

# Schottky Diodes Integrated On-chip with THz Quantum Cascade Lasers



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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.



Terahertz Microelectronics Transceiver



# Integrated Mixer Team

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With Support From:



MRS - 2009

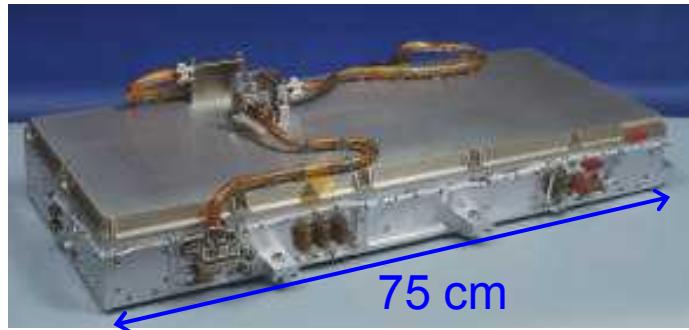
Slide 2



# THz QCLs: The Promise

- Miniature, all solid-state source from ~ 2 to 5 THz
  - Power output 1 to > 10 mW CW
- Very good intrinsic spectral characteristics
  - Decent free-running linewidth & stability
  - Can be locked to achieve ~ 10 Hz linewidth with low drift
- Relatively low ~ 1 W DC input power required
- Scalable production using microelectronic fab

Replace This:



Aura 2.5 THz LO (Coherent-DEOS)

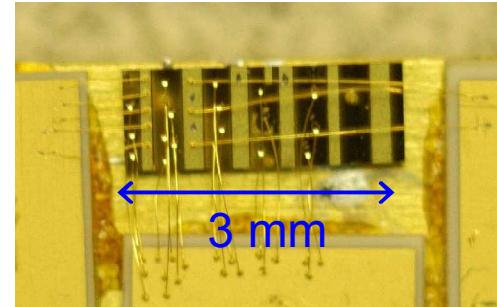
30 mW CW output

21 kg weight

120 W DC input power required

\$\$\$\$ per laser

With This:



Six THz QCLs on chip

≥ 10 mW CW output (each)

0.1 kg weight (not including cryostat)

1 W DC input power required

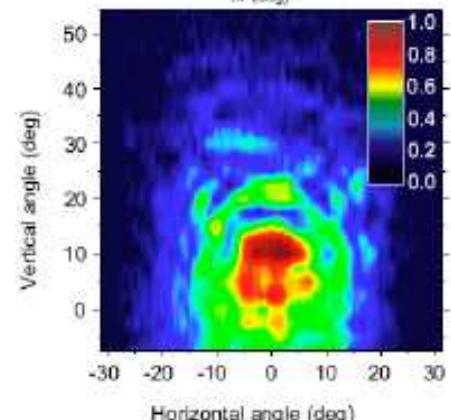
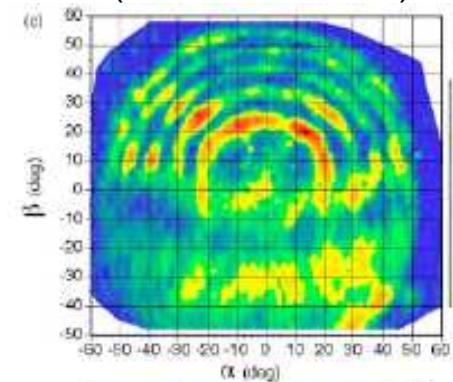
\$ (eventually ¢¢?) per laser

# THz QCLs: The Problems

*What do we want in a practical QCL LO?*

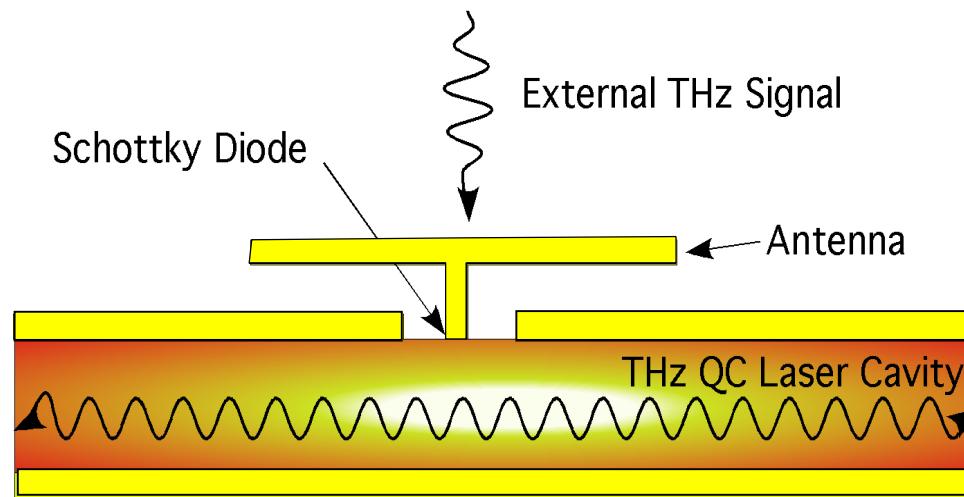
- Room temperature operation
  - Fundamental THz QCLs work up to 164 K (MIT/Sandia)
  - New mixed MIR design operate at 300K (Harvard/ETH)
- Precise absolute center frequency
  - QCL frequency depends on diced length/width
  - e.g., Hitting  $4.7448 \pm 0.001$  THz is *really* hard
- Continuous (electronic) tunability
  - Current or temperature tuned by 1 to 2 GHz
- Mated into existing THz infrastructure
- Predictable beam & power
  - Sub-wavelength aperture diffraction
  - Highly non-Gaussian beam
  - Very inefficient power coupling

QCL Beam Patterns  
(Delft/MIT/Sandia)

