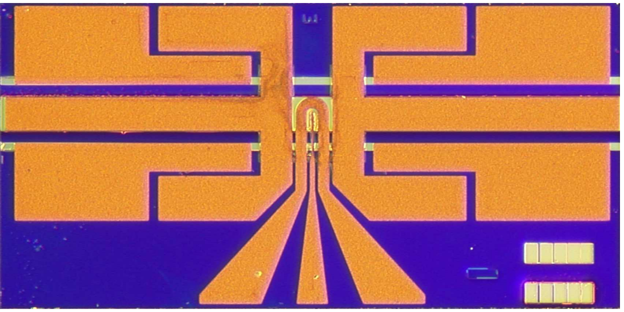
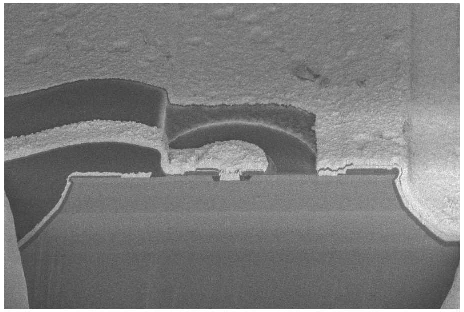
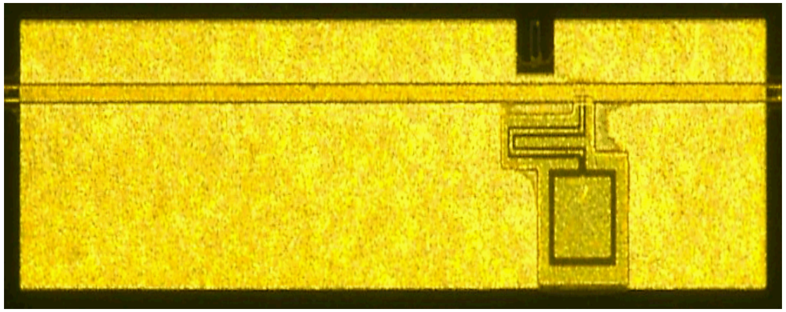
SAND2017-12089C







Mid-infrared and terahertz transceivers

Workshop on Infrared Technologies

Mike Wanke

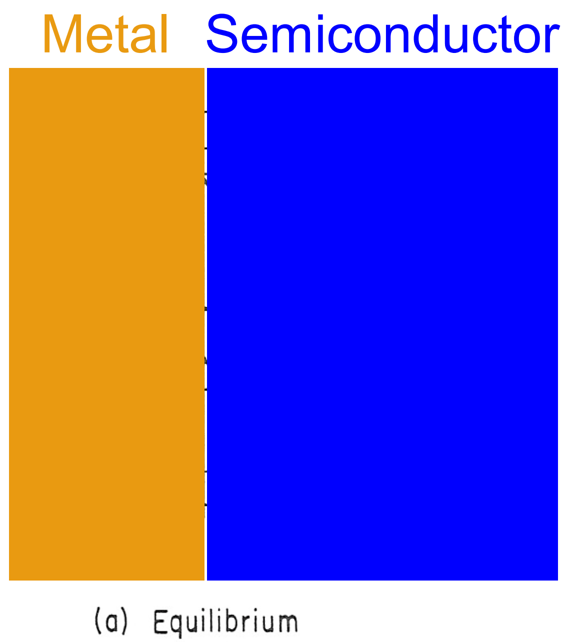
Nov 8, 2017

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

- Schottky diode heterodyne mixers
  - Background
- Integrated Schottky diodes and THz QCLs
  - Rectified (video) response
  - Mixer response
  - Receiver response
  - Coupling question
- Integrated Schottky diodes and MIR QCLs
  - Mixing demonstration

Schottky Diode Essentials



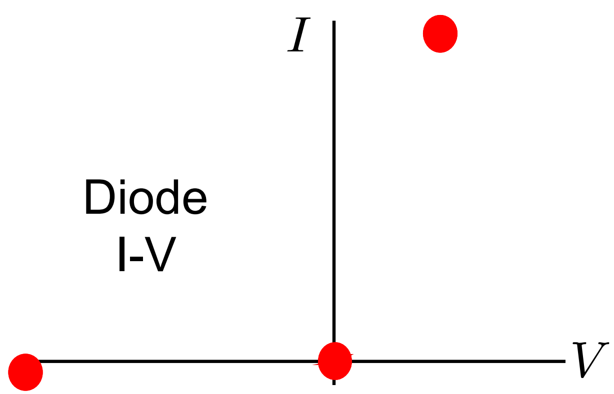
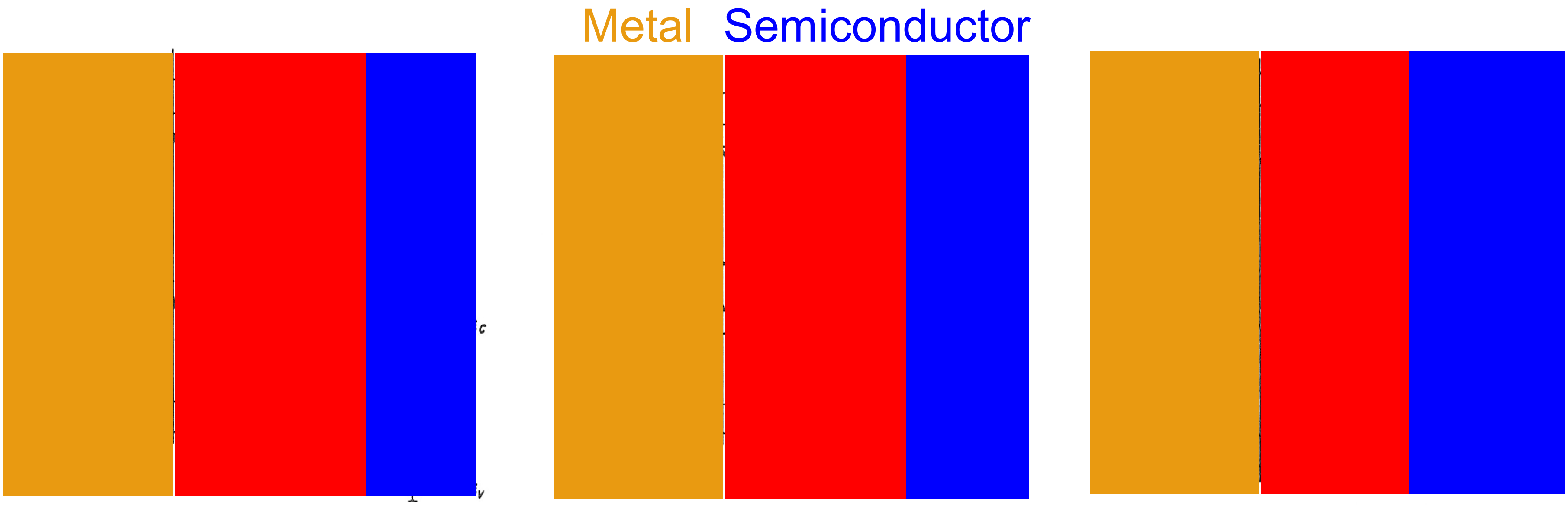


Figure from McKelvey – “Solid State and Semiconductor Physics”

Schottky Diode Essentials



<u>Important Point:</u>

The potential drop is near the interface.

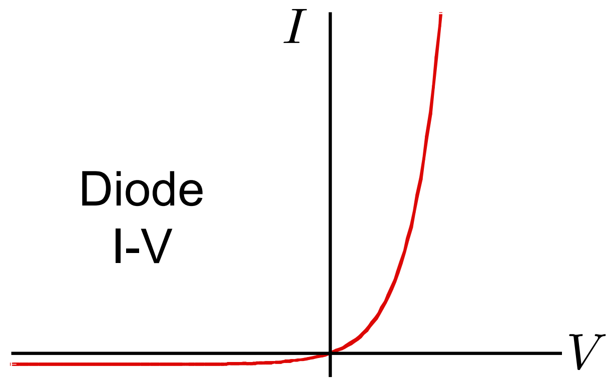
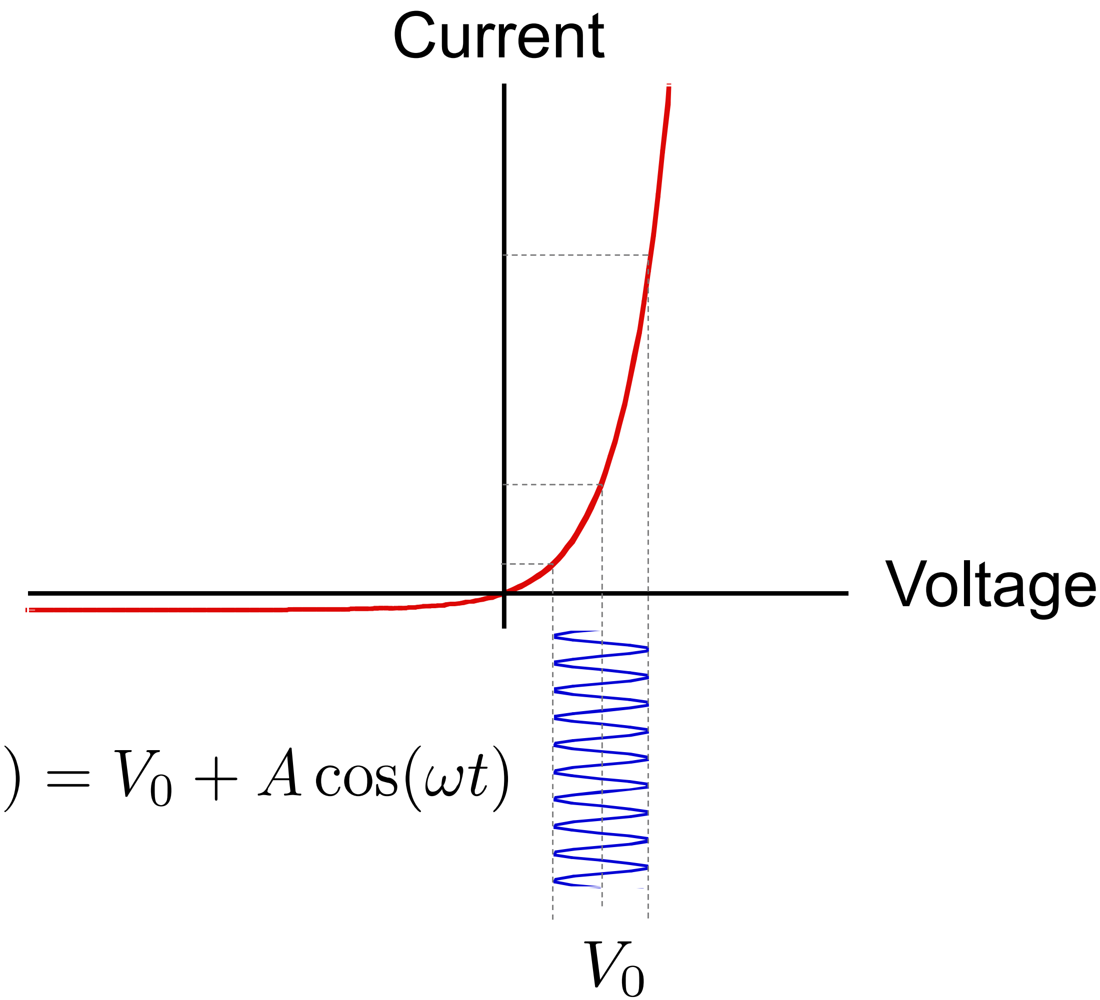


Figure from McKelvey – "Solid State and Semiconductor Physics"

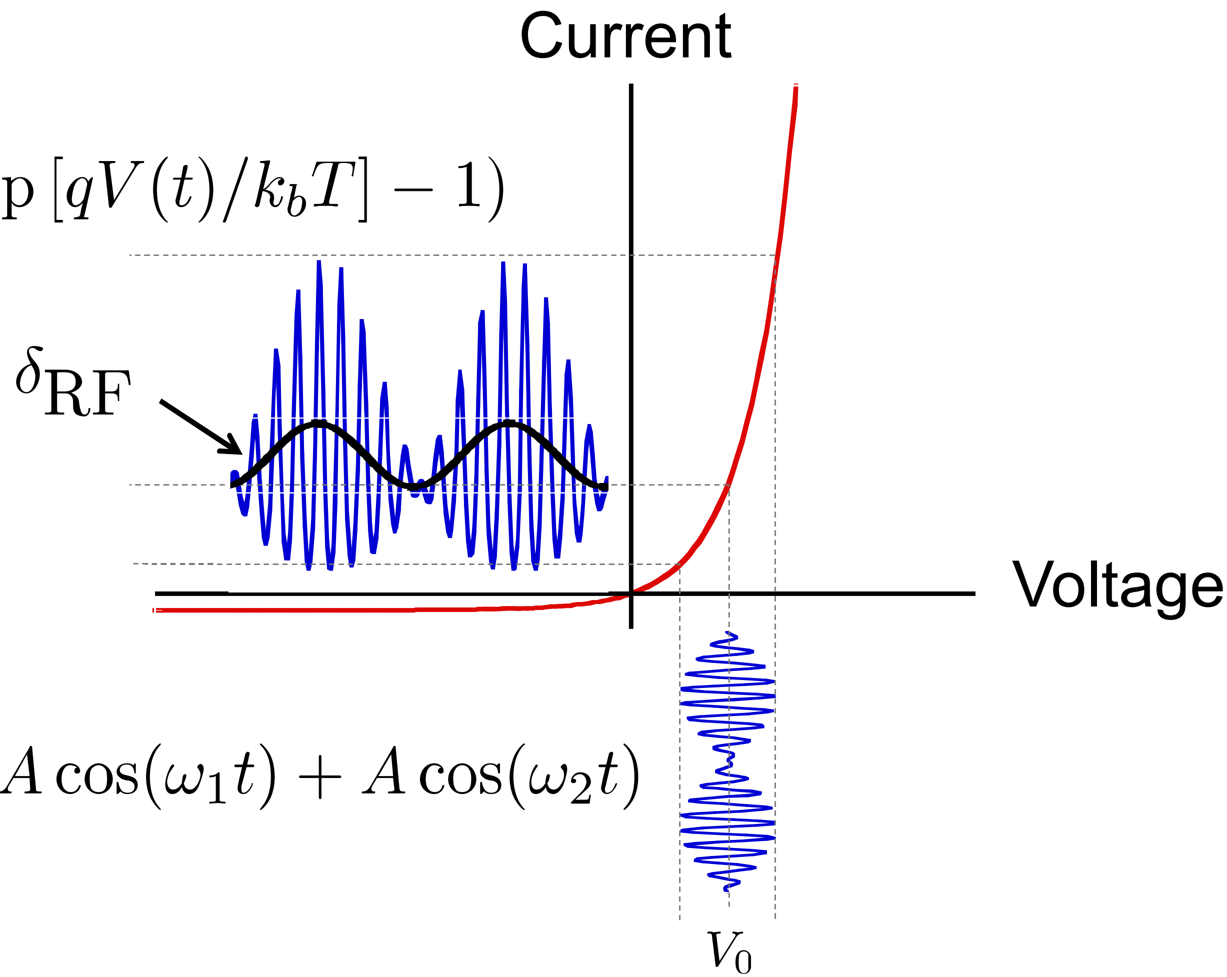
Diode Video Response



$$V(t) = V_0 + A\cos(\omega t)$$

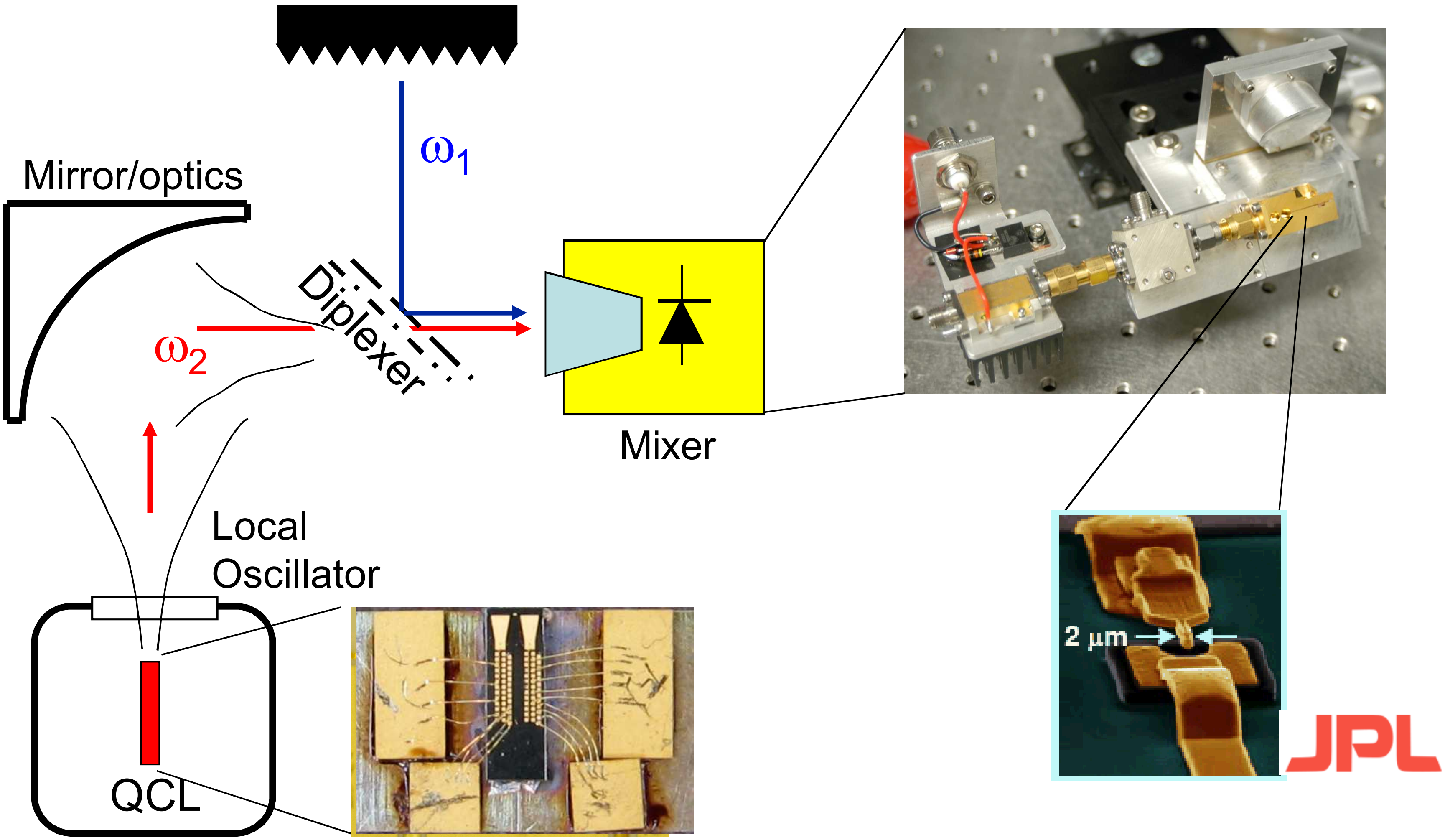
Diode Heterodyne Response

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



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

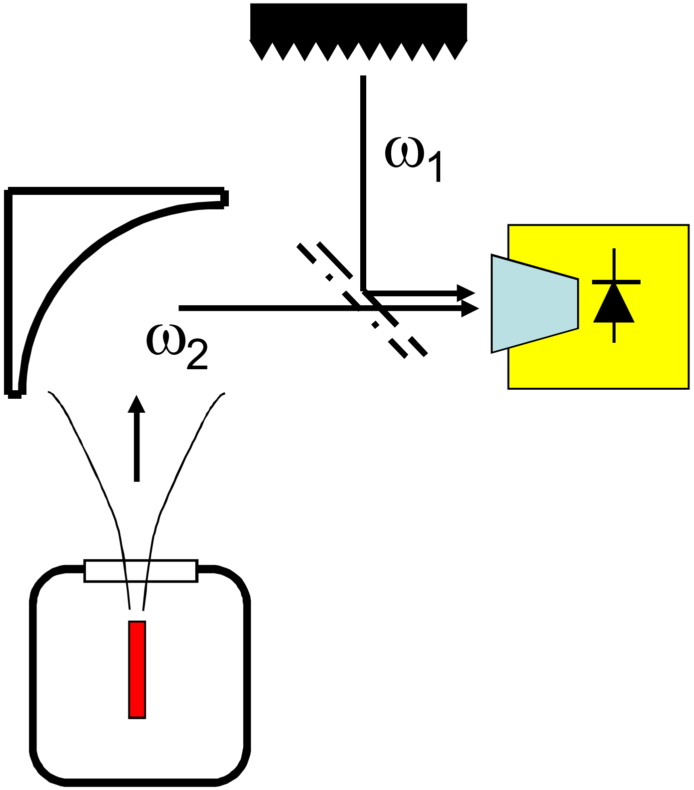
Basic Heterodyne Receiver



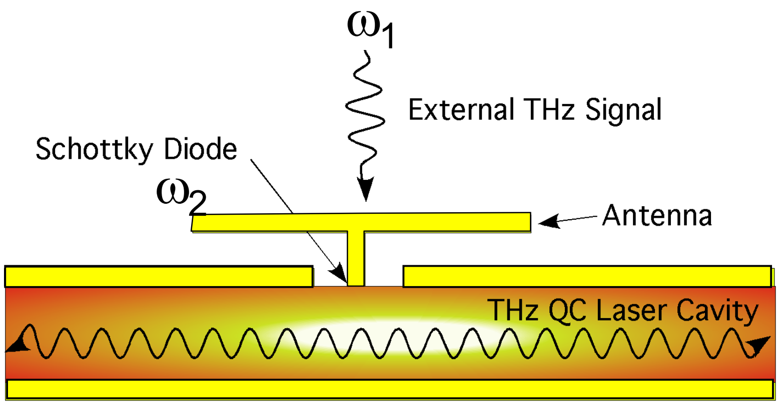
$$P \propto E_1 E_2 \cos(\omega_1 - \omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1 + \omega_2)$$

Goal : integrated, compact receiver

Shrink bulky optical system....



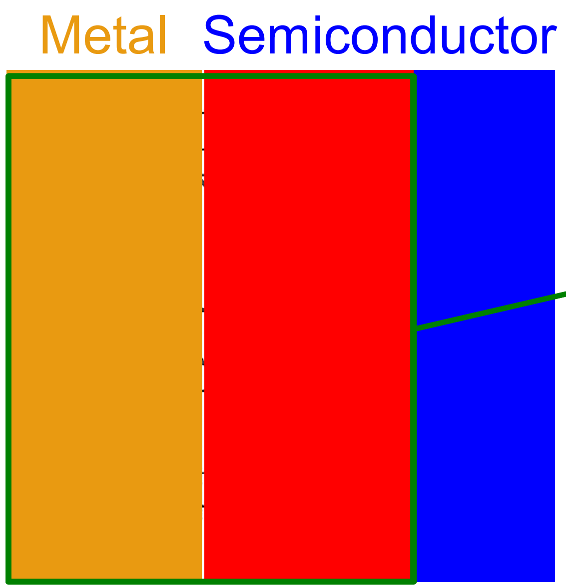
...put QCL and SD on the same chip !

