

THz Integrated Circuits

Mike C. Wanke

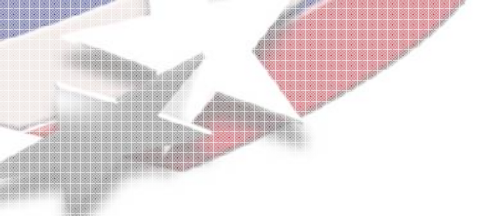
Sandia National Labs

IRMMW-THz

Oct 7, 2011

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.





Supporting Cast

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Michael J. Cich

Chuck T. Fuller

Eric A. Shaner

John L. Reno

Erik W. Young**

Now at Lumileds

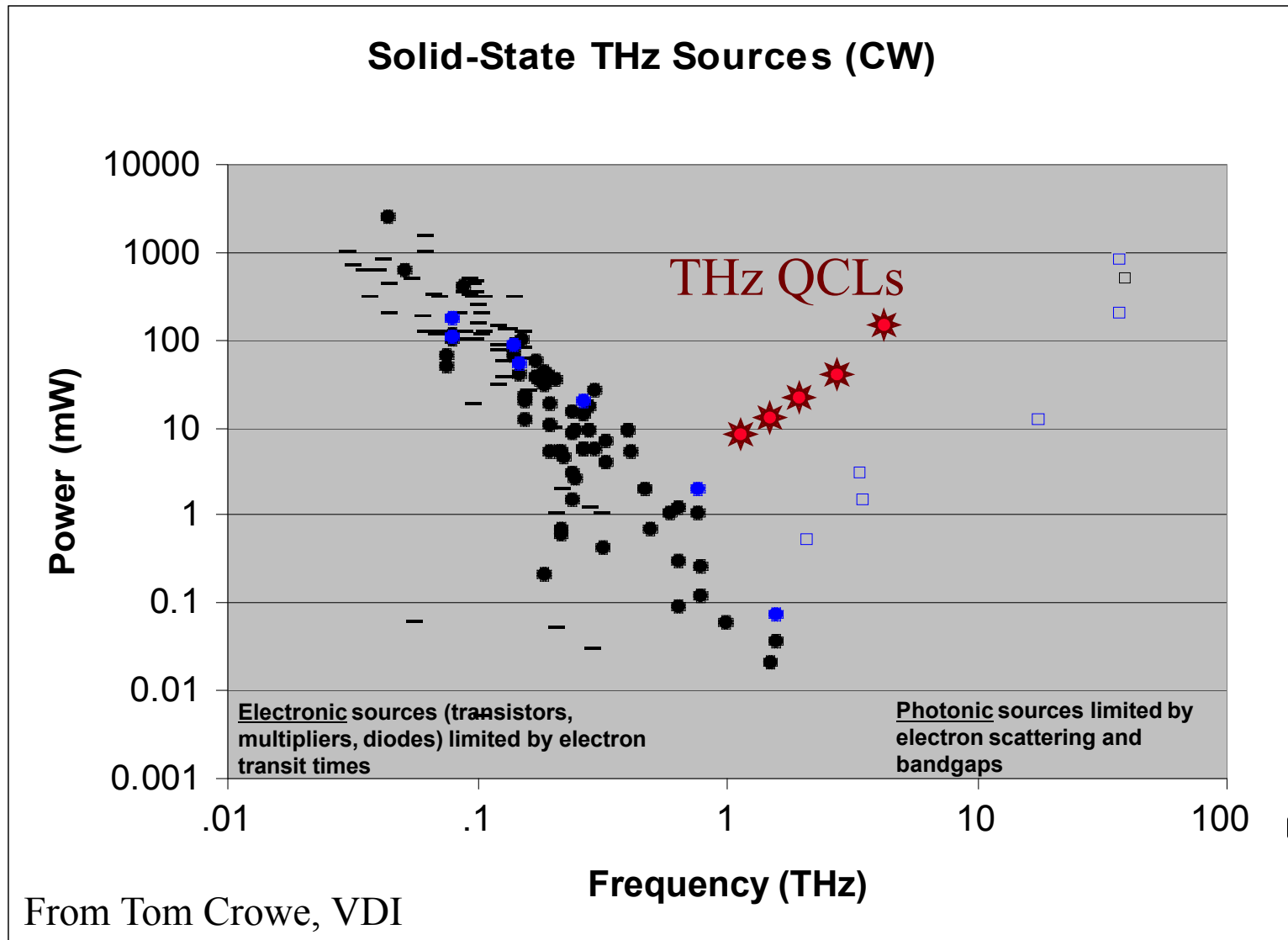
Albert D. Grine

LMATA Government Services

With Support From:

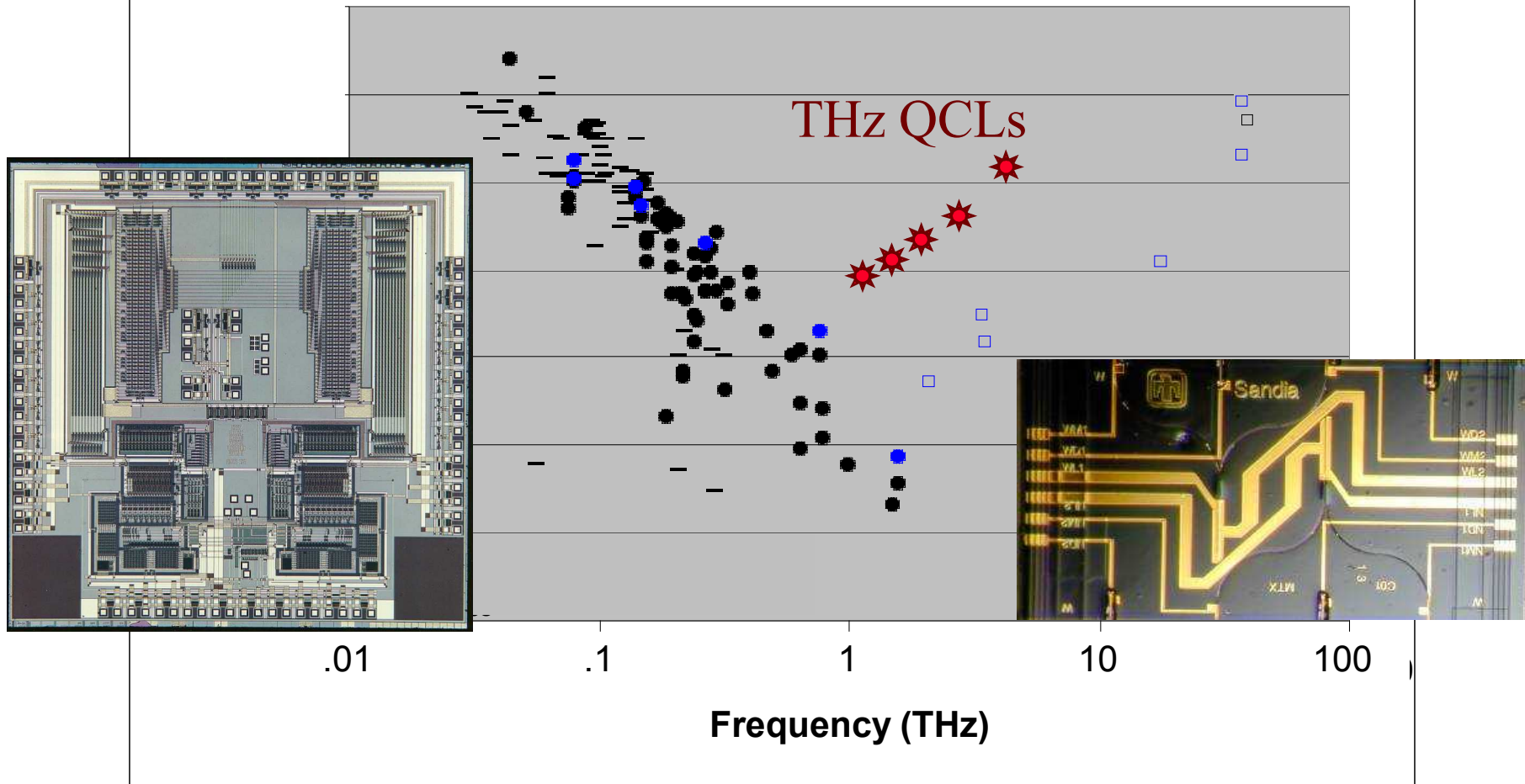


The “Shrinking” THz Gap



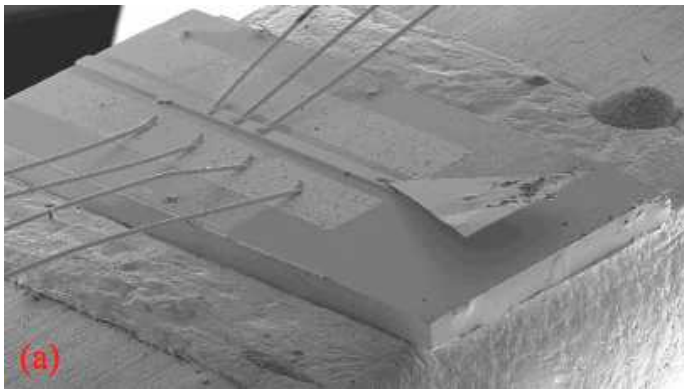
The THz Gap

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

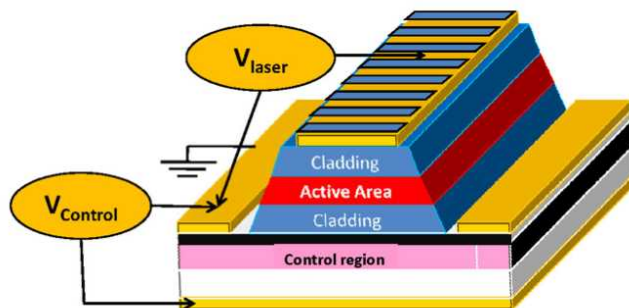
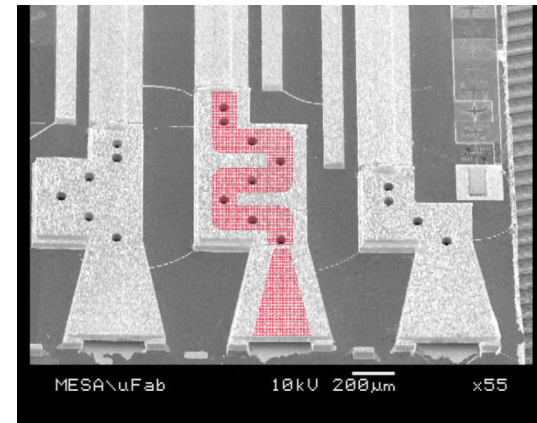


Integration examples

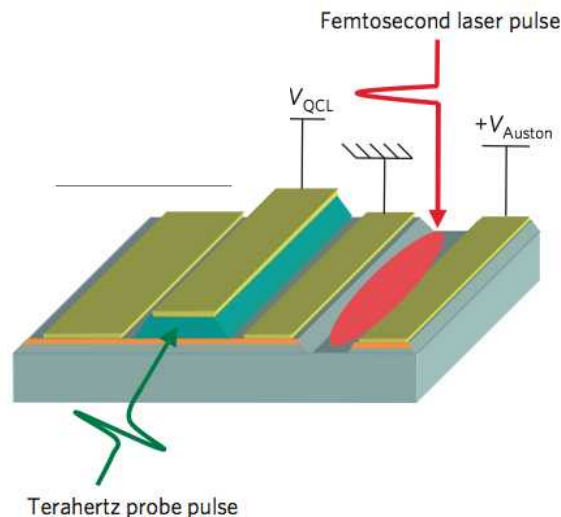
Antenna Coupling (IEMN/CNRS)



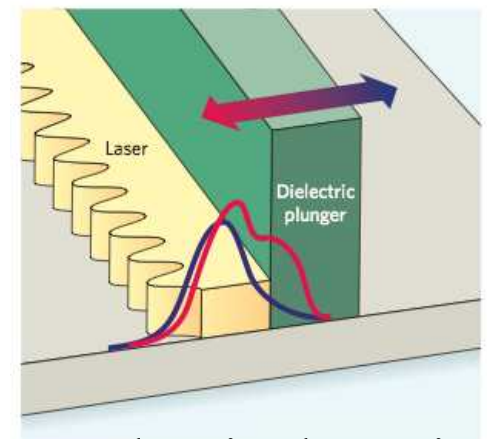
Integrated Waveguide (Sandia)



Modulator (U. Paris 7)

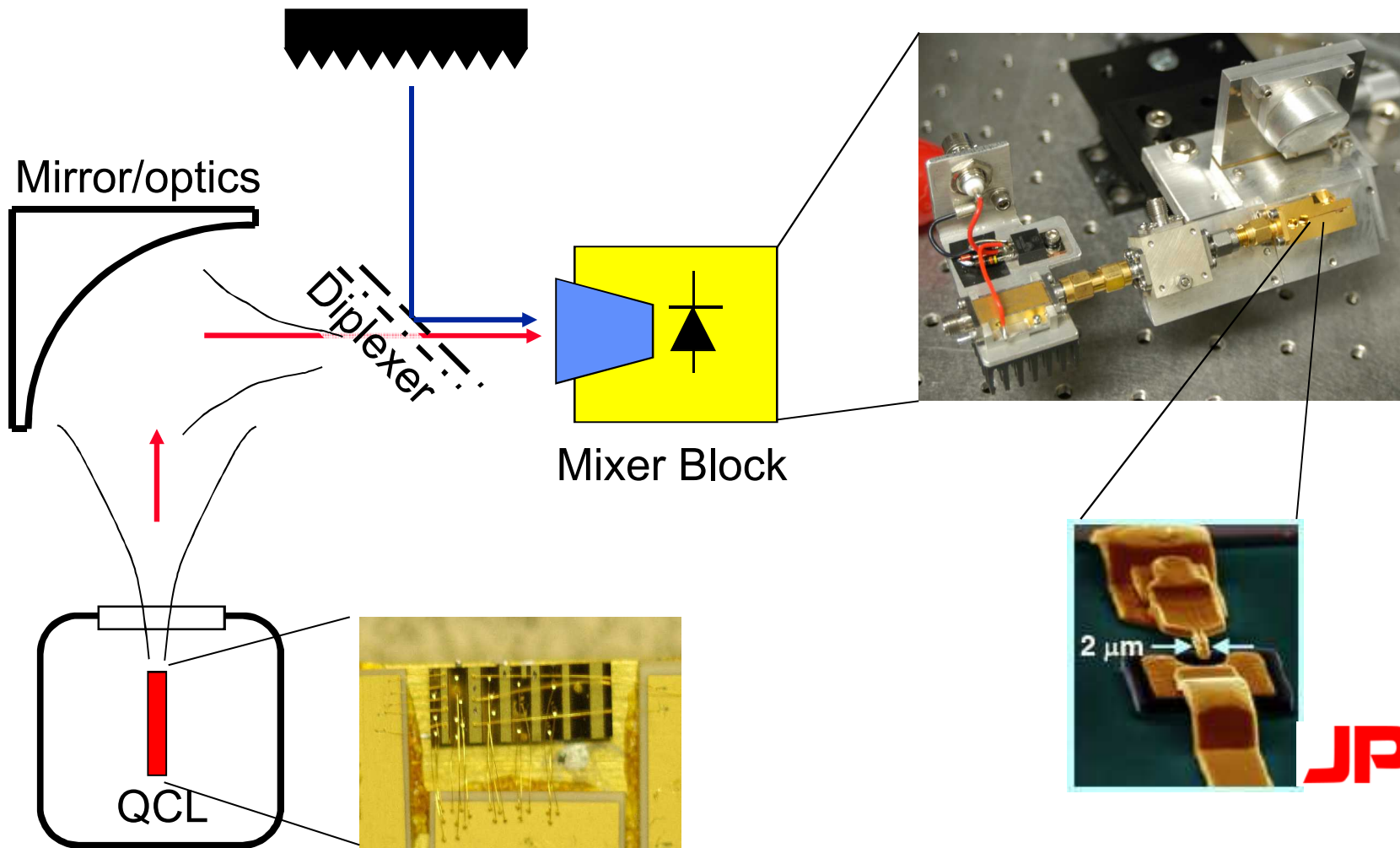


Pulse Amplifier (Ecole Normale Sup.)



