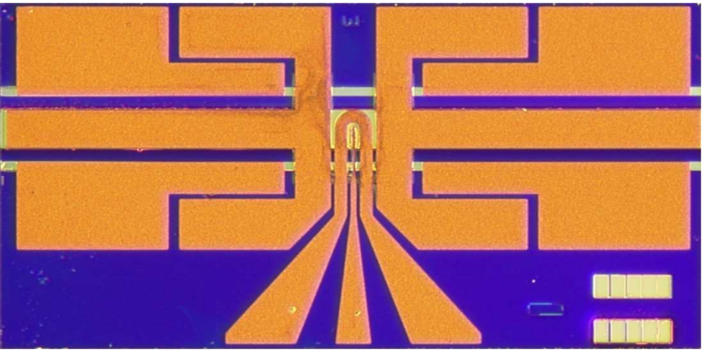
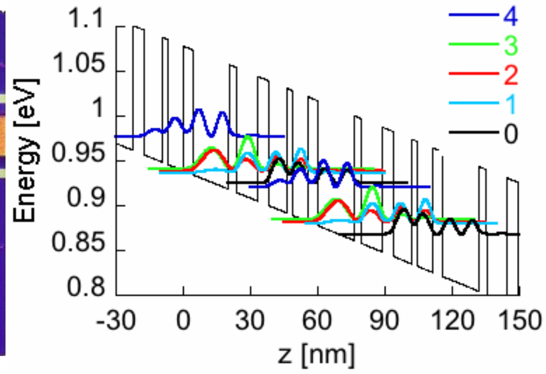
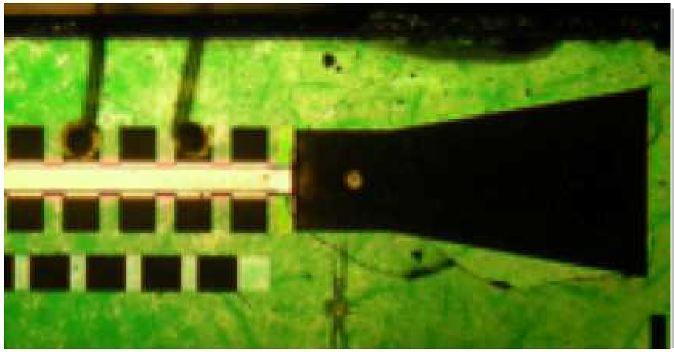






THZ Quantum Cascade Lasers

Michael C. Wanke

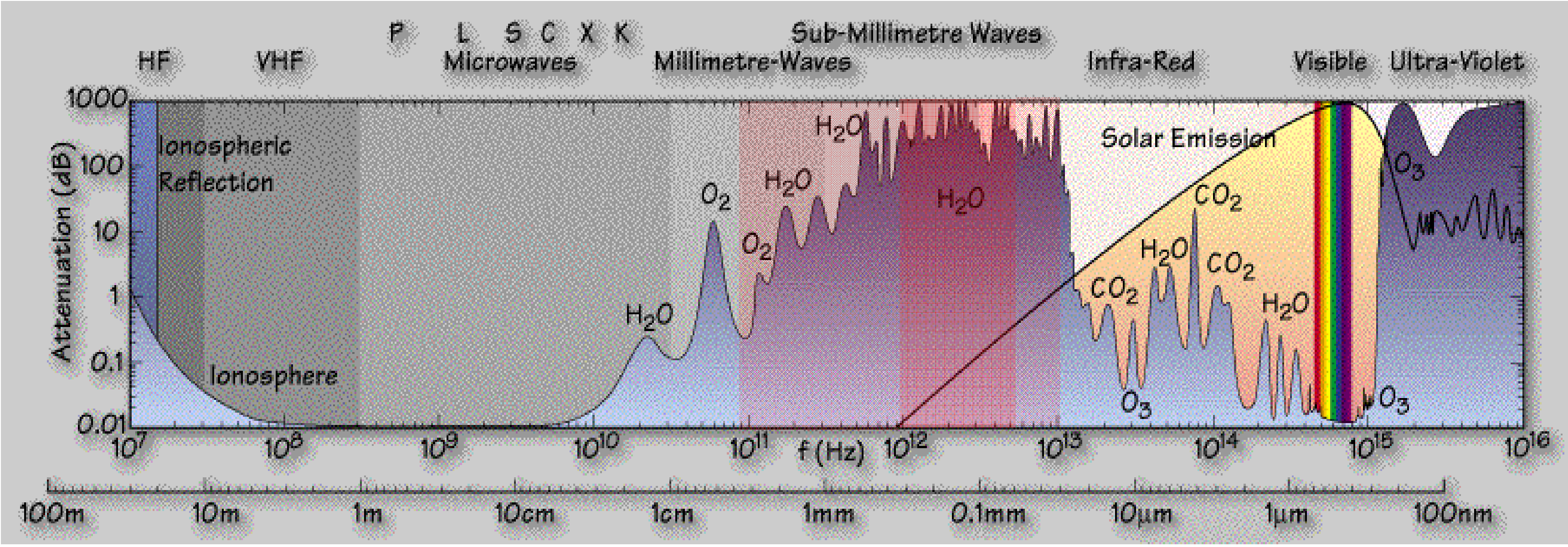
May 2013

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- THz basics
  - THz definition for this talk
  - promises
  - some reality
- THz Quantum Cascade Lasers
  - Basic performance status
  - Status on few key metrics and application impacts
  - Selected THz device work at Sandia

THz Definition

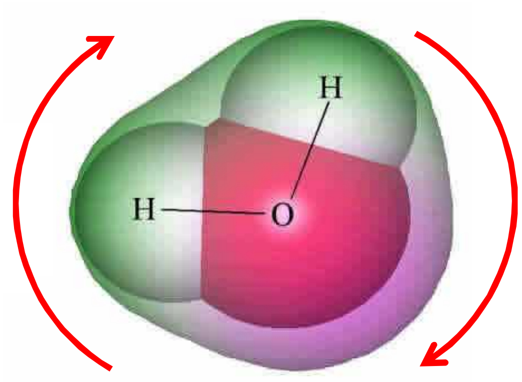


This Talk

Commonly called THz

Note : When people say THz can do something it most often applies over a limited frequency range!

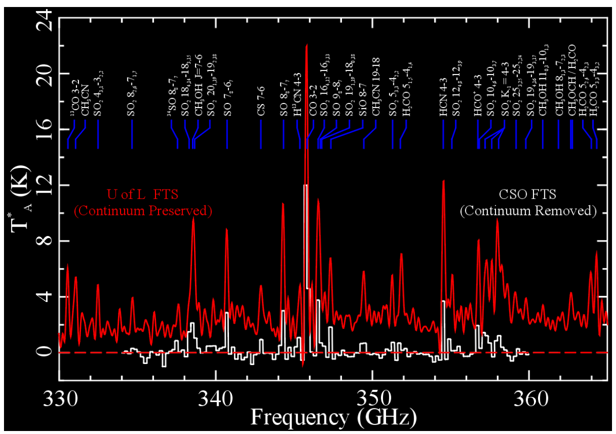
Molecular Identification



- Rotational resonances in the THz
  - Depends on *mass distribution*
  - Many distinctive spectral lines
- Potentially better chem detection & ID than using other spectral regions.*
- Caveat: high specificity normally requires low pressure (measure in vacuum not air)

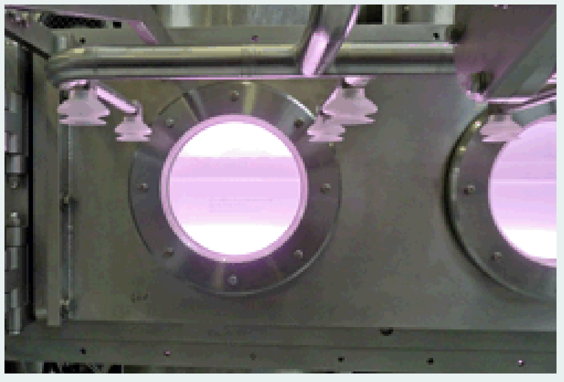
* (see Sensing with Terahertz Radiation,Dan Mittleman, (ed.))

Astrophysics

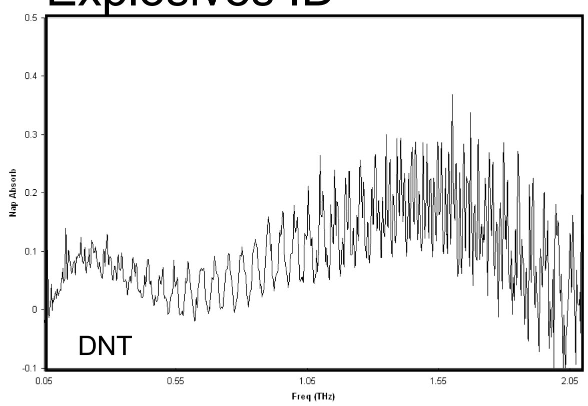


(courtesy D. Naylor, Univ. of Lethbridge)

Plasma Diagnostics

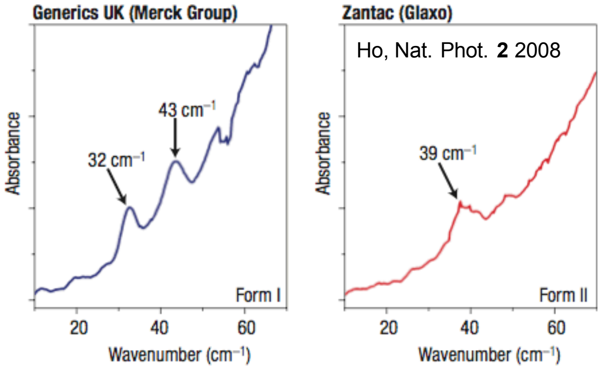


Explosives ID



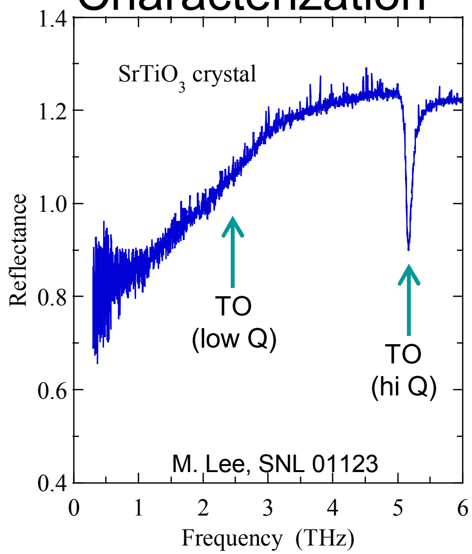
Solids Identification

Process / Quality Control

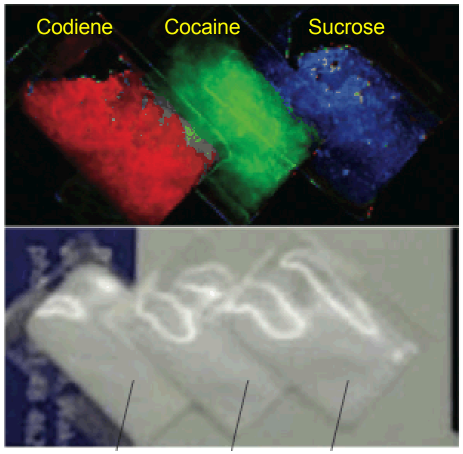


- Variety of physical mechanisms
  - Phonons, index, transit times, collective excitations, spin precesion, cyclotron resonance, confinement energies, bending modes, ….
- Caveat: Signatures are broad and often at higher frequencies where transmission is low and devices are limited.

