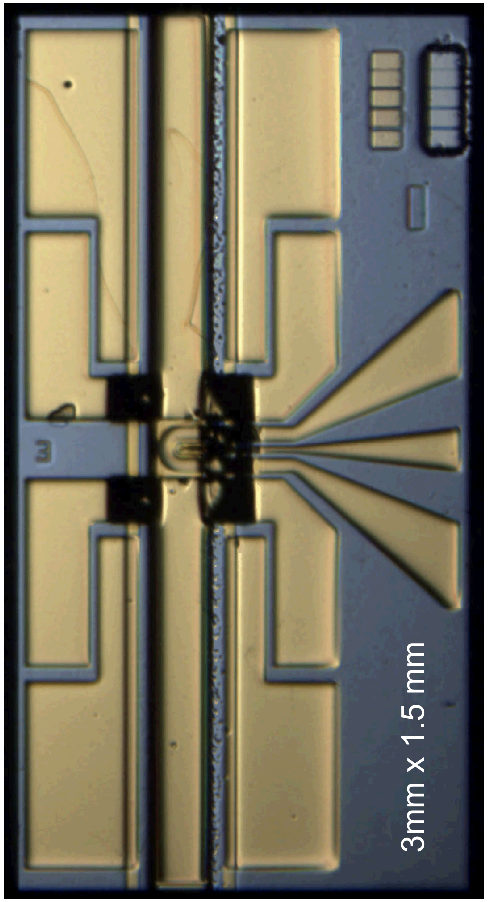


Diode responds to and mixes internal modes at room temperature !

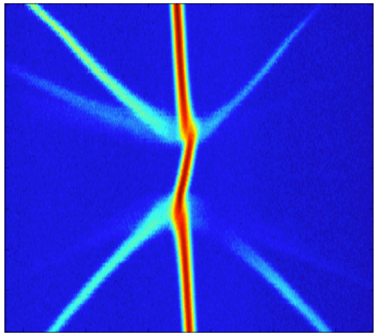
Still much more to learn....

Summary

THz Integrated Transceiver

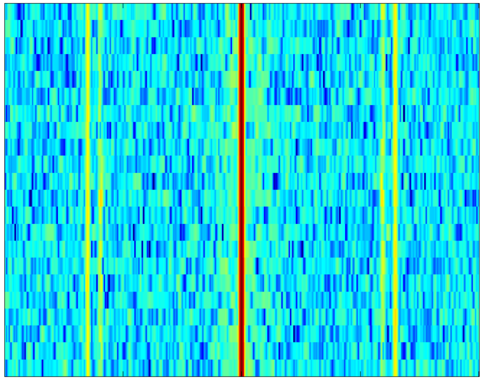


Laser Characterization
Injection Locking



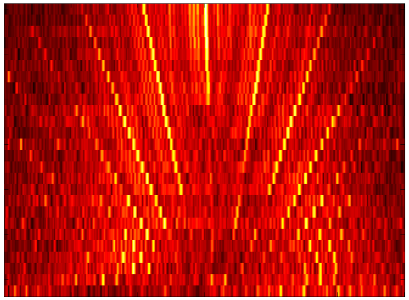
Wanke, Proc. SPIE, 7953, 2010

Phase Locking
Mode Coupling
Comb Locking



Wanke, Opt. Exp., 19 24810, 2011

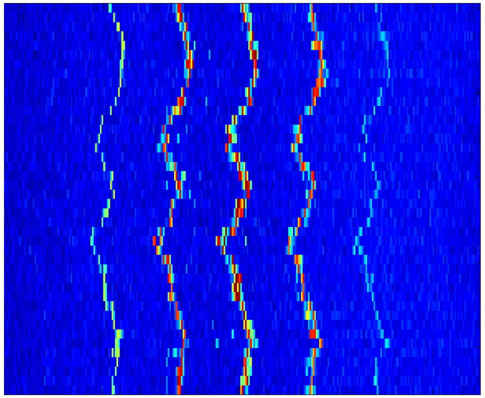
Vibrometry



Phase/Topo Imaging

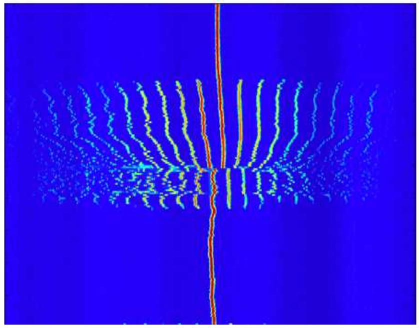
Wanke, Proc. SPIE, 8031, 2011

Comb Offset Stability



Wanke, Opt. Express, 19, 24810, 2011

Feedback / Chaos
Dynamics



Wanke, Proc. SPIE, 7953, 2010

Credits:

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Greg C. Dyer
Eric Shaner
Darin Leonhardt
Troy Ribaudo
Chuck T. Fuller
John F. Klem
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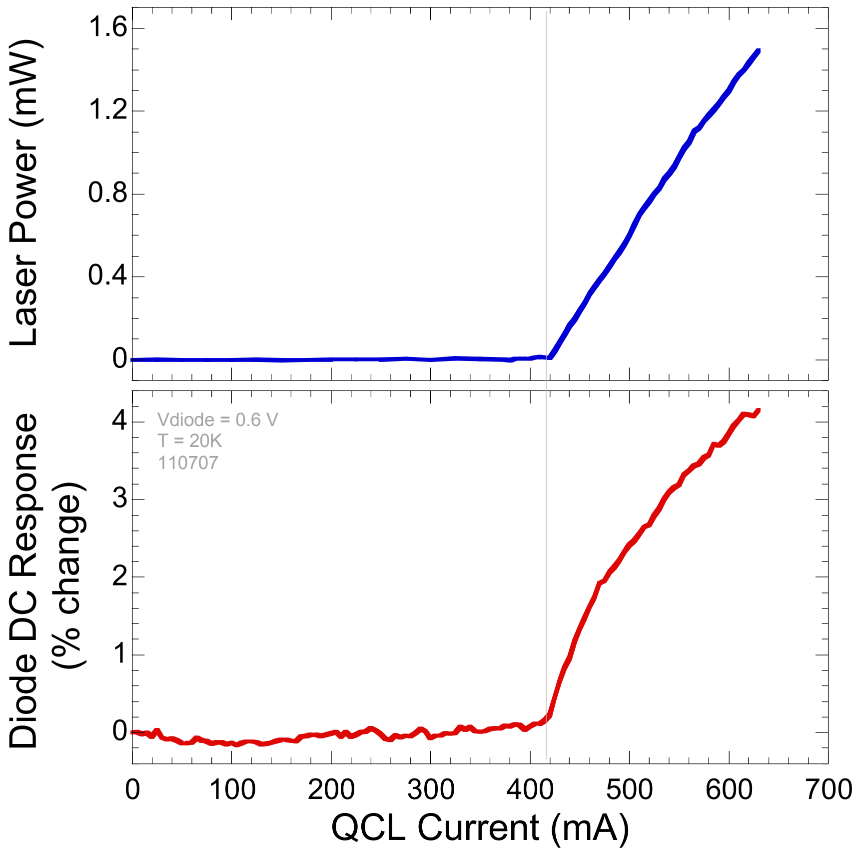
John L. Reno
Joyce Custer*
Michael J. Cich*
Mark Lee*
Erik W. Young*

<u>Special thanks to:</u>
Claire Gmachl
Alexey Belyanin

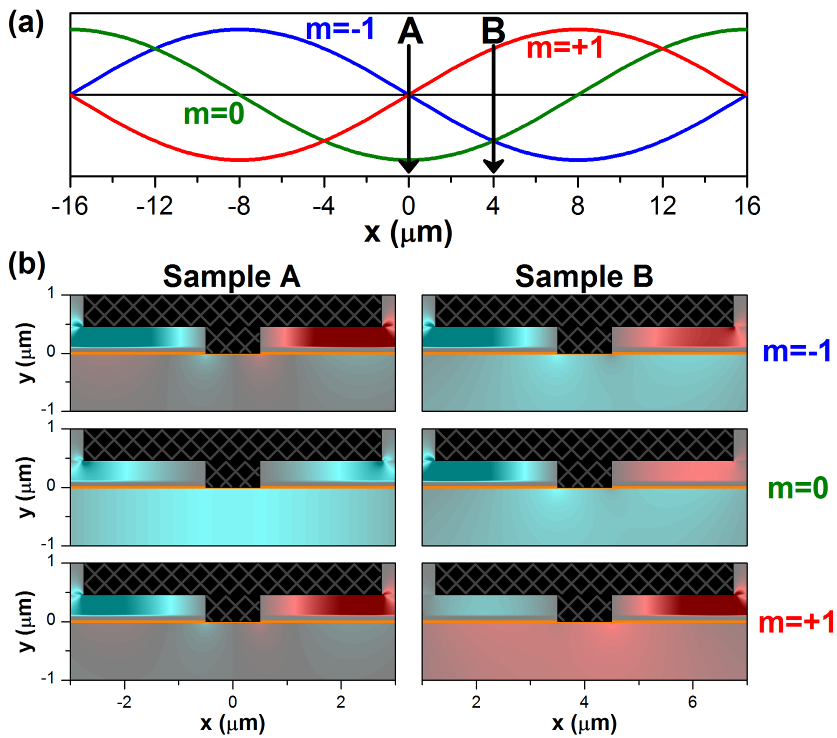
With Support From:

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Diode Response vs Laser Power



Simple Picture



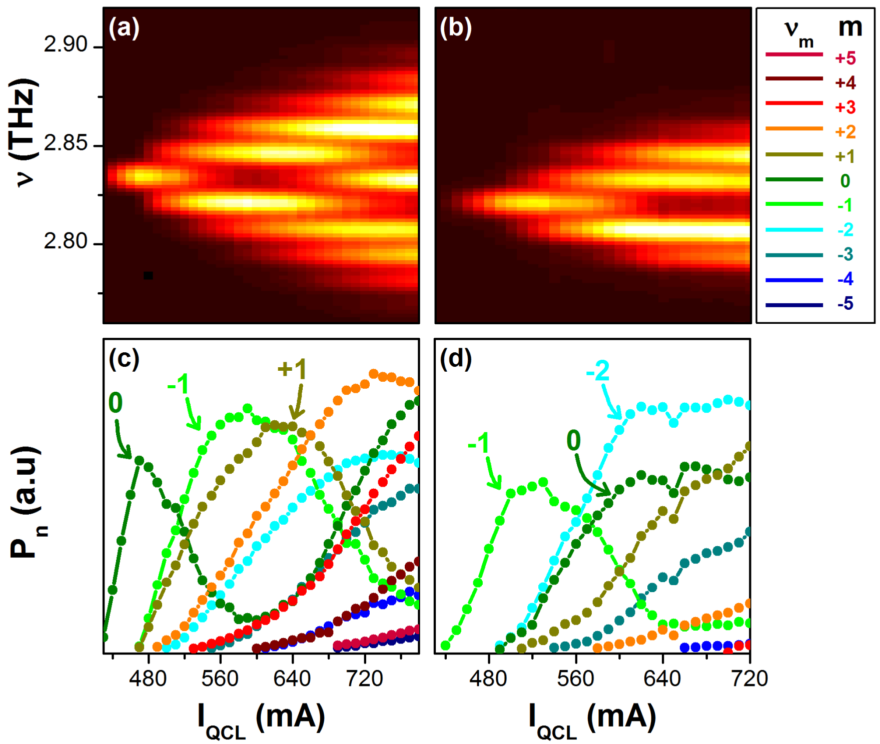
Lumerical Simulation

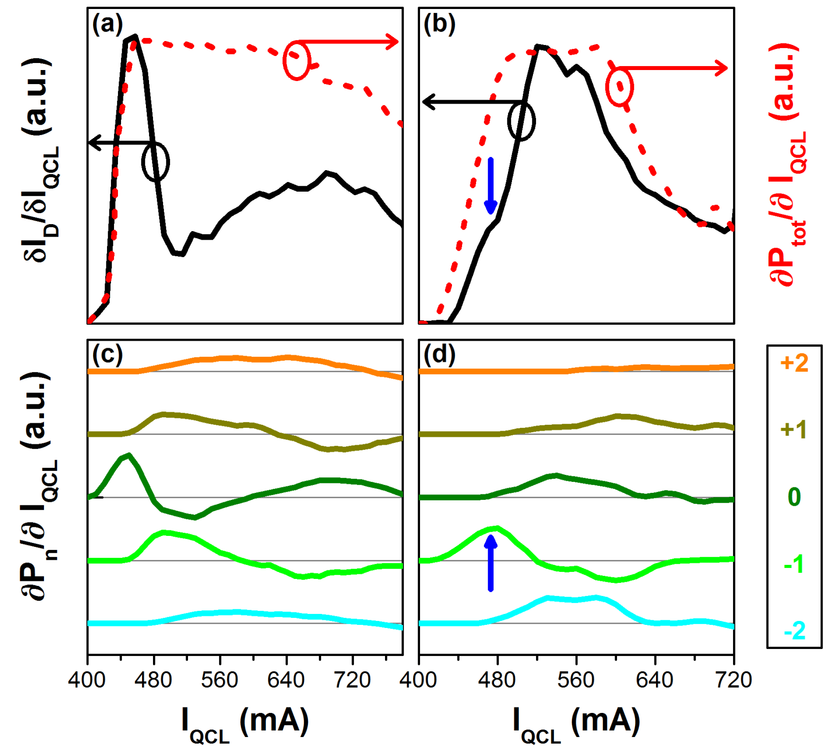
Diode response is not linear with laser power.