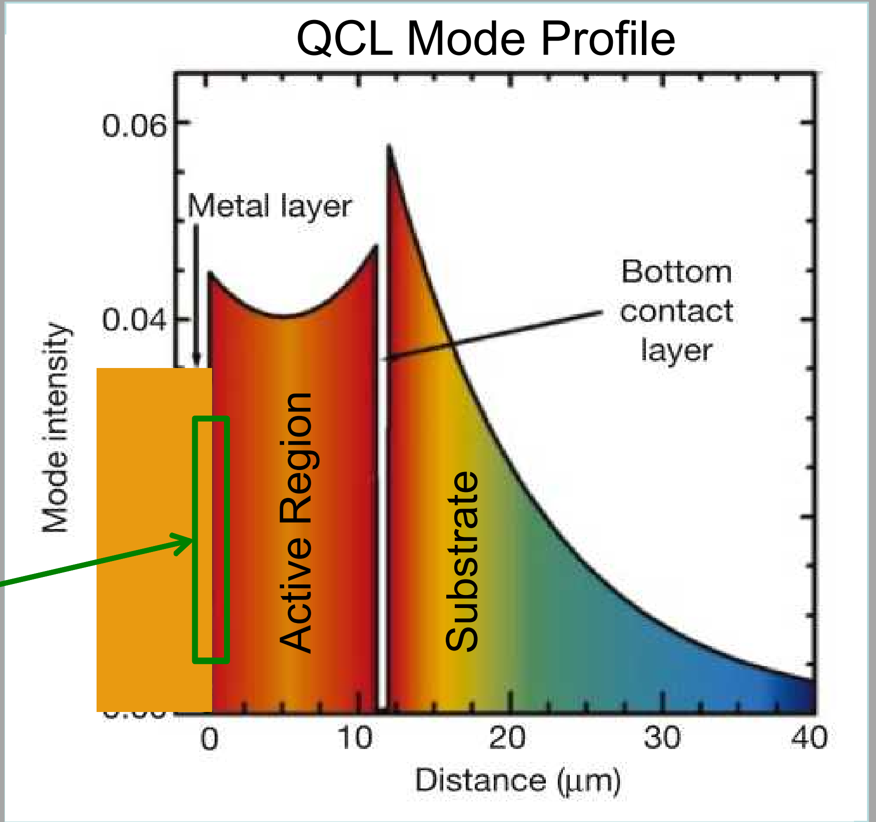


Schottky Diodes meet THz QCLs

Important Point:

Need to couple field into the semiconductor near the metal interface.

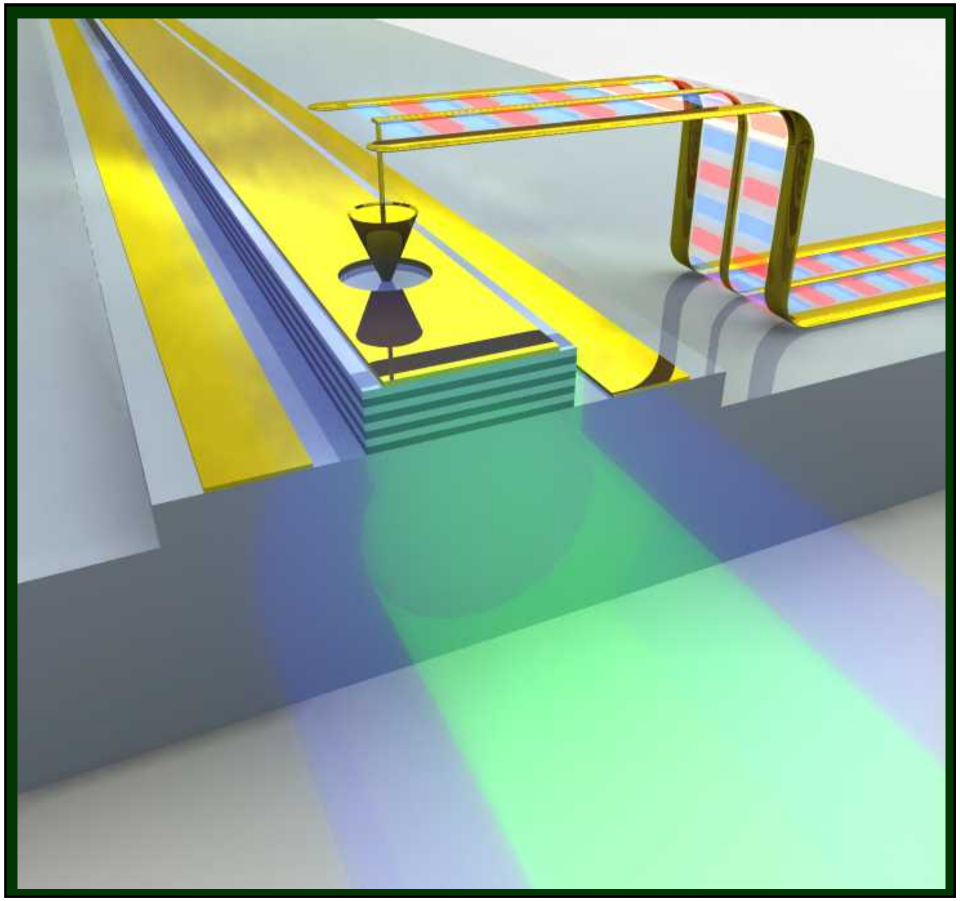




Kohler et al. , Nature, **417**, 2002

Monolithically Integrated Transceiver

Insert diode directly into laser core

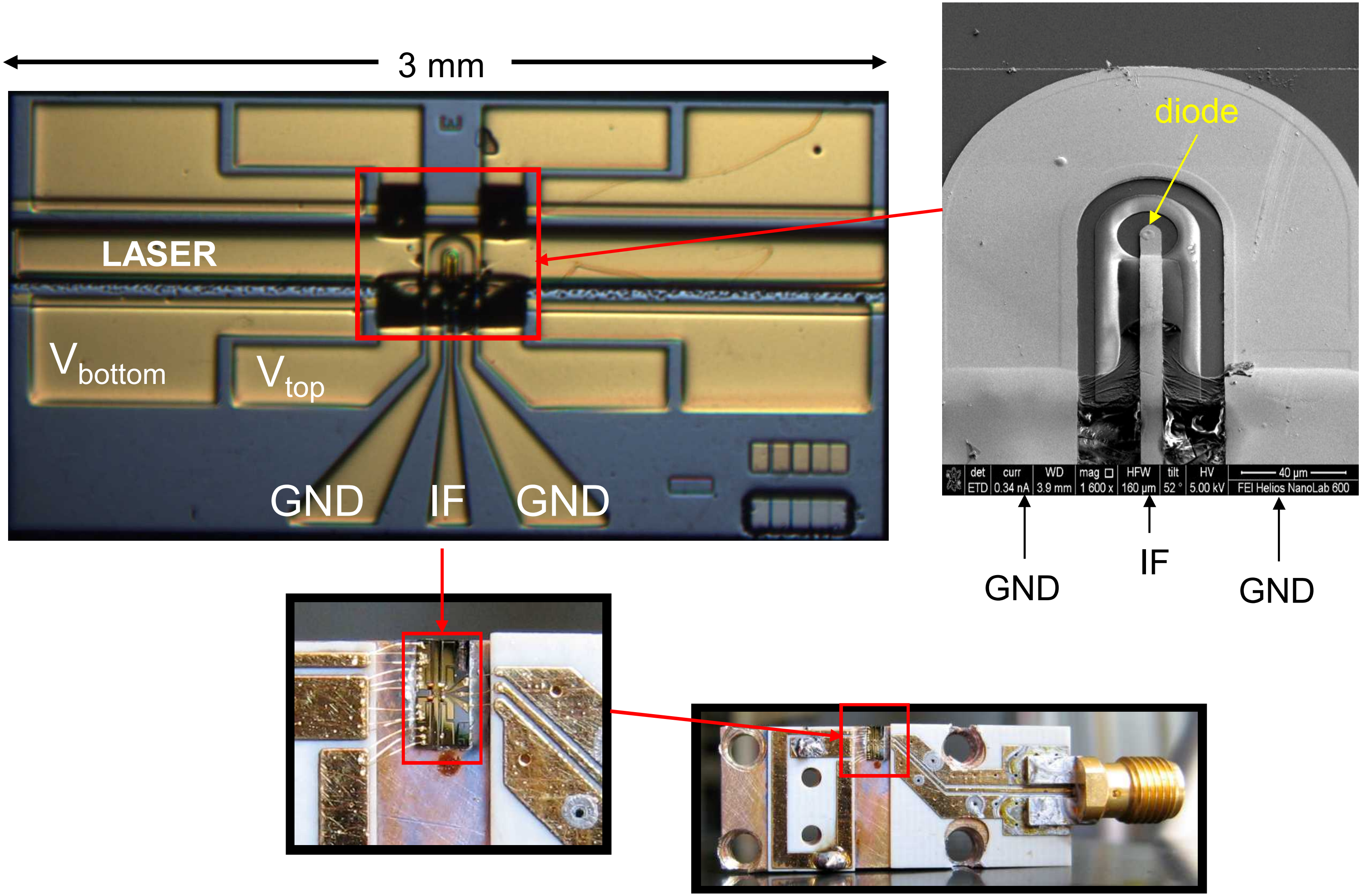


Benefits

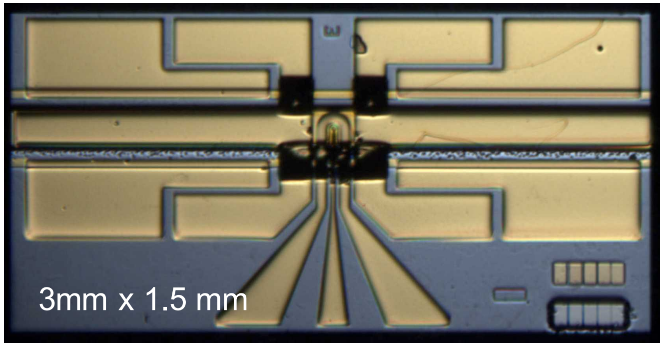
- Reduces size
- Eliminate components
- Ensures constant ‘alignment’
- Enhances laser/diode coupling
- Enables probing of laser dynamics

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

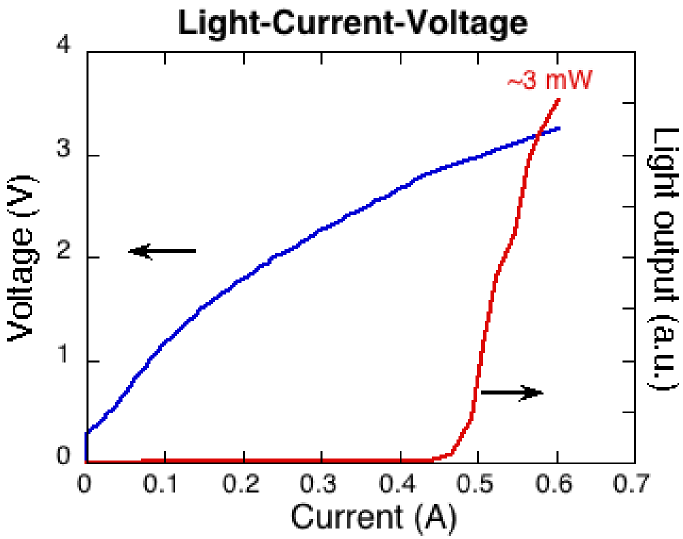
Fabricated Device



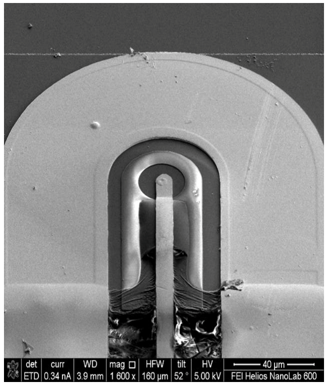
Diode and THz Laser DC Properties

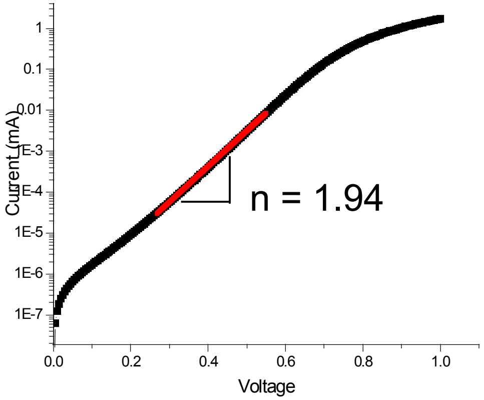


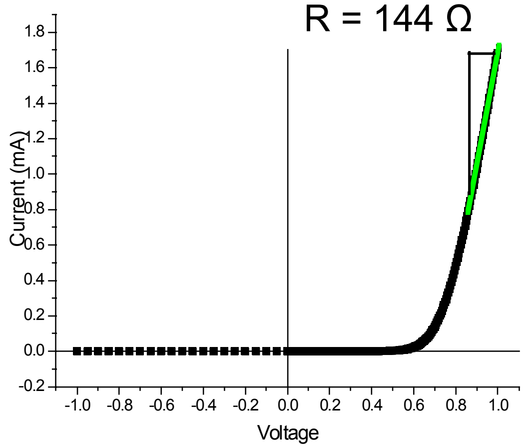
Typical QCL L-I-V Properties



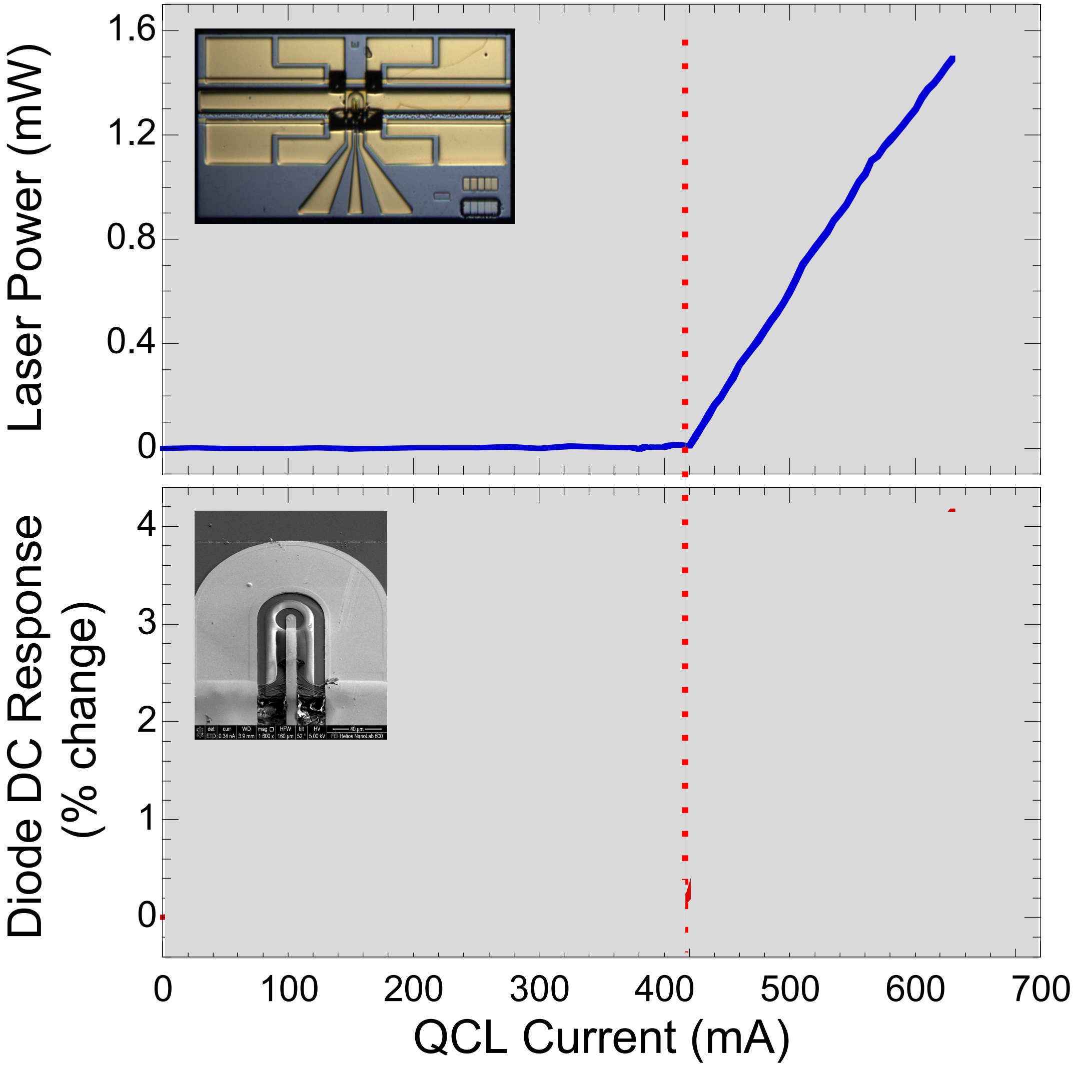
Typicial Diode DC I-V Properties

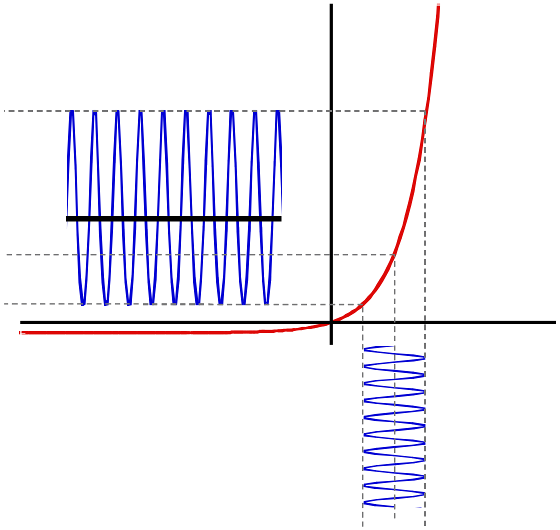






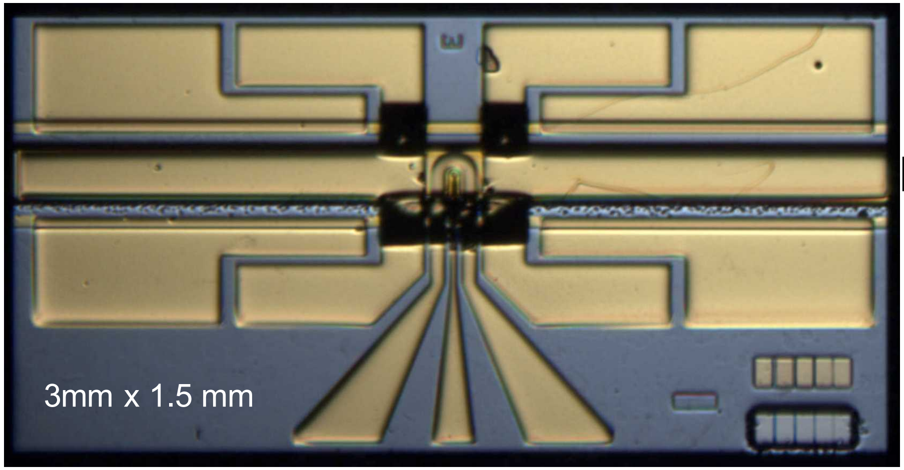
Diode Rectified (D.C.) Response

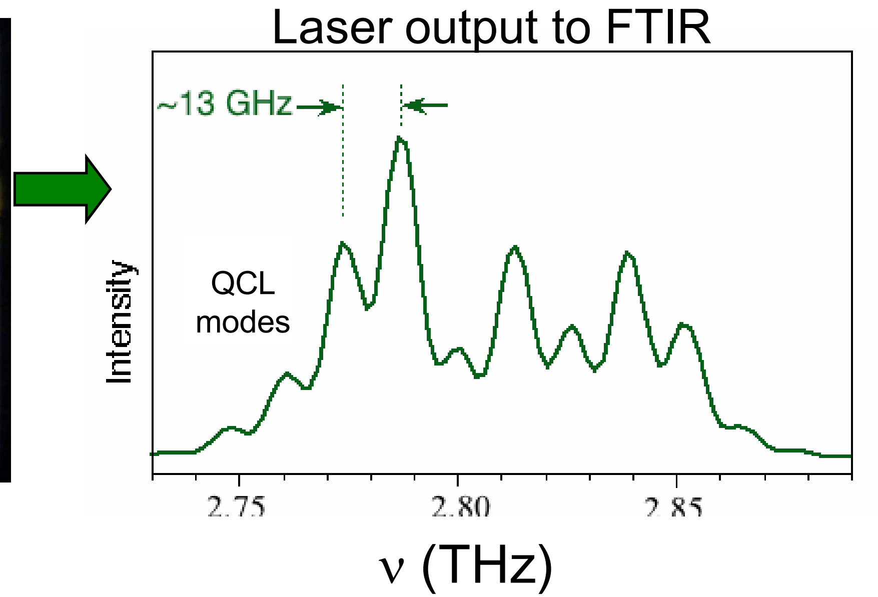




- Diode responds to internal QCL fields

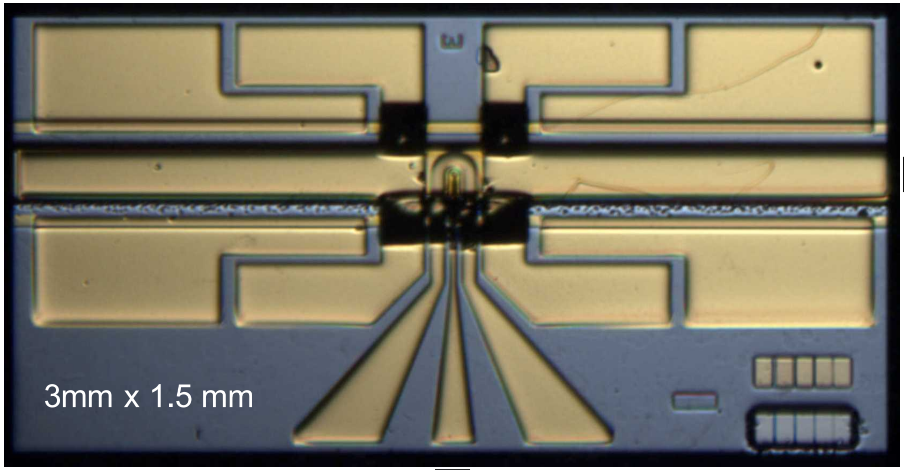
Laser Spectrum



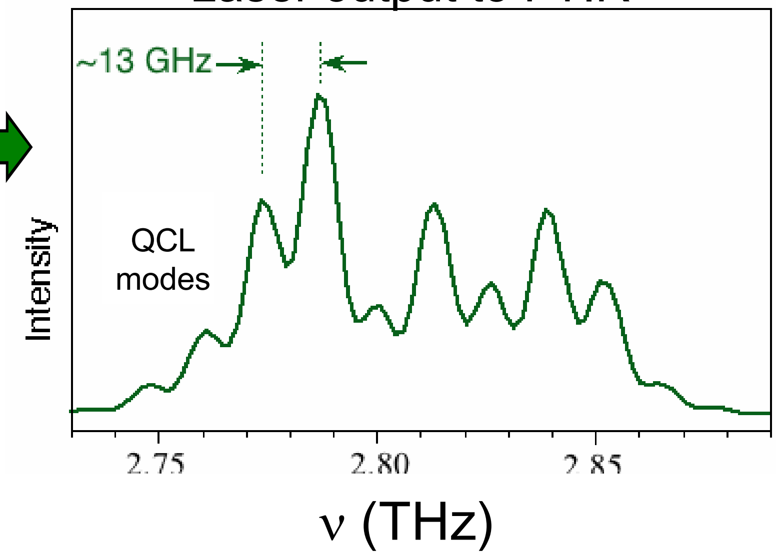


- **Multimoded QCL centered on 2.81 THz**
  - **QCL emission (FTIR) spectra show Fabry-Perot modes spaced by ~13 GHz**