Mechanical Tuning (MIT)

Coherent Detector: THz receiver



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

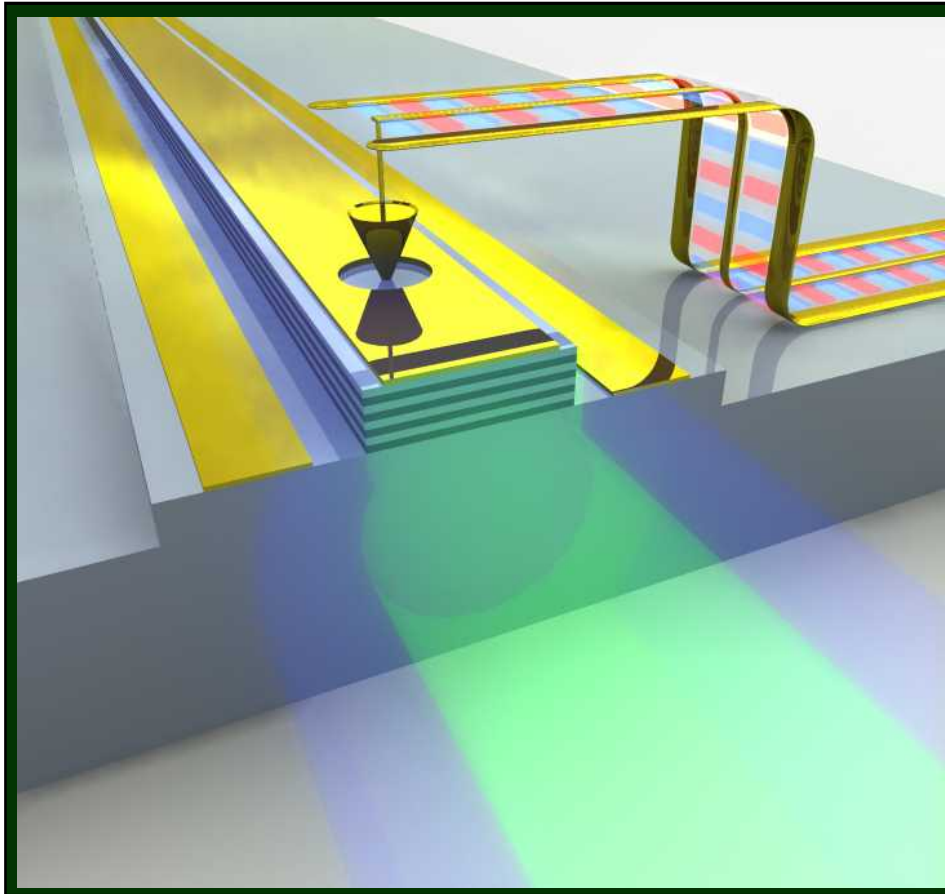


Outline

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

Monolithically Integrated Transciever

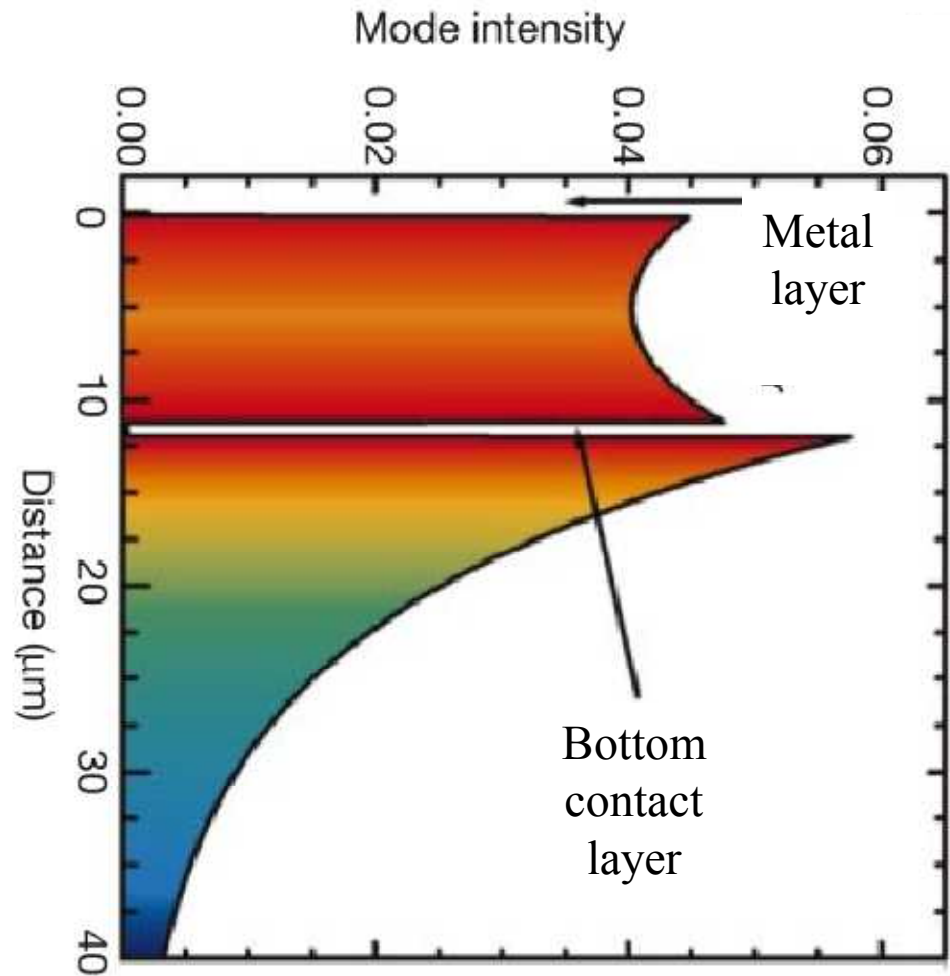
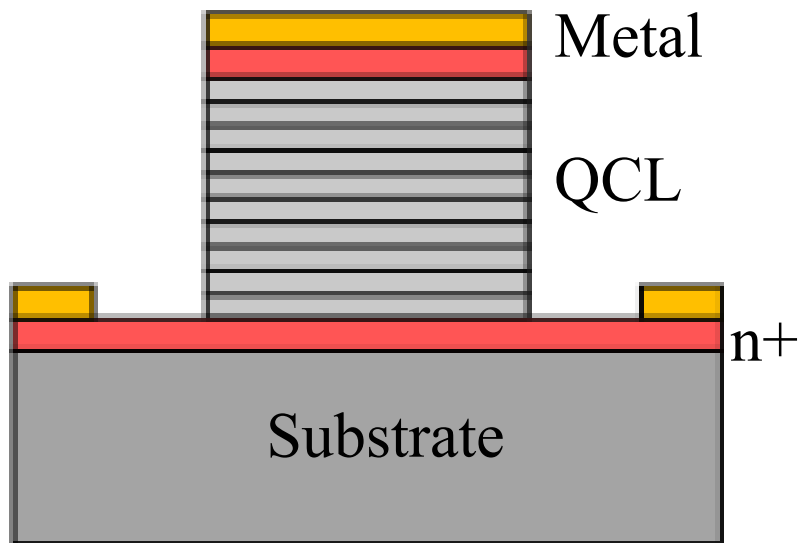
Insert diode directly into laser core



Benefits

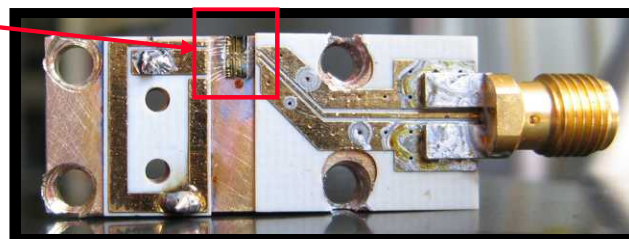
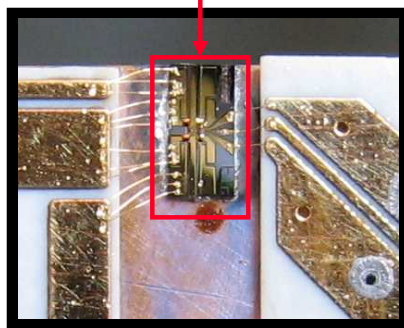
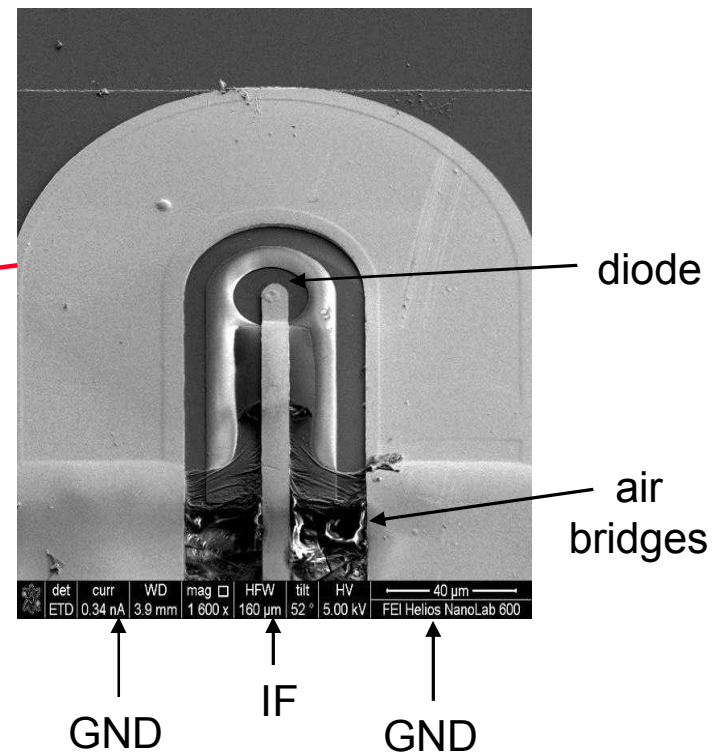
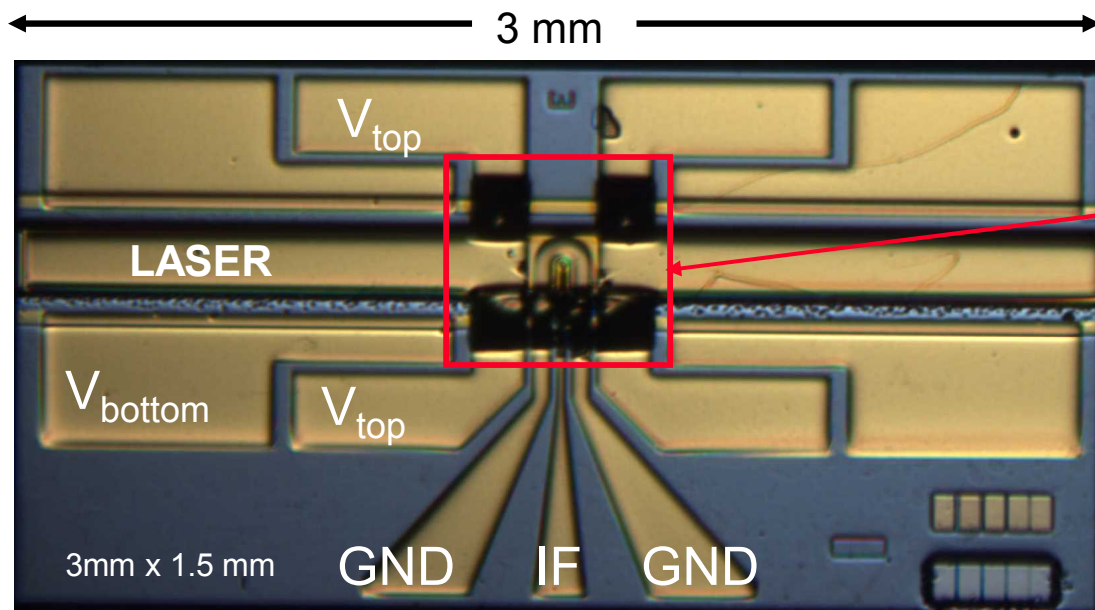
- Reduces size
- Eliminate components
- Ensures constant 'alignment'
- Enhances laser/diode coupling
- Bonus : laser diagnostic tool

Diode placement relative to internal field



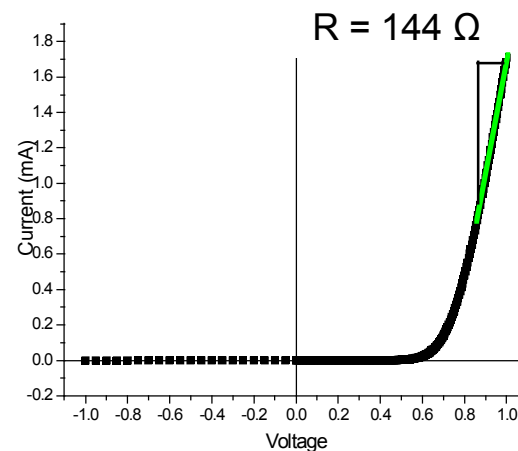
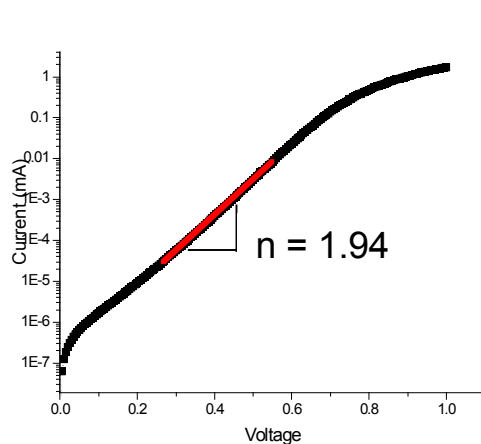
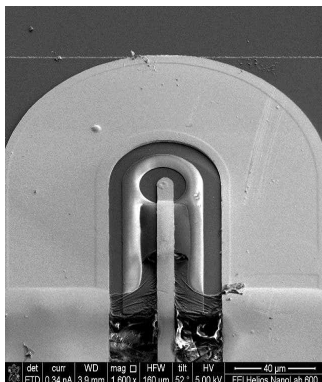
Kohler et al. , Nature, **417**, 2002

Completed QCL/Schottky THz IC

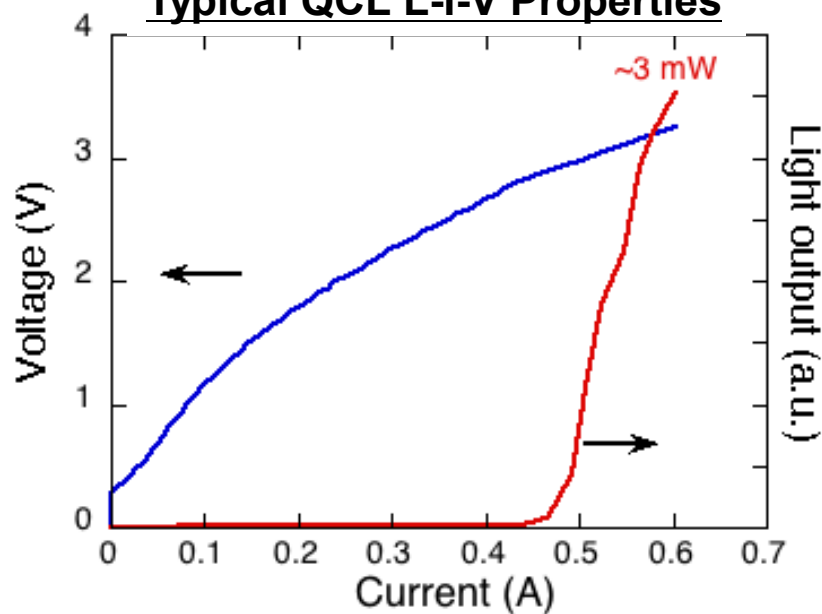
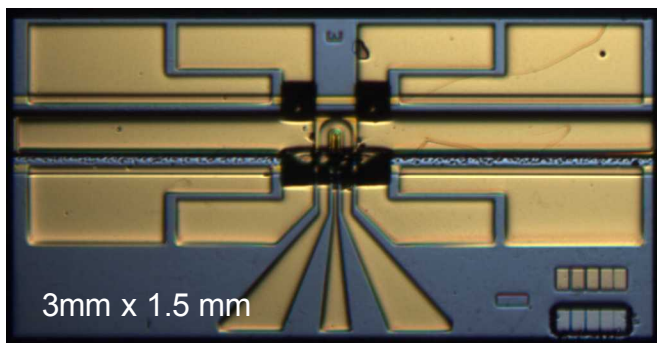