Materials Characterization

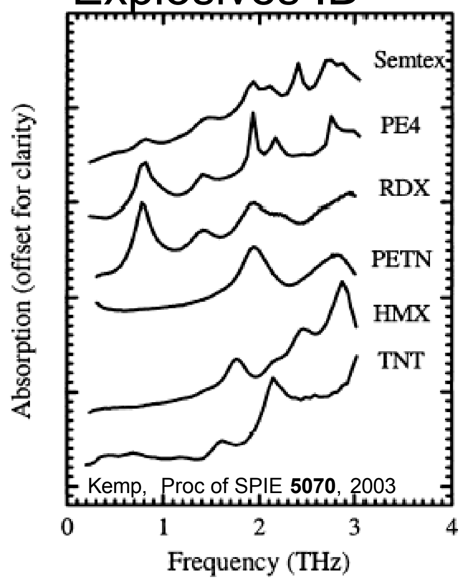


Drug ID



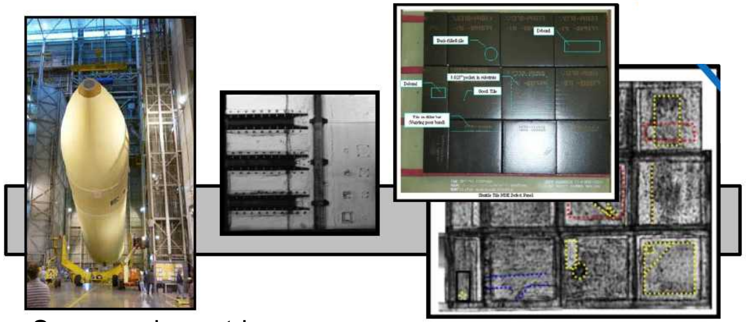
Tonouchi, Nat Phot 1, 2007

Explosives ID



Non-Destructive Evaluation

Shuttle Void /Corrosion Detection

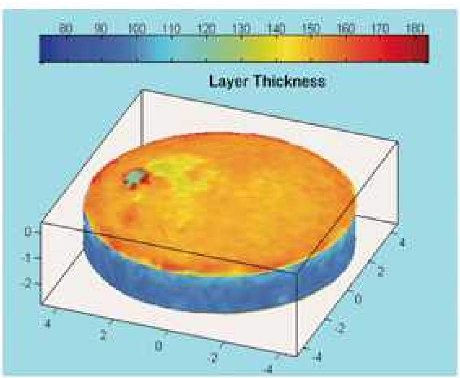


Source : picometrix

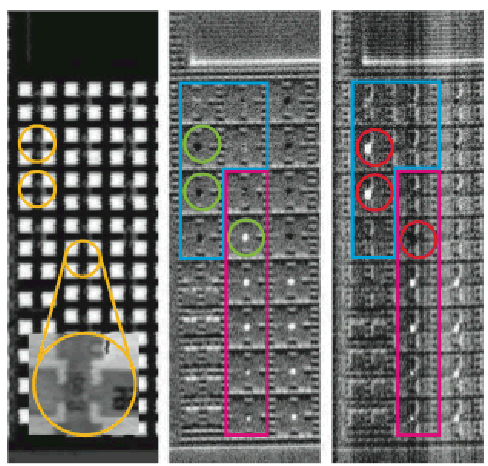
Paper Thickness Monitor

Source : picometrix

Pharmaceuticals

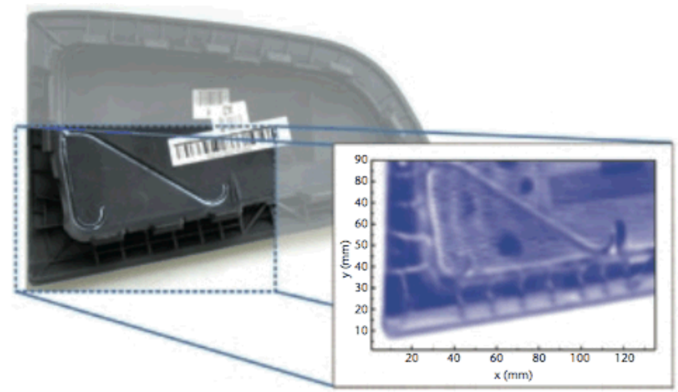


Electronics



Tonouchi, Nat Phot 1, 2007

Automotive

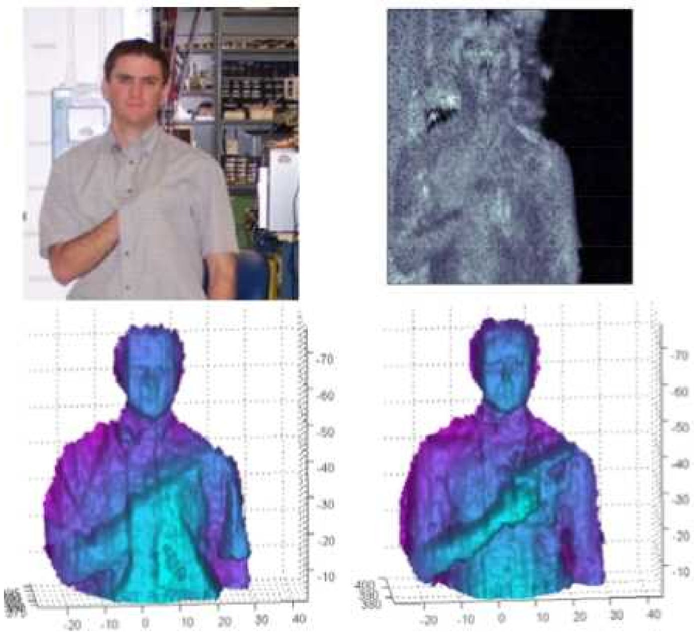


Source : Martin Koch

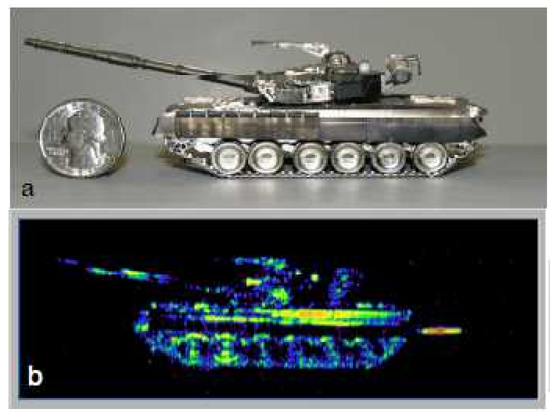
THz Imaging

- Many fabrics, packaging materials opaque to microwave and/or IR/vis are (semi)transparent in THz*

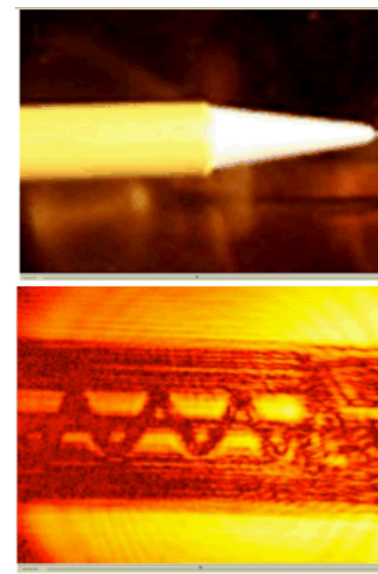
Source : Synview



Chattopadhyay, Proc. ISSTT, 2008



Danylov, Proc SPIE, **7601**, 2010



Qing Hu, MIT
Lee, IEEE PTL, 18, 1415 (2006)

* Caveat: In general transmission generally decreases with increasing frequency.

High Bandwidth Communication

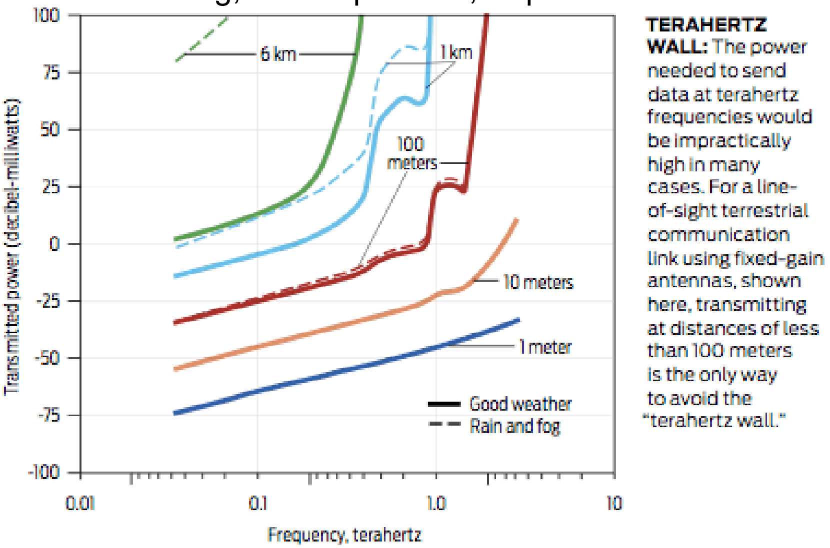
Commercial wireless cell phones (3G CDMA):

- Carrier frequency ≈ 2 GHz
- Data rate ~ 3 MB/s max
- Transmission range ~ 1 km

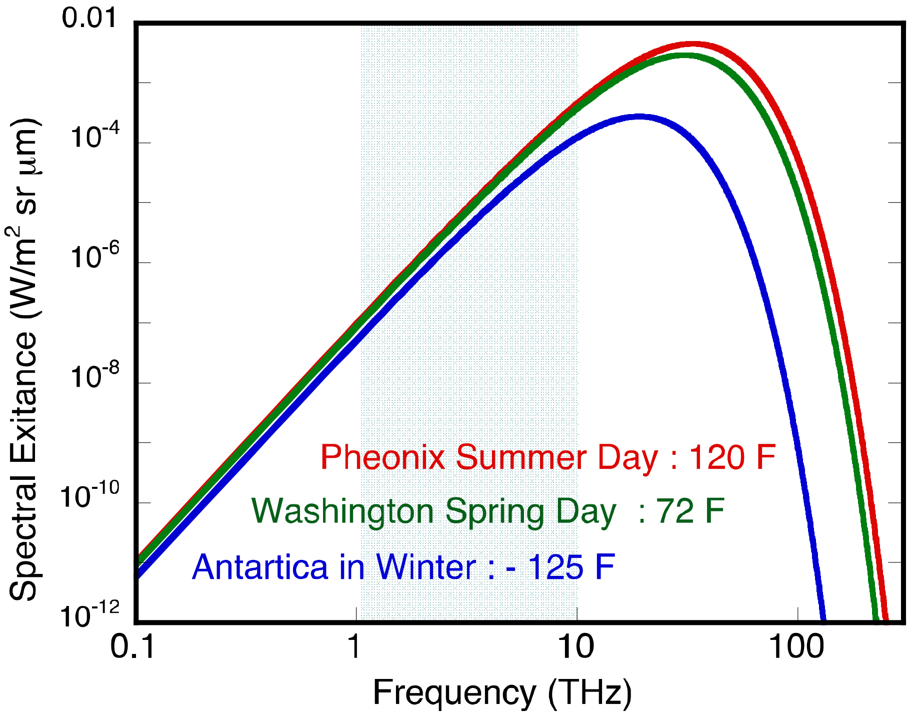
Using a THz carrier compared to microwaves…