Dyer, APL., submitted (2013)

Diode Response vs Laser Power

Why is the response not linear with laser power?

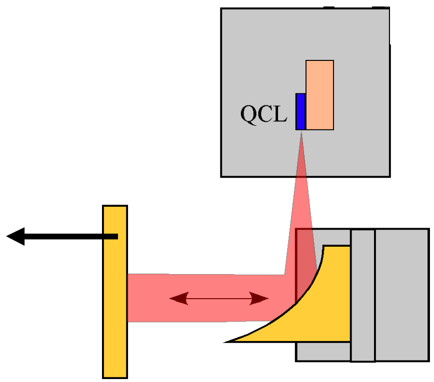


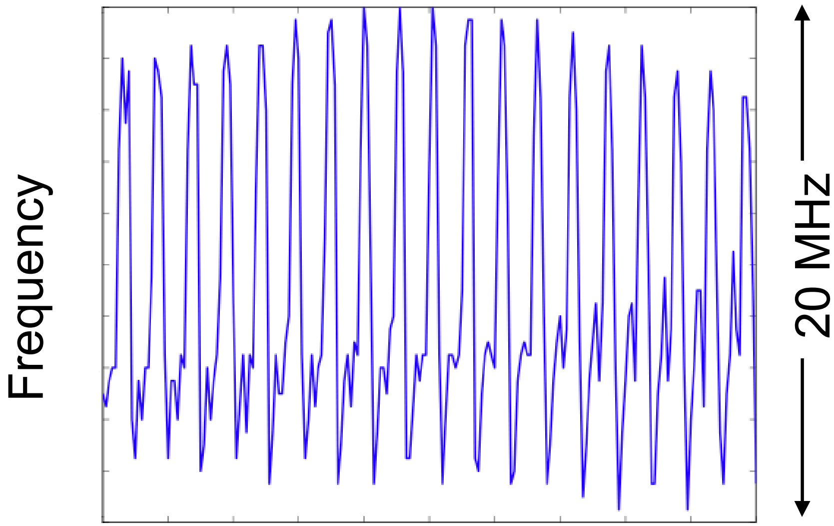


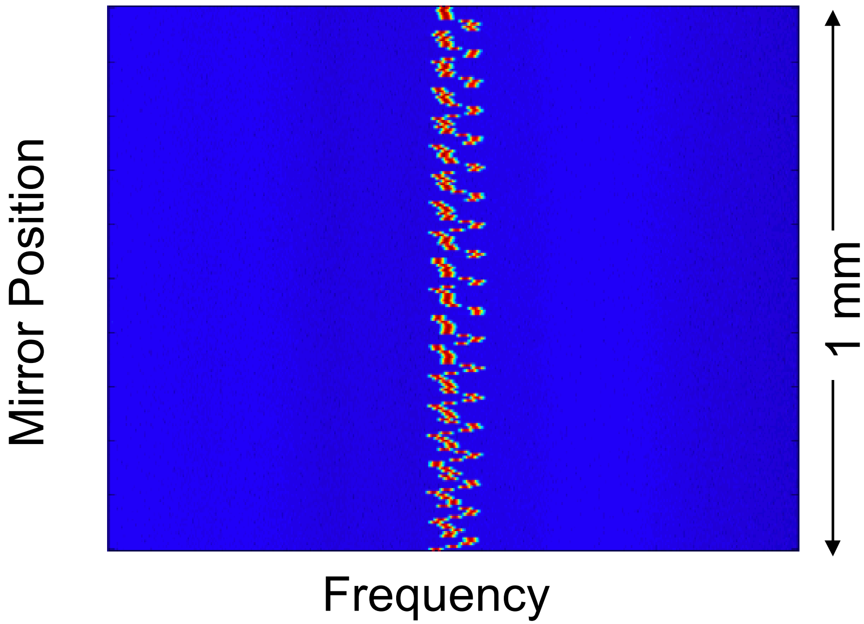
All modes do not have same overlap/coupling to diode.

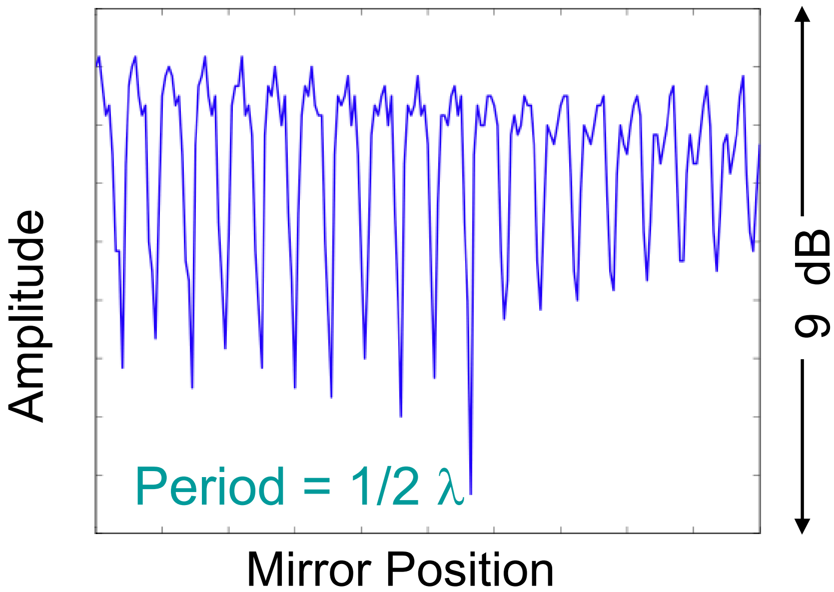
Dyer, APL., submitted (2013)

