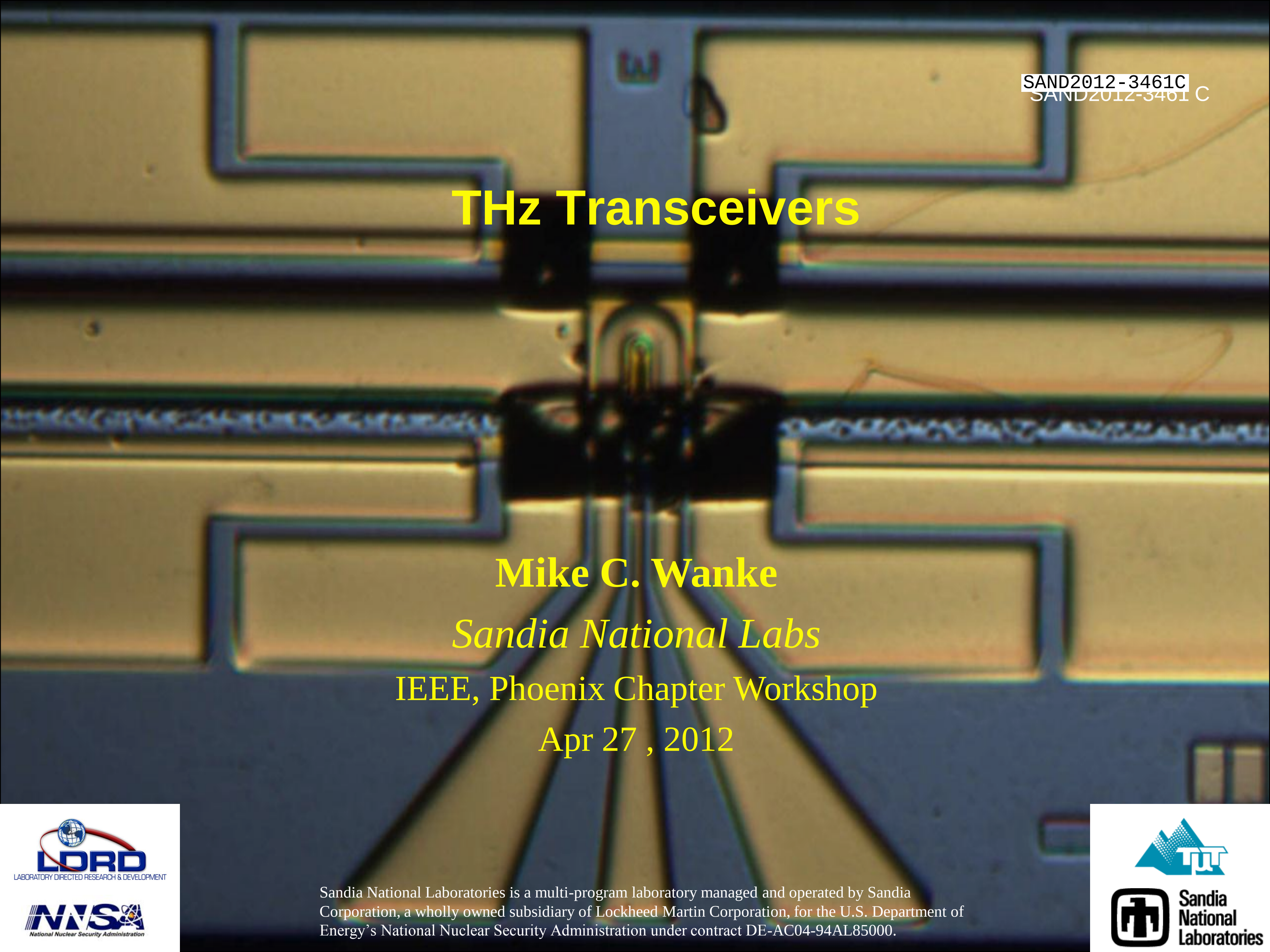

SAND2012-3461C
SAND2012-3461 C

THz Transceivers

Mike C. Wanke

Sandia National Labs

IEEE, Phoenix Chapter Workshop

Apr 27 , 2012

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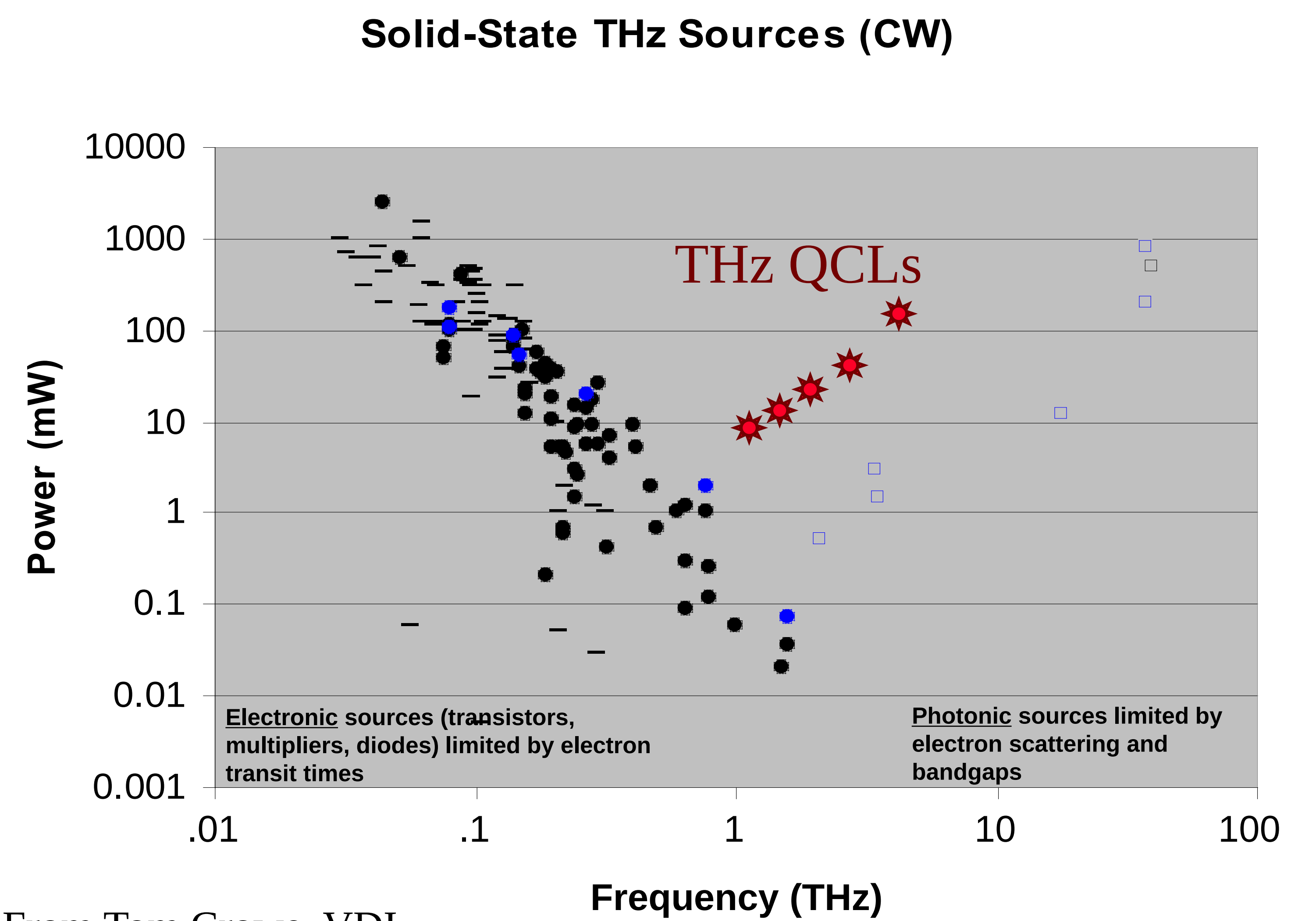
Supporting Cast

Michael C. Wanke	*Sandia National Laboratories*
Mark Lee**	Now at UT-Dallas
Christopher D. Nordquist	
Michael J. Cich**	Now at Soraa
Chuck T. Fuller	
Eric A. Shaner	
John L. Reno	
Greg C. Dyer	
Erik W. Young**	*Now at Lumileds*
Albert D. Grine	*LMATA Government Services*

With Support From:

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

The "Shrinking" THz Gap

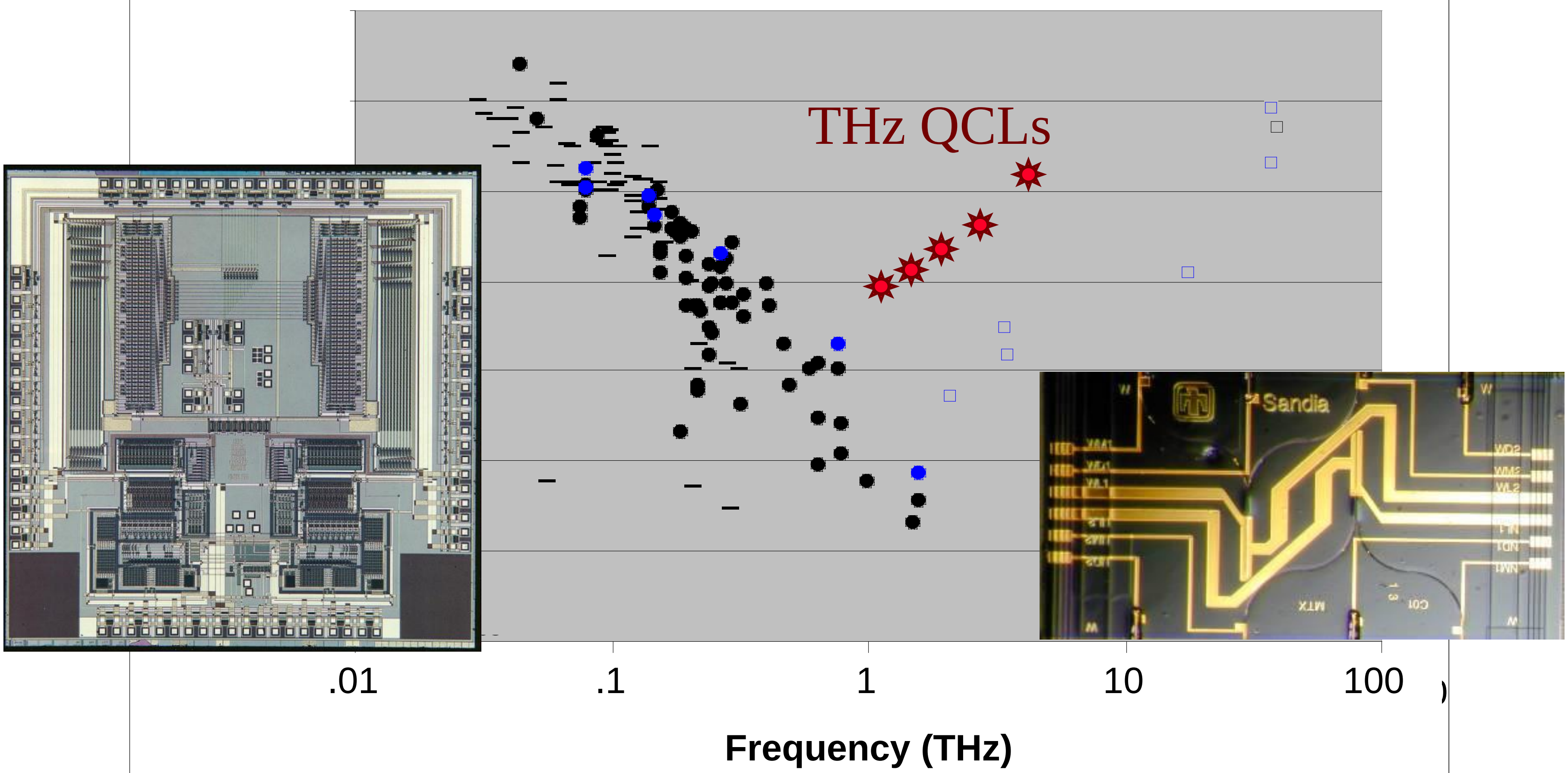


From Tom Crowe, VDI

The THz Gap

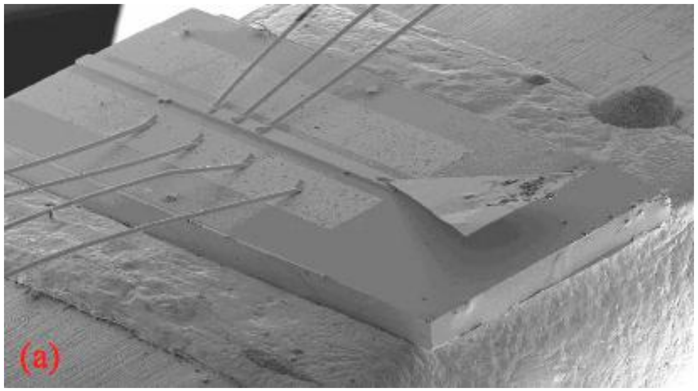
~~Solid-State THz Sources~~ (CW)

Integration

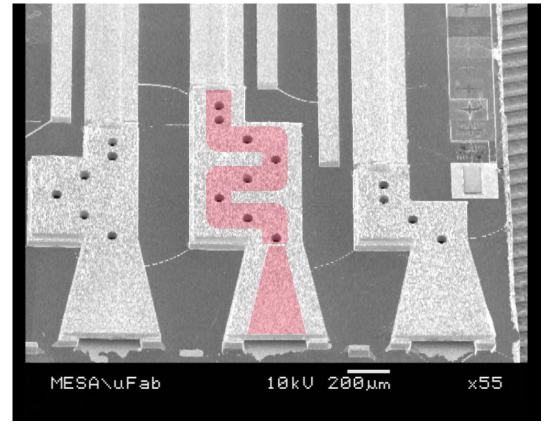


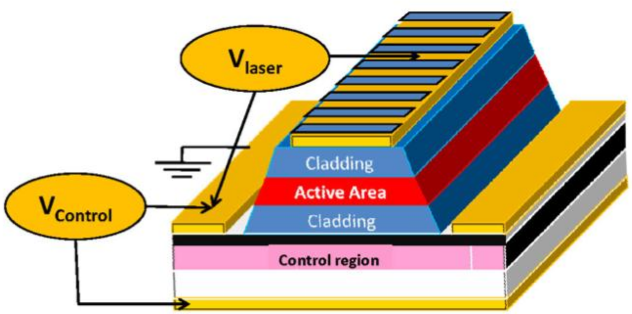
Integration examples

Antenna Coupling
(IEMN/CNRS)

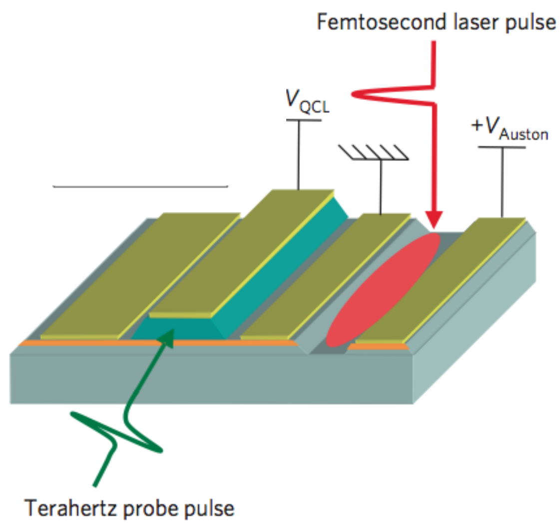


Integrated Waveguide
(Sandia)

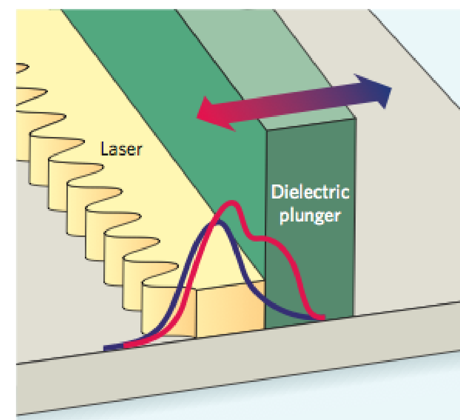




Modulator
(U. Paris 7)

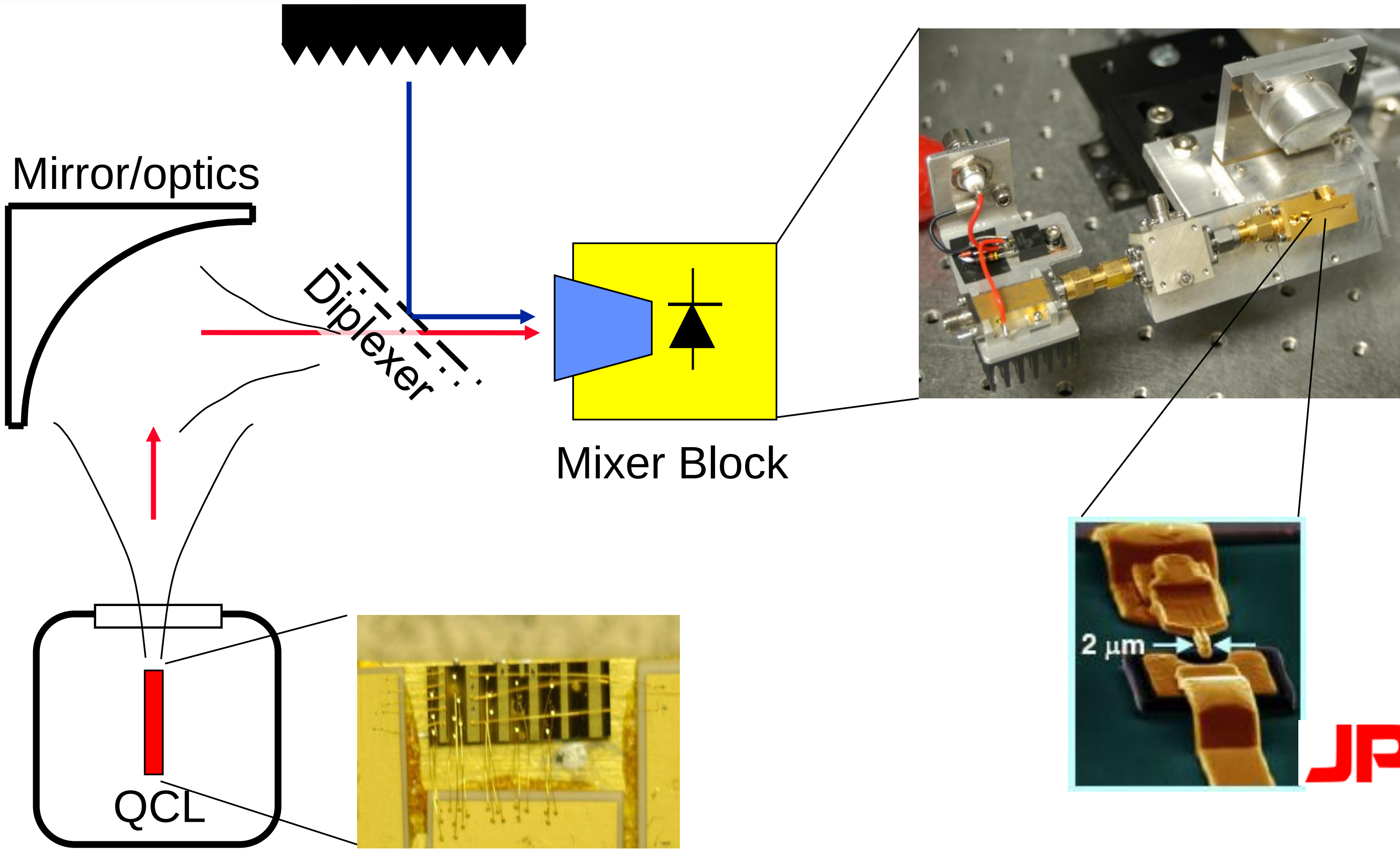


Pulse Amplifier
(Ecole Normale Sup.)



Mechanical Tuning
(MIT)

Coherent Detector: THz receiver



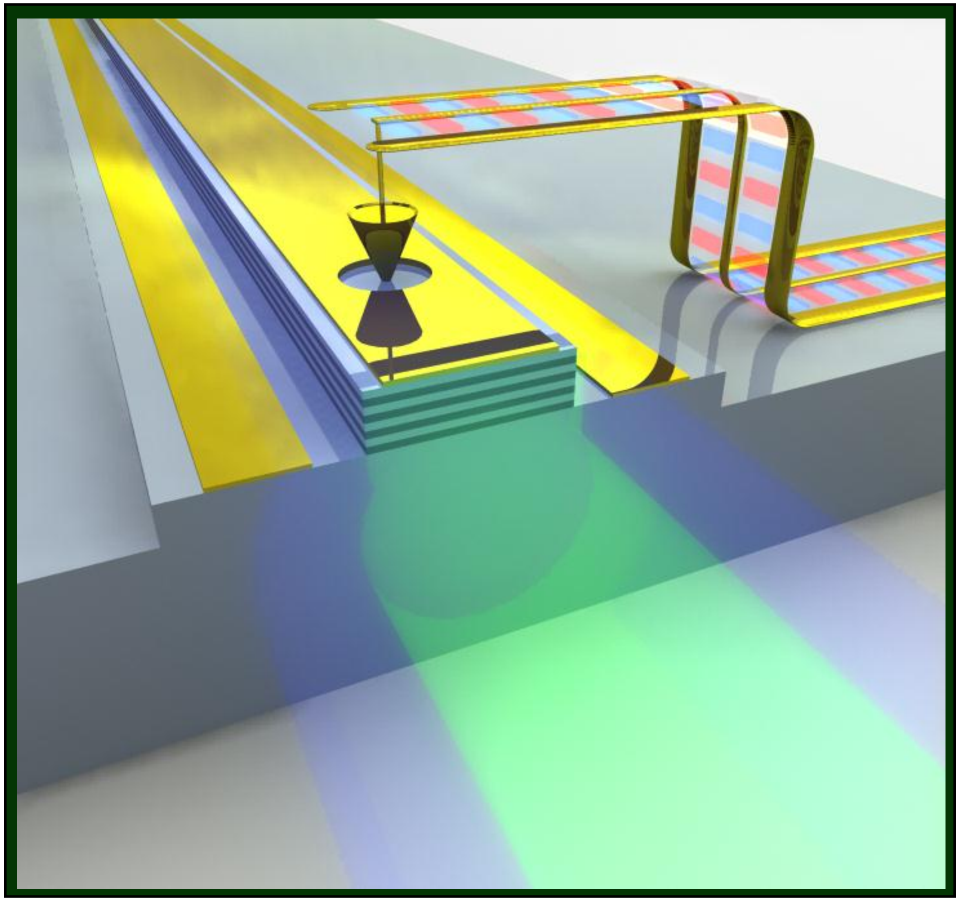
$$P \propto E_1E_2\cos(\omega_1-\omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1+\omega_2)$$

Outline

- Monolithically Integrated Transceiver Description
- Demonstration of Receiver Operation
- Laser Characterization

Monolithically Integrated Transciever

Insert diode directly into laser core



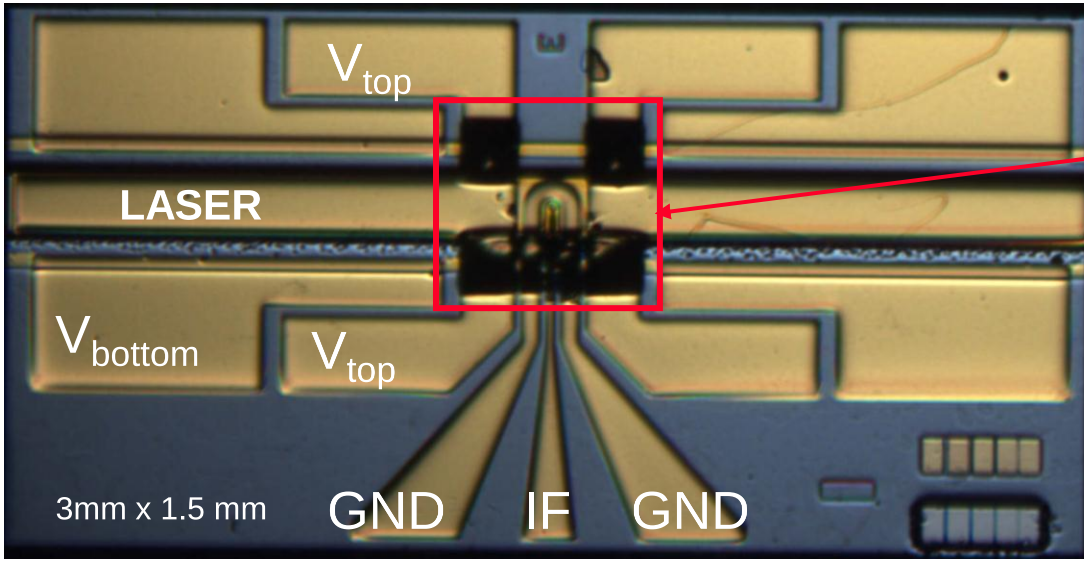
Benefits

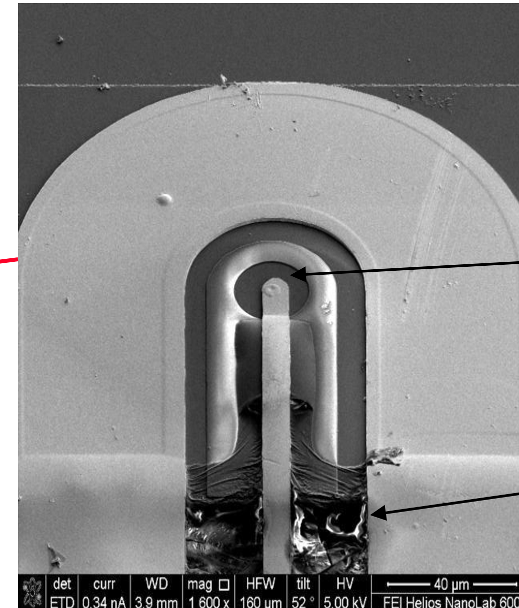
- Reduces size
- Eliminate components
- Ensures constant ‘alignment’
- Enhances laser/diode coupling
- Bonus : laser diagnostic tool