- Higher carrier ⇒ higher data rates (~10 GB/s)
- Shorter wavelength ⇒ higher directionality
- Atmospherically limited range < 100 m
  ⇒ less susceptible to intercept / interference

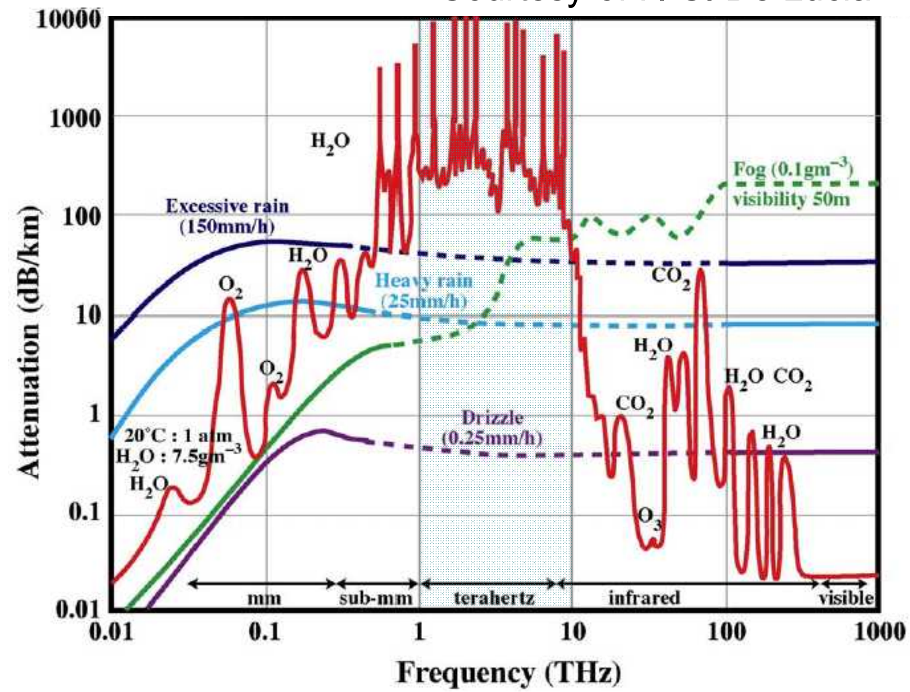
Armstrong, IEEE Spectrum, Sept 2012



Issues with THz Applications *



Courtesy of F. C. De Lucia



- Everything emits THz (including the atmosphere)
- Strong atmospheric absorption

→ For open air applications probably need coherent detection to mitigate strong losses and large backgrounds

Good reference to assess THz applications Carter Armstrong, "The Truth about Terahertz", IEEE Spectrum, 36, Sept 2012.

Atmospheric Impacts on Spectroscopy

Ren, APL, 97, 161105, (2010)

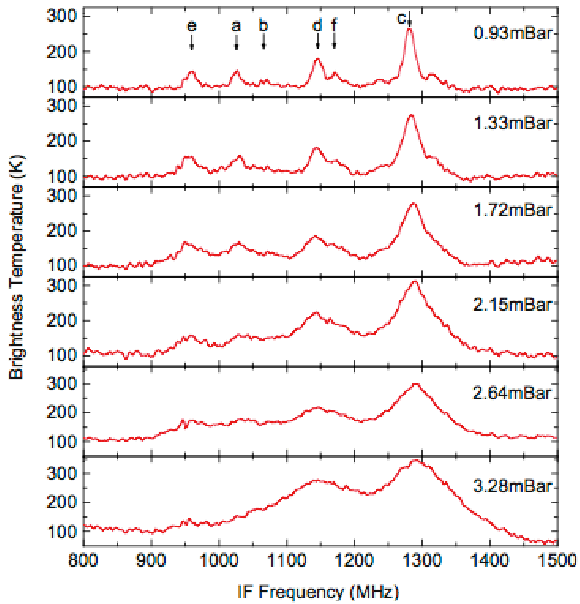
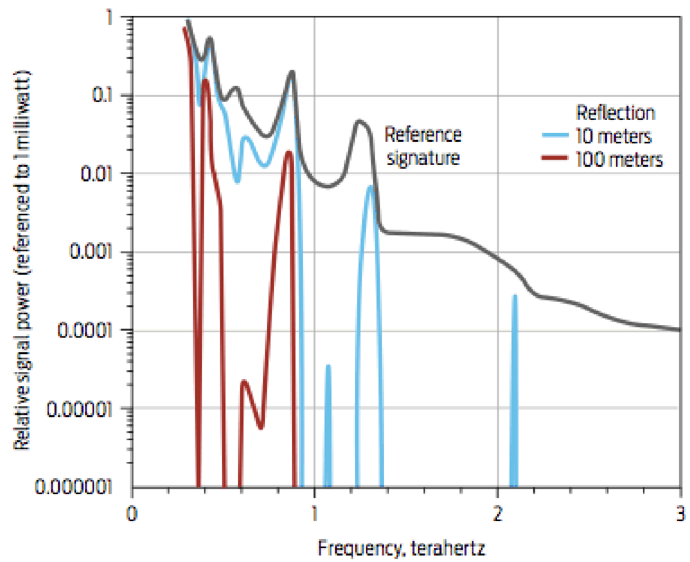


FIG. 3. (Color online) Measured methanol (CH_3OH) emission spectra within the IF range between 0.8 and 1.5 GHz at different gas cell pressure which varies from 0.93 to 3.28 mbar. The QCL's frequency is 2915.6 GHz.



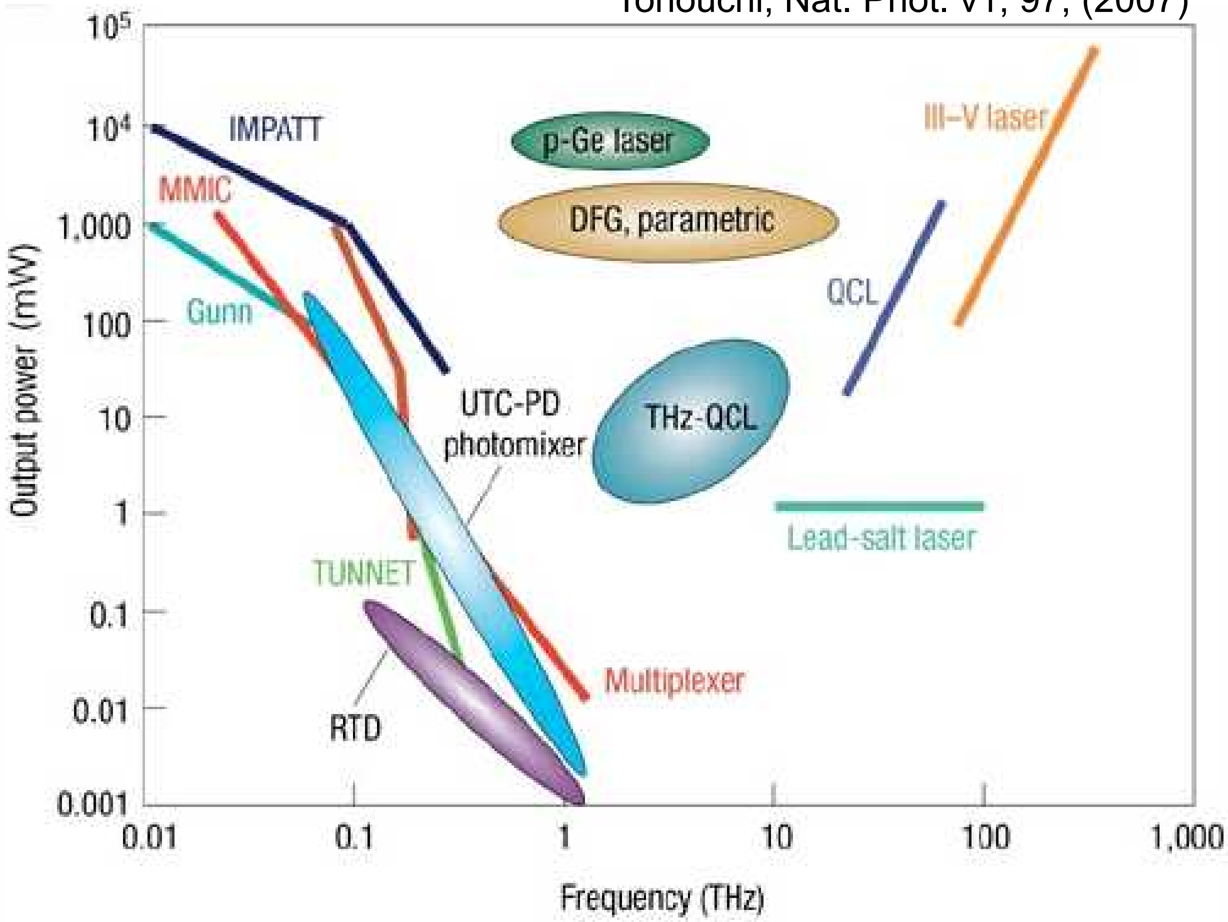
THE UNDETECTED: When attempting to identify unknown substances at a distance, nearly all of the terahertz signal will be lost or distorted by the atmosphere. Here, the gray line is a fictitious signature for a sample being probed in reflection mode. At distances of 10 meters and 100 meters [blue and red lines], the sample's distinct spectral features are washed away.

Atmospheric attenuation may dominate spectral features

Pressure broadening of lines may wipe out features.