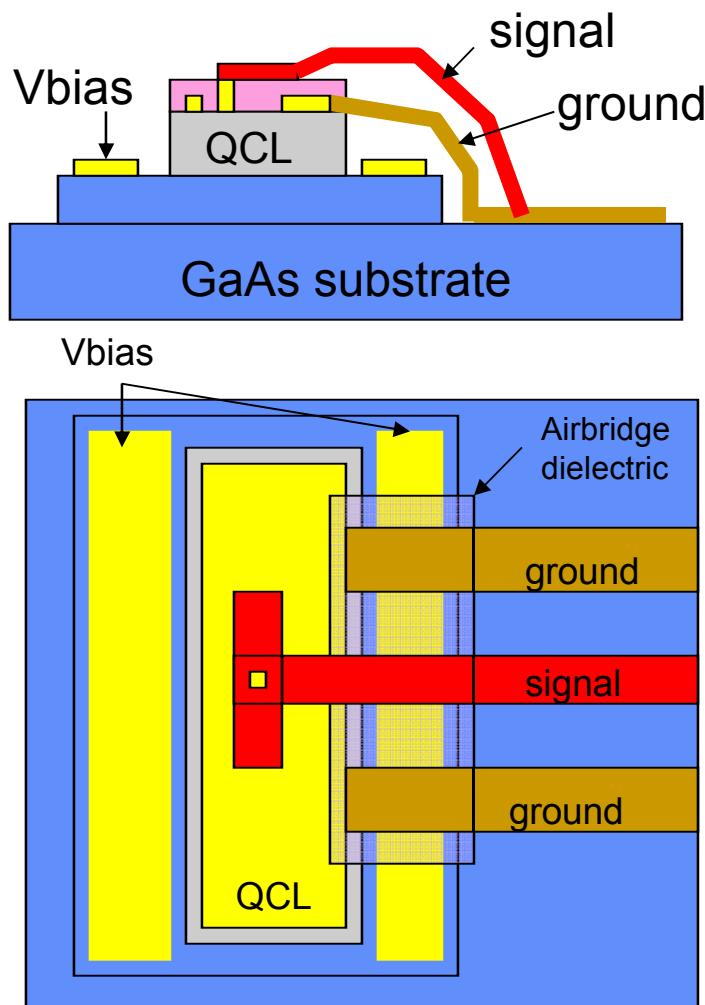


# Monolithic Integration

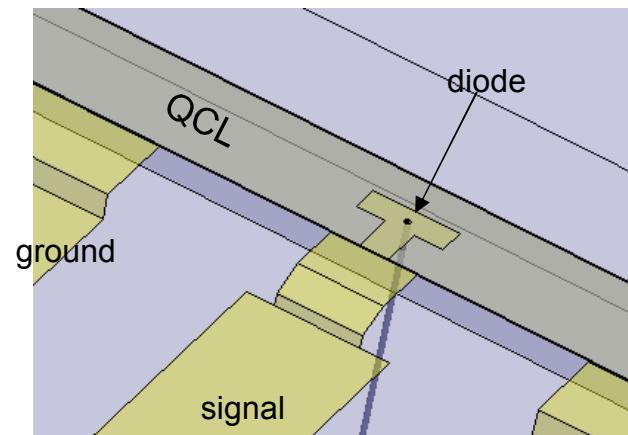
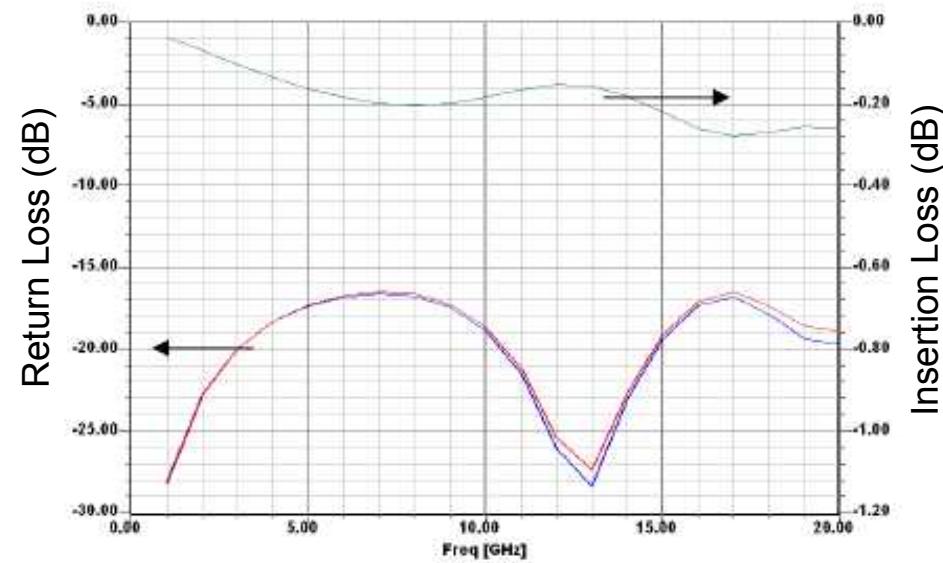
- **Goal: monolithic integration of detector diode with QCL and antenna**
- **Payoff: integration without plumbing**
  - Use integrated antenna and diode to mix external THz source directly with laser
  - Observation of internal mode mixing – diagnostics



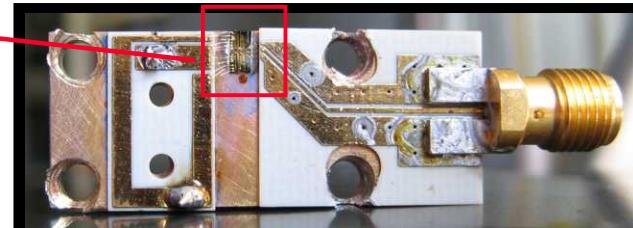
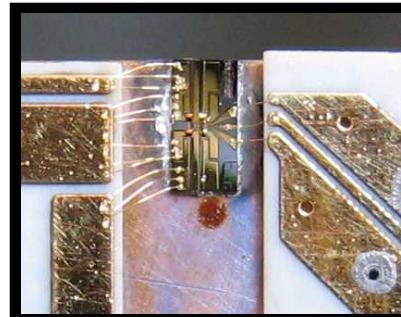
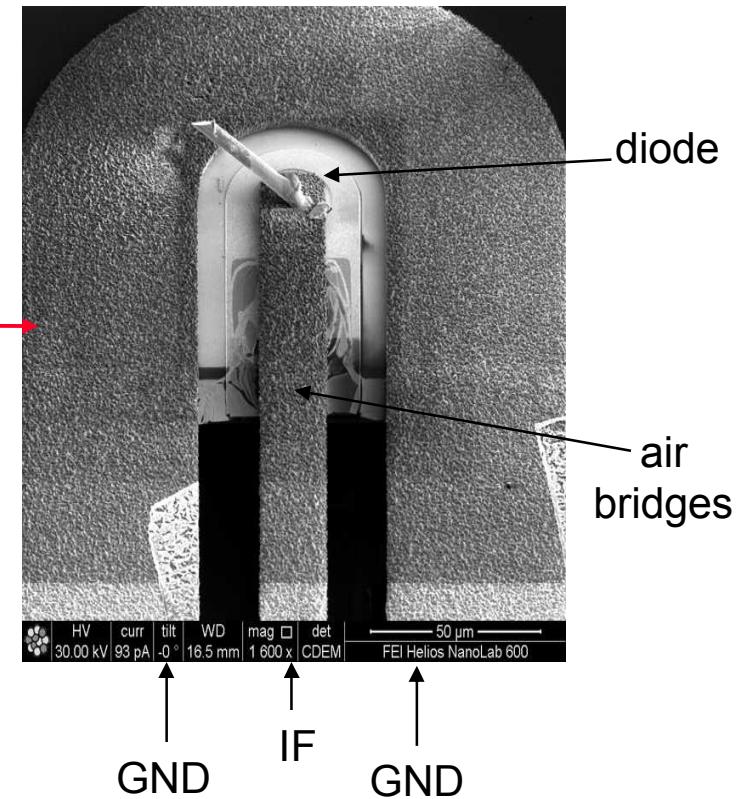
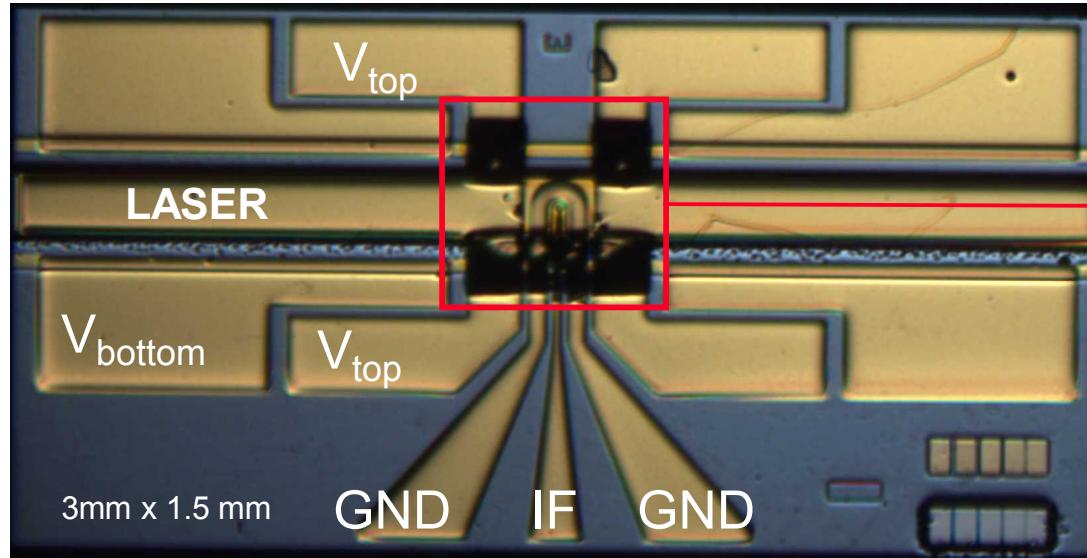
# Monolithic Integration Design



Simulated diode/CPW IF characteristics

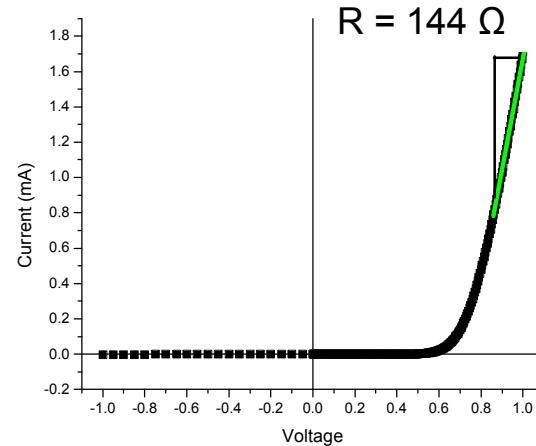
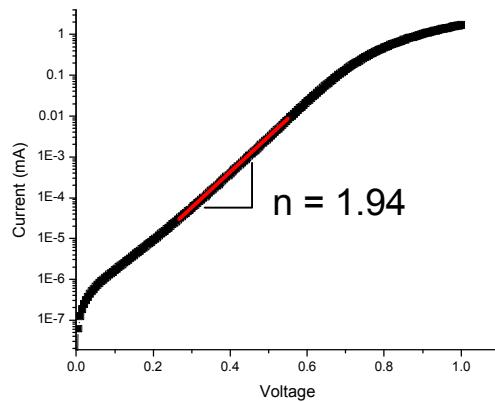