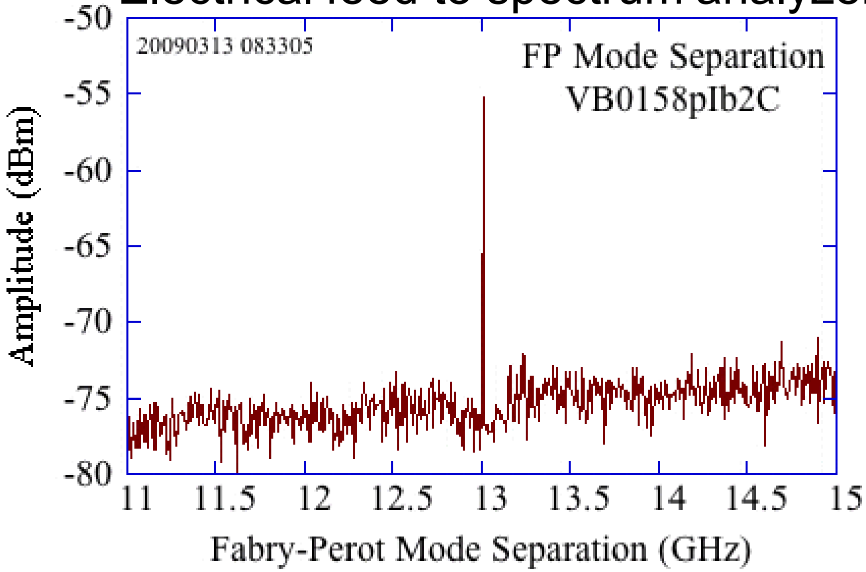
Demonstration of Mixing



Laser output to FTIR

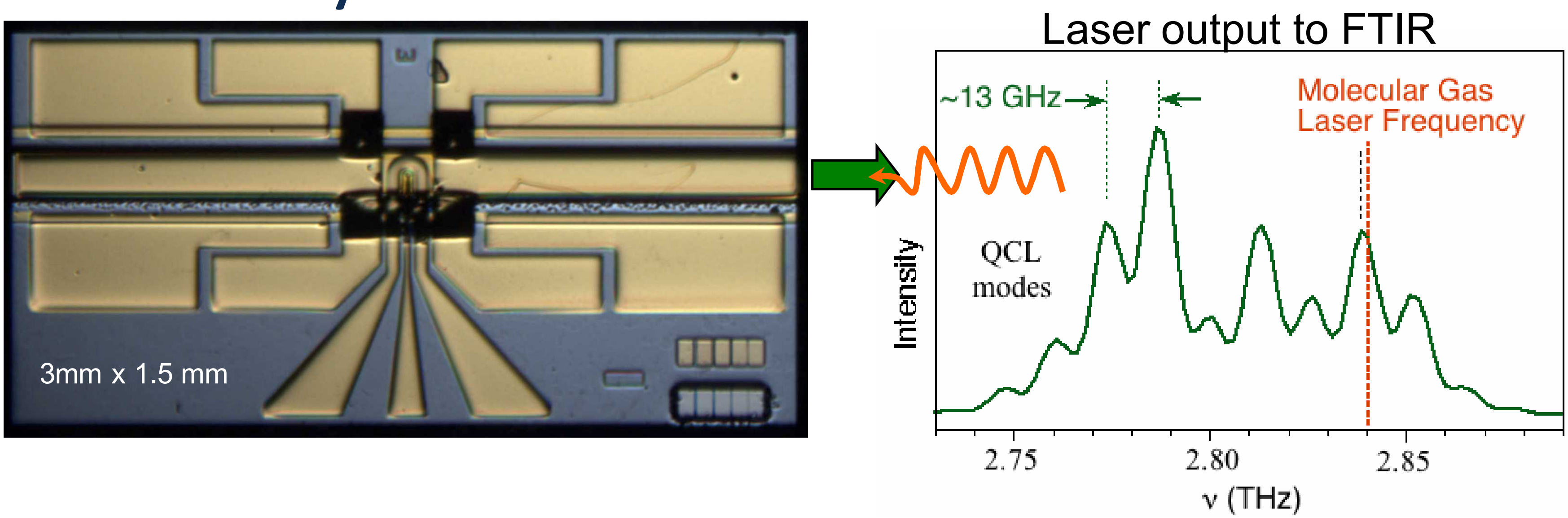


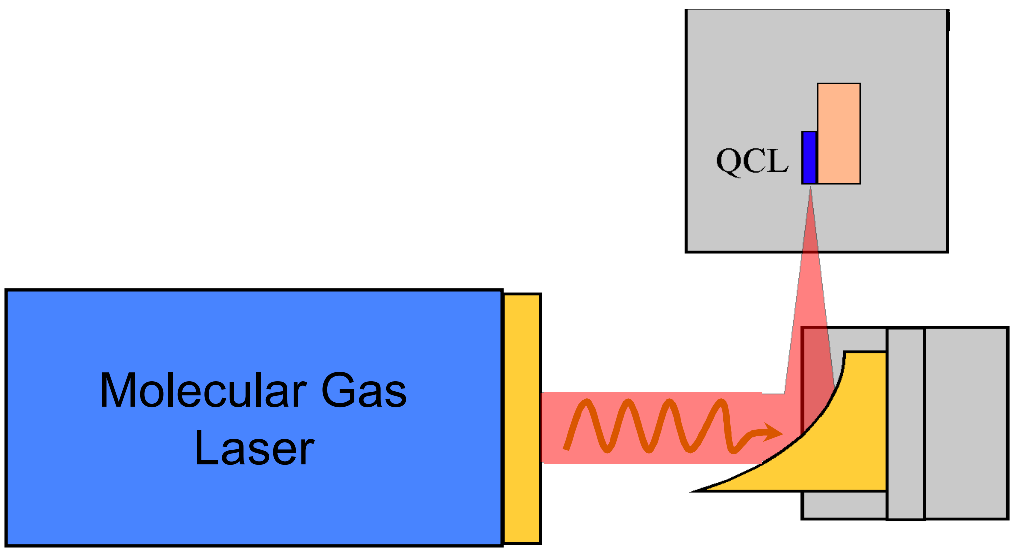
Electrical feed to spectrum analyzer



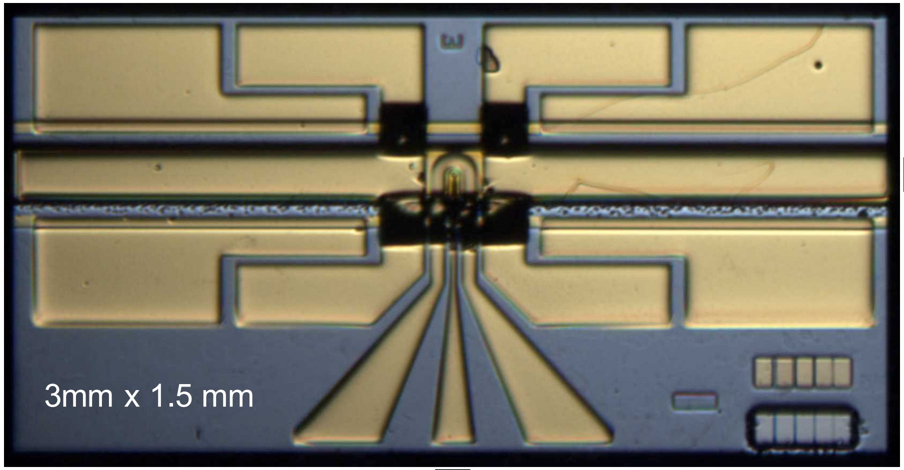
- Diode outputs IF signal at the spacing between QCL modes

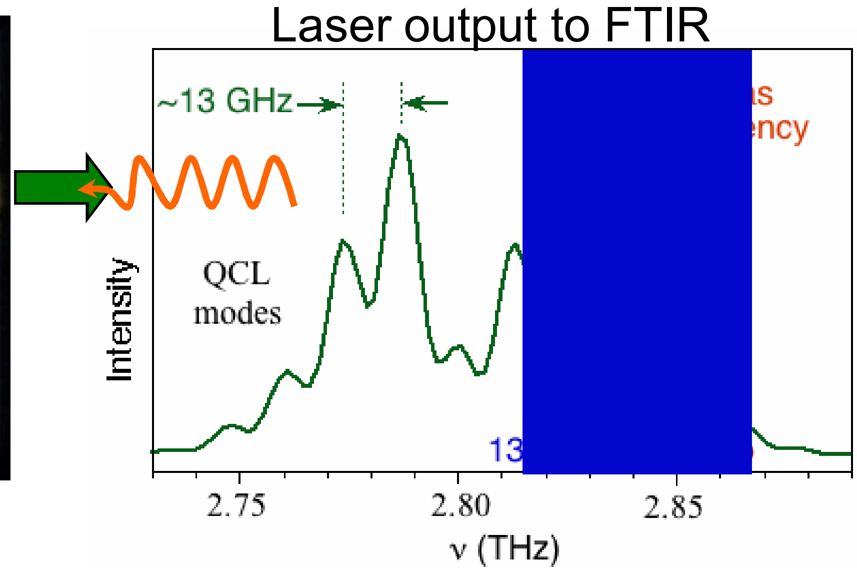
Heterodyne Receiver Demo

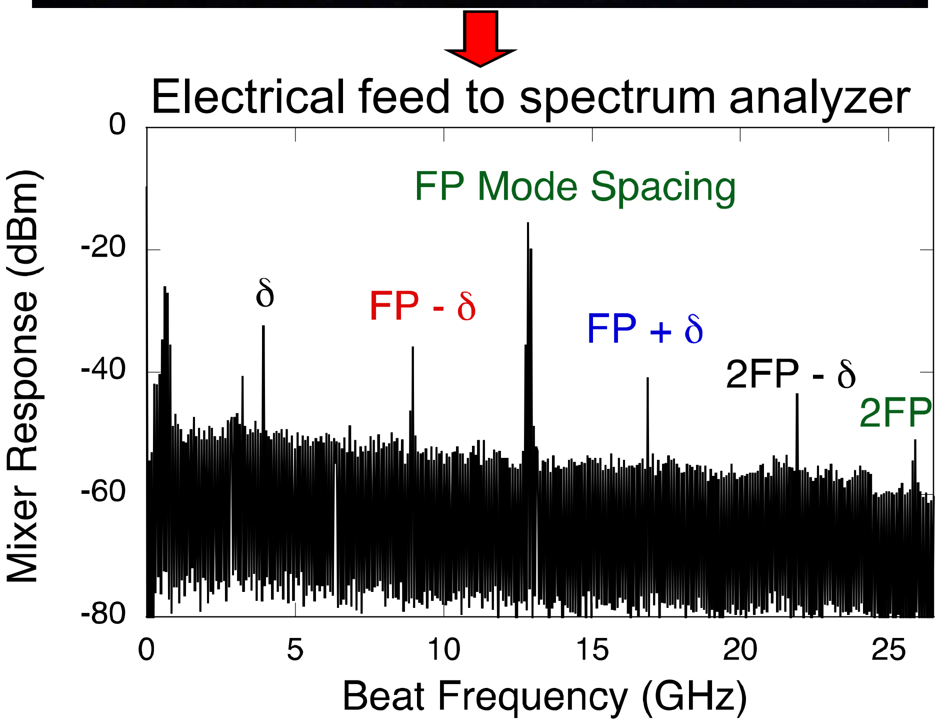




Heterodyne Receiver Demo



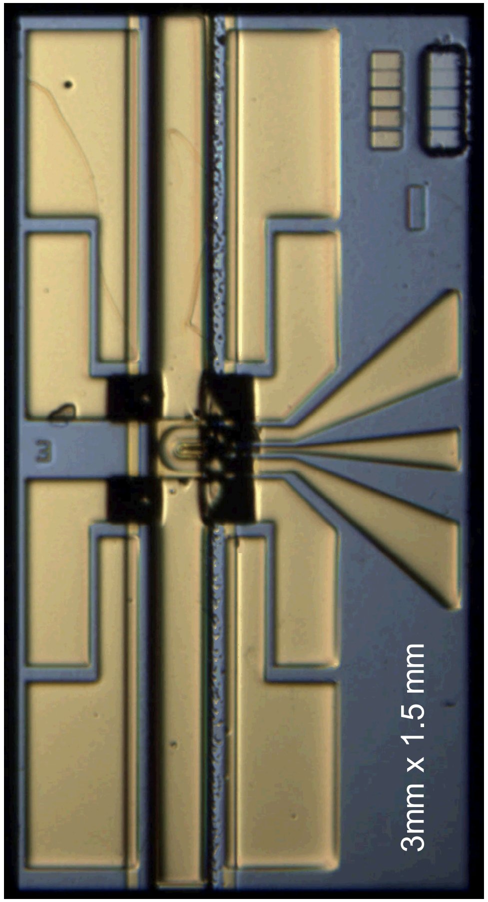




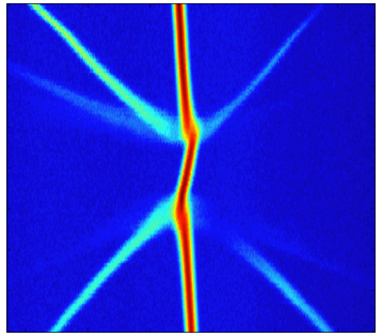
- It detects external signals

Things you can do.

THz Integrated Transceiver

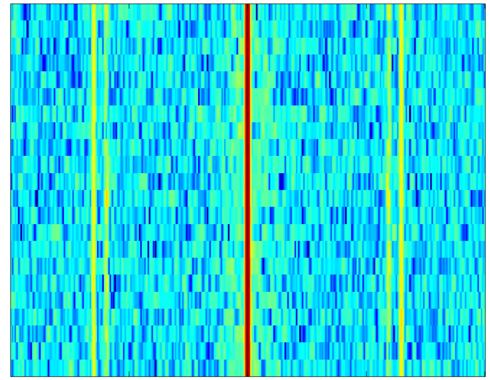


Laser Characterization
Injection Locking



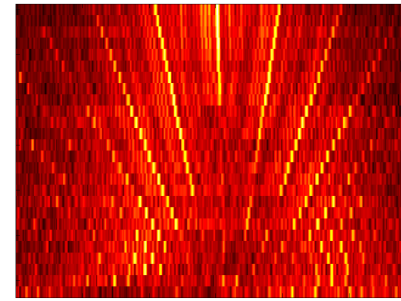
Wanke, Proc. SPIE, 7953, 2010

Phase Locking
Mode Coupling
Comb Locking



Wanke, Opt. Exp., 19 24810, 2011

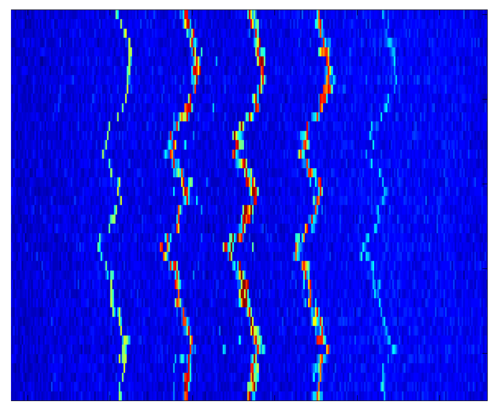
Vibrometry



Phase/Topo Imaging

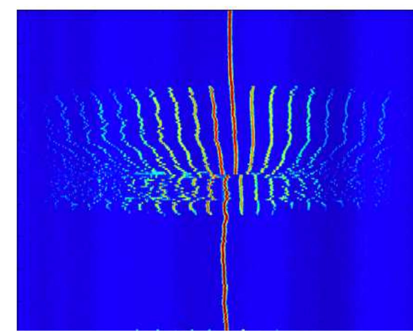
Wanke, Proc. SPIE, 8031, 2011

Comb Offset Stability



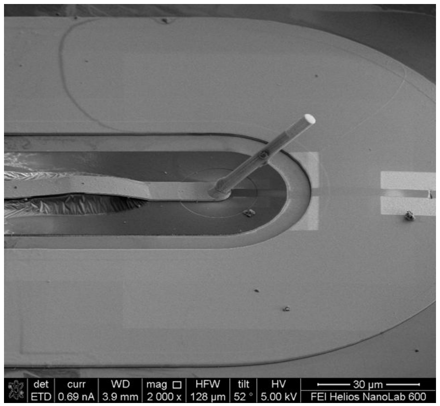
Wanke, Opt. Express, 19, 24810, 2011

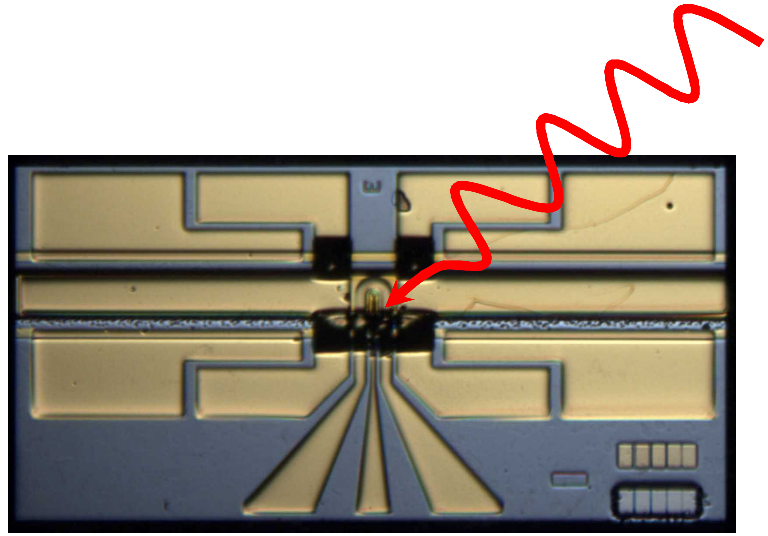
Feedback / Chaos
Dynamics

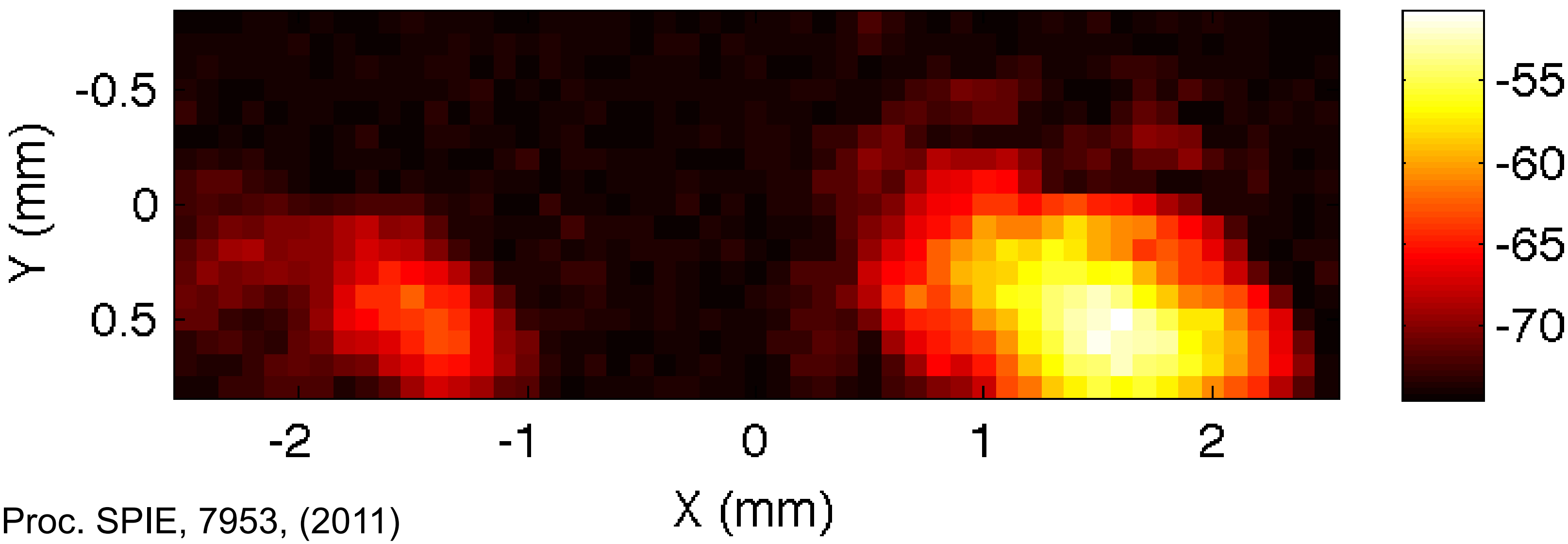


Wanke, Proc. SPIE, 7953, 2010

Coupling to the diode



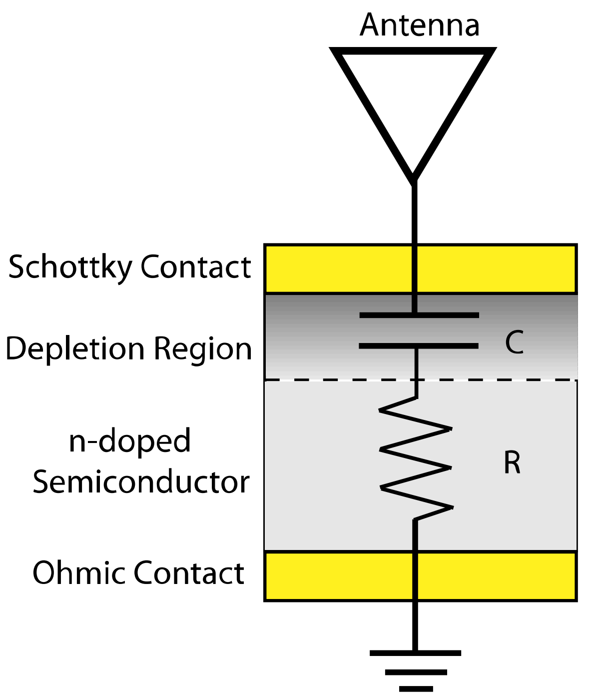


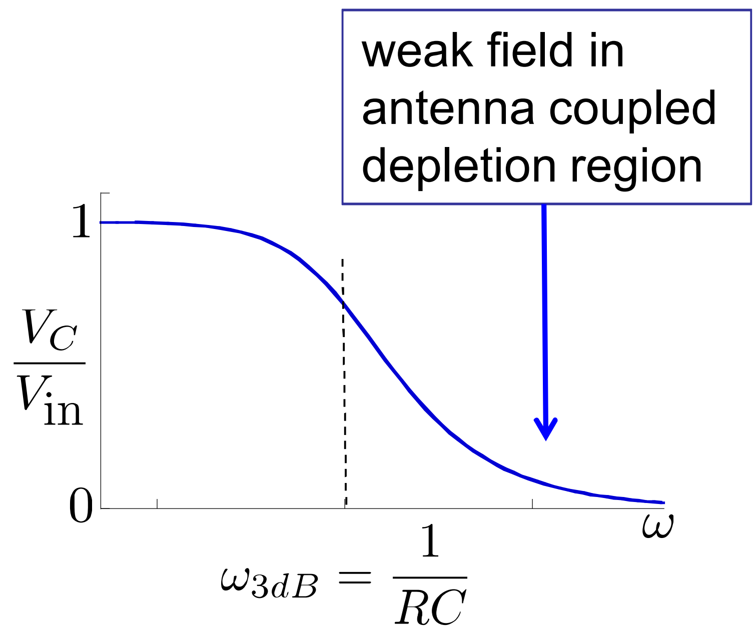


Wanke, Proc. SPIE, 7953, (2011)

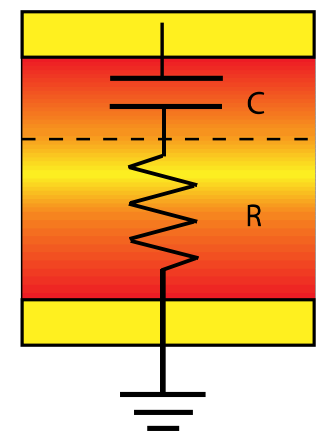
Antenna Coupling vs Surface Plasmon Coupling

Antenna Coupling





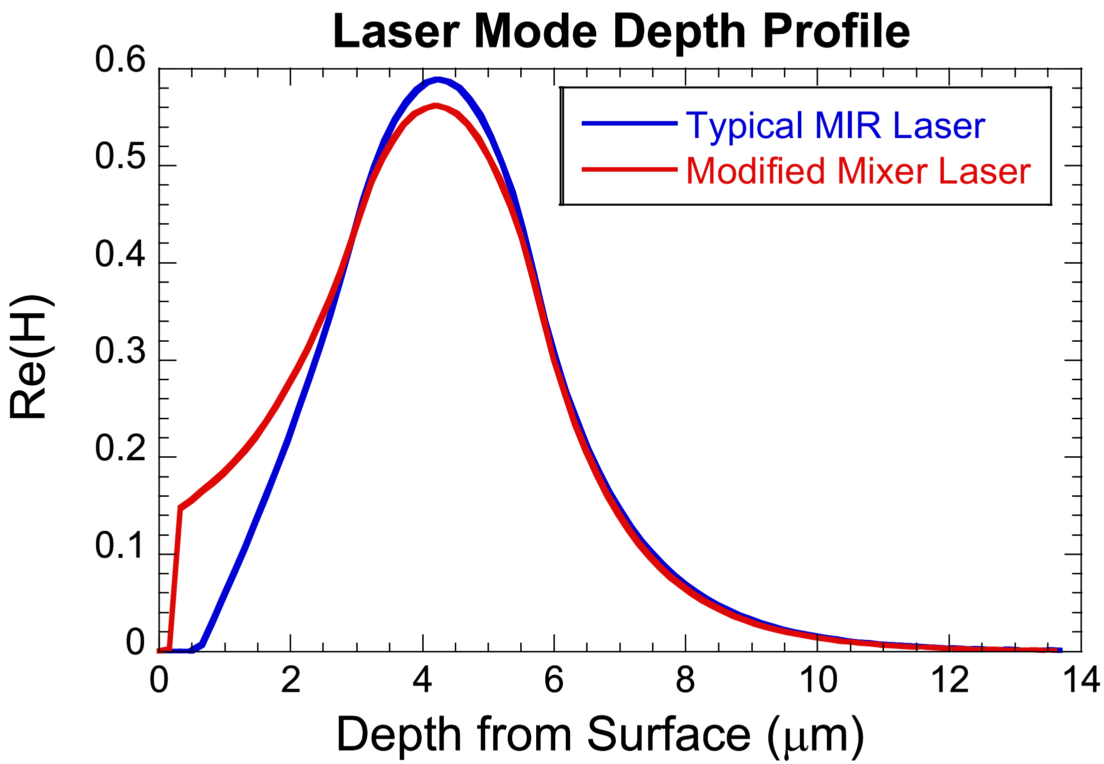
Surface Plasmon Coupling



Suggests possibility of MIR operation of planar Schottky diodes !