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

Completed QCL/Schottky THz IC

3 mm





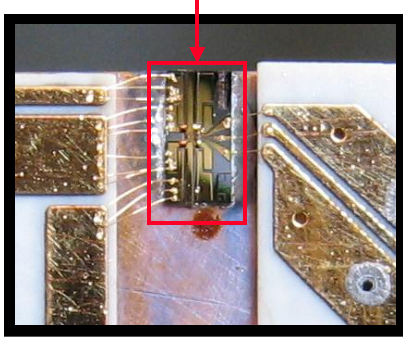
diode

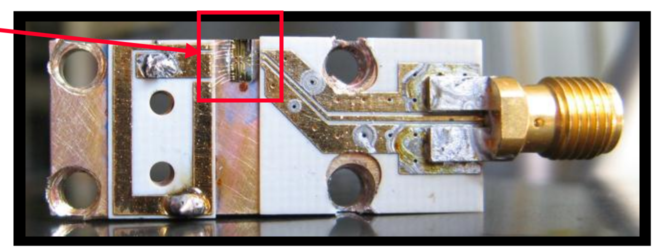
air bridges

GND

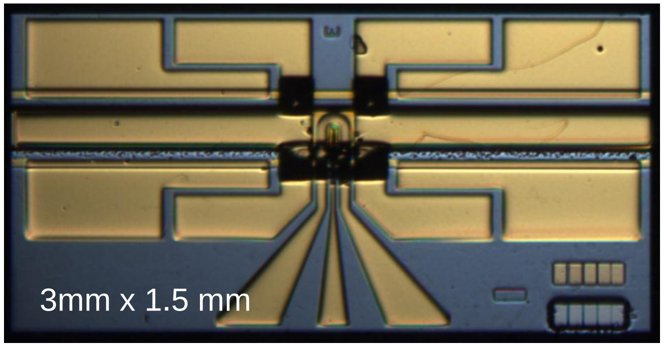
IF

GND

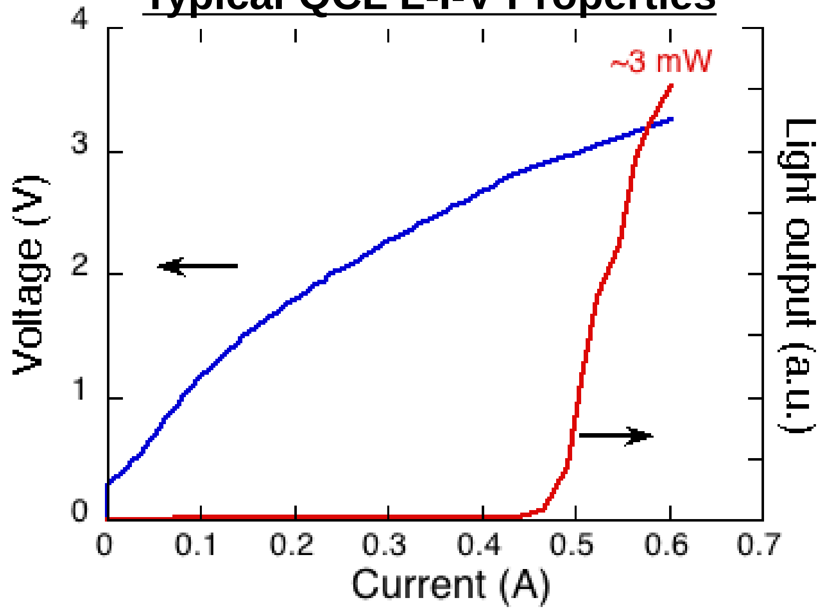




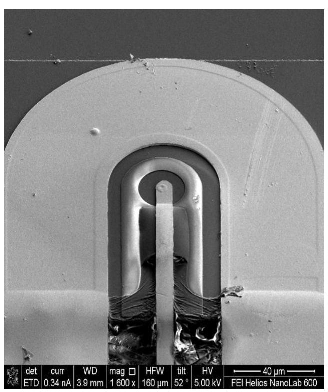
Diode and Laser DC Properties

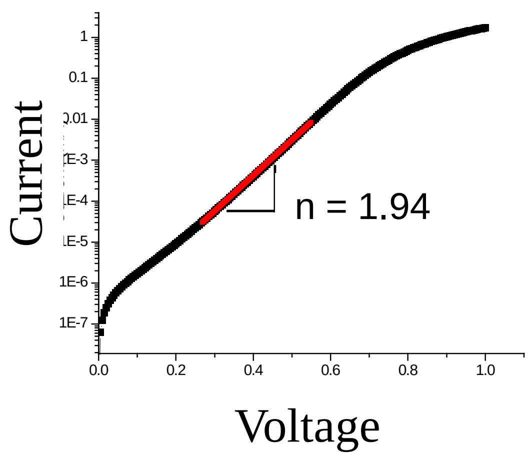


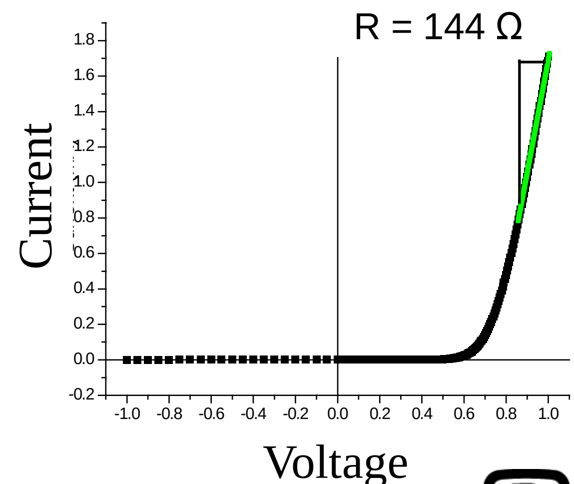
Typical QCL L-I-V Properties



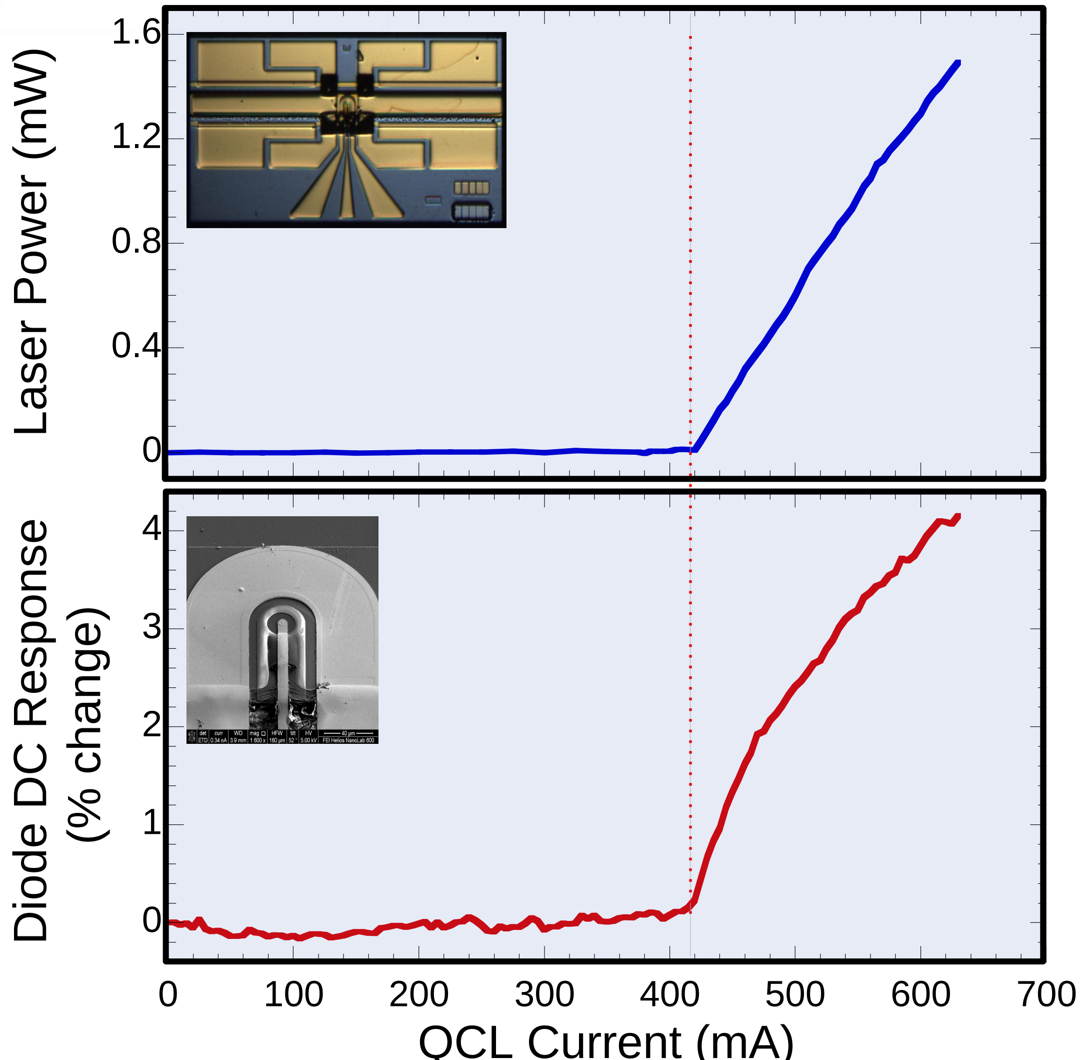
Typicial Diode DC I-V Properties





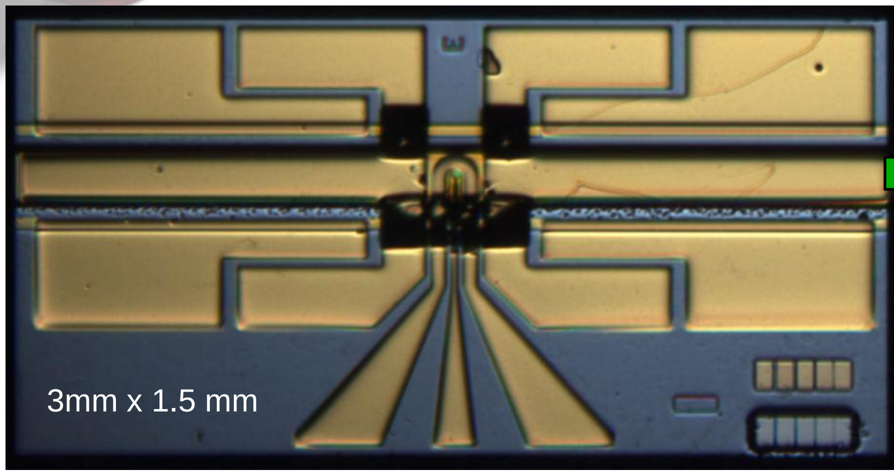


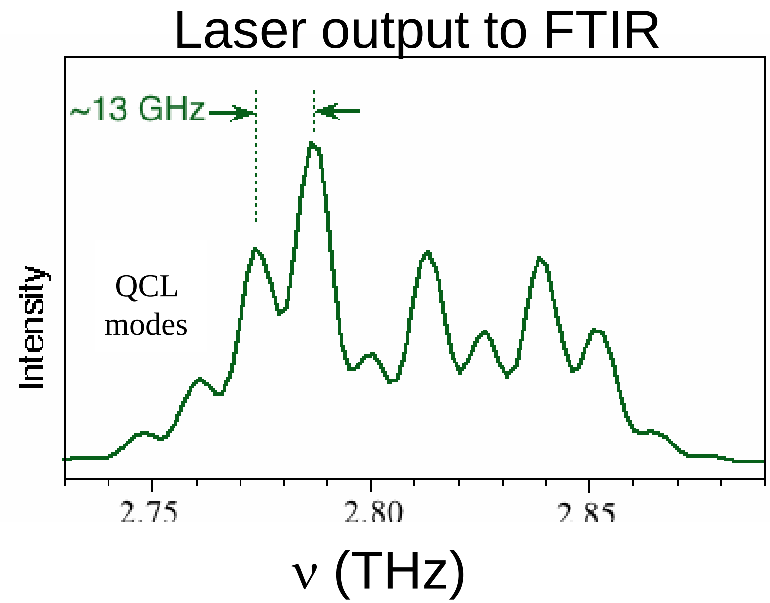
Diode Rectified Response



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

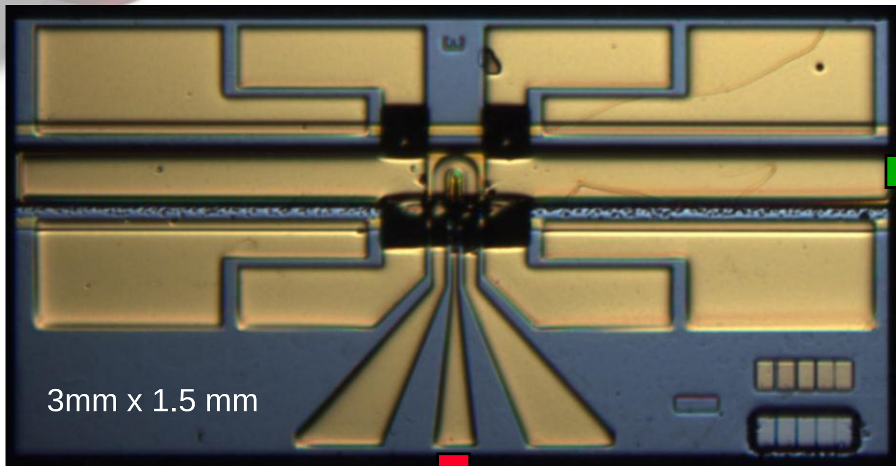
Integrated Diode THz Mixer



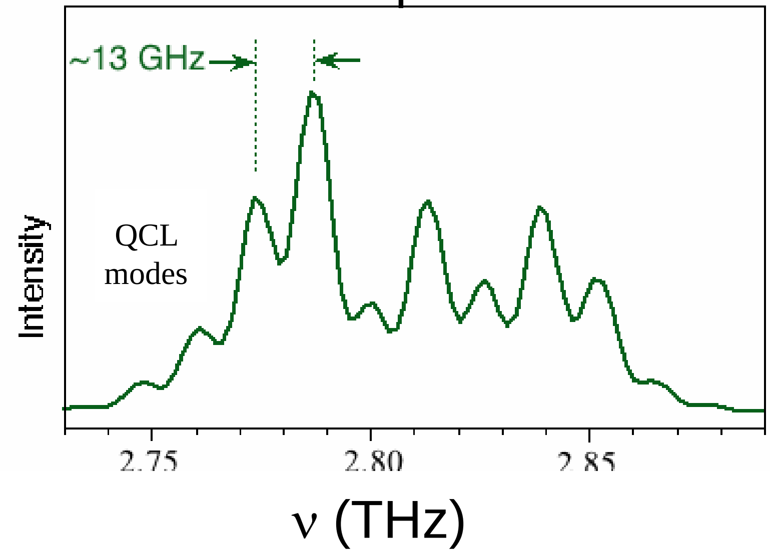


- **Purposely built a multimoded QCL centered on 2.81 THz**
  - **QCL emission (FTIR) spectra show Fabry-Perot modes spaced by ~13 GHz**

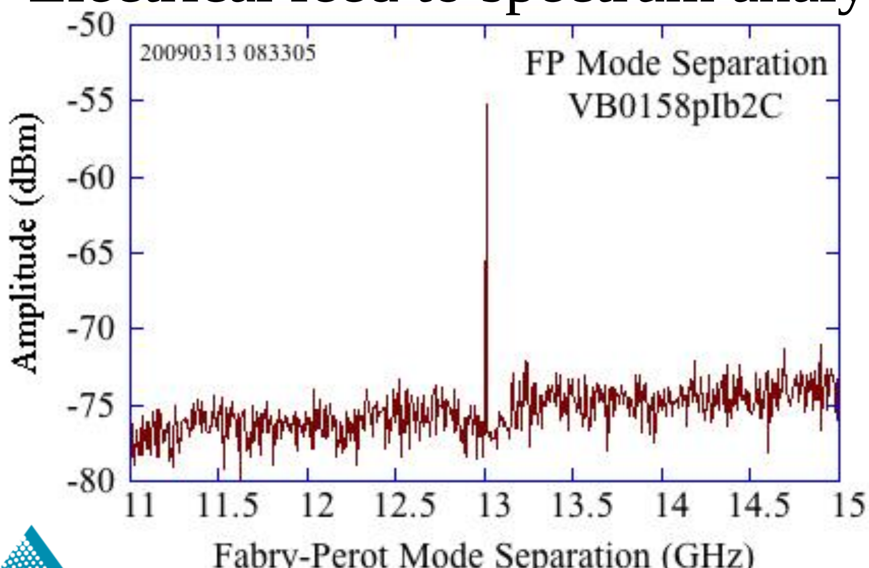
Integrated Diode THz Mixer



Laser output to FTIR

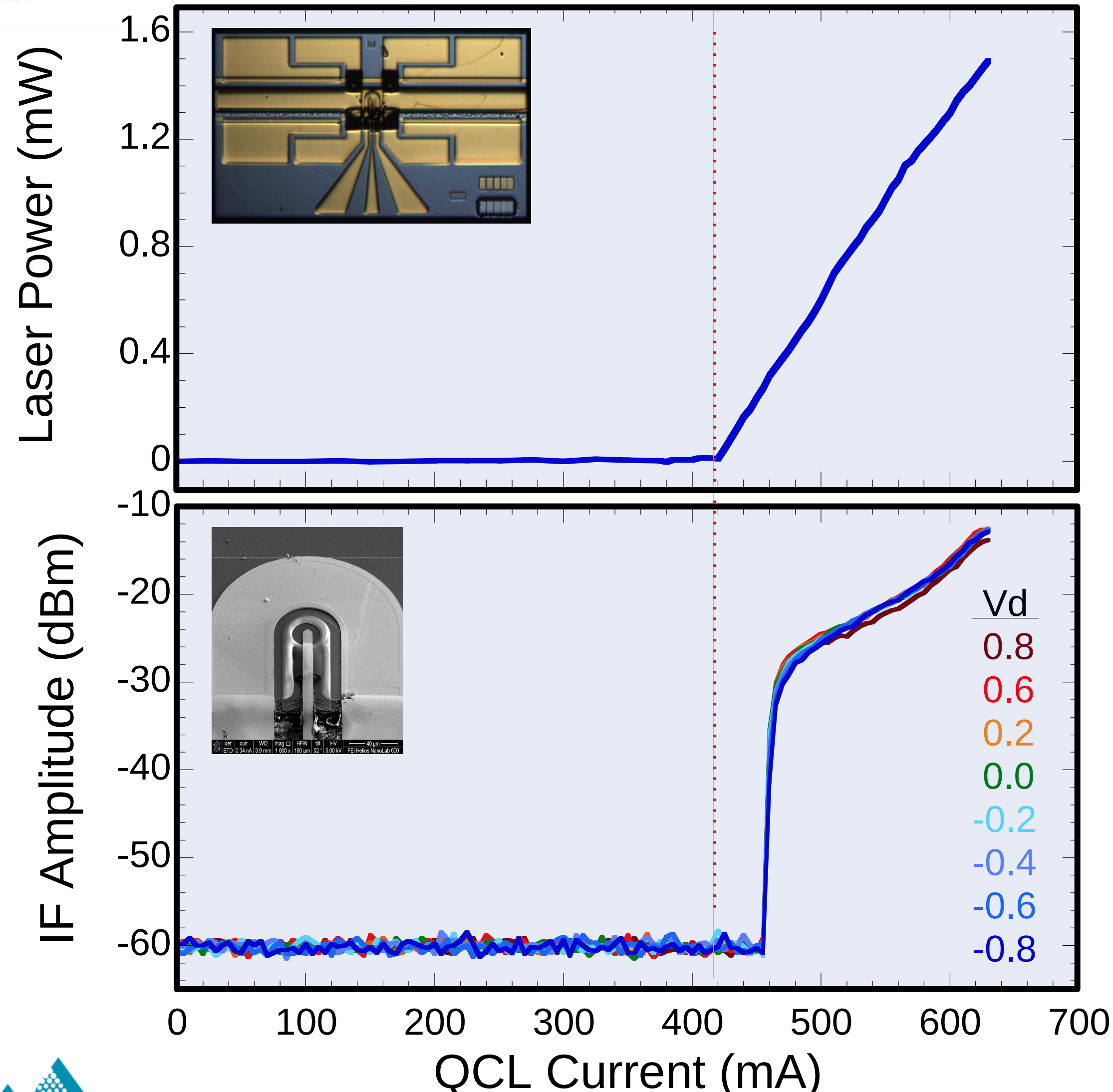


Electrical feed to spectrum analyzer



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

IF dependence on laser power



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

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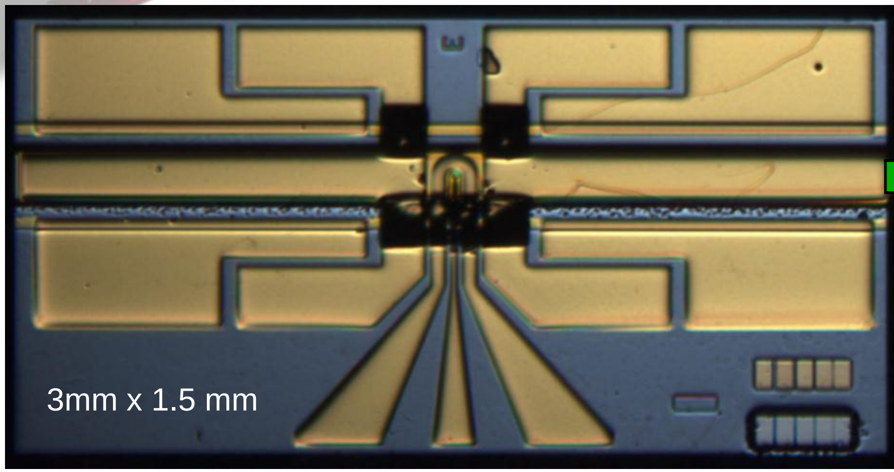
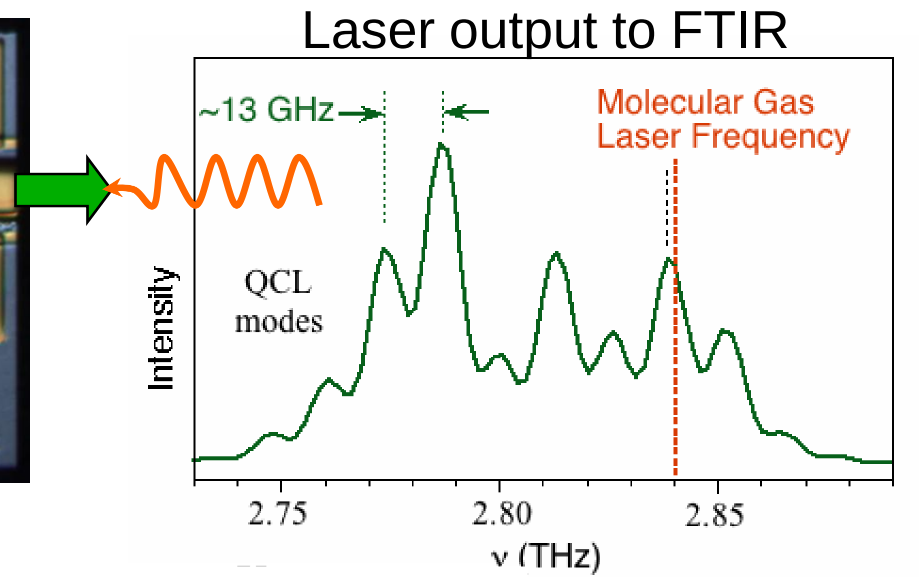
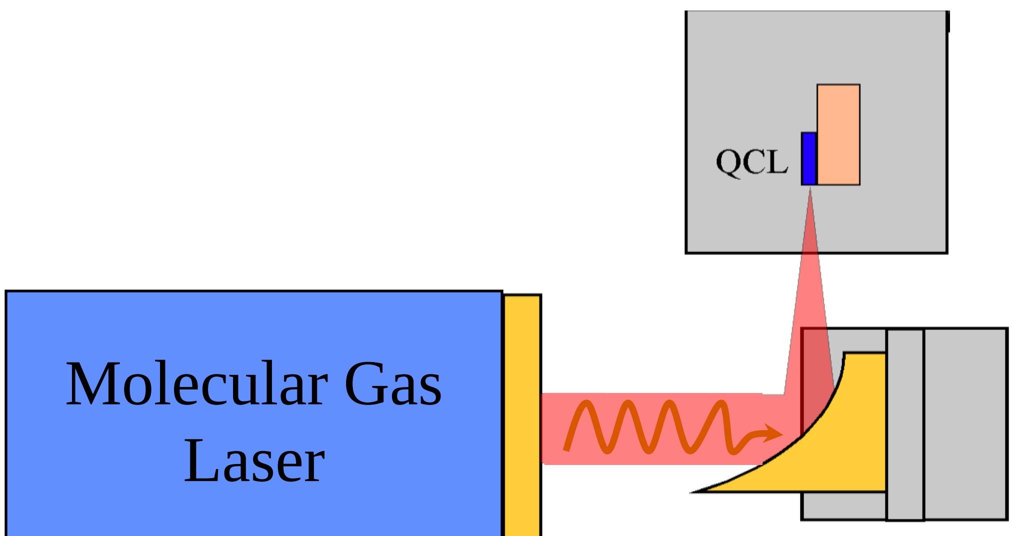
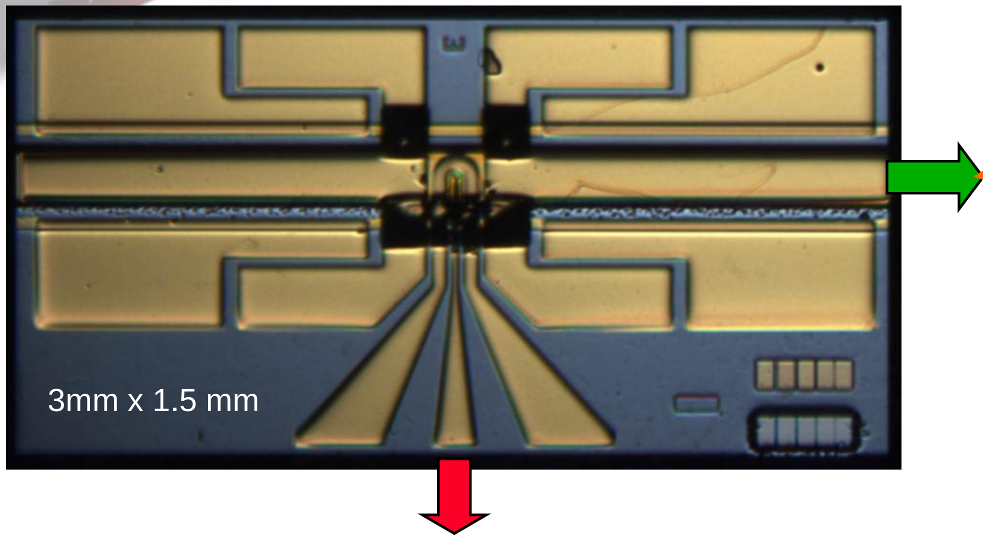
Integrated THz Receiver

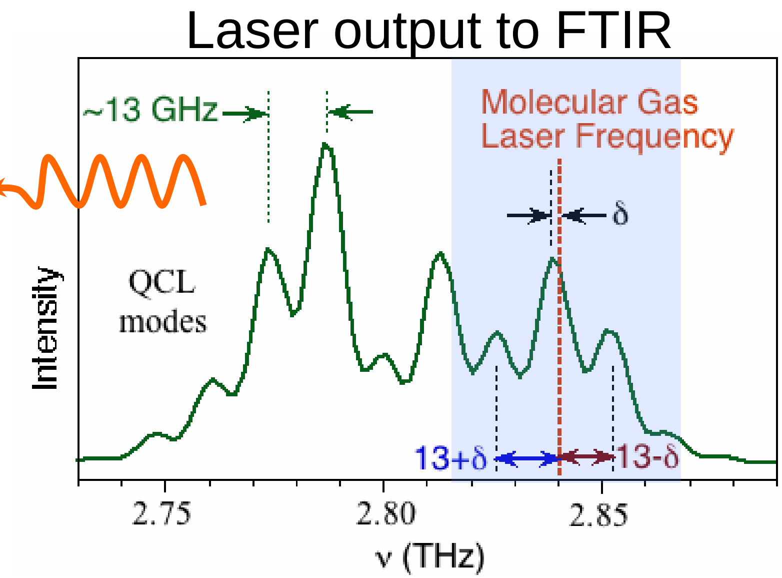


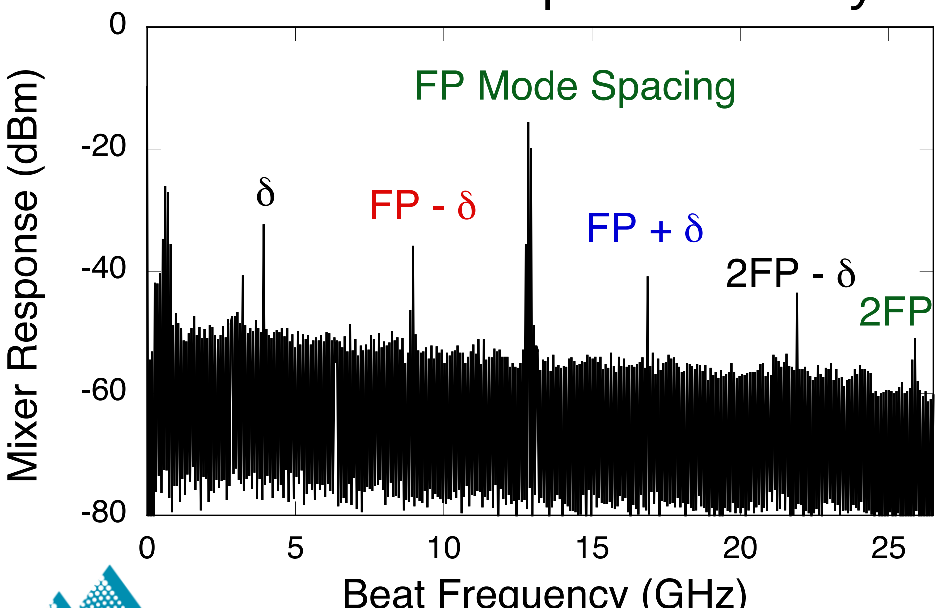




Integrated THz Receiver







Hi-res, coherent, reciever

Outline

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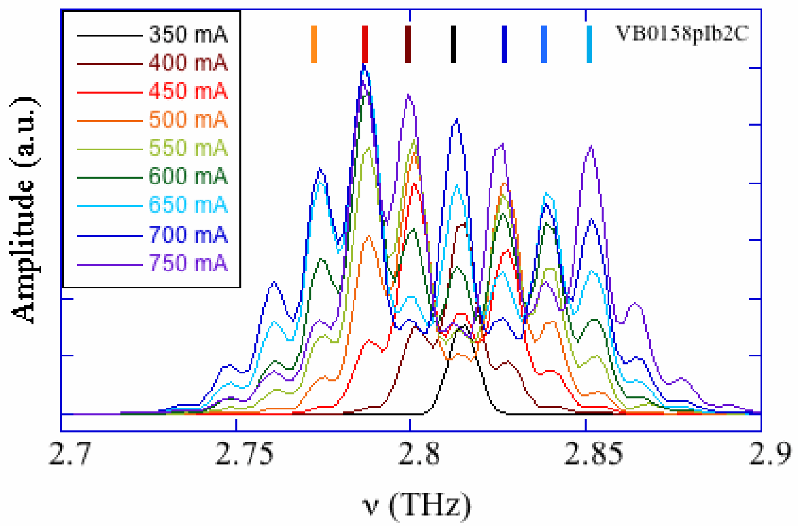
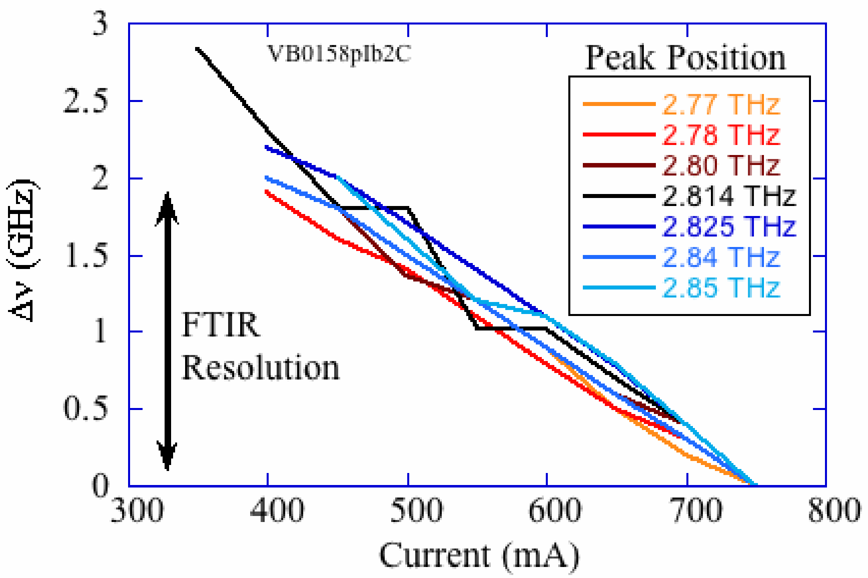
  - Current Tuning / Temperature Tuning
  - Injection/Phase Locking
  - Feedback Sensitivity