Diode and Laser DC Properties

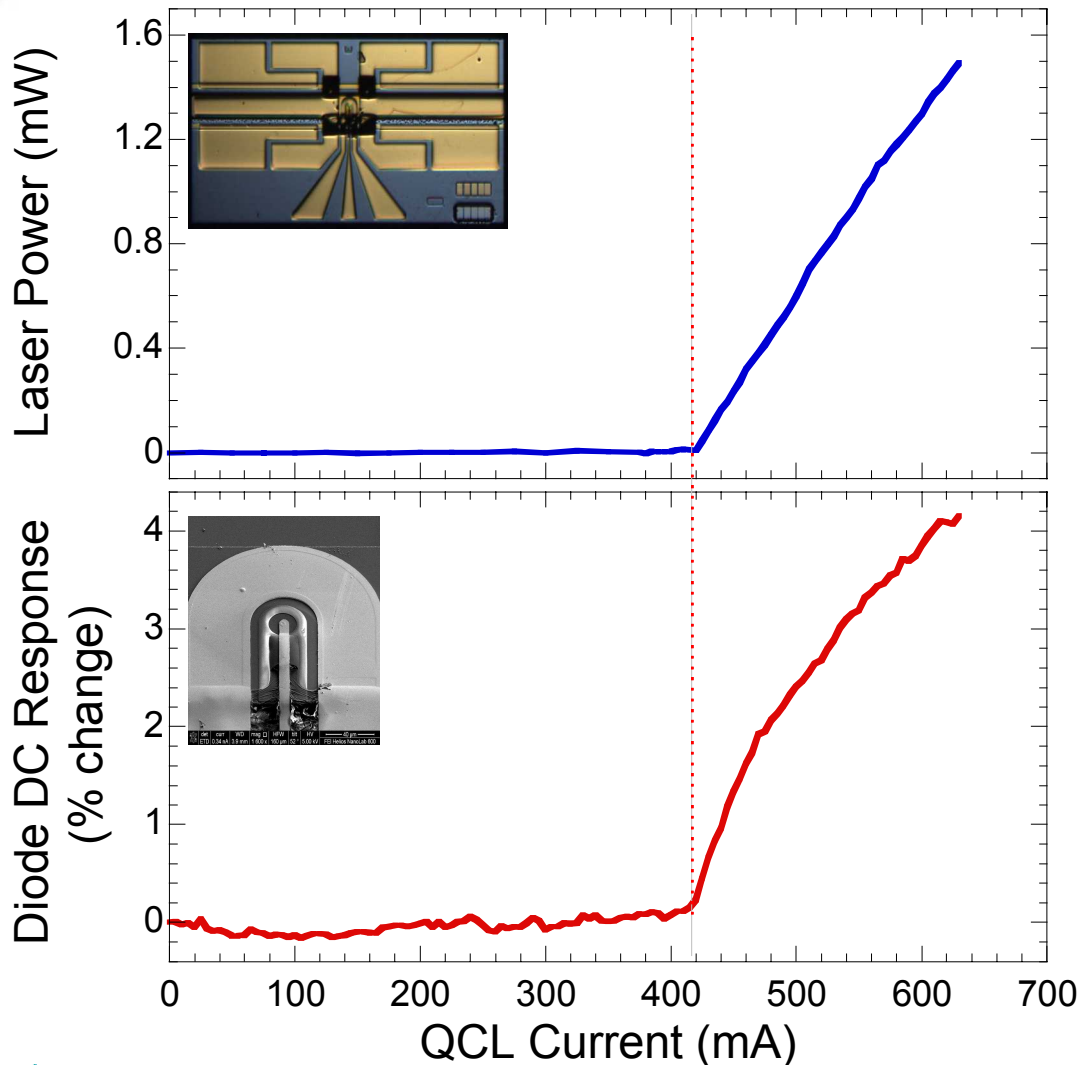
Typical Diode DC I-V Properties



Typical QCL L-I-V Properties

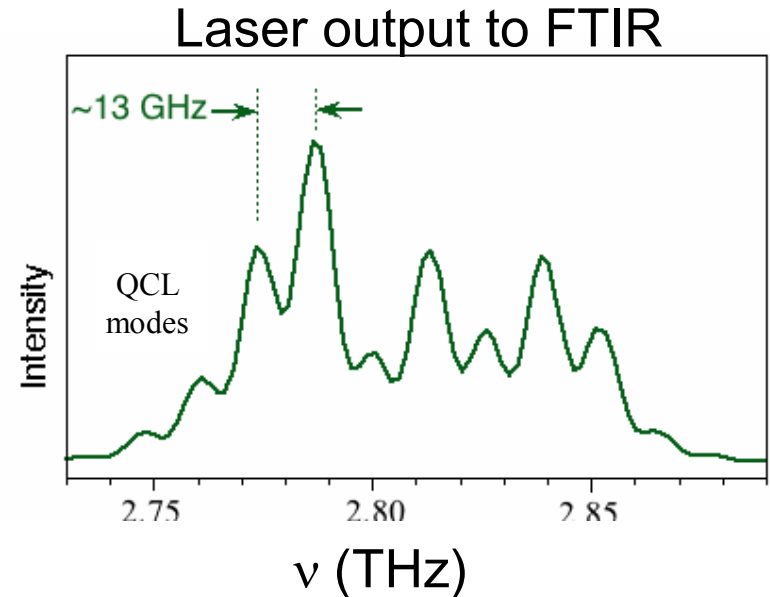
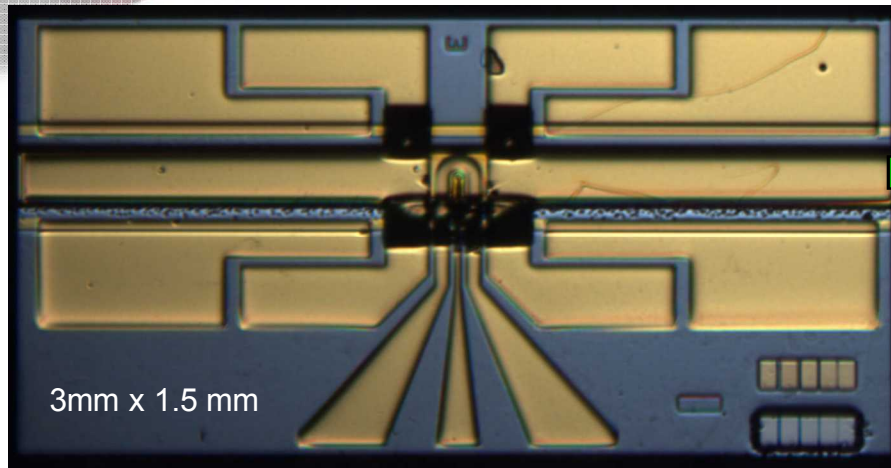


Diode Rectified Response



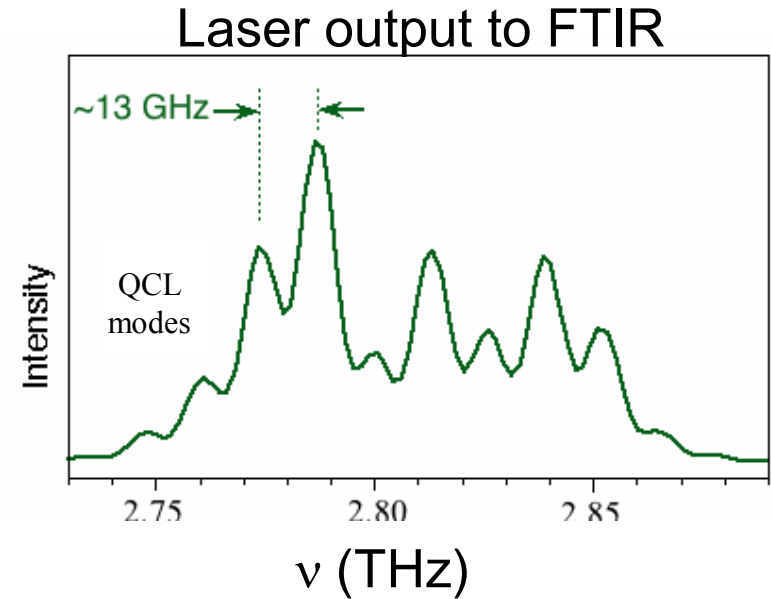
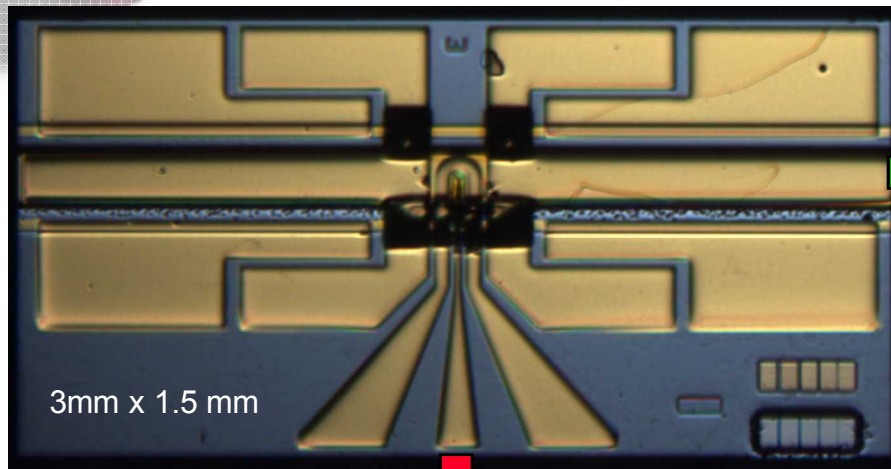
- Diode responds to QCL power
- But not linear in power

Integrated Diode THz Mixer

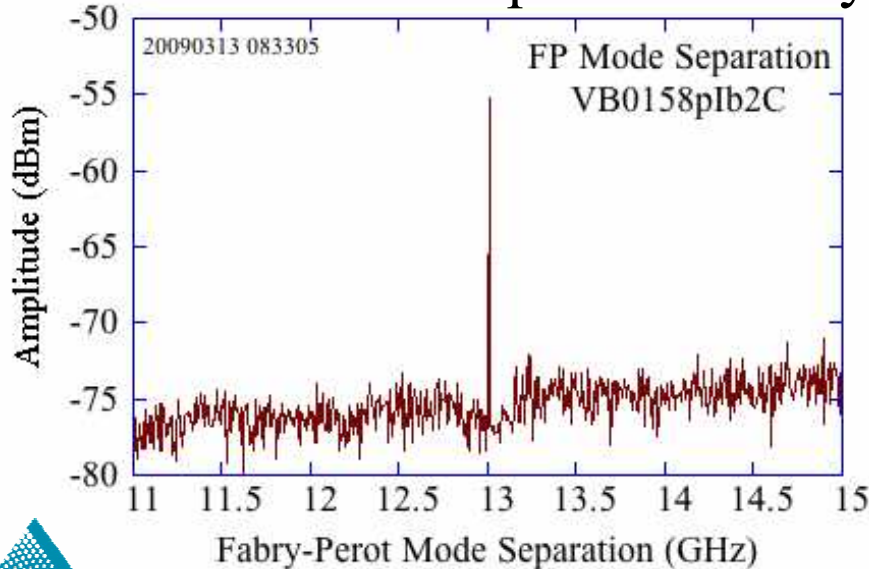


- Purposely built a multimoded QCL centered on 2.81 THz
 - QCL emission (FTIR) spectra show Fabry-Perot modes spaced by ~ 13 GHz

Integrated Diode THz Mixer

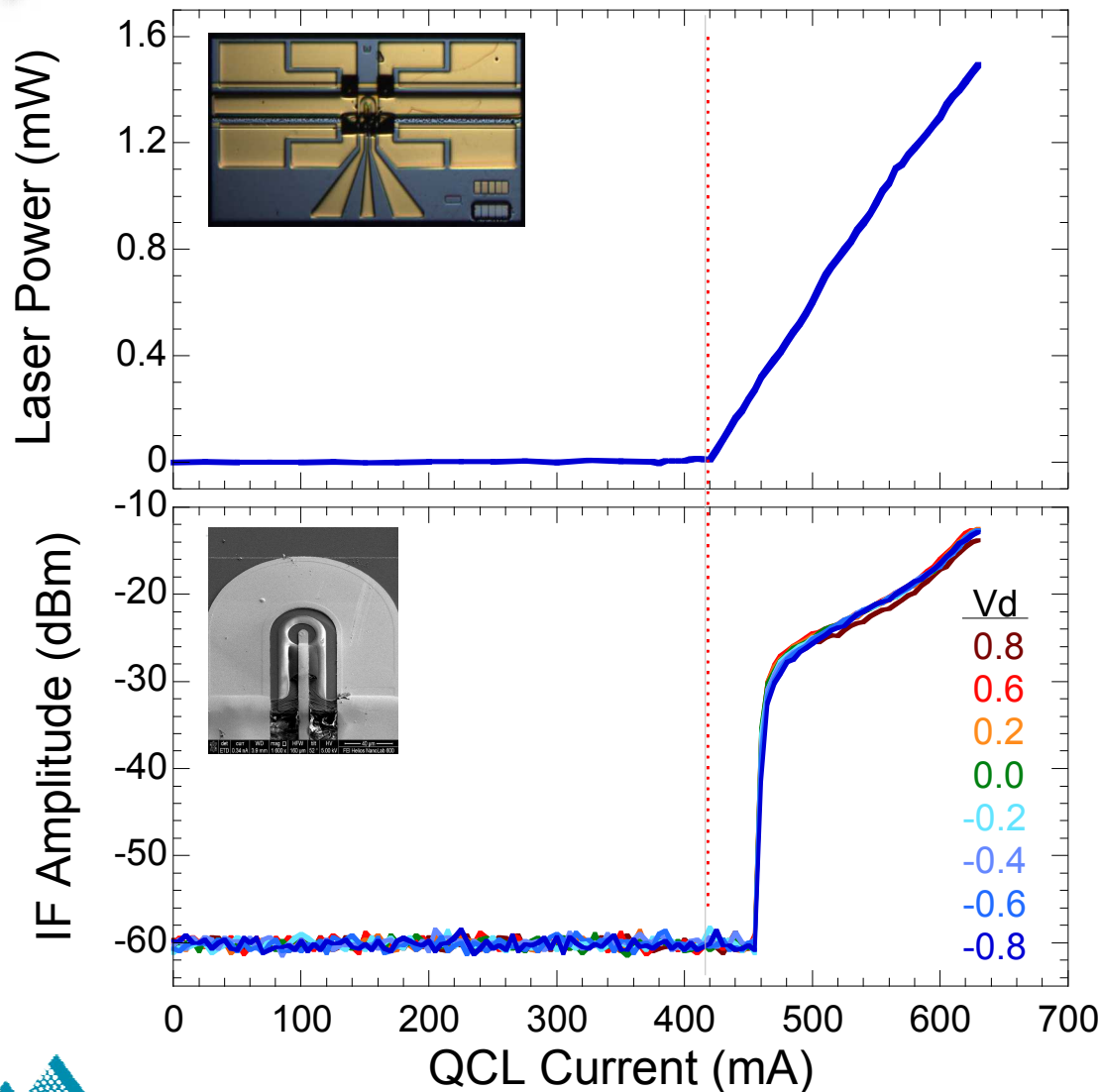


Electrical feed to spectrum analyzer

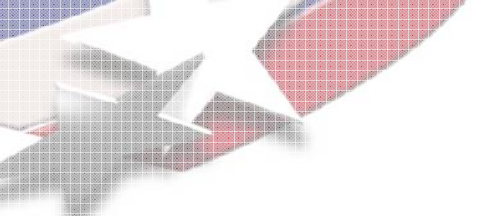


- Diode outputs IF signal at spacing between QCL modes

IF dependence on laser power



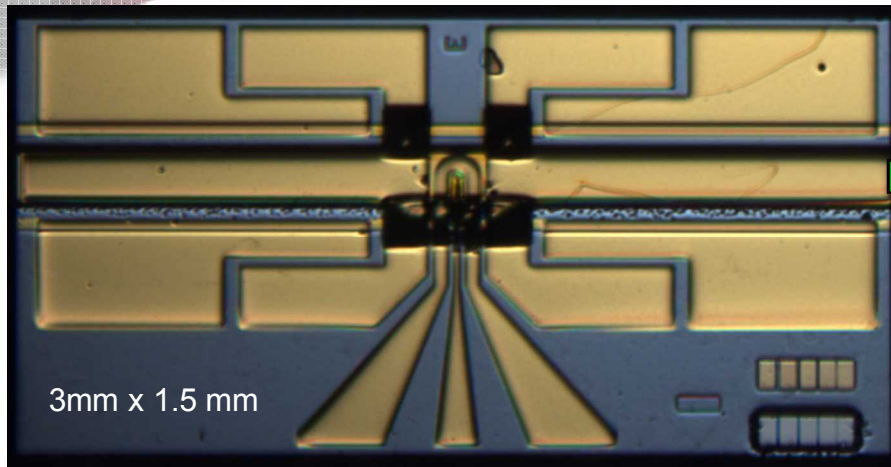
- IF indicates when laser turns multimoded.
- IF amplitude is fairly independent of diode bias.