MIR mode profile

Normally no field at metal interface

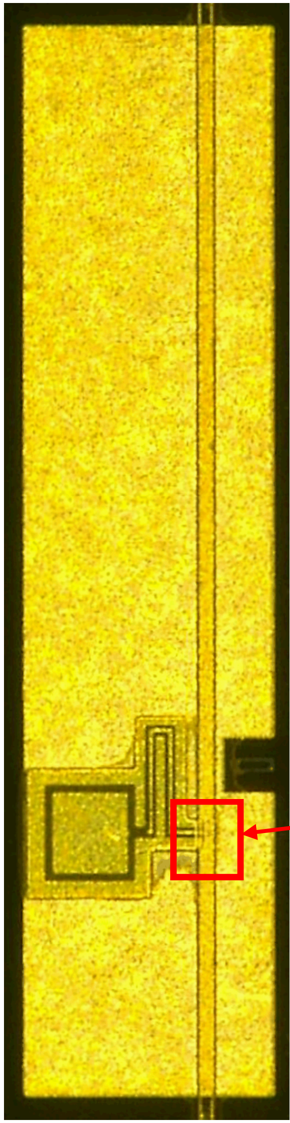


Top two layers differ:

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

Compromise between loss and surface coupling

MIR device structure

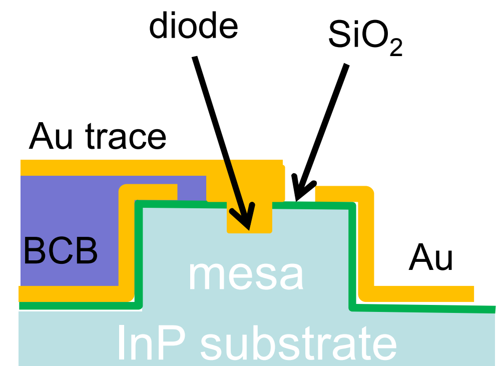


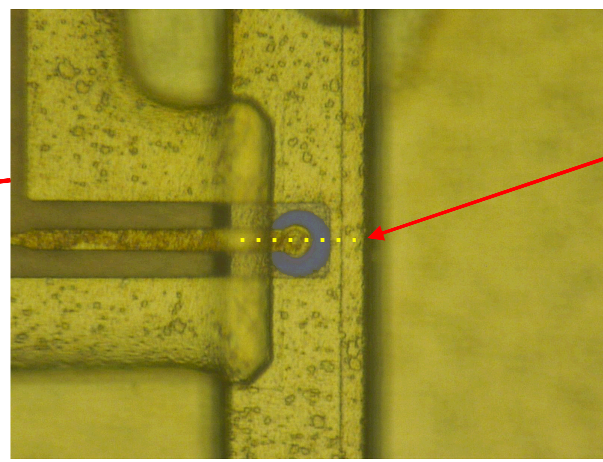
Laser

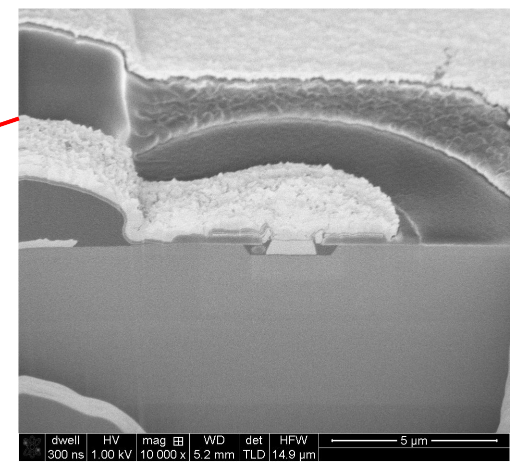
- 8 µm wavelength
  - Active region courtesy of C.Gmachl
  - Cladding courtesy of A. Belyanin
- 2 or 3 mm x 25 µm
- InGaAs/AlInAs/InP

Diode

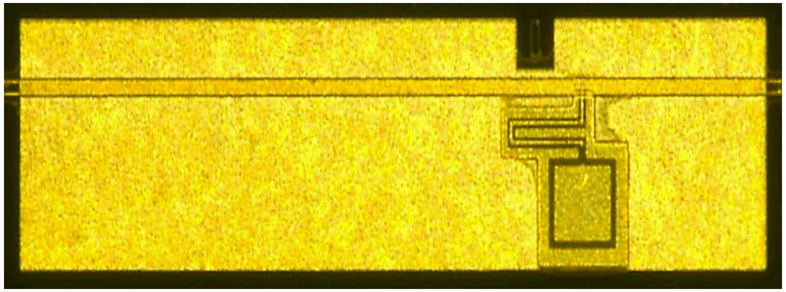
- 2 or 5 um diameter
- TiAu on InGaAs
- Recessed below n+

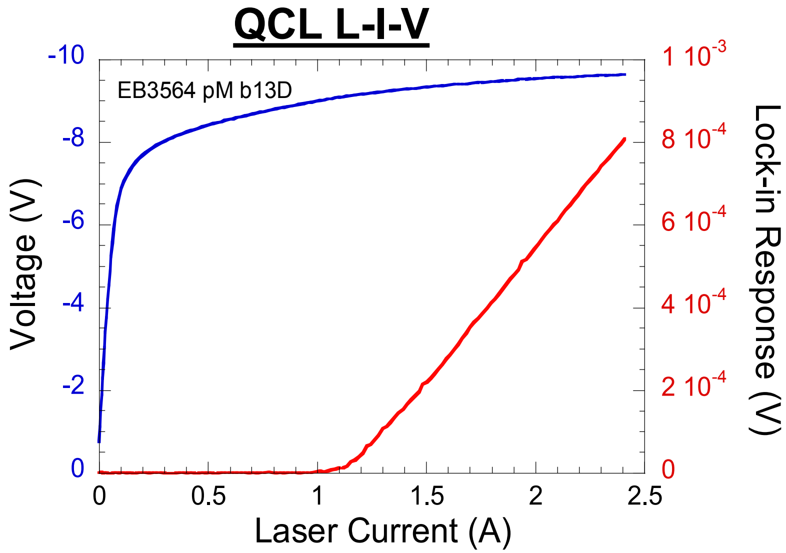


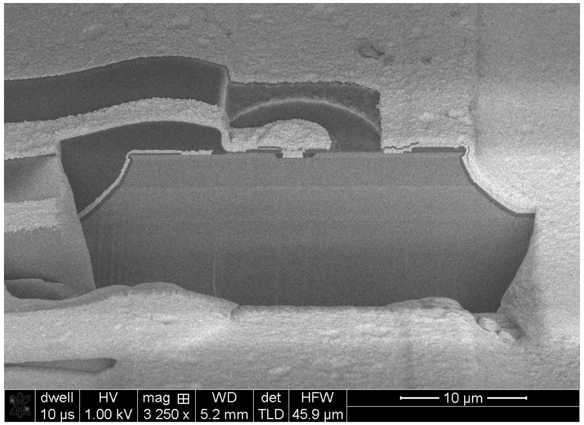


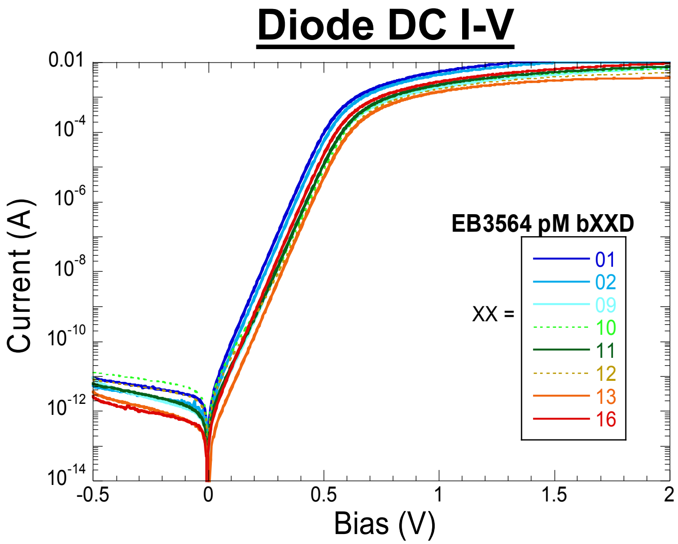


Diode and MIR Laser DC Properties

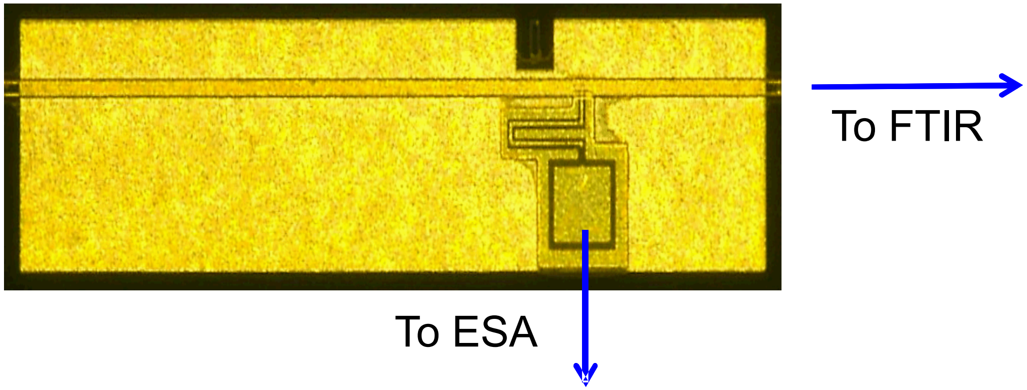


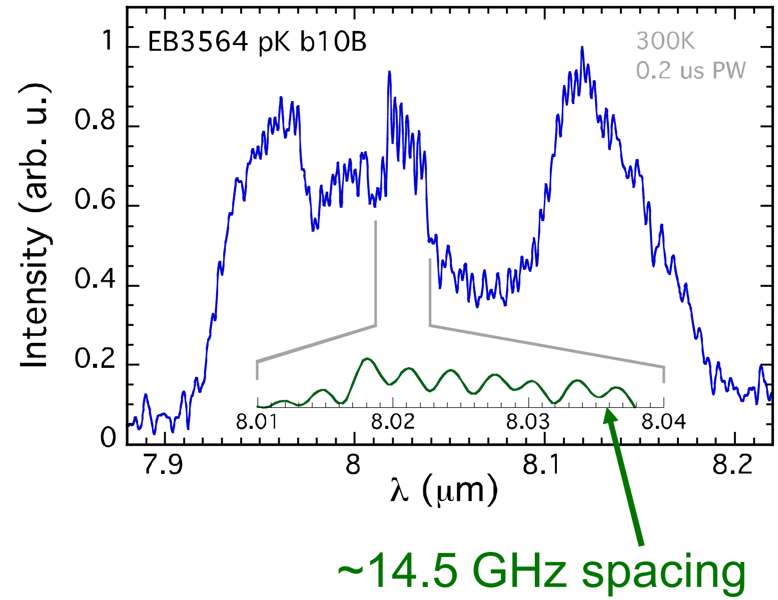


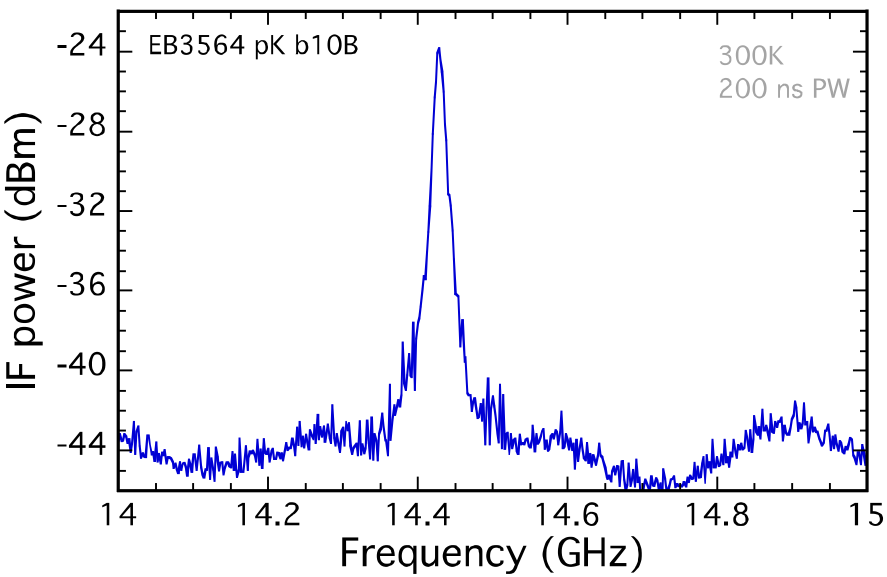




Demonstration of MIR mixing

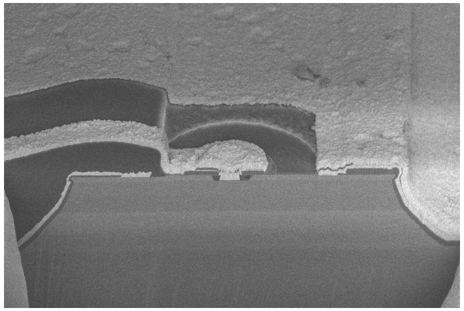




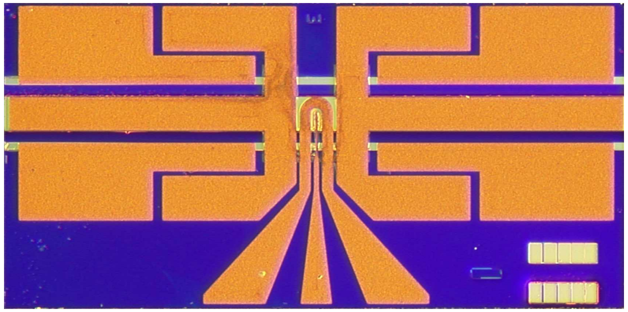


Diode responds to and mixes internal MIR modes at room temperature !

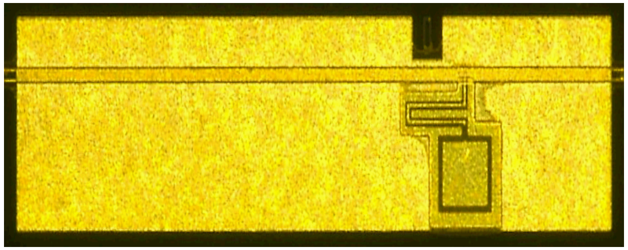
Summary



Schottky diodes can be monolithically integrated with QCLs



Integrated THz transcievers can be used to:
- measure incident radiation
- characterize the laser



Integrated MIR mixers respond the laser, and may respond to incident radiation.

Credits:

Sandia National Laboratories

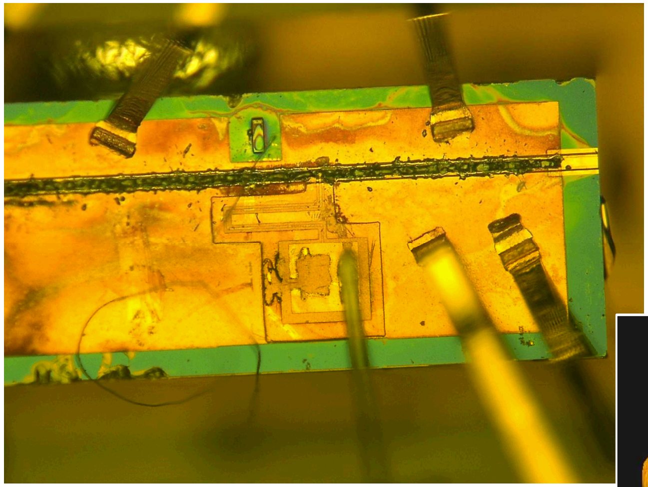
Christopher D. Nordquist
Greg C. Dyer
Darin Leonhardt
Troy Ribaudo
Chuck T. Fuller
John F. Klem
Albert D. Grine
John L. Reno
Joyce Custer*
Michael J. Cich*
Mark Lee*
Erik W. Young*

Special thanks to:
Claire Gmachl
Alexey Belyanin

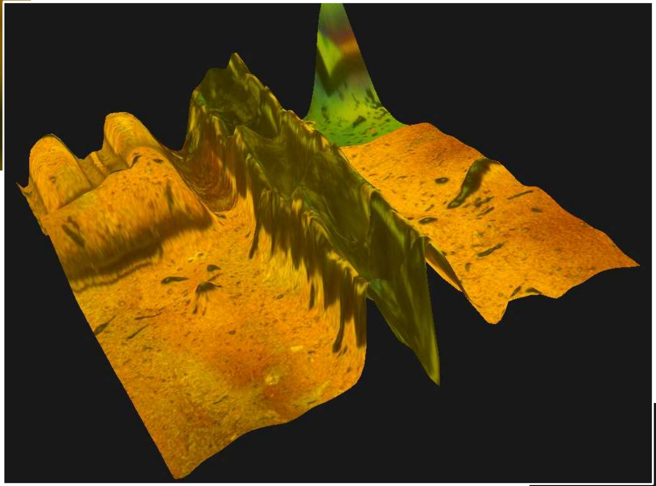
With Support From:

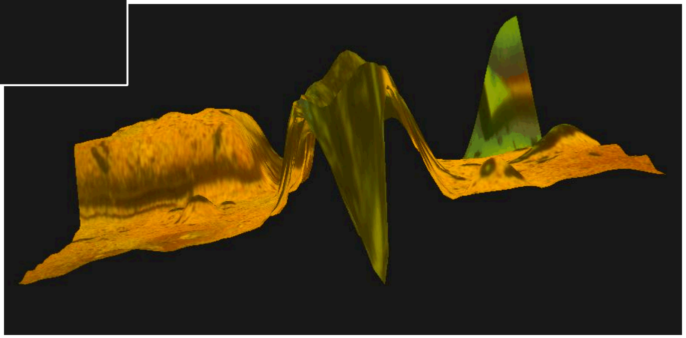
LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Only pulsed operation



Aftermath of CW operation attempt.

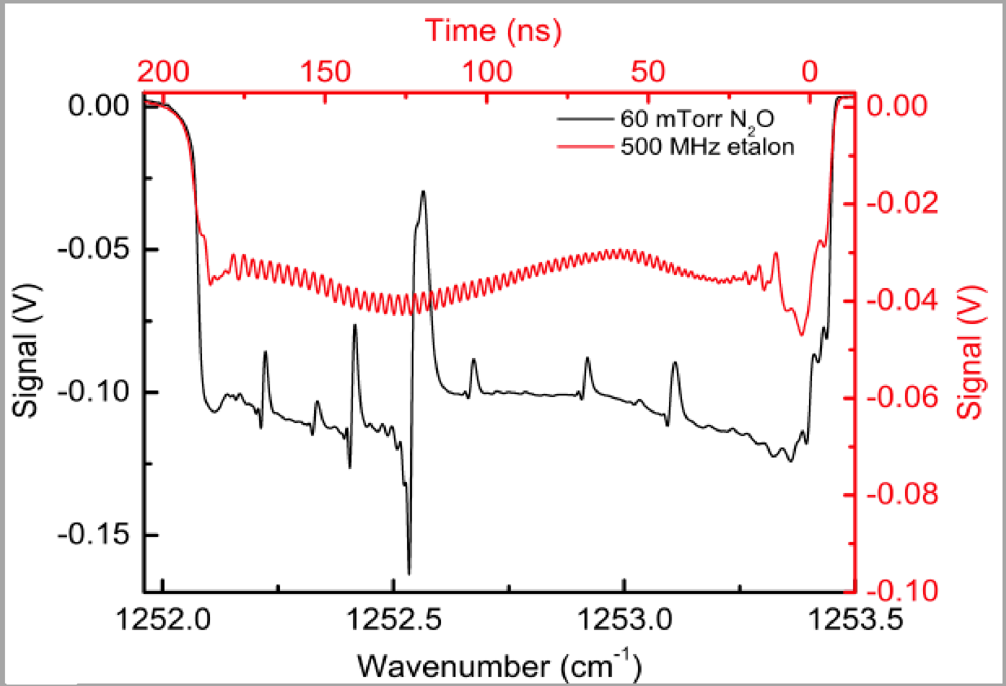




Pulsed operation much harder for heterodyne measurements.

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

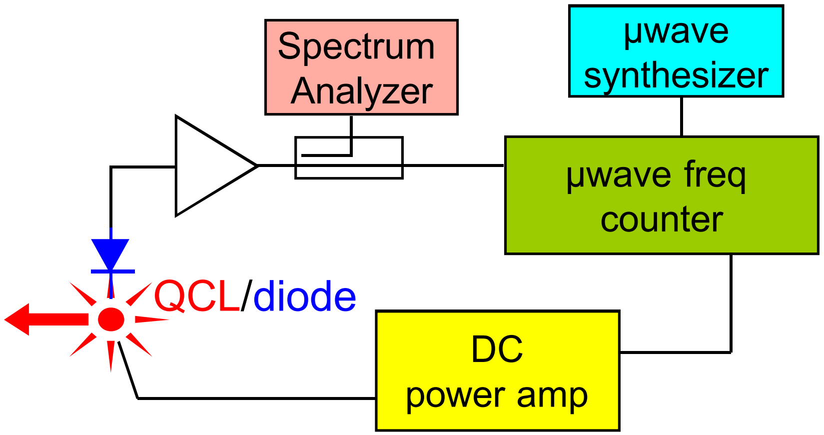
Any beat frequency generated by mixing against stable external signal can be changing by ~ 200 MHz / ns.

What can we learn and do with an integrated transceiver ?