Laser Characterization



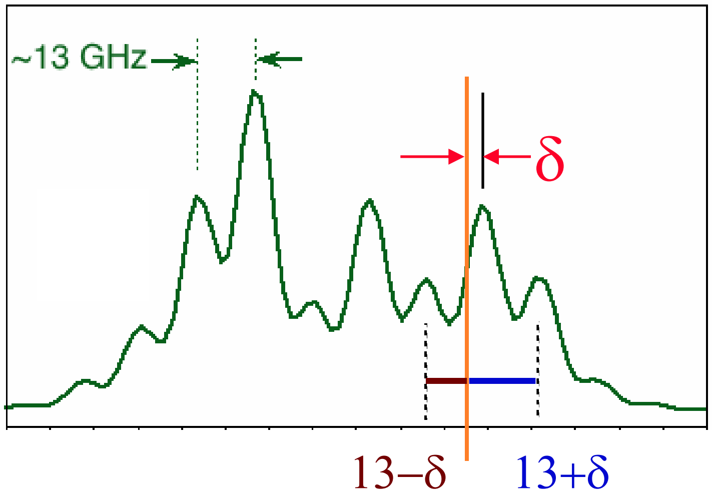
Current Tuning

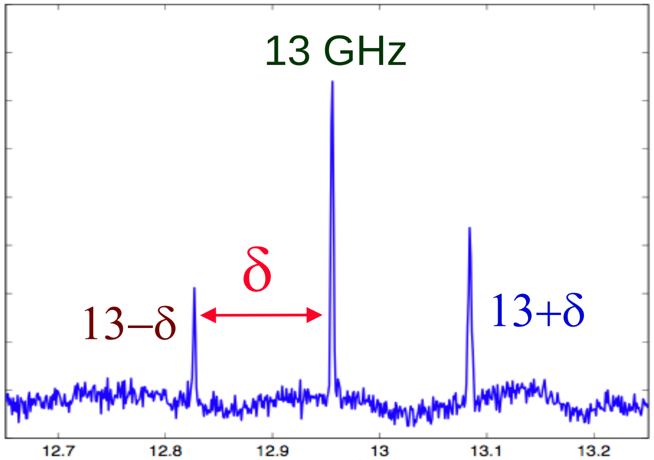


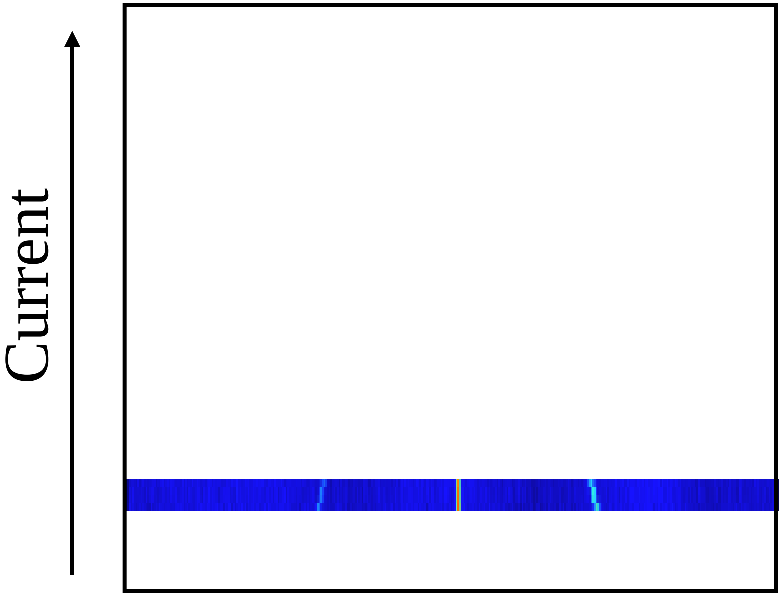
Small redshift with current

- Smaller than FTIR resolution
- Fairly noisy measurement

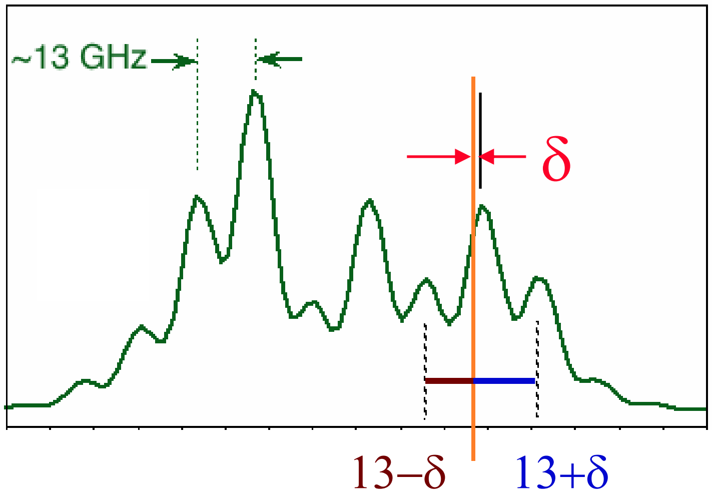
Current Tuning

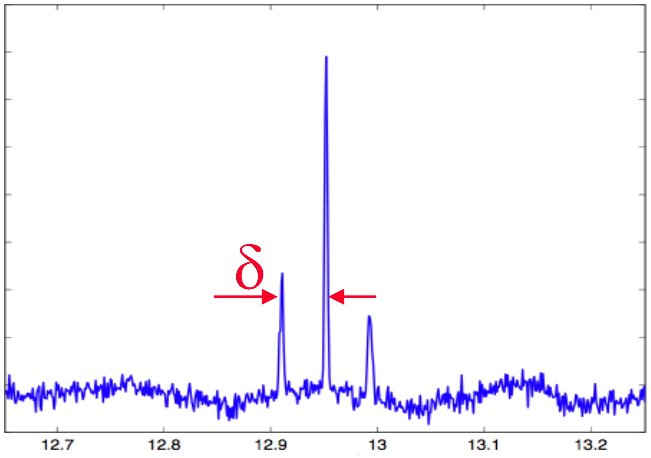


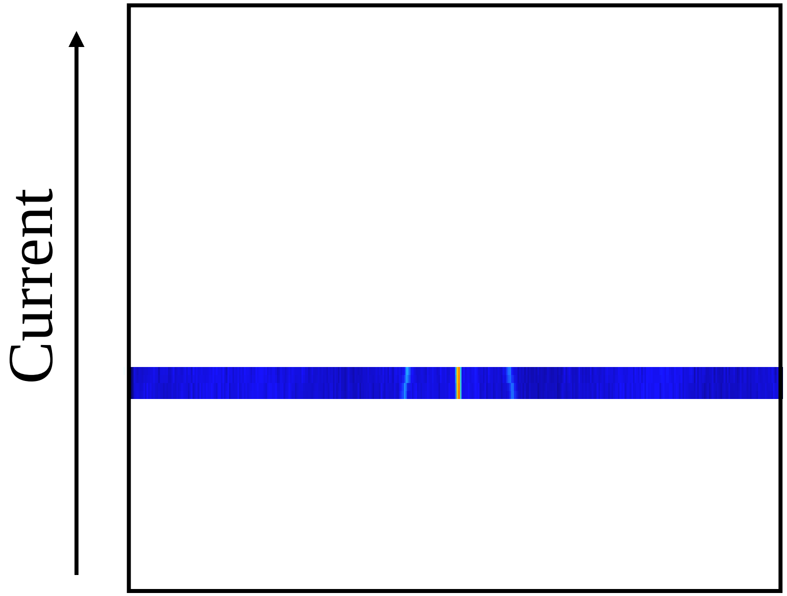




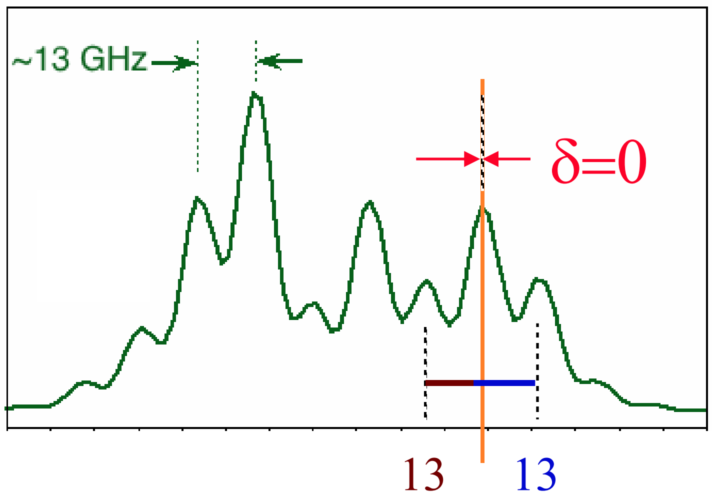
Current Tuning

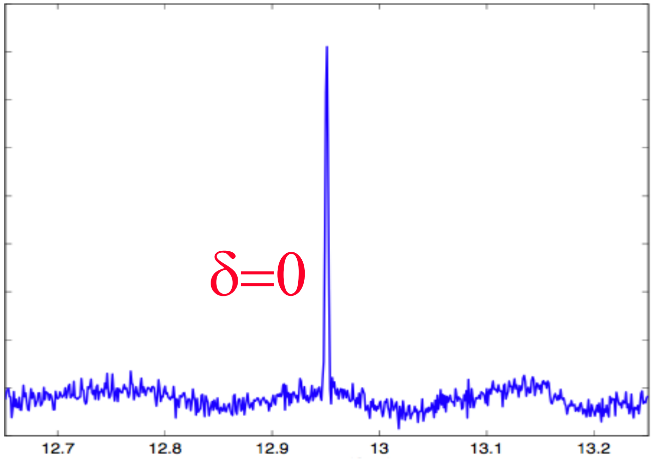


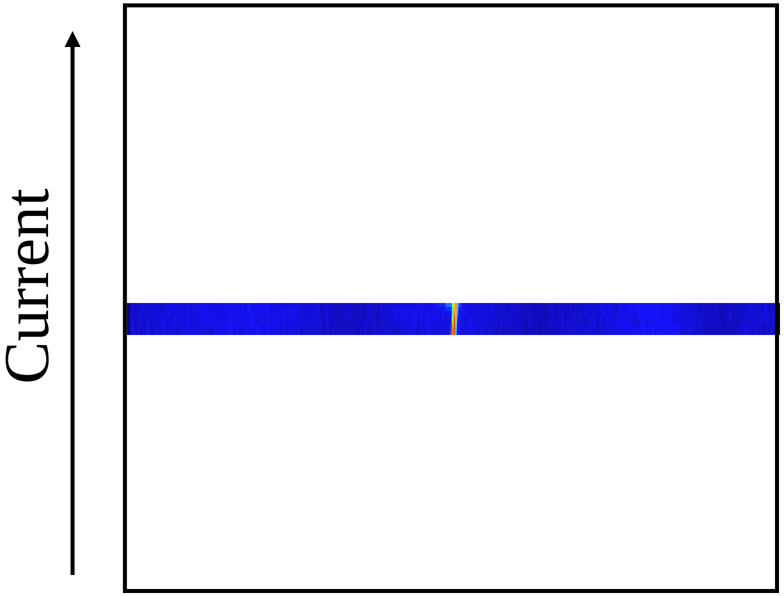




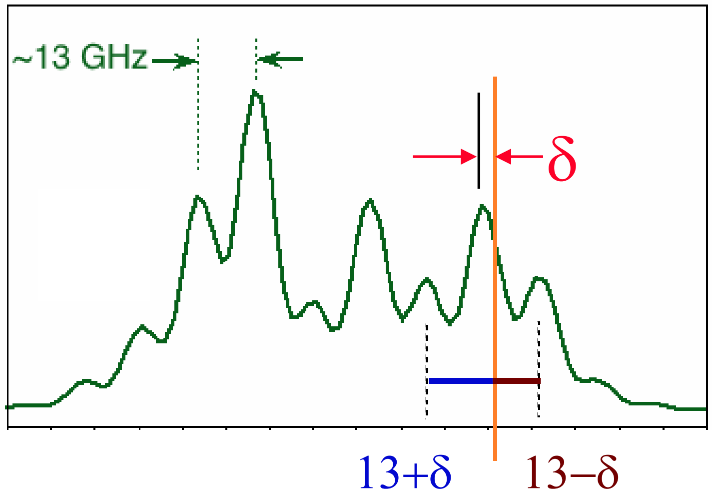
Current Tuning

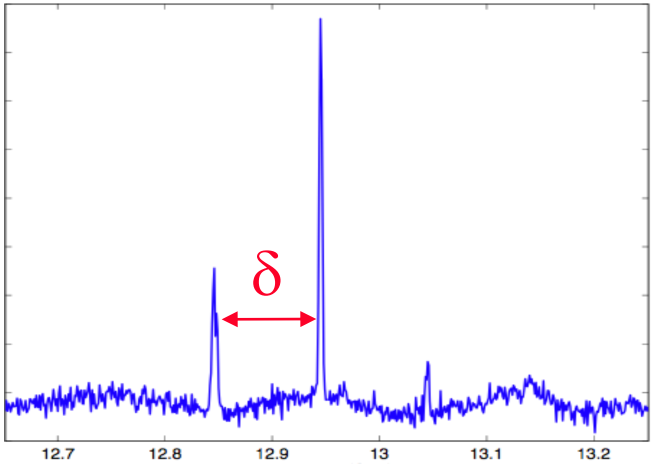


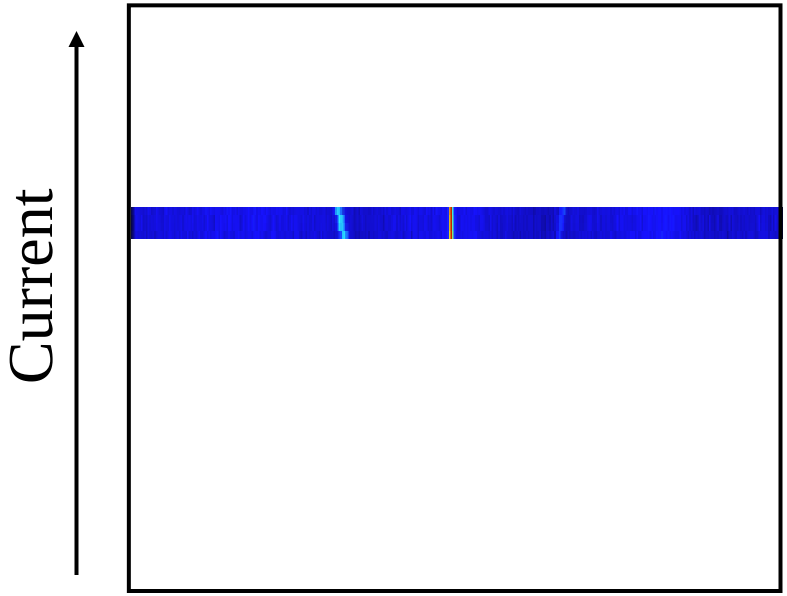




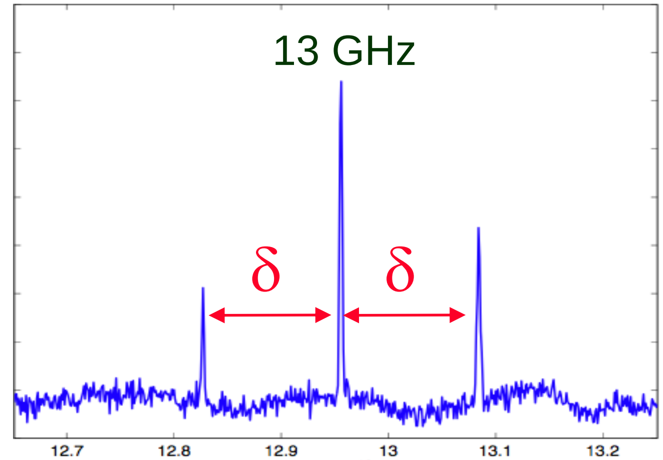
Current Tuning



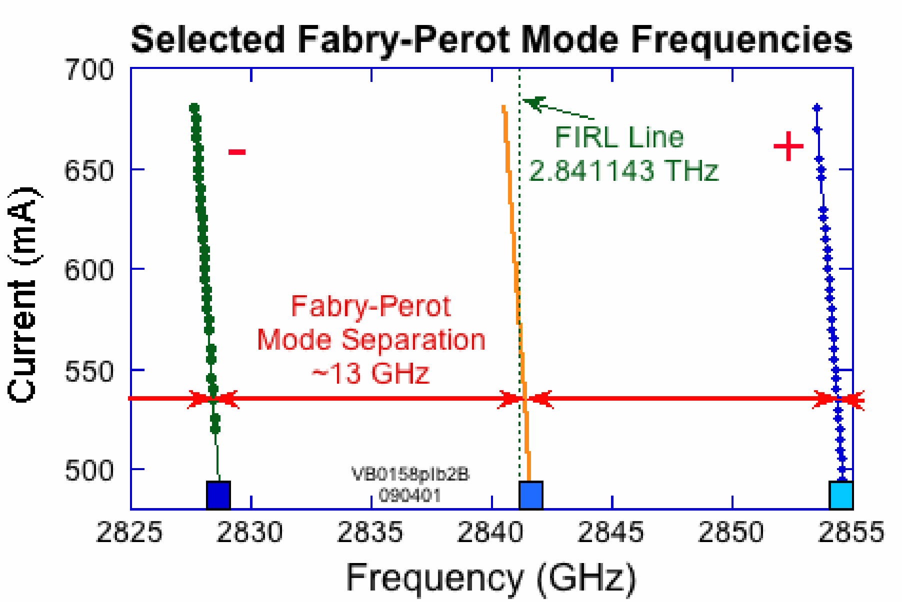


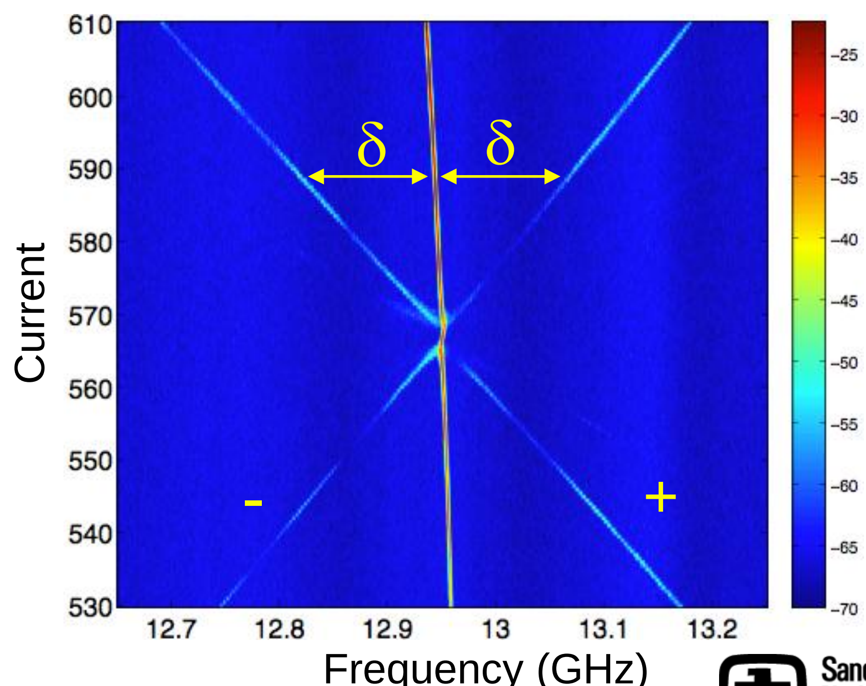


Current Tuning

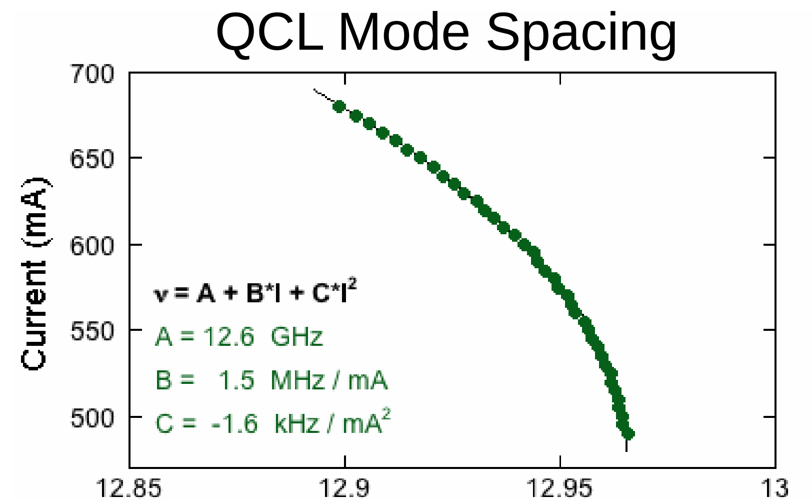


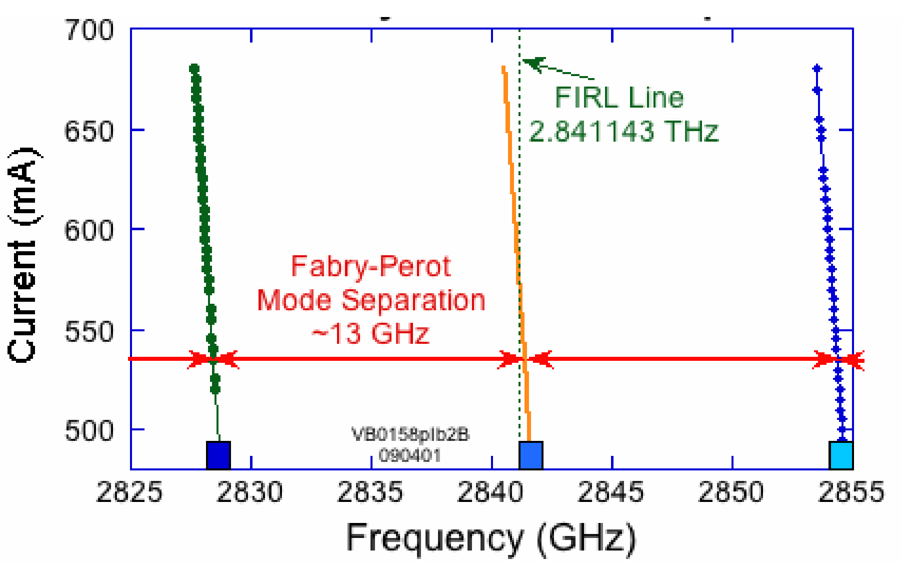
~ 6 MHz / mA

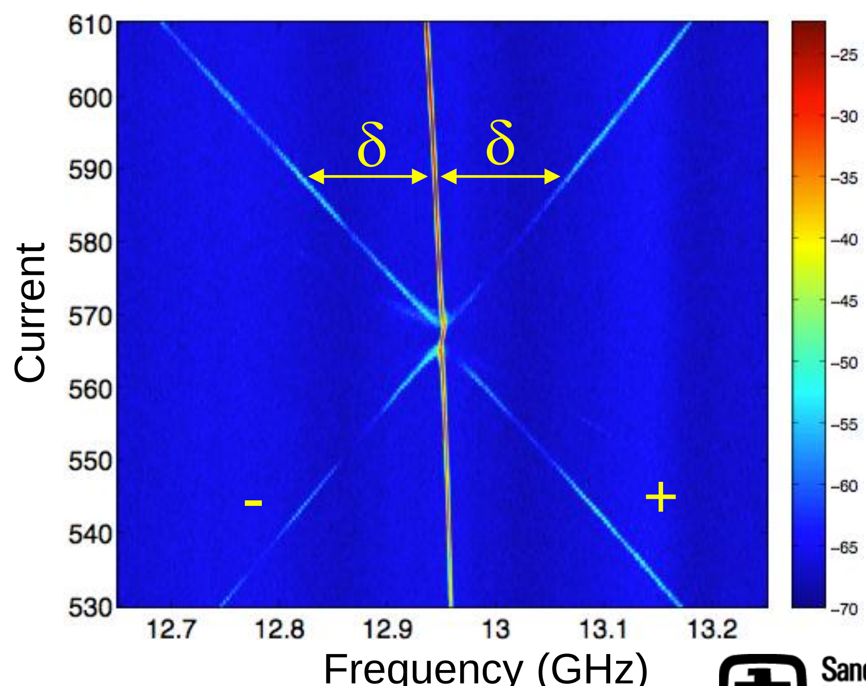




Current Tuning







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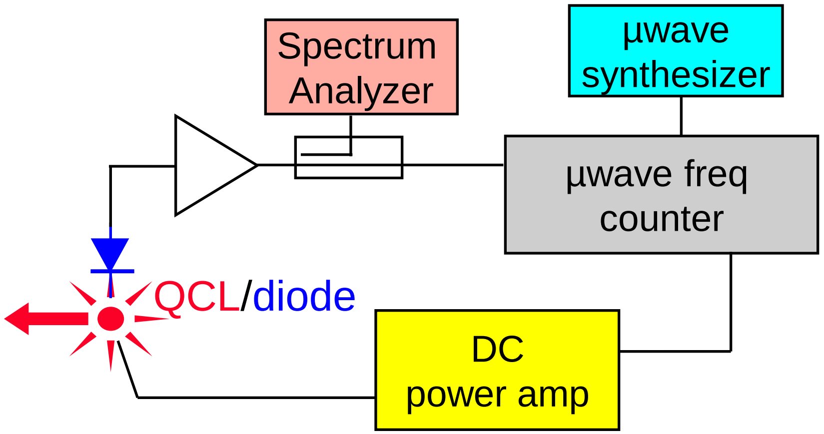
  - Feedback Sensitivity

Frequency/Phase Locked THz IC

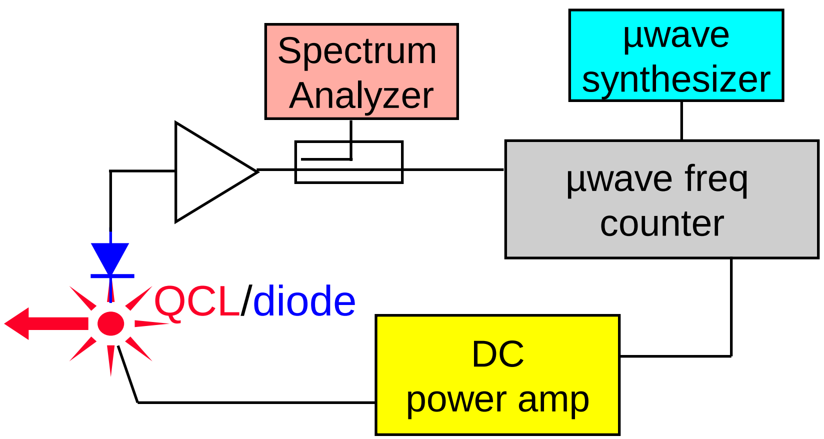
- **Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations***

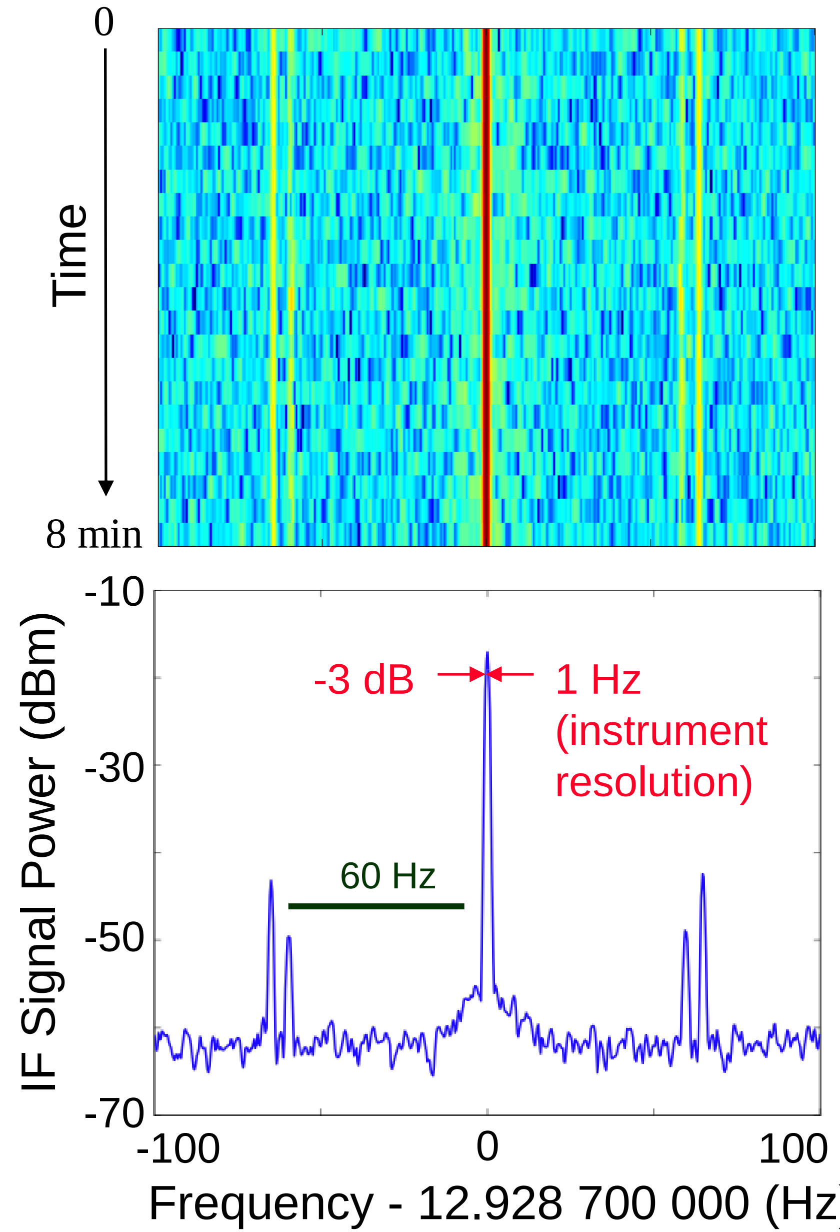


*Following Betz, Opt. Lett. **30**, 1837, (2005)
Baryshev, APL, **89**, 031115, (2006)

Frequency/Phase Locked THz IC

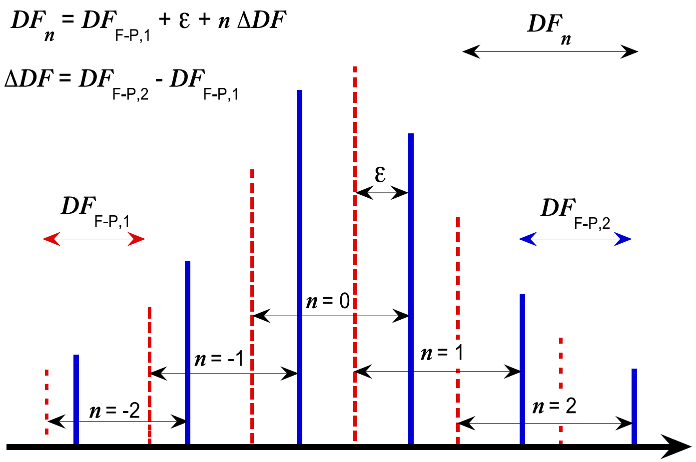
- Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations*
- **Locked IF linewidth ~1 Hz**
- **Extremely stable IF frequency and amplitude**

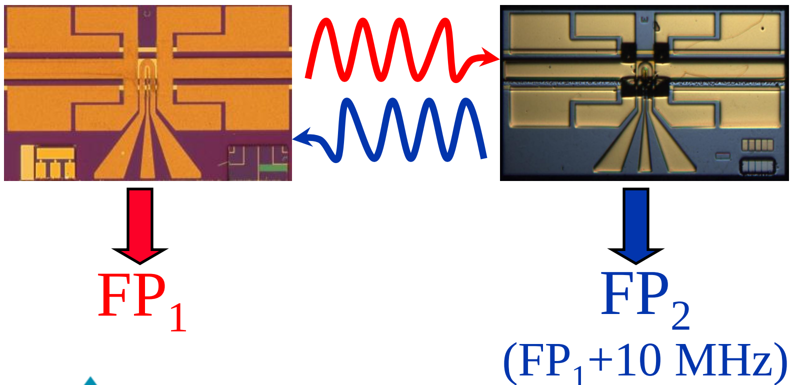


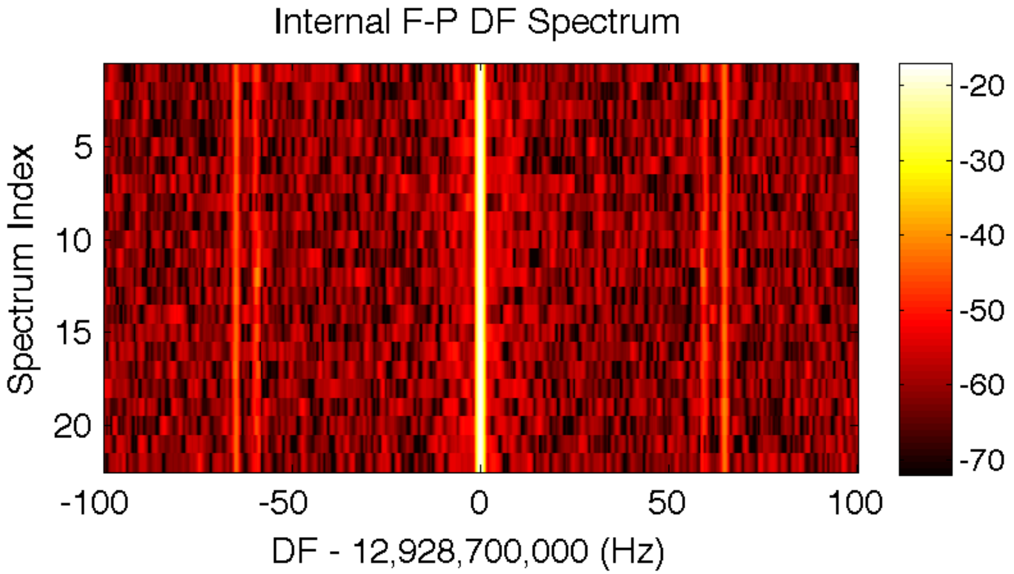


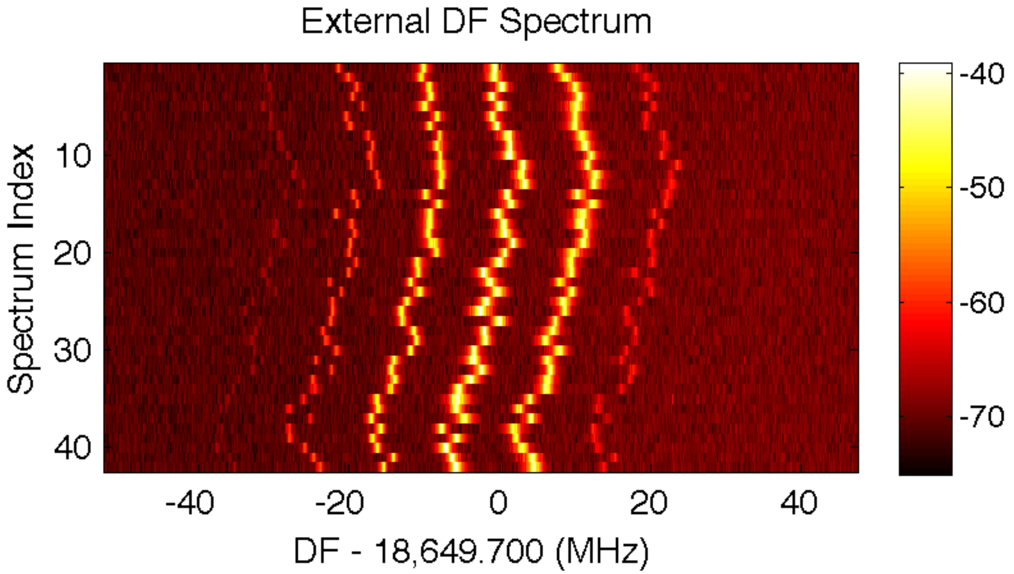
*Following Betz, Opt. Lett. **30**, 1837, (2005)
Baryshev, APL, **89**, 031115, (2006)

Absolute Frequency not Simultaneously Locked...



