SAND2009-2611C

Terahertz Microelectronics Transceiver

Integration of Terahertz Quantum Cascade Lasers for use as Local Oscillators

Mike C. Wanke

Sandia National Labs

ISSTT - April 20, 2009

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.

National Nuclear Security Administration

Sandia National Laboratories

Acknowledgements

Michael C. Wanke — *Sandia National Laboratories*
Mark Lee
Christopher D. Nordquist
Adam M. Rowen
Michael J. Cich
Chuck T. Fuller
Eric A. Shaner
John L. Reno
Dan G. Allen

Albert D. Grine — *LMATA Government Services*
Christian L. Arrington

Erik W. Young — *Now at Lumileds*

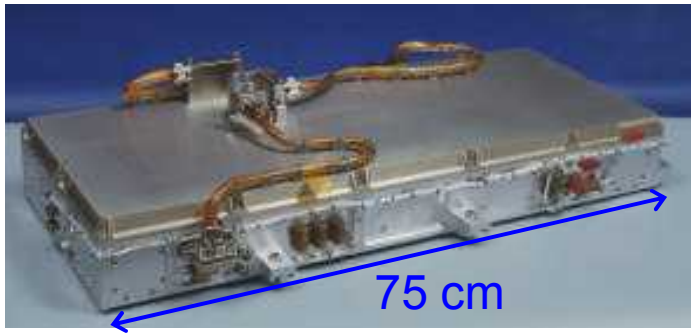
With Support From:

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

THz QCLs: The Promise

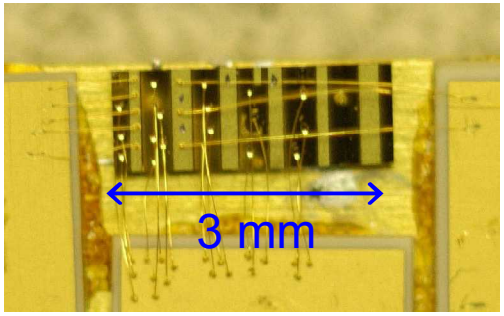
- **Miniature, all solid-state source from ~ 2 to 5 THz**
  - **Power output 1 to > 10 mW CW**
- **Very good intrinsic spectral characteristics**
  - **Decent free-running linewidth & stability**
  - **Can be locked to achieve ~ 10 Hz linewidth with low drift**
- **Relatively low ~ 1 W DC input power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

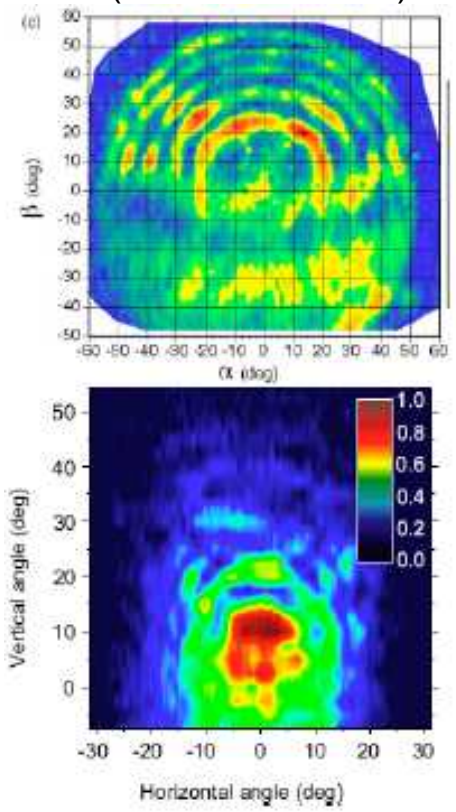


Six THz QCLs on chip
≥ 10 mW CW output (each)
0.1 kg weight (not including cryostat)
1 W DC input power required
$ (eventually ¢¢?) per laser

THz QCLs: The LO Problems

- QCLs still requires cryogens
  - Fundamental THz QCLs work up to 184 K (MIT/Sandia)
  - New mixed MIR design gives 8 μW at 300K (Harvard/ETH)
- Difficult to provide precise absolute frequency
  - *e.g.*, Hitting 4.7448 ± 0.001 THz is *really* hard
- Lack of connection to existing THz infrastructure
- Beam quality is fairly poor
  - Sub-wavelength aperture diffraction
  - Highly non-Gaussian beam
  - Very inefficient power coupling

QCL Beam Patterns
(Delft/MIT/Sandia)



THz QCLs: The LO Problems

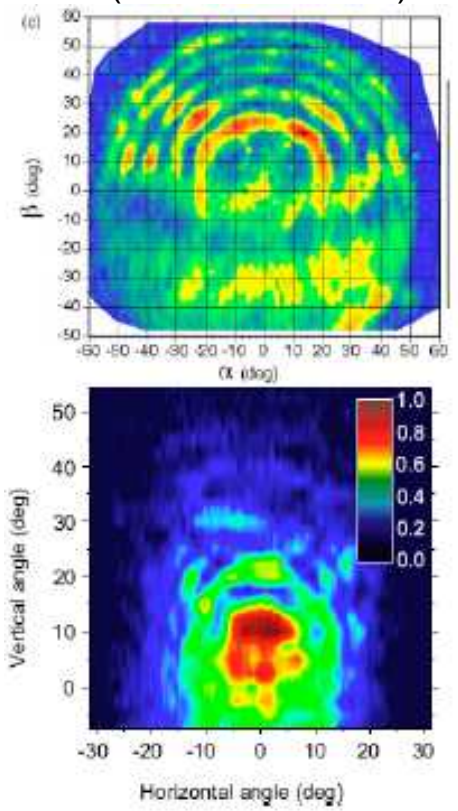
- QCLs still requires cryogens
  - Fundamental THz QCLs work up to 184 K (MIT/Sandia)
  - New mixed MIR design gives 8 μW at 300K (Harvard/ETH)
- Difficult to provide precise absolute frequency
  - *e.g.*, Hitting 4.7448 ± 0.001 THz is *really* hard
- Lack of connection to existing THz infrastructure
- Beam quality is fairly poor
  - Sub-wavelength aperture diffraction
  - Highly non-Gaussian beam
  - Very inefficient power coupling

- **THz QCL: Integration Solutions**

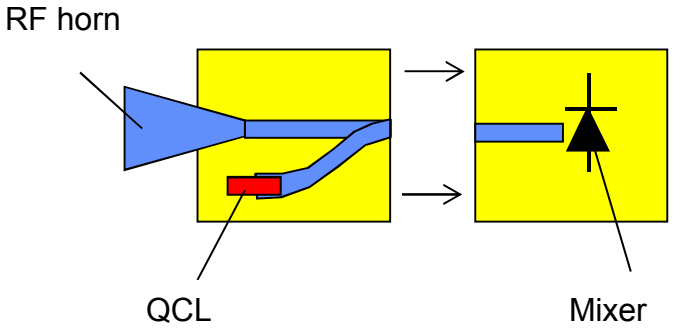
  1 - Mate the THz QCL into rectangular waveguide

  2 - Monolithic integration of a THz QCL/mixer heterodyne circuit

QCL Beam Patterns
(Delft/MIT/Sandia)

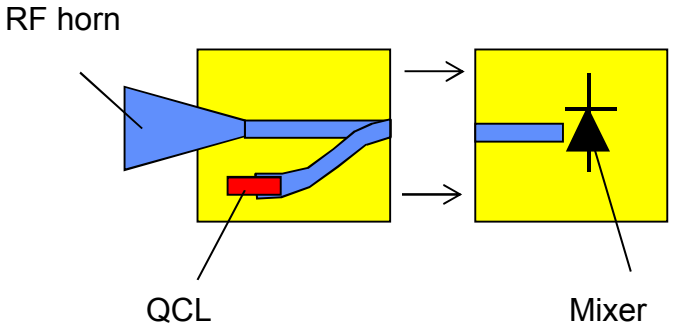


Solution 1:
Integrate QCLs into rectangular waveguide



- **Payoffs**
  - RWG is a widely used standard
  - Propagation mode structure in RWG known
  - Horns should improve beampatterns and coupling
  - Waveguide elements (couplers, splitters, horns) can be used
  - Mixers can also be placed in RWG

Integrate QCLs into rectangular waveguide



- **Payoffs**
  - RWG is a widely used standard
  - Propagation mode structure in RWG known
  - Horns should improve beampatterns and coupling
  - Waveguide elements (couplers, splitters, horns) can be used
  - Mixers can also be placed in RWG

  - **<u>Problem</u>: Converntional machined split-block RWG doesn't work well with QCLs**

Micromachining Rectangular Waveguides

- **Solution: Build waveguide around QCL using microfab techniques and additive electroplating techniques.**

Micromachining Rectangular Waveguides

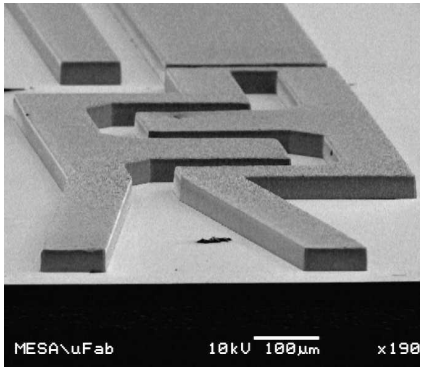
1. Deposit seed metal and pattern photoresist