Example 2 : Phase Locking

Frequency/Phase Locked THz IC

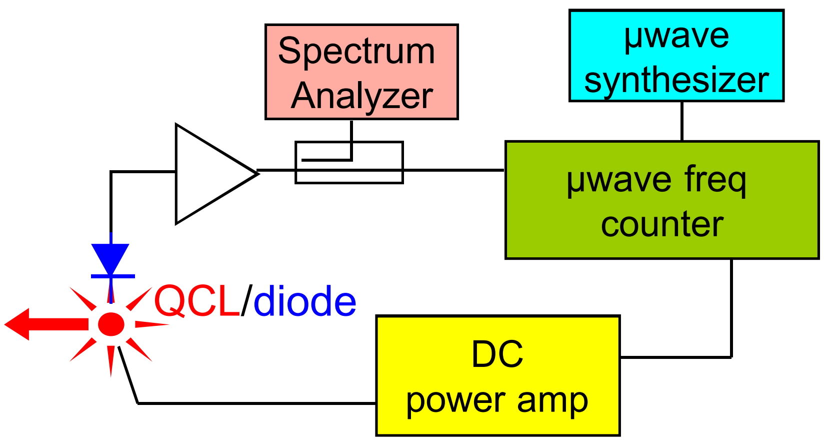
- **Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations***



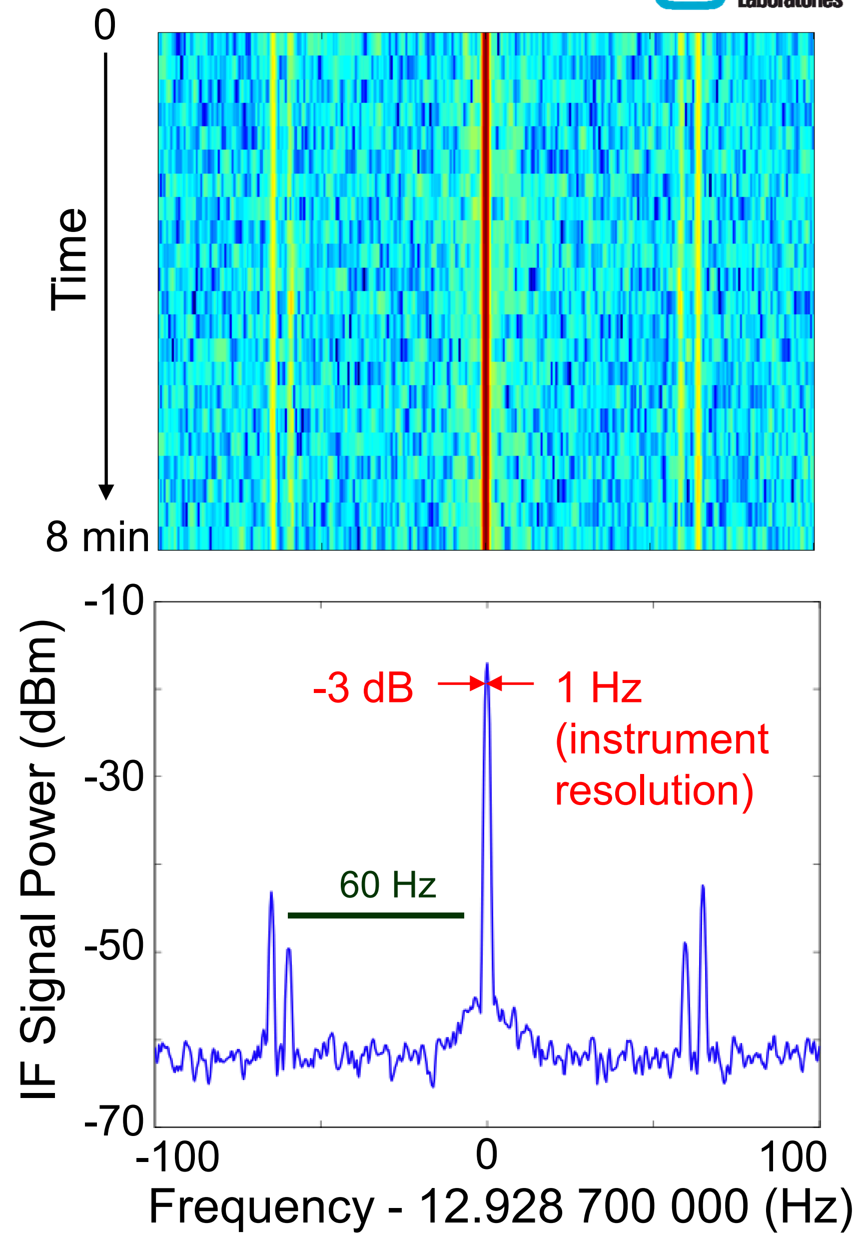
*Following Betz, Opt. Lett. **30**, 1837, (2005)
Baryshev, APL, **89**, 031115, (2006)

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**

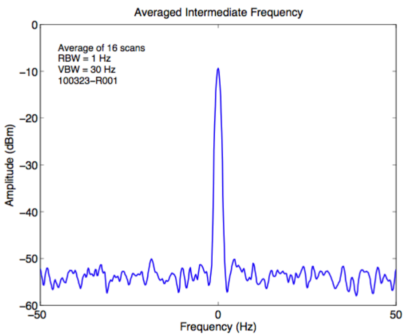


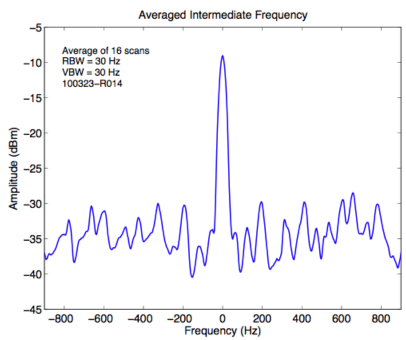
*Following Betz, Opt. Lett. **30**, 1837, (2005)
Baryshev, APL, **89**, 031115, (2006)

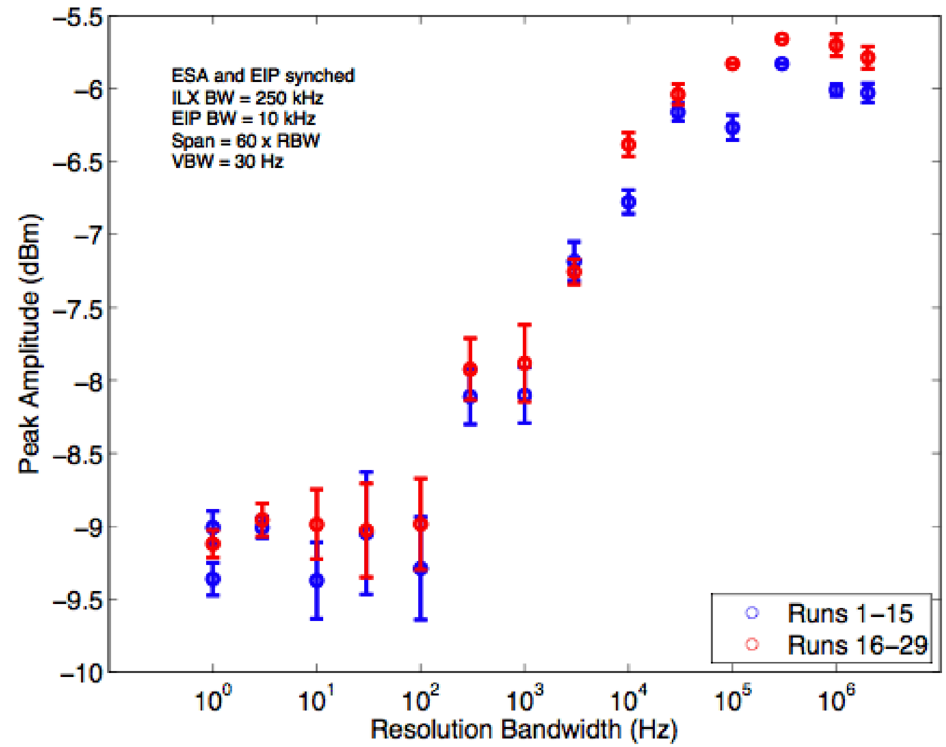


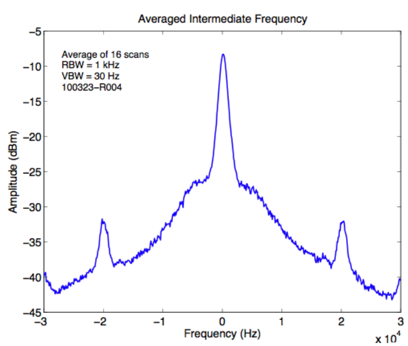
Wanke, Nat. Phot., **4**, 565, (2010)

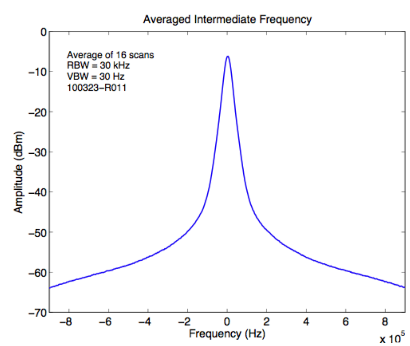
Phase Locking Bandwidth

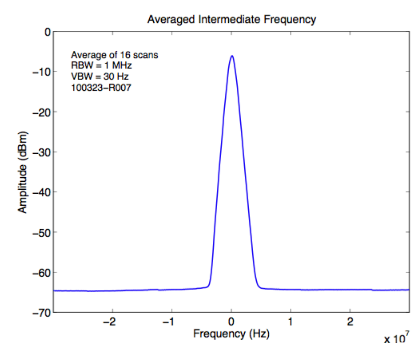






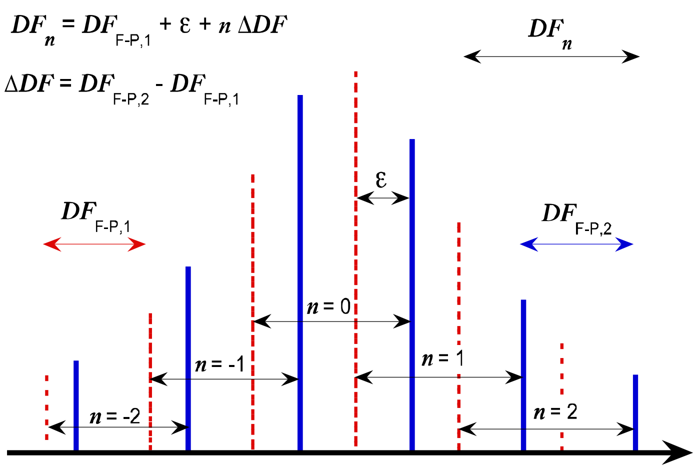


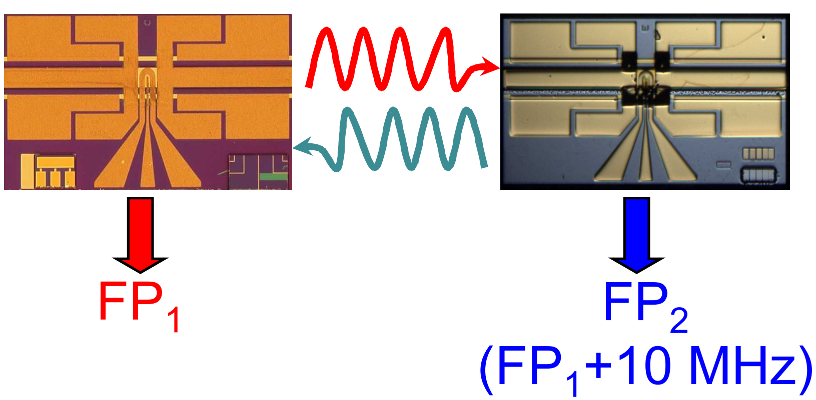


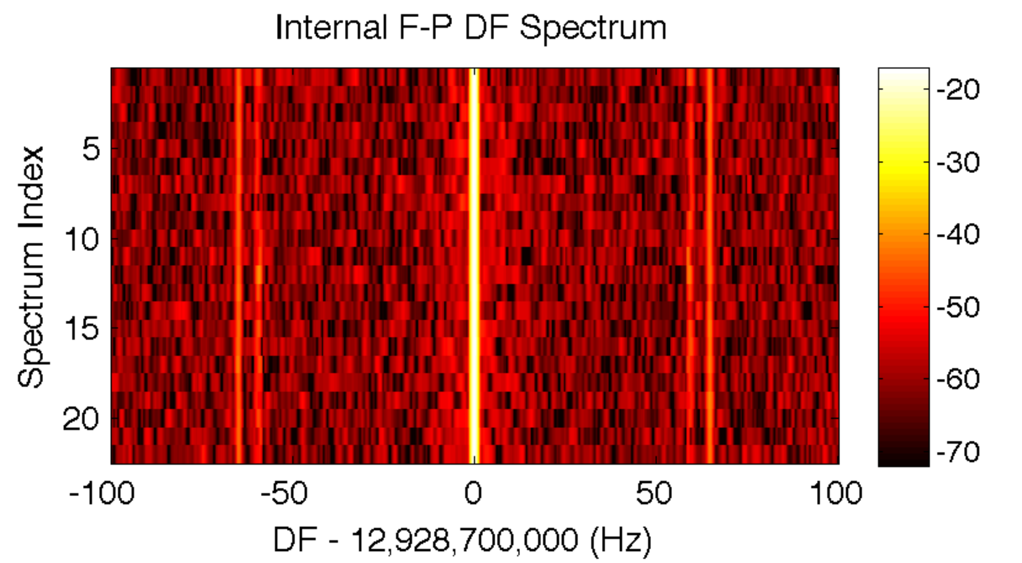


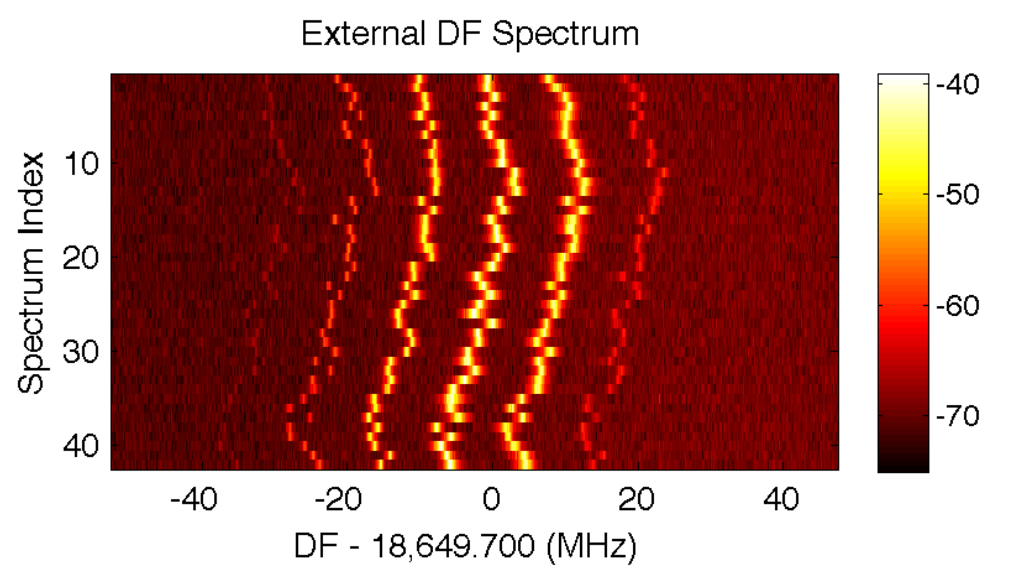
Absolute Frequency not Simultaneously Locked…

Sandia National Laboratories



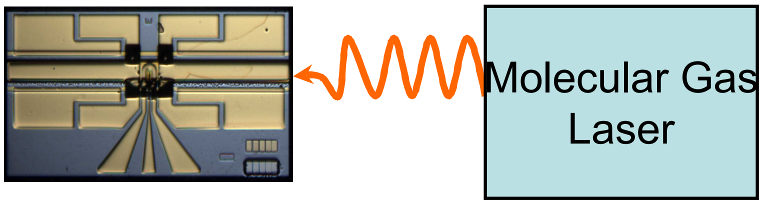


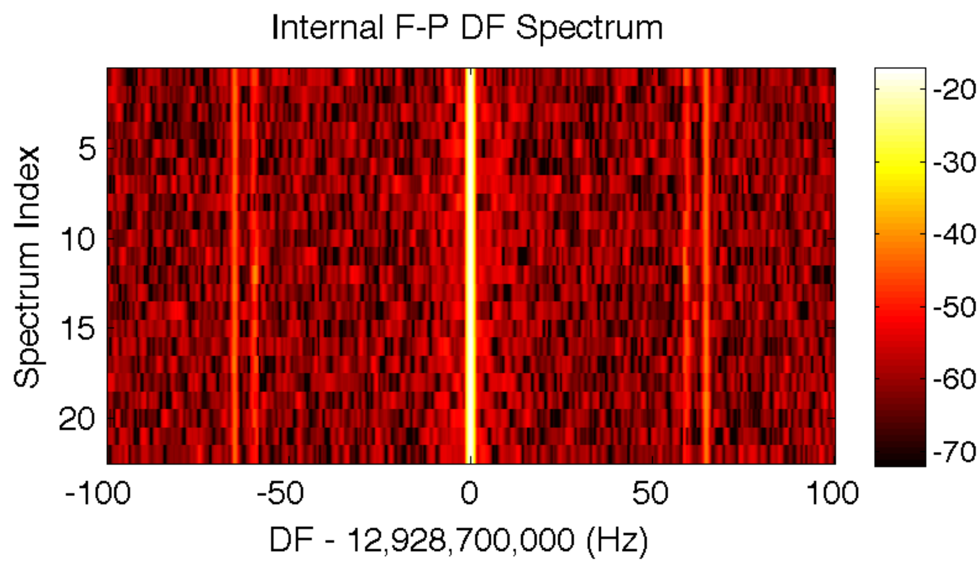


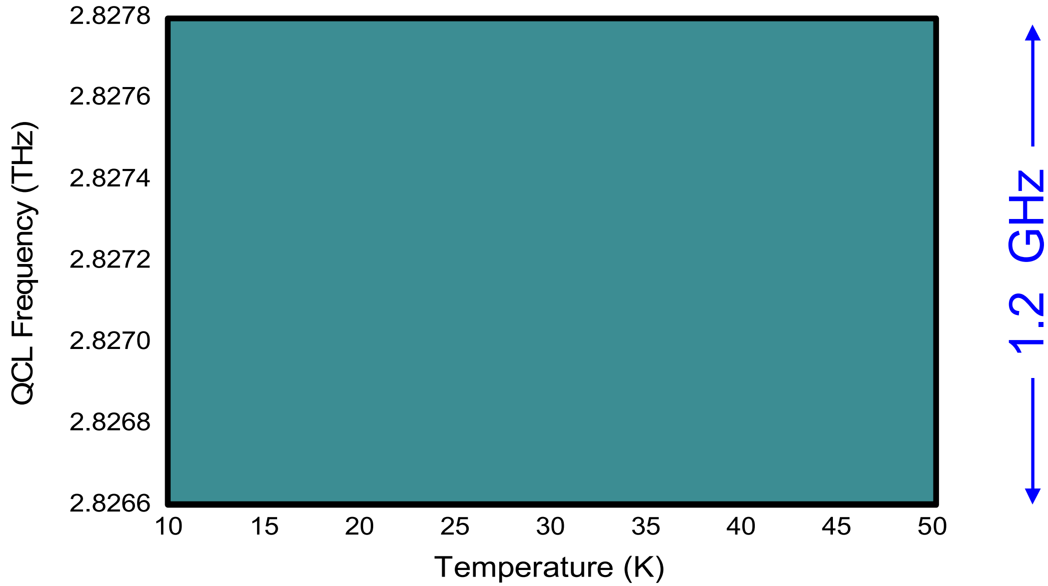


Wanke, Opt. Express, **19**, 24810 (2011)

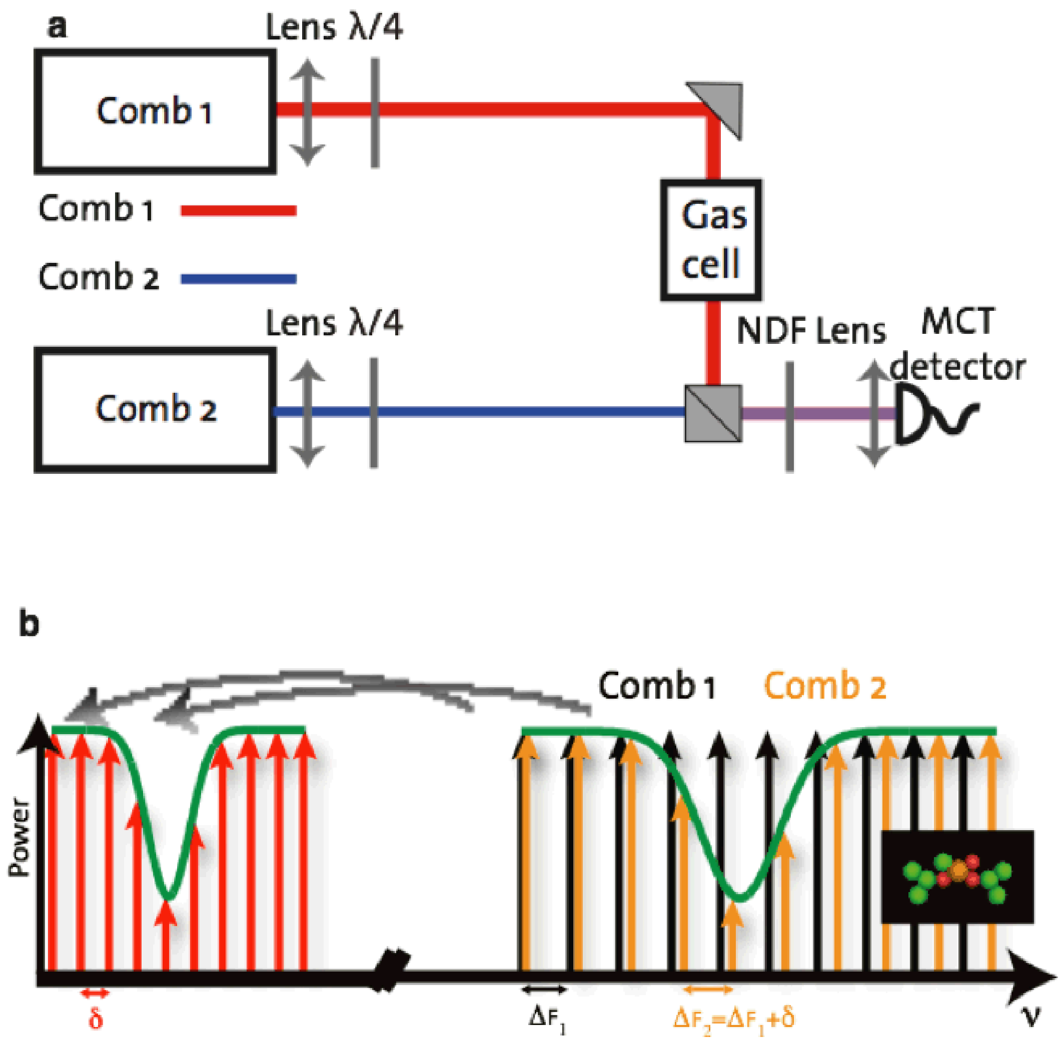
… which allows tuning of the comb…



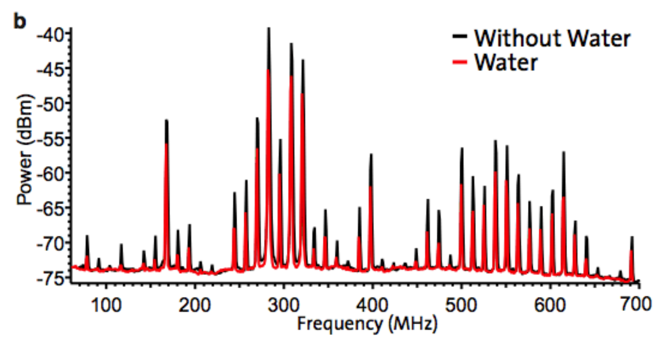




… and dual comb spectroscopy.