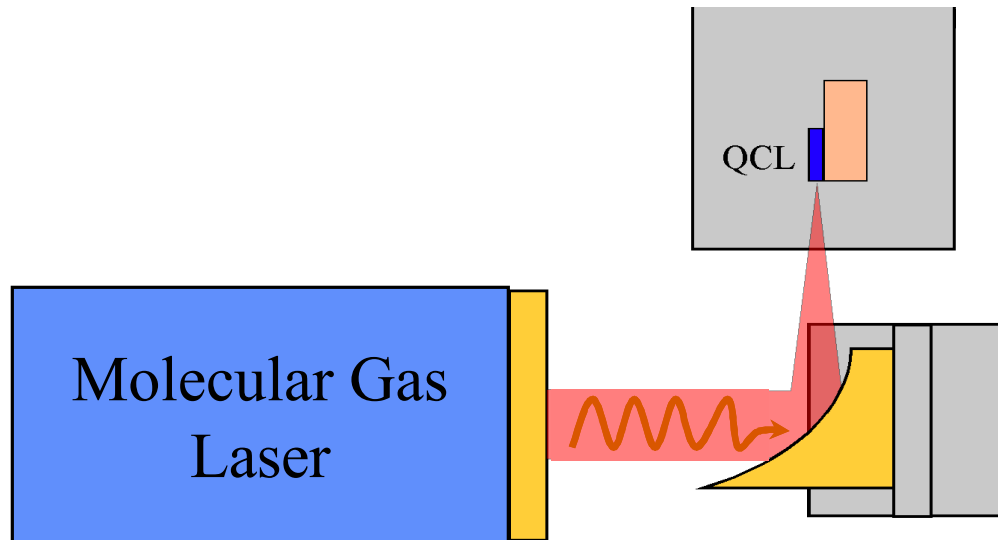
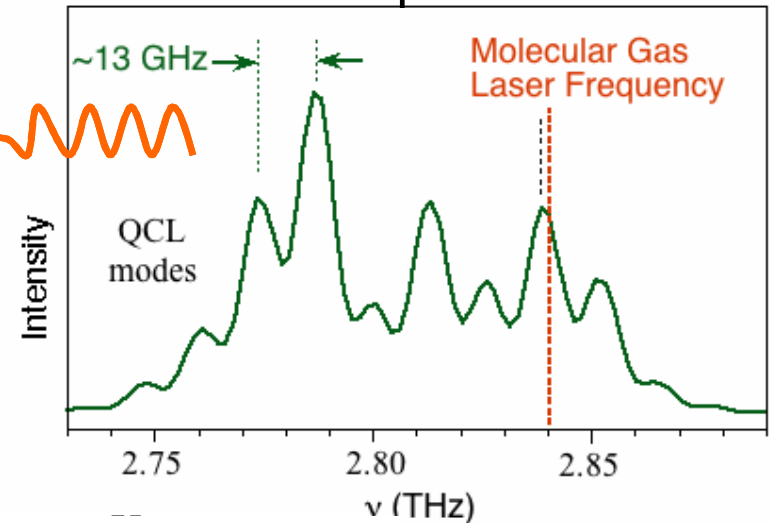
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- Monolithically Integrated Transceiver Description
- Demonstration of Receiver Operation
- Laser Characterization

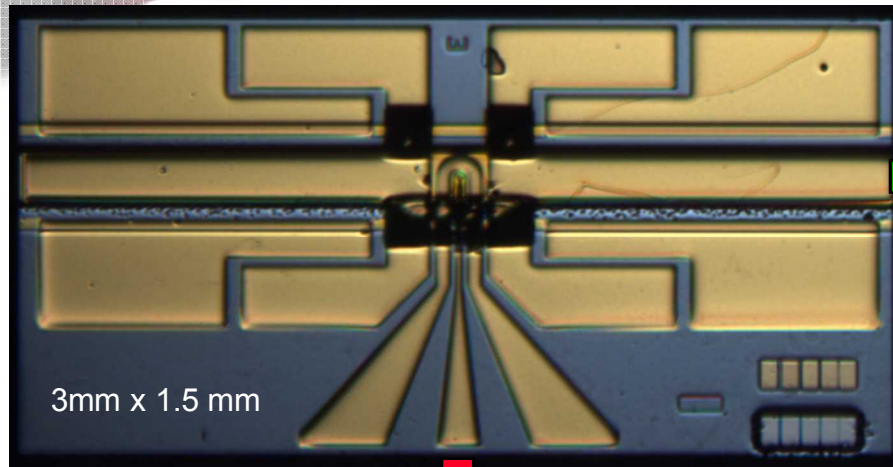
Integrated THz Receiver



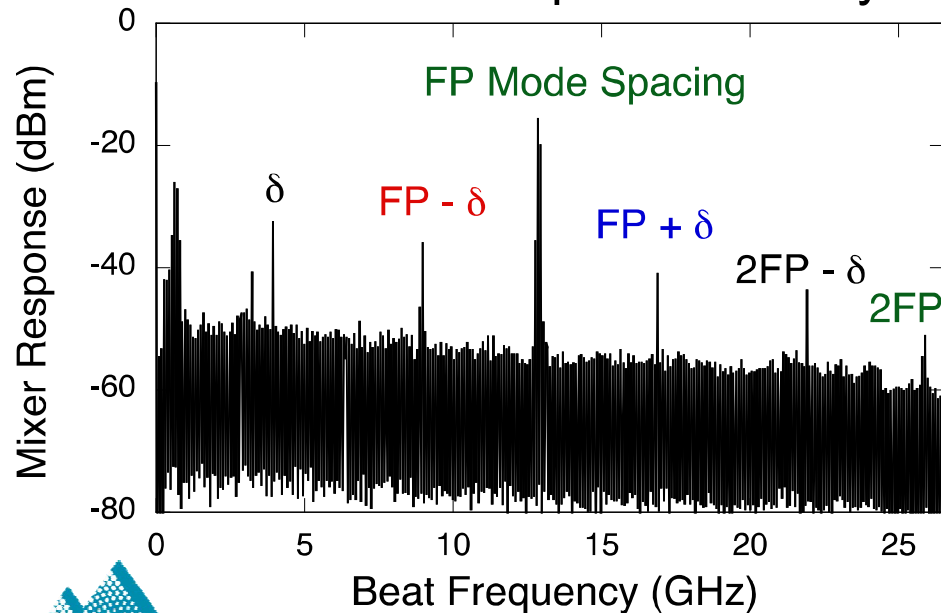
Laser output to FTIR



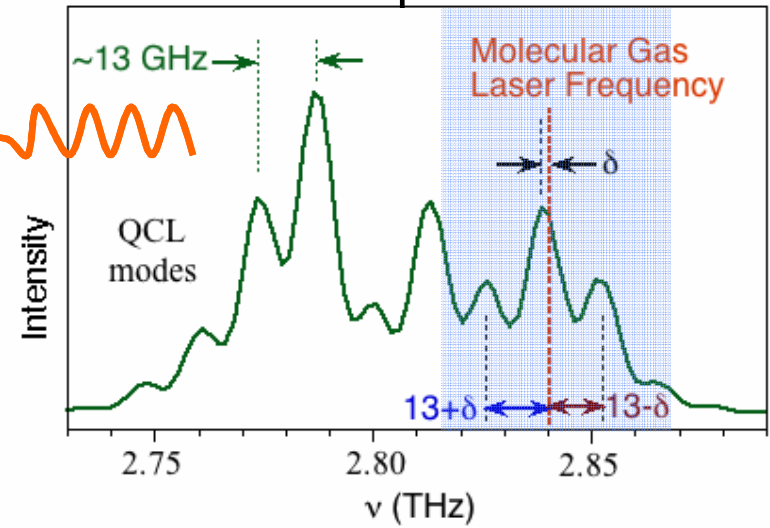
Integrated THz Receiver



Electrical feed to spectrum analyzer

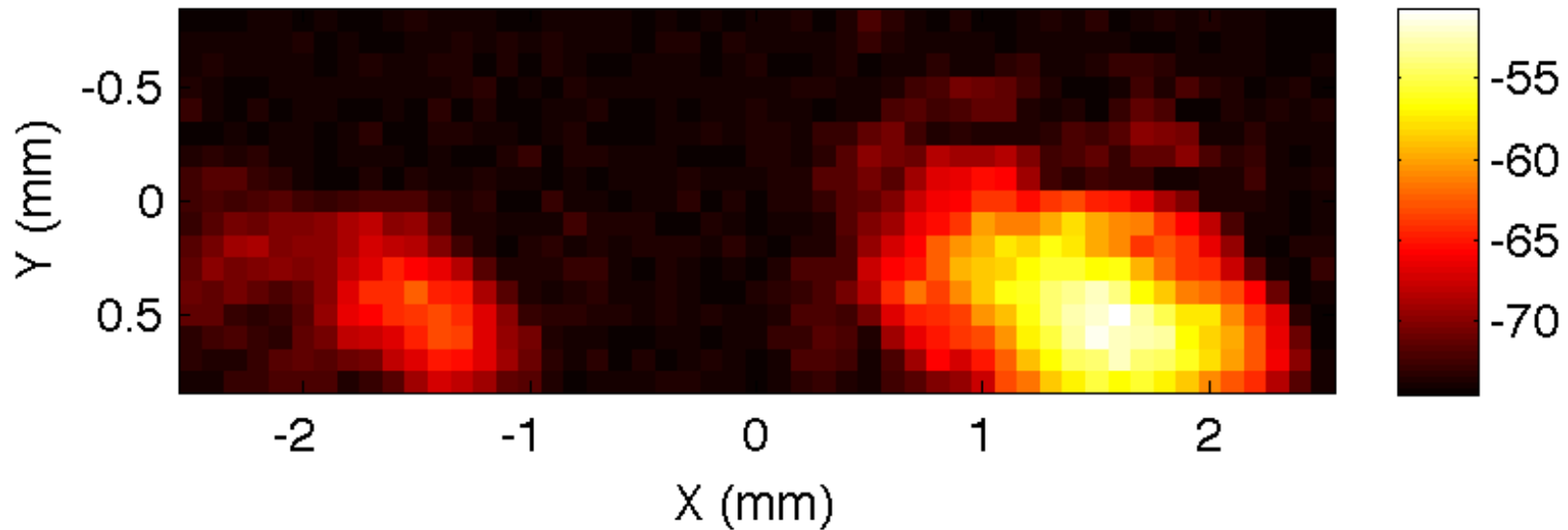
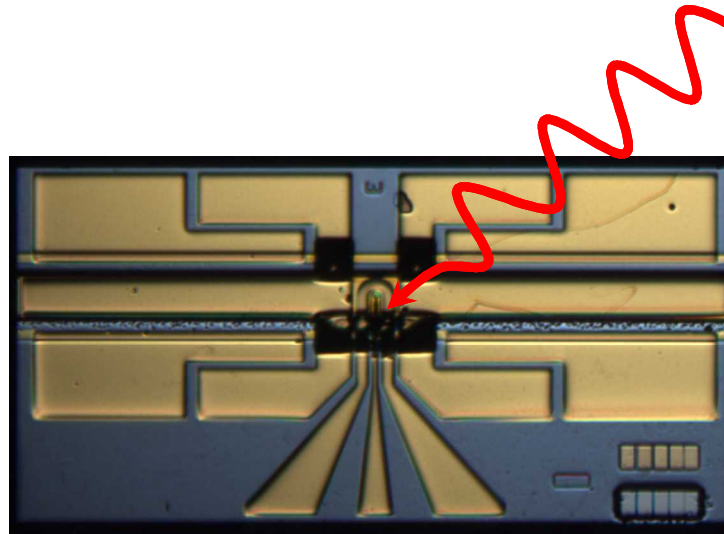
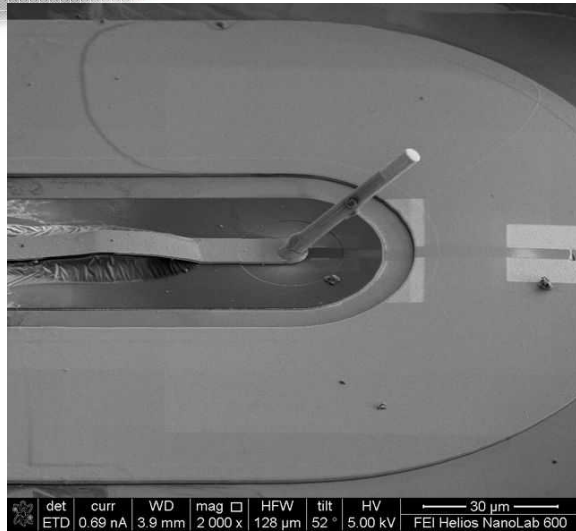


Laser output to FTIR



High-resolution
coherent
receiver

External Coupling to Receiver



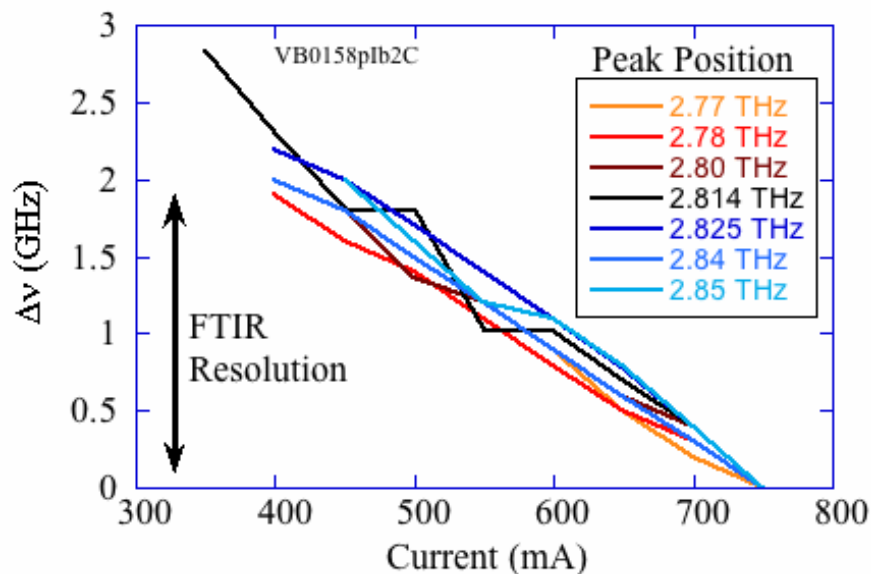
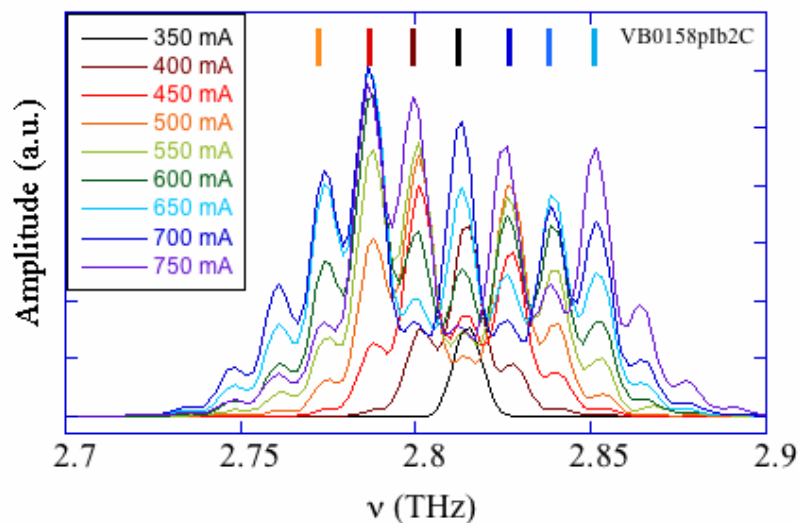