Sandia National Laboratories

Micromachining Rectangular Waveguides

1. Deposit seed metal and pattern photoresist

2. Electoplate Au in photoresist openings

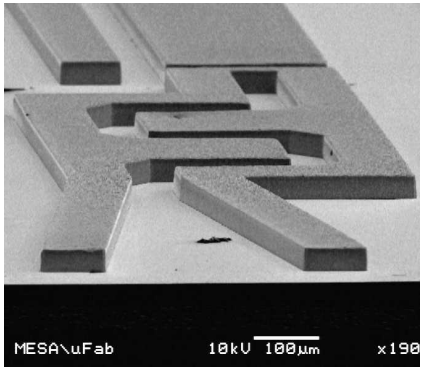


Micromachining Rectangular Waveguides

1. Deposit seed metal and pattern photoresist

2. Electoplate Au in photoresist openings

3. Deposit 2nd seed metal, pattern 2nd resists, and plate in opening to create tops



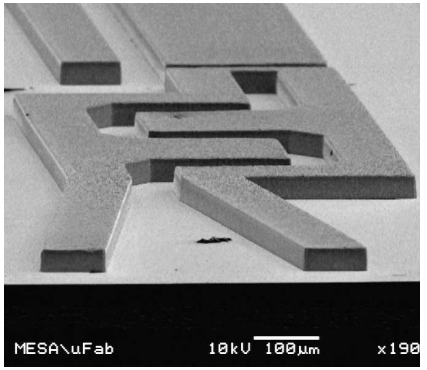
Micromachining Rectangular Waveguides

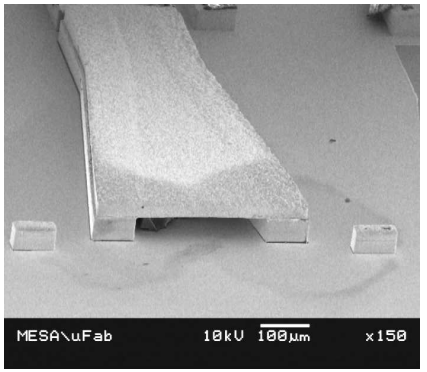
1. Deposit seed metal and pattern photoresist

2. Electoplate Au in photoresist openings

3. Deposit 2nd seed metal and plate in opening to create tops

4. Remove photoresist and 2nd seed metal





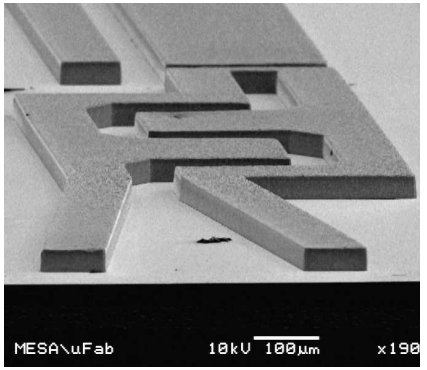
Micromachining Rectangular Waveguides

1. Deposit seed metal and pattern photoresist

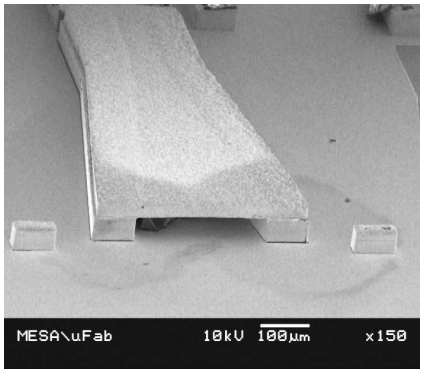
2. Electoplate Au in photoresist openings

3. Deposit 2nd seed metal and plate in opening to create tops

4. Remove photoresist and 2nd seed metal

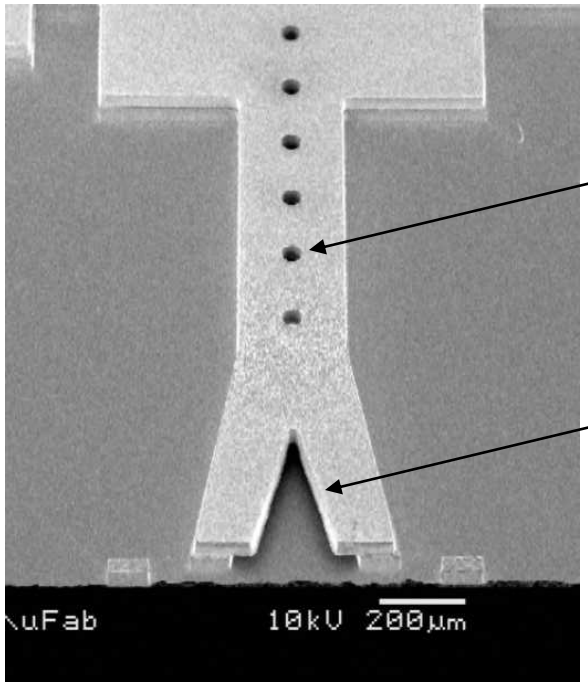


- **Additive electroplating technique suitable for various substrates**
  - **Allows waveguide fabrication on QCL or other wafers**