Cavity Length Sensitivity



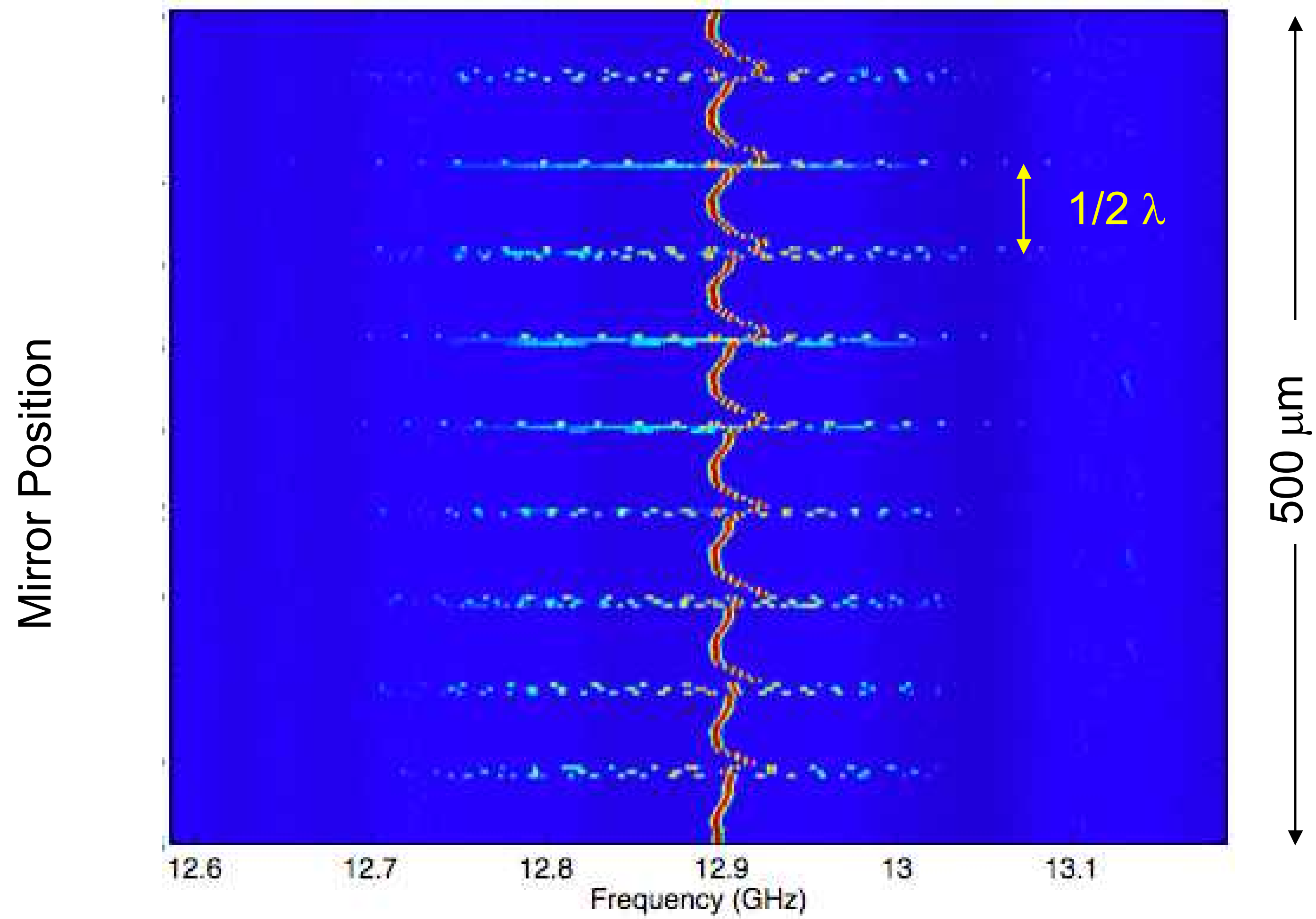




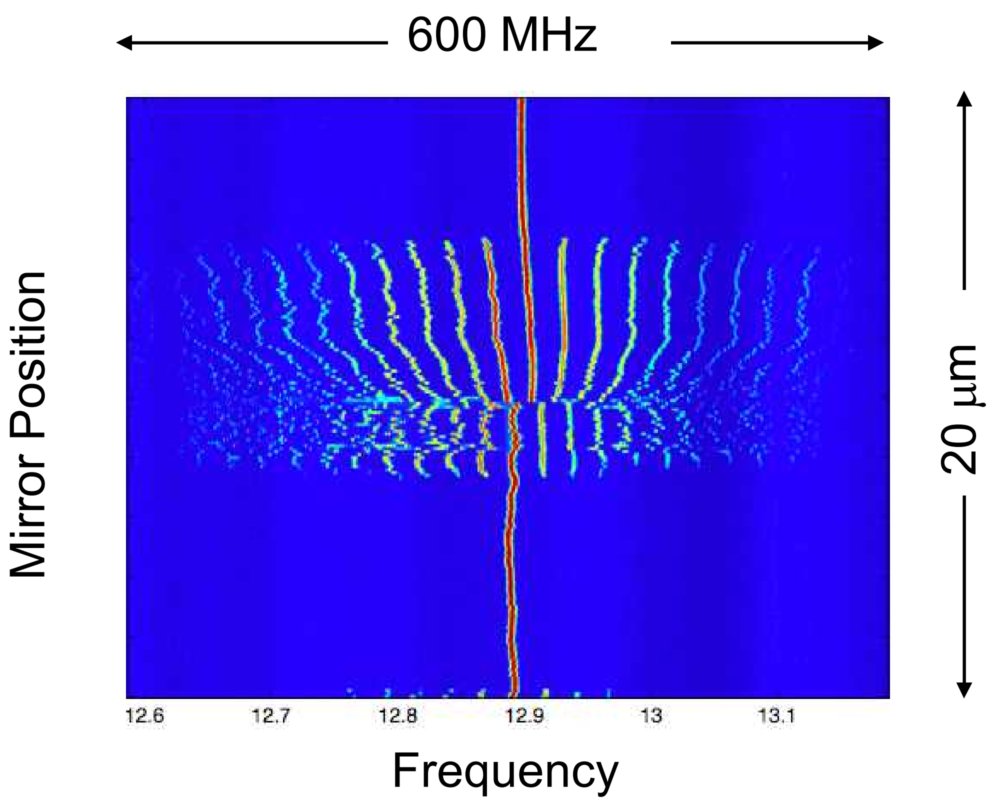


Feedback Effects on FP mode

Not always a single beat frequency



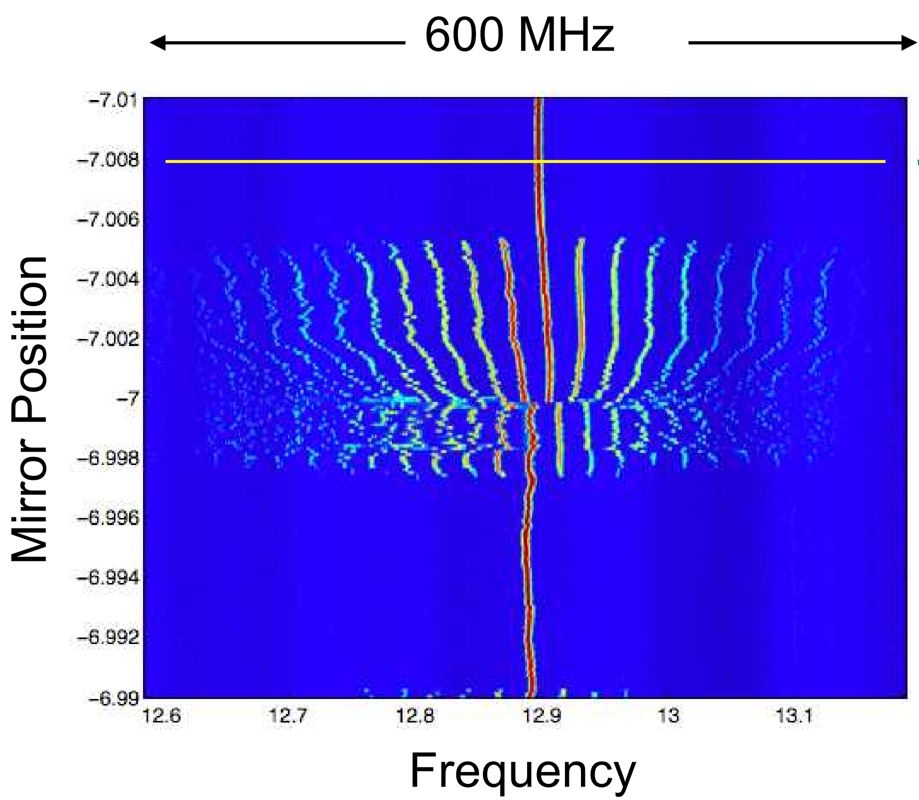
Feedback Effects on FP mode

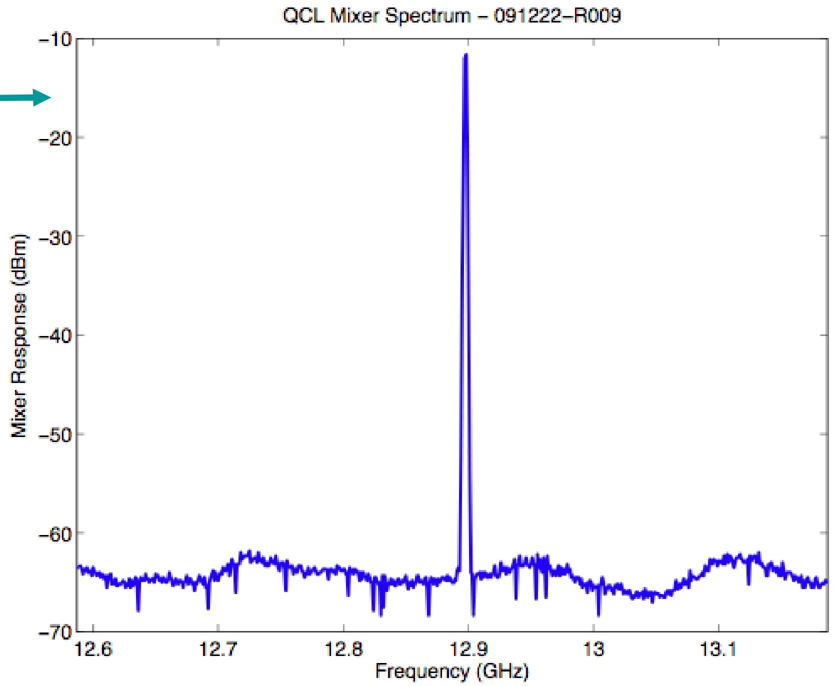


FP Modes Split into multiple lines

Feedback Effects on FP mode

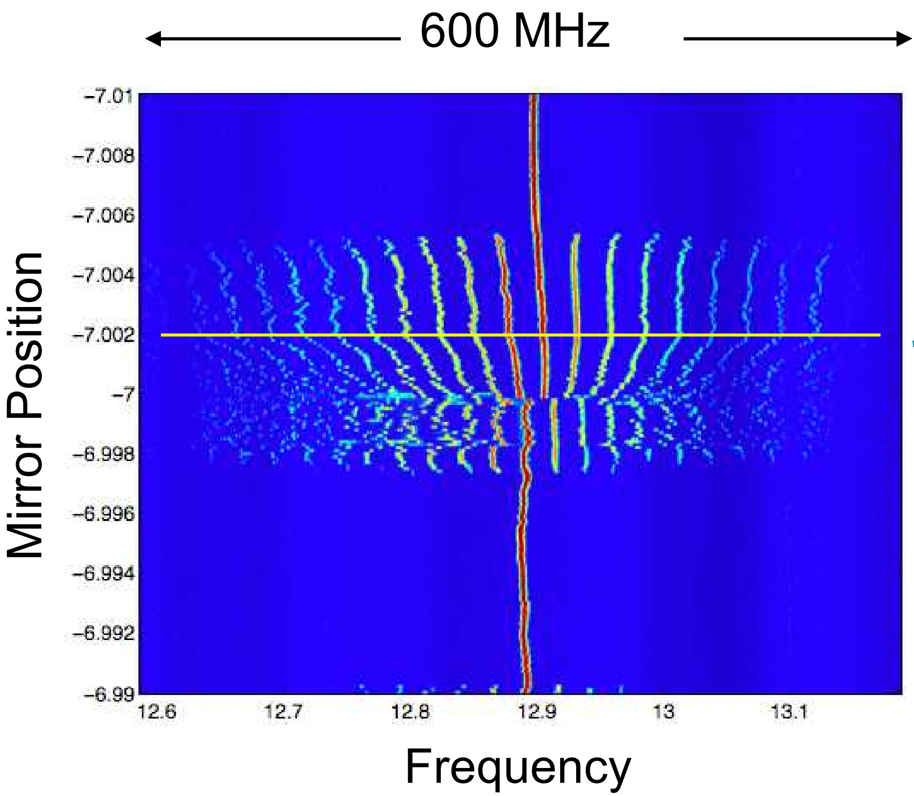
Region I - Normal Fabry-Perot Modes

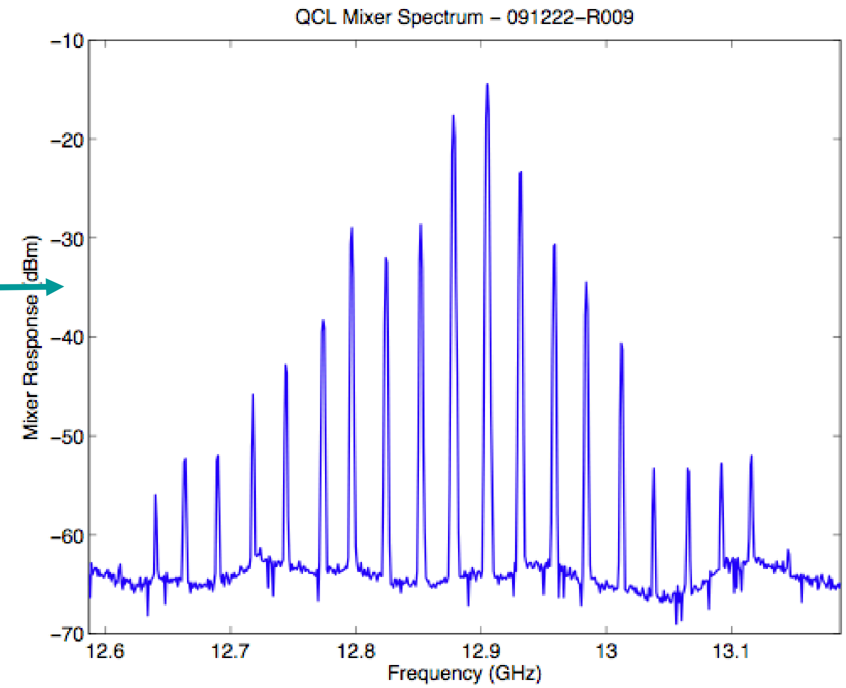




Feedback Effects on FP mode

Region II - Fabry-Perot Modes Bifurcate

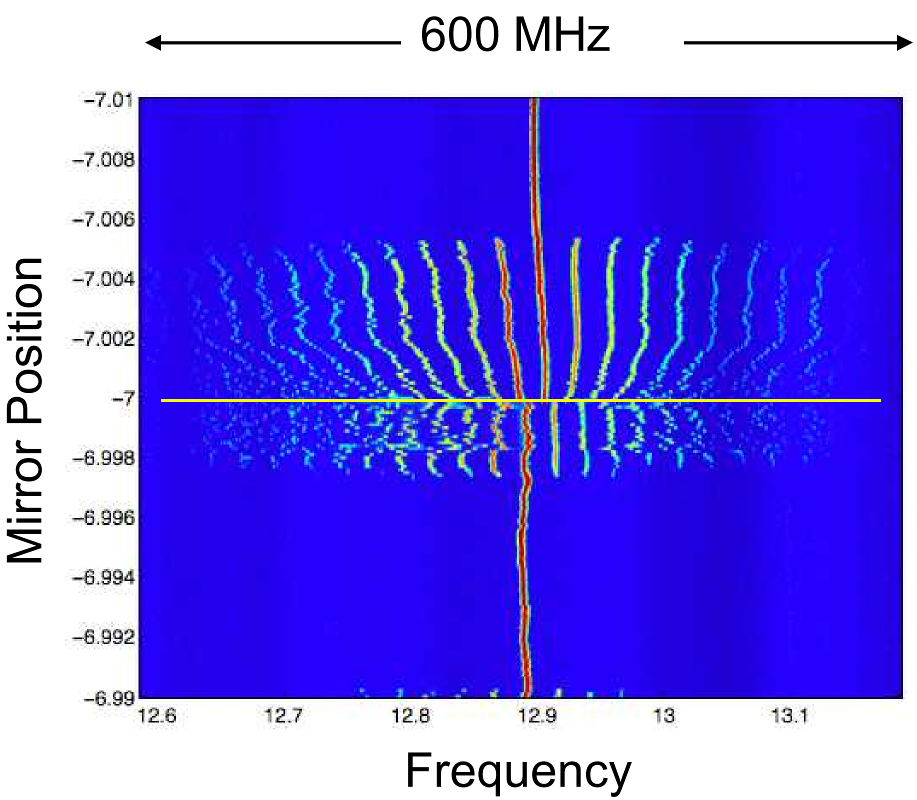


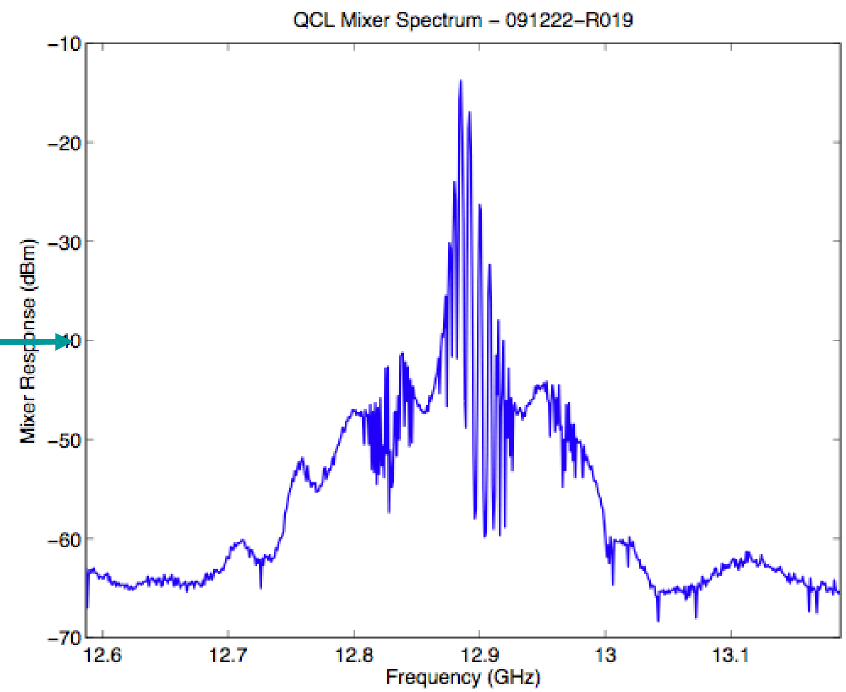


Stable Spectrum

Feedback Effects on FP mode