Compact Sources – still limited

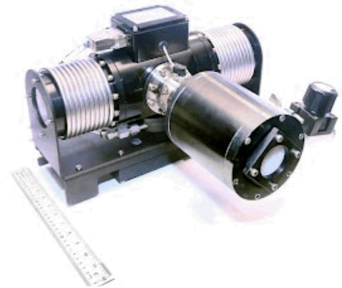
Tonouchi, Nat. Phot. v1, 97, (2007)

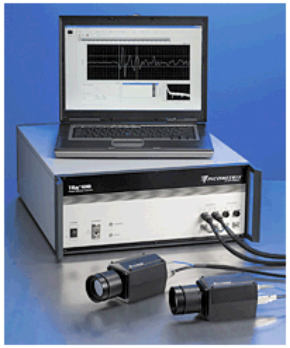


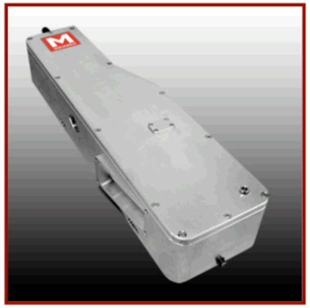
Selected Commercial THz Sources*

*That go above 1 THz

Standard Package + Spectroscopy Kit





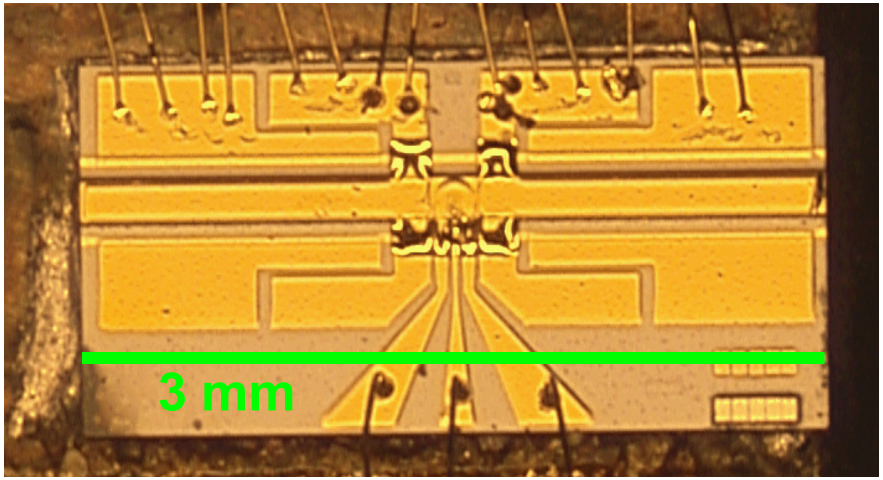


- OPOs
- BWOs
- CW photomixers
- Time-domain systems
- Harmonic mixers
- Molecular gas lasers
- Quantum cascade lasers

THz QCLs

- Advantages
  - compact
  - frequency agile
  - narrow linewidth
  - phase lockable
  - high modulation rates
  - integratable
- Disadvantages
  - still cryogenic
  - currently low wall plug efficiency
  - relatively low output powers
  - limited direct active tuning

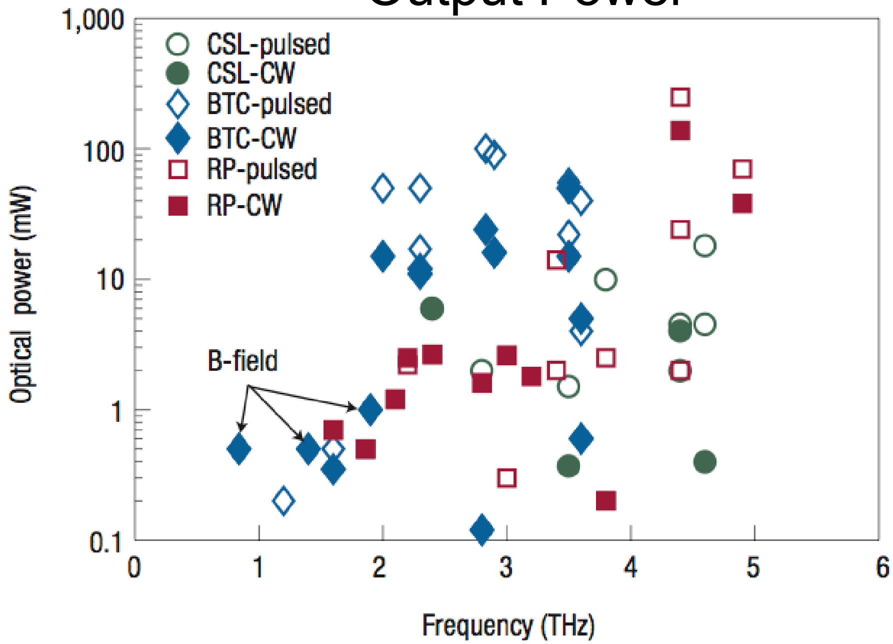
THz QCL based Integrated Transceiver



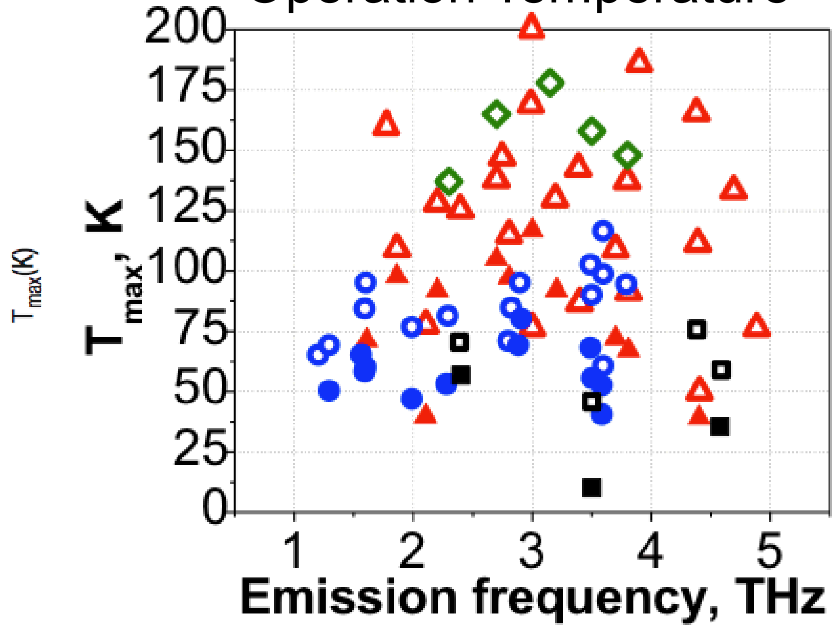
THz QCL Performance*

*Taken from : B.S. Willams, Nat. Phot. **1**, 517 (2007)*

Output Power



Operation Temperature*



* updated plot from Mikhail Belkin

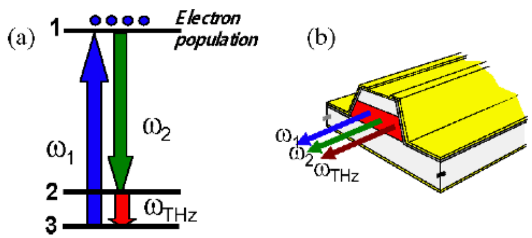
- **Wavelength – 60 μm – 250 μm (1.2 – 5.0 THz)**
- **Temperature – up to 200 K (pulsed), 117 K (cw)**
- **Power – 248 mW pulsed, 138 mW cw @ 10 K, 1.5 mW cw @ 77 K**
- **Threshold – J_{th} ~ 1 – 1000 A/cm^2 200 typical**
- **Max wall plug efficiency – 5%**
- **Linewidth –6 kHz freq. locked, 10 Hz phase locked**
- **Single Mode – DFB structure**

Room Temperature “THz” QCLs

Use difference frequency generation to generate THz

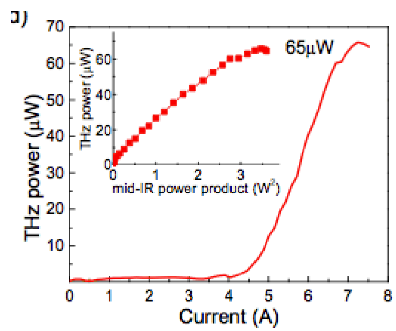
- Relatively small powers
- Limited efficiency
- Highest output power at 300K ✔
- Widely tunable ✔

Nat. Phot. **1**, 288, 2007



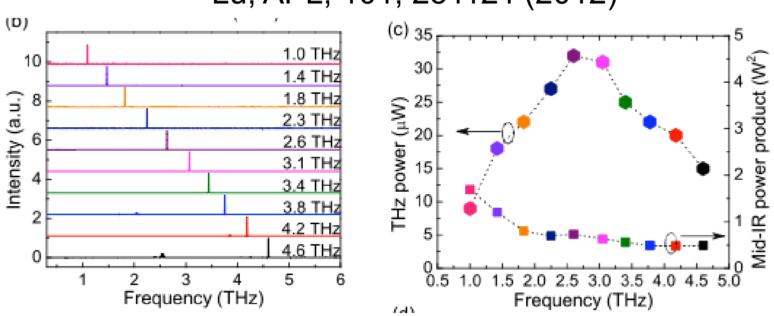
- First DFG demo

Lu, Opt Exp,21, 968 (2013)



- 65 µW at 300K

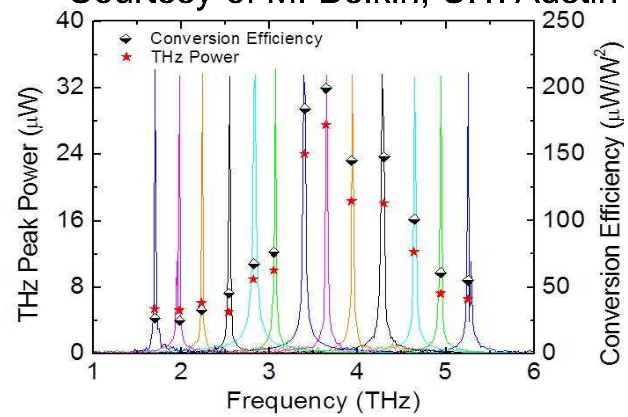
Lu, APL, 101, 251121 (2012)