Sandia National Laboratories

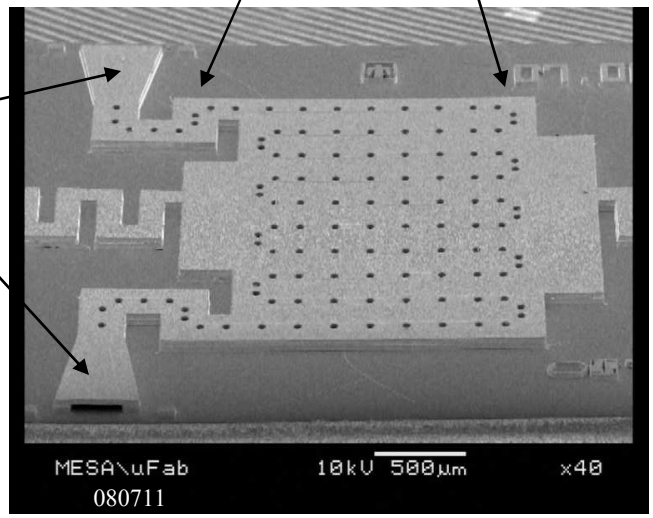
Micromachined THz Waveguides

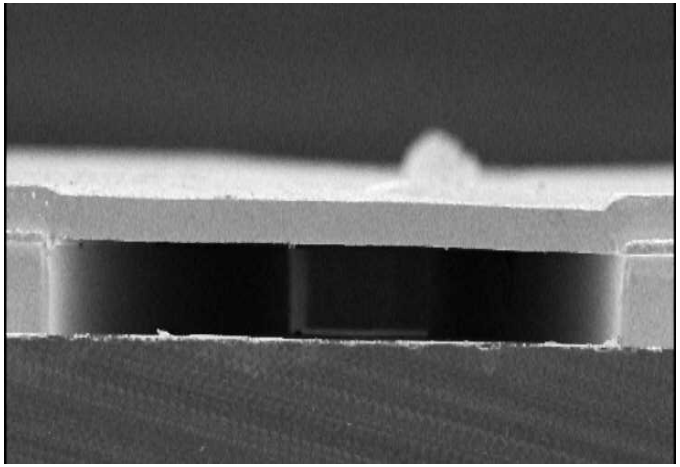


Photoresist removal holes

Horn antenna

H-Plane Bends

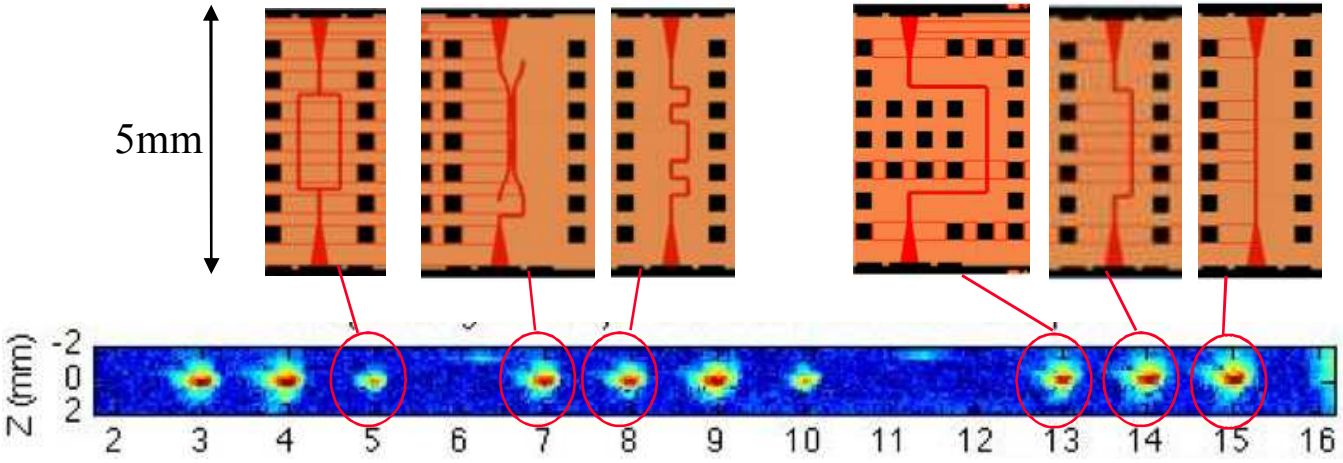




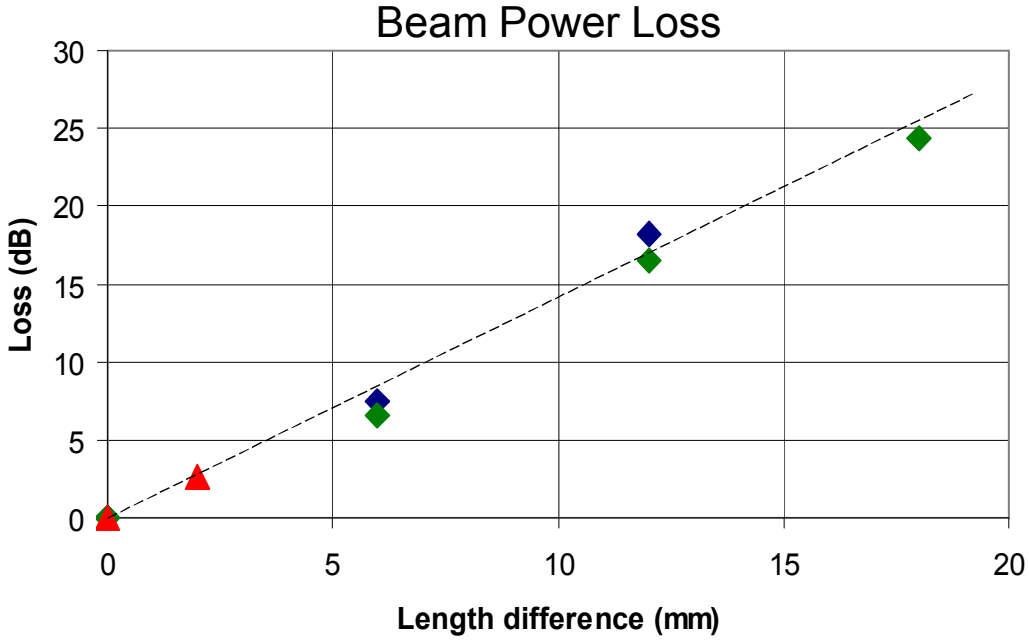
End view of waveguide horn antenna

Sandia National Laboratories

Promising Waveguide Propagation

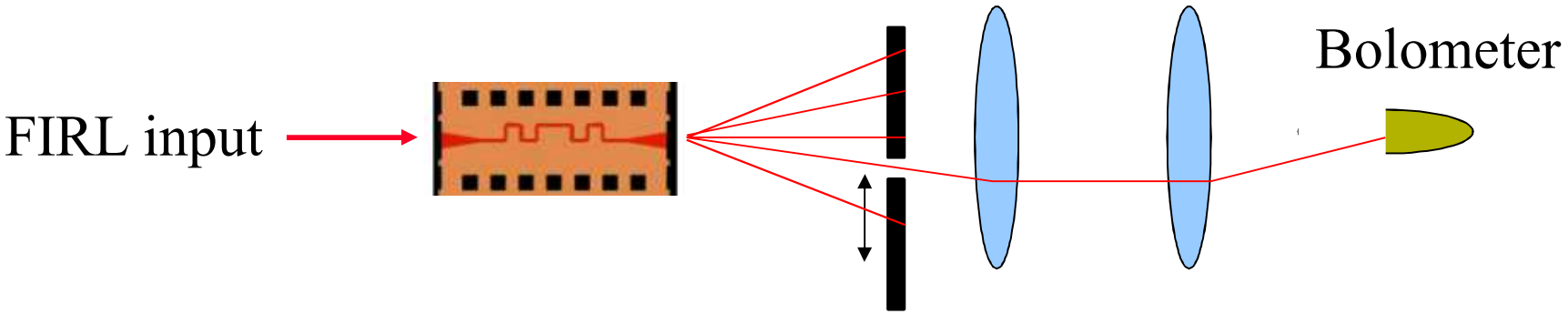


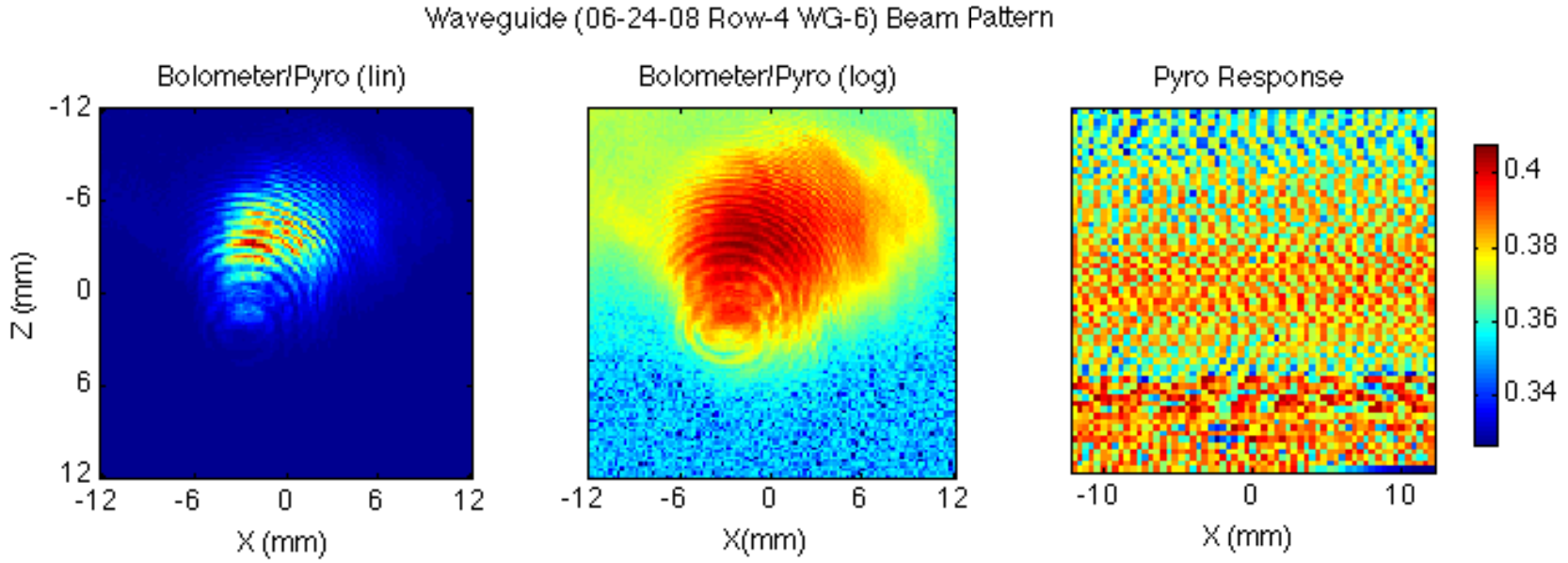
- **Made straight waveguides, bends, tees, splitters, couplers, horns**
- **Low propagation & bend losses near 2.9 THz**
  - **1.4 dB/mm propagation loss (0.17 dB/wavelength)**
  - **≤ 0.15 dB/bend loss**



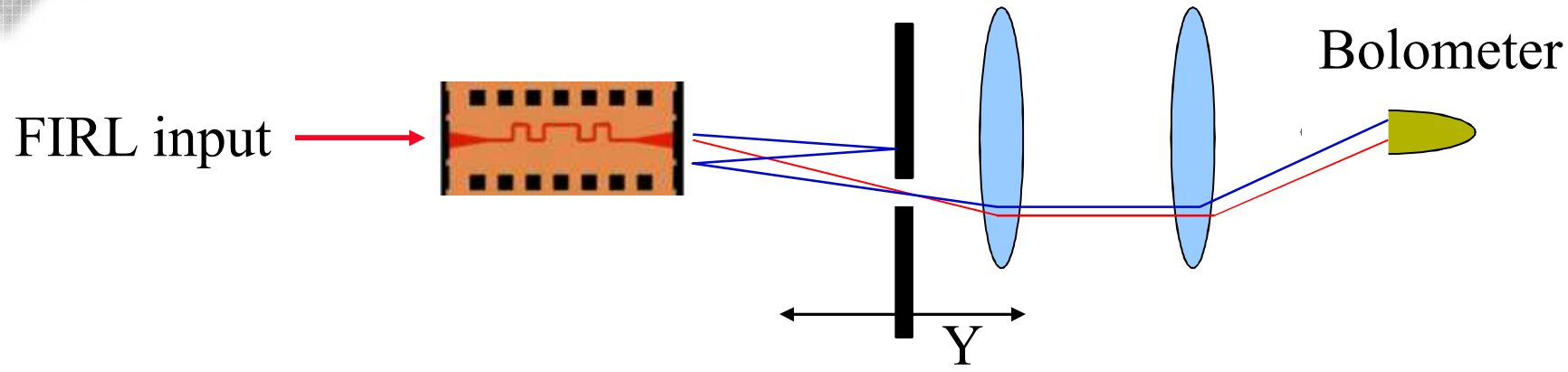
Beampattern
(Empty RWGs)