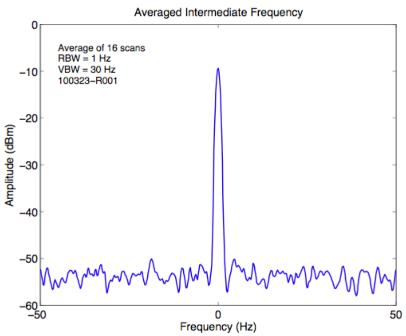
Region III - Chaos Onset

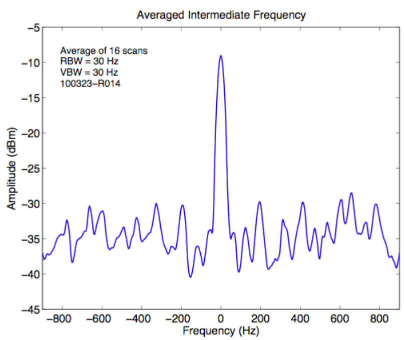


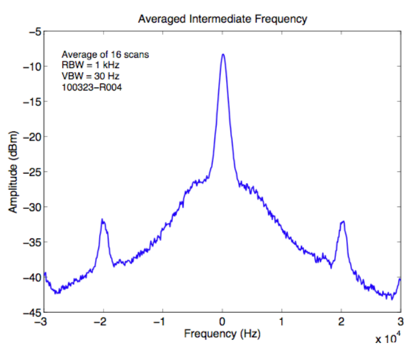


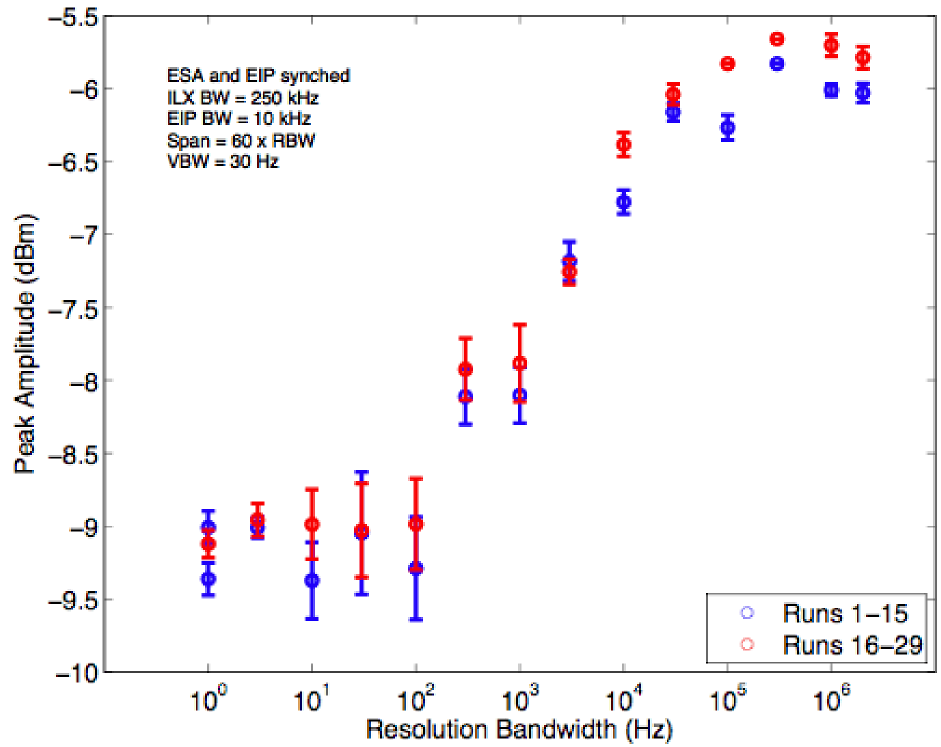
Unstable Spectrum

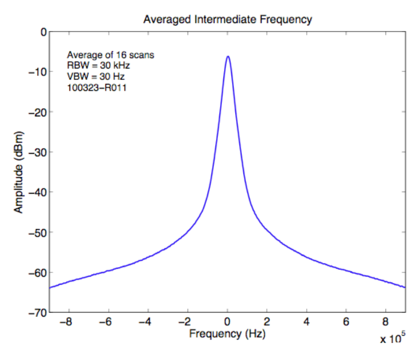
Phase Locking Bandwidth

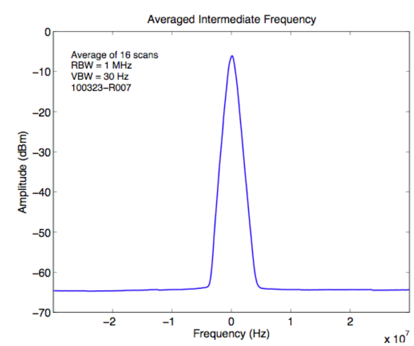






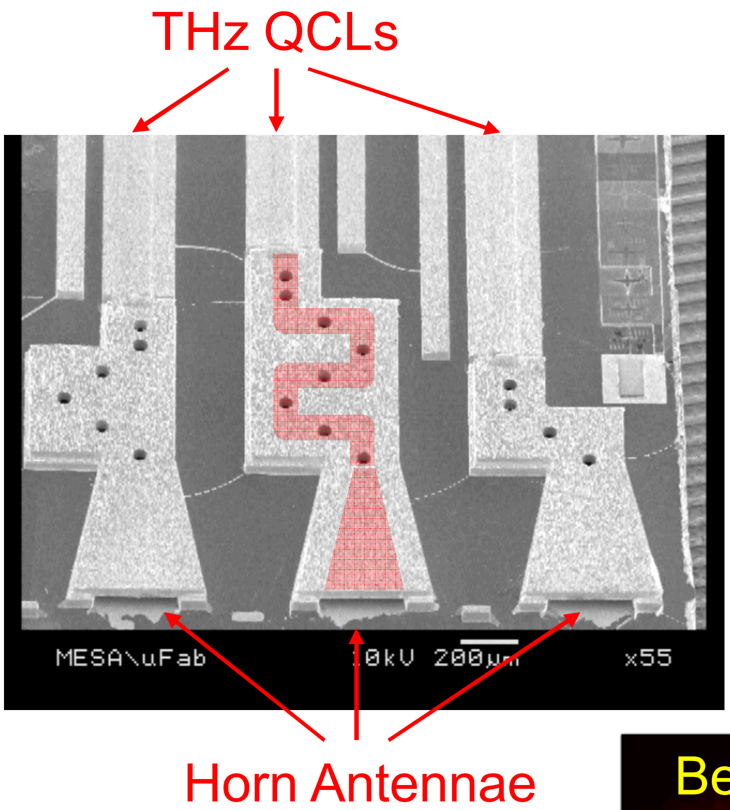


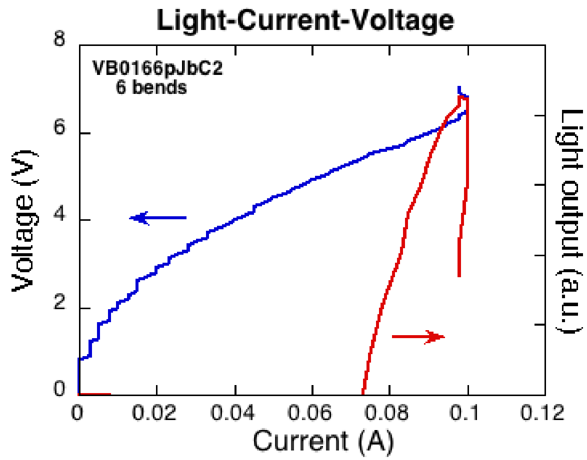


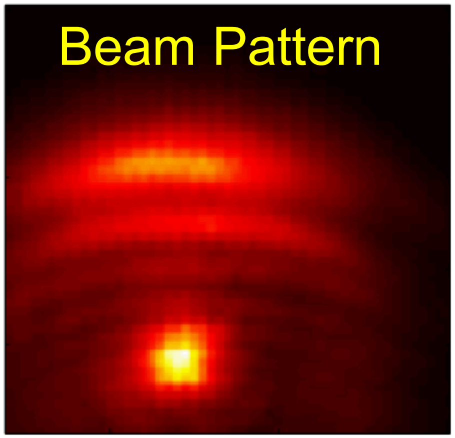


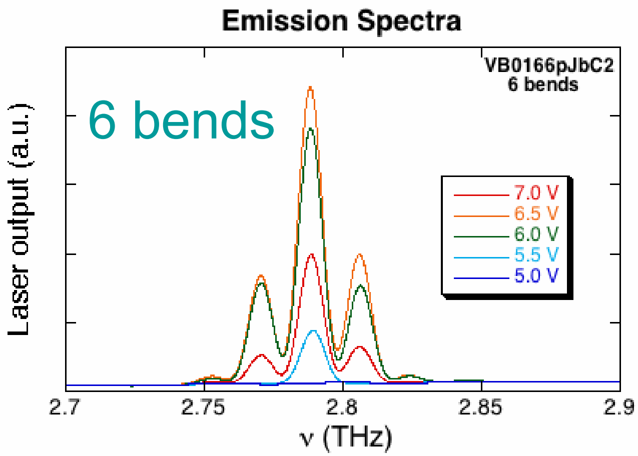
Integrated Waveguide Performance

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

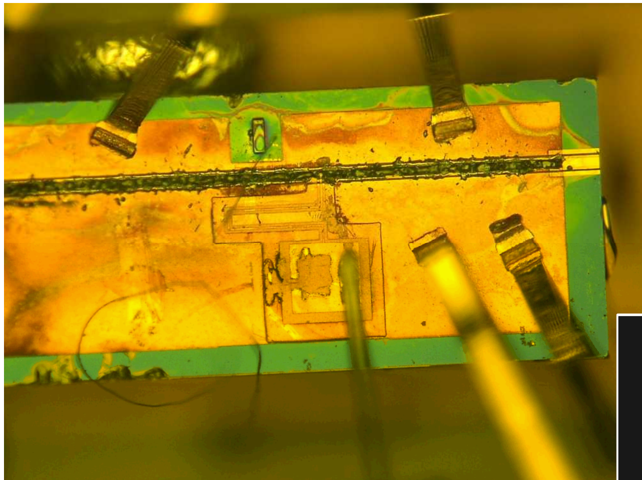




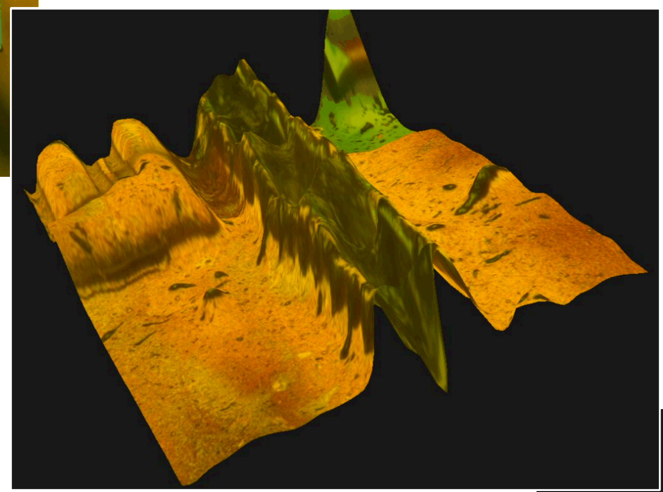