# Completed QCL/Schottky THz IC

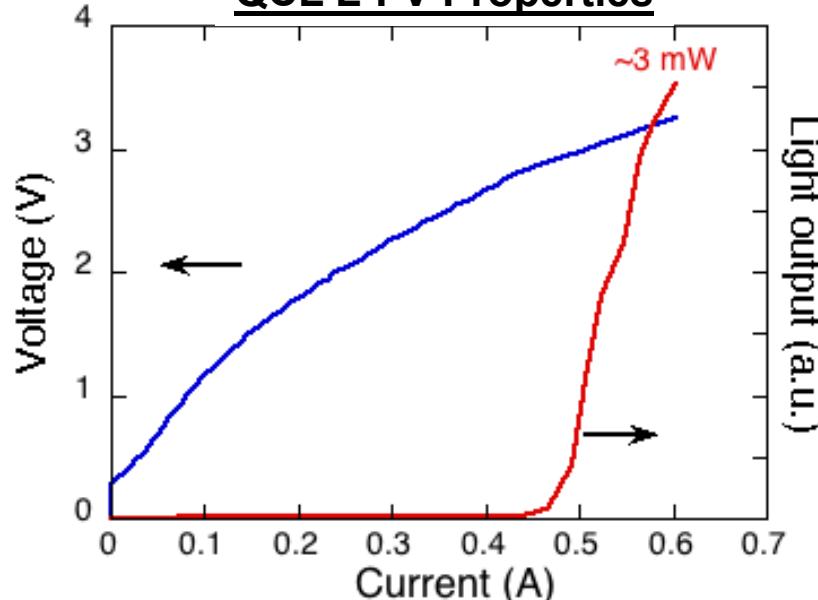


# Diode and Laser both Work

## Diode DC I-V Properties

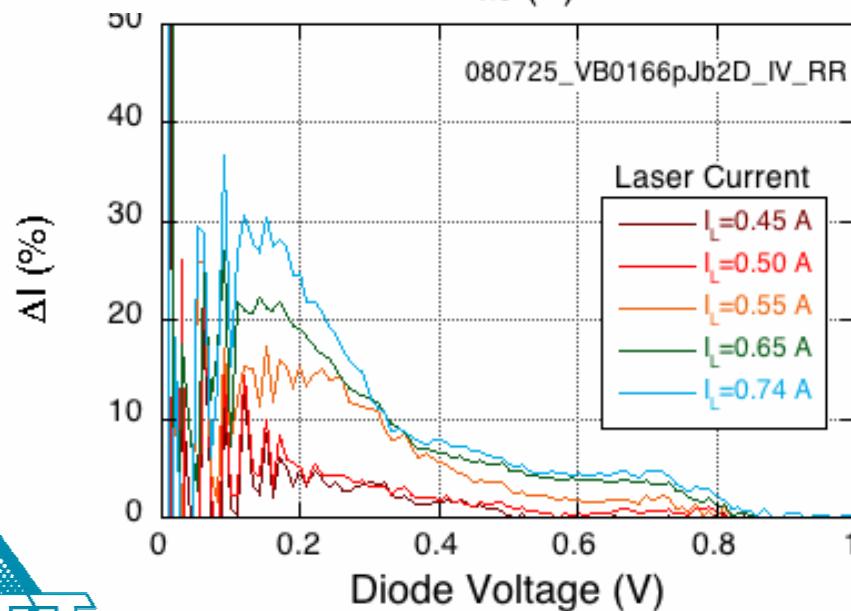
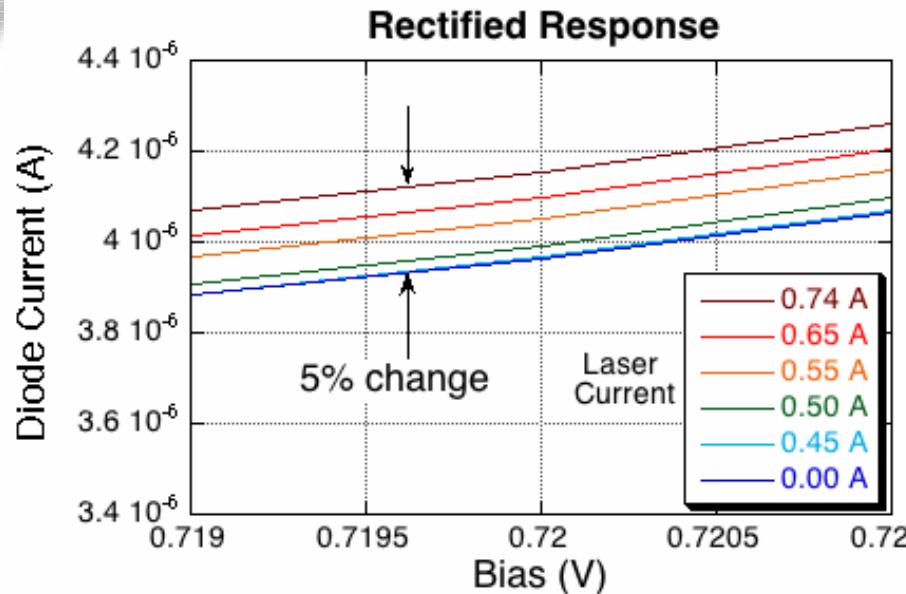


## QCL L-I-V Properties



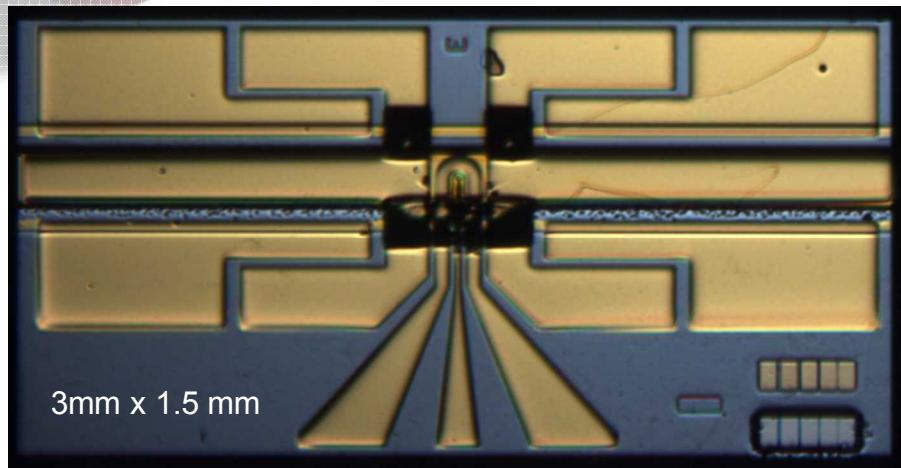
These are measured separately on a completed and mounted THzIC device

# Diode Responds to Intracavity Light

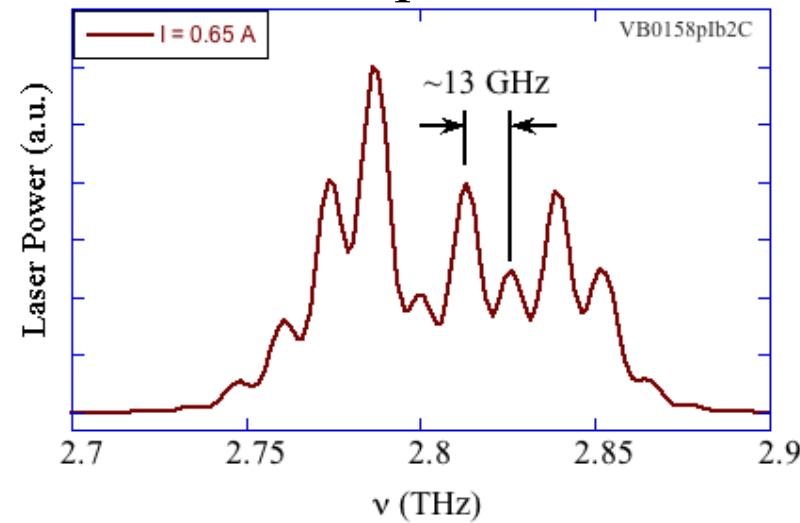


- Above laser threshold the diode I-V changes
- The change increases with increasing laser power
- A maximum 30% change of the diode DC I-V has been observed.