- Tuning from 1 to 4.6 THz
- 30 µW at room temperature

Widely tunable external-cavity THz DFG-QCLs

Courtesy of M. Belkin, U.T. Austin

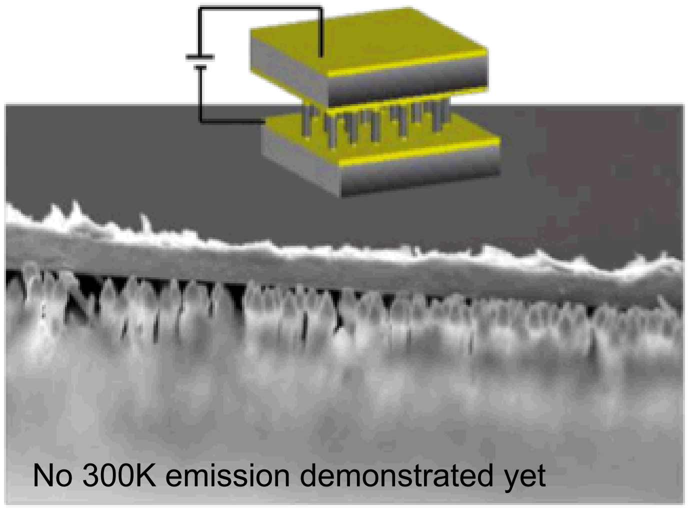


Towards Room Temperature “THz” QCLs

Using “1D”-confinement

Use nanopillars to create “1D” transport

Amanti, Opt. Exp., 21, 10917, 2013



Use B-field to create “1D” transport

Wade, Nat. Phot., 3, 41, 2008

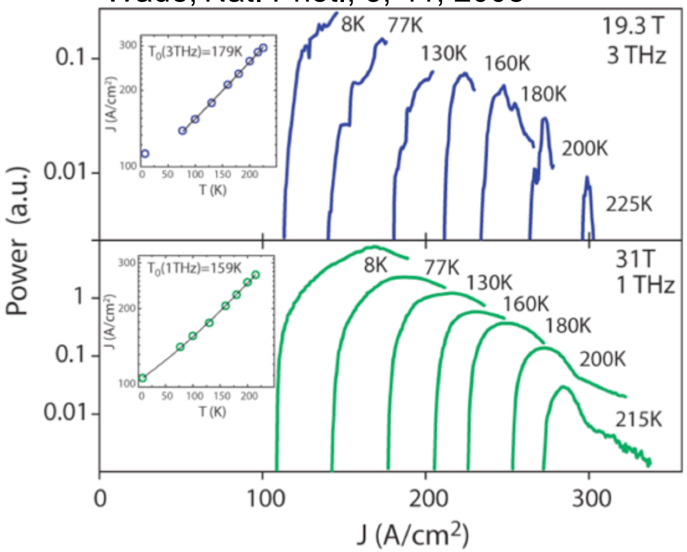


Fig Courtesy of Qing Hu - MIT

$$k_B T \sim 4.7 \times \hbar\omega$$

Strong-coupling approaches also promising approach to higher temperatures

QCL Direct Modulation Rate Limits

Sandia National Laboratories

APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 16 15 OCTOBER 2001

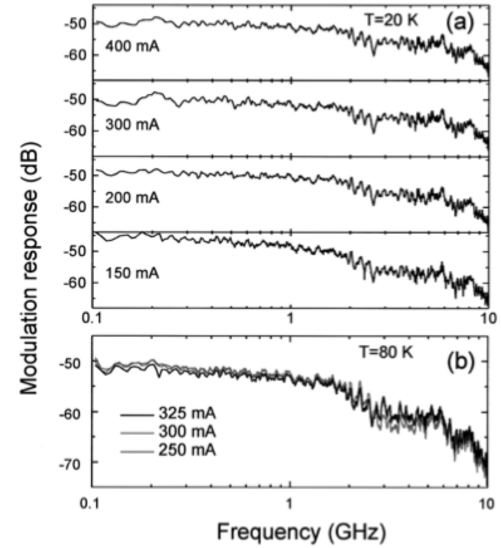
High-frequency modulation without the relaxation oscillation resonance in quantum cascade lasers

Roberto Paiella,[a] Rainer Martini, Federico Capasso,[b] Claire Gmachl, Harold Y. Hwang, Deborah L. Sivco, James N. Baillargeon,[c] and Alfred Y. Cho
Bell Laboratories, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Edward A. Whittaker
Department of Physics and Engineering Physics, Stevens Institute of Technology, Hoboken, New Jersey 07030

H. C. Liu
Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario K1A R6, Canada

- Demonstrated 10 GHz modulation
- Predicted intrinsic speed around 1 THz

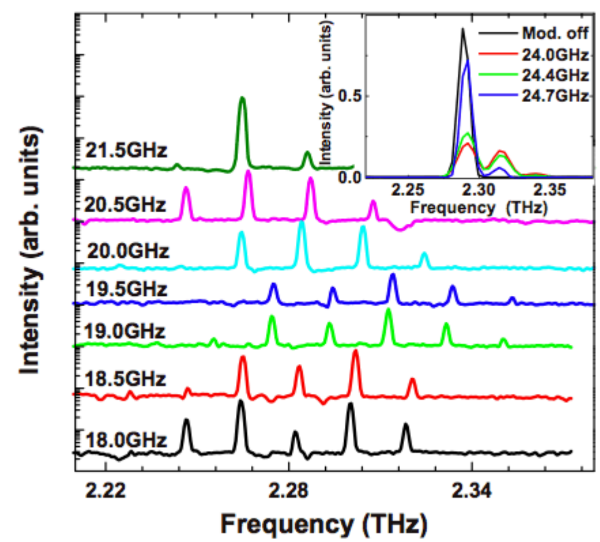


APPLIED PHYSICS LETTERS **96**, 021108 (2010)

Microwave modulation of terahertz quantum cascade lasers: a transmission-line approach

W. Maineult,[1] L. Ding,[1] P. Gellie,[1] P. Filloux,[1] C. Sirtori,[1] S. Barbieri,[1,a)] T. Akalin,[2] J.-F. Lampin,[2] I. Sagnes,[3] H. E. Beere,[4] and D. A. Ritchie[4]
[1]*Laboratoire Matériaux et Phénomènes Quantiques (MPQ), UMR CNRS 7162, Université Paris 7, 10, rue A. Domont et L. Duquet, 75205 Paris, France*
[2]*Institut d'Electronique de Microélectronique et de Nanotechnologie (IEMN), UMR CNRS 8520, Université de Lille 1, Avenue Poincaré B.P. 60069, 59652 Villeneuve d'Ascq, France*
[3]*Laboratoire LPN, Route de Nozay, 91460 Marcoussis, France*
[4]*Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*

- Demonstrated 25 GHz modulation
- Estimated circuit limited BW of 70 GHz



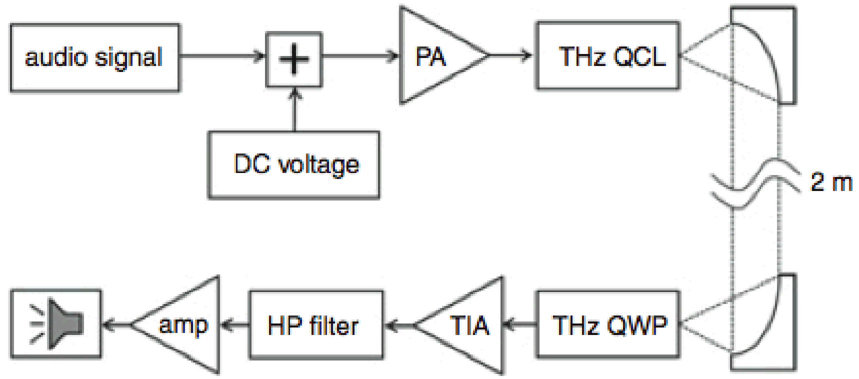
Communication Link Demo

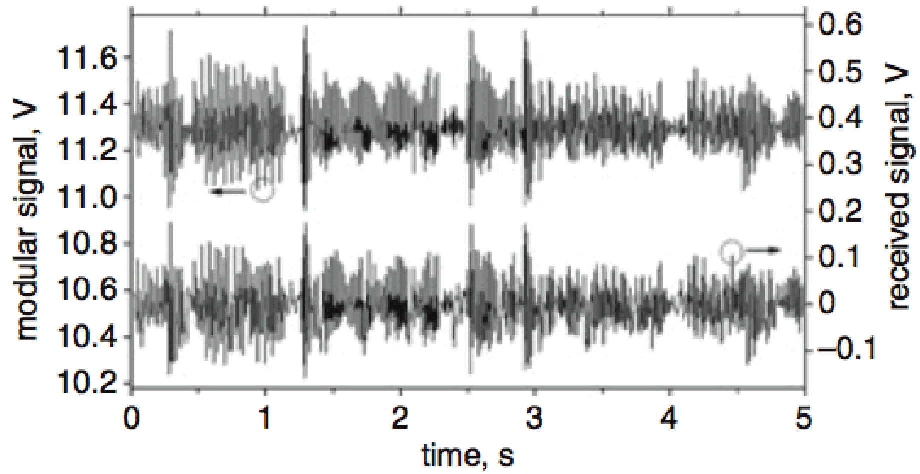
Wireless communication demonstration at 4.1 THz using quantum cascade laser and quantum well photodetector

Z. Chen, Z.Y. Tan, Y.J. Han, R. Zhang, X.G. Guo, H. Li, J.C. Cao and H.C. Liu

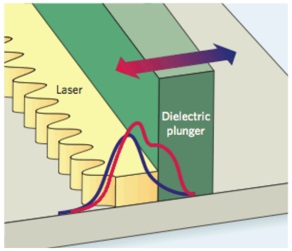
A wireless terahertz (THz) analogue communication link using a quantum cascade laser (QCL) as the source and a quantum well photodetector as the receiver is demonstrated. The QCL operates in continuous-wave mode. By directly modulating the QCL emitting at 4.1 THz, analogue signals are transmitted over a distance of 2 The circuit-limited modulation bandwidth is about 580 kHz.

Chen, *Elec. Lett.*, **47**, 1002, 2011



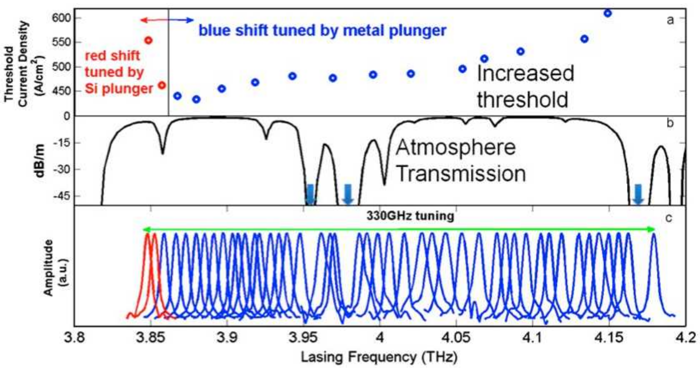


Capable of Broadband Spectroscopy



Integrated MEMs Tuning Element

Direct tuning over 330 GHz



Qin, Opt. Lett. 36, 693, (2011)

Comb Spectroscopy
- employ wide gain bandwidth of QCLs

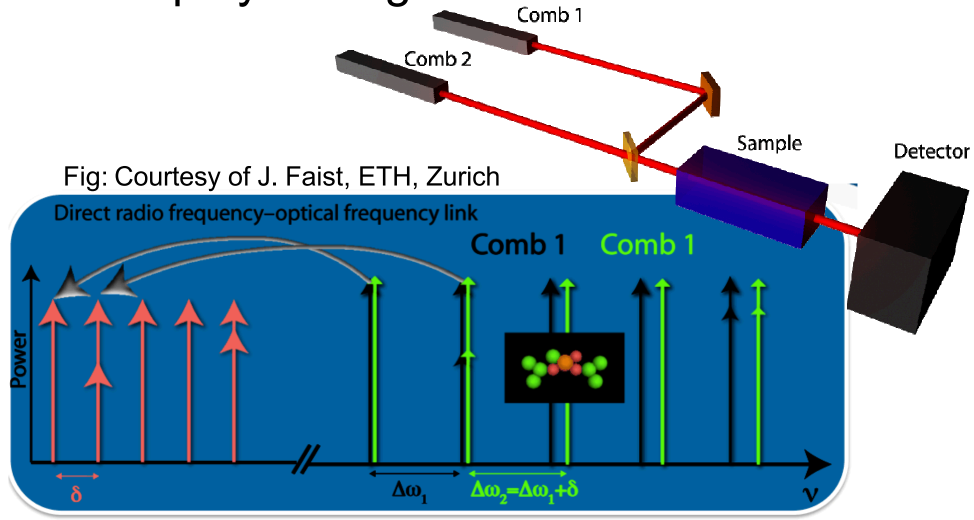
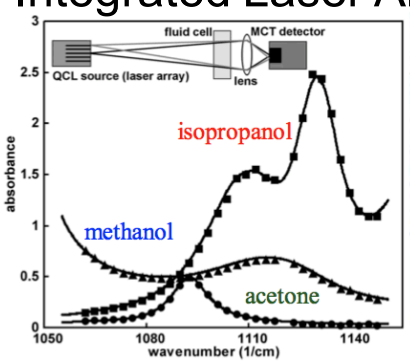