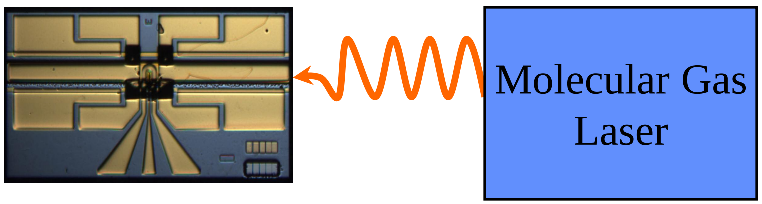


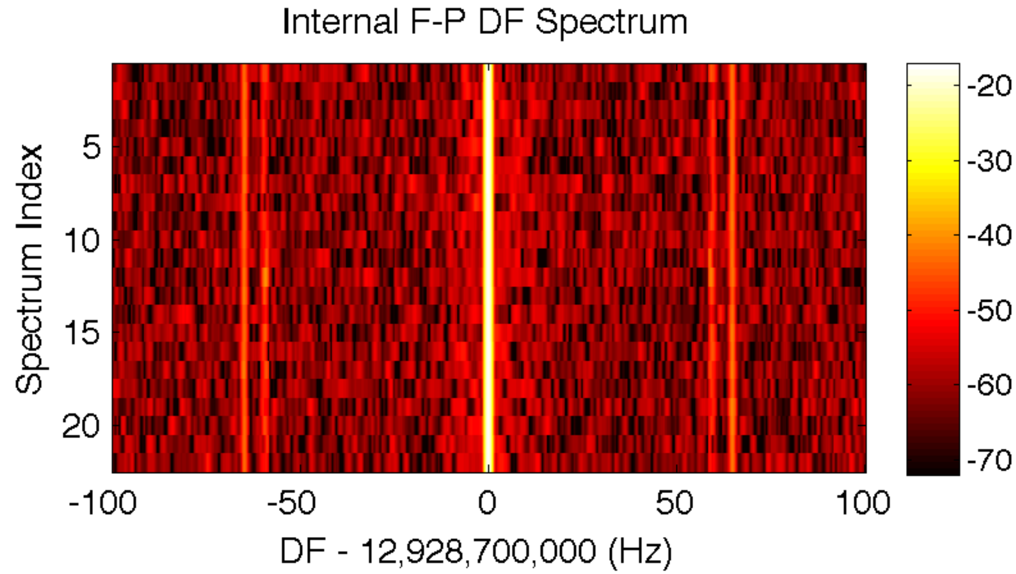


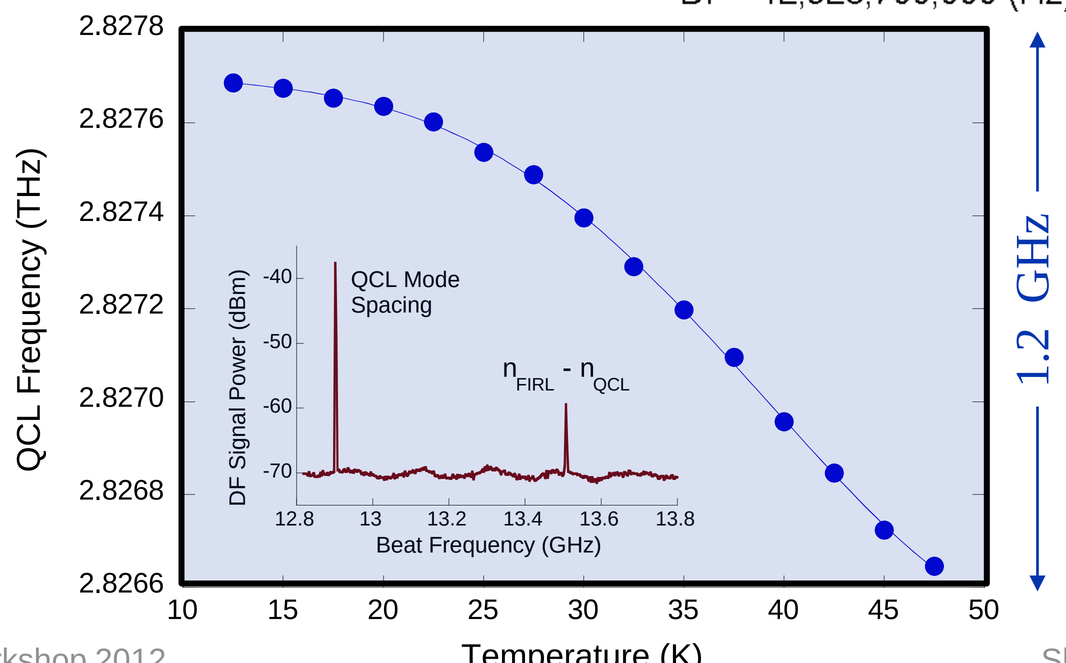


National Laboratories

... Partly because of Temp drift

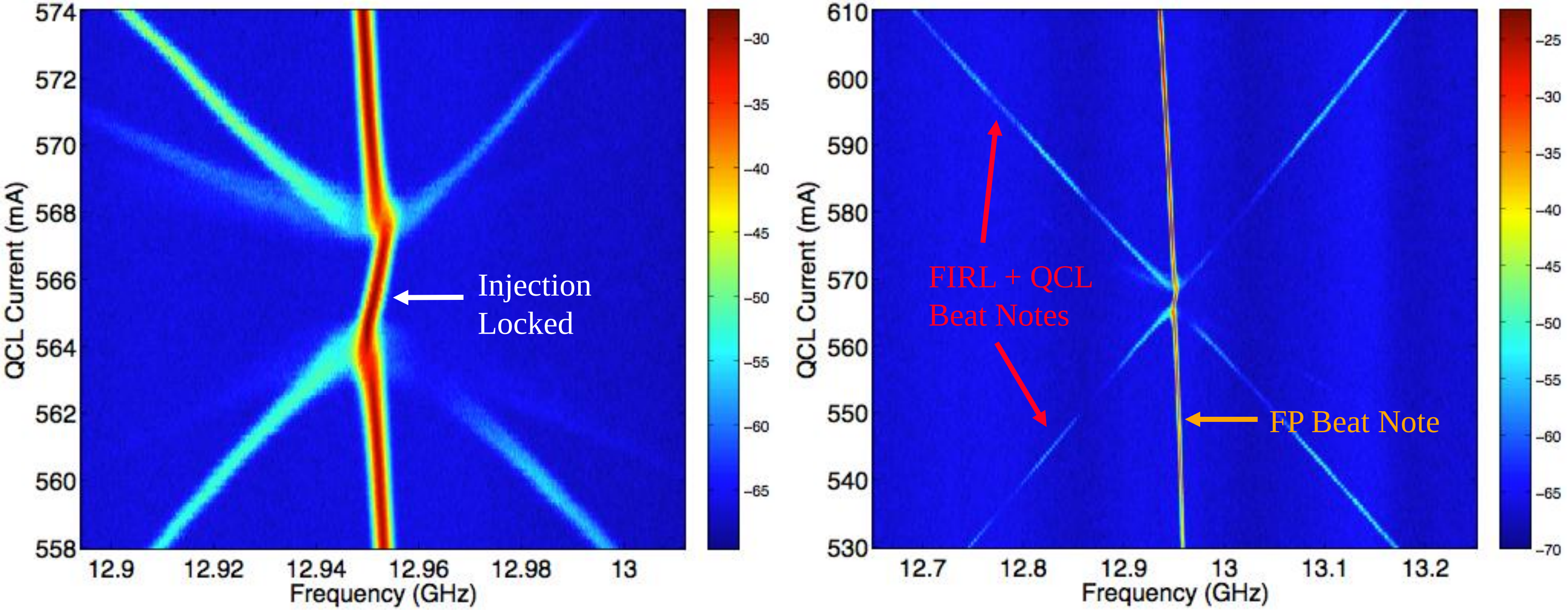






What happens when lasers cross?

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



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

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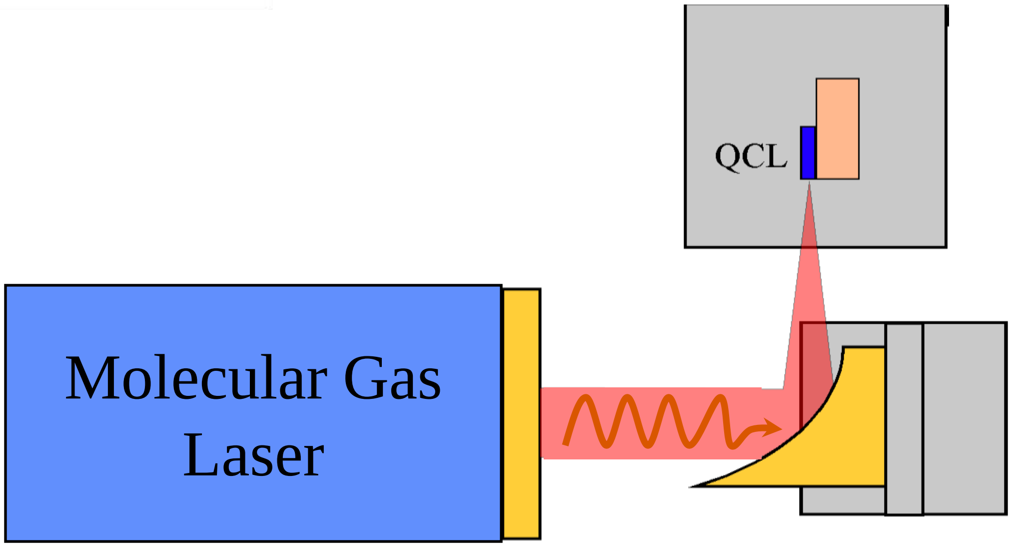
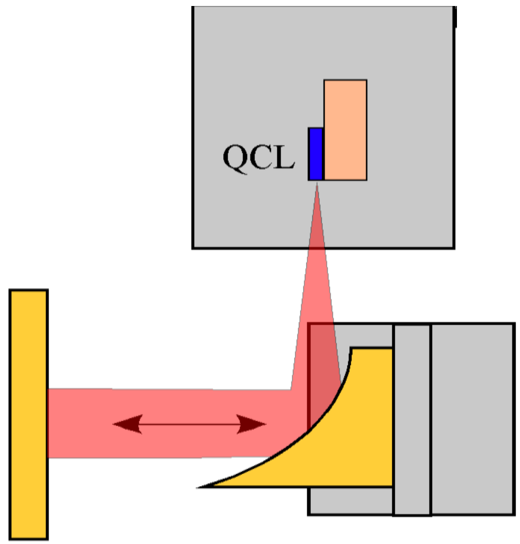
Feedback Sensitivity



Some of the QCL emission retroreflects

Feedback Sensitivity



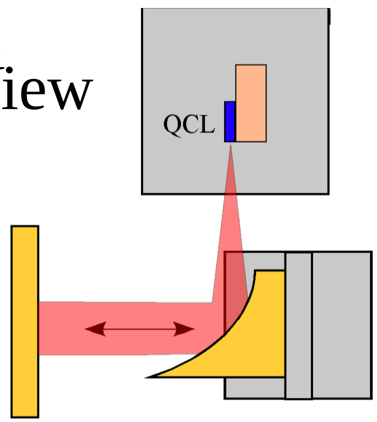
Some of the QCL emission retroreflects

- Another laser facet
- Window or lens
- External mixers

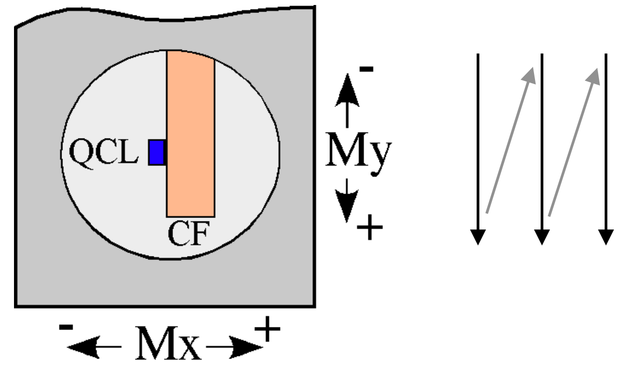
Wanke, Proc SPIE, **7953**, (2011)

Focal Position Sensitivity

Top View



Front View



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

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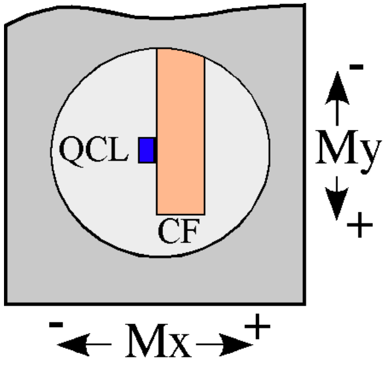
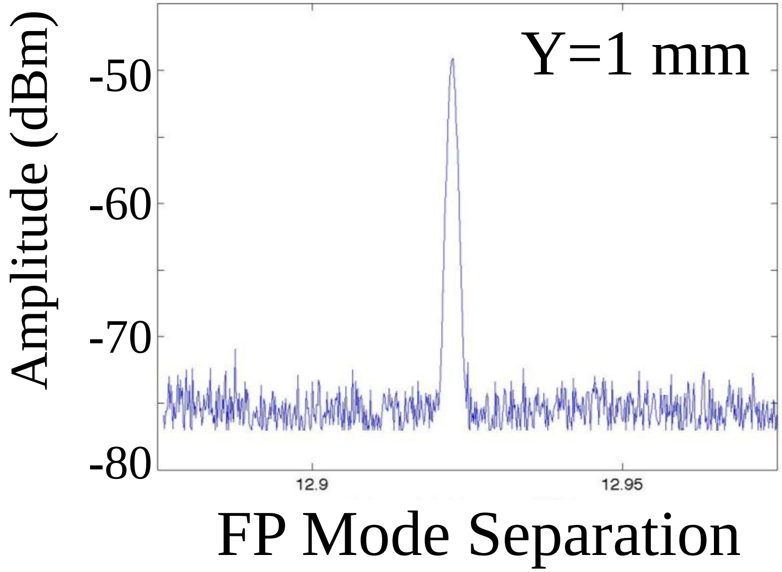
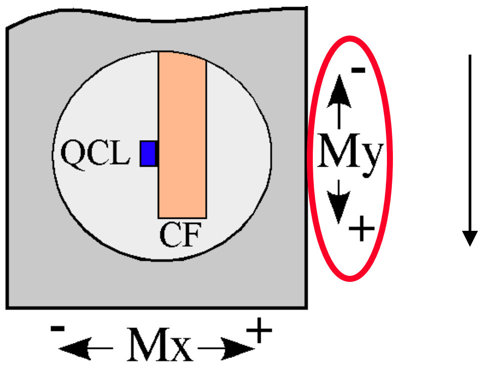
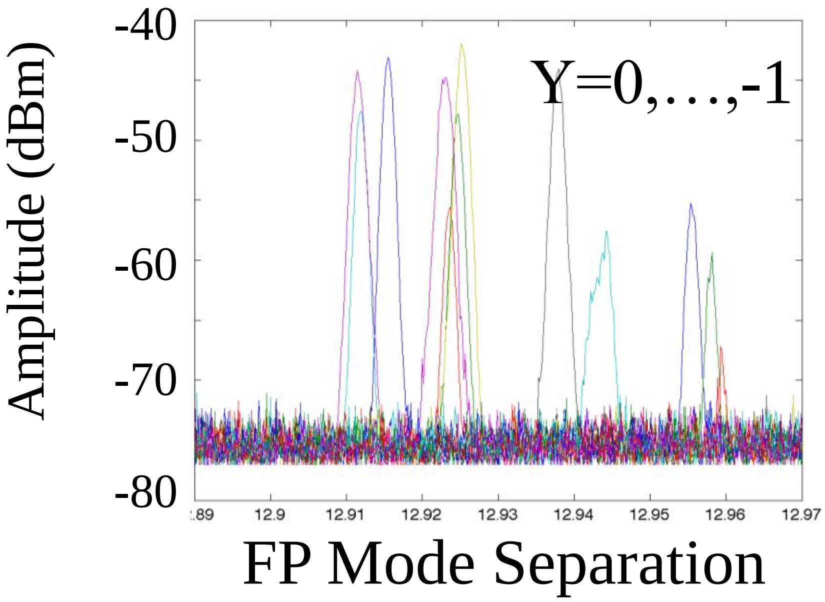
Focal Position Sensitivity

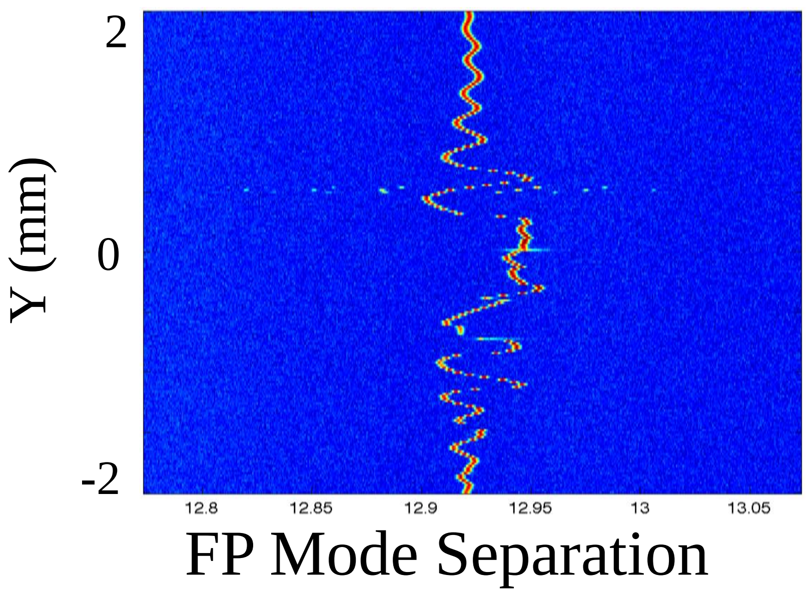




Focal Position Sensitivity



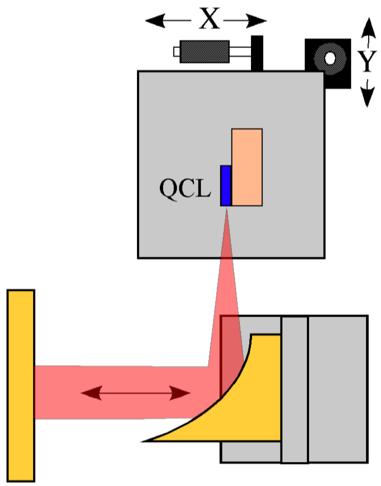


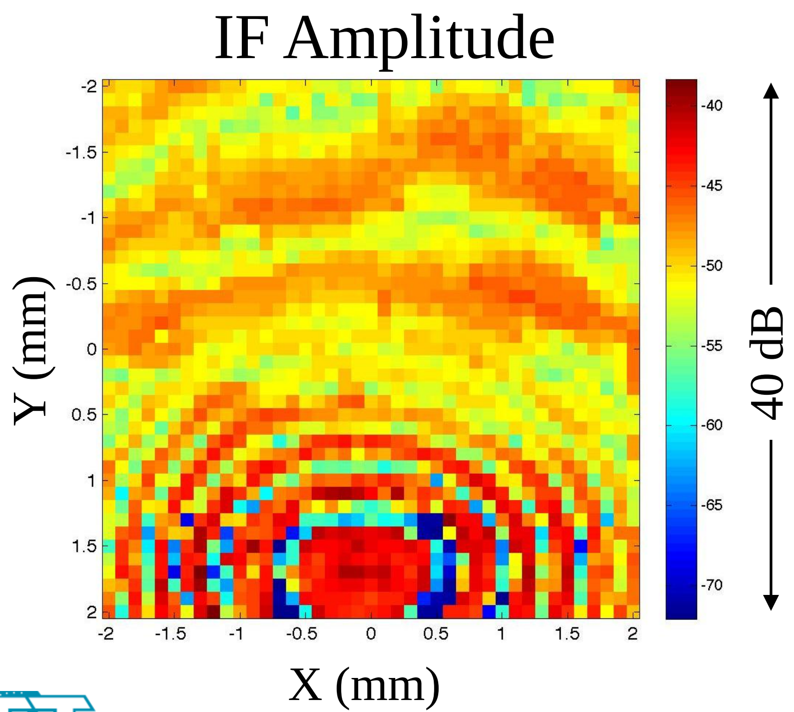


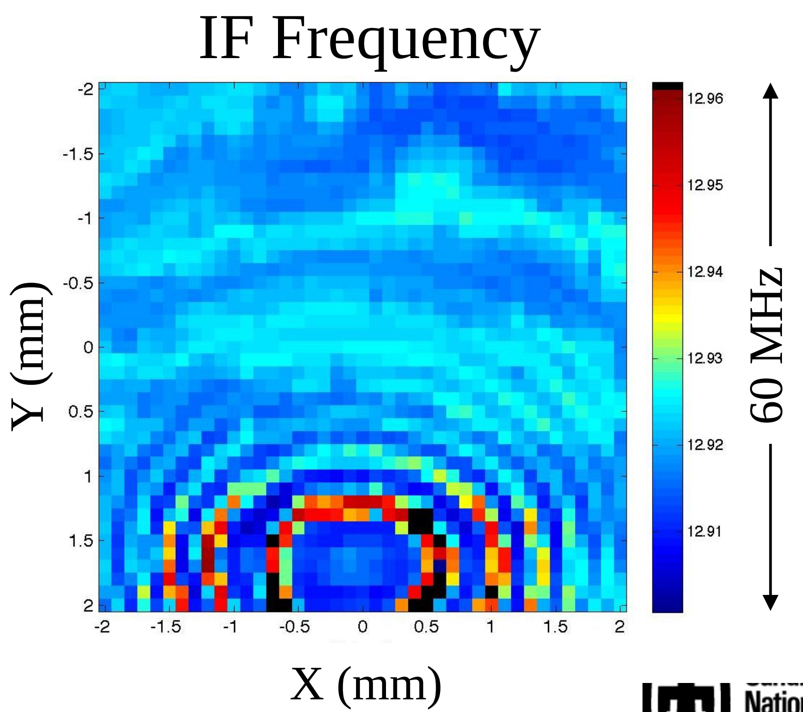
Focal Position Feedback Sensitivity

Strong frequency and amplitude pulling

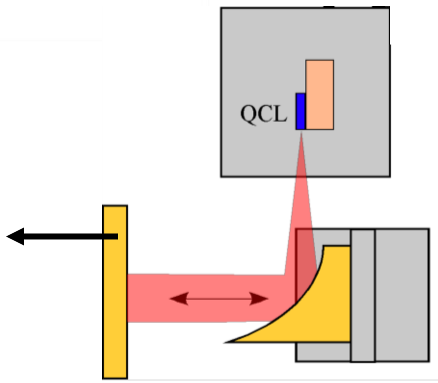
Simple demonstration of Airy diffraction pattern