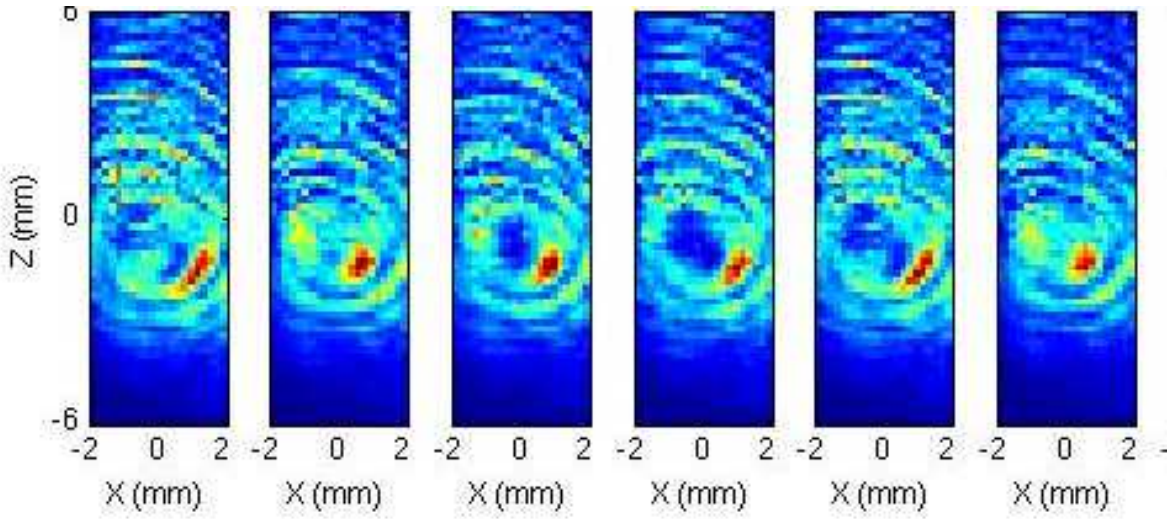
Scanned pinhole
4.5° resolution





Multiple Interference Effects

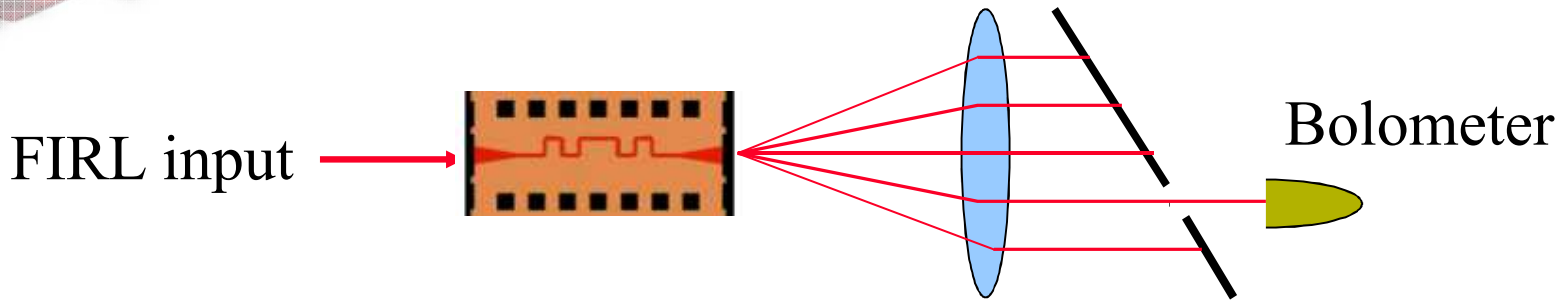


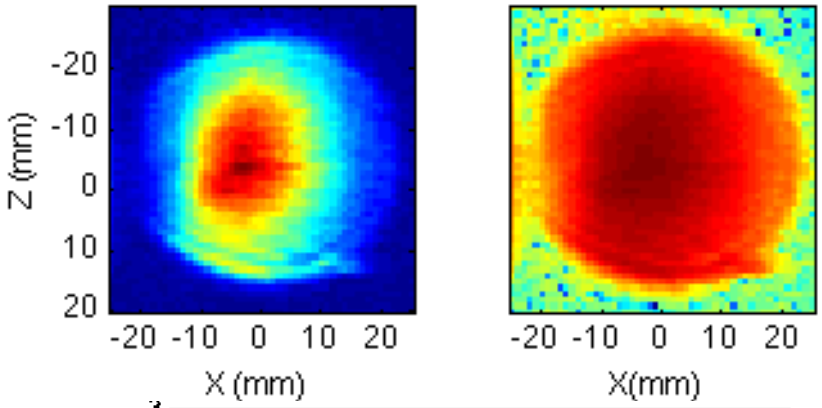


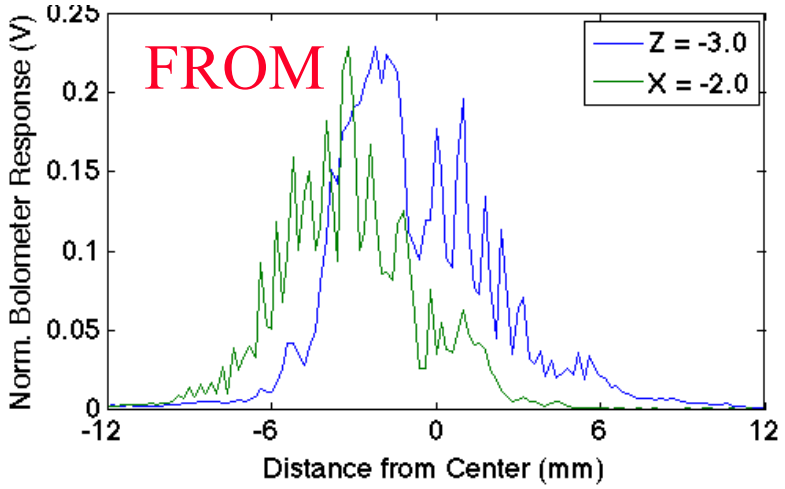
Phase periodically oscillates in Y every λ/2