# Integrated Diode THz Mixer

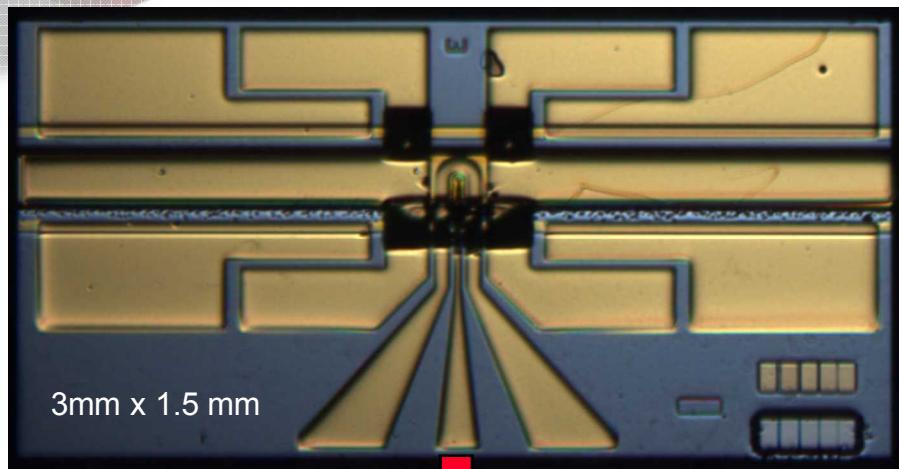


Laser output to FTIR

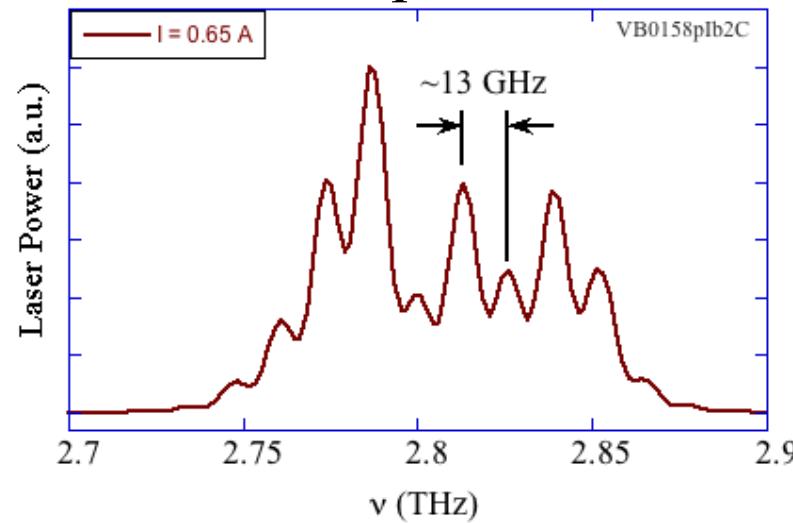


- Purposely built a multimoded QCL centered on 2.81 THz
  - QCL emission (FTIR) spectra show Fabry-Perot modes spaced by  $\approx 13$  GHz

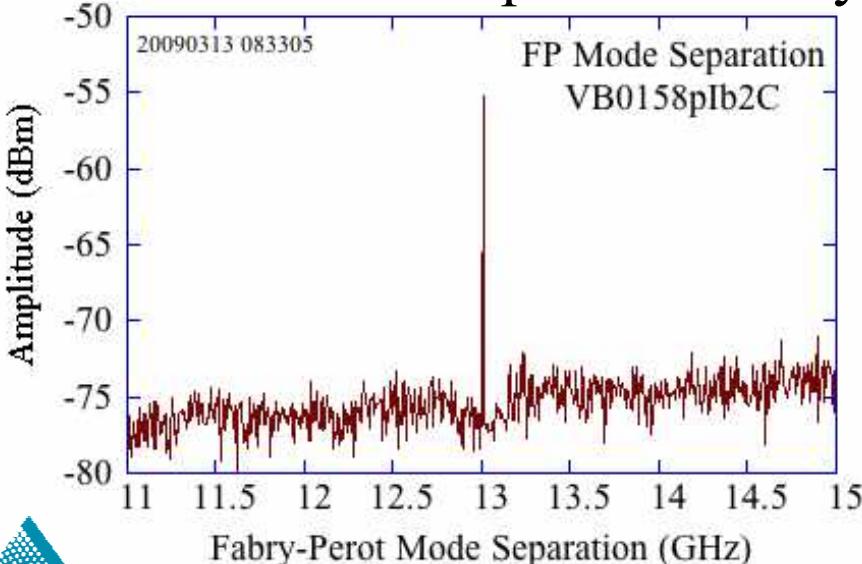
# Integrated Diode THz Mixer



Laser output to FTIR



Electrical feed to spectrum analyzer

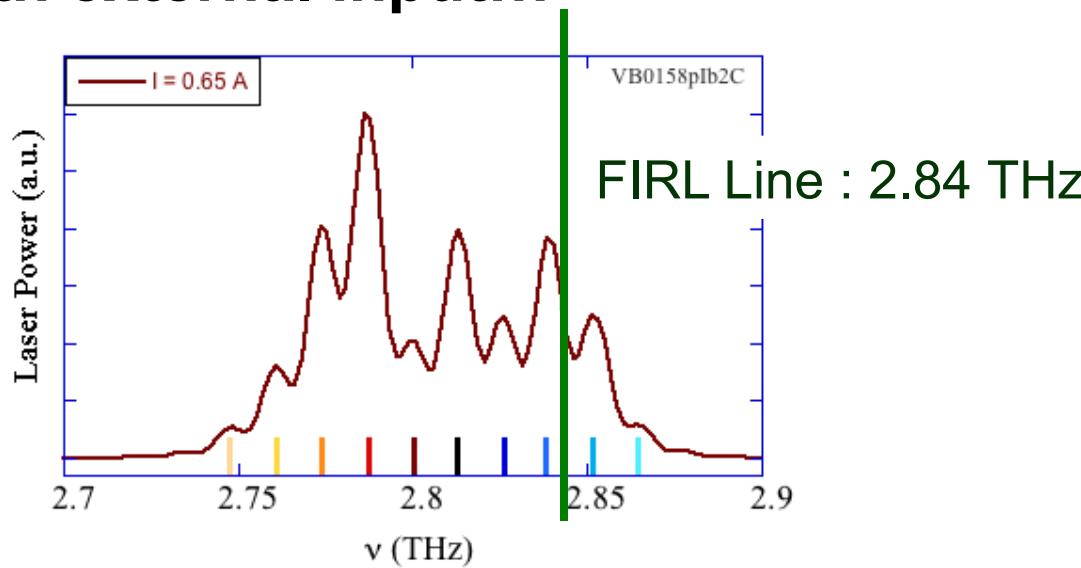
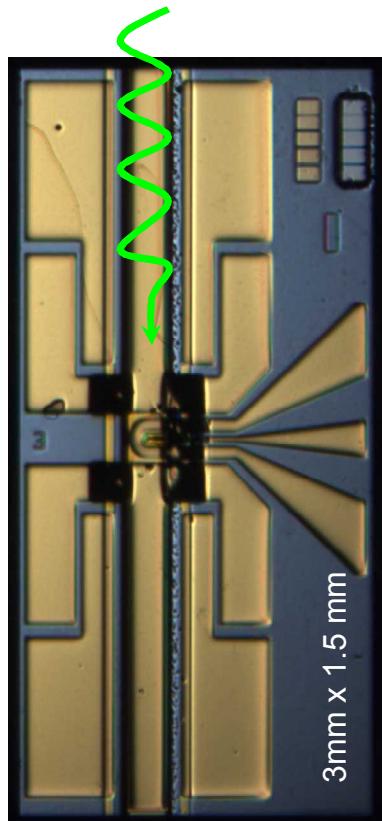


- Diode outputs IF signal at spacing between QCL modes
- Strong IF power: up to -53 dBm without amplifiers

# Integrated Diode THz Transceiver

With external input...