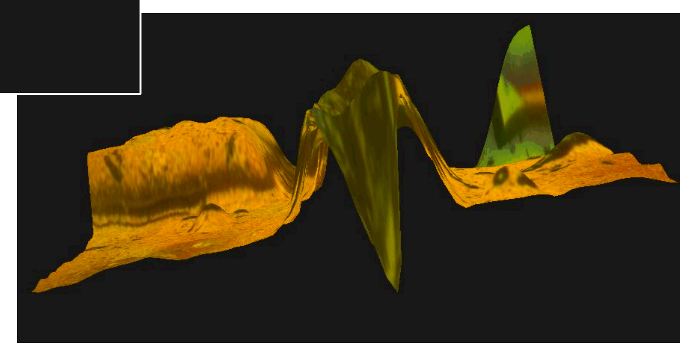


Only pulsed operation



Aftermath of CW operation attempt.

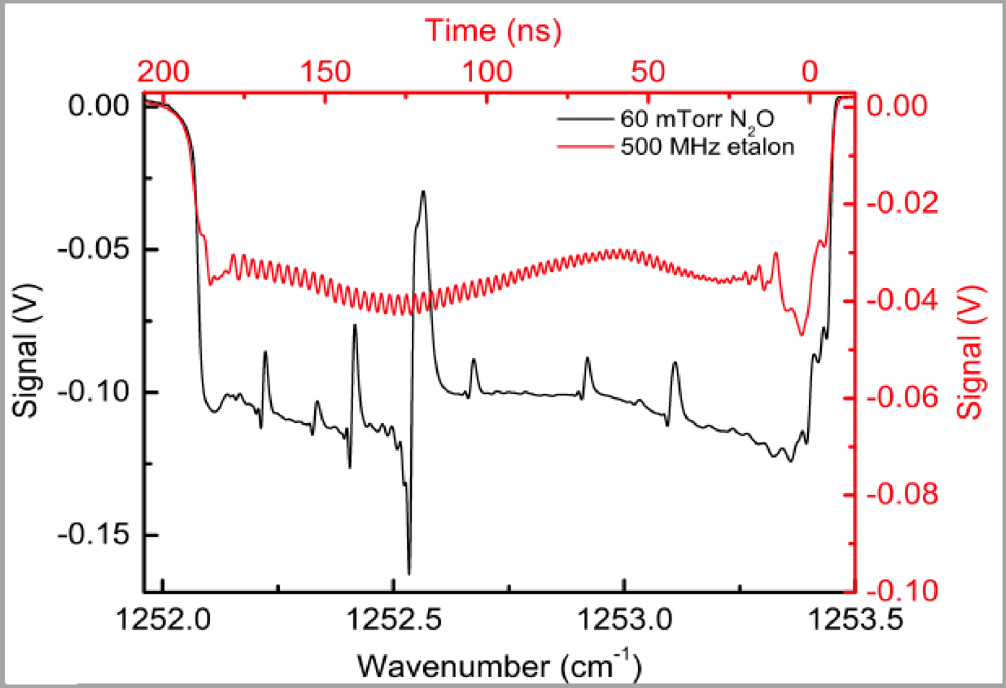




Pulsed operation much harder for heterodyne measurements.

Not a receiver yet.

Issue with pulsed operation – Chirp!



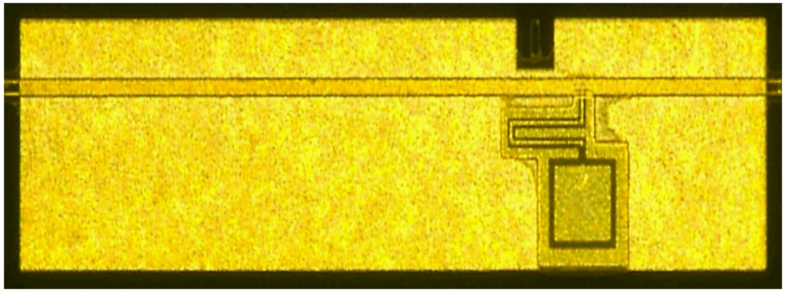
Northern, et al. Appl. Phys. B, 102, 37, (2011)

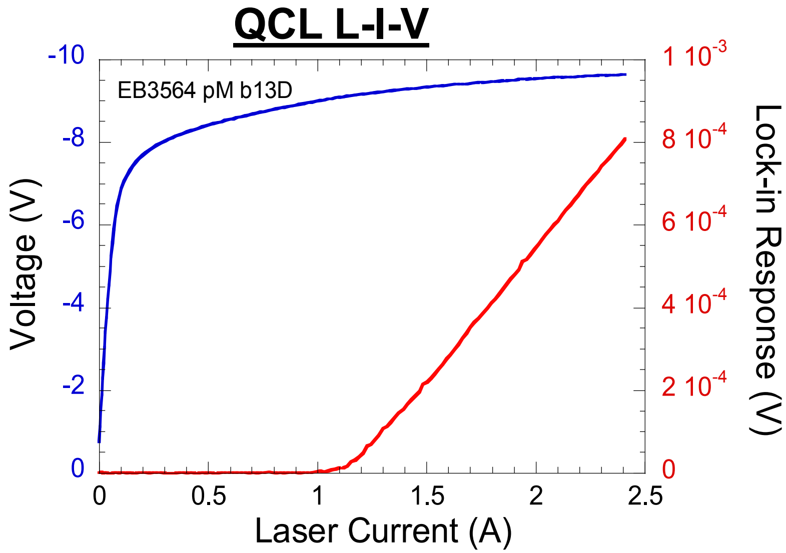
Example 8 um laser chirp from literature

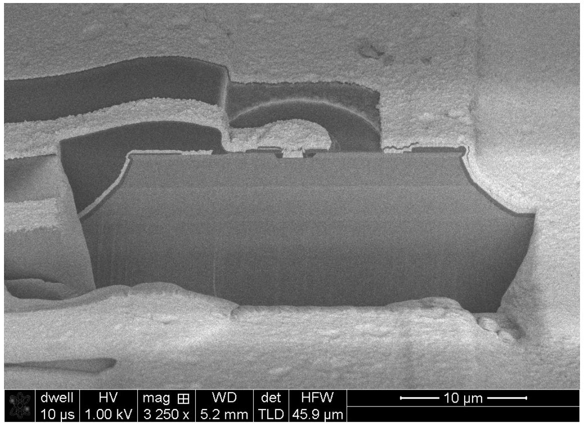
- 40 GHz chirp
- 200 ns pulse

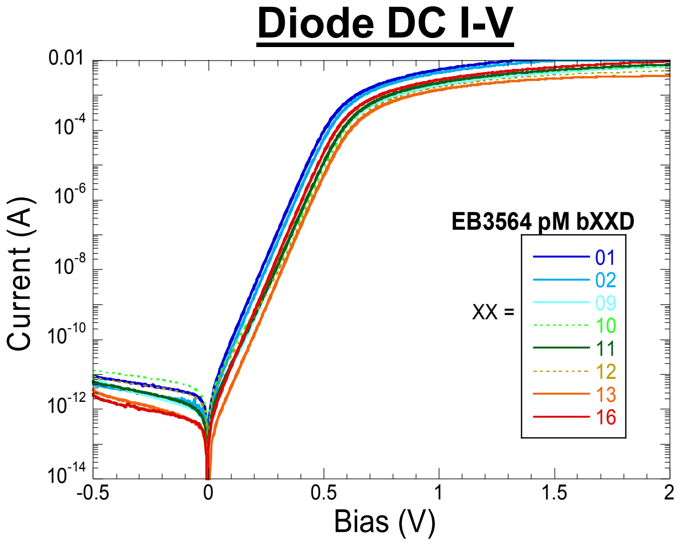
Any beat frequency generated by mixing against stable external signal can be changing by ~ 200 MHz / ns.