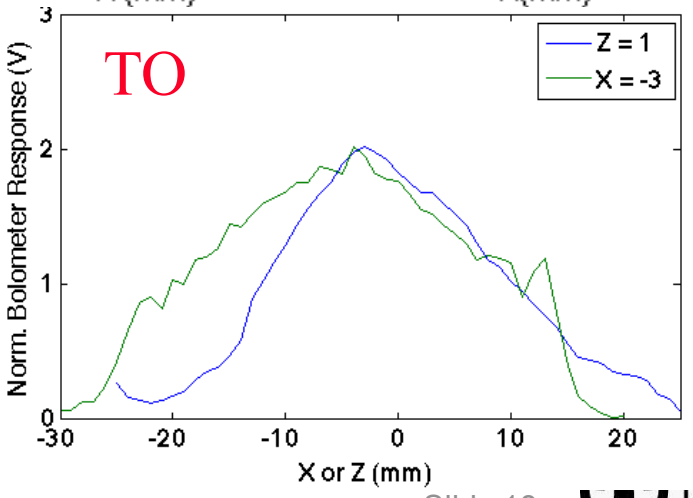
Sandia National Laboratories

Improved Beampattern

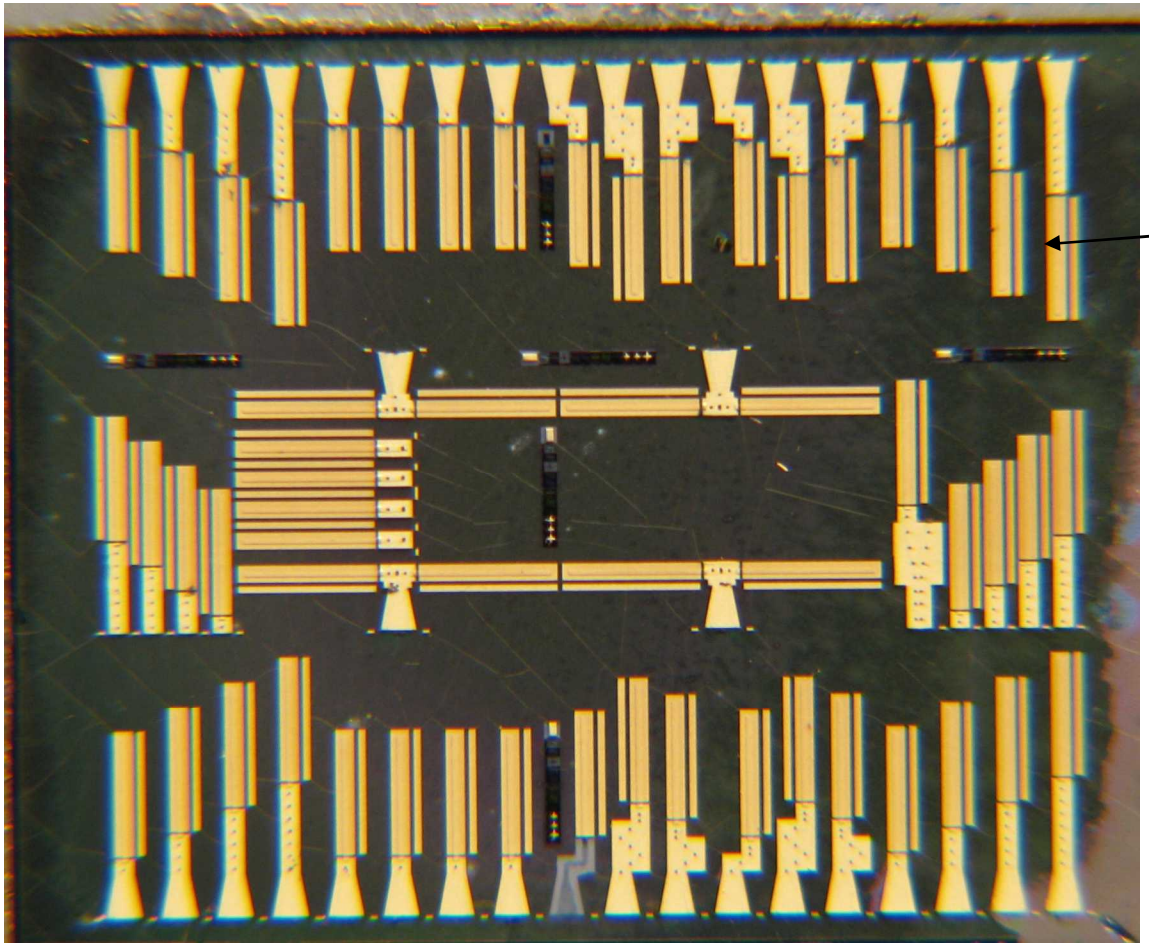








Integrated Lasers with Waveguides



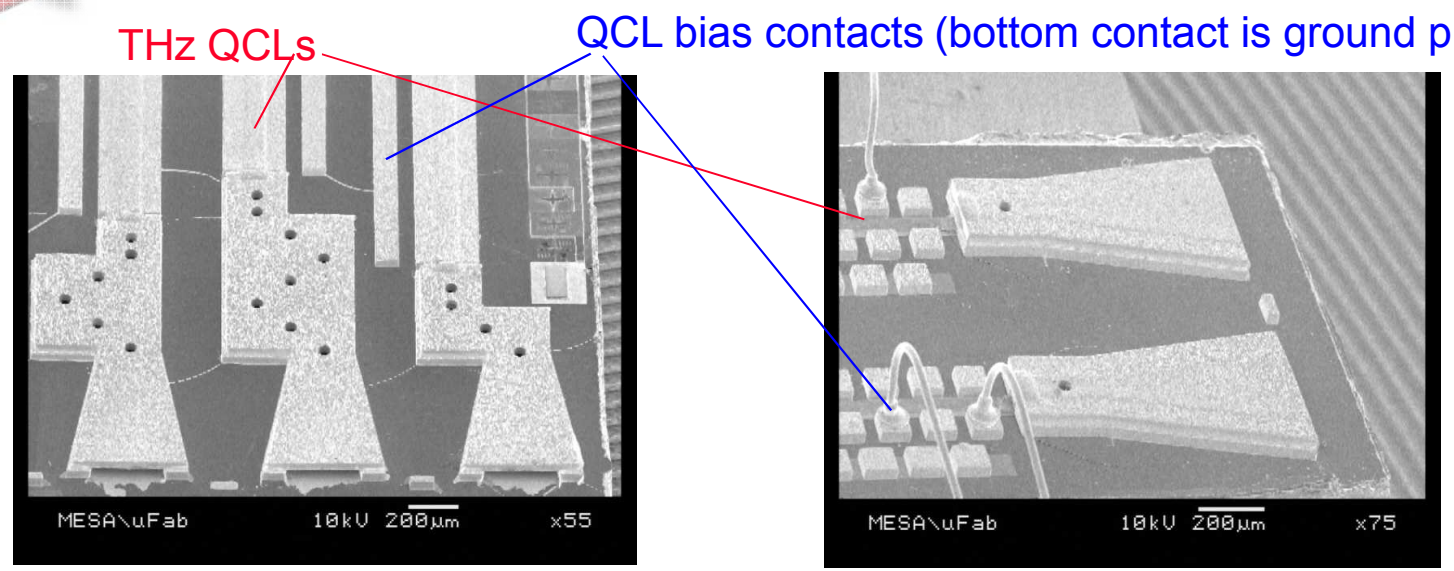
Built waveguides on top of lasers

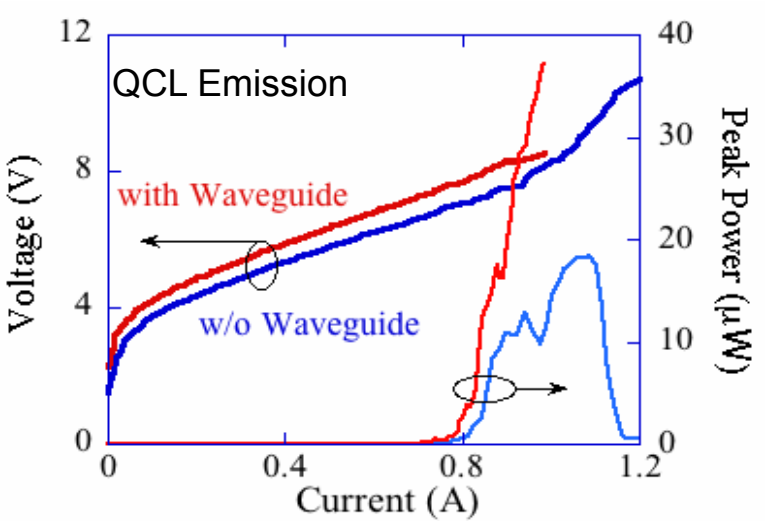
Chip Tests

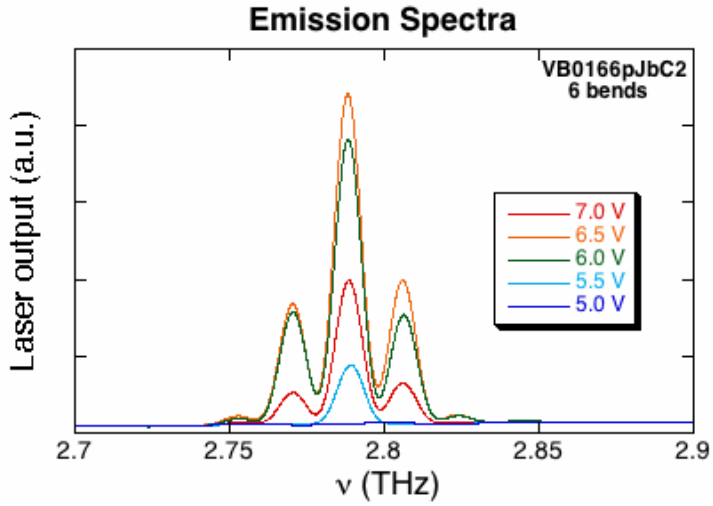
- Insertion position
- WG length
- H-plane bends
- E-plane bends
- Magic-Tees
- Horns