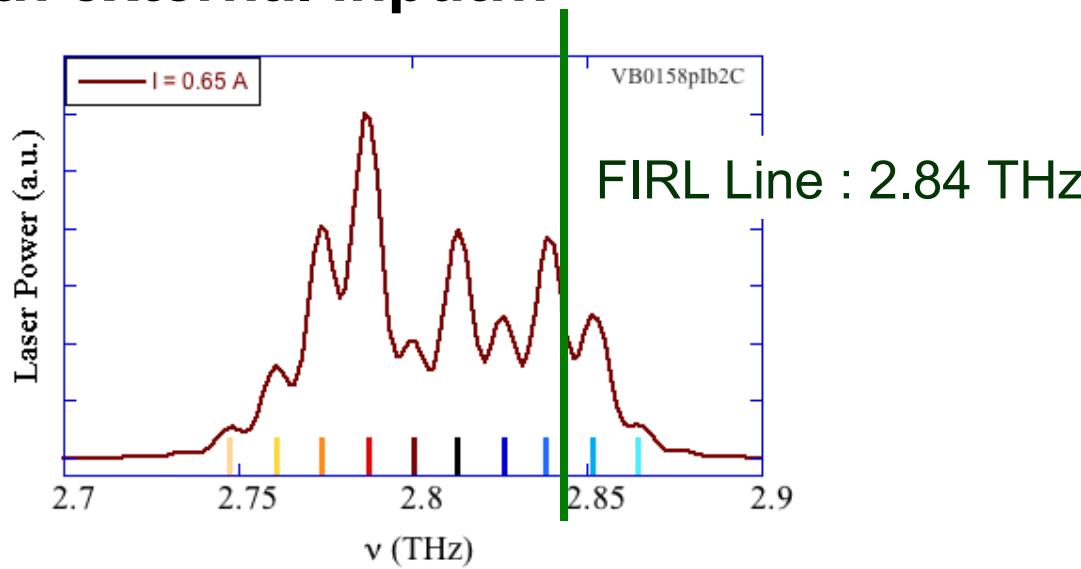
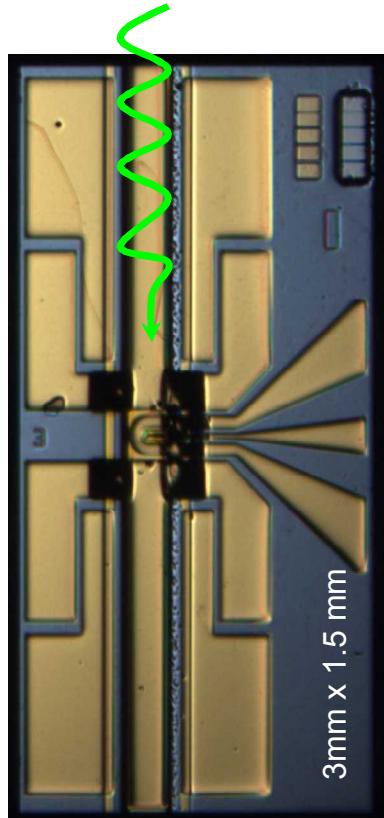
External  
Radiation



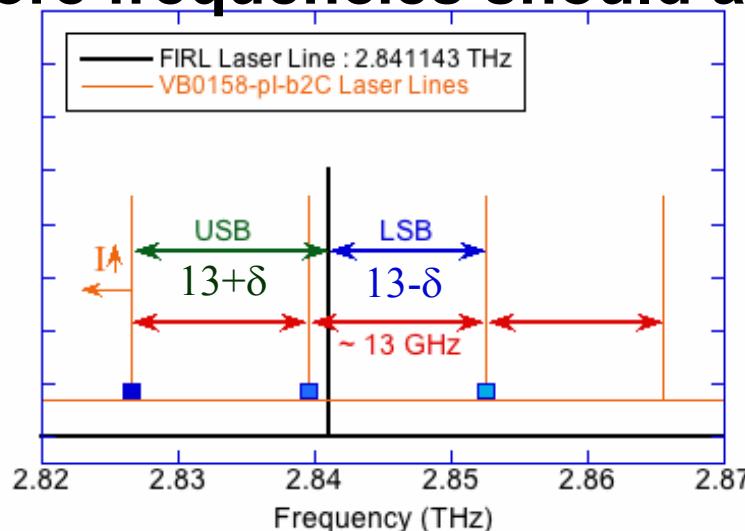
# Integrated Diode THz Transceiver

With external input...

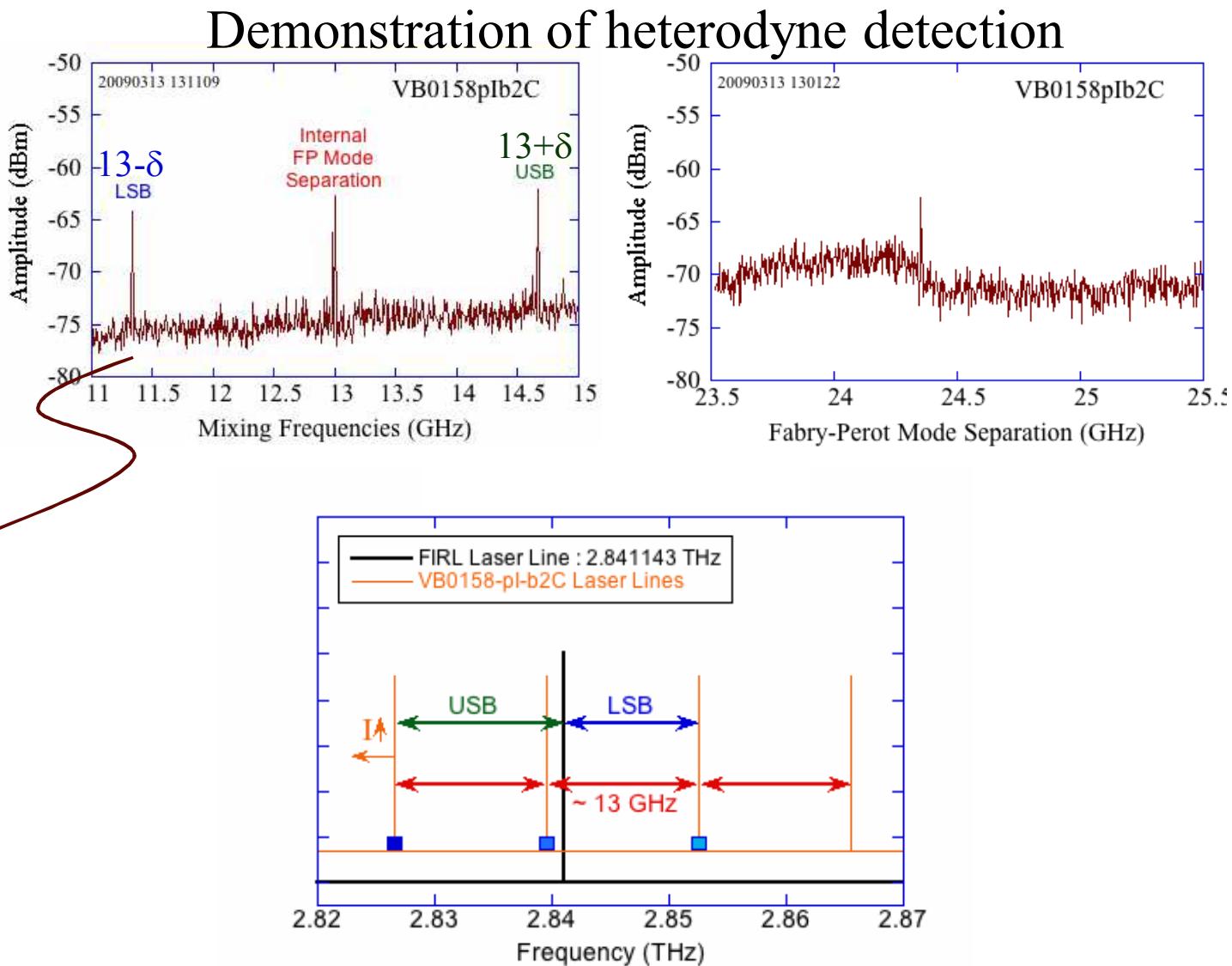
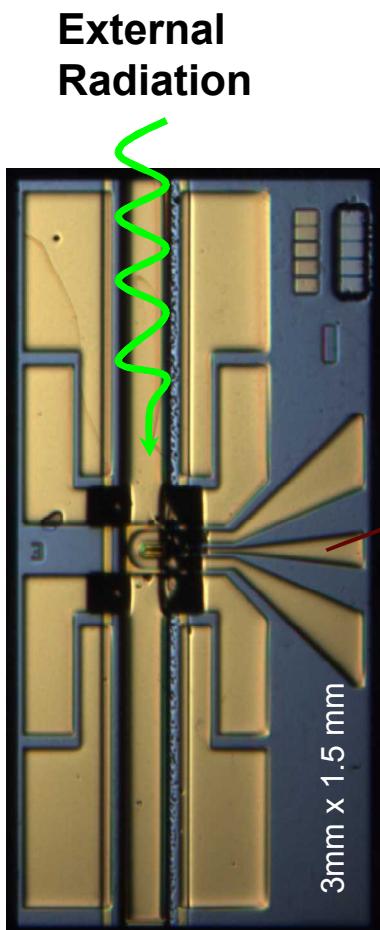
External  
Radiation