Diode and MIR Laser DC Properties





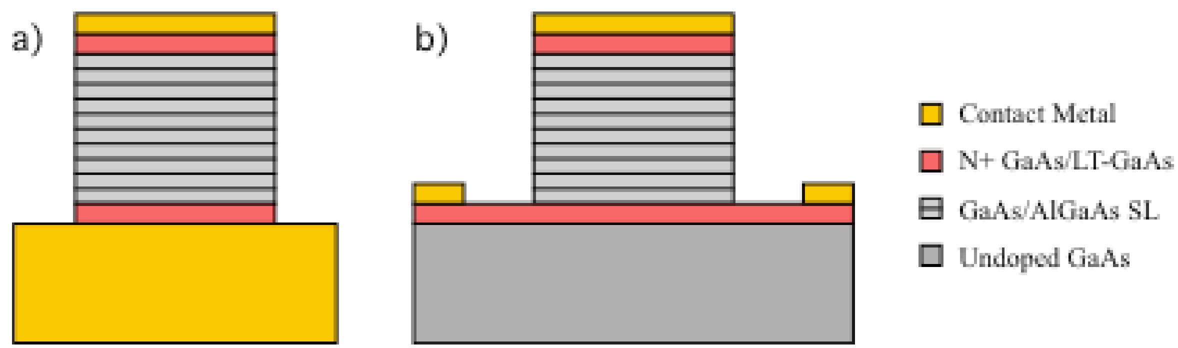


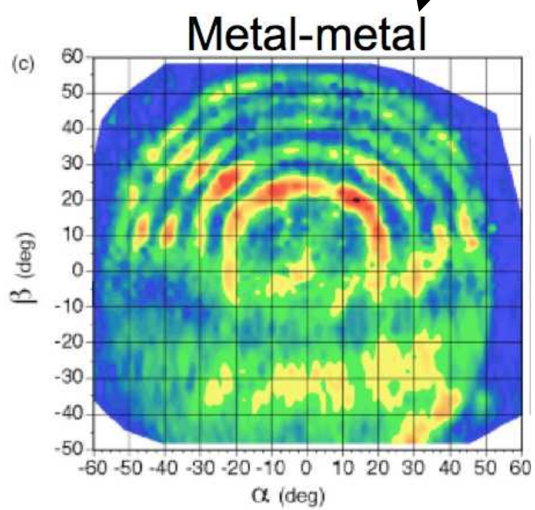


QCL Far Field Issues

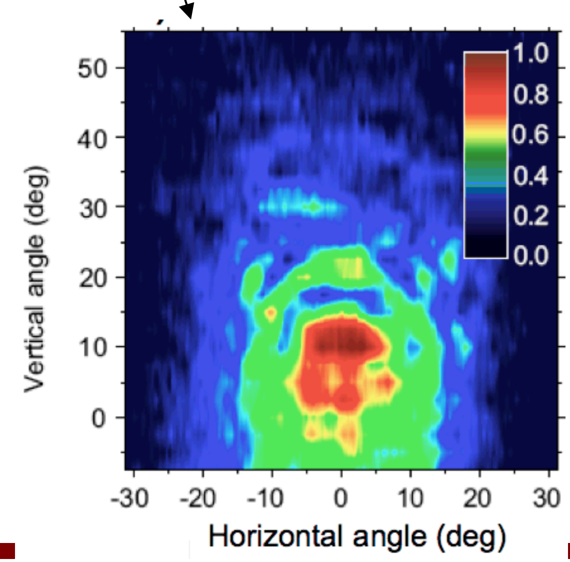
Metal-Metal Waveguide

Surface Plasmon Waveguide



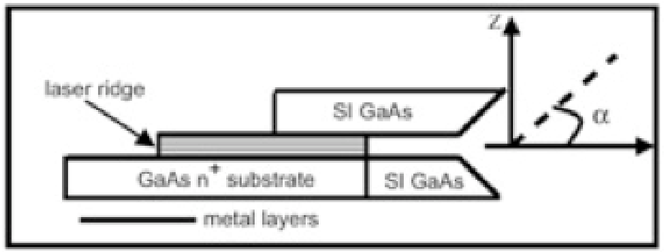


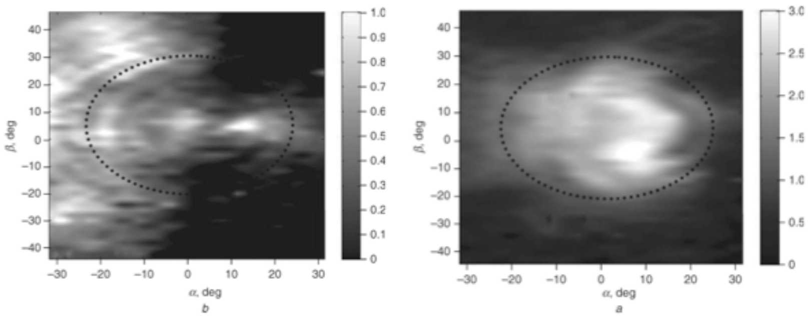
(Courtesy J. R. Gao, TU Delft)



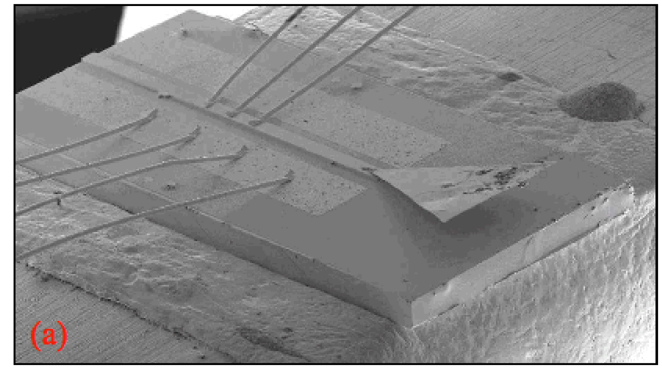
Fixing the beam pattern

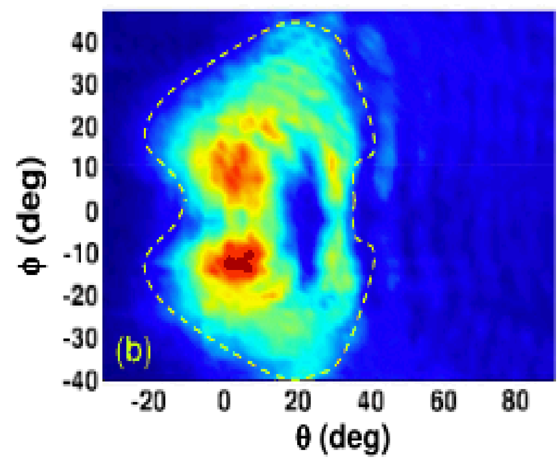
Amanti, *Elec. Lett.*, **43**, p573, 2007

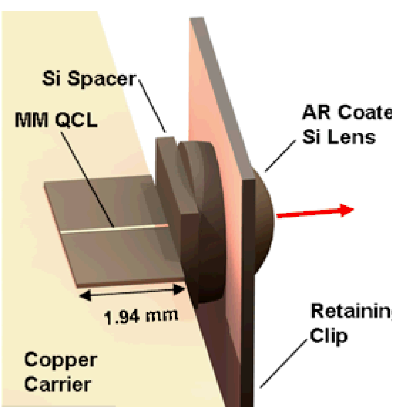




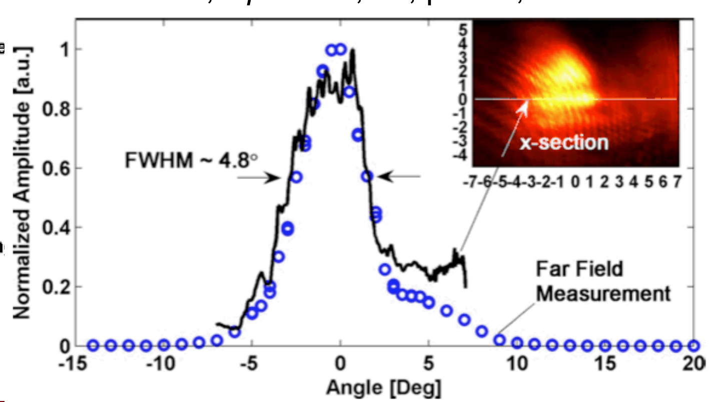
Maineult, *Appl. Phys. Lett. 93, 183508 (2008)*





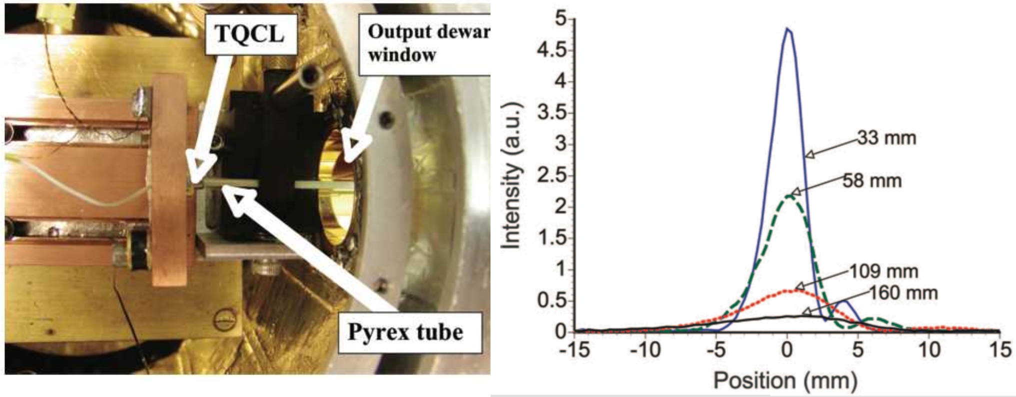


Lee, *Opt. Lett.*, **32**, p2840, 2007

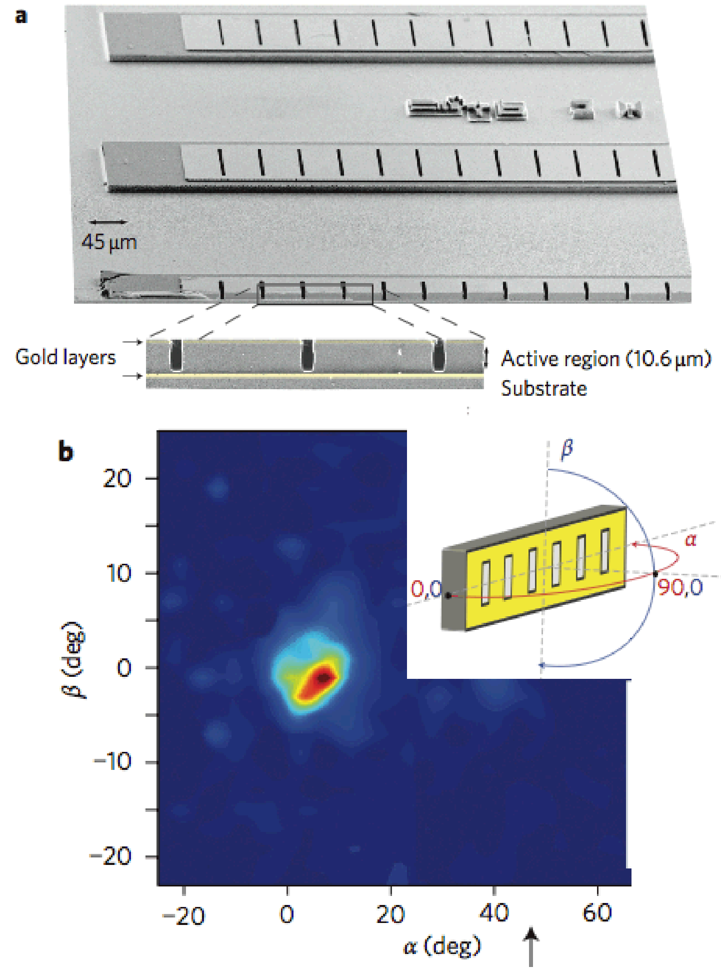


Controlling the Beampattern

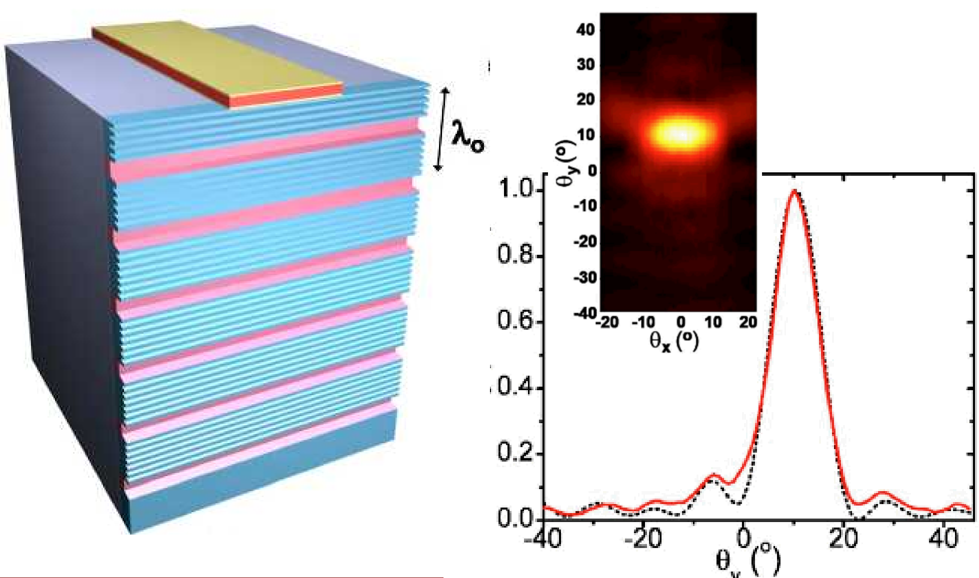
Danylov, Appl. Opt. 46, 5051 (2007)