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 - Current Tuning / Temperature Tuning
 - Injection/Phase Locking
 - Feedback Sensitivity

Laser Characterization

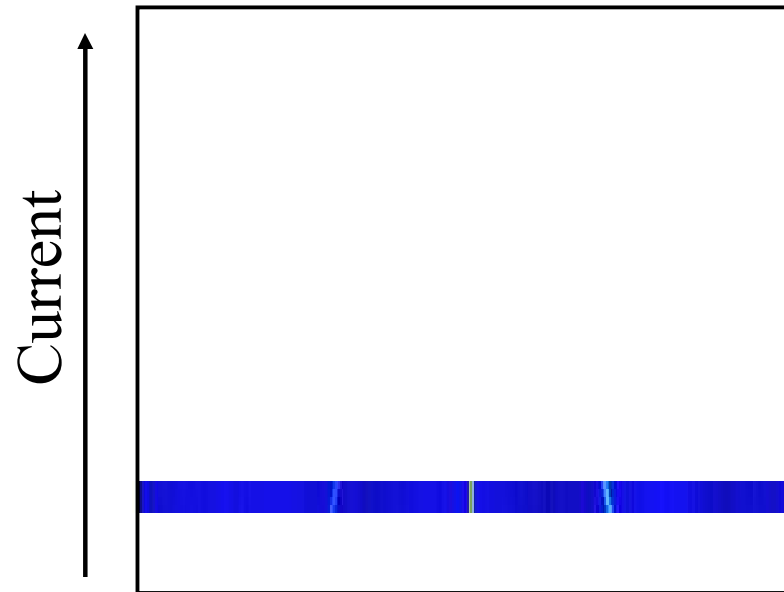
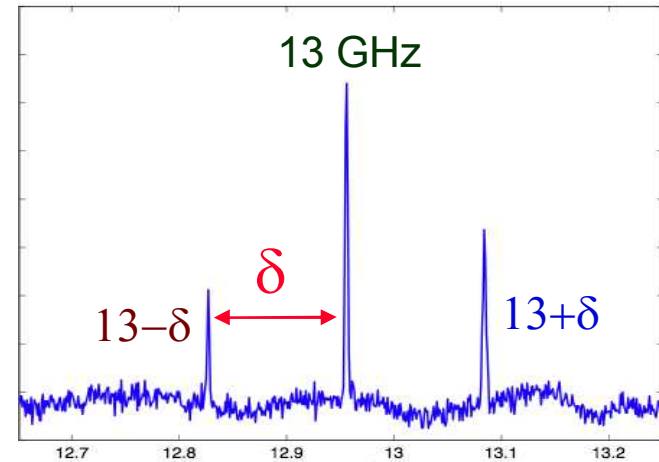
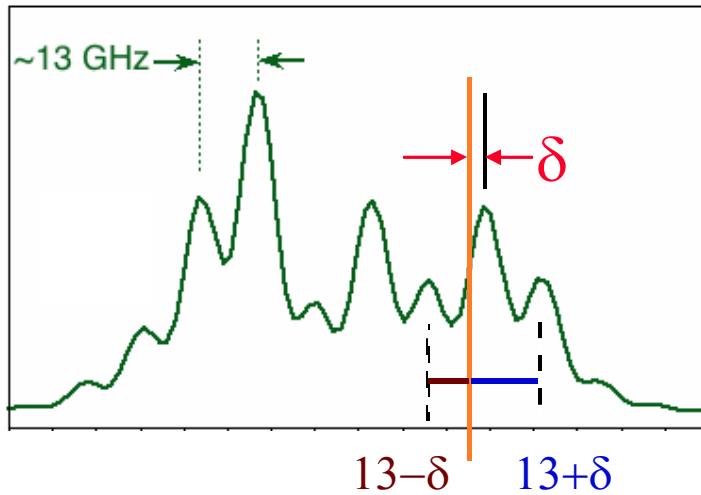
Current Tuning



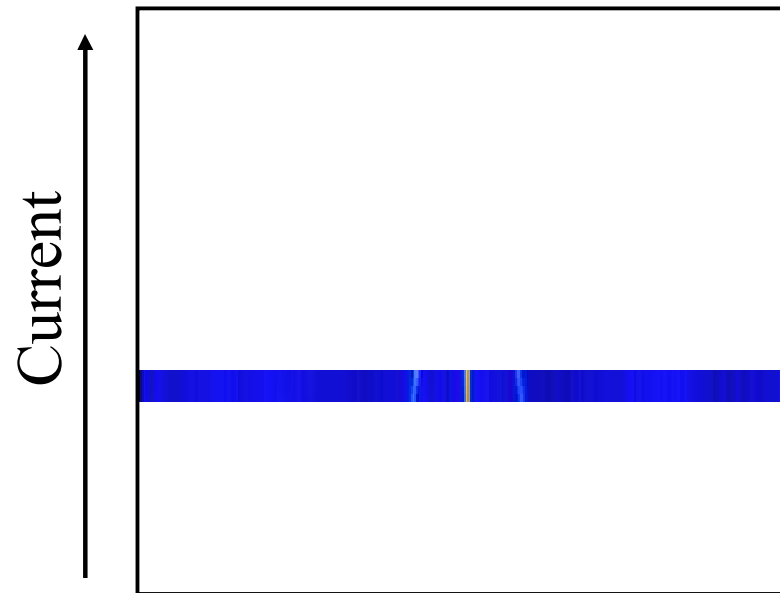
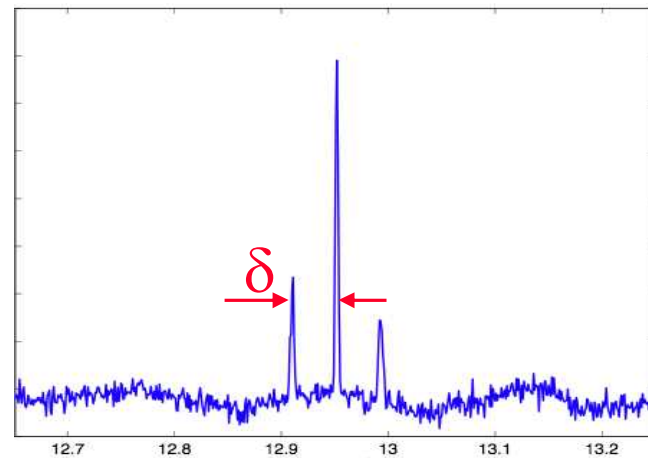
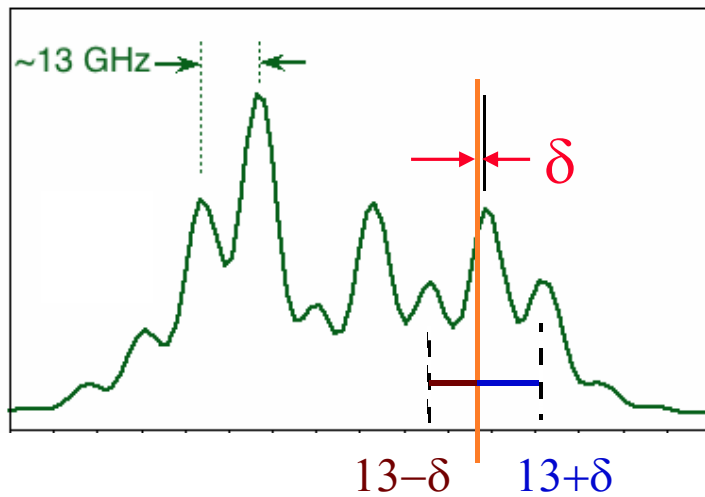
Small redshift with current

- Smaller than FTIR resolution
- Fairly noisy measurement

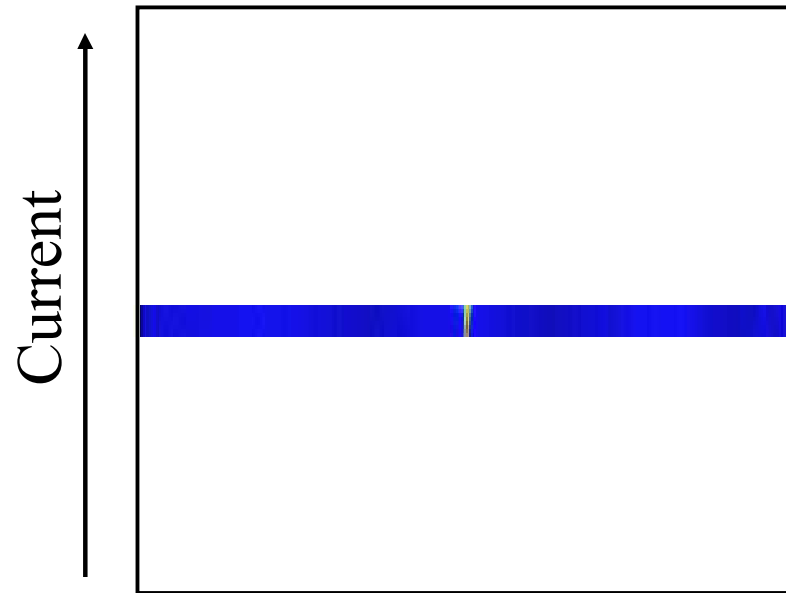
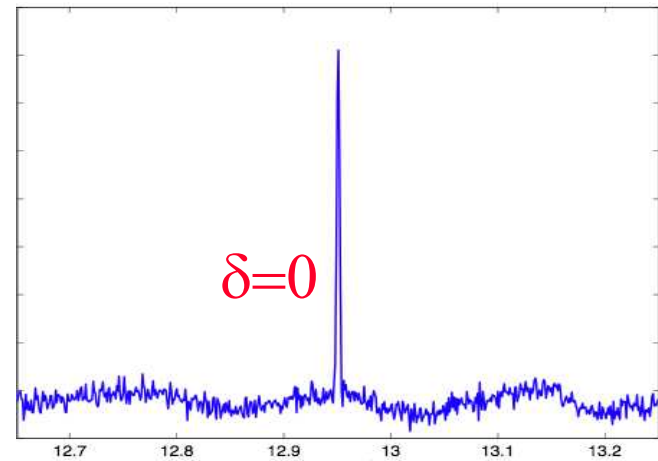
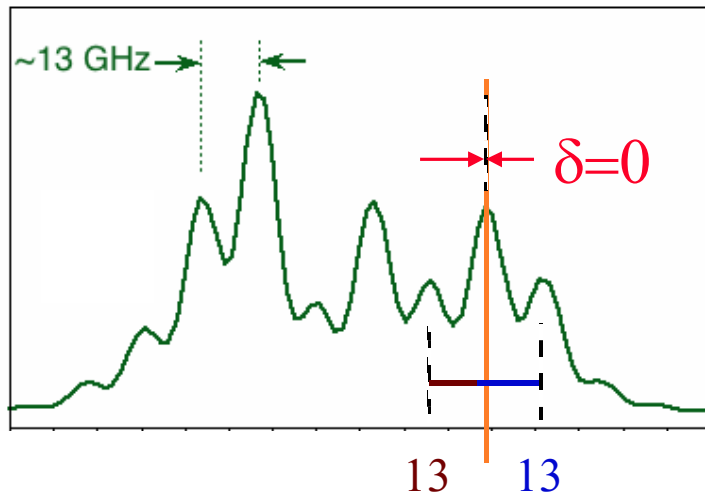
Current Tuning



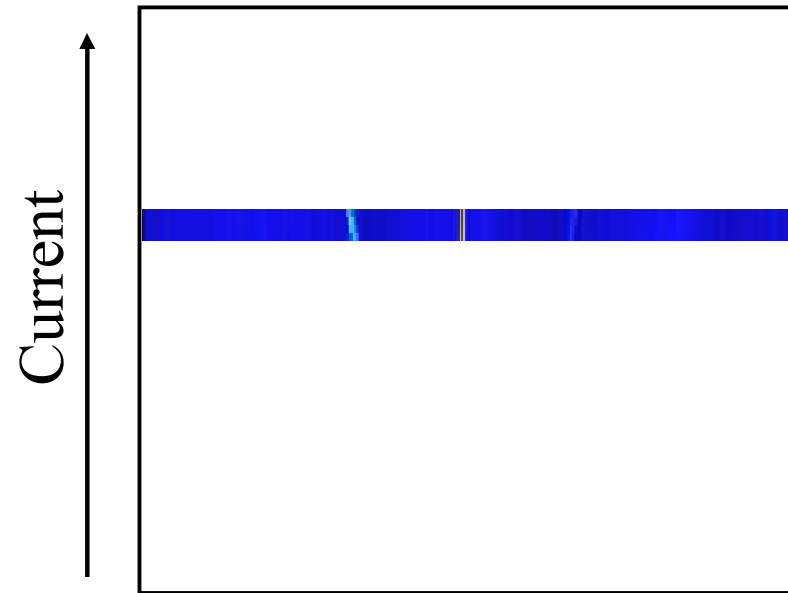
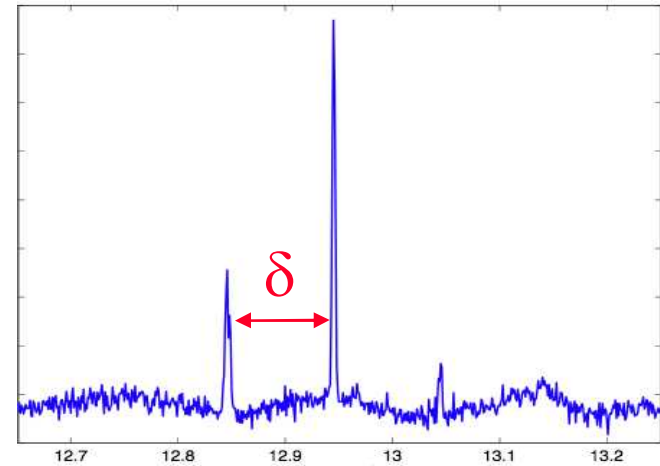
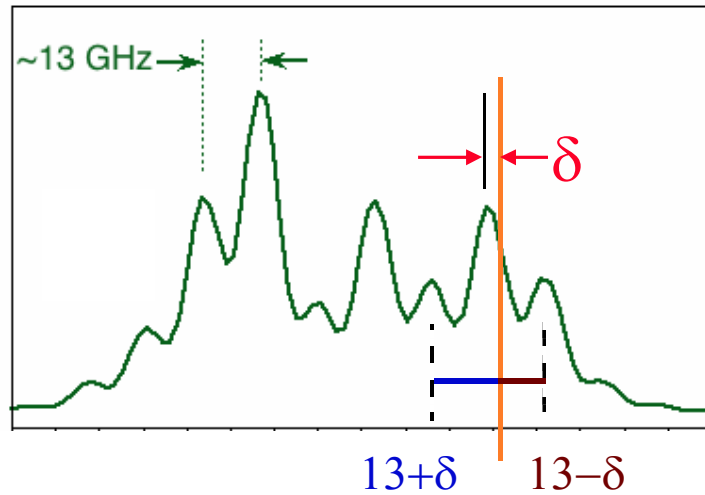
Current Tuning