...more frequencies should appear

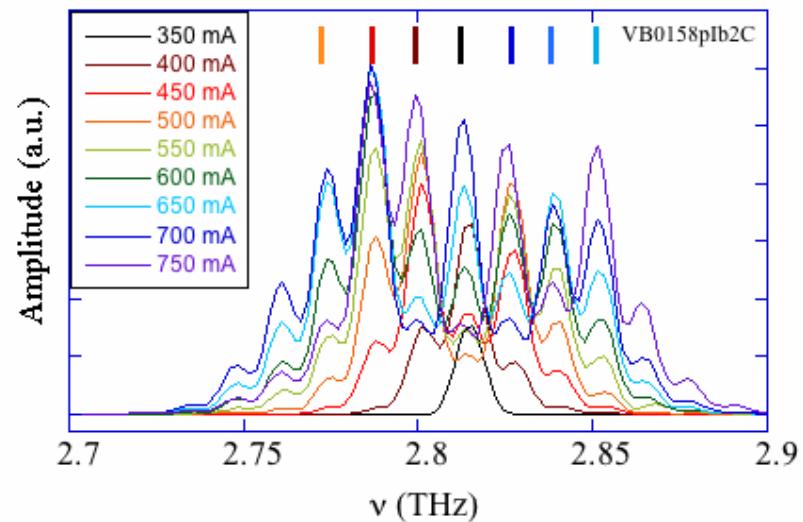


# Integrated Diode THz Transceiver



# Laser Characterization

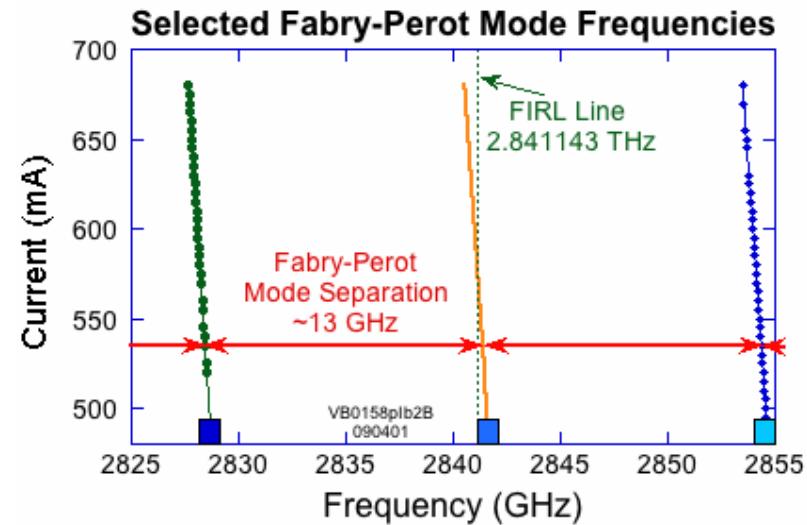
- Current Tuning



Small redshift with current  
- Much smaller than linewidth of FTIR

# Laser Characterization

- Current Tuning
  - $\sim 6 \text{ MHz / mA}$

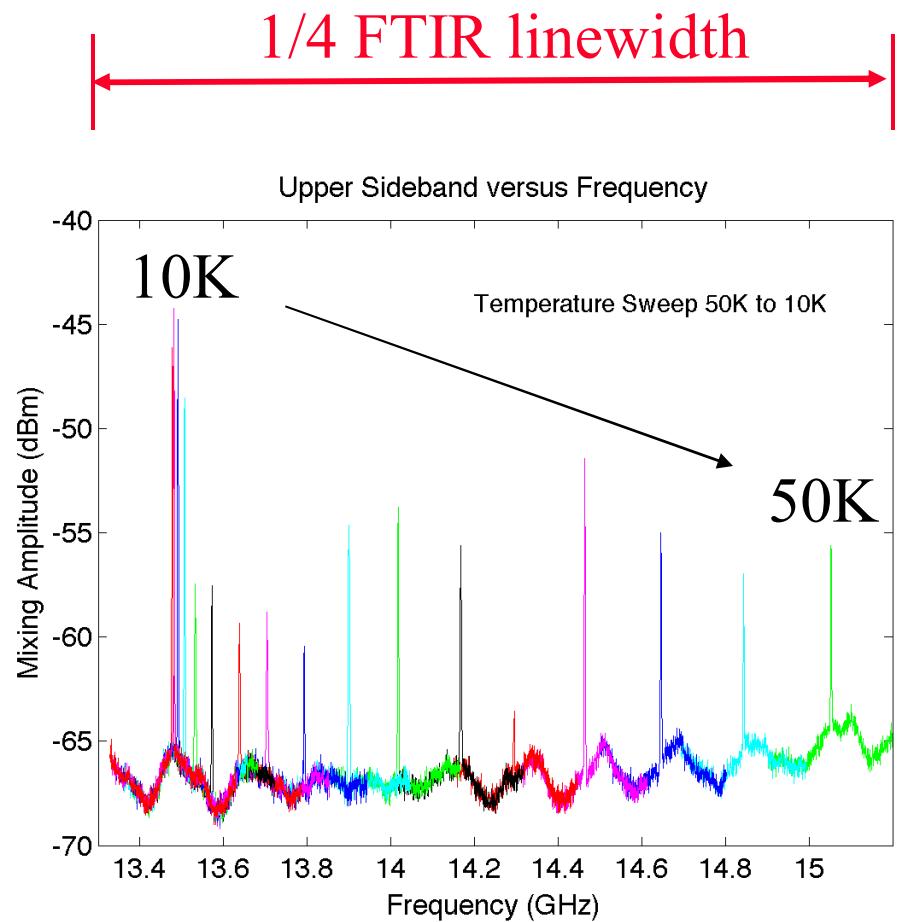


Small redshift with current

- Easy to see with mixer

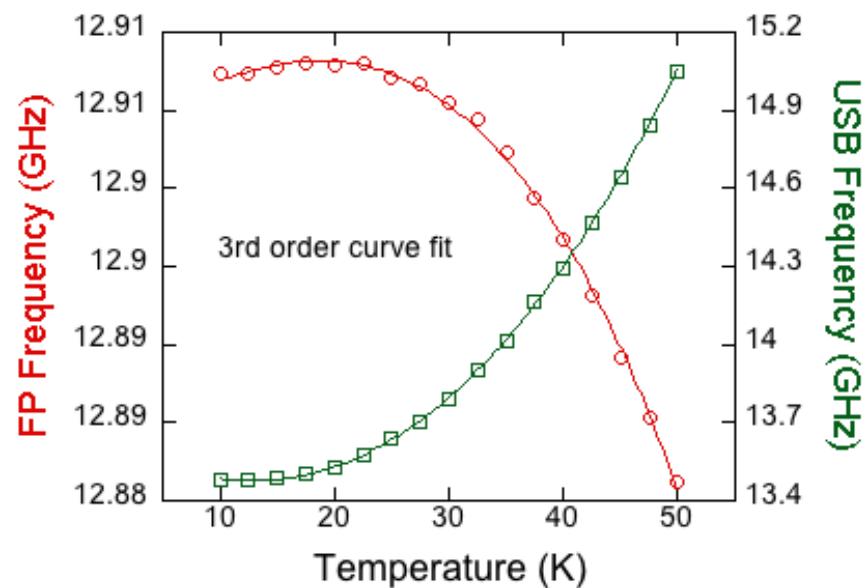
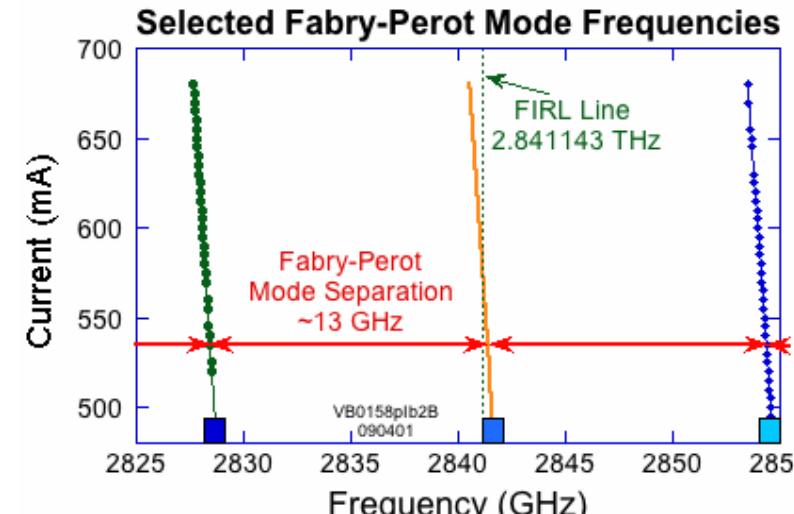
# Laser Characterization