Fig: Courtesy of J. Faist, ETH, Zurich

Essentials for combs already demonstrated in MIR and THz QCLs

Hugi, Nature, 492, 229 (2012)
Barbieri, Nat. Phot., 5, 306 (2011)

Integrated Laser Arrays



demonstrated in MIR

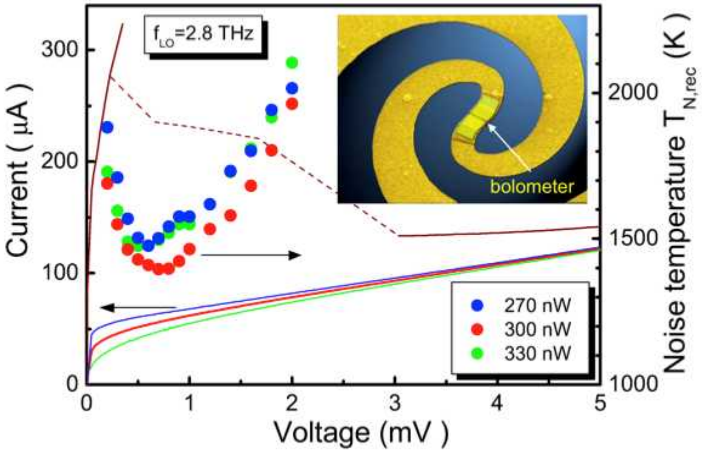
Fig. courtesy of F. Capasso, Harvard

THz QCL as heterodyne local oscillator

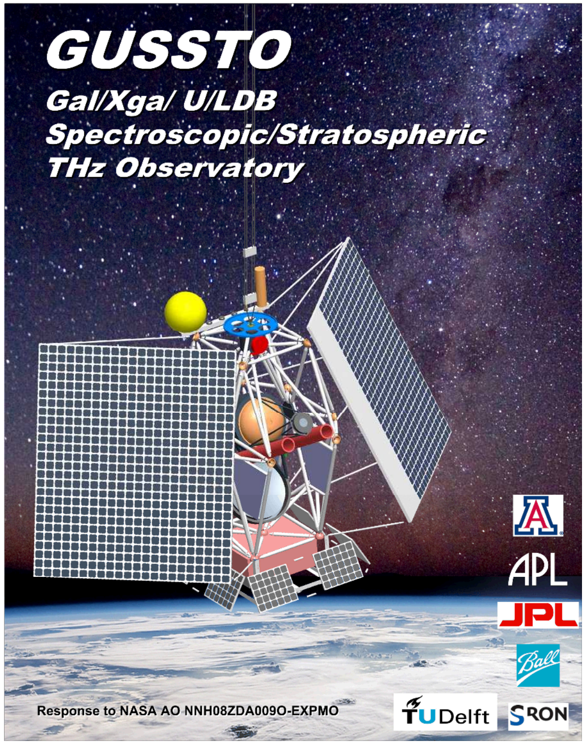
For high sensitivity detection and high resolution spectroscopy

THz Heterodyne Receiver with QCL LO

Gao, APL, 86, 244104, 2005

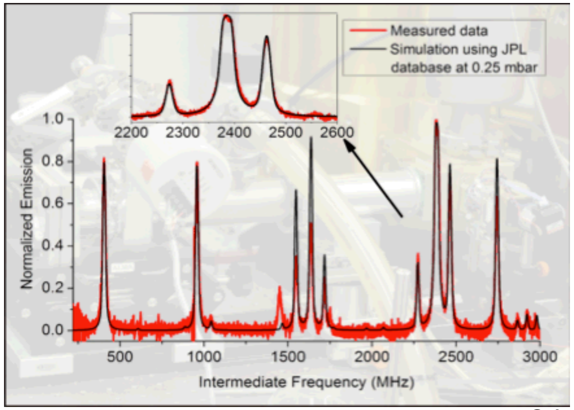


4.7 THz QCL LO



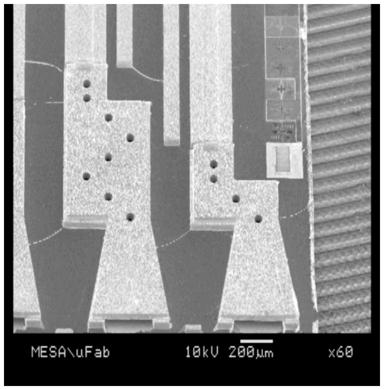
Heterodyne Receiver with 4.7 THz QCL

Kloosteman, APL, 102, 011123 (2013)

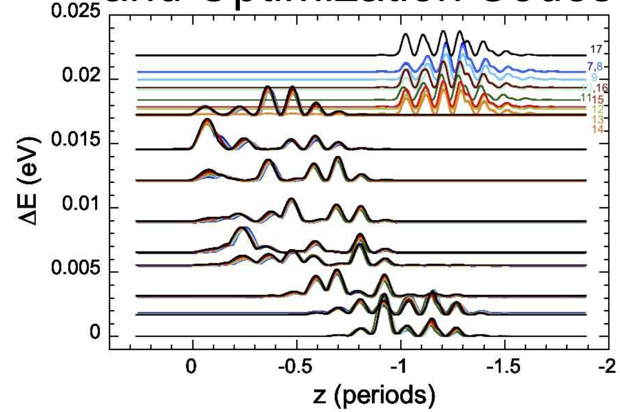


Sandia THz Devices and Integration Efforts

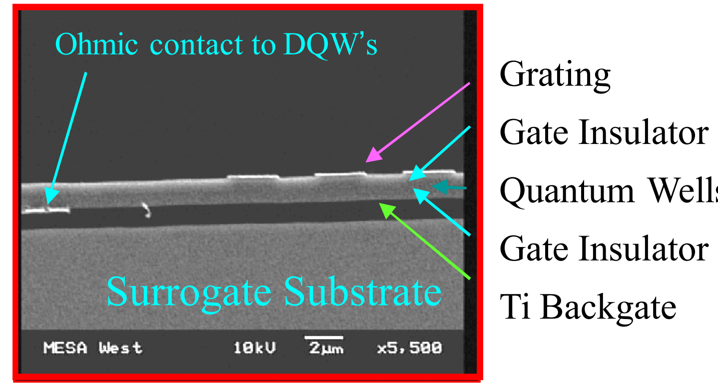
QCL / Waveguide Integration



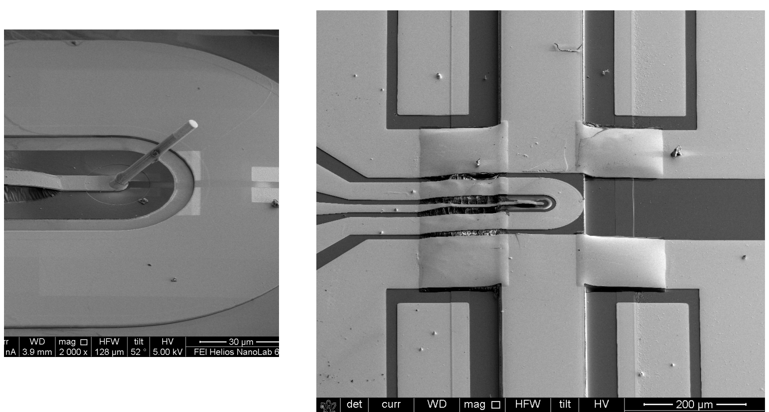
QCL Model Development and Optimization Codes