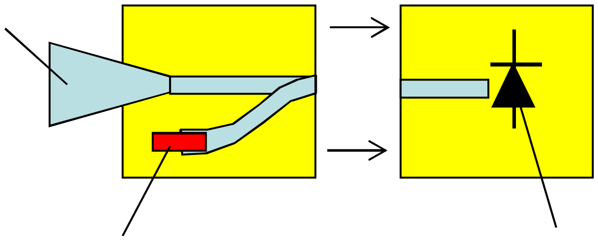
Amanti, Nat. Phot..3, 586 (2009)

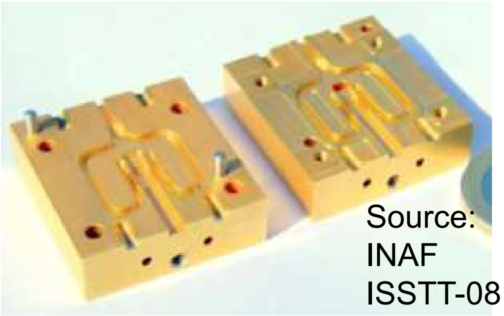


Yu, J. Opt. Soc. Am. B, 27, B30, 2010



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**

Micromachining Rectangular Waveguides

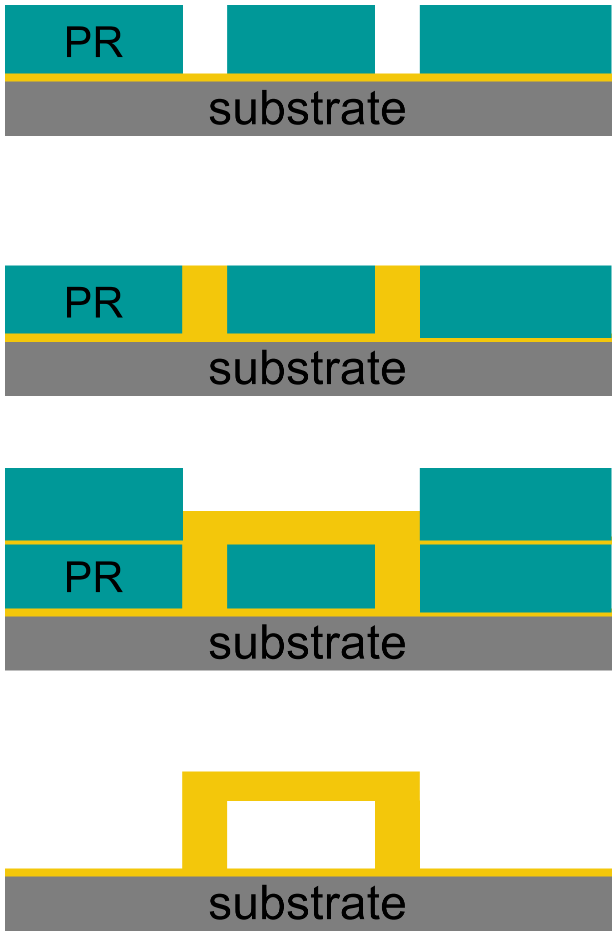
Sandia National Laboratories

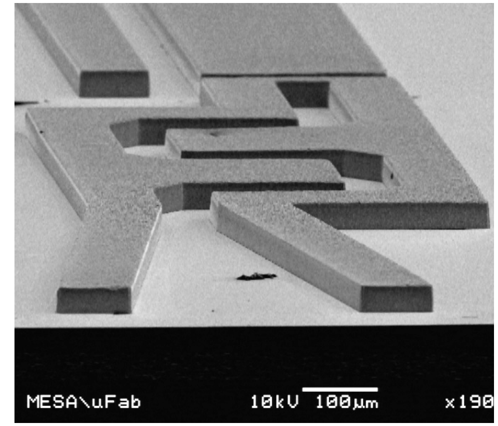
1. Deposit seed metal and pattern photoresist

2. Electoplate Au in photoresist openings

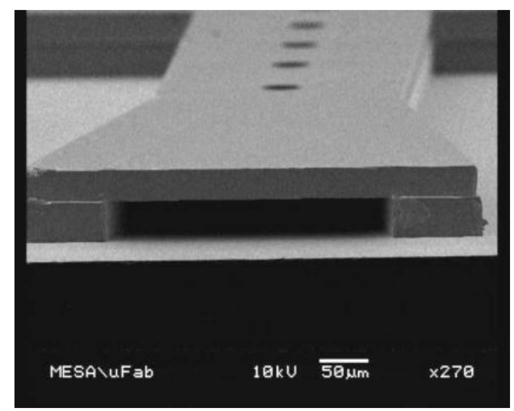
3. Deposit 2nd seed, pattern 2nd PR, and plate lids

4. Remove photoresist and 2nd seed metal





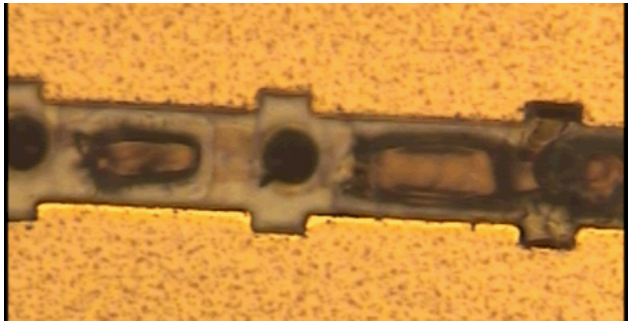
- **Additive electroplating technique suitable for various substrates**
  - *Allows waveguide fabrication on QCLs or other devices*



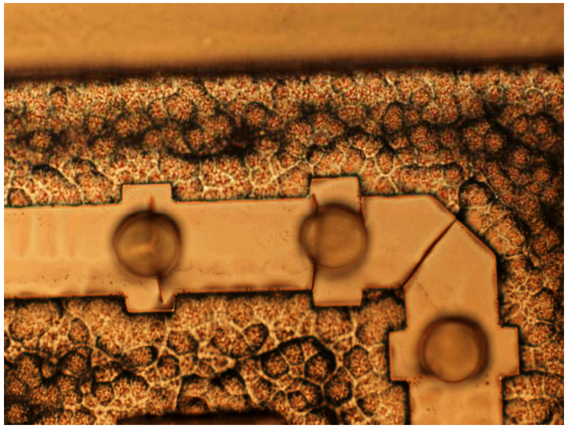
Rowen, Proc. SPIE, **7590**, 2010

The dirty little secret...