- Current Tuning
  - $\sim 6 \text{ MHz / mA}$
- Temperature Tuning
  - Frequency shift easily seen by mixer



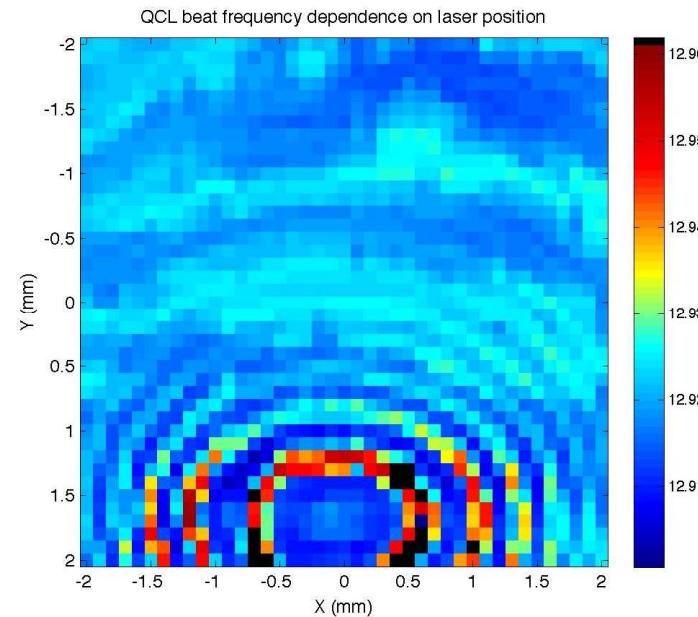
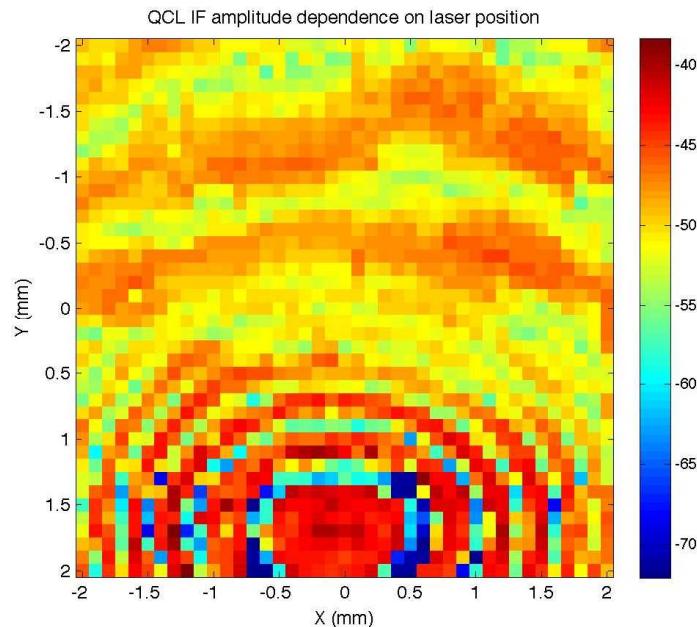
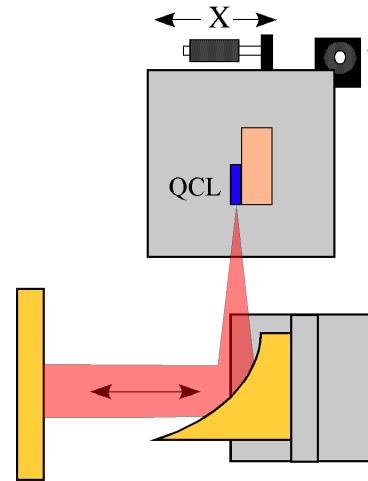
# Laser Characterization

- Current Tuning
  - $\sim 6 \text{ MHz / mA}$
- Temperature Tuning
  - Non-linear
  - Max rate  $\sim 90 \text{ MHz/K}$

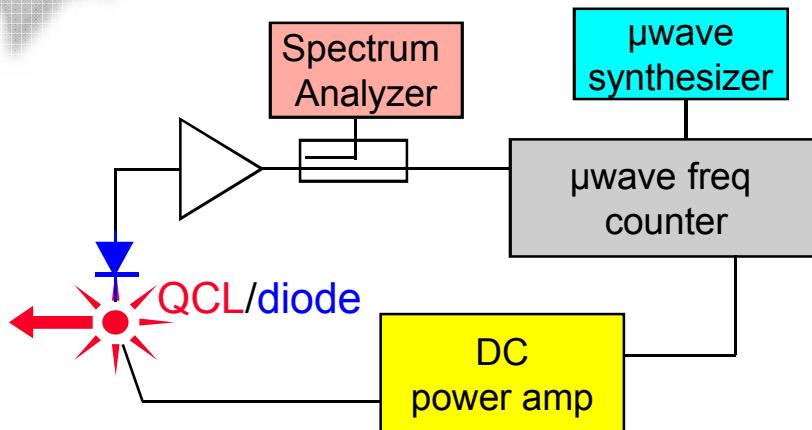


# Laser Characterization

- Current Tuning
- Temperature Tuning
- Feedback
  - Strong frequency and amplitude effects