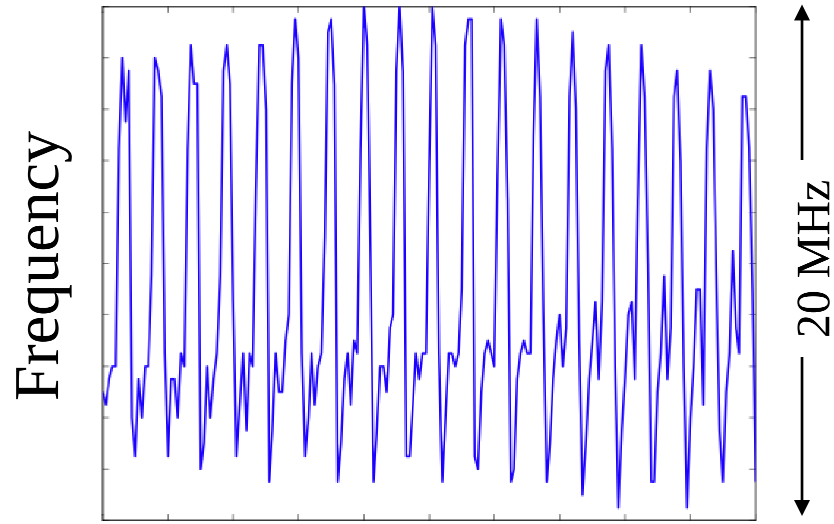


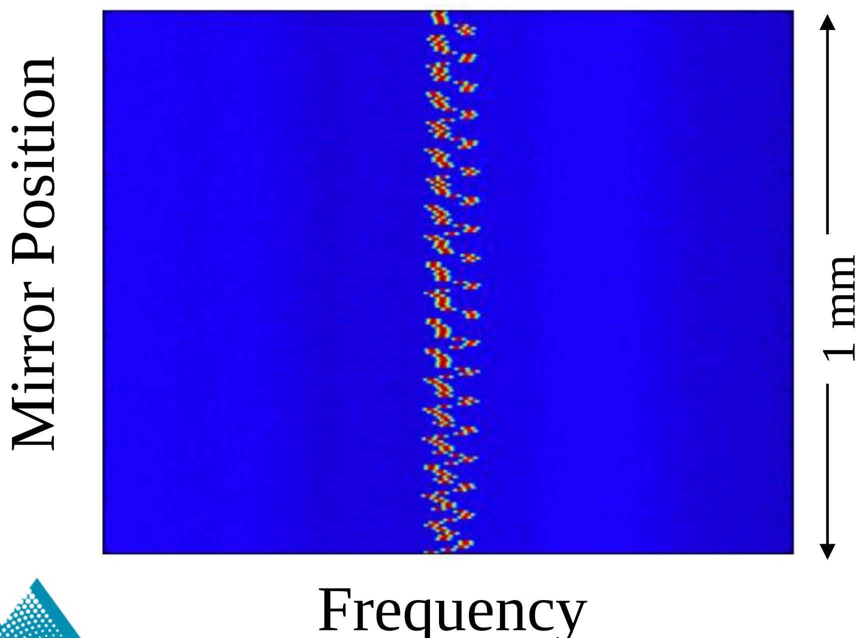


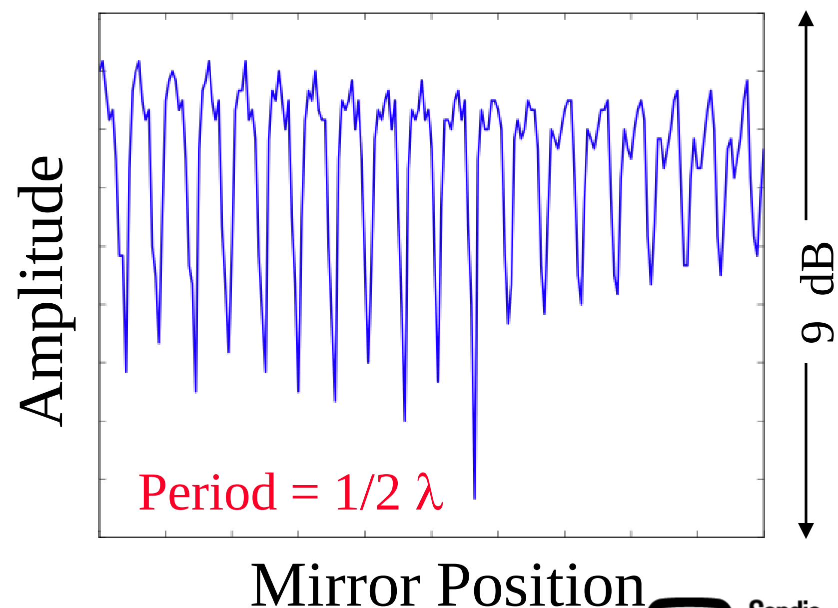


Cavity Length Sensitivity



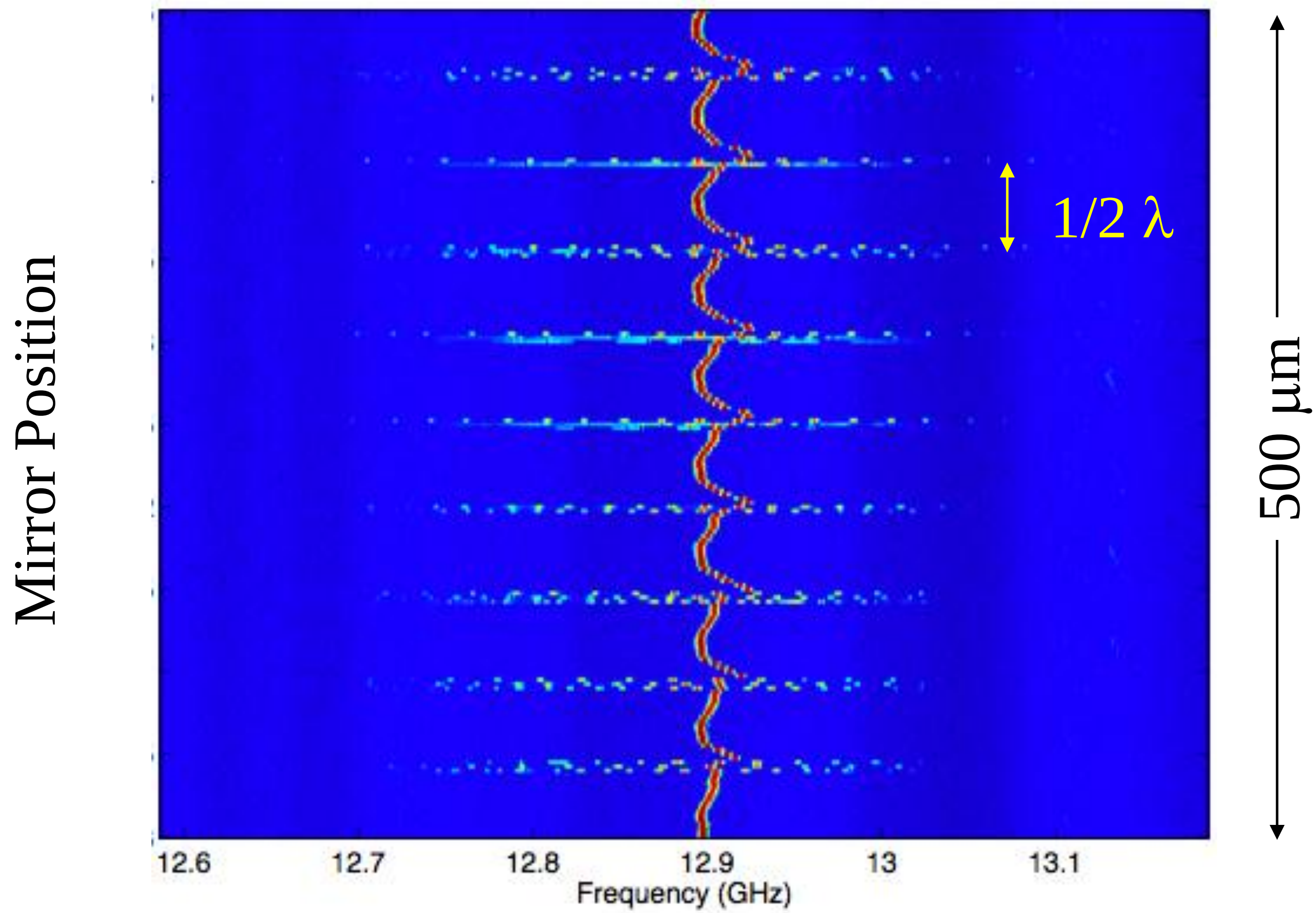






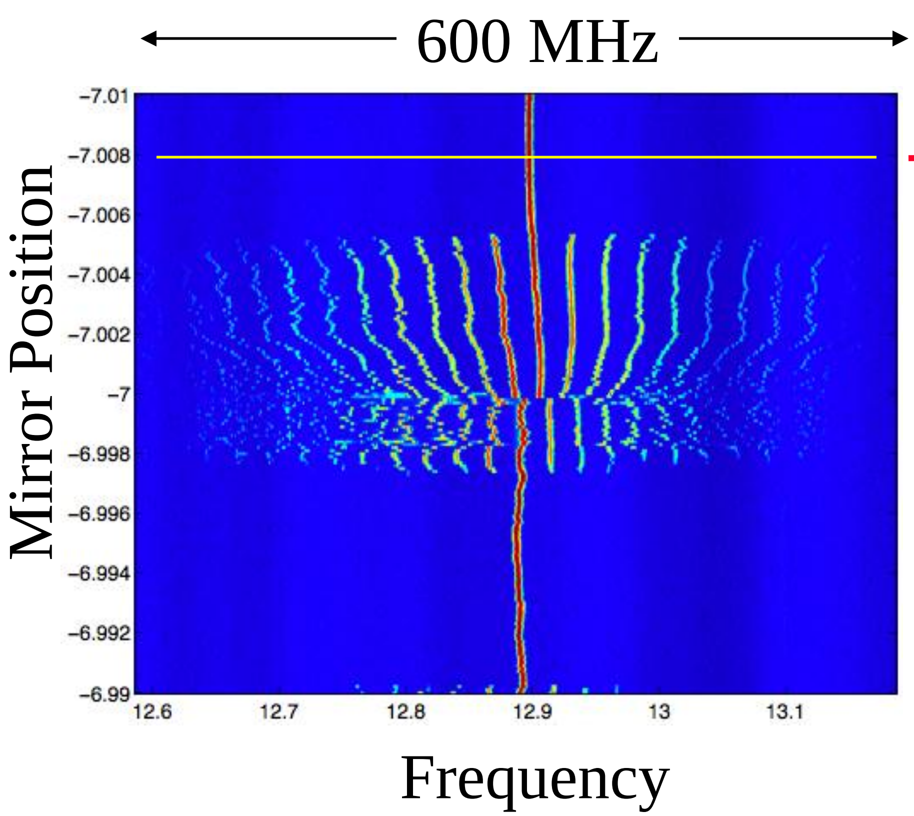
Feedback Effects on FP mode

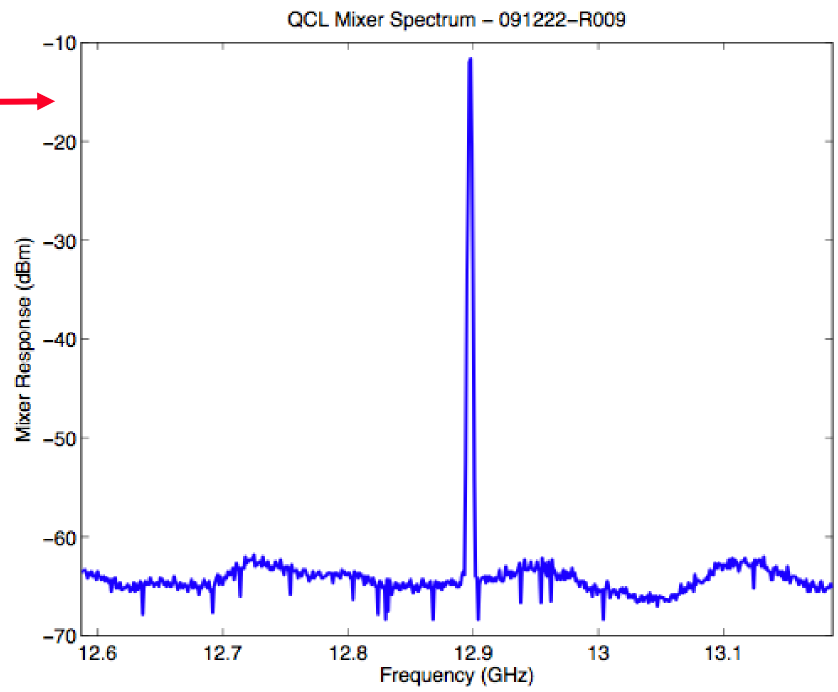
Not always a single beat frequency



Feedback Effects on FP mode

Region I - Normal Fabry-Perot Modes



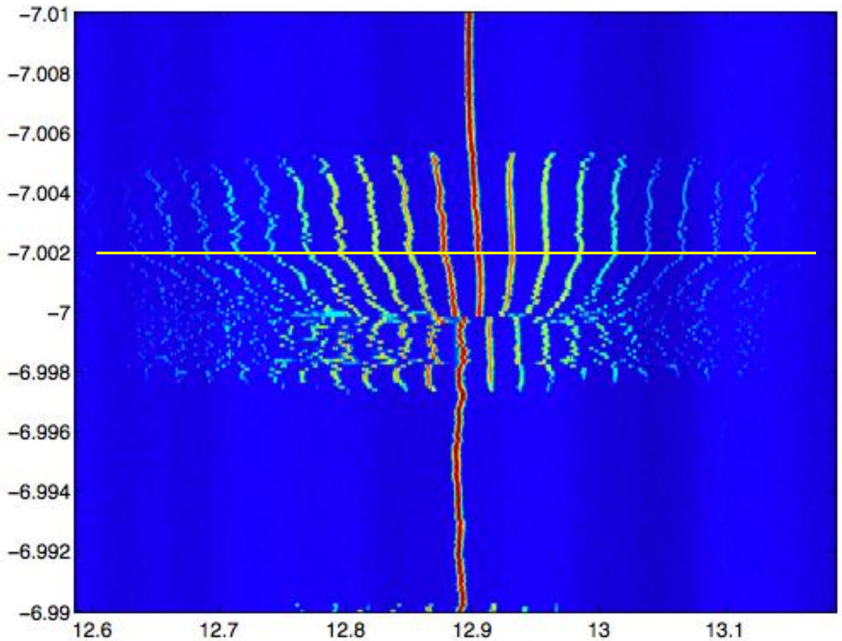


Feedback Effects on FP mode

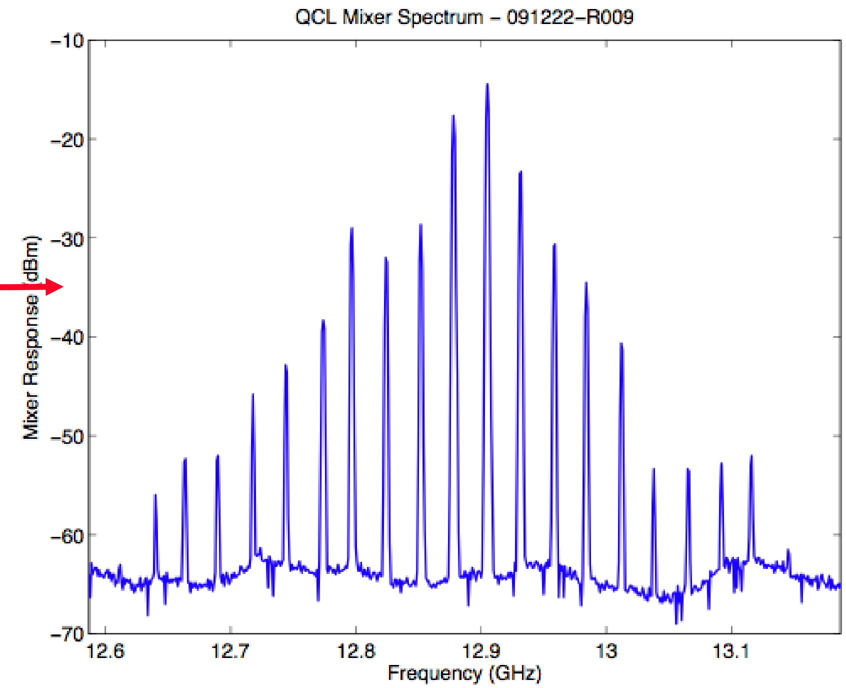
Region II - Fabry-Perot Modes Bifurcate

600 MHz

Mirror Position



Frequency



Stable Spectrum

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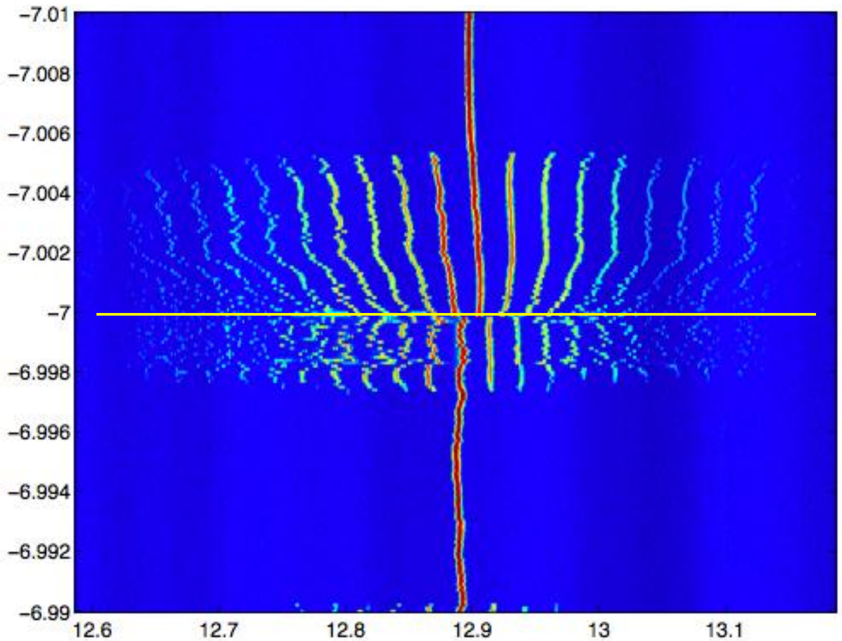
Feedback Effects on FP mode

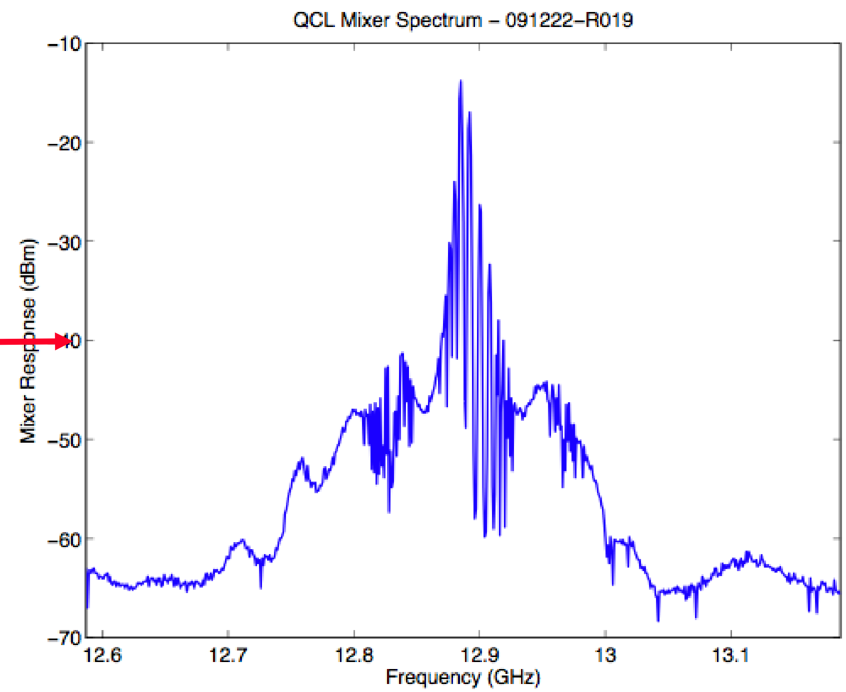
Region III - Chaos Onset

600 MHz

Mirror Position



Frequency



Unstable Spectrum

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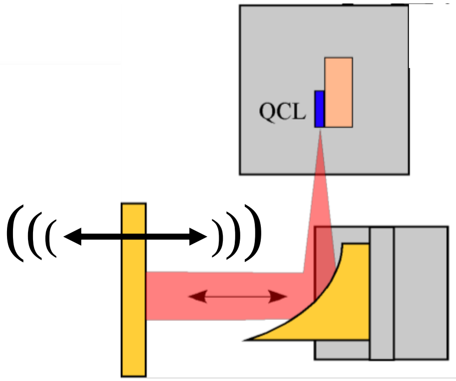
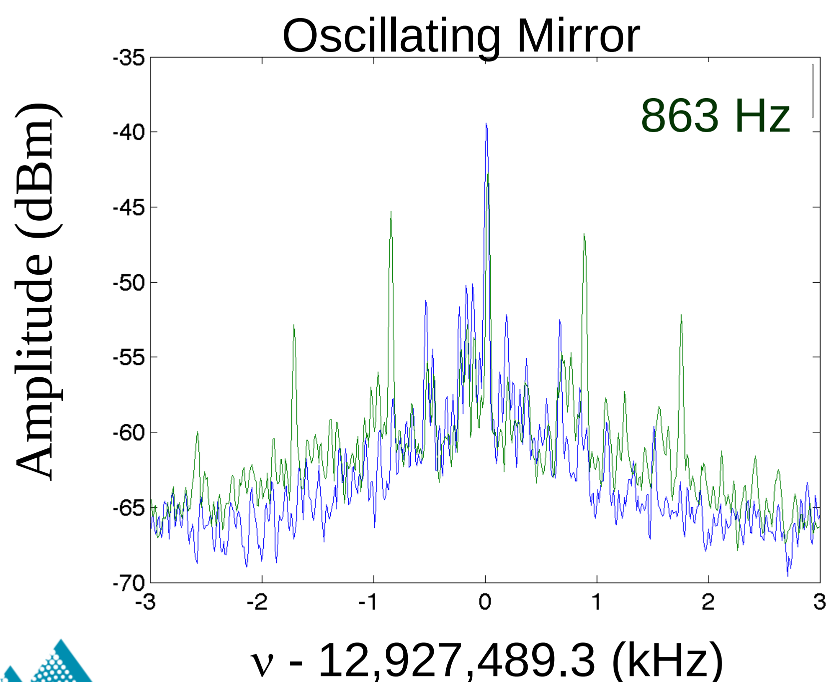
When life gives you ~~lemons~~ peaches...

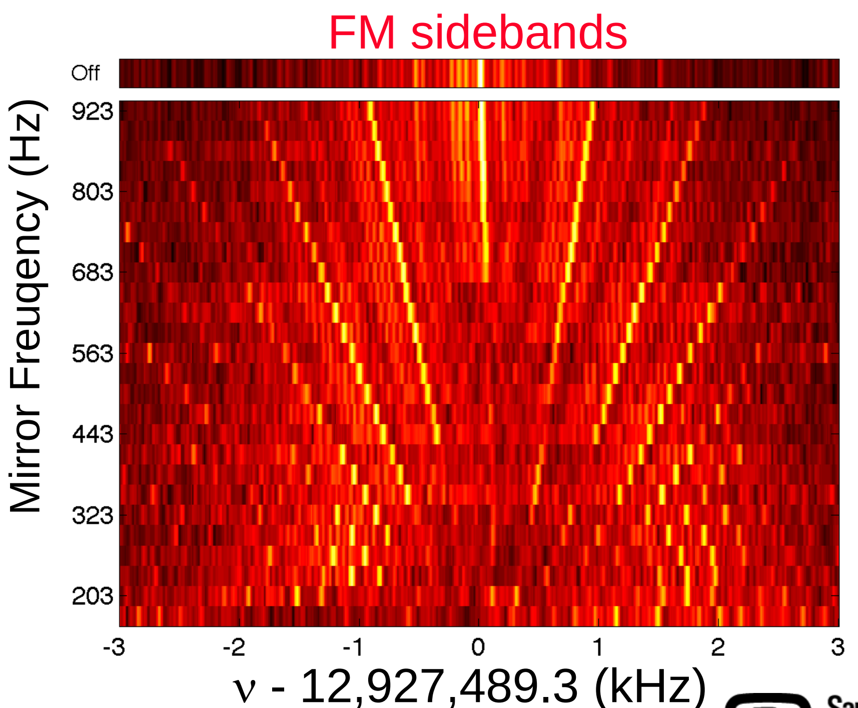
... use feedback to image the topography

Or...



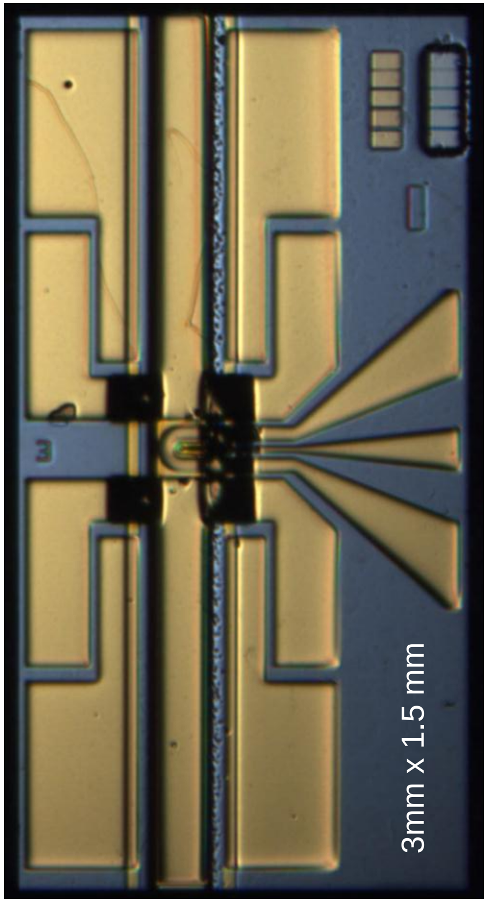
... use feedback to measure vibration frequency of a reflector



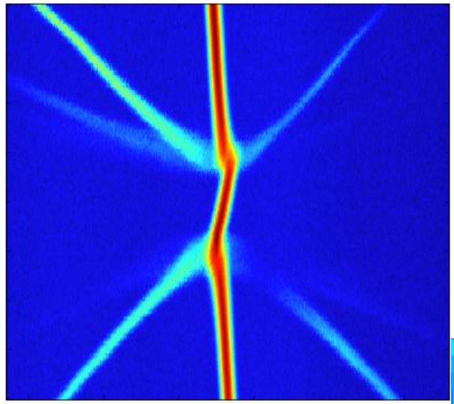


Summary

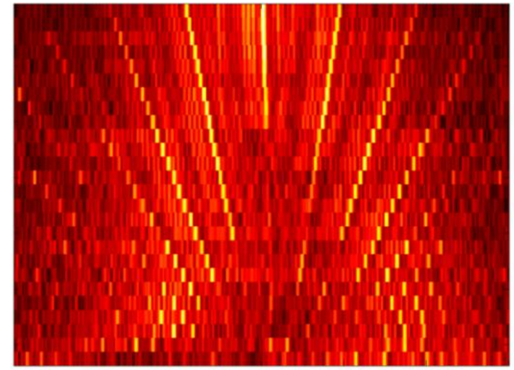
THz Integrated Transceiver



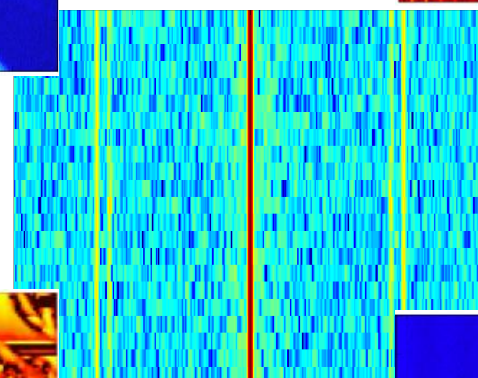
Laser Characterization
Injection Locking



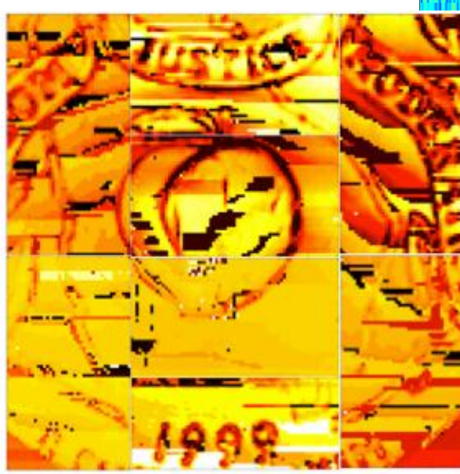
Vibrometry



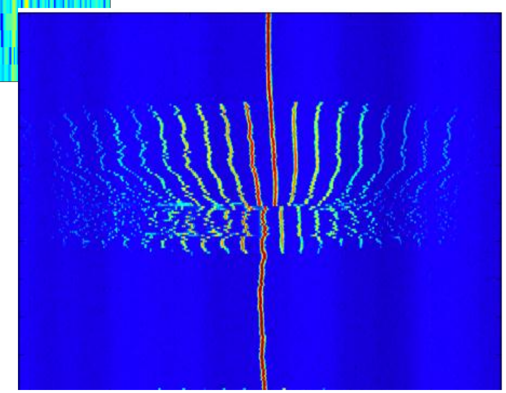
Phase Locking



Imaging

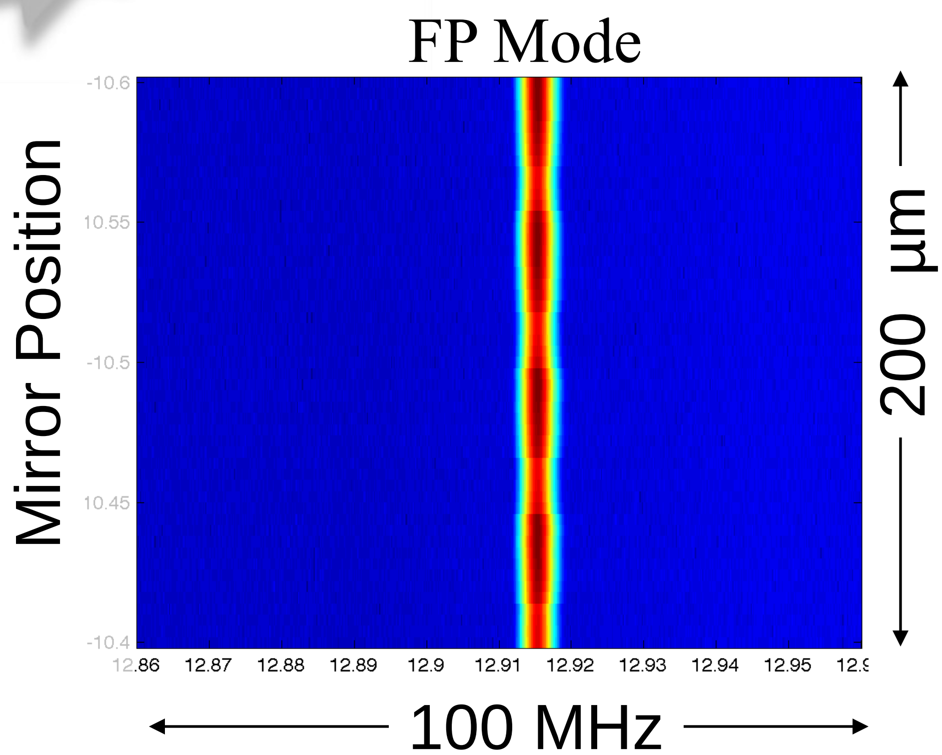


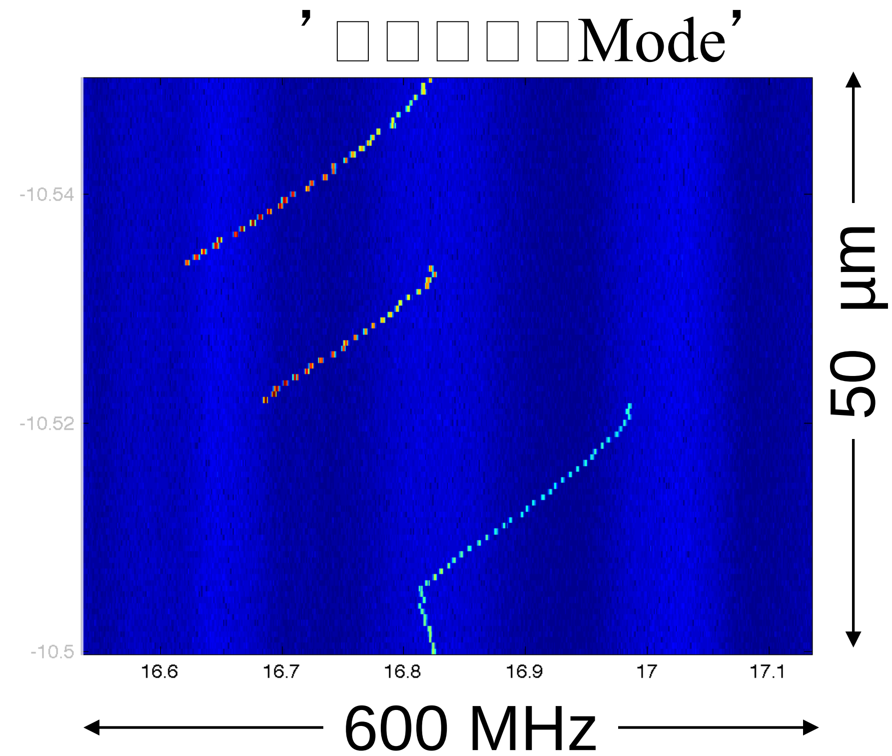
Feedback / Chaos



Extras

Feedback Effects for Locked FP

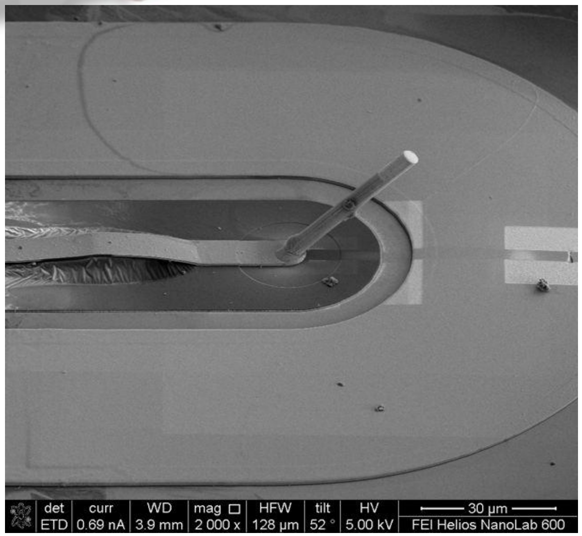


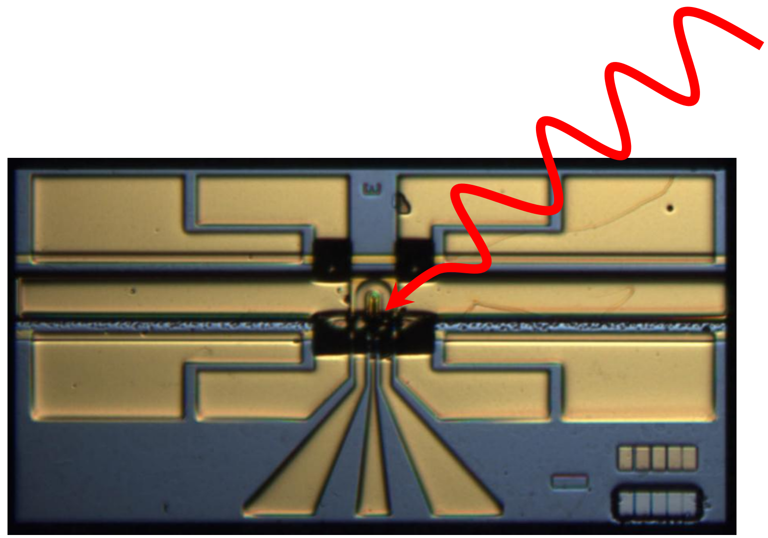


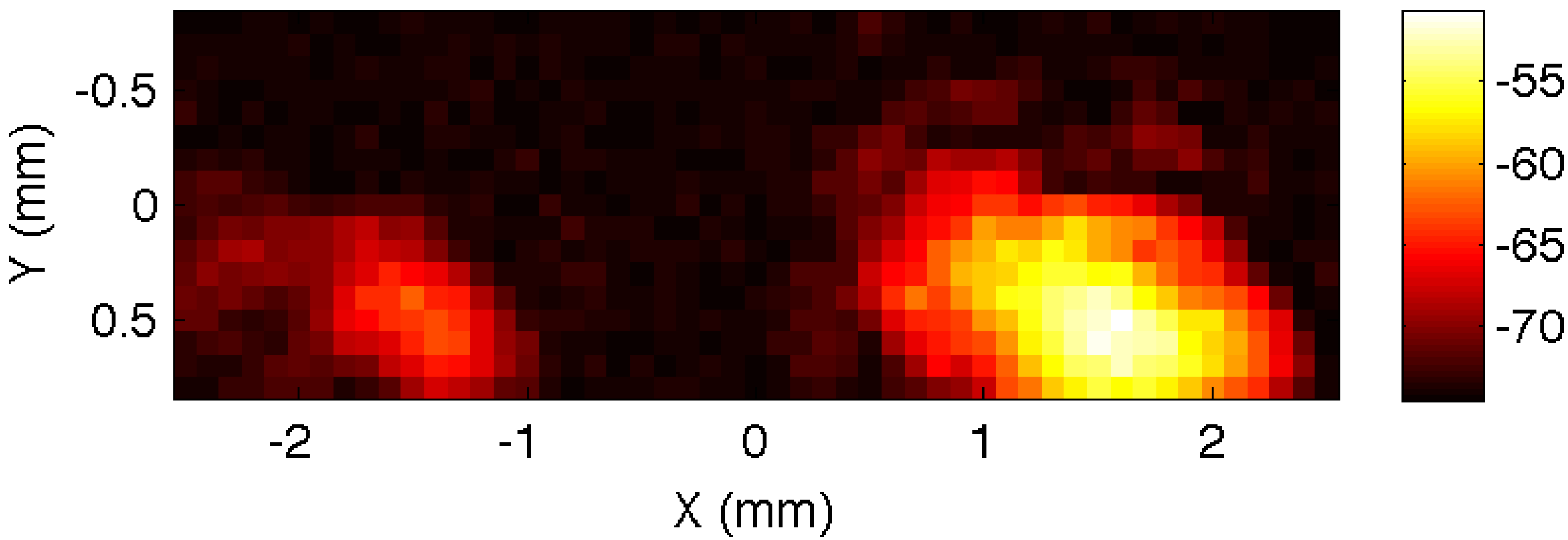
FP frequency is locked (~1 Hz) … but amplitude is not.

… absolute frequency is not.