Current Tuning

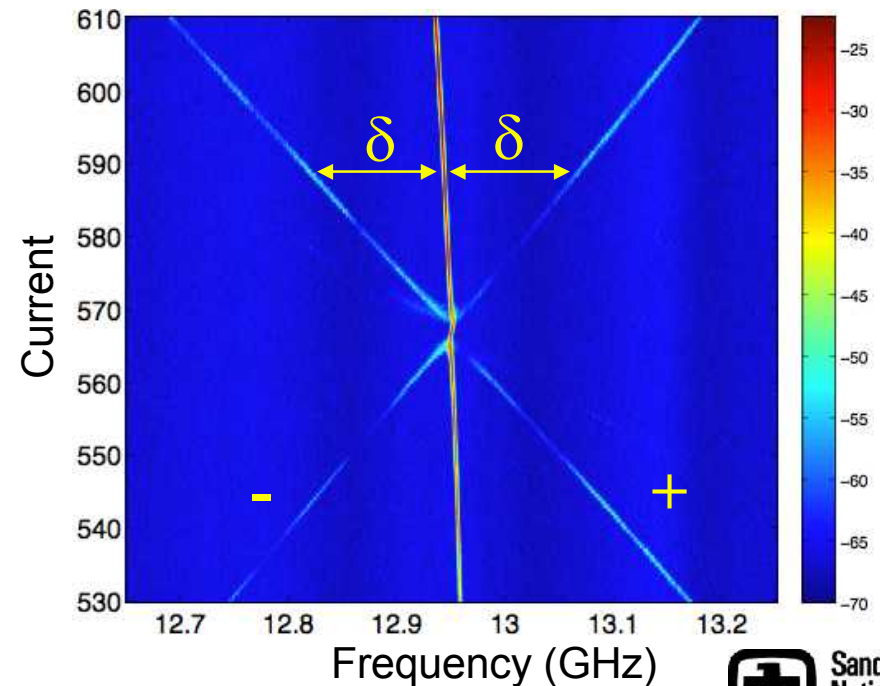
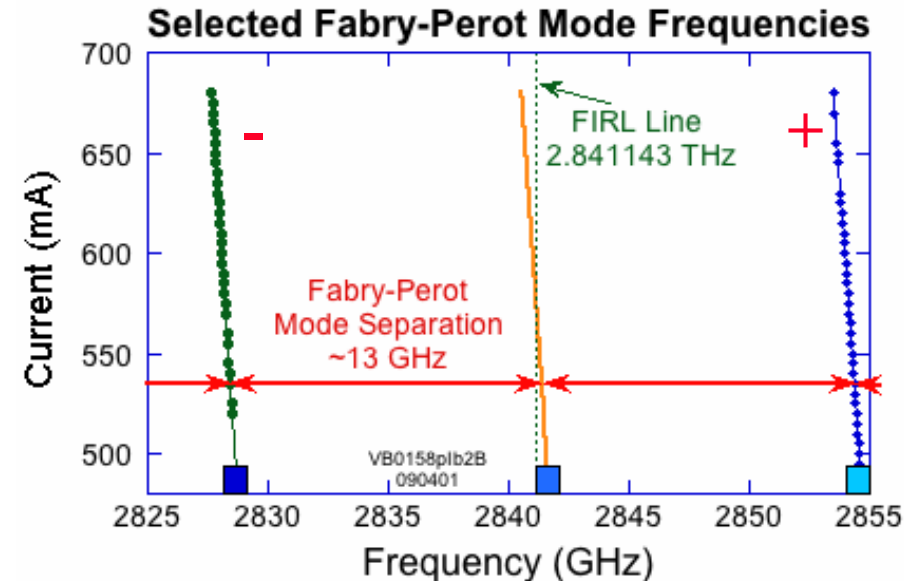
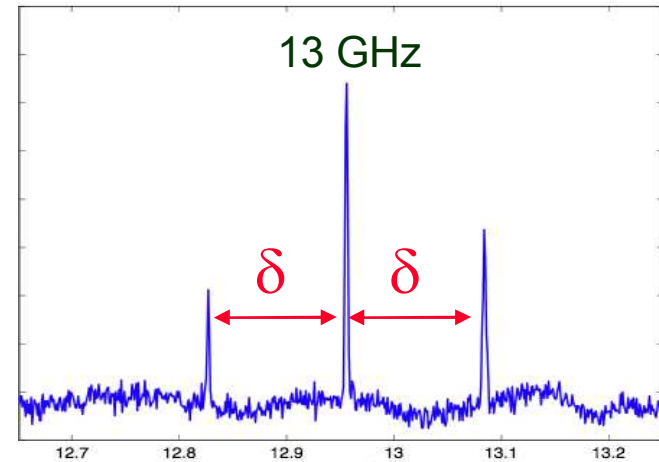


Current Tuning



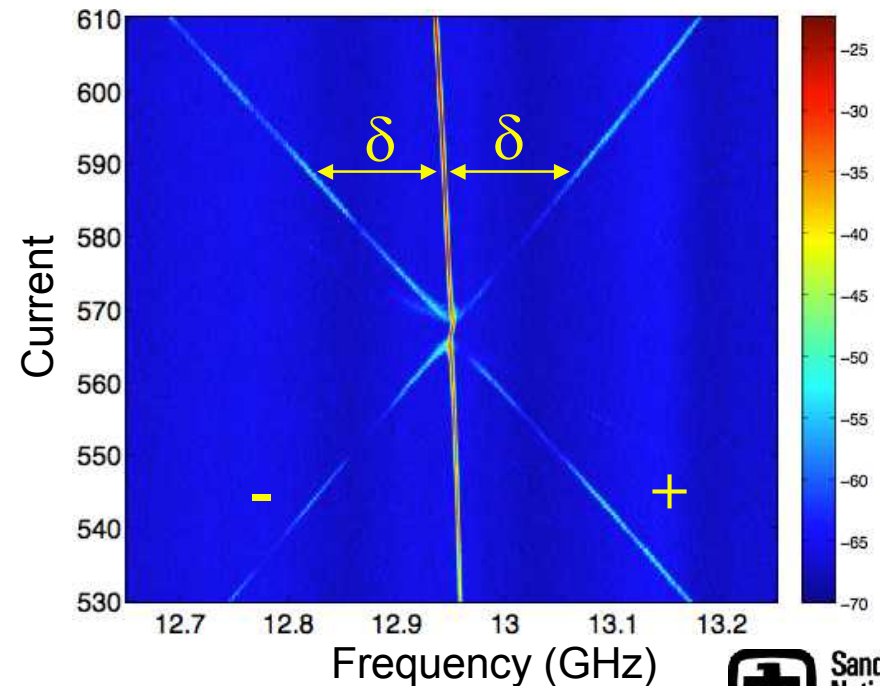
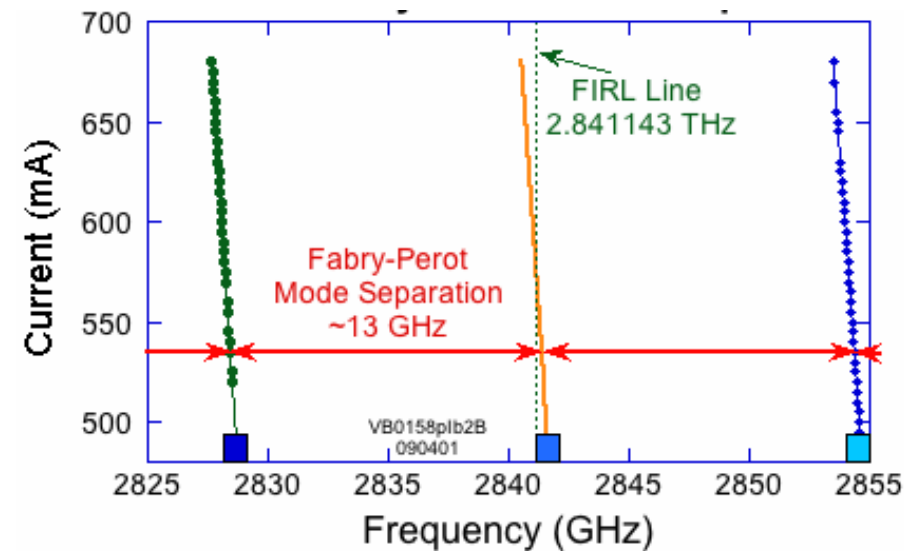
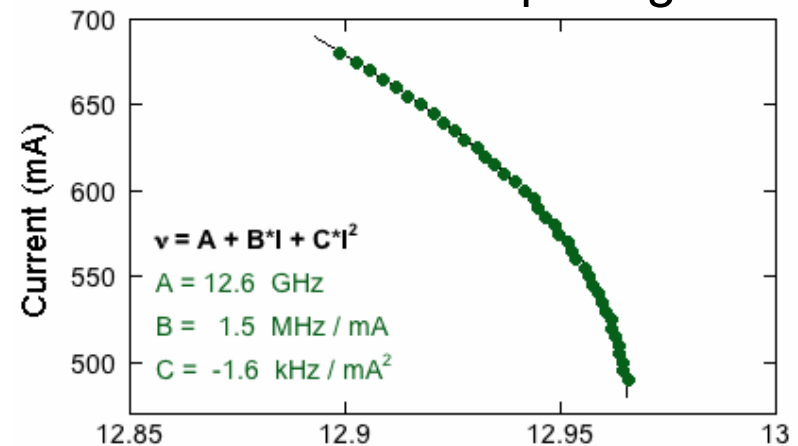
Current Tuning

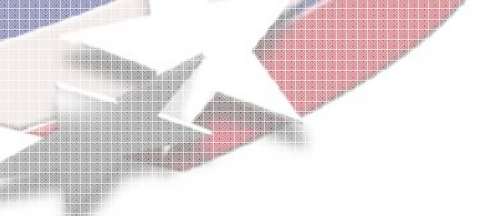
~ 6 MHz / mA



Current Tuning

QCL Mode Spacing



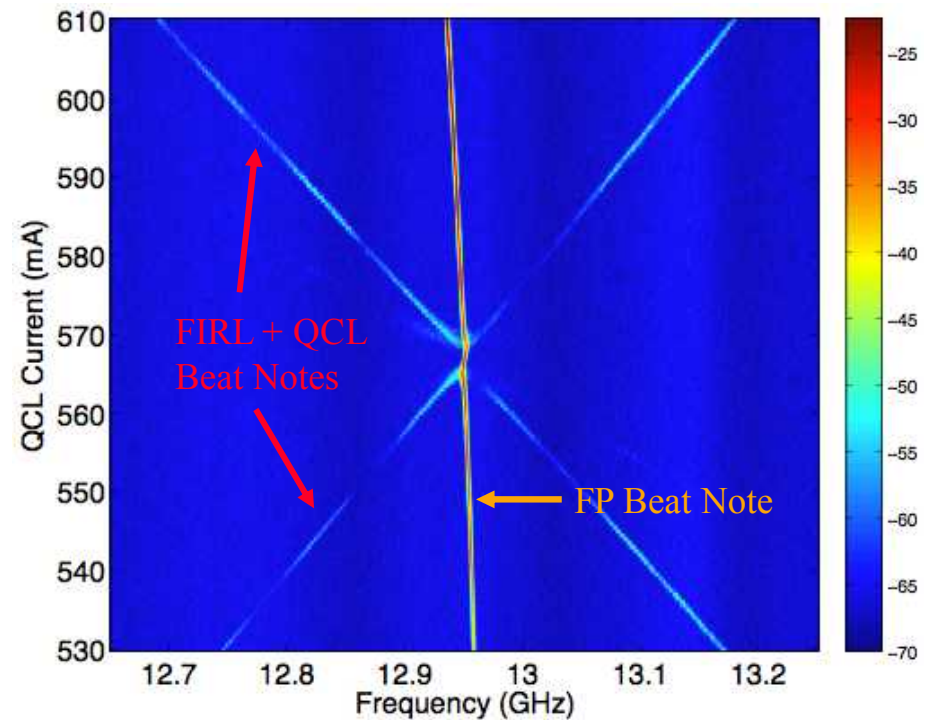
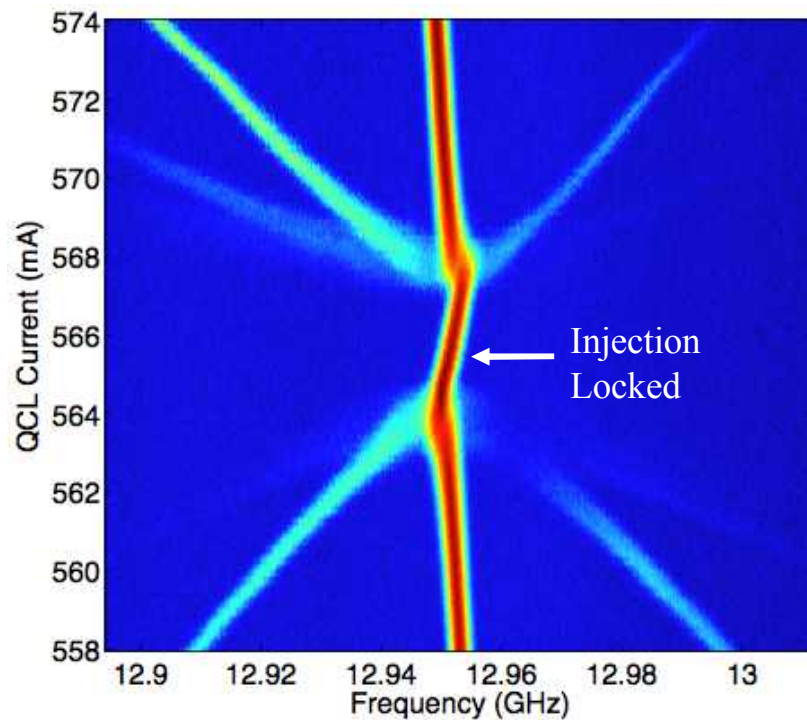


Outline

- Monolithically Integrated Transceiver Description
- Demonstration of Receiver Operation
- **Laser Characterization**
 - Current Tuning / Temperature Tuning
 - Injection/Phase Locking
 - Feedback Sensitivity

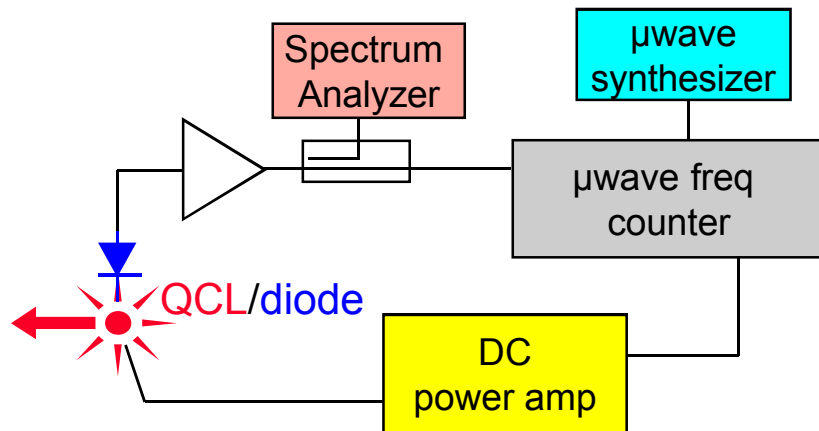
Injection Locking

- For $\delta < 23$ MHz, the lasers lock.