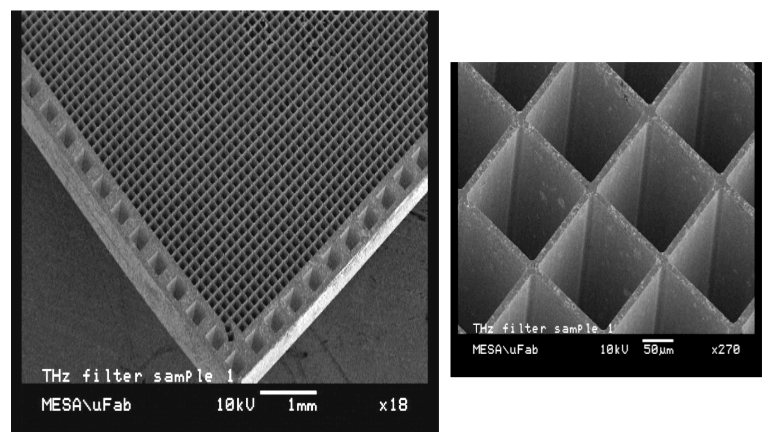
THz Tunable Plasmon Detectors



QCL / Diode Integration

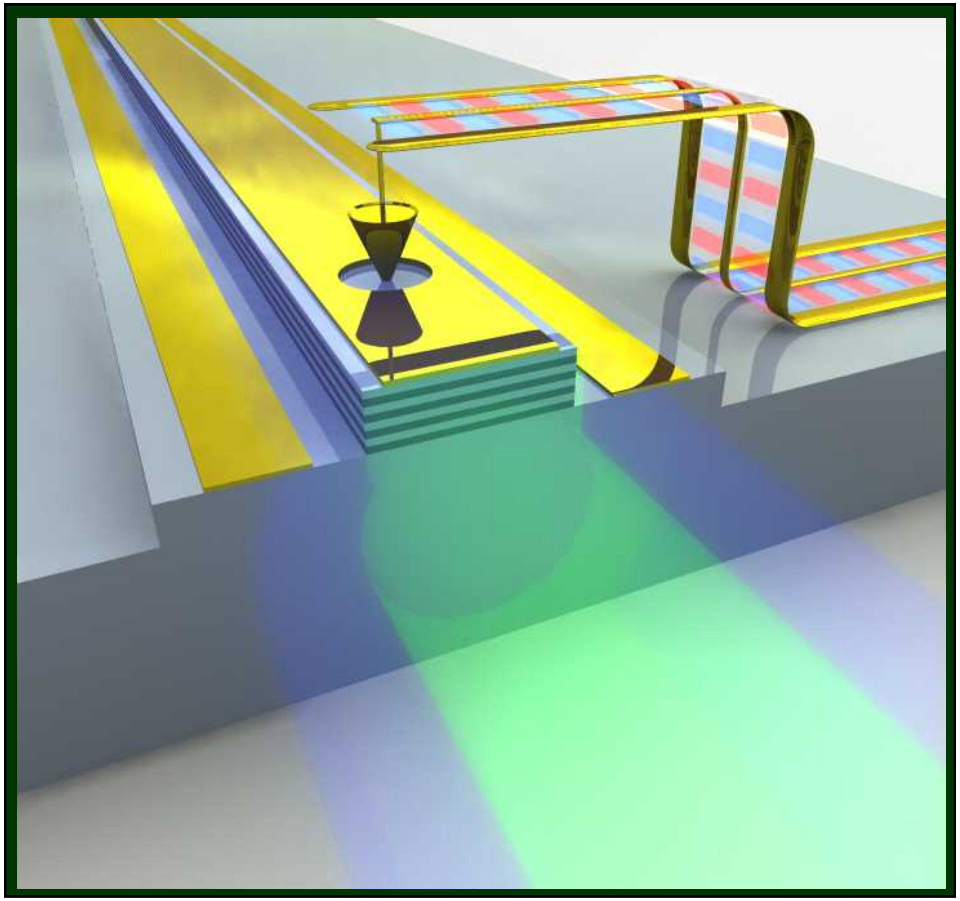


THz High Pass Filters



Monolithically Integrated Transceiver

Inserts diode directly into laser core

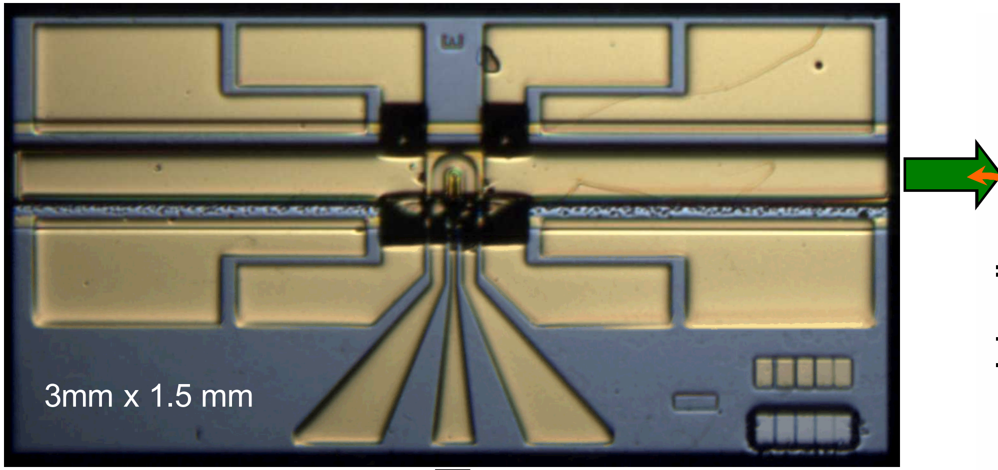


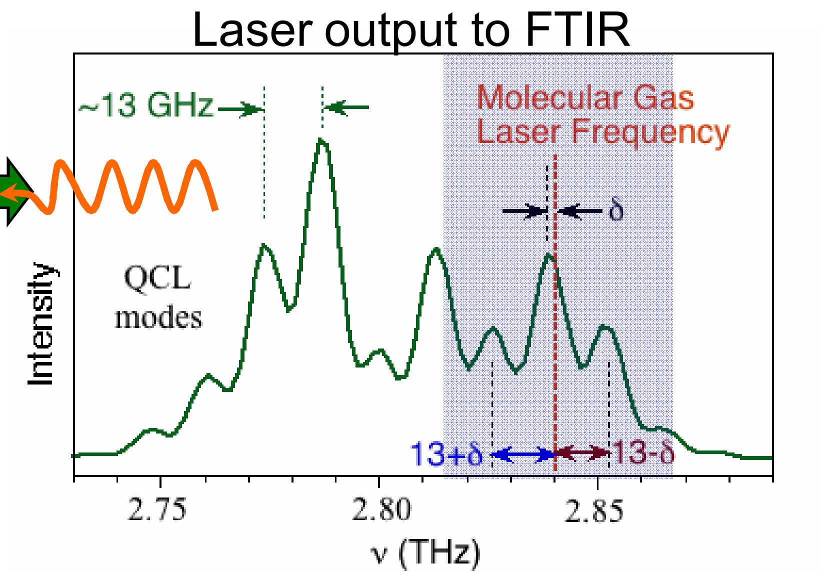
Wanke, Nat. Phot., **4,** 565, (2010)

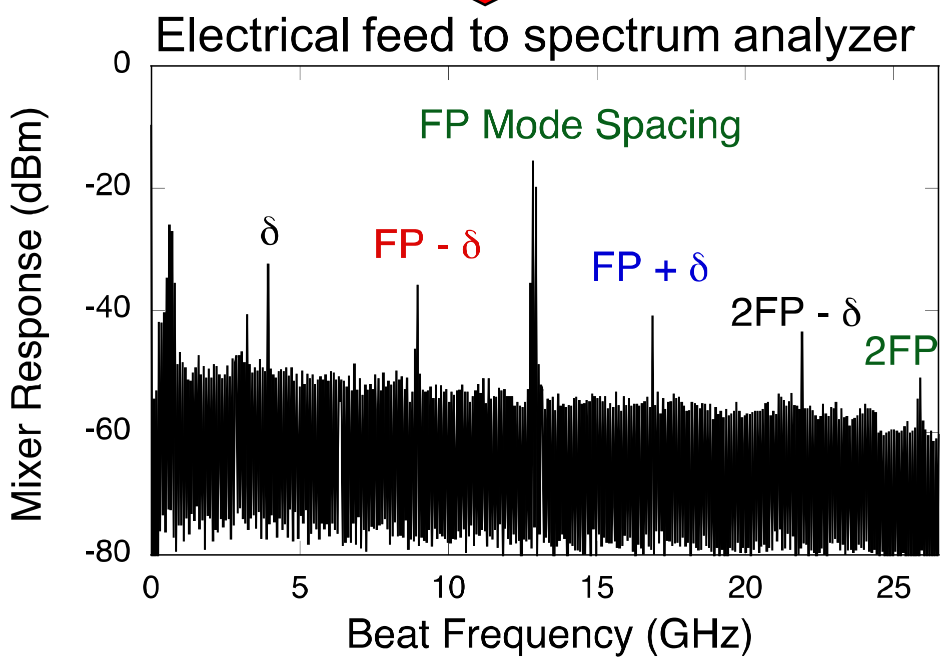
Benefits

- Reduces size
- Eliminate components
- Ensures constant ‘alignment’
- Enhances laser/diode coupling
- Enables probing of laser dynamics not otherwise possible

Integrated Heterodyne Receiver Demo





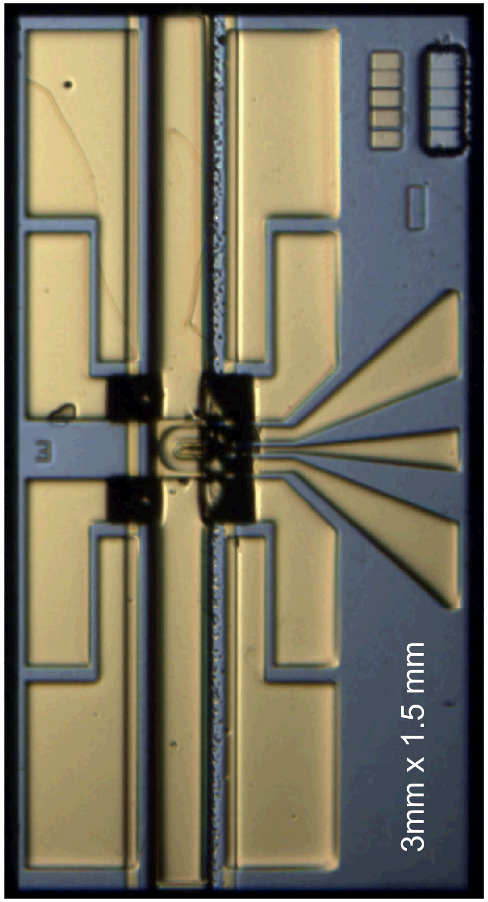


- Wanke, Nat Phot., **4**, 565, (2010)