External Coupling to Receiver



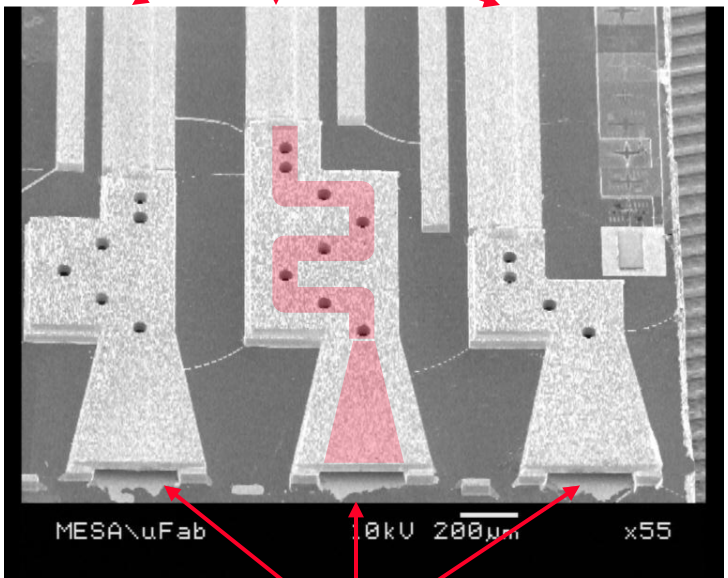




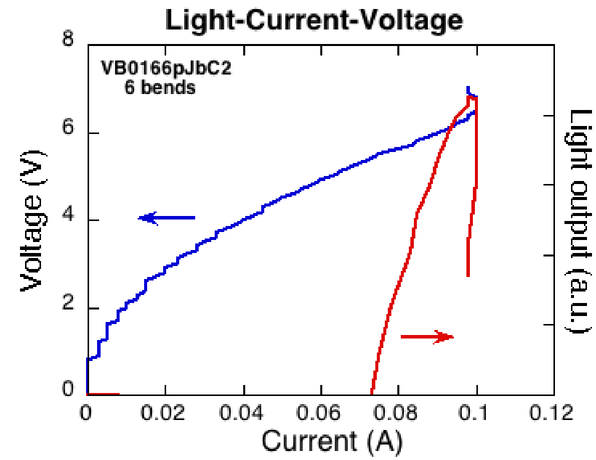
Integrated Waveguide Performance

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

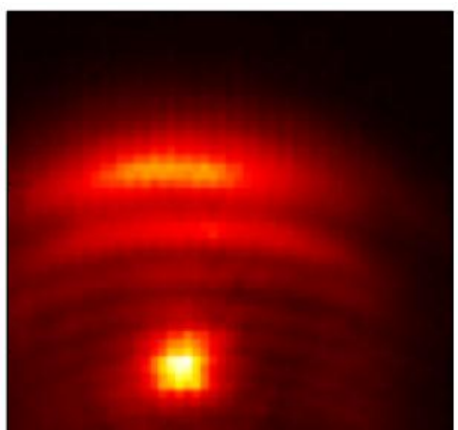
THz QCLs

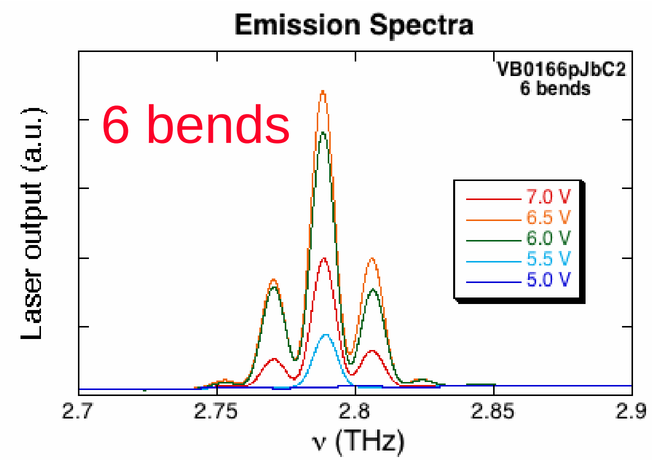


Horn Antennae



Beam Pattern





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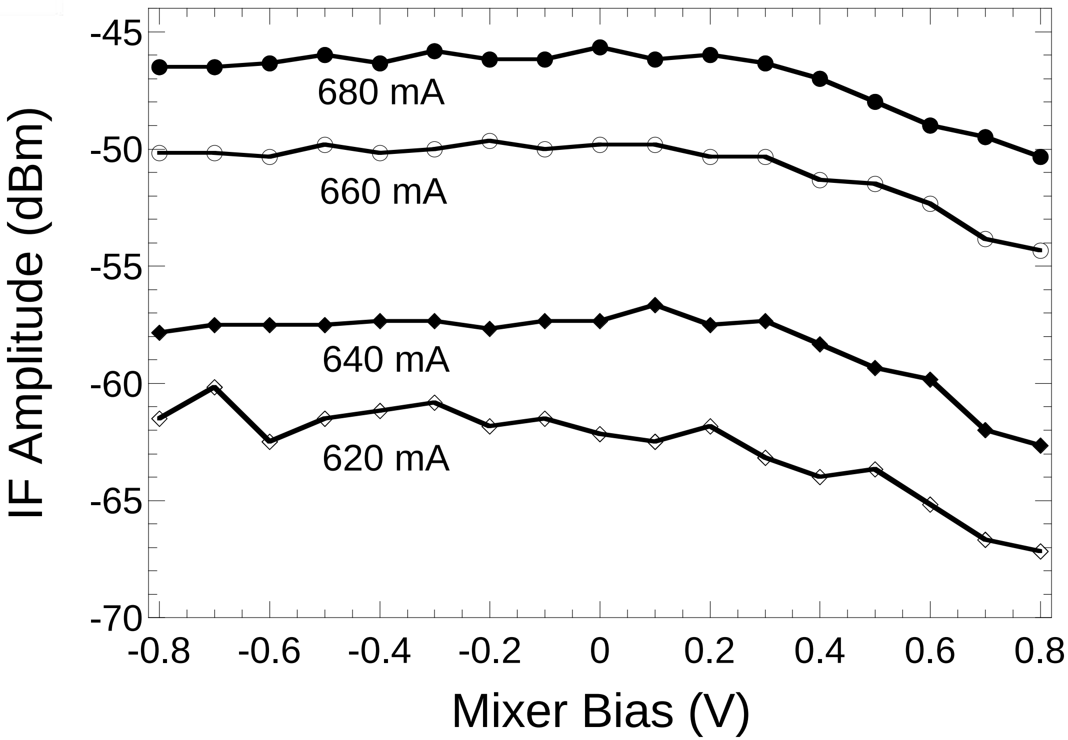
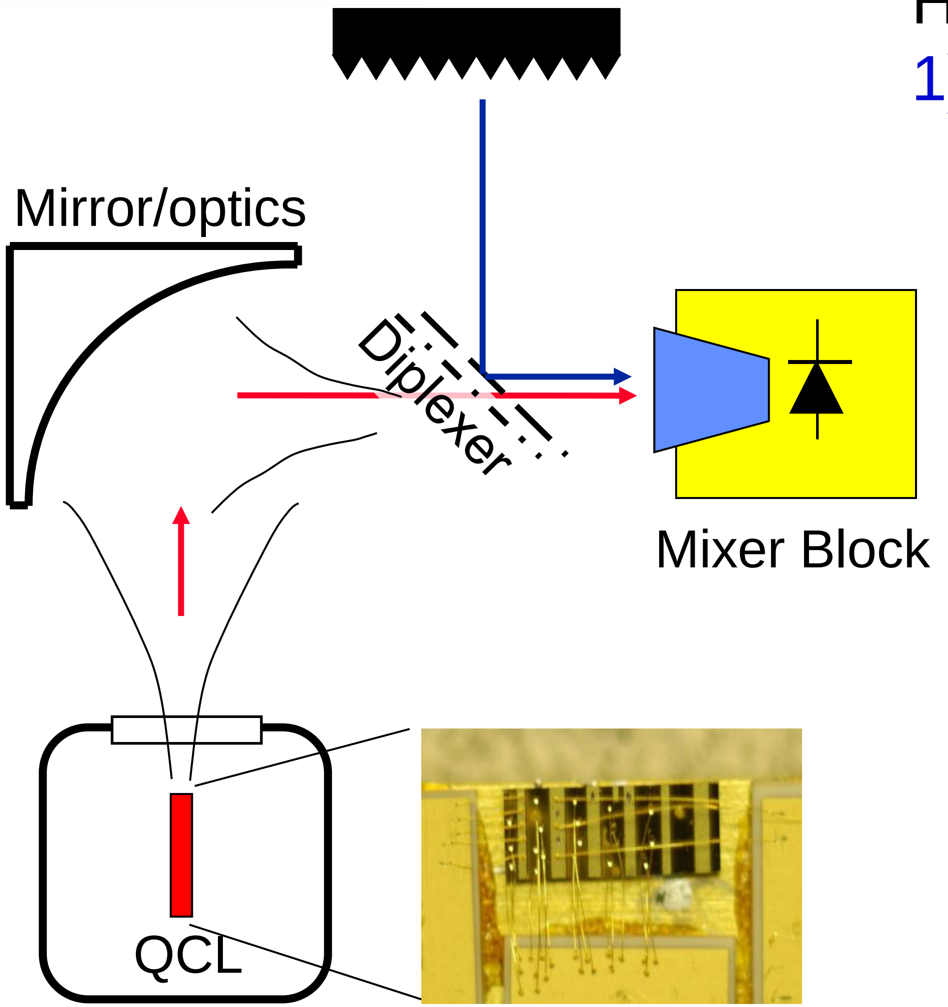
Mixer Response vs Diode Bias

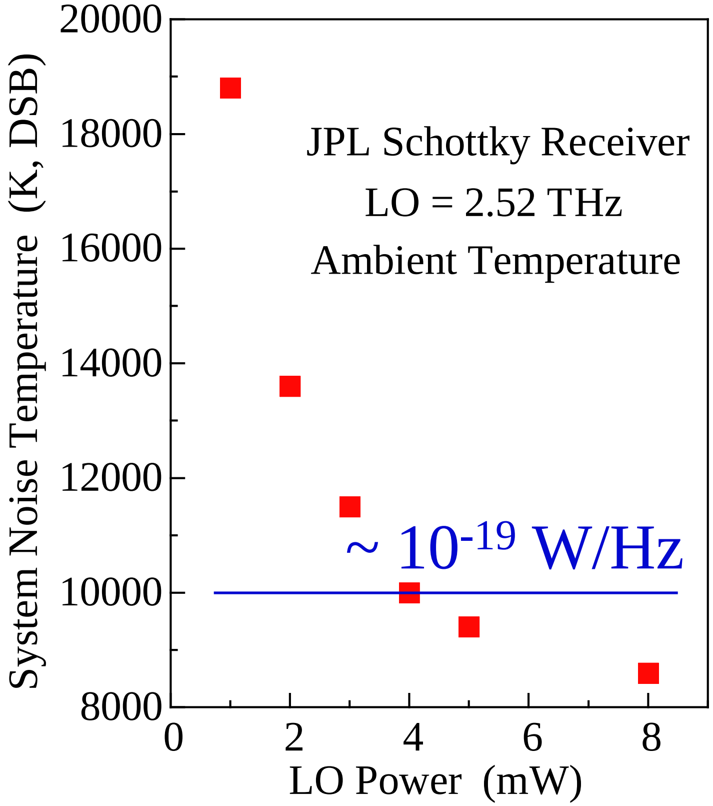


Coherent Detector: THz receiver



Heterodyne receivers enable:

1) high sensitivity detection



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

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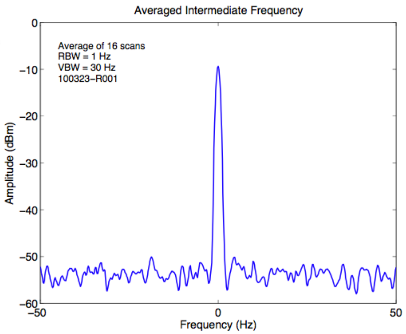
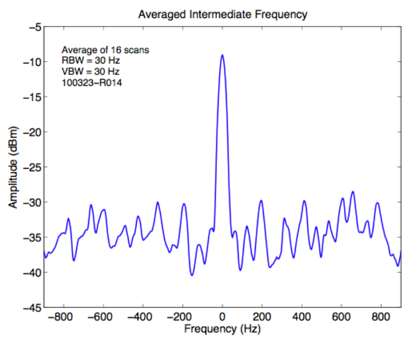
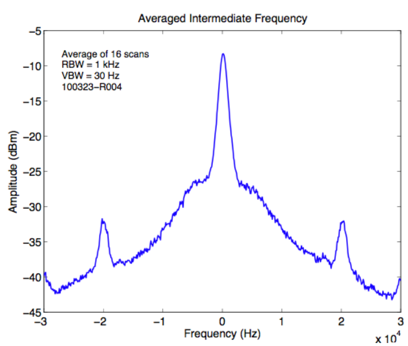
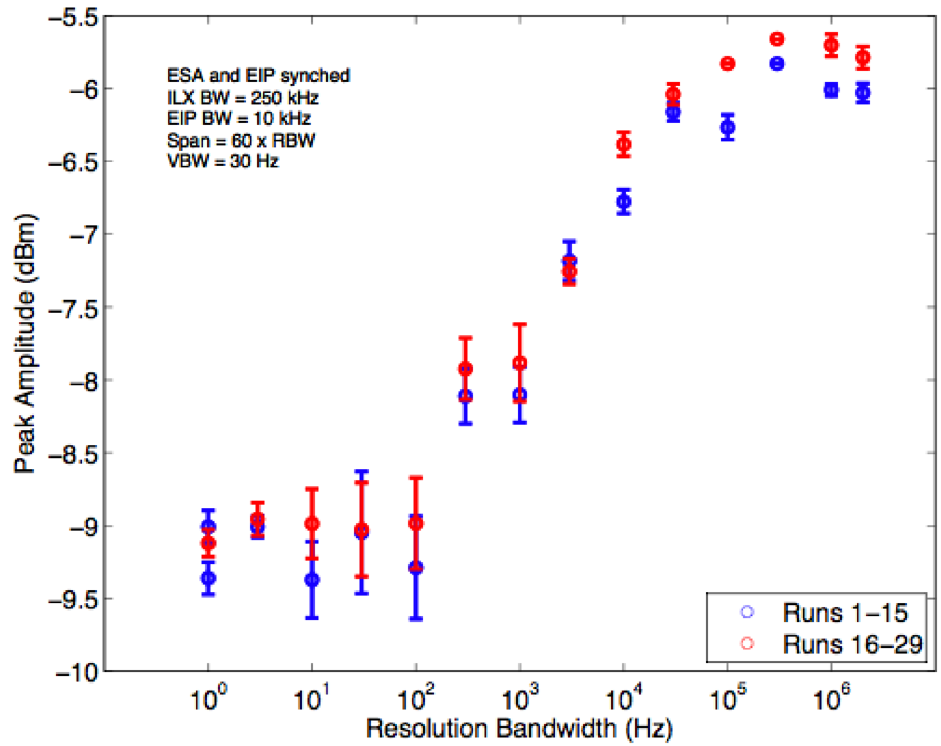
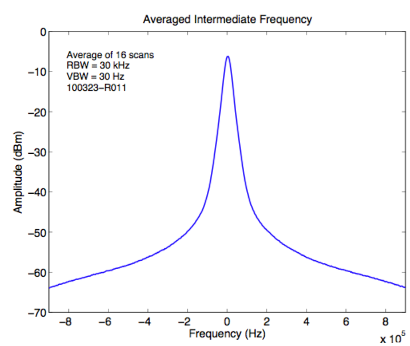
Phase Locking Bandwidth

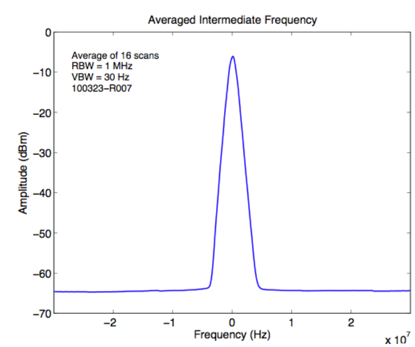












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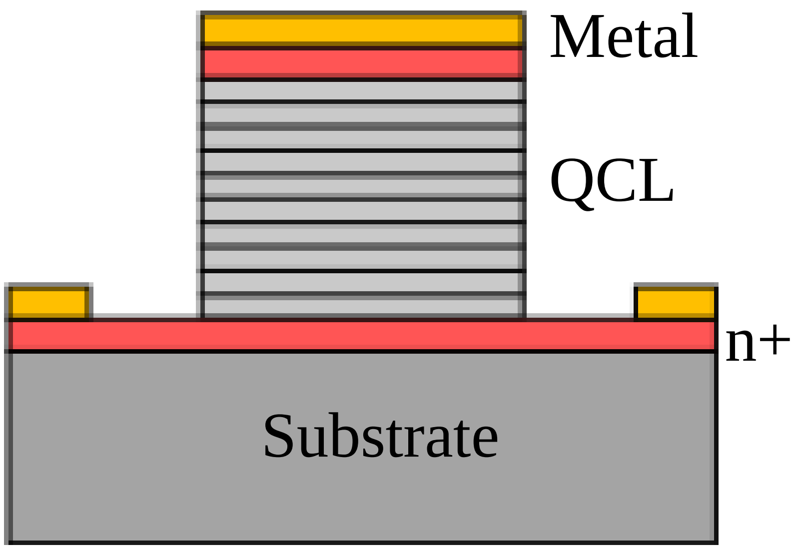
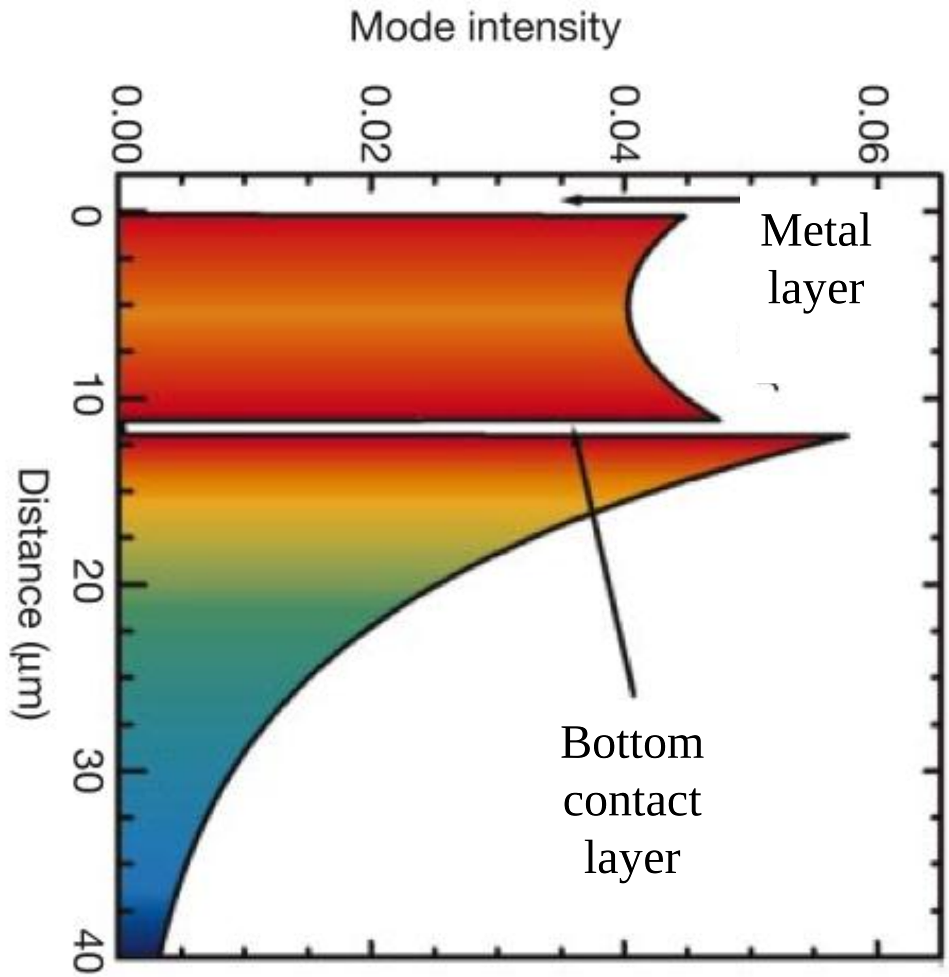
Diode placement relative to internal field



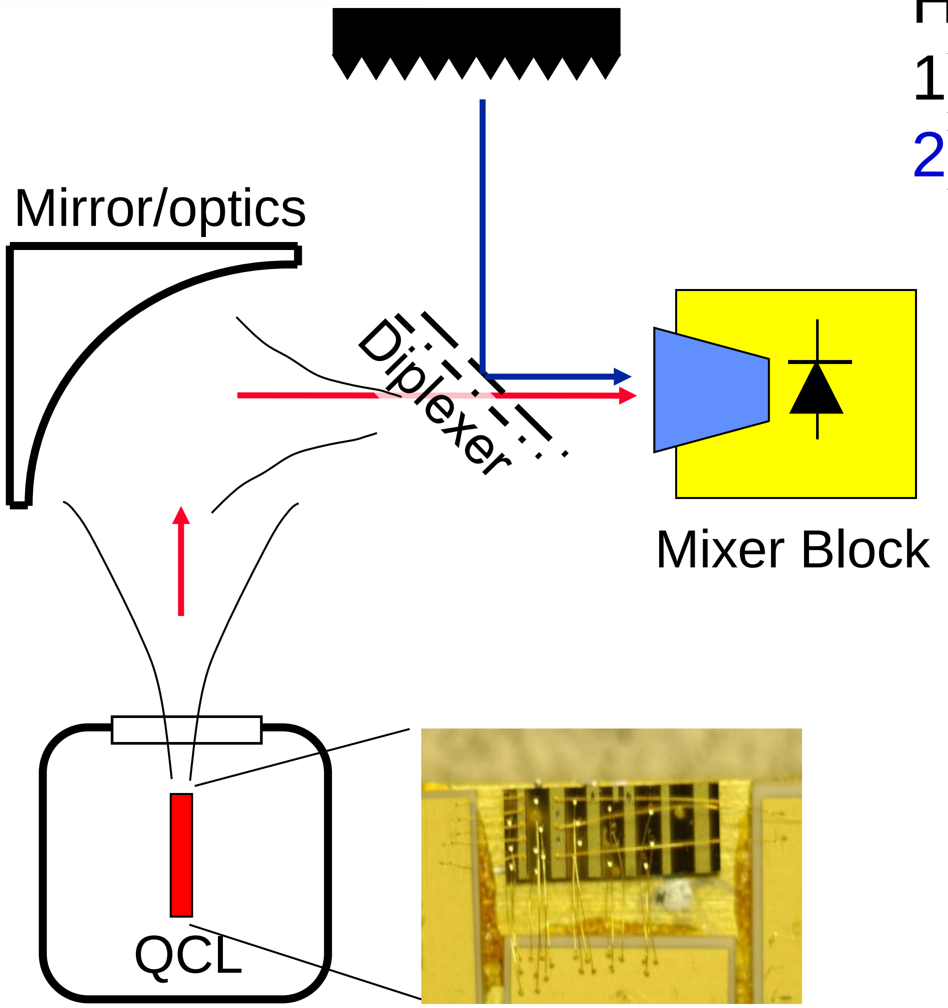


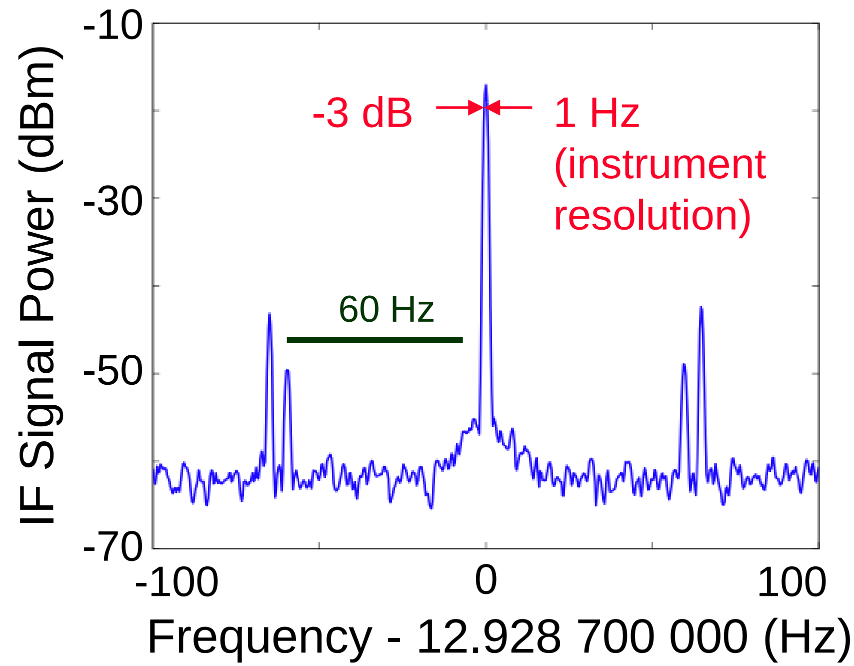
Kohler et al. , Nature, **417**, 2002

Coherent Detector: THz receiver

Heterodyne transceivers enable:

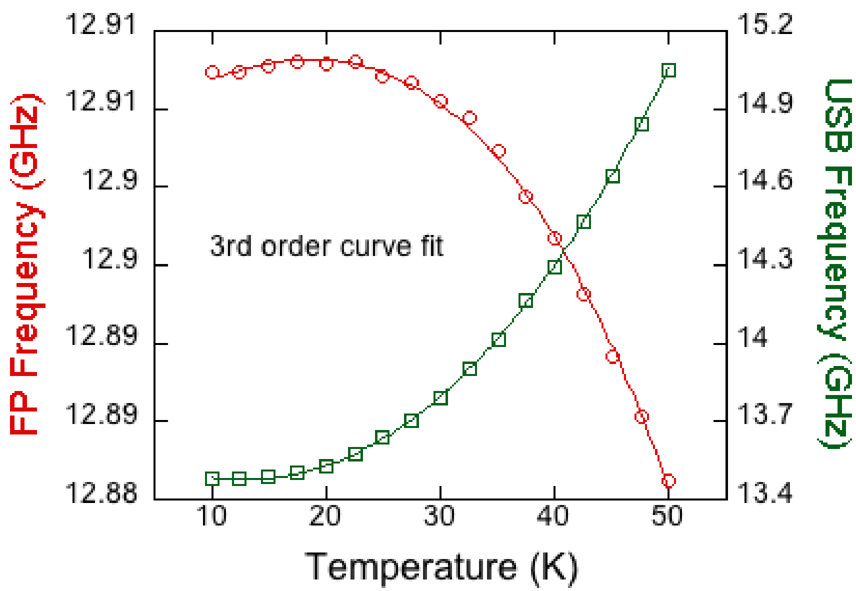
1) high sensitivity detection
2) high spectral resolution

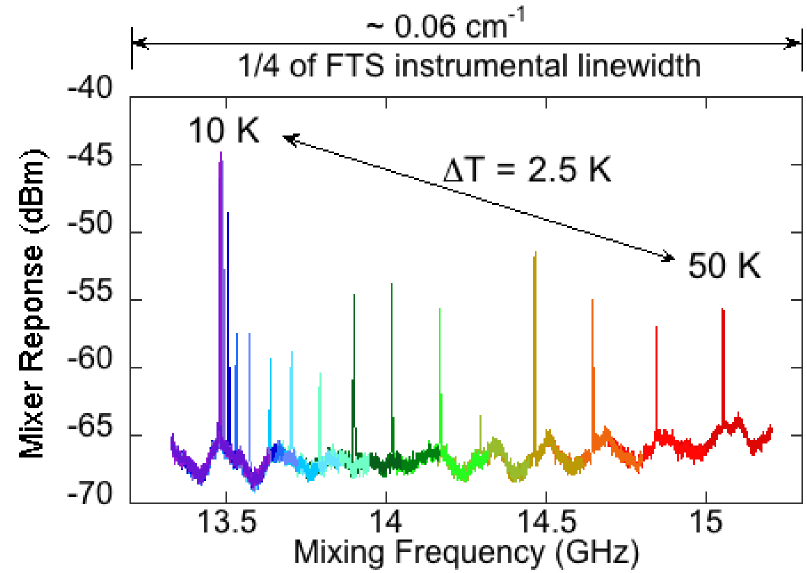




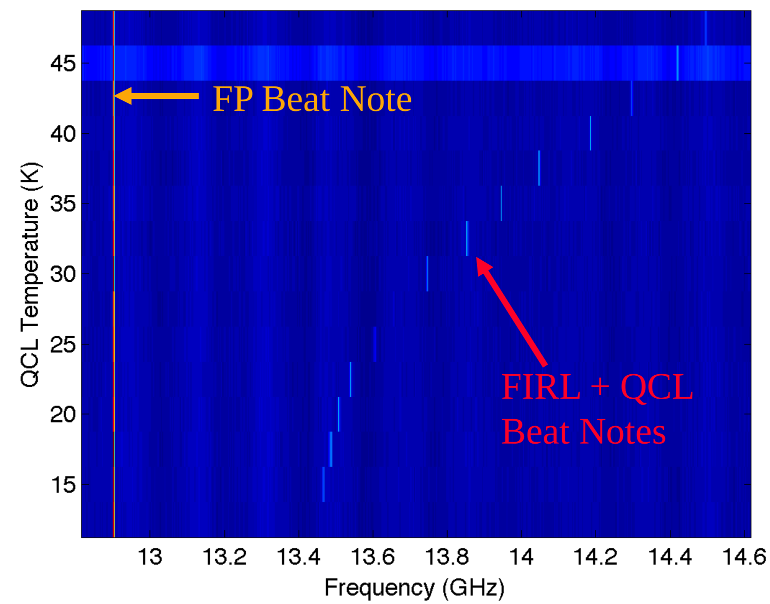
$$P \propto E_1E_2\cos(\omega_1-\omega_2) + f(\omega_1) + f(\omega_2) + f(\omega_1+\omega_2)$$

Similar for Temperature Tuning





- Can see the small shifts at low temperature
- Can see the FP mode spacing change
- Can see non-monotonic behavior of the FP mode spacing



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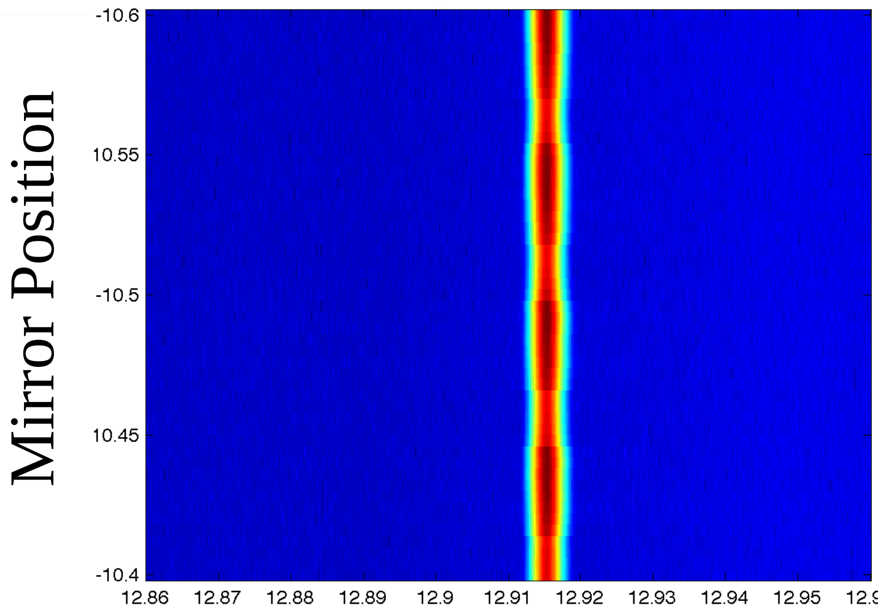
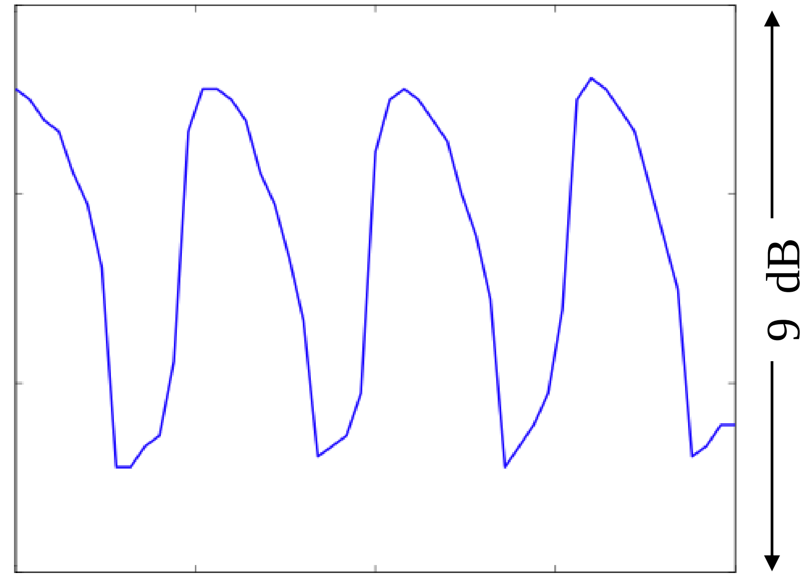
Feedback Effects for Locked FP

FP Mode



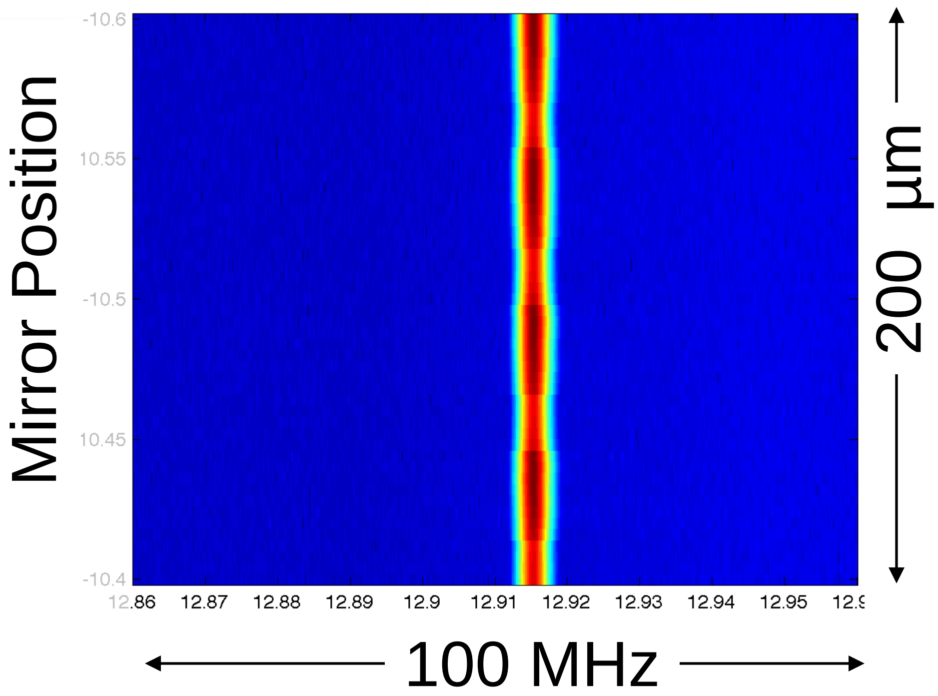
FP Mode Amplitude



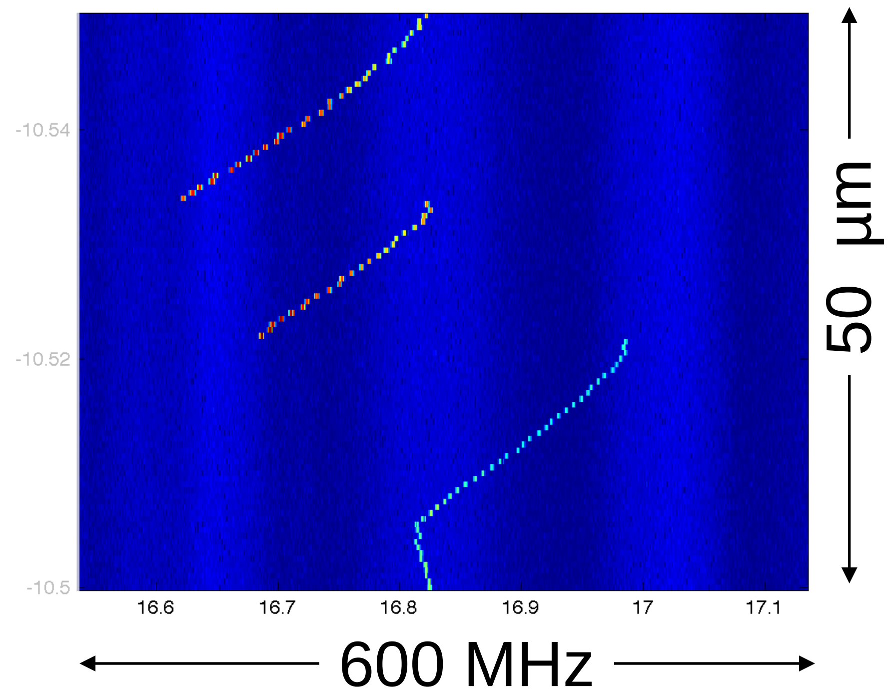
FP frequency is locked (~1 Hz) … but amplitude is not.