Frequency/Phase Locked THz IC

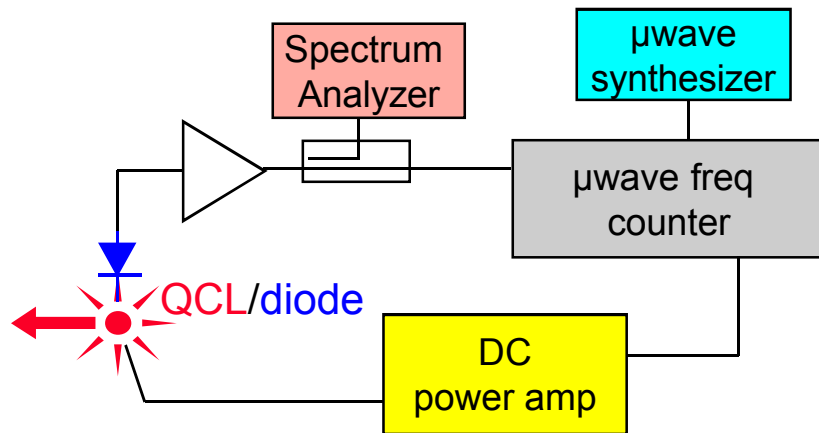
- Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations*



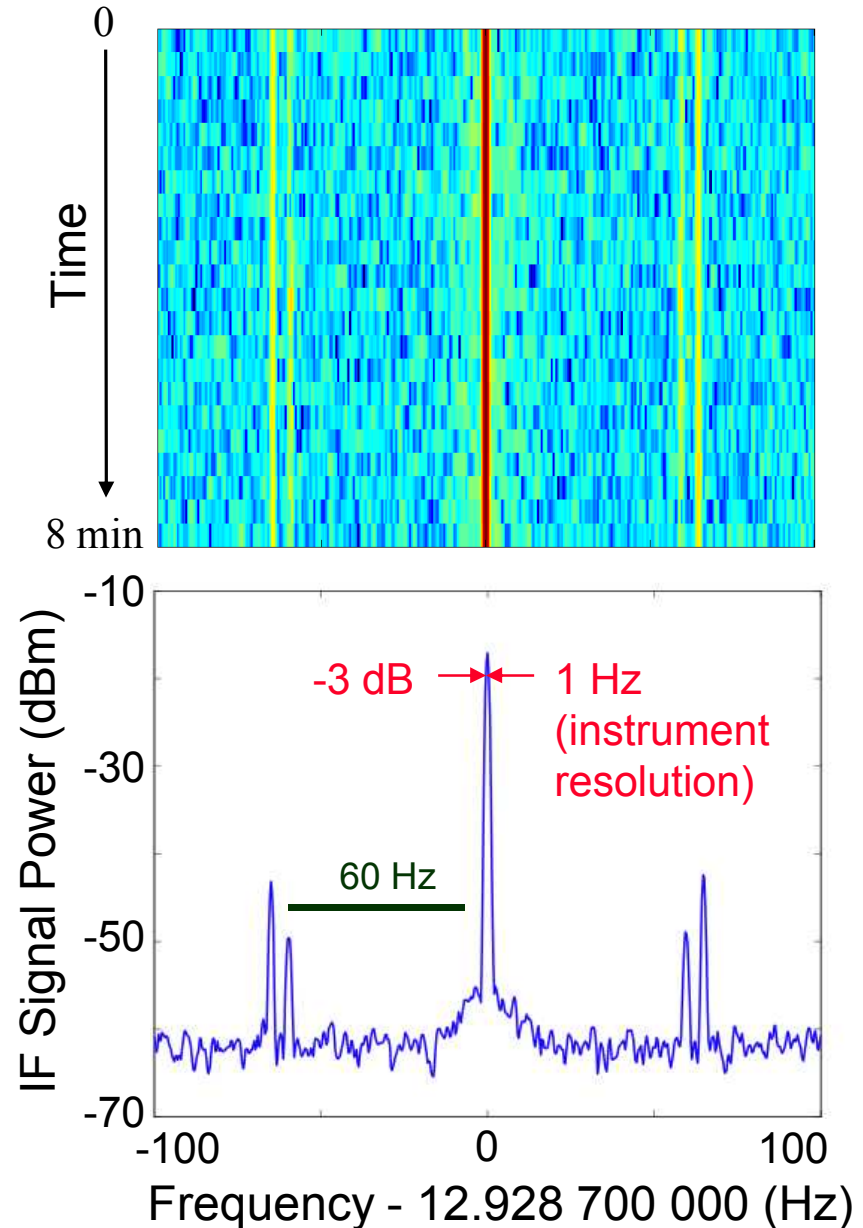
*Following Betz, Opt. Lett. **30**, 1837, (2005)
Baryshev, APL, **89**, 031115, (2006)

Frequency/Phase Locked THz IC

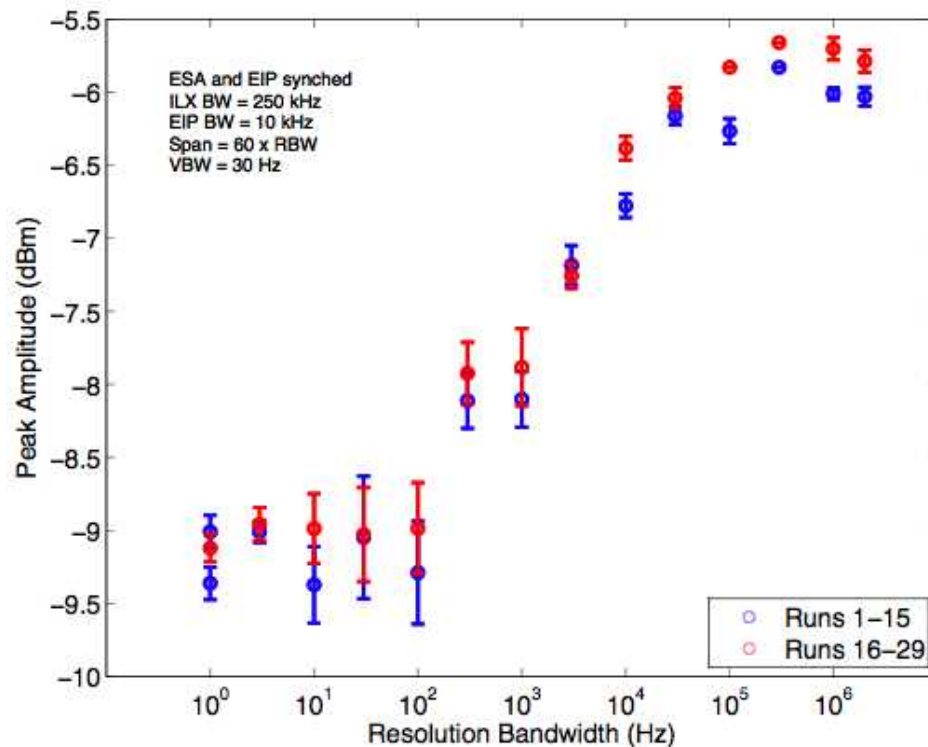
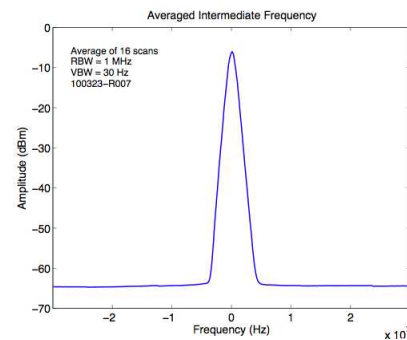
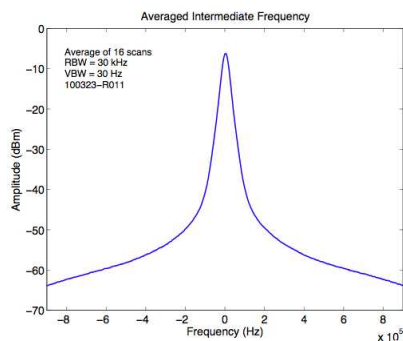
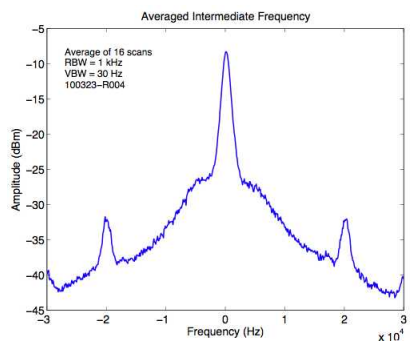
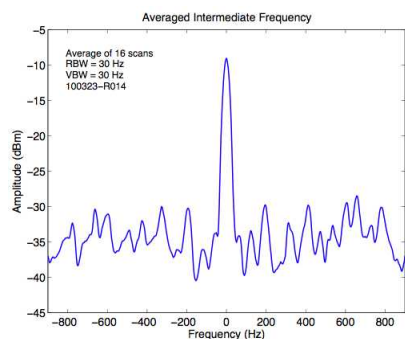
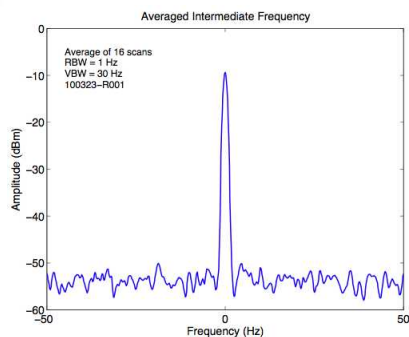
- Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations*
- Locked IF linewidth ~ 1 Hz
- Extremely stable IF frequency and amplitude



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

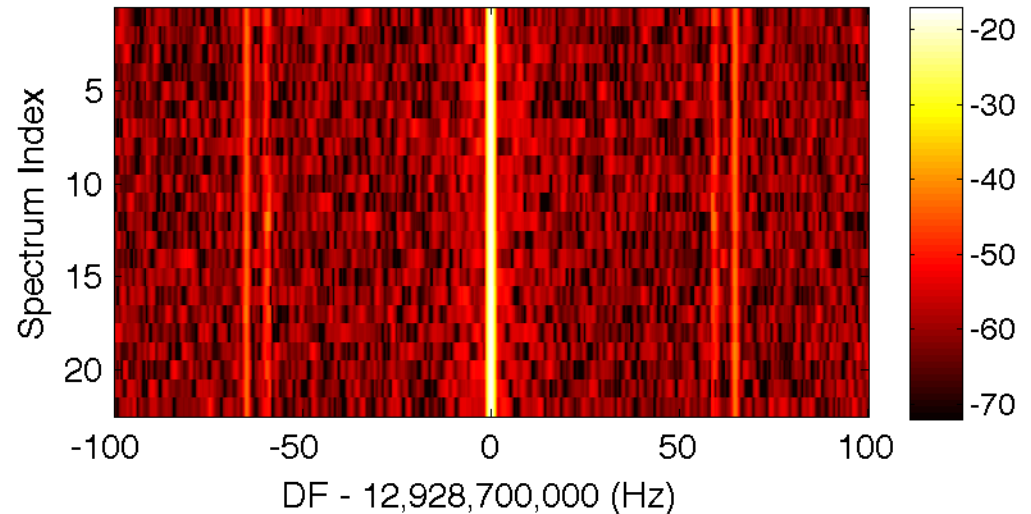


Phase Locking Bandwidth

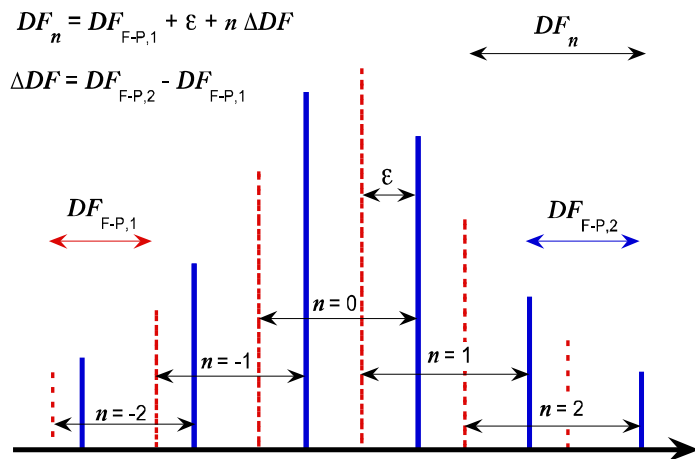
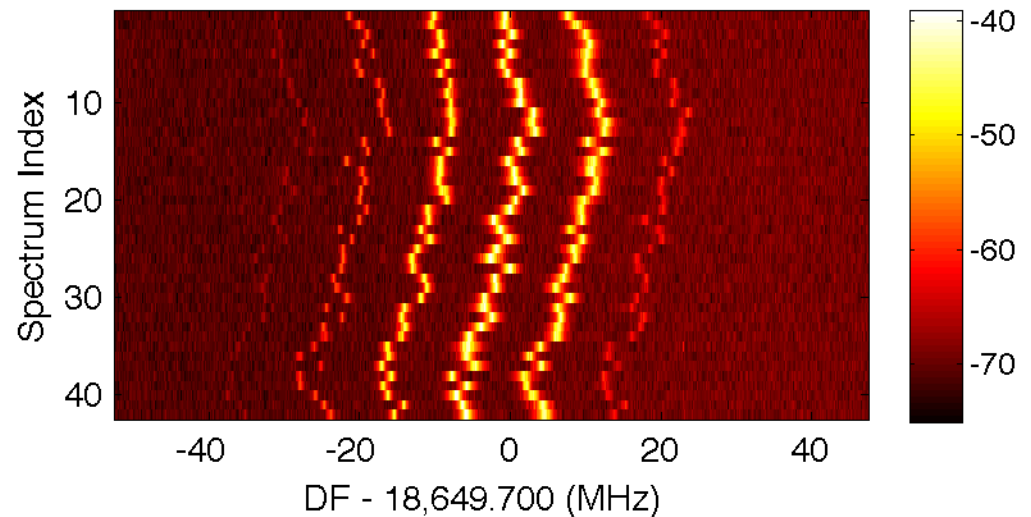


Absolute Frequency not Simultaneously Locked

Internal F-P DF Spectrum



External DF Spectrum



$$DF_n = DF_{F-P,1} + \varepsilon + n \Delta DF$$

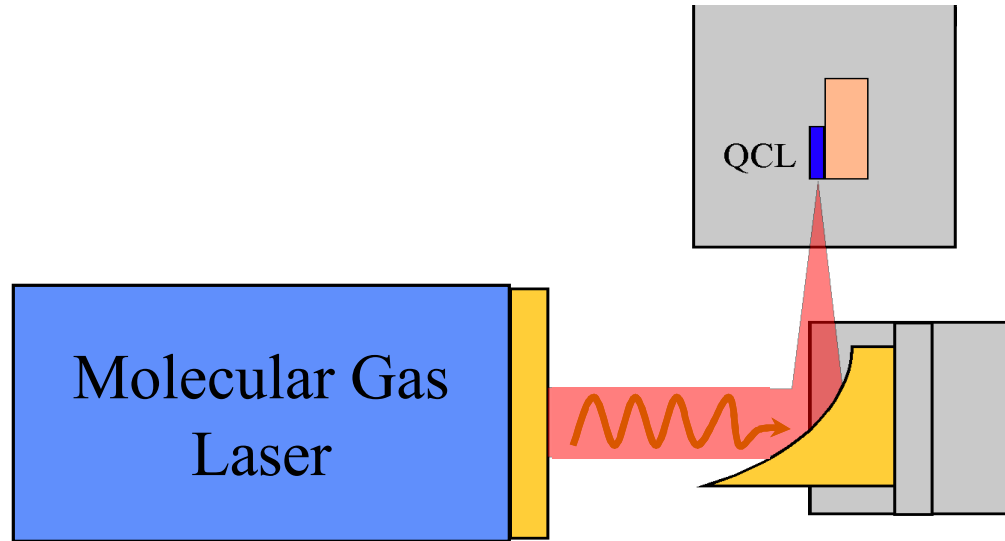
$$\Delta DF = DF_{F-P,2} - DF_{F-P,1}$$



Outline

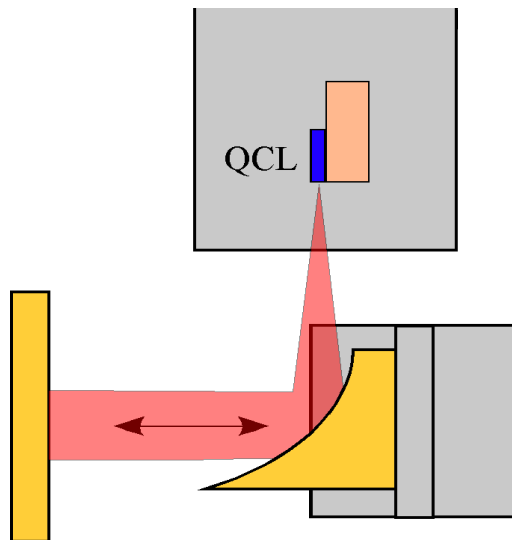
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Feedback Sensitivity