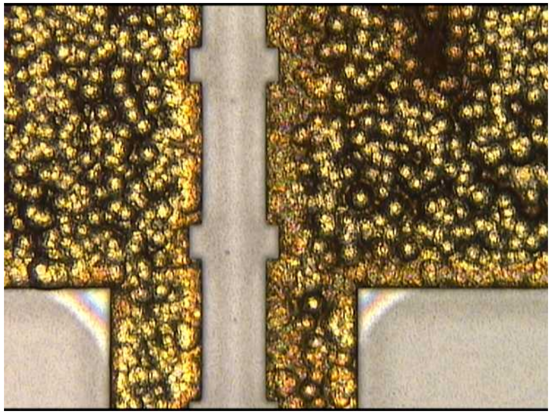
Removing Photoresist



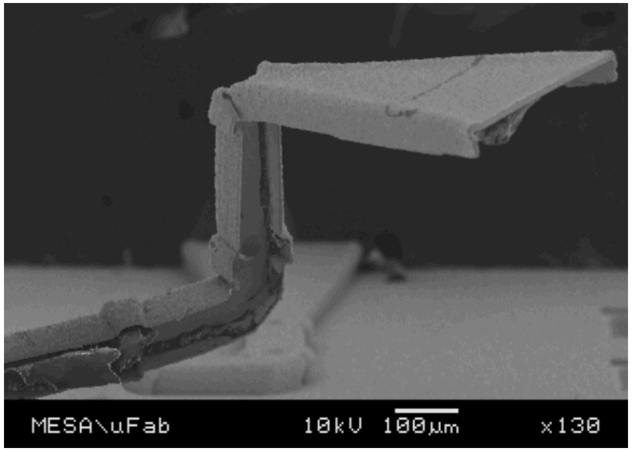
Alignment



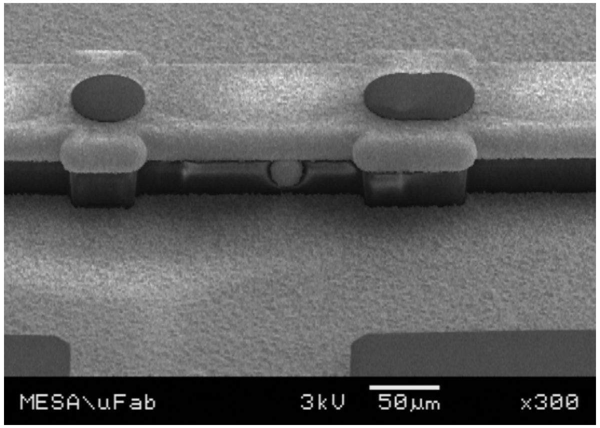
Nonuniform Electroplating



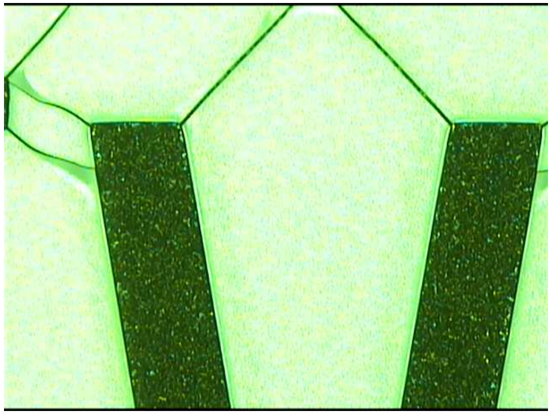
Delamination



Step Coverage

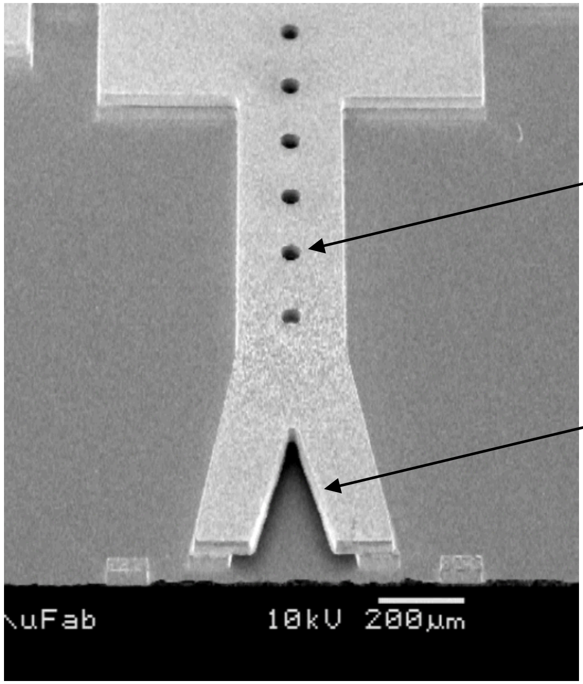


Photoresist Cracking



...simple processes are never simple

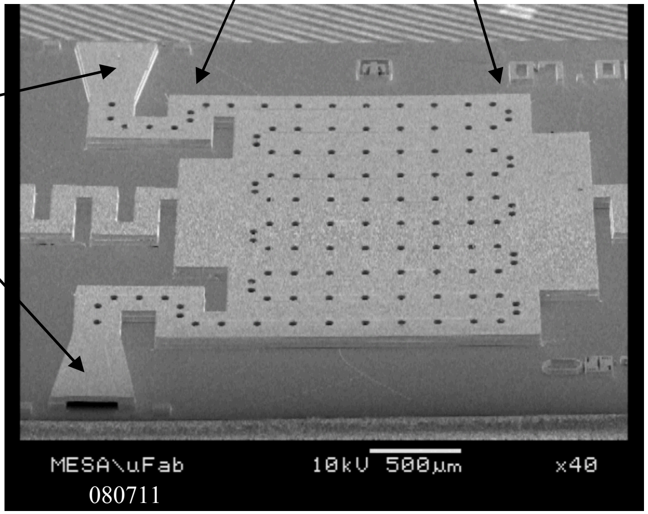
Micromachined THz Waveguides

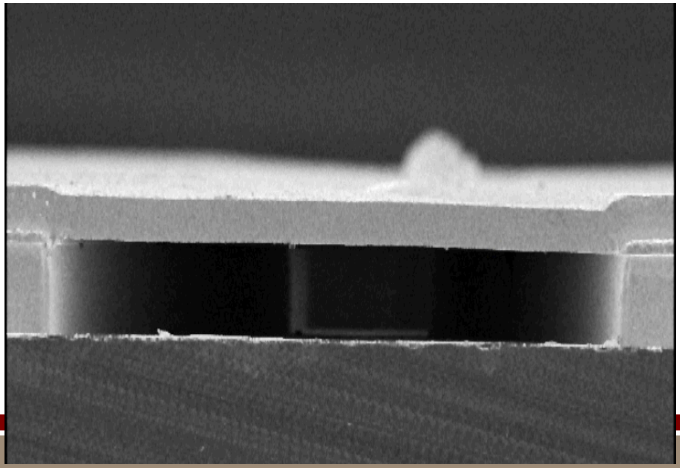


Photoresist removal holes

Horn antenna

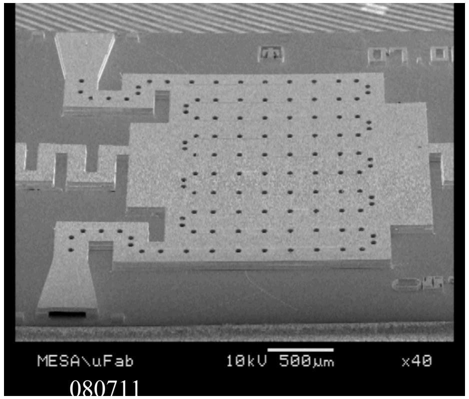
H-Plane Bends

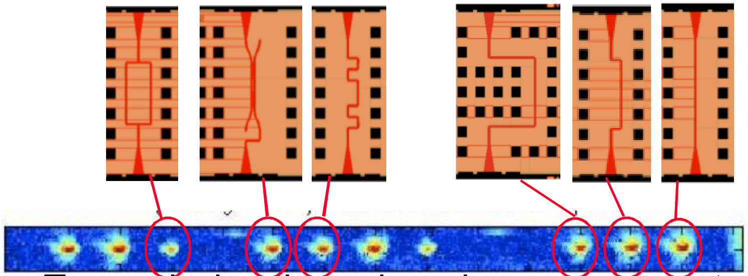




End view of waveguide horn antenna

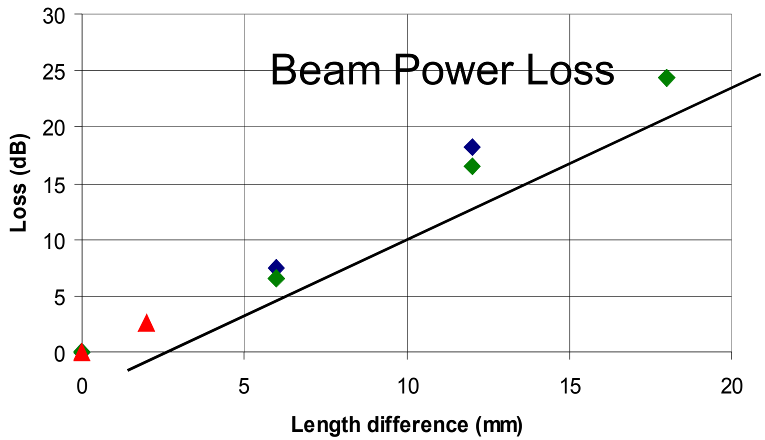
THz Micromachined Waveguide Components



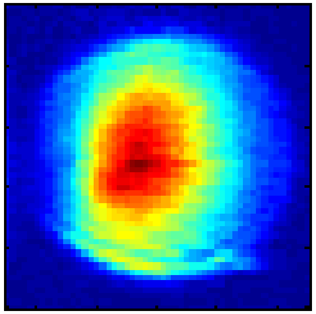


Transmission through various components

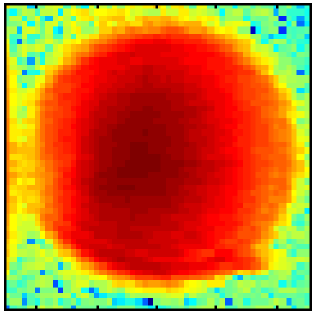
- Demonstrated THz components (waveguides, bends, tees, and couplers) needed for THz integrated circuits.
- Achieved low propagation and bend losses (at 2.9 THz).
  - 1.4 +/- 0.15 dB / mm (.15 dB / λ)
  - 0.15 +/- 0.15 dB / bend
- Observed good far-field beam patterns.



Antenna Beam Pattern

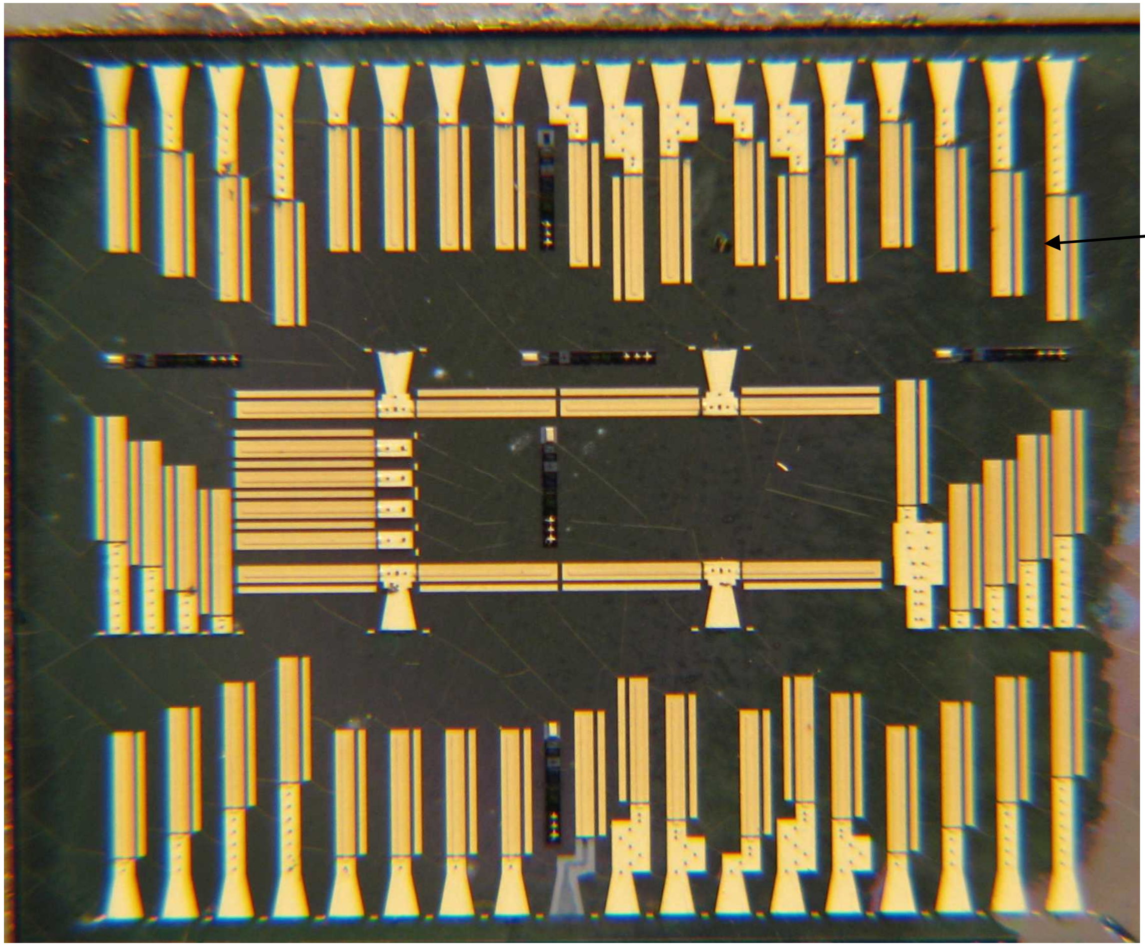


Linear Scale



Log Scale

Integrated Lasers with Waveguides



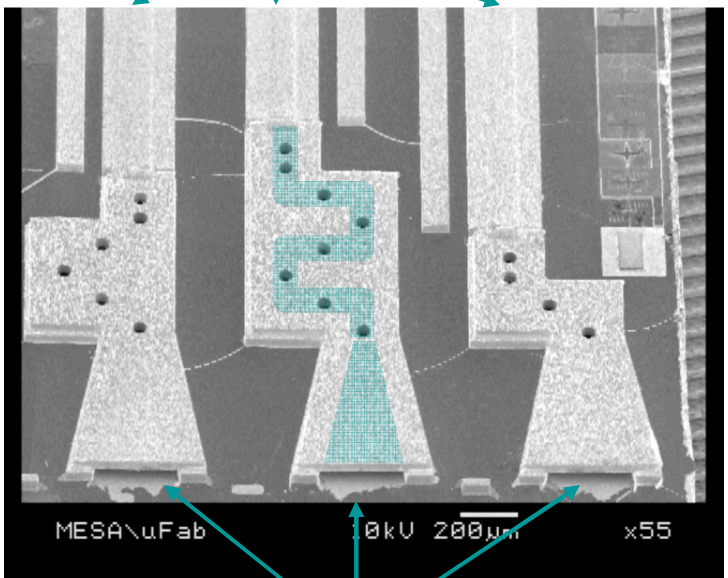
Built waveguides on top of lasers

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

Note: parallel assembly advantage

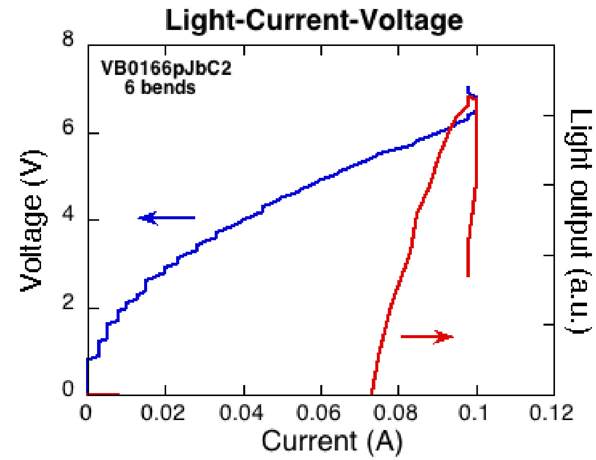
Integrated Waveguide Performance

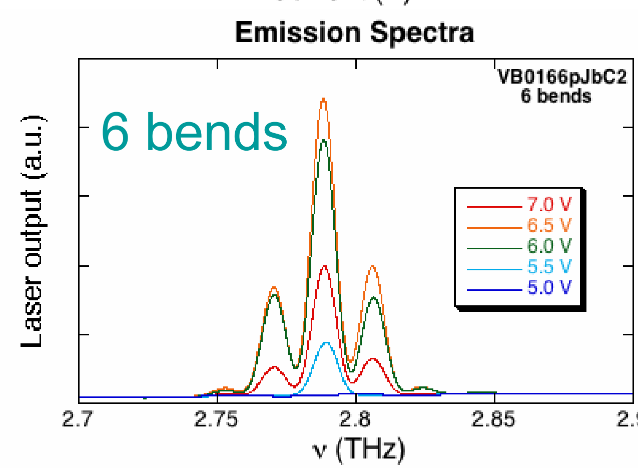
THz QCLs



Horn Antennae

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





Beam Pattern