Note: parallel assembly advantage

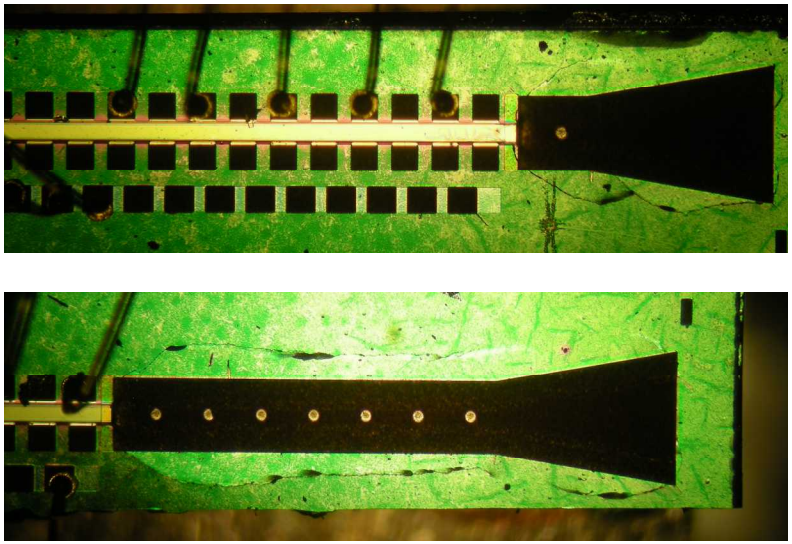
QCLs integrated with RWGs work…

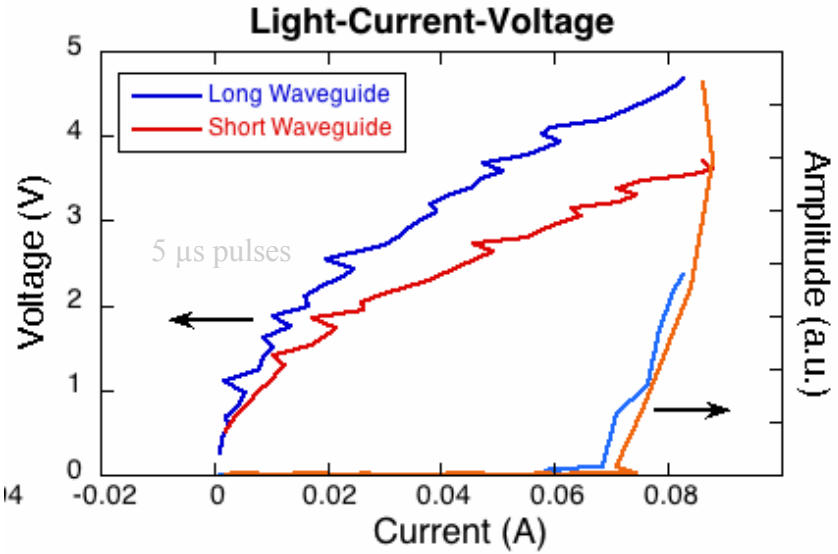


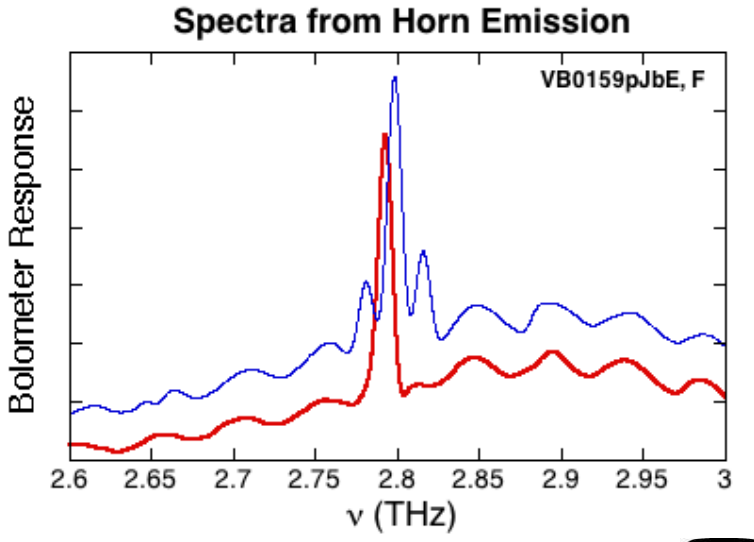




…with long or short waveguides…

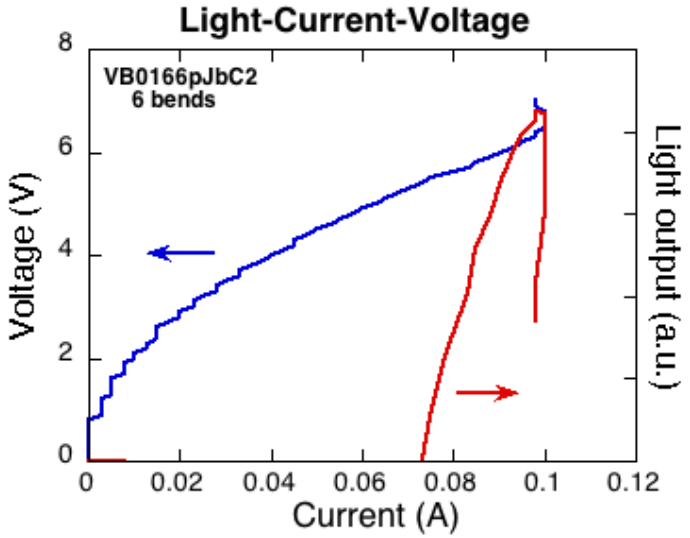


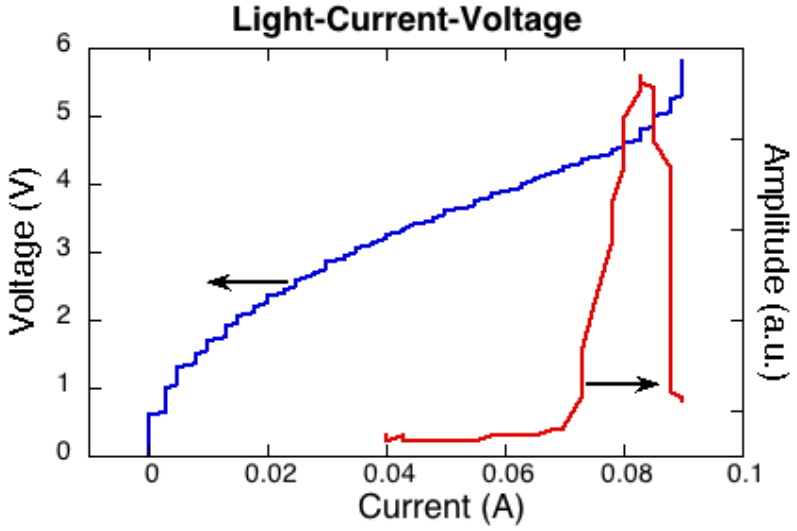




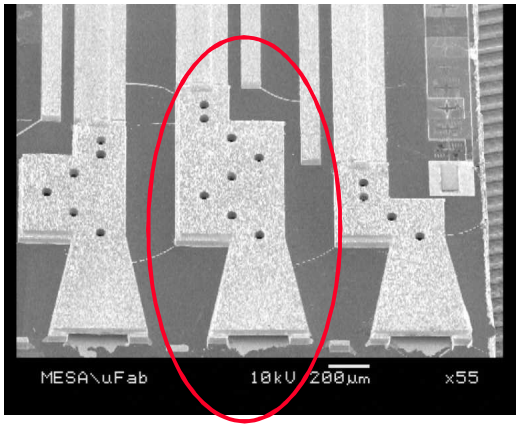
• No significant performance change with length.