Some of the QCL emission retroreflects

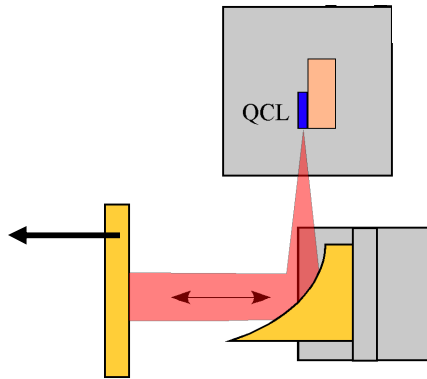
Feedback Sensitivity



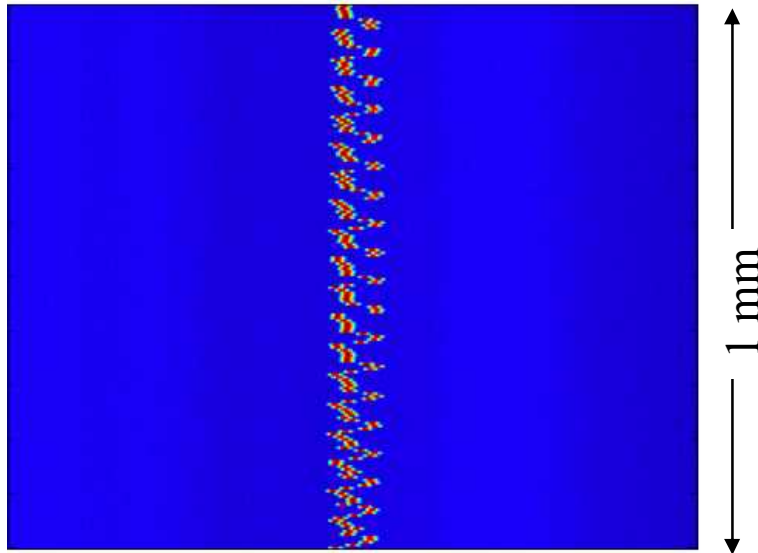
Some of the QCL emission retroreflects

- Another laser facet
- Window or lens
- External mixers

Cavity Length Sensitivity

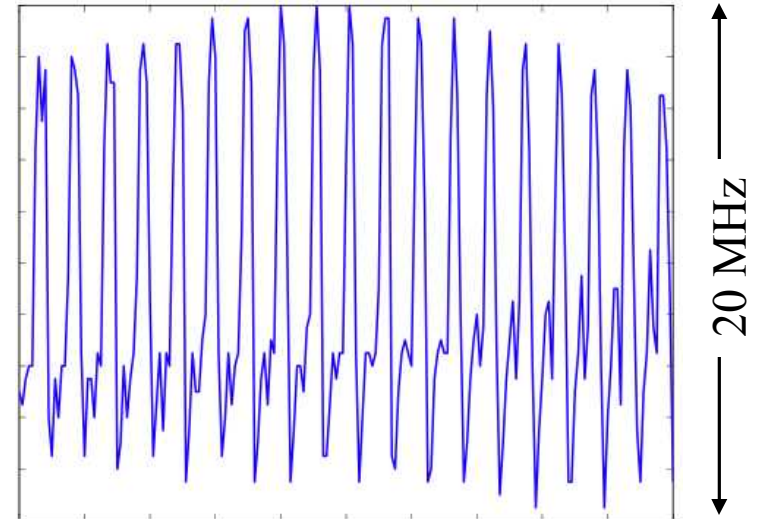


Mirror Position

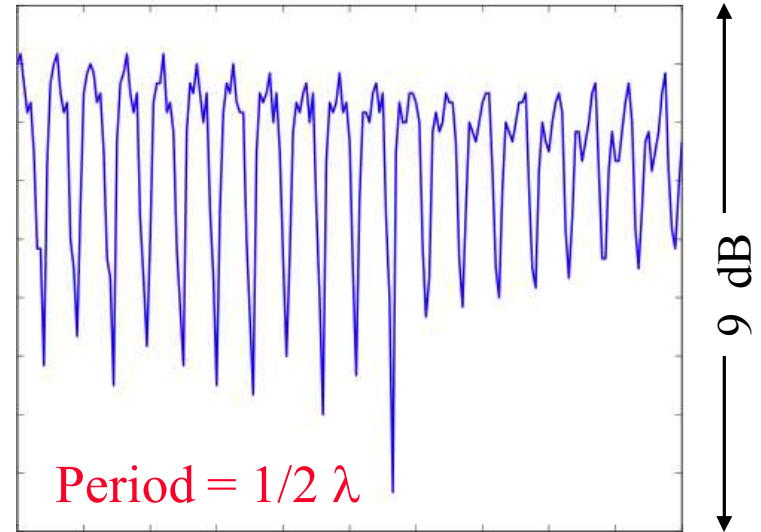


Frequency

Frequency

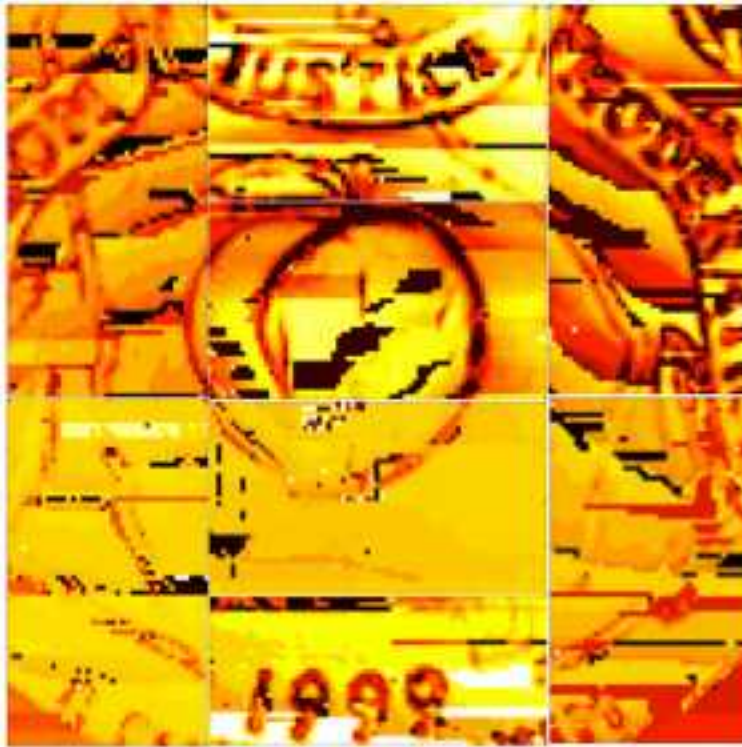


Amplitude



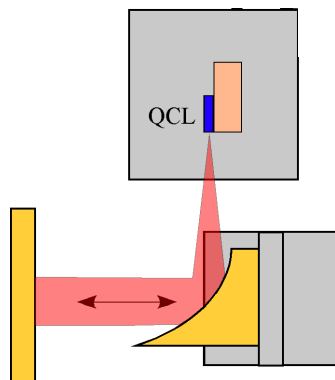
Mirror Position

Path Length Imaging

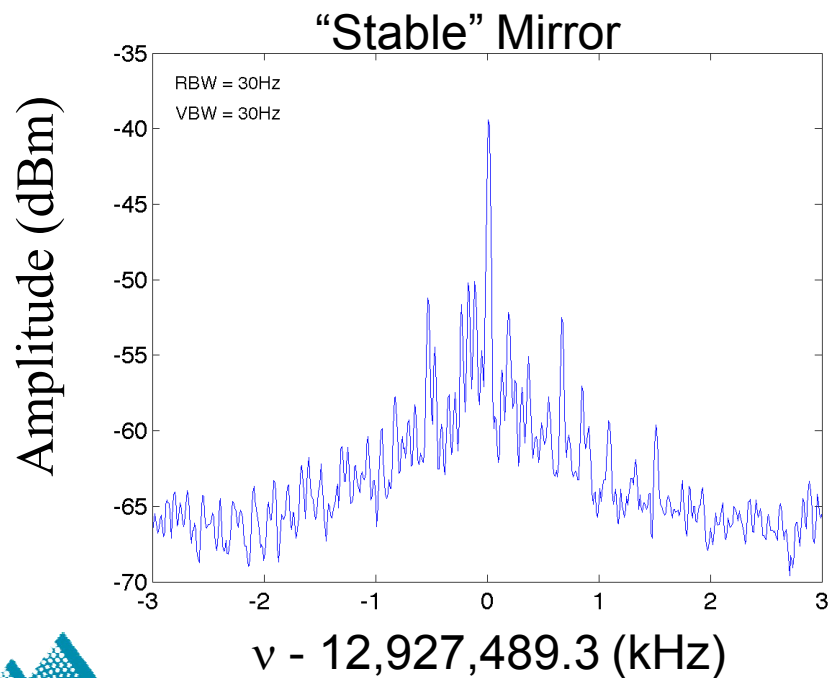


... can image the topography

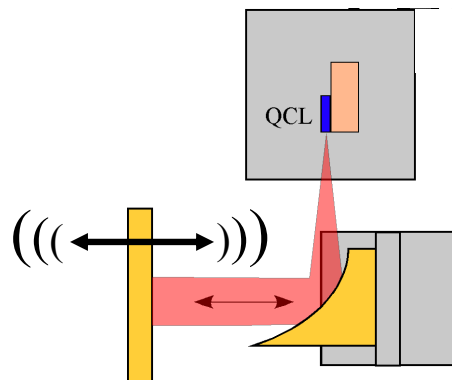
Vibration Sensitivity



FP spacing locked to 12.927 489 300 GHz

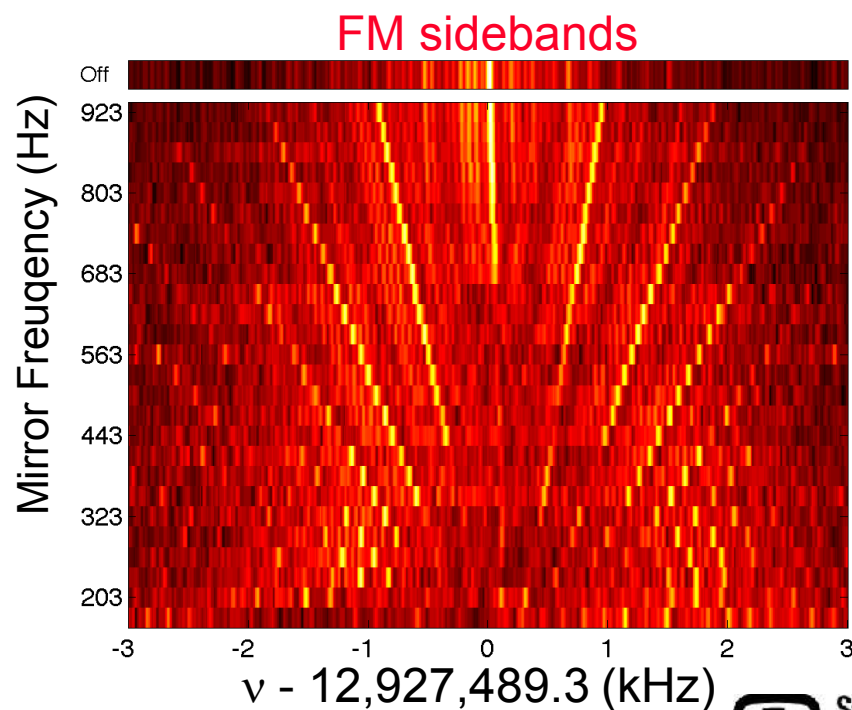
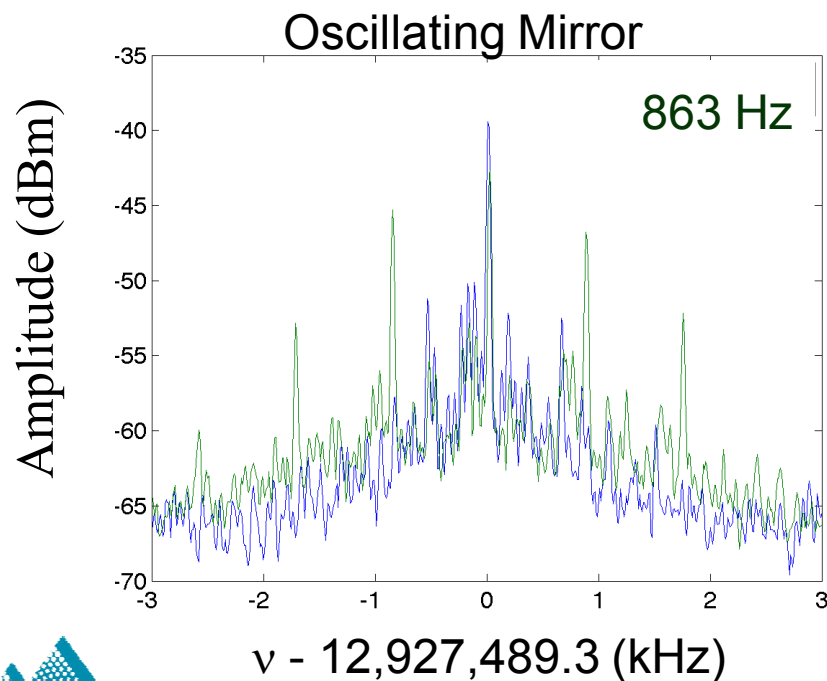


Vibration Sensitivity



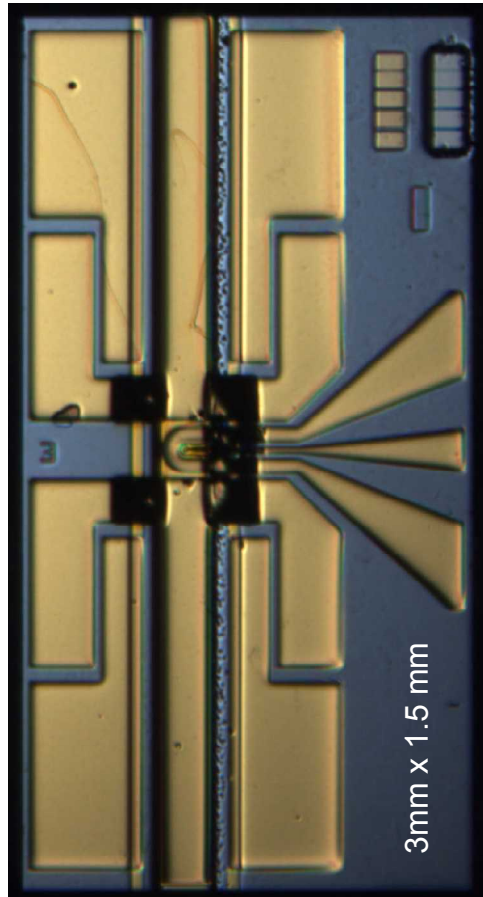
With an oscillating mirror

- FM sidebands occur
- Spacing = mirror frequency

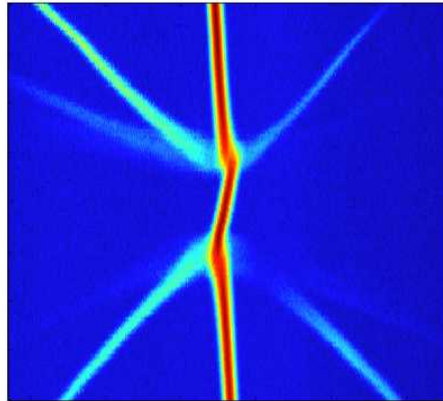


Summary

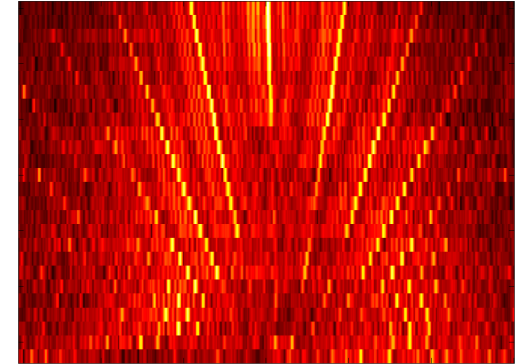
THz Integrated Transceiver



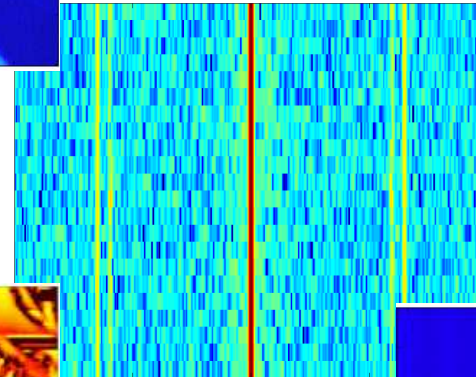
Laser Characterization Injection Locking



Vibrometry



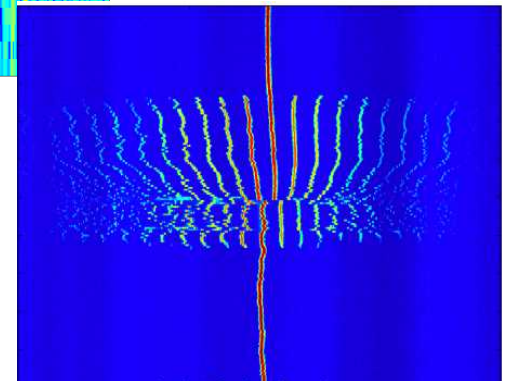
Phase Locking



Imaging



Feedback / Chaos





Any Questions?