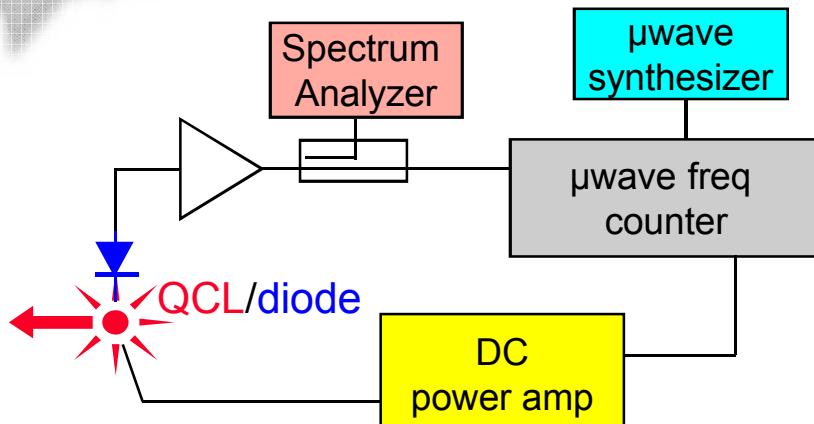


# Frequency Locked THz IC

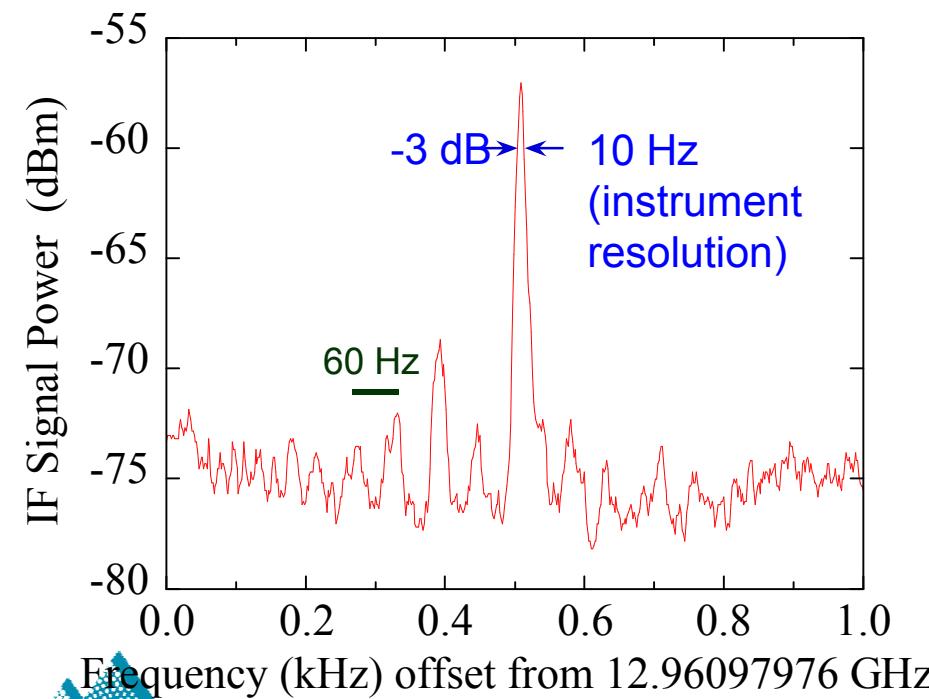


- Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations

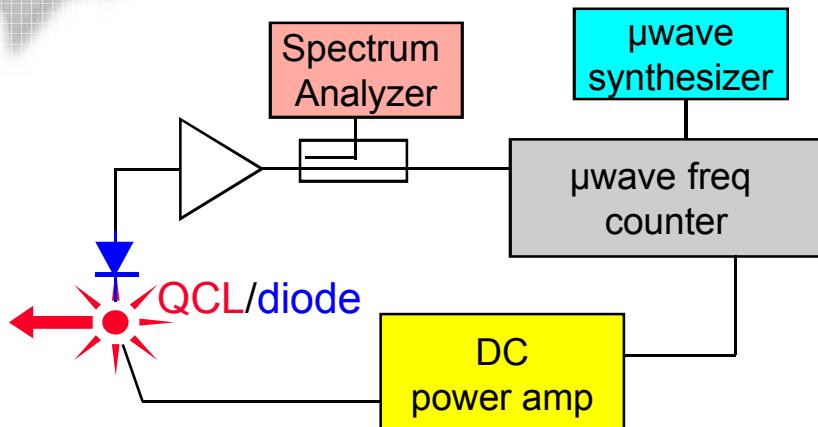
# Frequency Locked THz IC



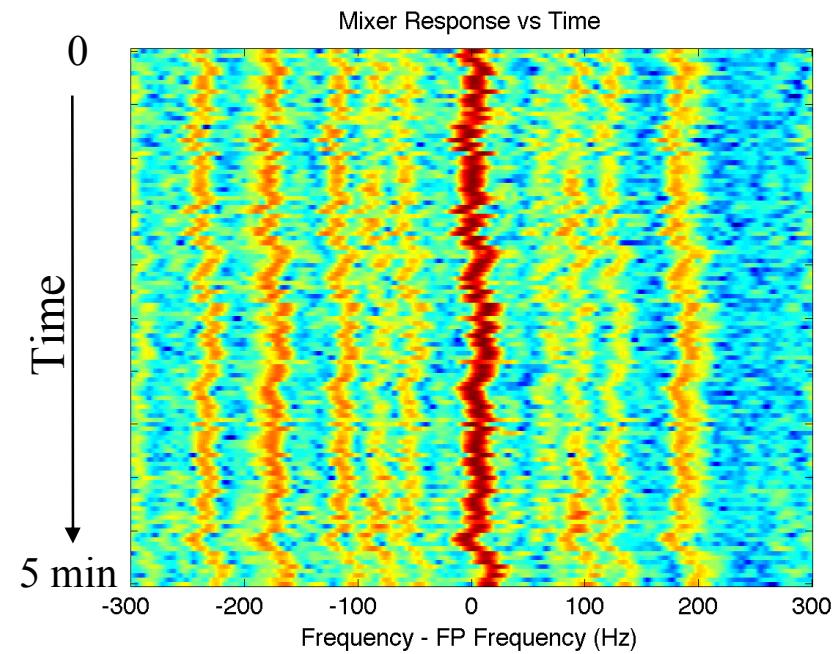
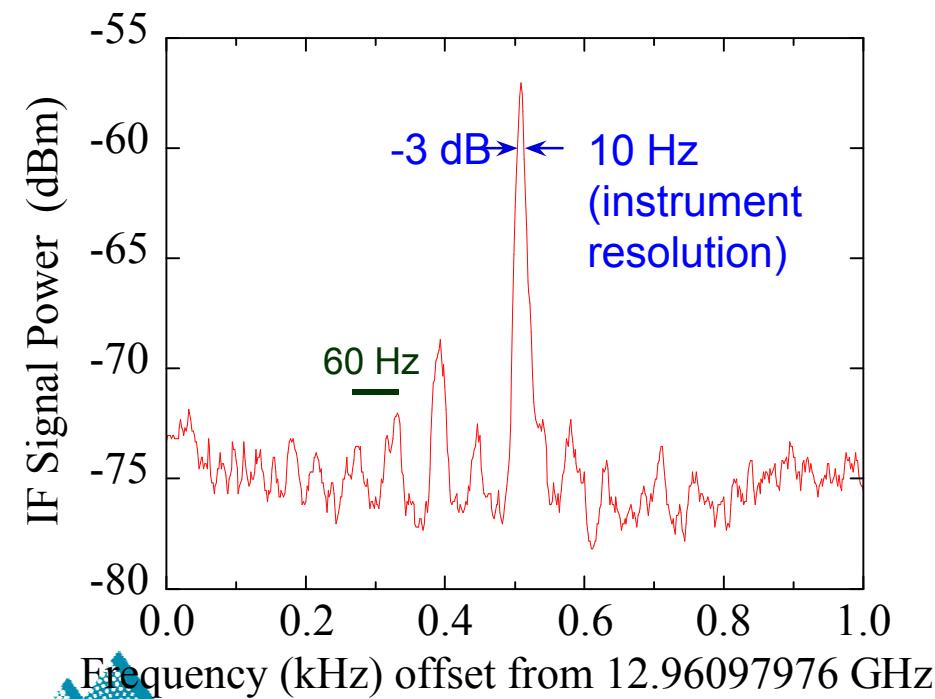
- Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations
- Locked IF linewidth  $\leq 10$  Hz



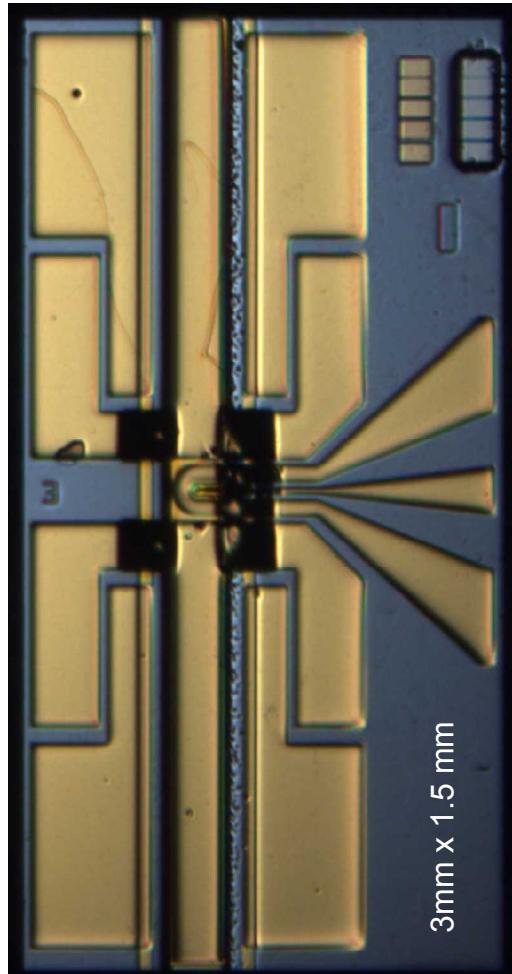
# Frequency Locked THz IC



- Use integrated diode's IF output as feedback to lock the QCL modes against differential fluctuations
- Locked IF linewidth  $\leq 10$  Hz
- Extremely stable IF frequency & amplitude once locked



# Summary



- We have demonstrated a THz Integrated Circuit:
  - Integrated a QCL with a Schottky diode
  - LO path never leave the chip
- ...which has demonstrated:
  - Rectified response
  - Internal mixing
  - Heterodyne detection
  - Laser diagnostic capability
  - Frequency locking

A photograph of a sunset over a mountain range. The sky is filled with orange and yellow clouds, with the sun partially visible on the horizon. In the foreground, a dark silhouette of a tree branch with small leaves is visible on the left side.

**Any Questions?**