Feedback Effects for Locked FP

FP Mode



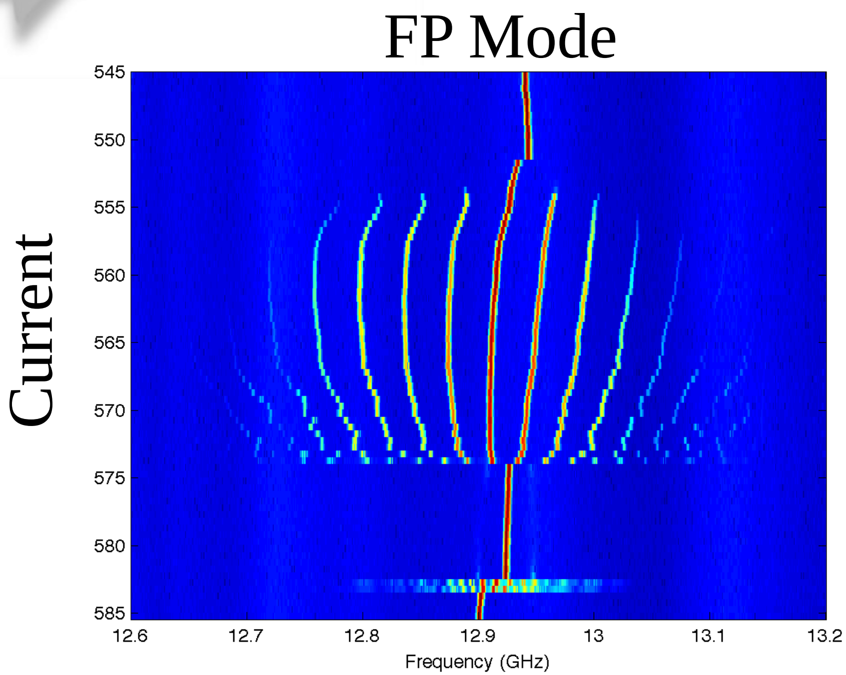
’□□□□□Mode’

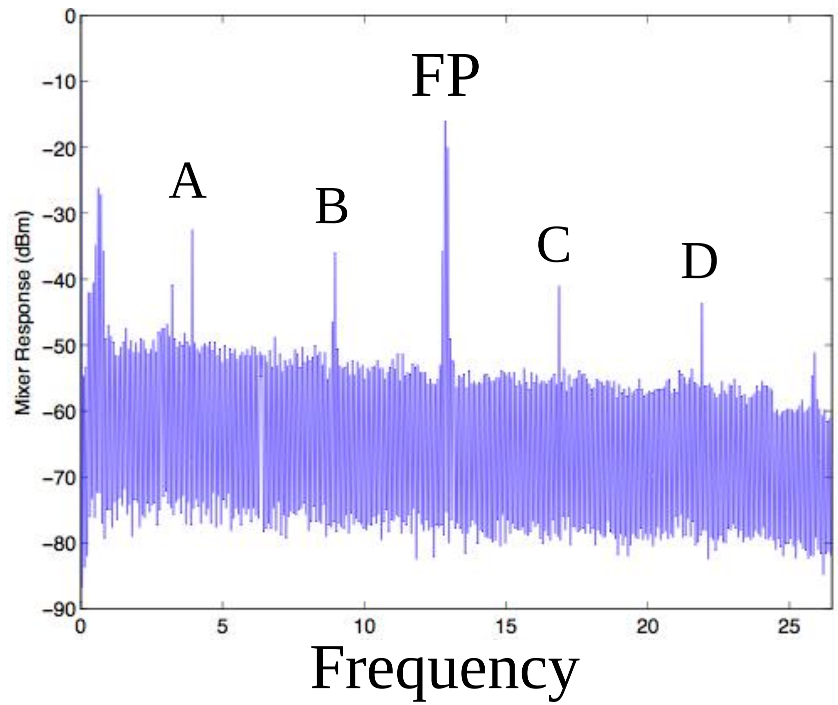


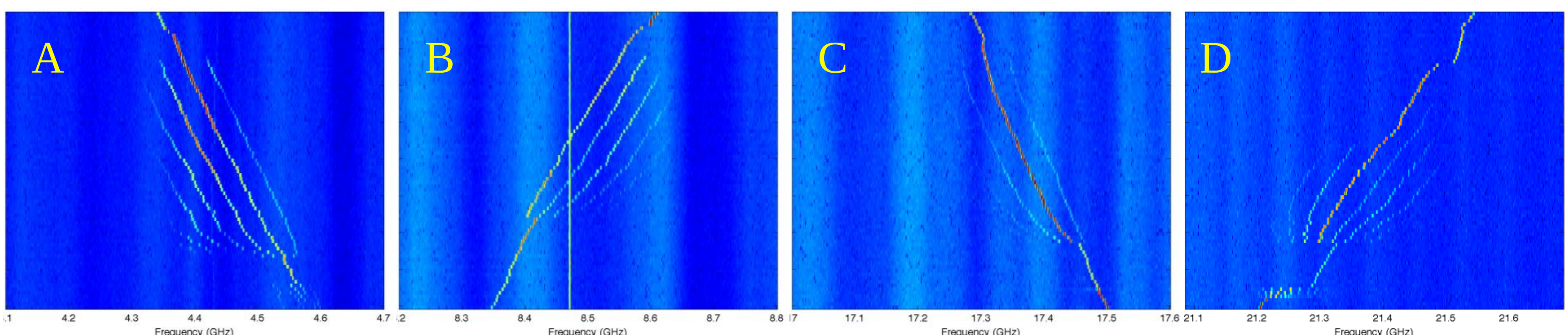
FP frequency is locked (~1 Hz) … but amplitude is not.

… absolute frequency is not.

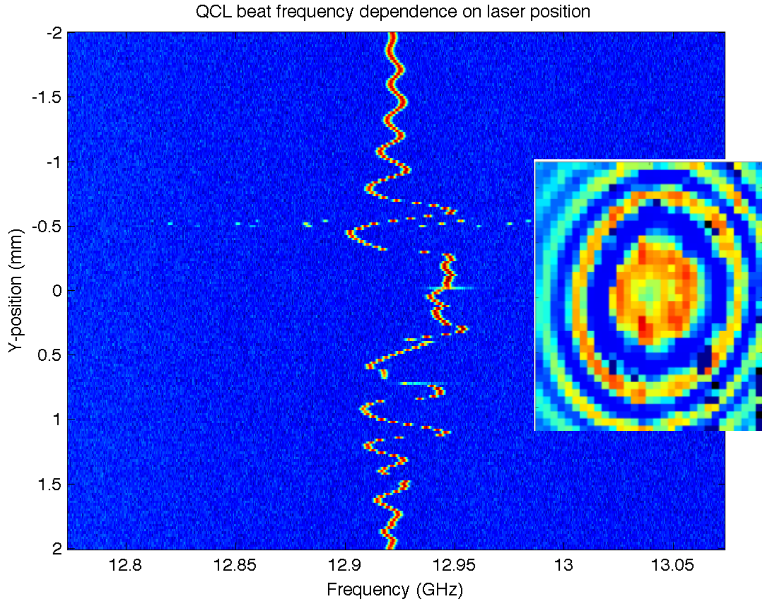
Proof of asymettric splitting of FP modes





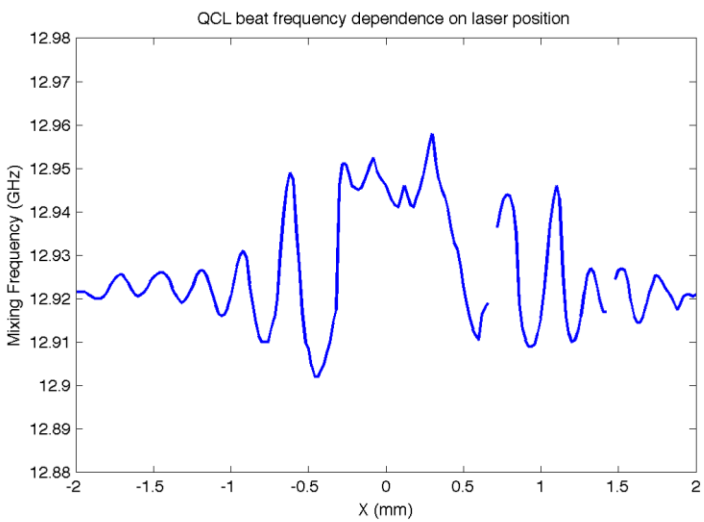


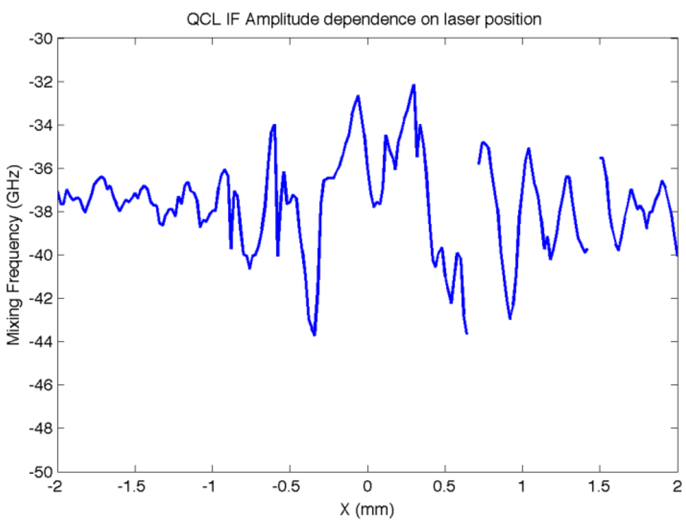
Focal Position Sensitivity



Hi-resolution slice

- 3 mm out of focal plane
- phase flips every 1/4 λ





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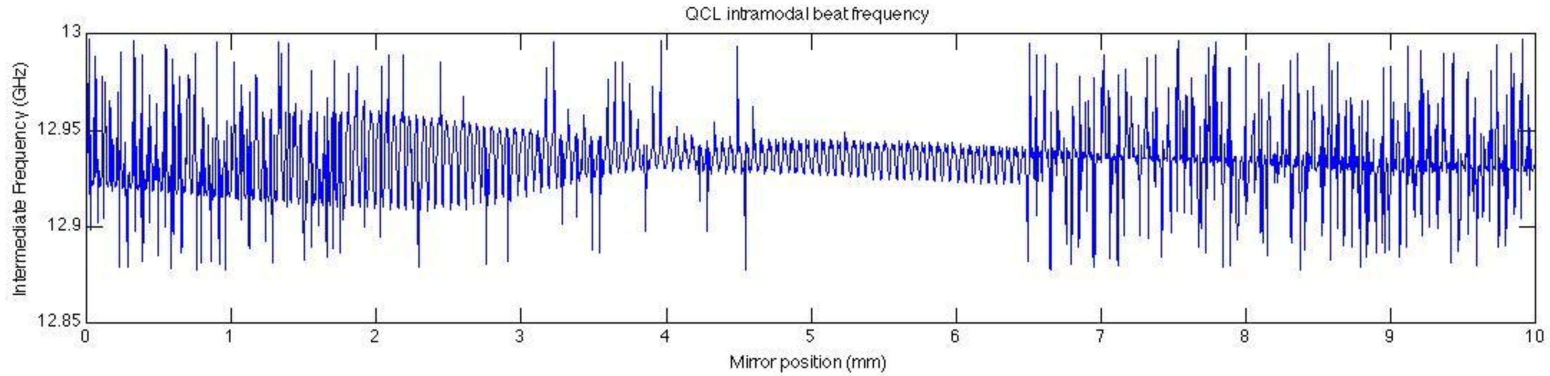
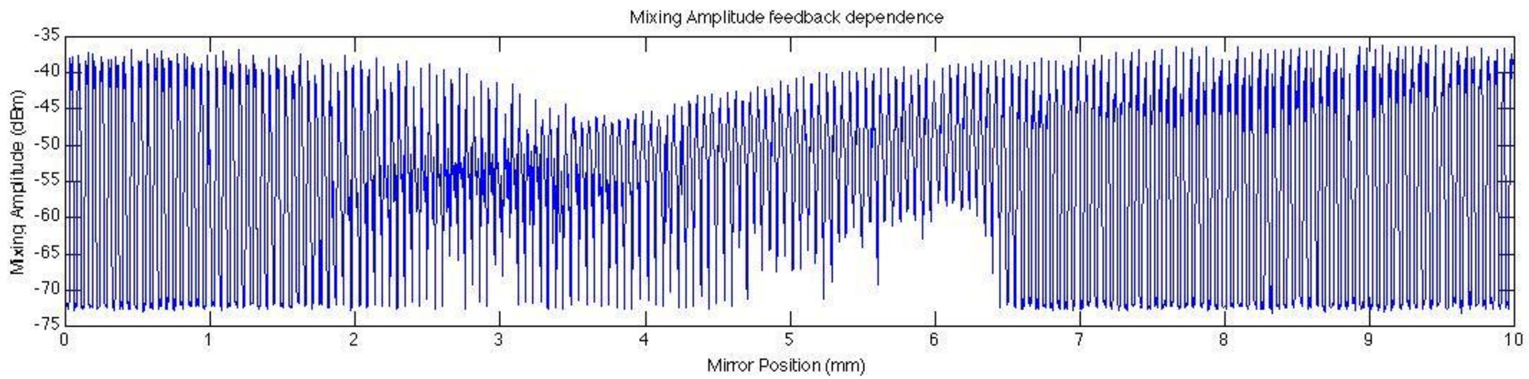
Feedback over long scan

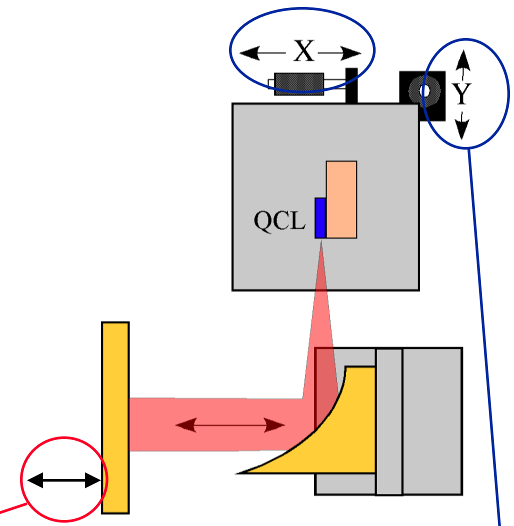


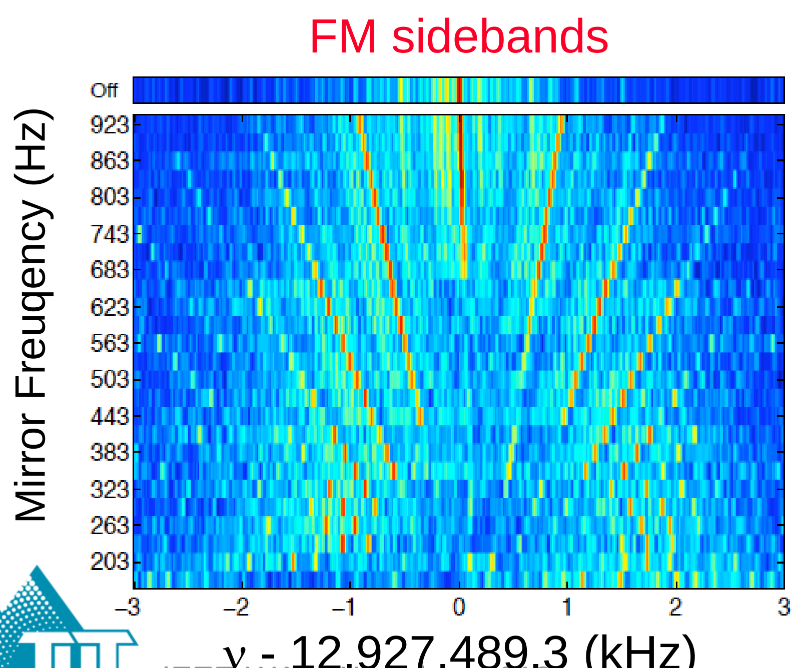


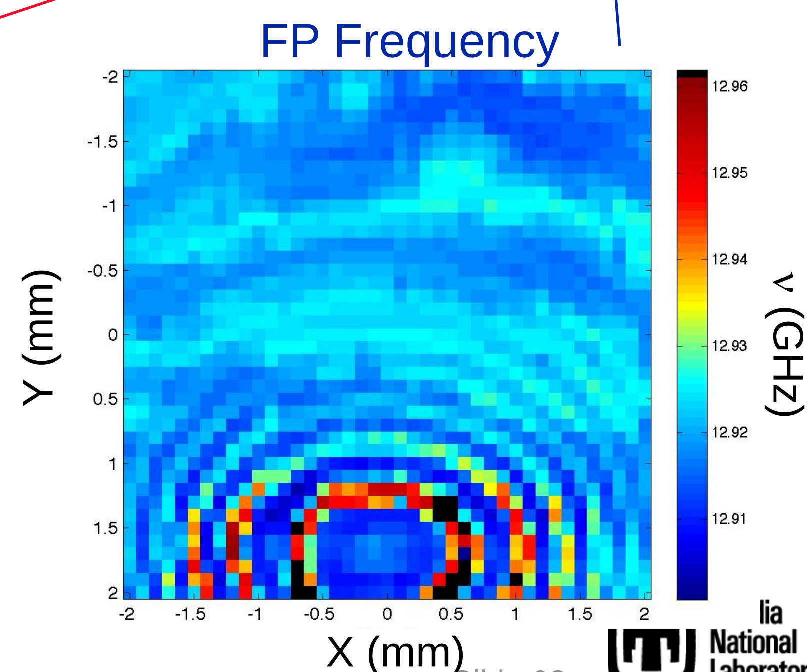
Regions where signal goes away may be single mode

Unique Tool to Explore Feedback Sensitivity

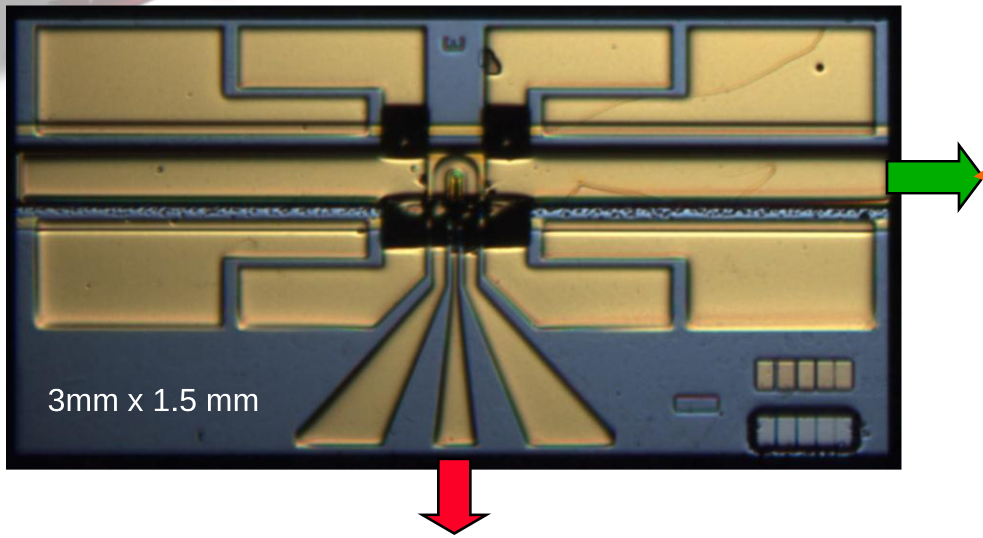
- Found QCL is strongly sensitive to feedback.
  - Difficult to measure other ways.
  - Bad when frequency stability is needed.
  - But possibly useful for vibrometery.
  - Possible reason for odd beampatterns.
  - Demonstrates need for isolators.

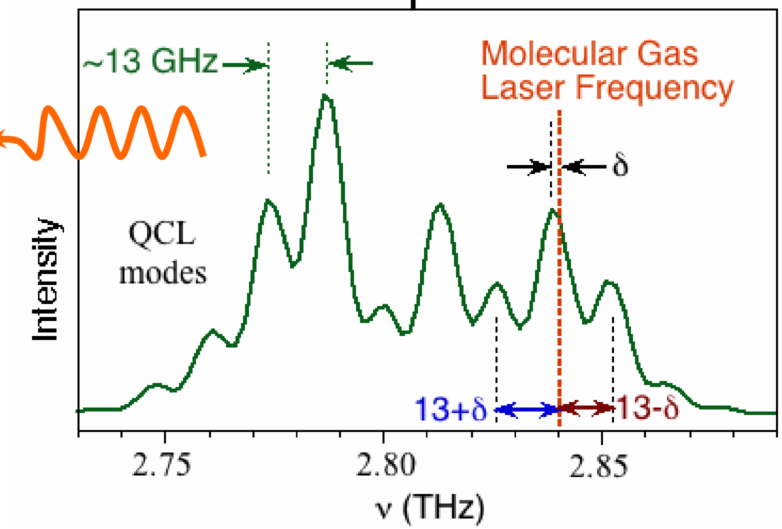




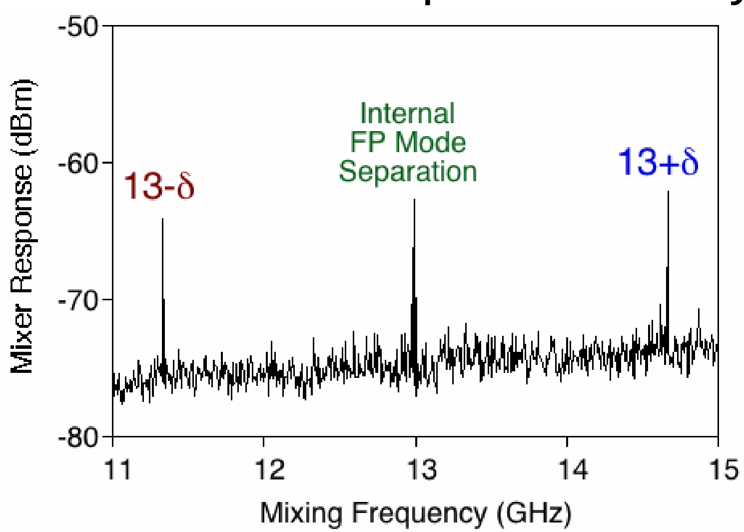


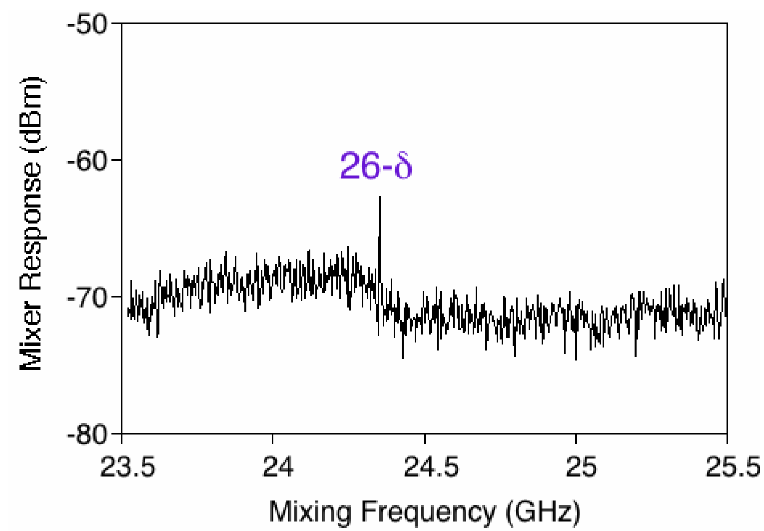
Integrated THz Receiver





Electrical feed to spectrum analyzer





High-resolution, coherent detection of incident radiation

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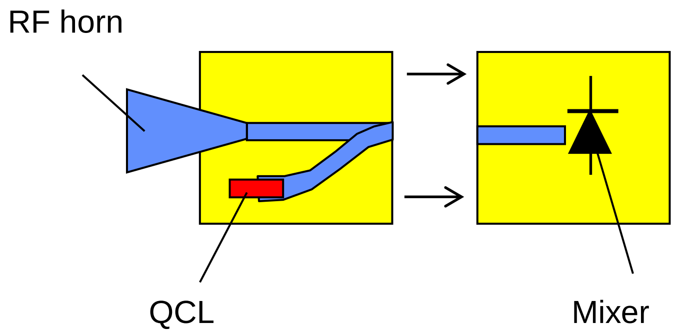
Mid-scale Integration: QCLs in rectangular waveguides



- **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
  - $$$

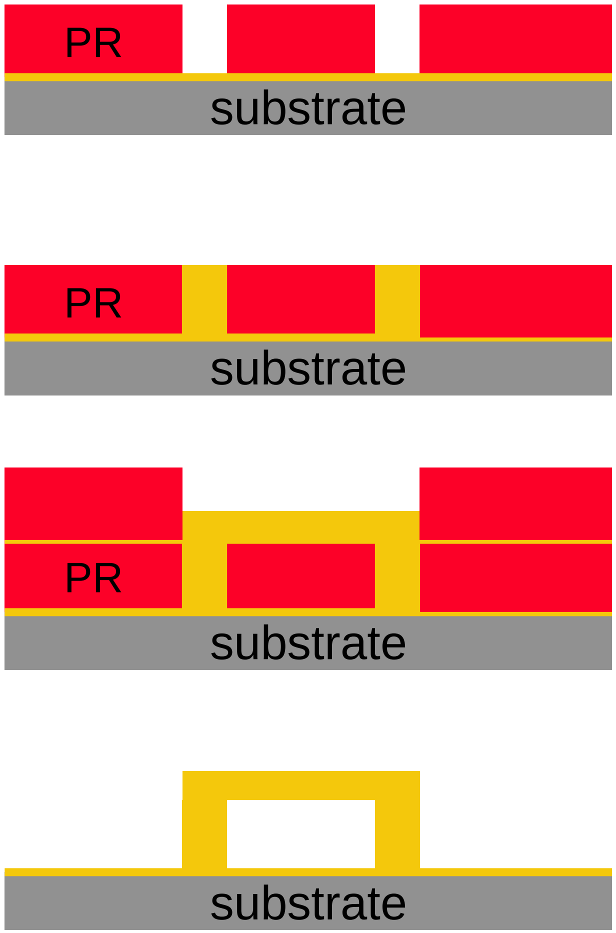
Micromachining Rectangular Waveguides

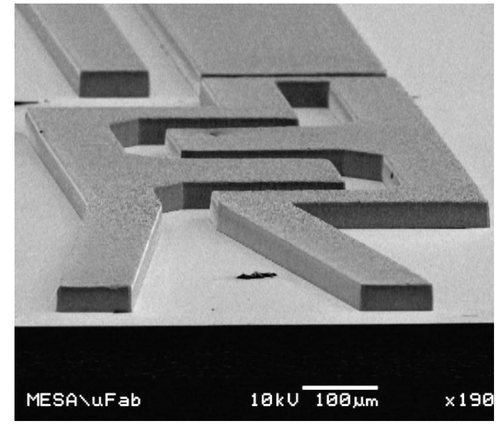
1. Deposit seed metal and pattern photoresist

2. Electoplate Au in photoresist openings

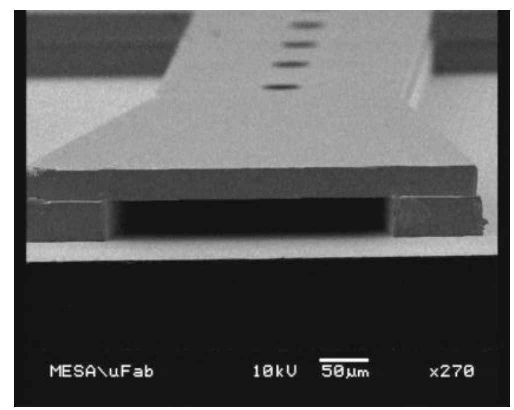
3. Deposit 2nd seed, pattern 2nd PR, and plate lids