… and through various bends





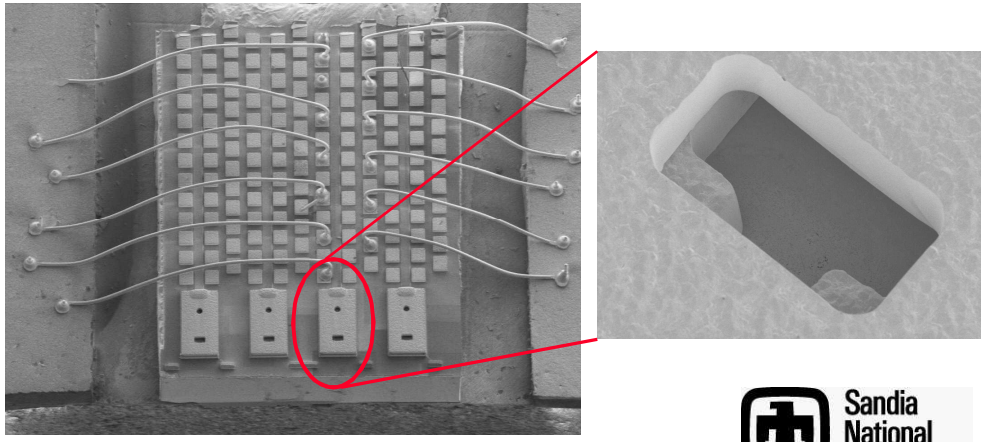
H-plane bend



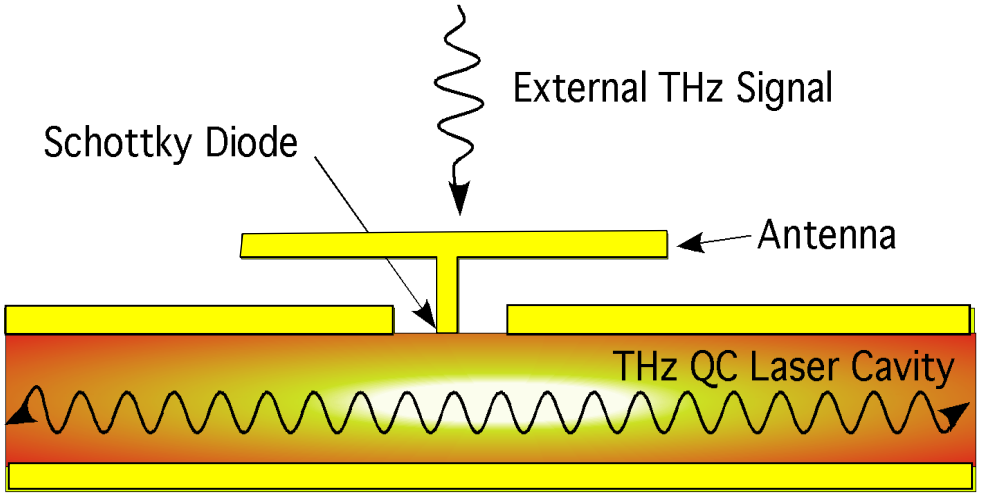
6 bends

E-plane bend

- Vertical Emission

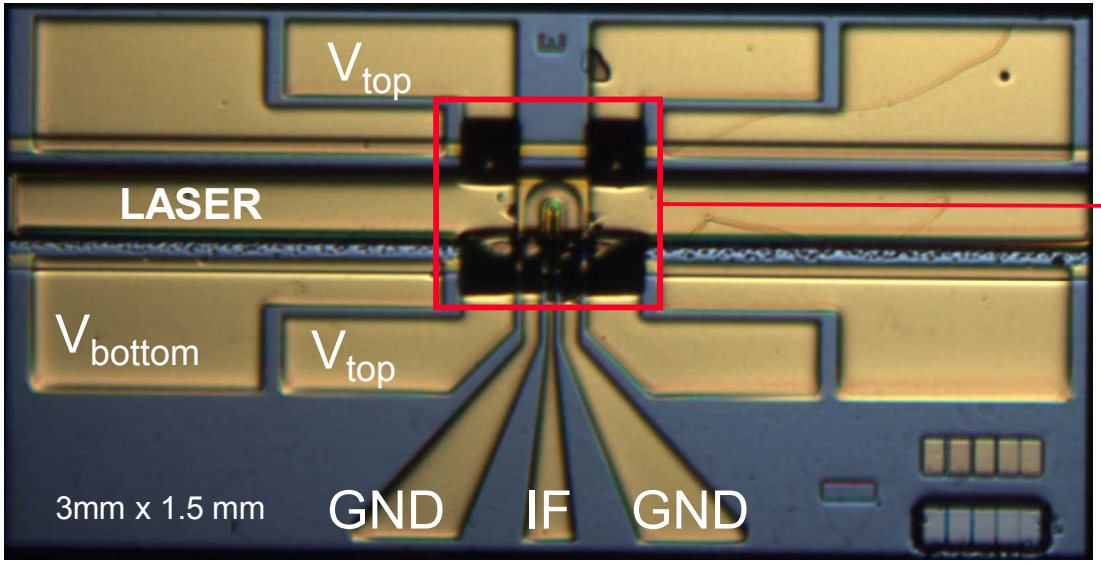


Solution 2:
Monolithically Integrate mixer *into* a QCL

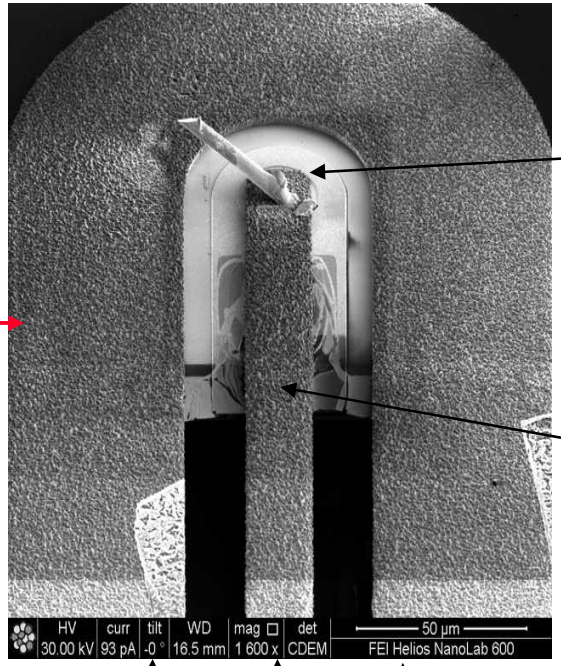


- **Payoffs**
  - No external optics to align LO to mixer.
  - Internal field coupling can be much larger.
  - Can monitor laser behavior.

QCL/Schottky THz IC



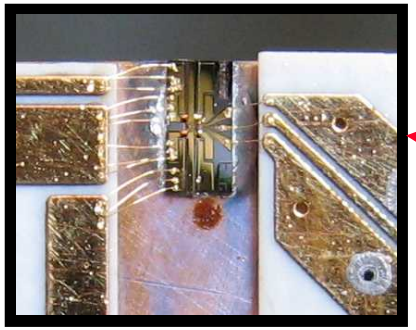
3 mm

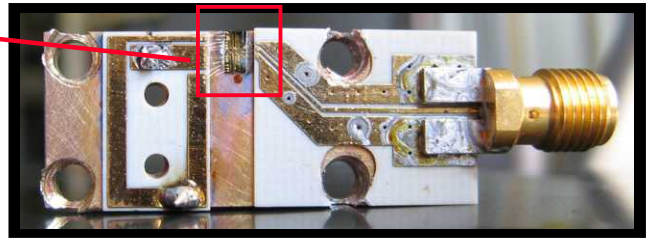


diode

air bridges

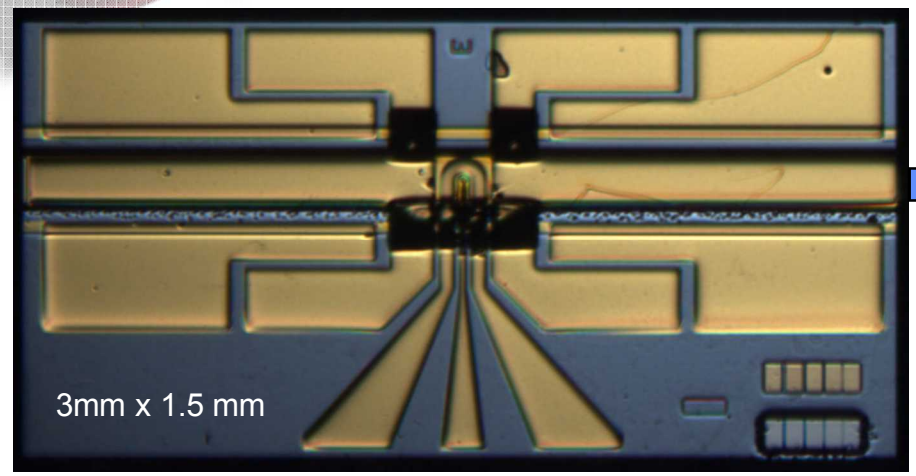
GND IF GND

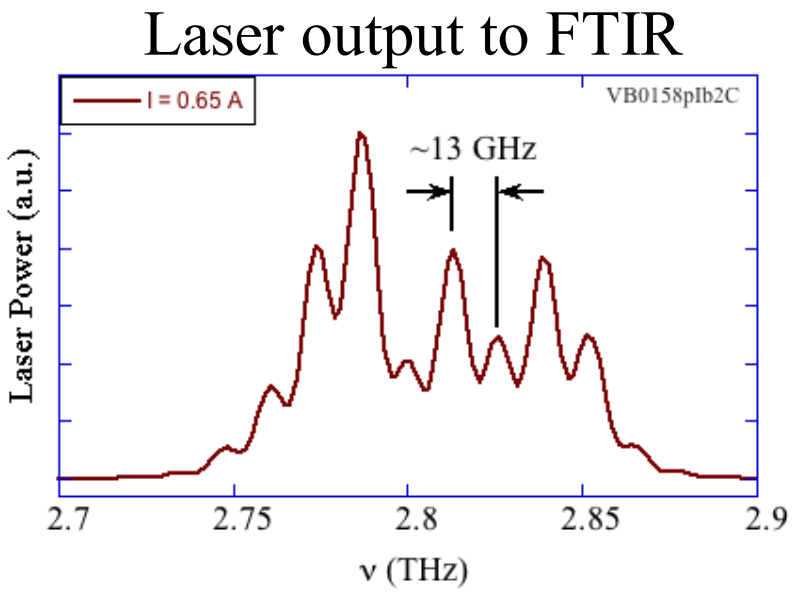




Sandia National Laboratories

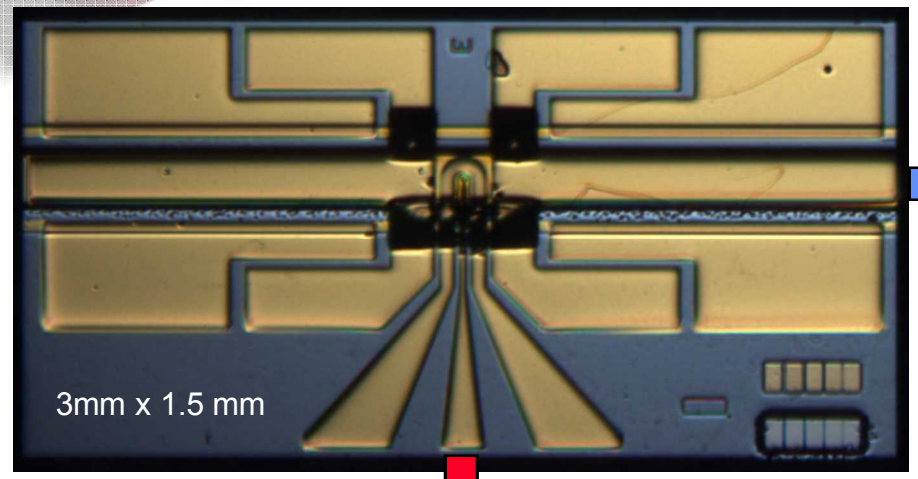
Integrated Diode THz Mixer



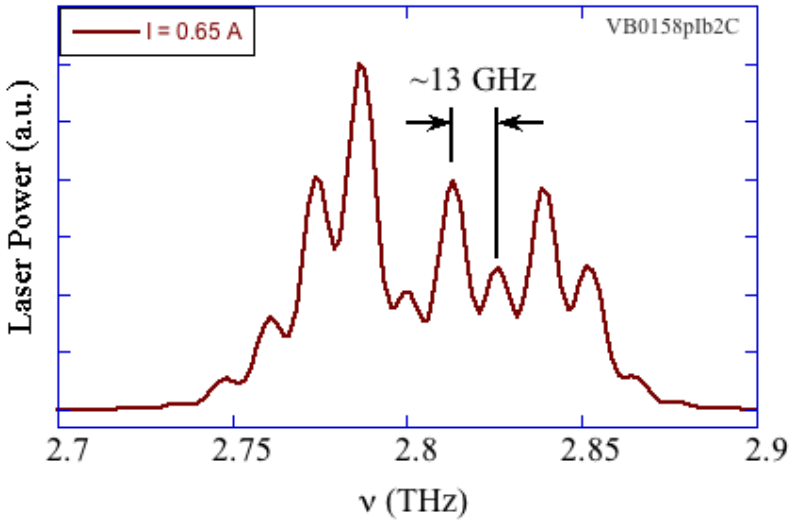


- **Purposely built a multimoded QCL centered on 2.81 THz**
  - **QCL emission (FTIR) spectra show Fabry-Perot modes spaced by ~13 GHz**