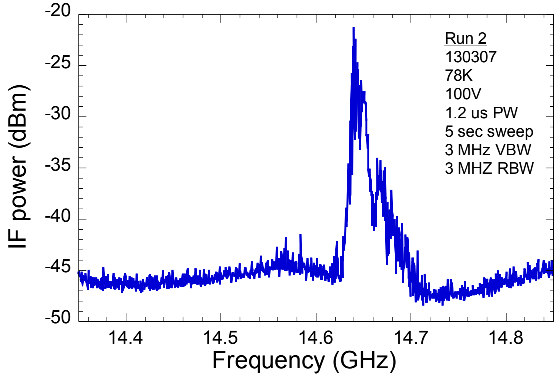


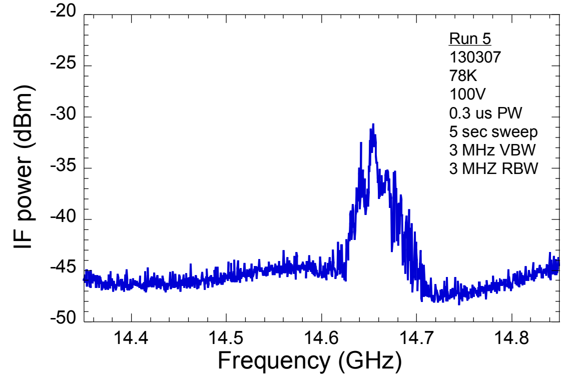
Borrowed from Faist, et.al, ITQW 2013 Abstract

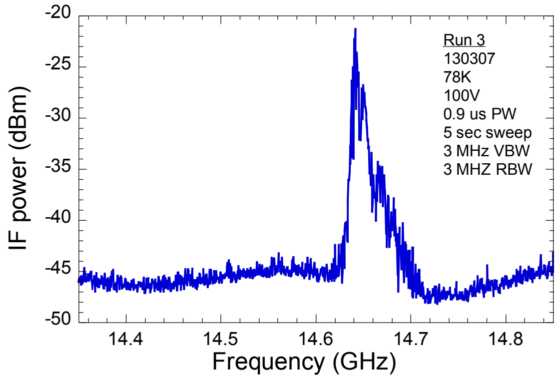


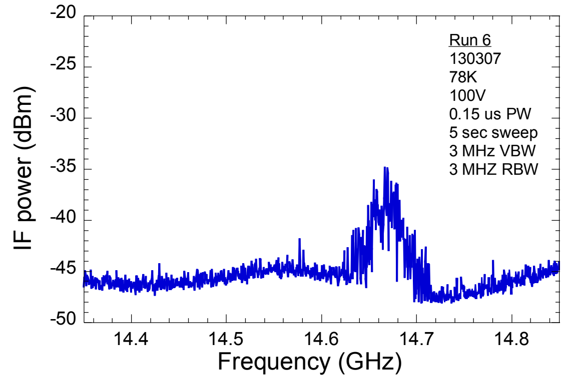
Wanke, Opt. Express, **19**, 24810 (2011)

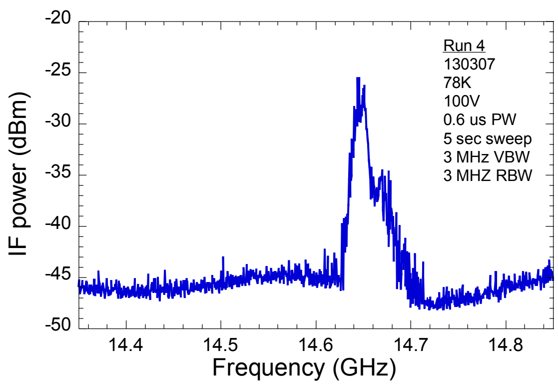
IF response dependence on pulse width







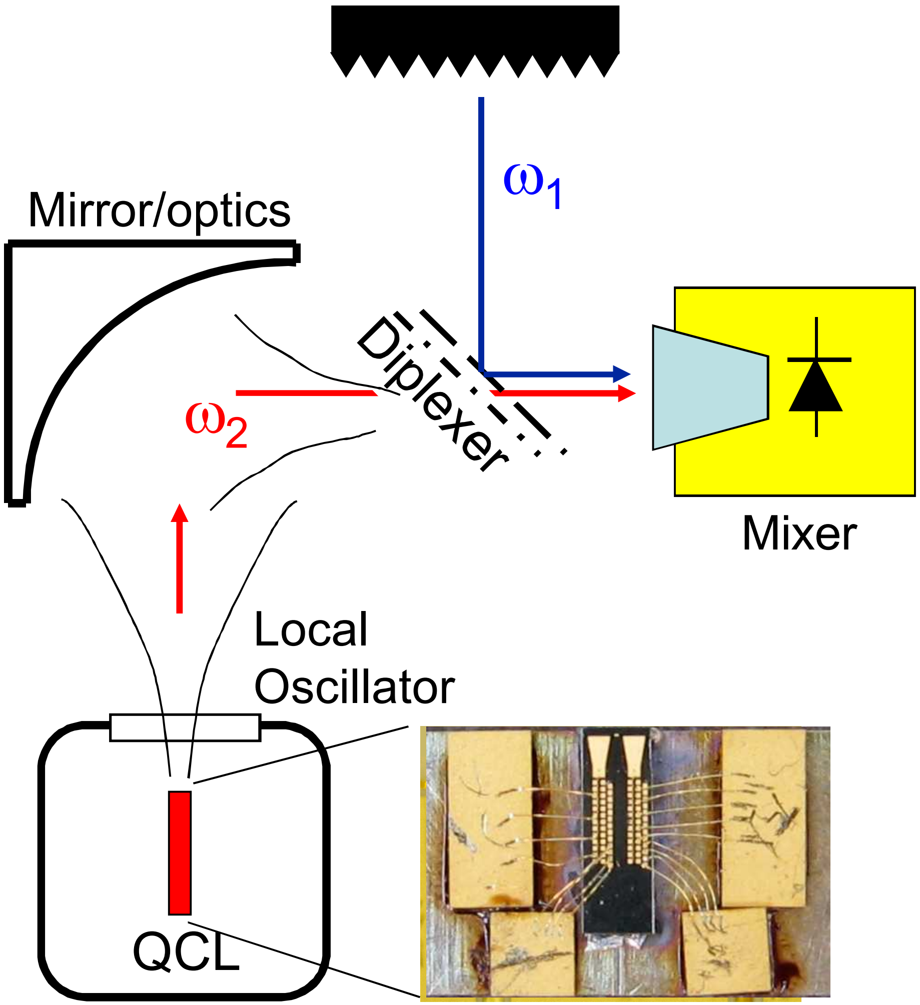




EB3564 pM b 13D

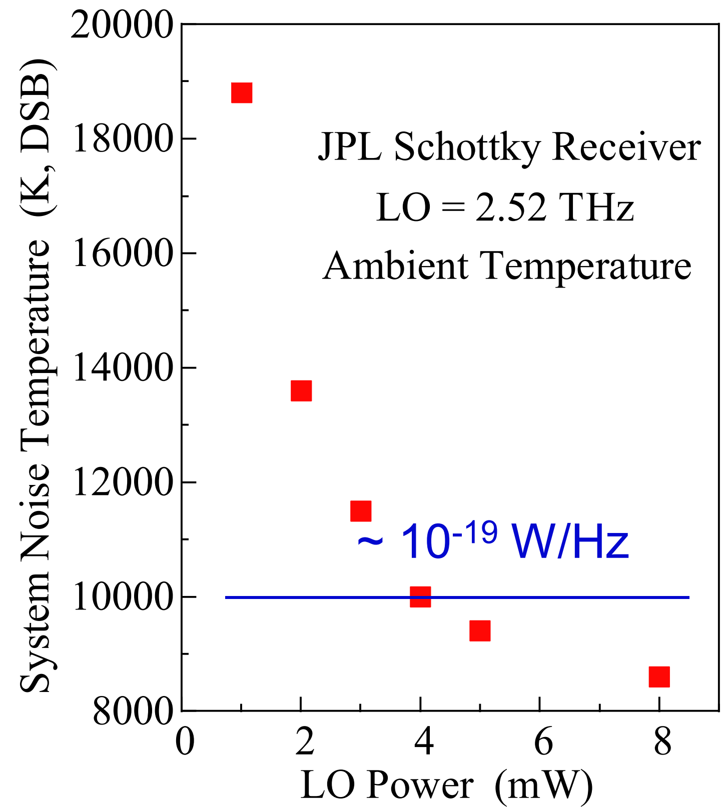
- 130307
- 150-1200 ns PW
- 1 kHZ rep rate
- 100 V
- 5 second ESA sweep rate
- 2 uF cap in pulser circuit (large ringing of voltage)
- The narrower, taller peak grows after the voltage settles – suggests the initial baseline is partially due to frequency instability due to voltage oscillation.
- Another possible cause is time it takes for temperature to reach steady state.

Coherent Detector: THz receiver



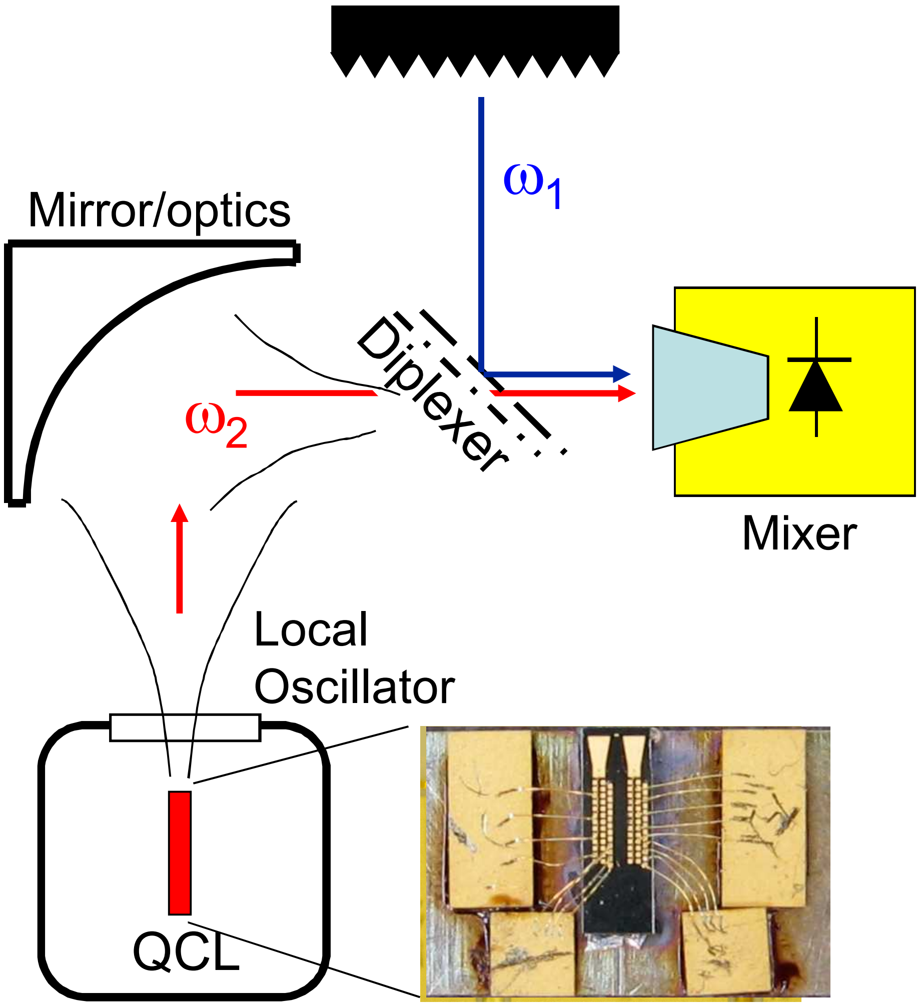
Heterodyne receivers enable:

1) high sensitivity detection

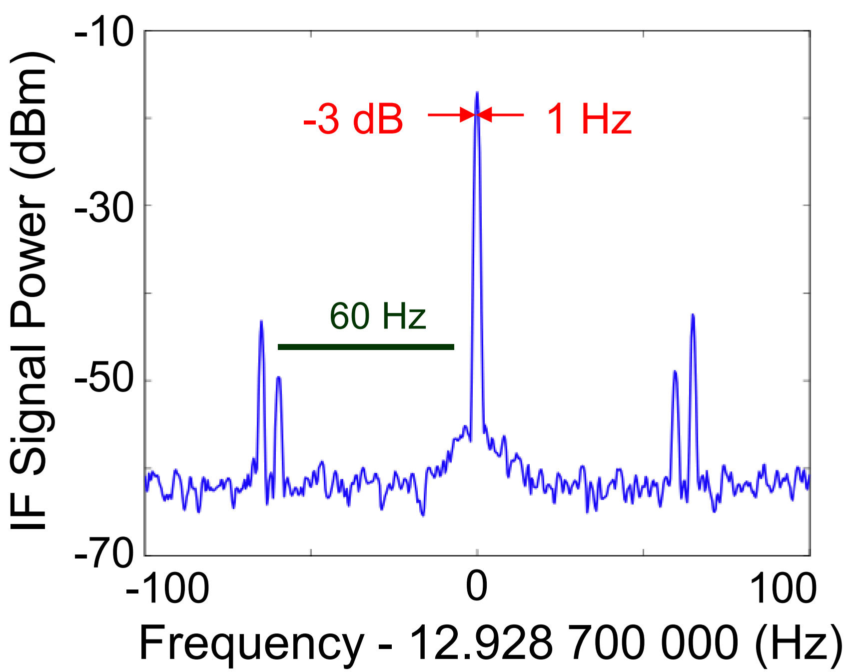


$$P \propto E_1E_2\cos(\omega_1-\omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1+\omega_2)$$

Coherent Detector: THz receiver



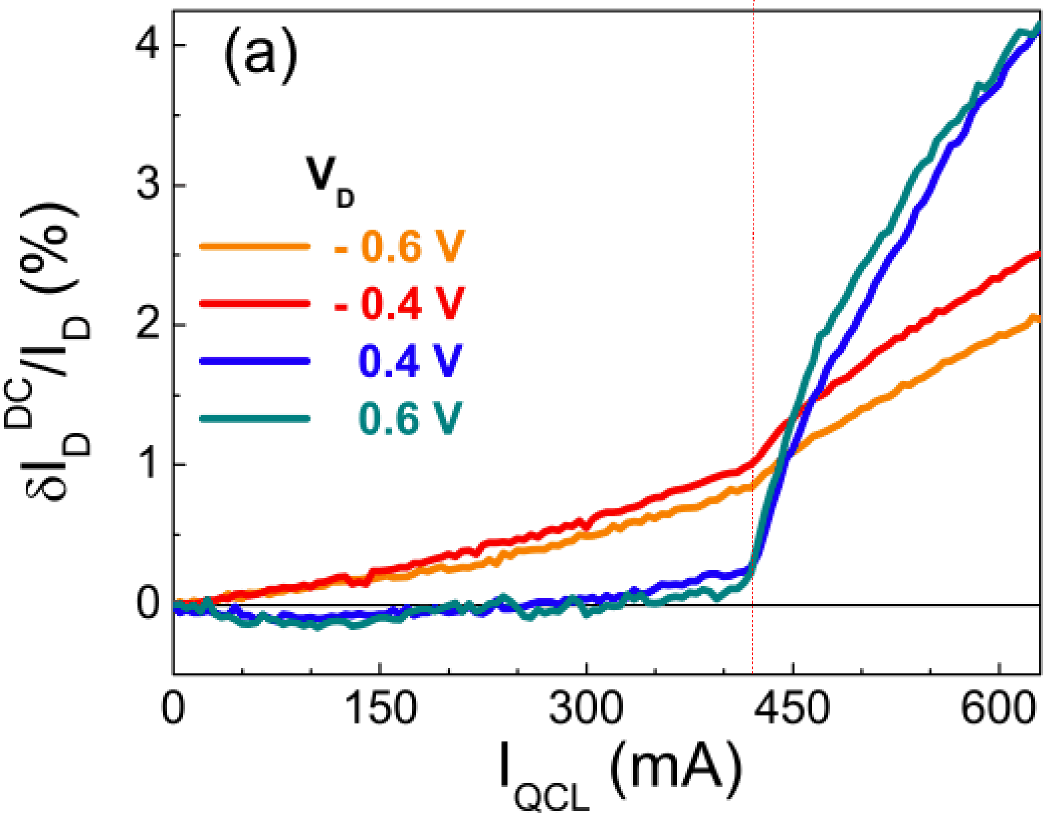
Heterodyne receivers enable:
1) high sensitivity detection
2) high spectral resolution



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

More Complete Diode Response

Laser Threshold



Why is there a rectified response below threshold?

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

Quantitative Diode Behavior

Simple Diode Equation

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

Expression for current change

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

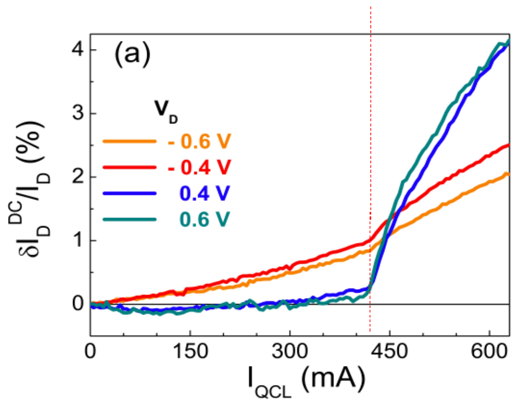
Keeping only lowest order terms in Taylor Series expansion

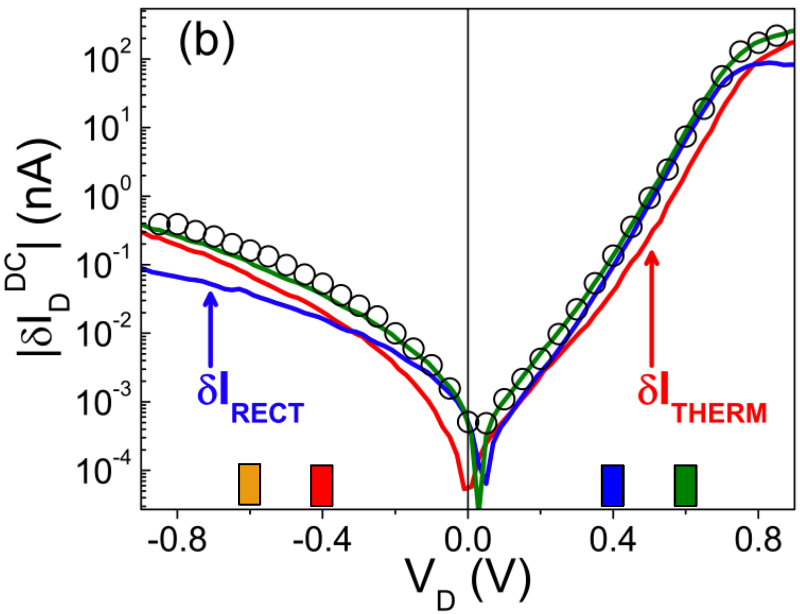
$$\delta I_D^{DC} = \frac{1}{4}\frac{\partial^2 I_D}{\partial V_D^2}\delta V_{THz}^2 + \frac{\partial I_D}{\partial T}\delta P_{QCL}\Theta_T$$

<u>Fit Parameters</u>

$$\delta V_{THz}^2 = 6.92 \times 10^{-5} \pm 0.35 \times 10^{-5}\, V^2$$

$$\Theta_T = 12.28 \pm 0.53\, W/K$$

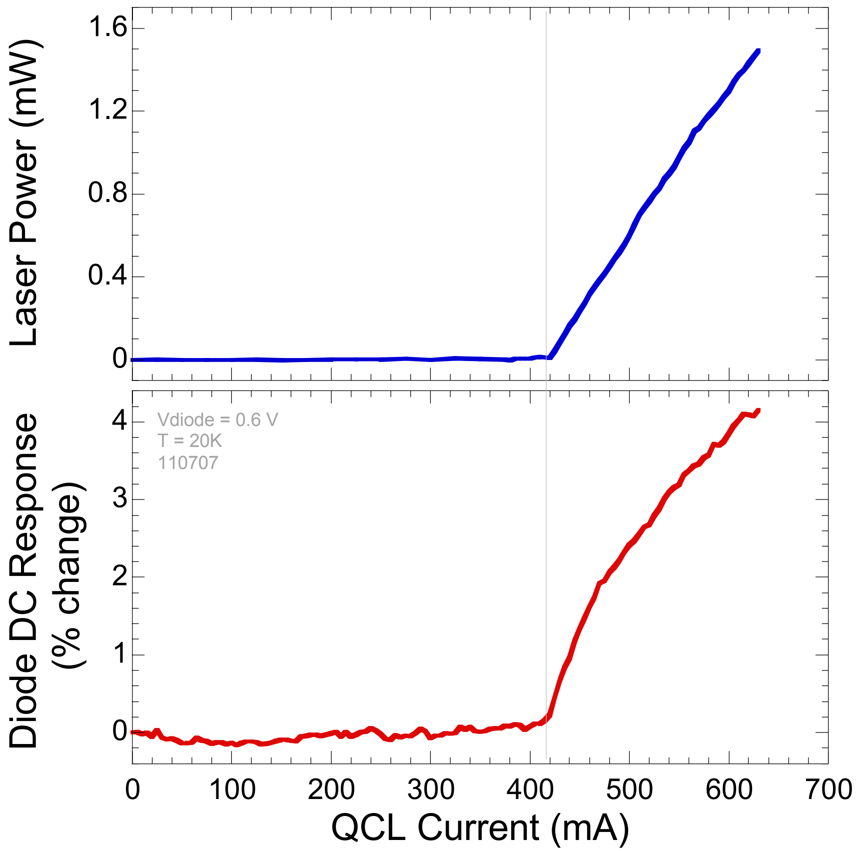




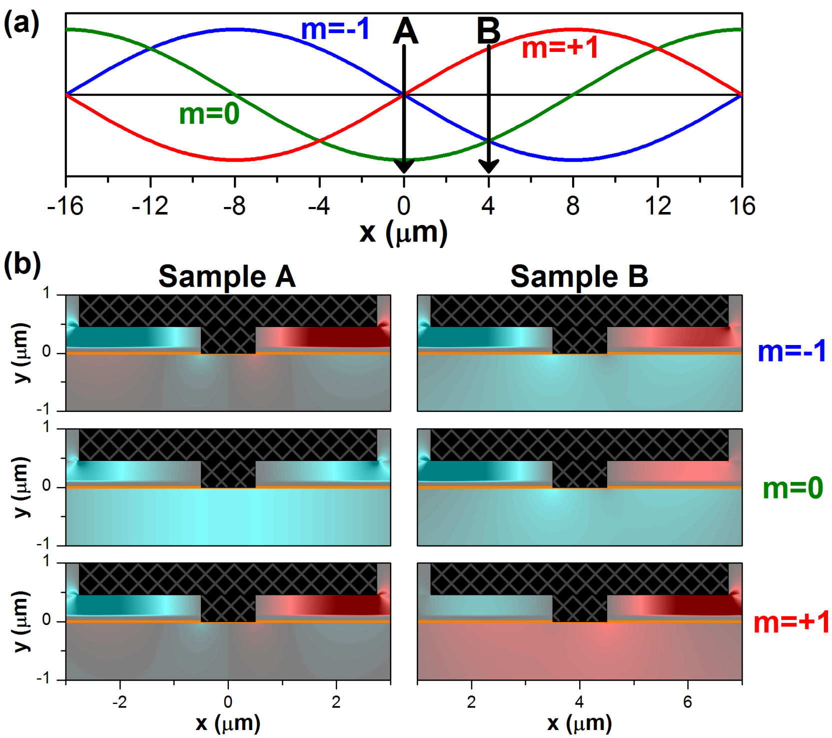
Diode responds depends on both laser power and laser temperature.