4. Remove photoresist and 2nd seed metal



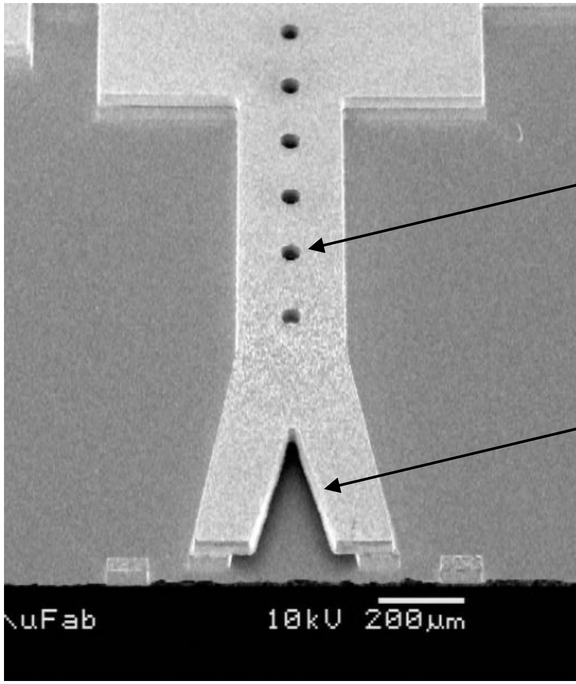


- **Additive electroplating technique suitable for various substrates**
  - *Allows waveguide fabrication on QCLs or other devices*



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

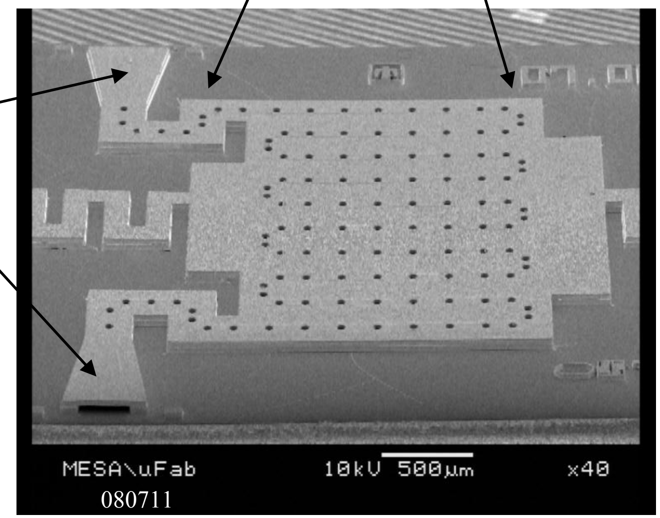
Micromachined THz Waveguides

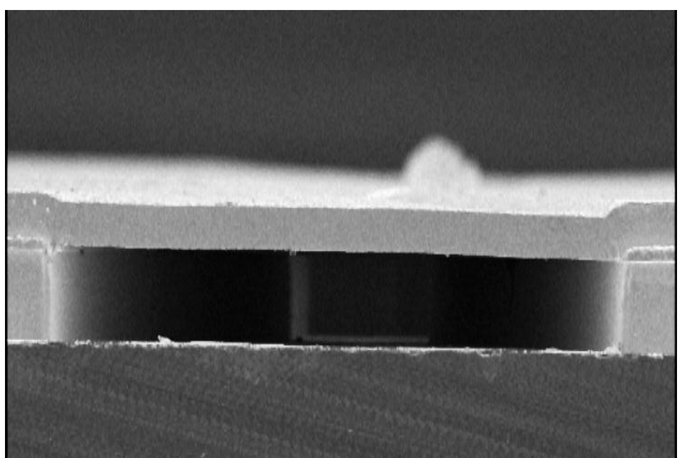


Photoresist removal holes

Horn antenna

H-Plane Bends

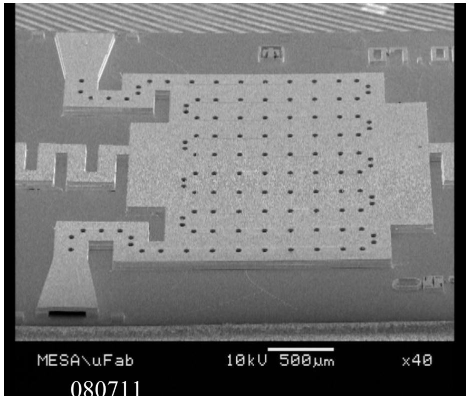


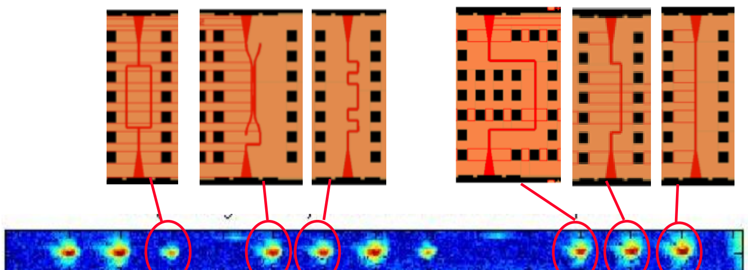


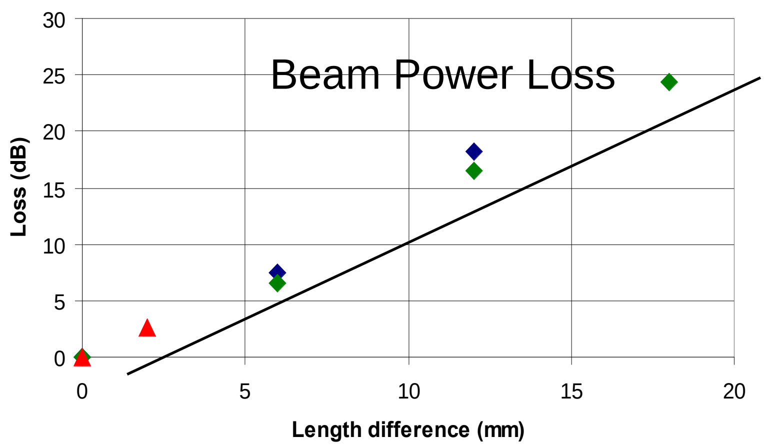
End view of waveguide horn antenna

THz Micromachined Waveguide Components

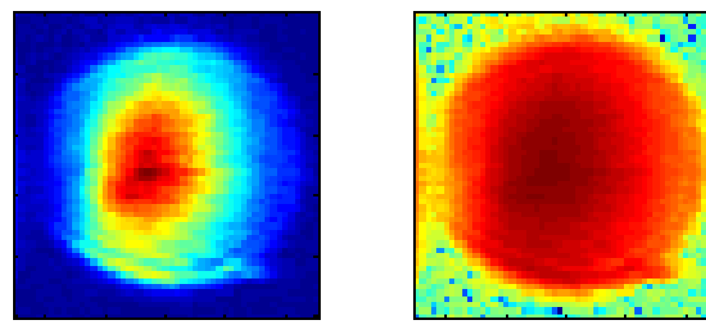
- Demonstrated THz components (waveguides, bends, tees, and couplers) needed for THz integrated circuits.
- Achieved low propagation and bend losses (at 2.9 THz).
  - 1.4 +/- 0.15 dB / mm (.15 dB / λ)
  - 0.15 +/- 0.15 dB / bend
- Observed good far-field beam patterns.




Transmission through various components

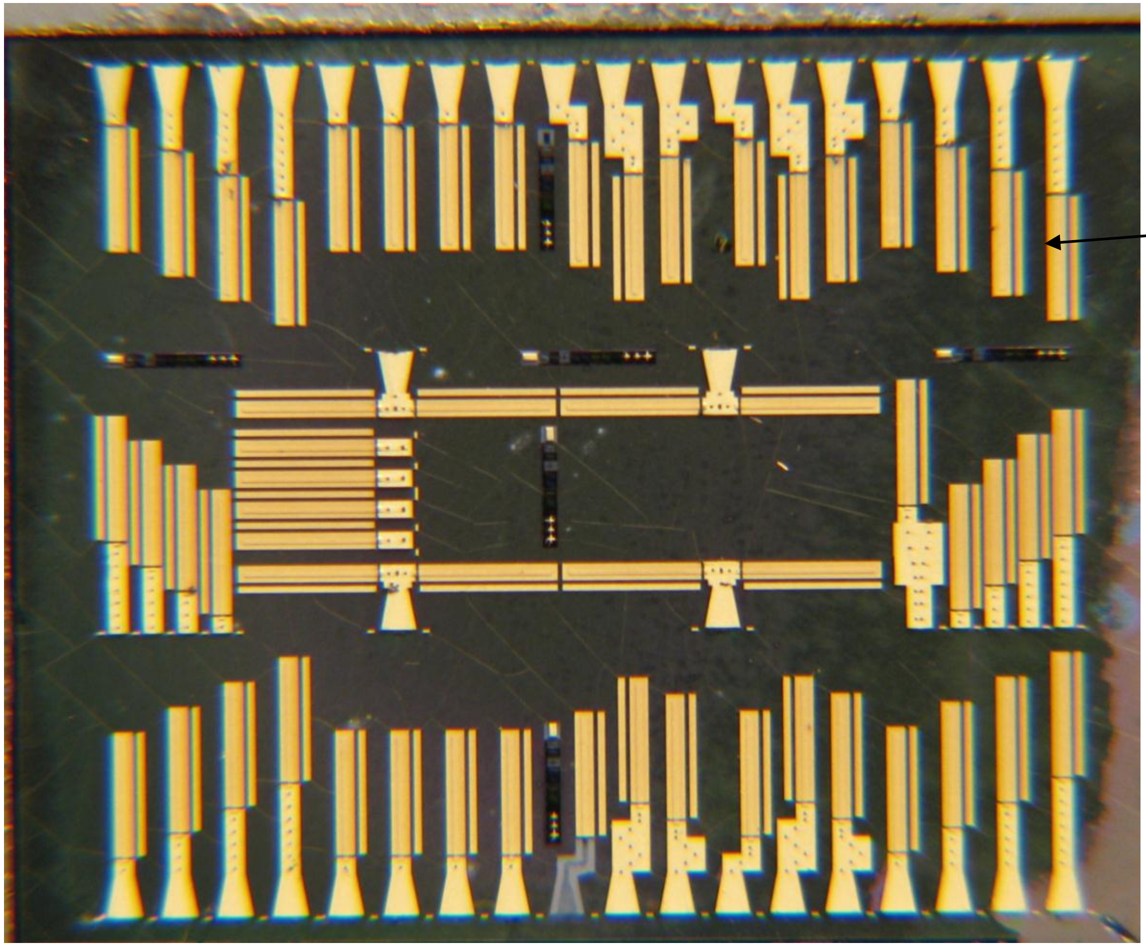


Preliminary Antenna Beam Pattern


Linear Scale
Log Scale

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

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

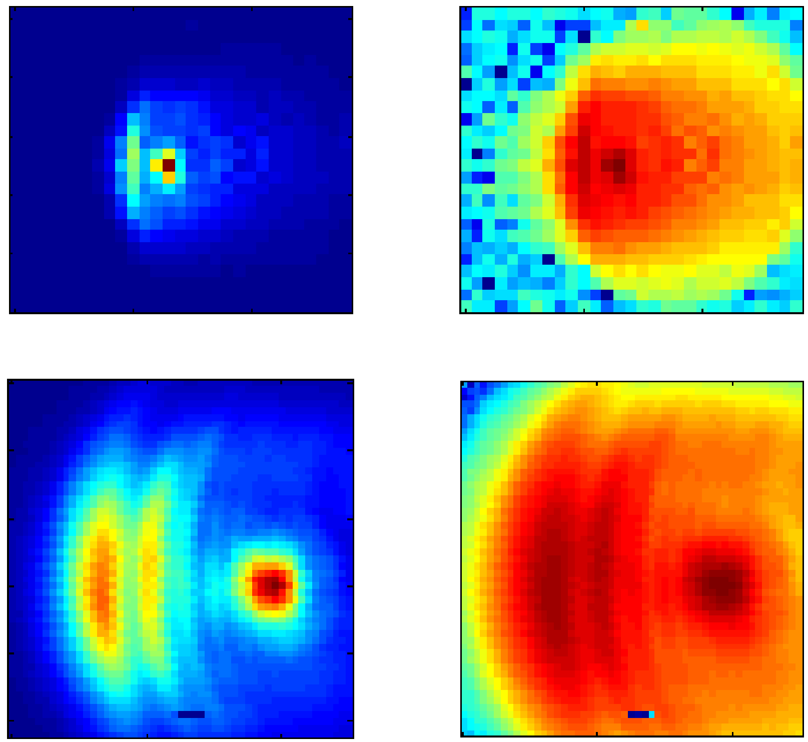
Wanke, Proc SPIE, **7215**, (2009)

Integrated Waveguide Performance

Integrated Far-field beampatterns

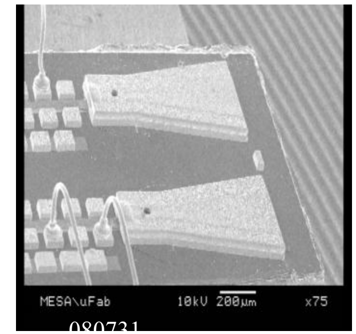
Low Res

High Res



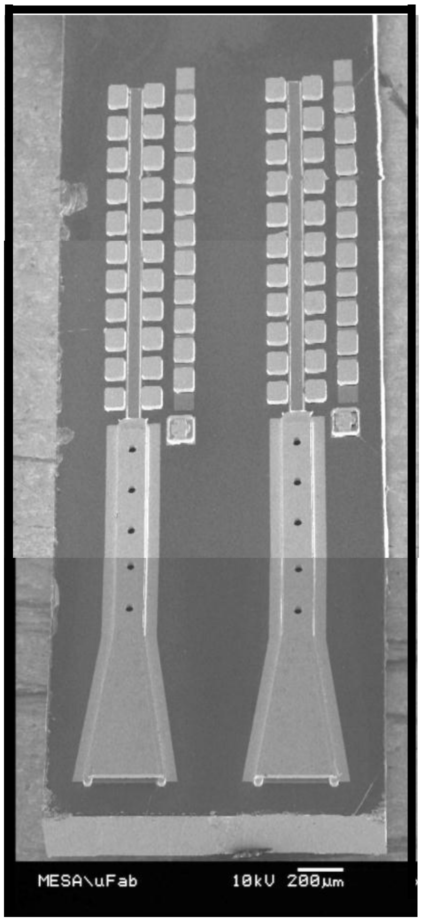
Linear Scale

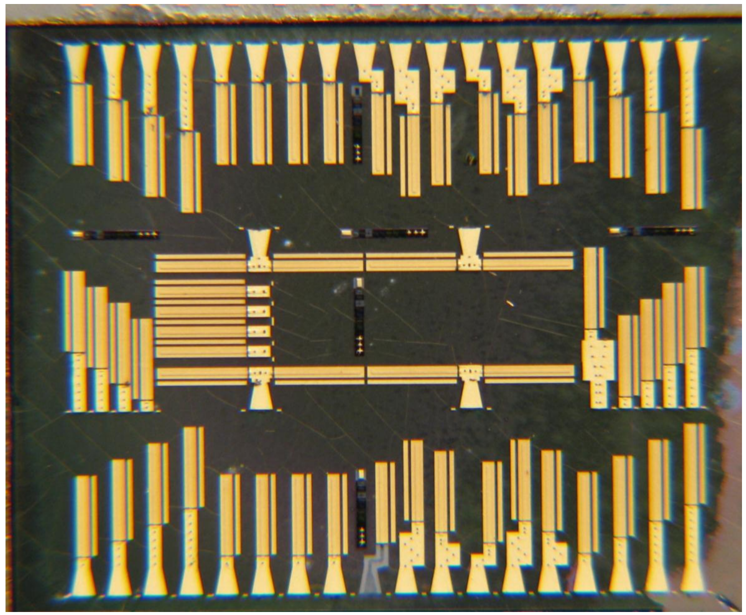
Log Scale

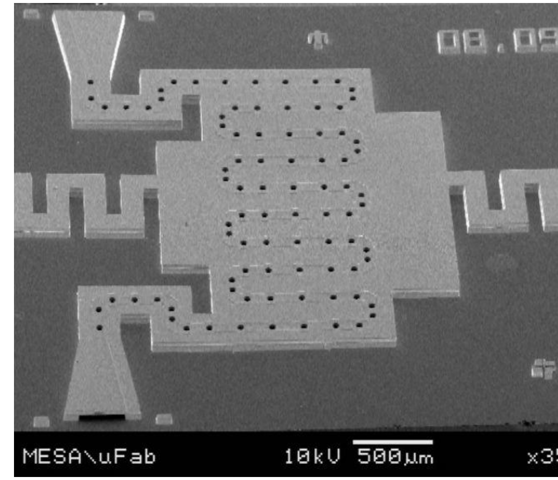


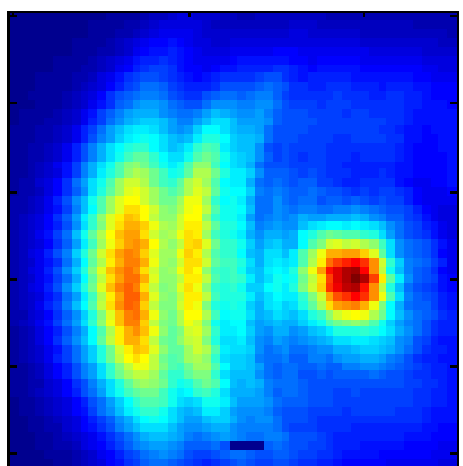
- **Improvement over bare laser beampattern**

Integrated Waveguide Summary







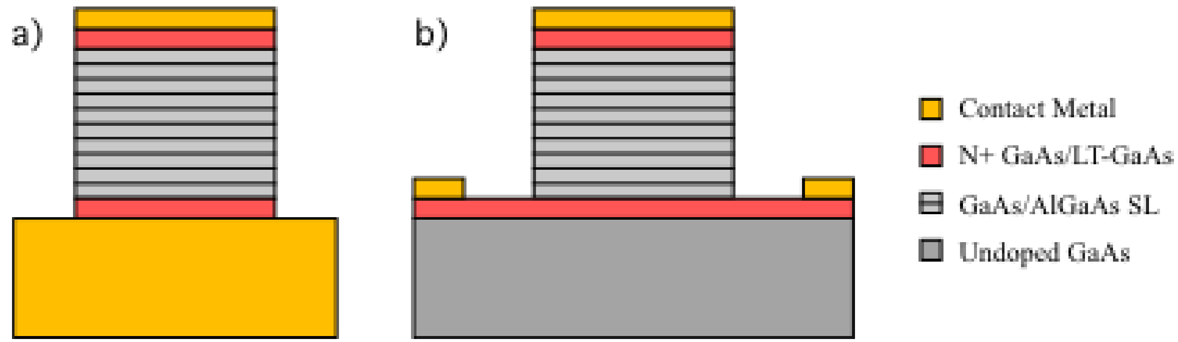


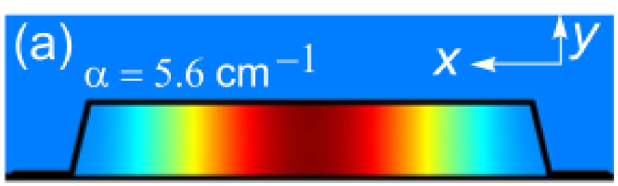
- **Successfully merged of optical and electronic technologies**
- **Opens the door for THz on chip routing and integrated circuits**

Two THz Waveguides

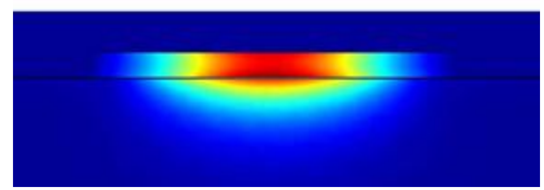
Metal-Metal Waveguide

Surface Plasmon Waveguide





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

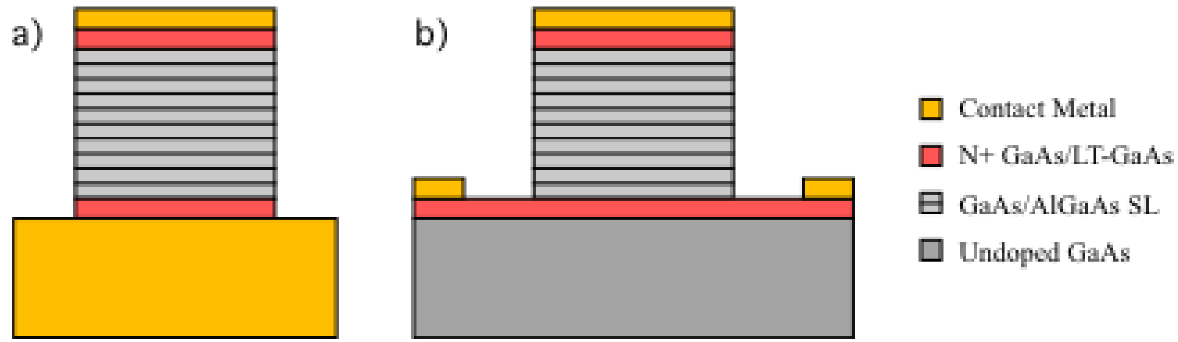


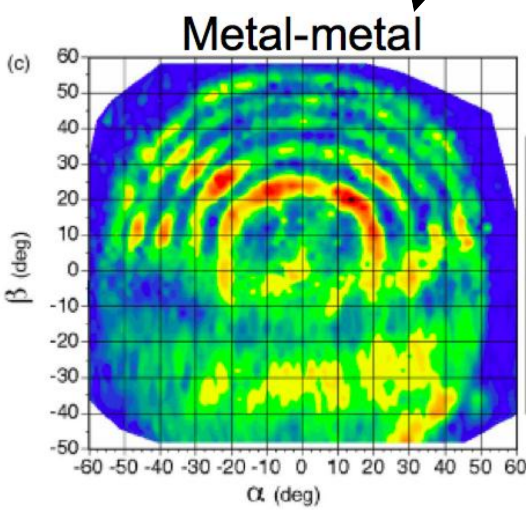
Demichel, *Opt. Exp.*, **14**, 5335, 2006

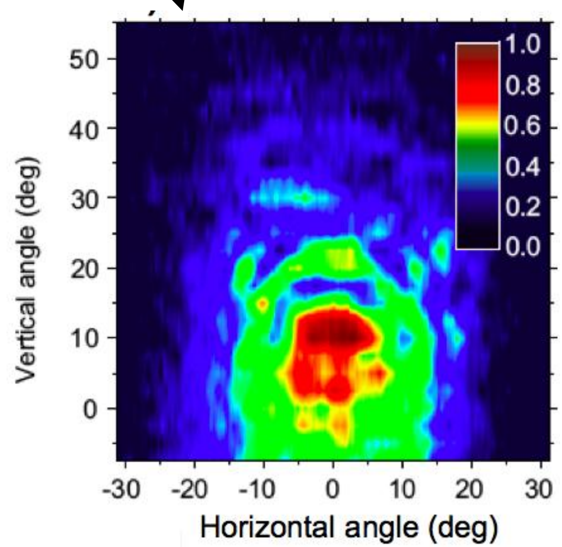
QCL Far Field Issues

Metal-Metal Waveguide

Surface Plasmon Waveguide







(Courtesy J. R. Gao, TU Delft)

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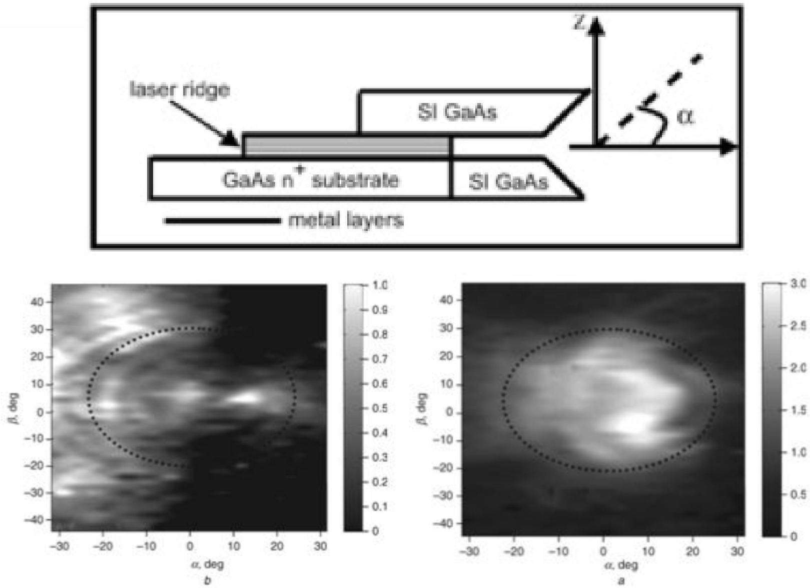
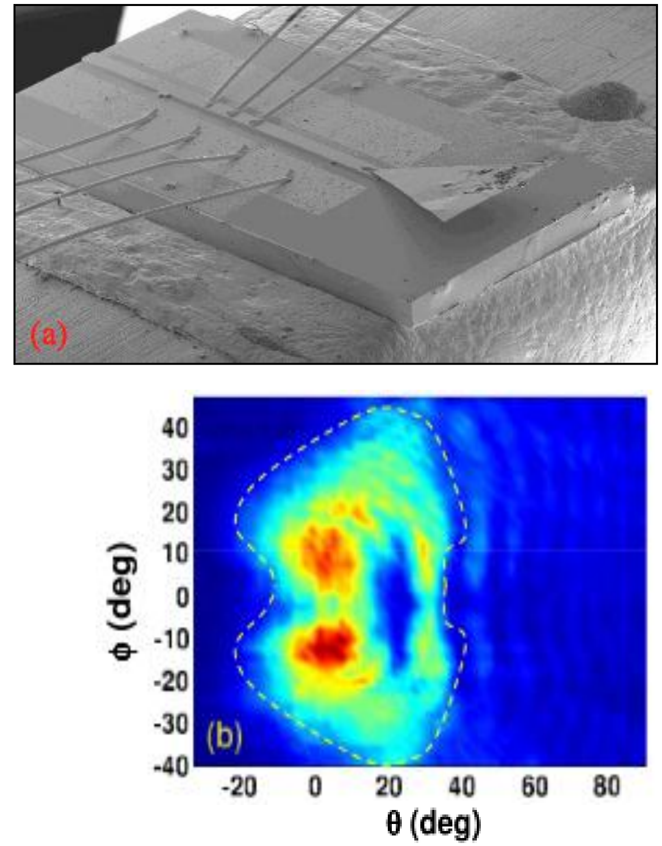
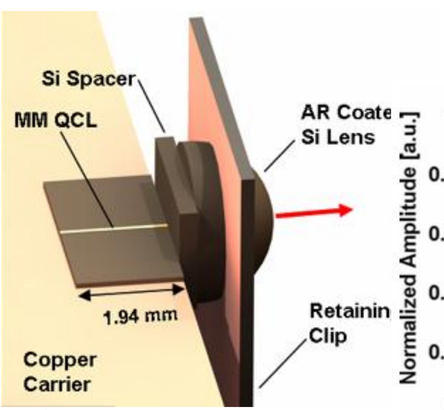
Fixing the beam pattern

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

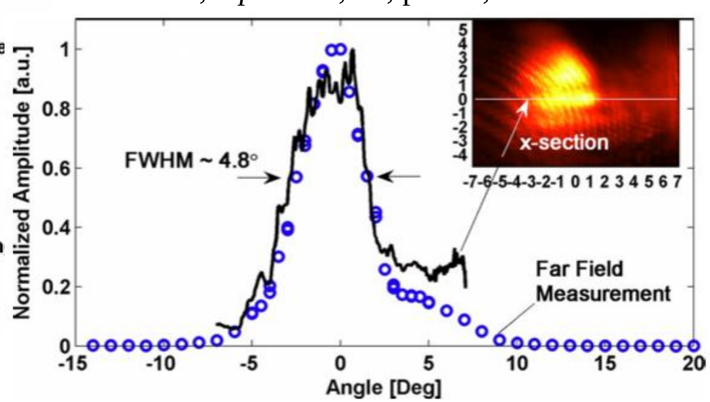


Maineult, Appl. Phys. Lett. 93, 183508 (2008)





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



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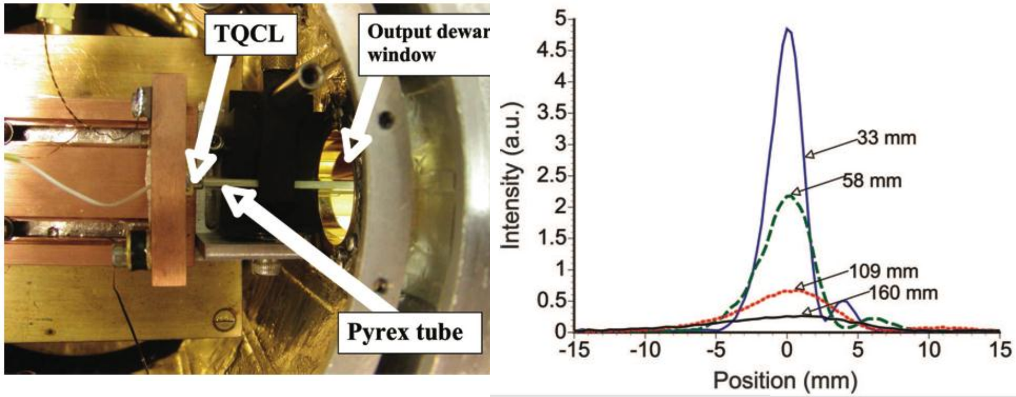
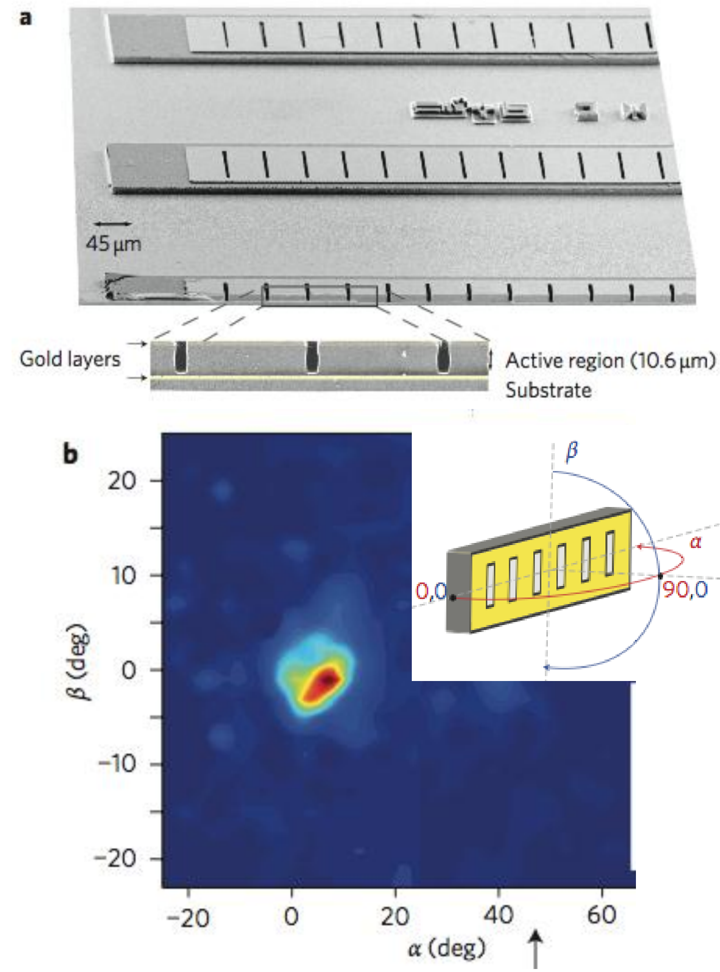
Controlling the Beampattern

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



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



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