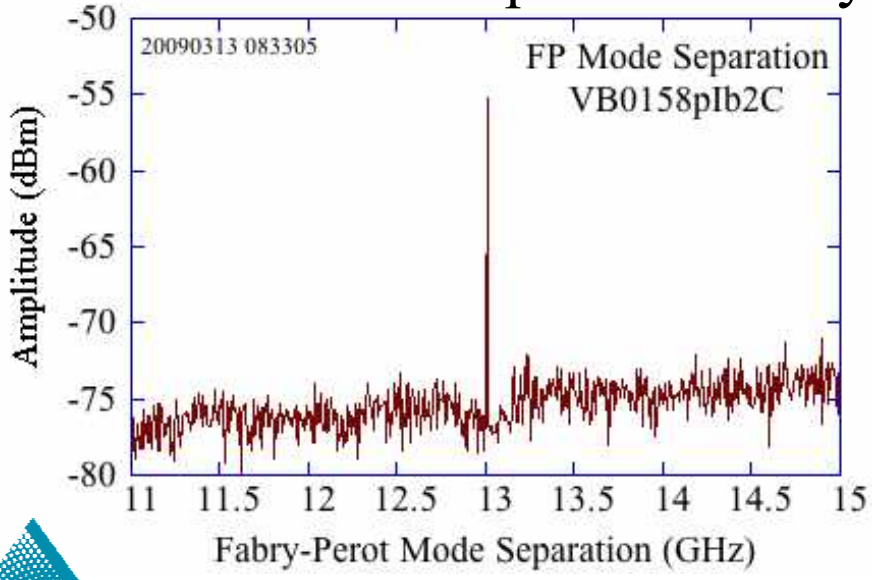
Diode detects the QCL LO



Laser output to FTIR



Electrical feed to spectrum analyzer

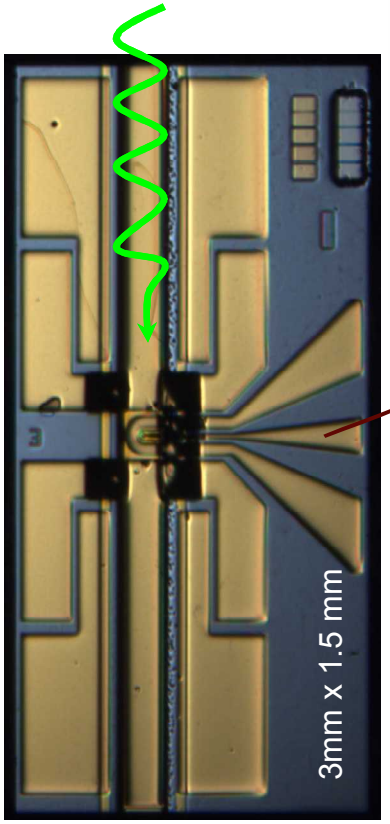


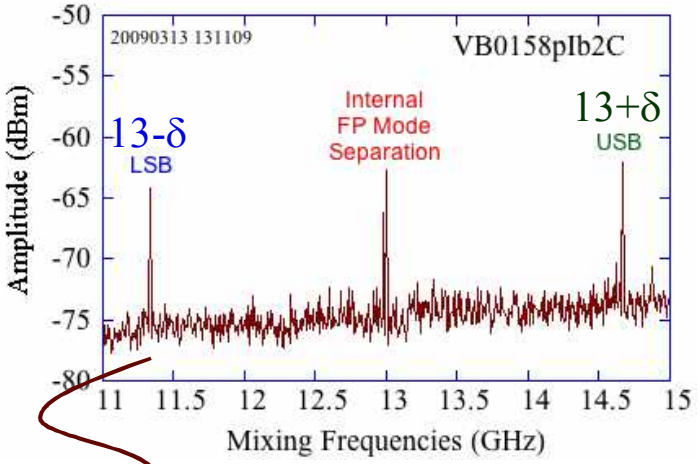
- **Diode outputs IF signal at spacing between QCL modes**
- **Strong IF power: up to -53 dBm without amplifiers**

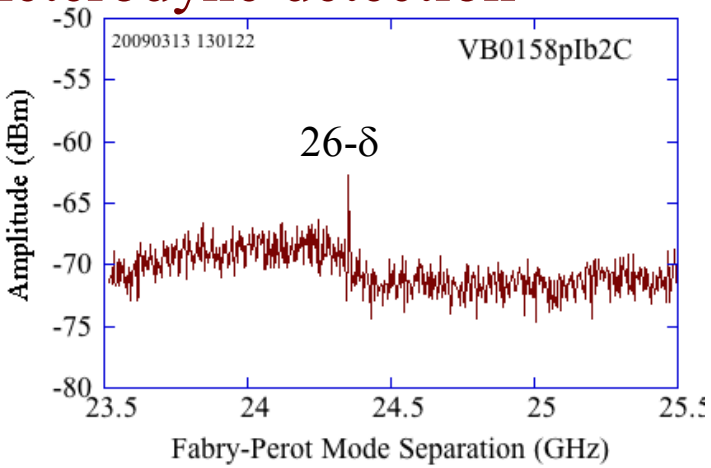
Integrated Diode acts as THz Transceiver

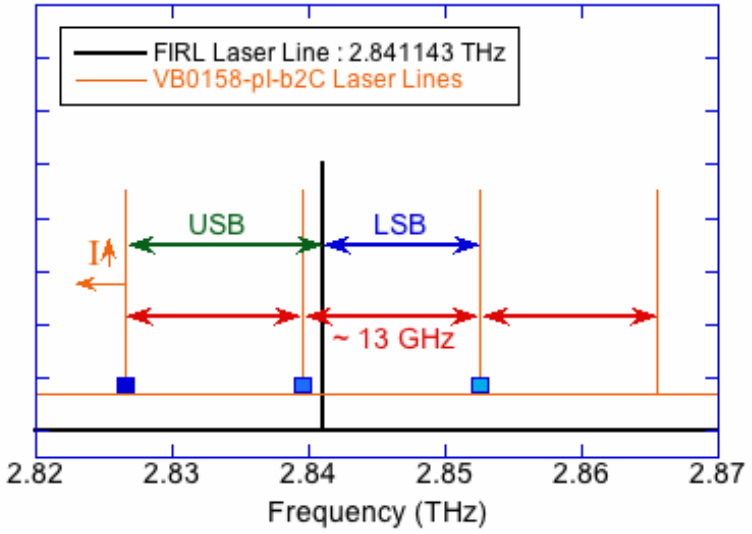
Demonstration of heterodyne detection

External Radiation



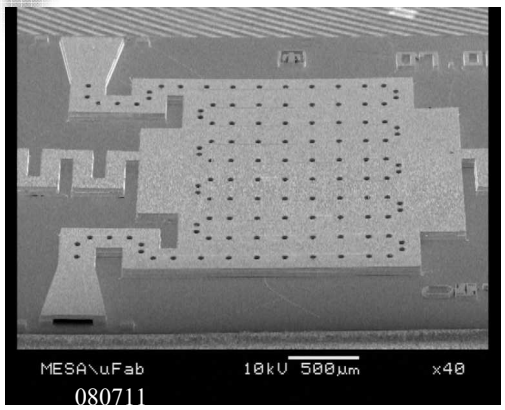


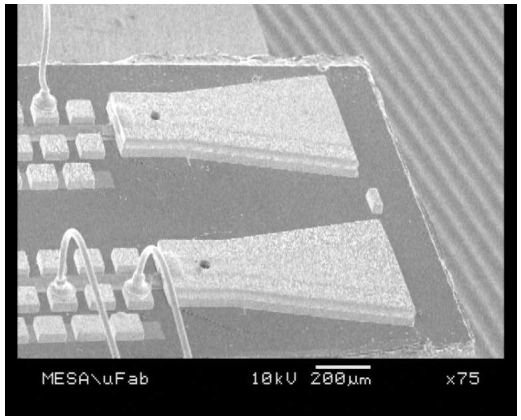


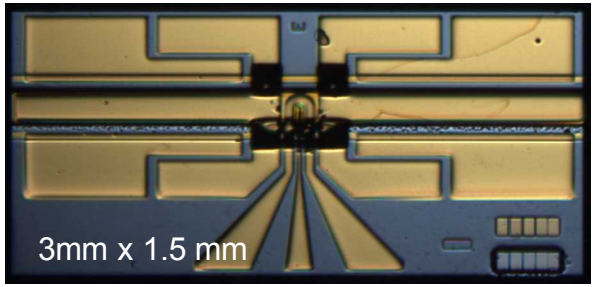


Sandia National Laboratories

Summary







- **THz QCLs continue to improve and hold promise as miniature, solid-state local oscillators.**
- **Electroplated rectangular waveguide circuit elements exhibit good performance > 2.5 THz.**
- **QCLs can be integrated into on-chip rectangular waveguide components and circuits.**
- **Heterodyne mixing can be achieved in a monolithically integrated diode/QCL.**


Questions?