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

Diode Response vs Laser Power



Simple Picture



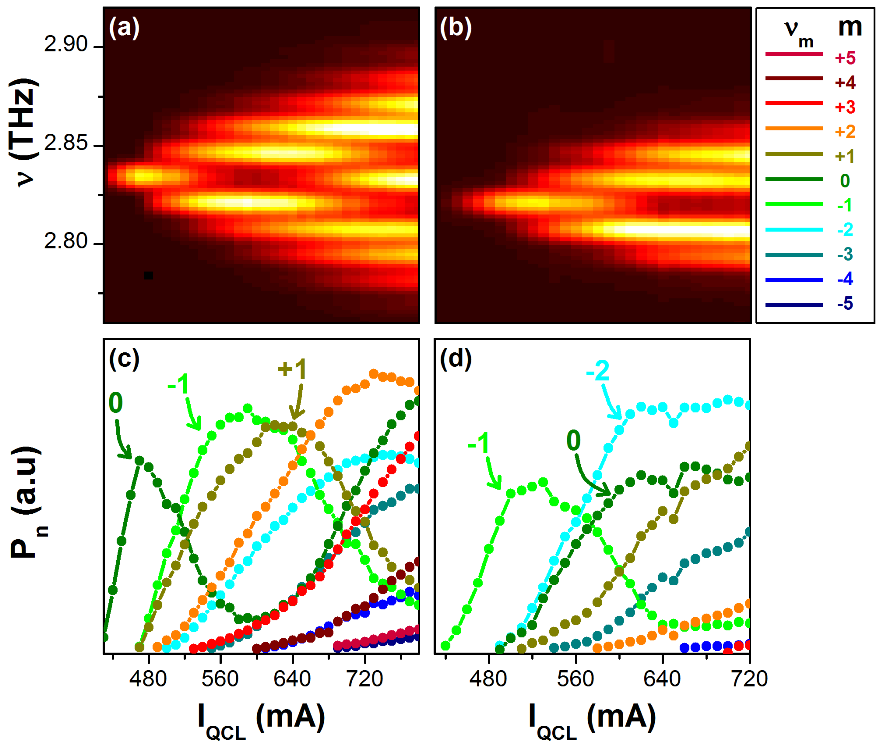
Lumerical Simulation

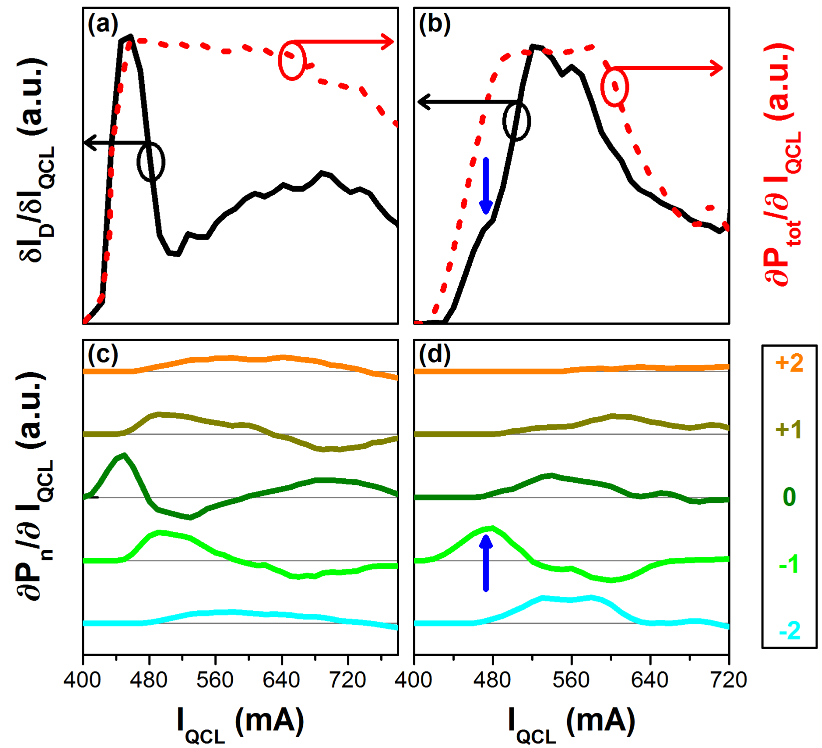
Diode response is not linear with laser power.

Dyer, APL., submitted (2013)

Diode Response vs Laser Power

Why is the response not linear with laser power?





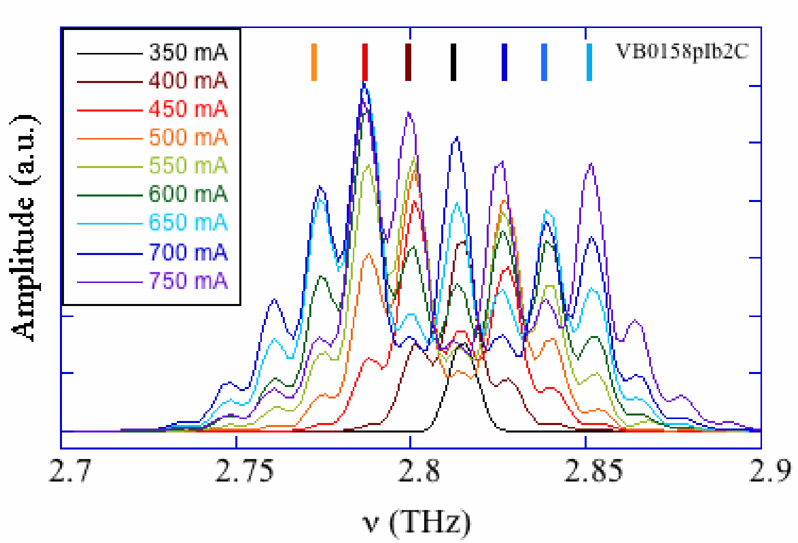
All modes do not have same overlap/coupling to diode.

Dyer, APL., submitted (2013)

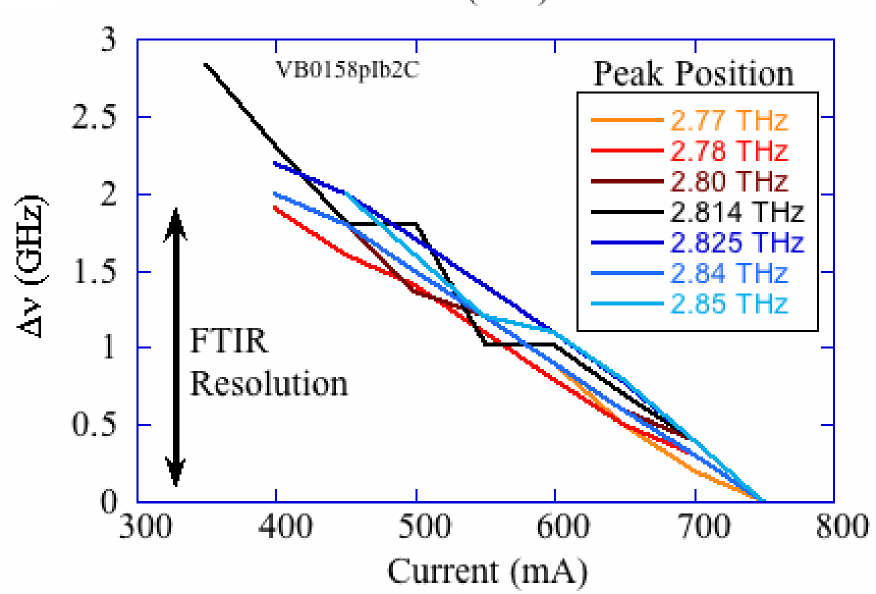
What can we learn and do with an integrated transceiver ?

Example : Laser Characterization

Laser Characterization



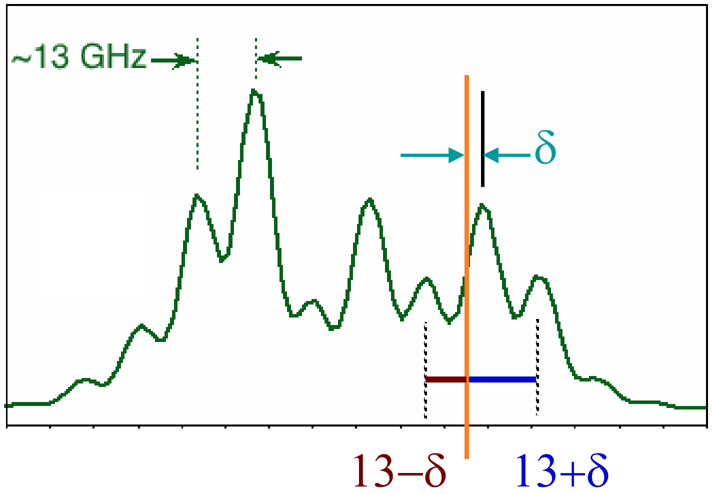
Current Tuning

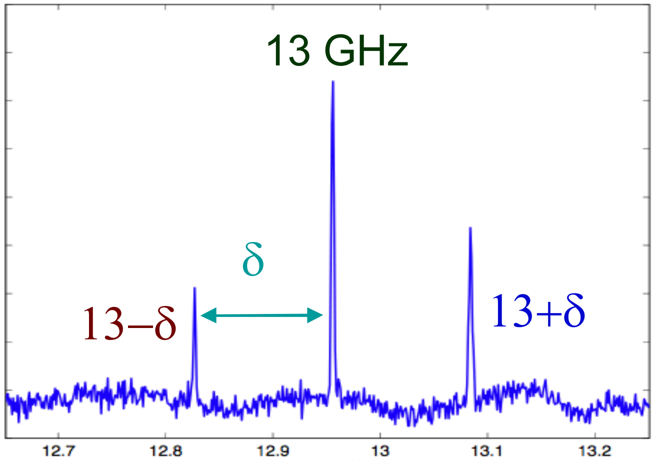


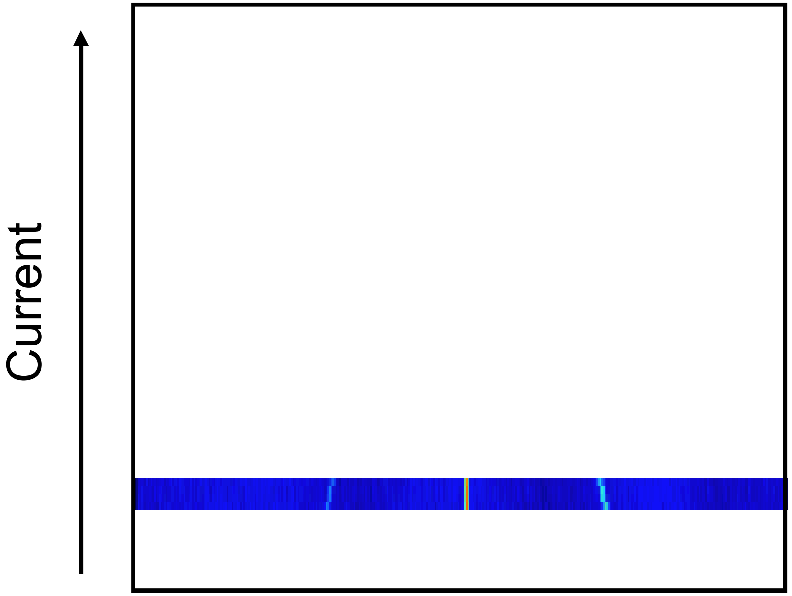
Small redshift with current

- Smaller than FTIR resolution
- Fairly noisy measurement

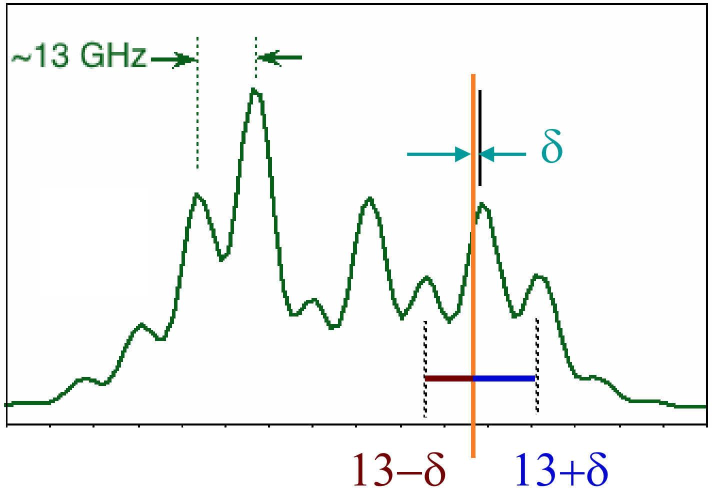
Current Tuning

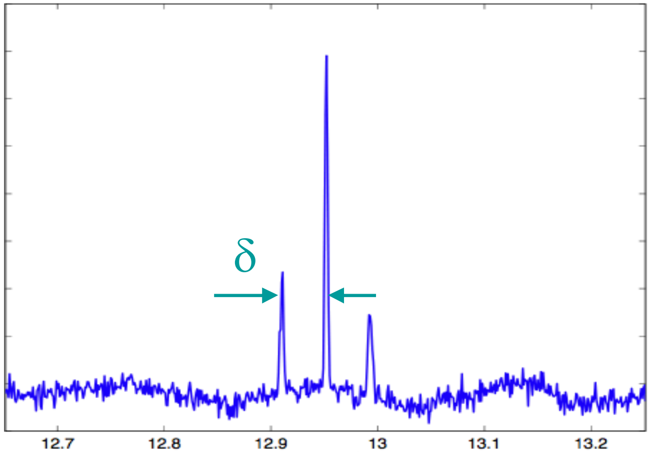


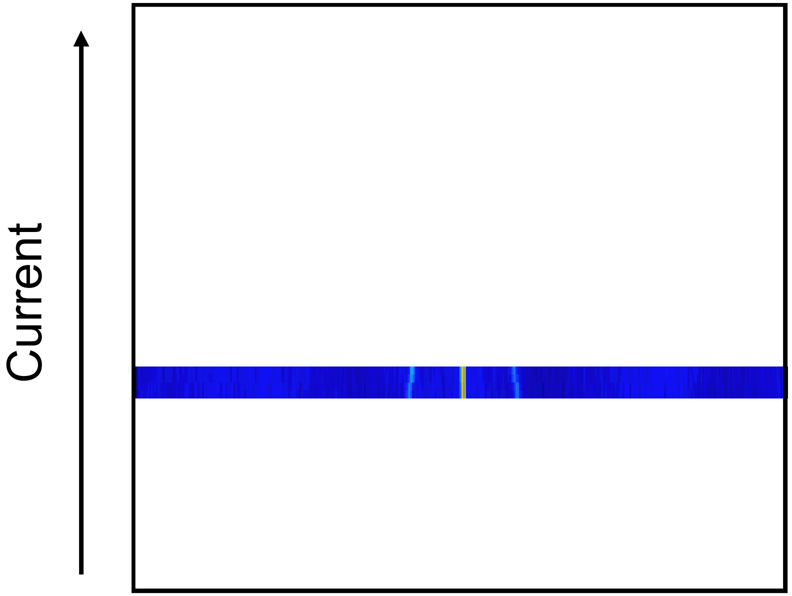




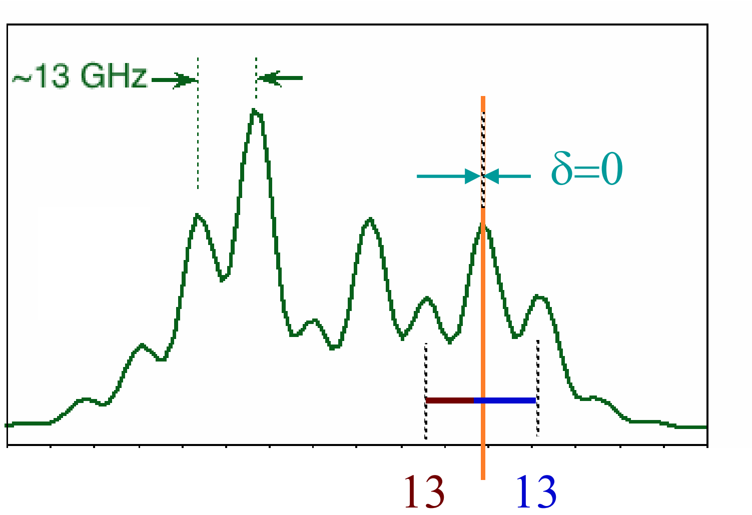
Current Tuning

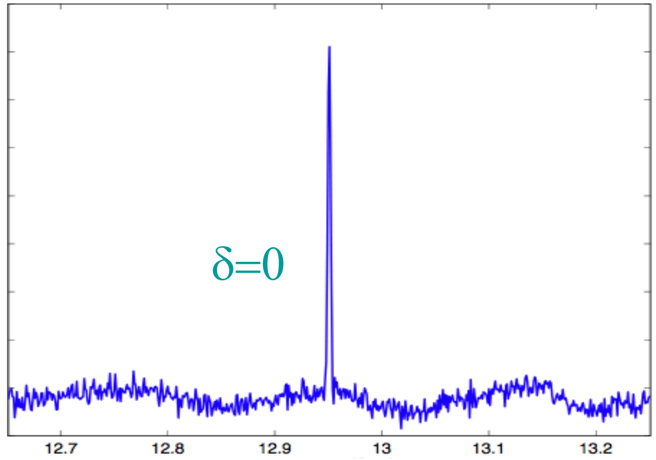


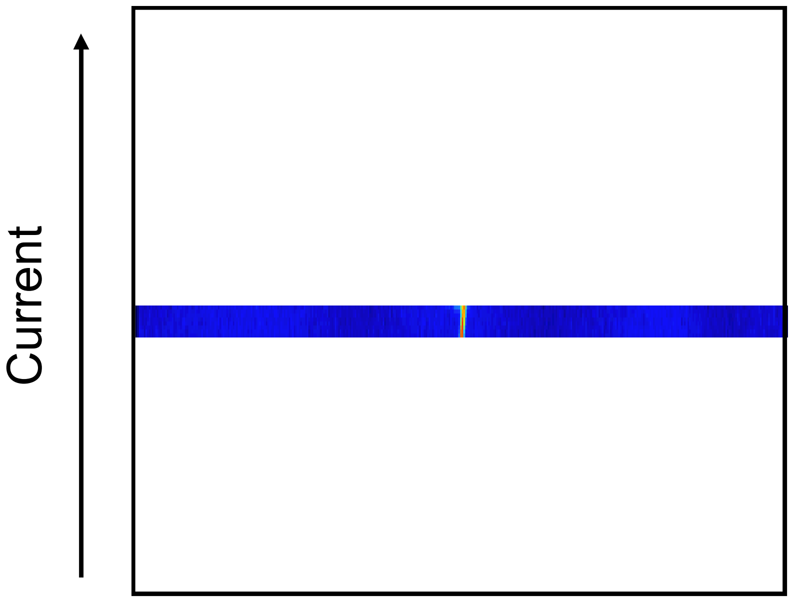




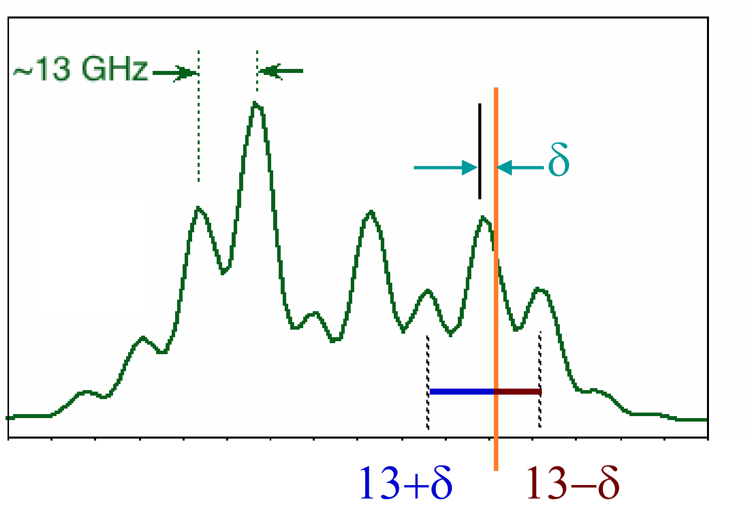
Current Tuning

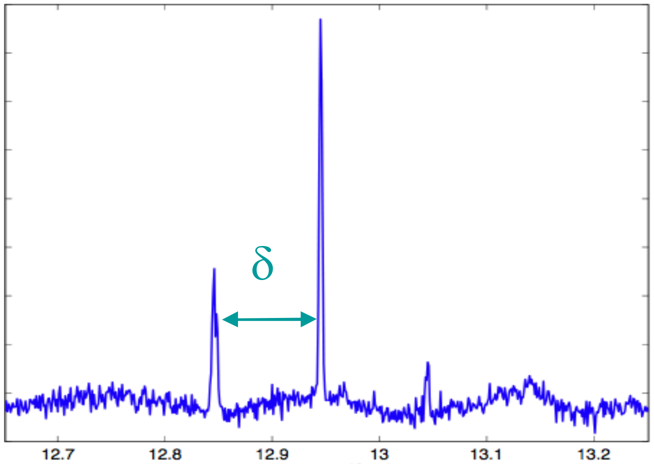


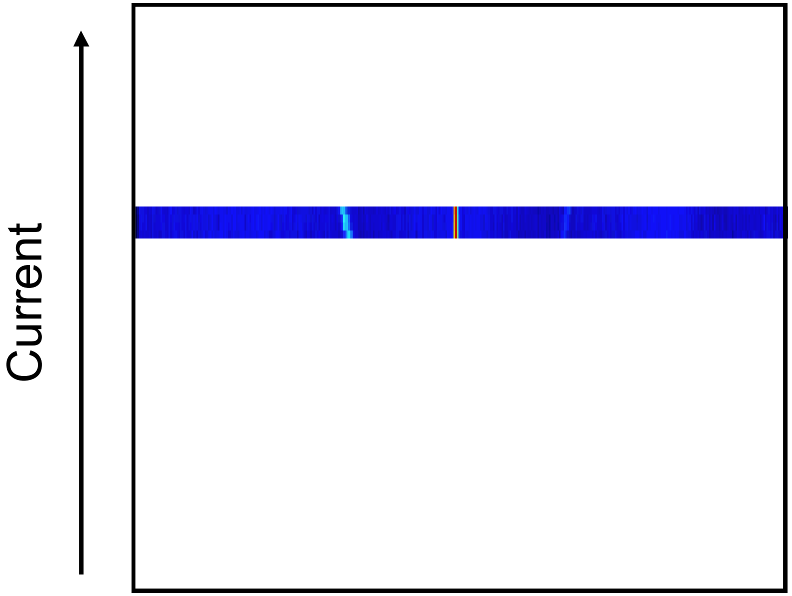




Current Tuning

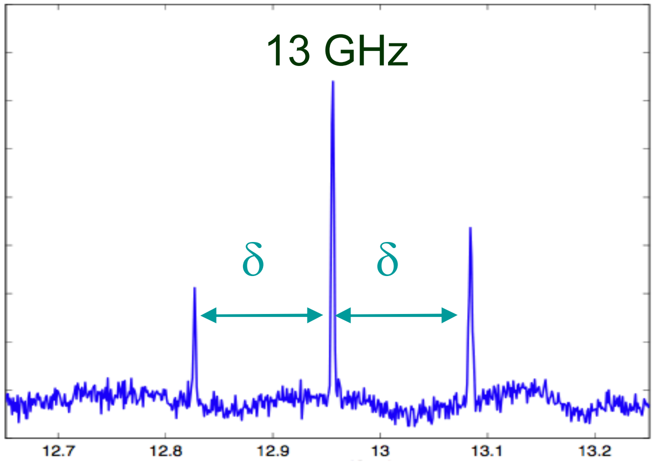


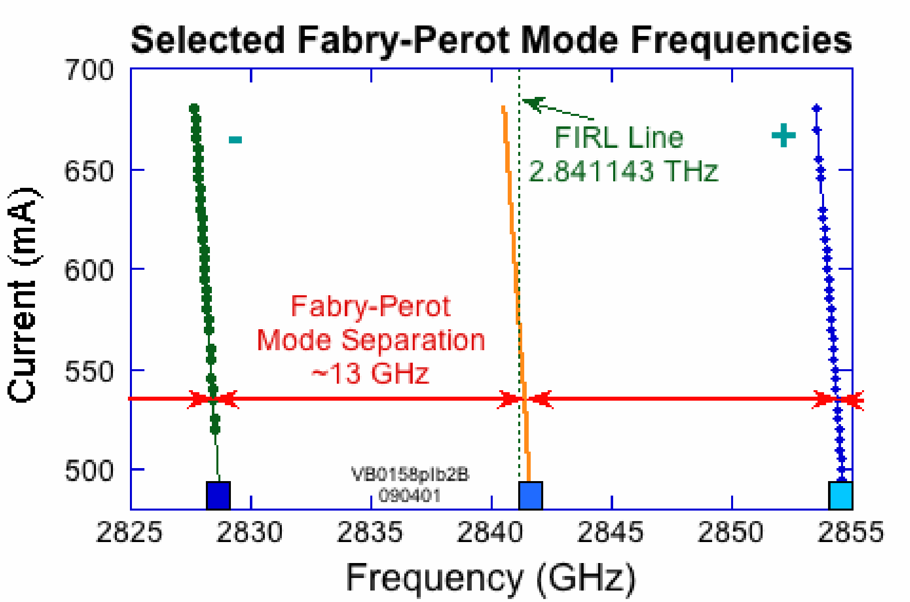


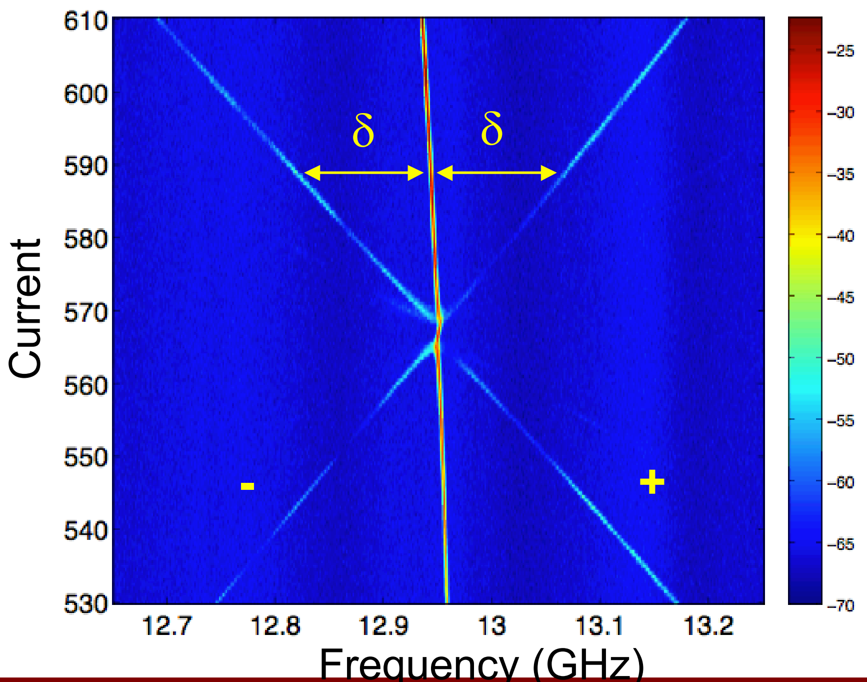


Current Tuning

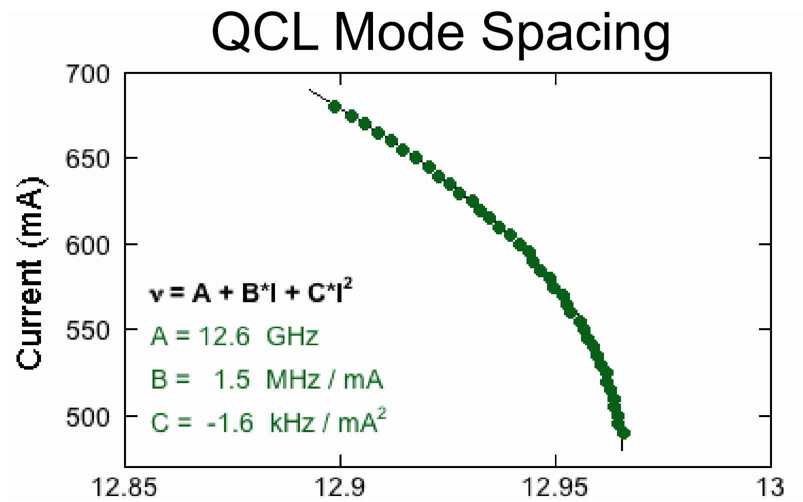
~ 6 MHz / mA

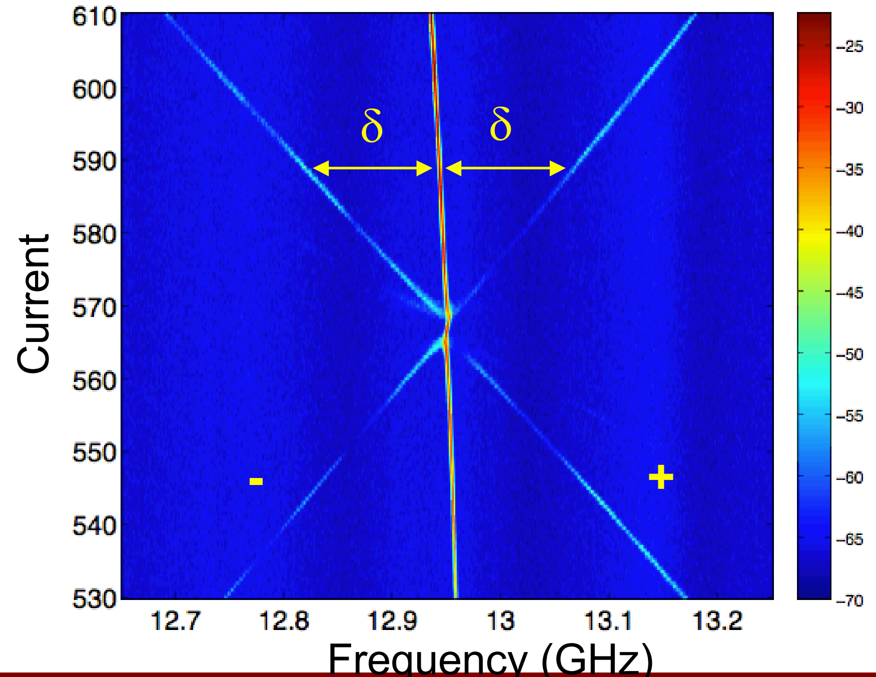


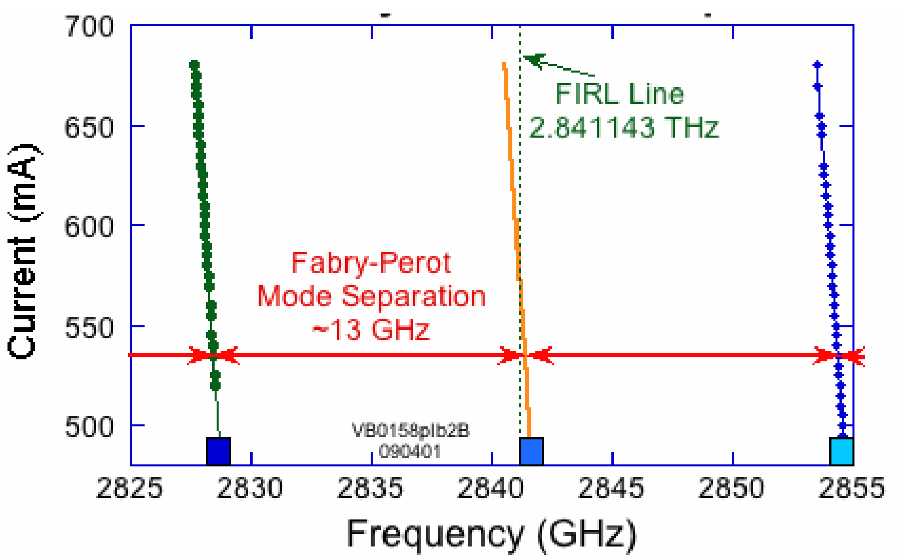




Current Tuning

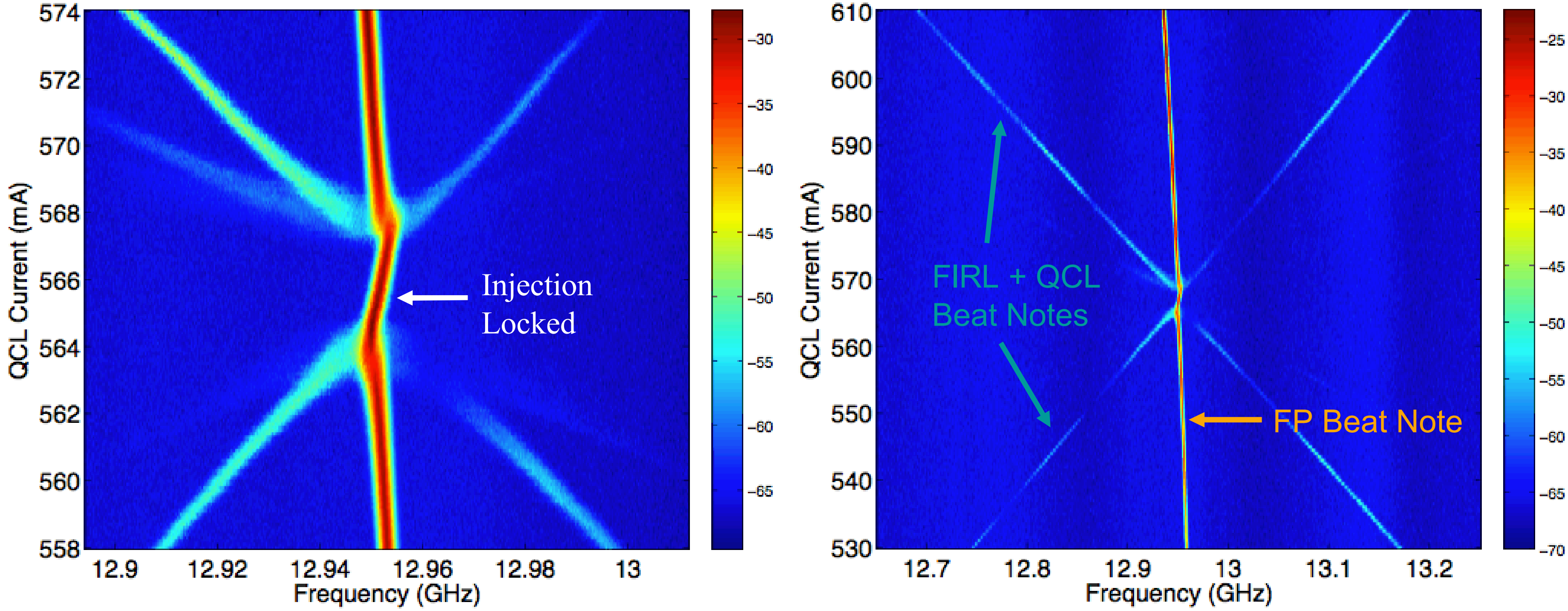






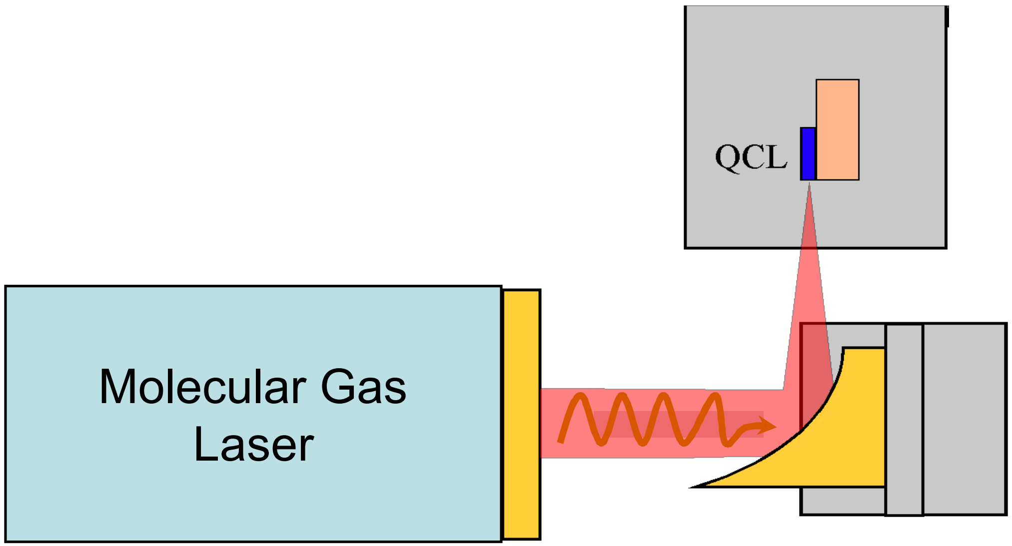
What happens when lasers cross?

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



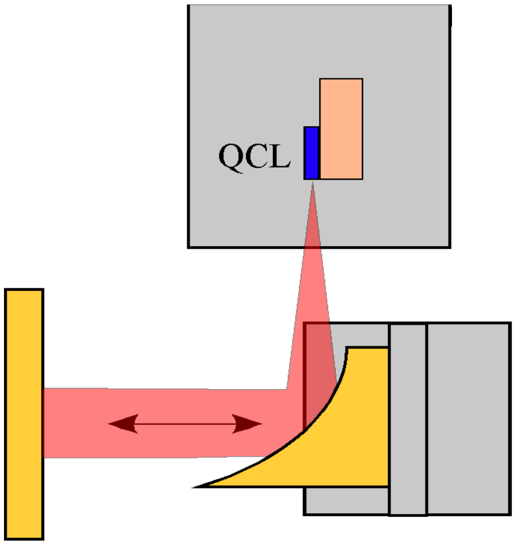
What people never tell you (3)...

...what they see is often not what they were looking for.



Some of the QCL emission retroreflects

Feedback Sensitivity



Why should we care?

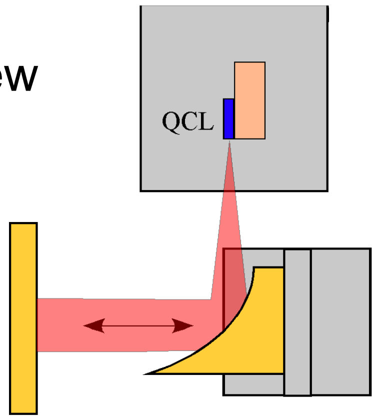
QCL is not a good LO if it is not stable.

No good THz isolators and there are always reflective components:

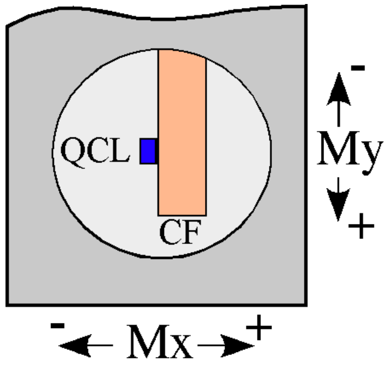
- Another laser facet
- Window or lens
- External mixers

Focal Position Feedback Sensitivity

Top View

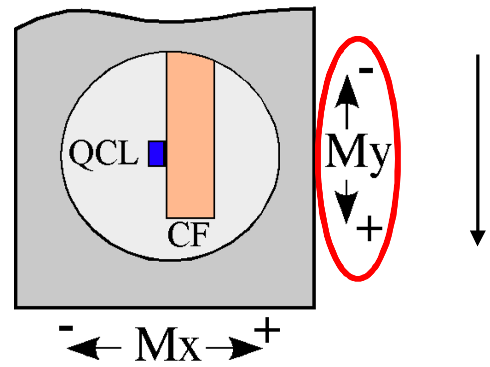


Front View

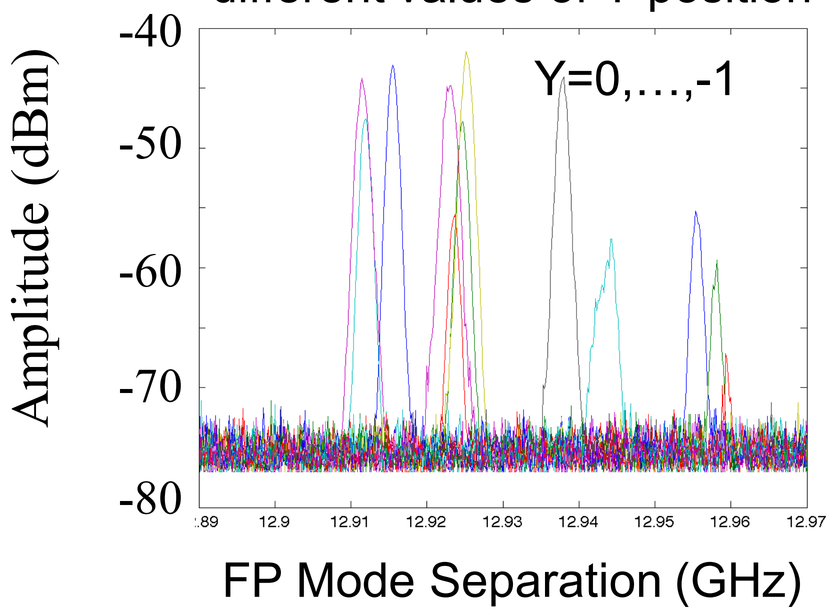


What happens when we scan the cryostat to find the FIRL beam?

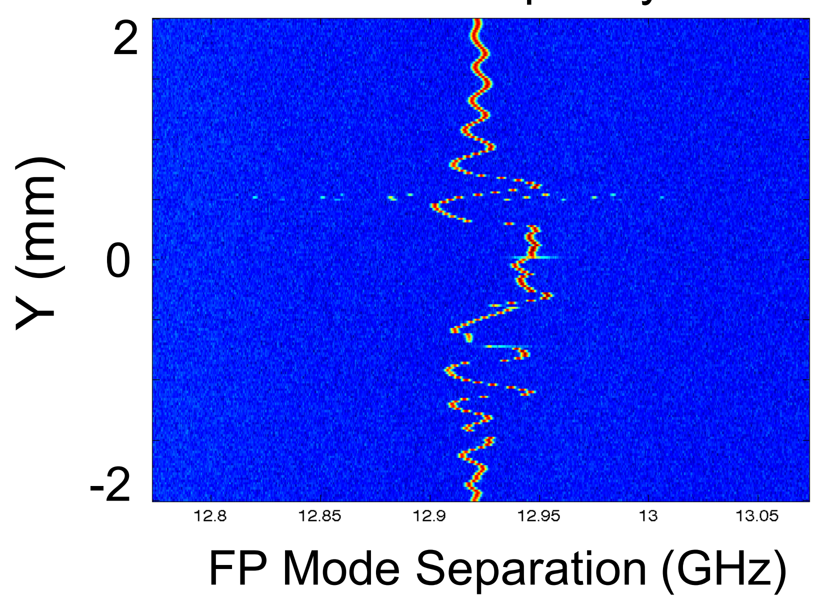
Focal Position Sensitivity



Overlayed RF spectra for different values of Y position

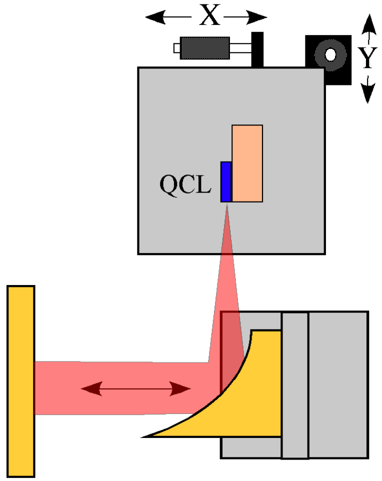


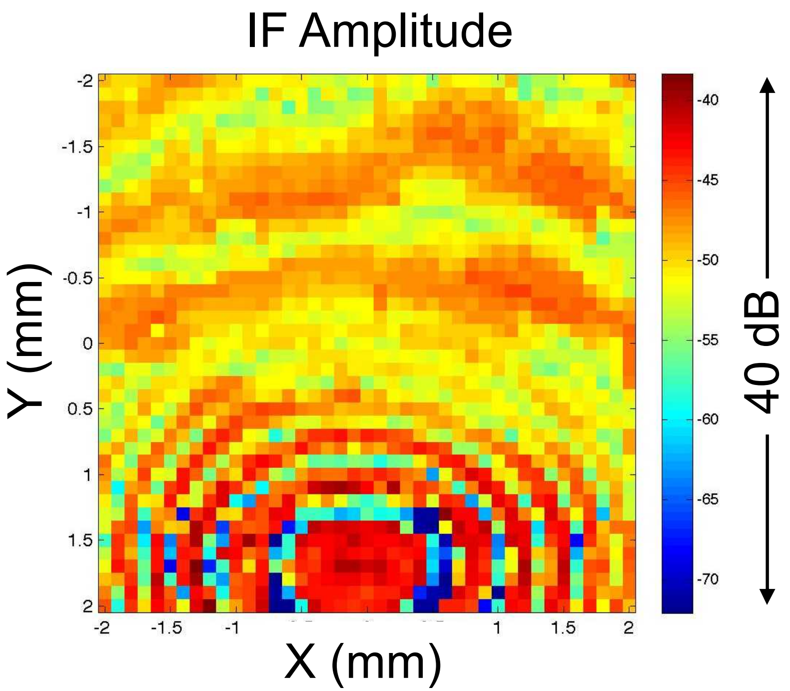
Peak Frequency

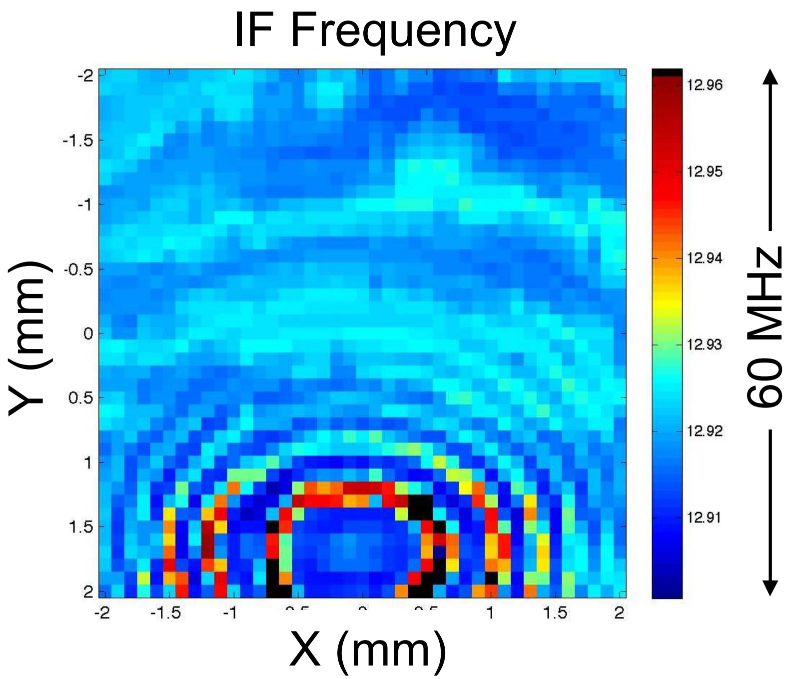


Focal Position Feedback Sensitivity

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





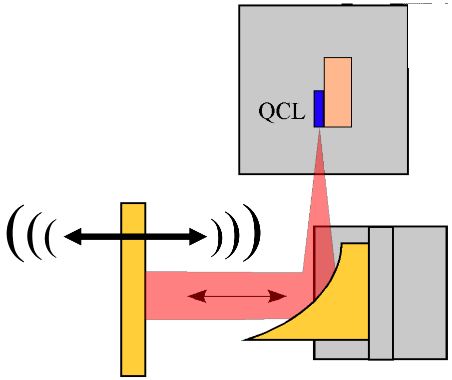


When life gives you ~~lemons~~ peaches...

... use the feedback to image the topography

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

Or...



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