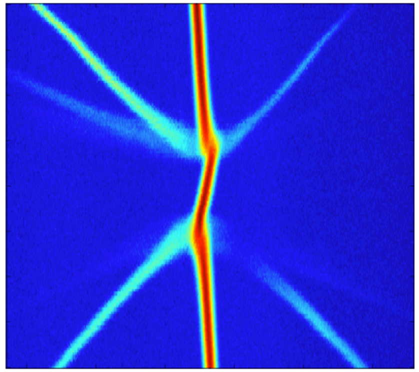
Beyond TμT : Science Enabling Device

Sandia National Laboratories

THz Integrated Transceiver

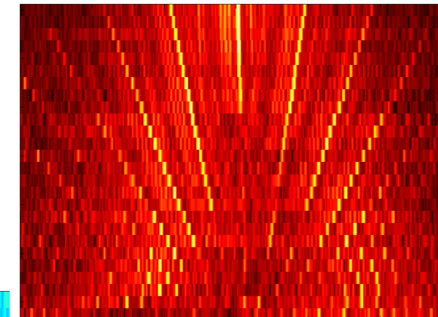


Laser Characterization
Injection Locking

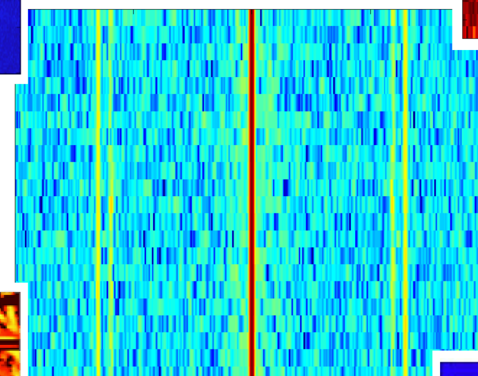


Wanke, Proc. SPIE, 7953, 2010

Vibrometry



Phase Locking
Mode Locking

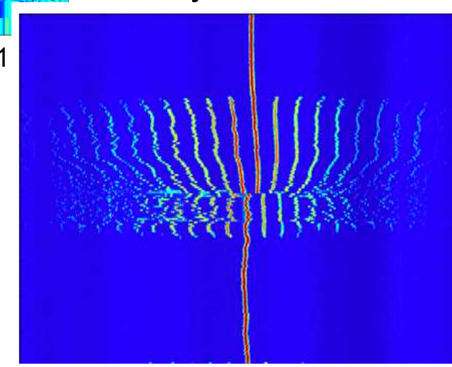


Wanke, Opt. Exp., 19 24810, 2011

Phase/Topo Imaging

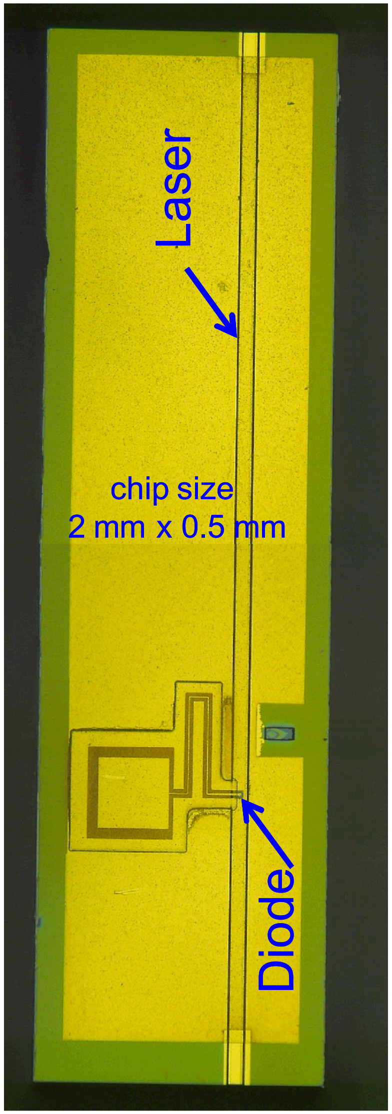
Wanke, Proc. SPIE, 8031, 2011

Feedback / Chaos
Dynamics

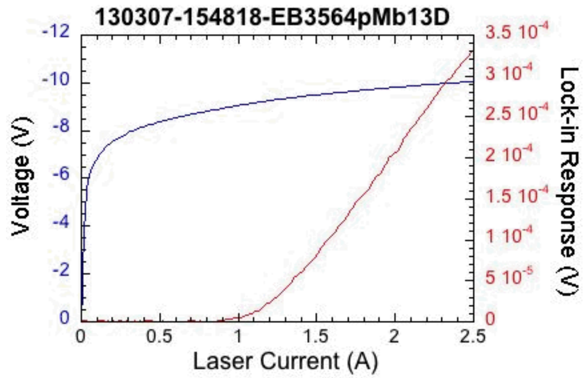


Wanke, Proc. SPIE, 7953, 2010

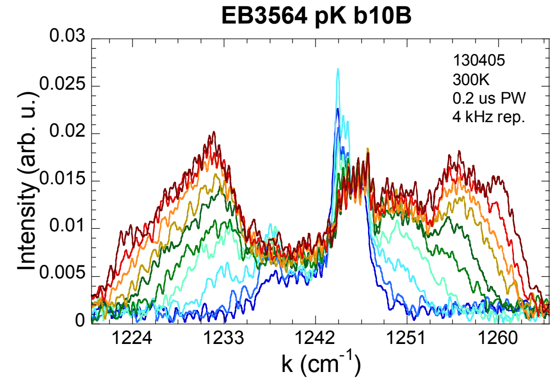
Also works in the MIR



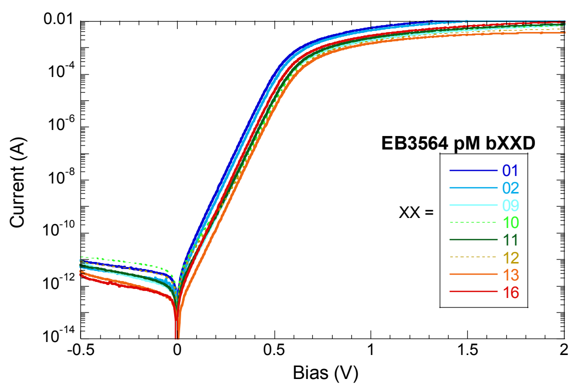
Pulsed Laser L-I-V



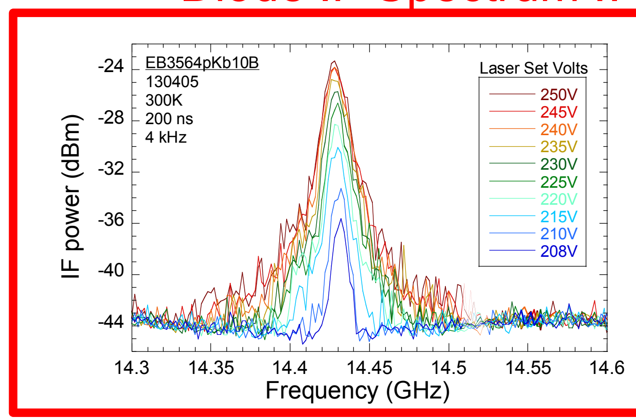
Pulsed Laser Spectrum



Diode I-V



Diode IF Spectrum !!



Integrated Schottky diode acts as detector and mixes internal MIR laser modes to generate heterodyne beat signal. May enable sensitive, spectrally selective, room temperature detection.

Micromachining THz Waveguides

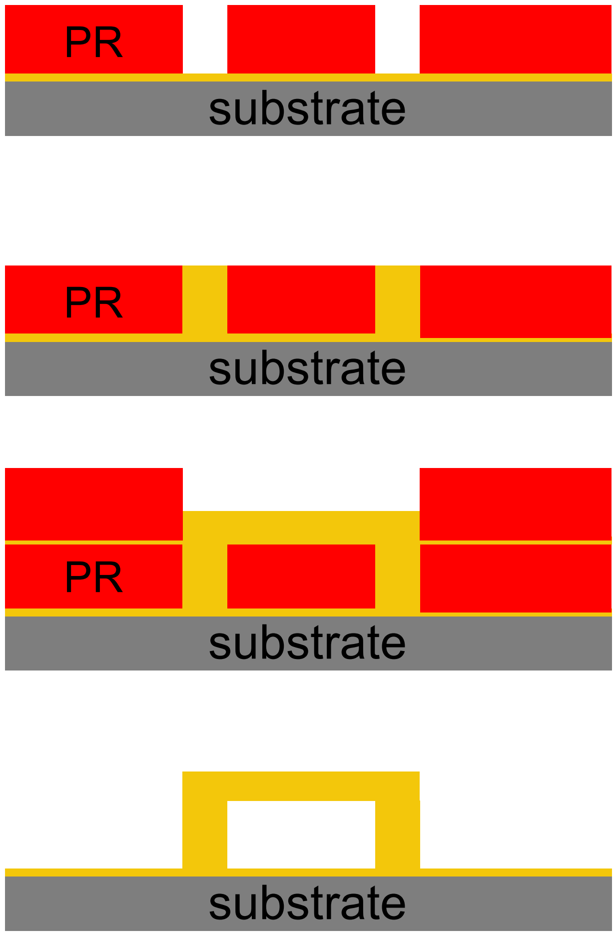
Sandia National Laboratories

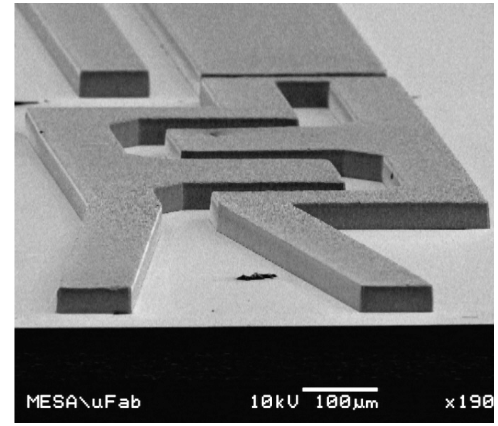
1. Deposit seed metal and pattern photoresist

2. Electoplate Au in photoresist openings

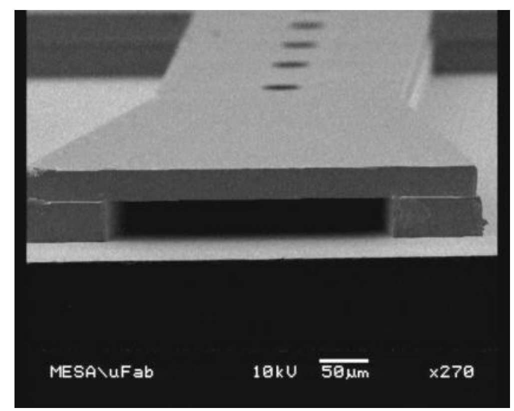
3. Deposit 2nd seed, pattern 2nd PR, and plate lids

4. Remove photoresist and 2nd seed metal





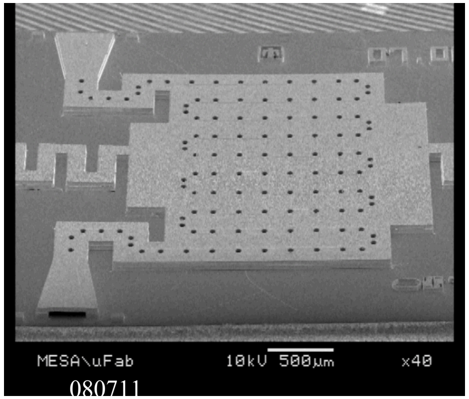
- **Additive electroplating technique suitable for various substrates**
  - *Allows waveguide fabrication on QCLs or other devices*



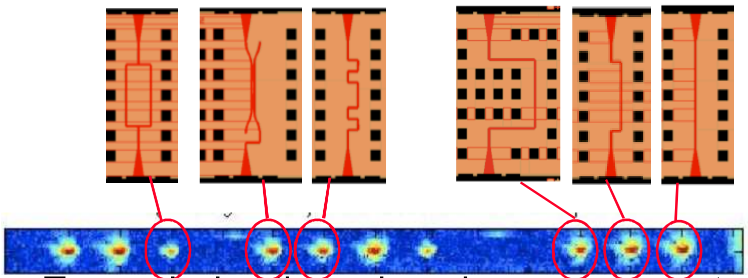
Rowen, Proc. SPIE, **7590**, 2010

THz Micromachined Waveguide Components

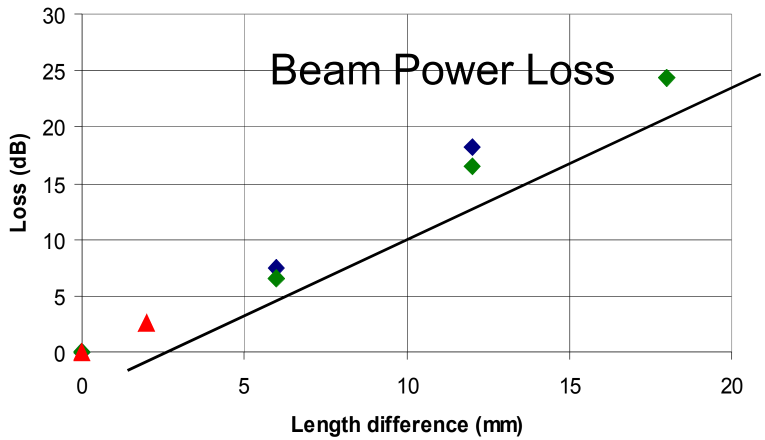
Sandia National Laboratories



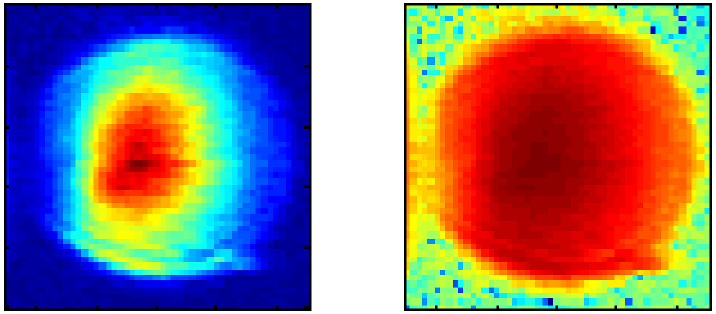
- Demonstrated THz components (waveguides, bends, tees, and couplers) needed for THz integrated circuits.
- Achieved low propagation and bend losses (at 2.9 THz).
  - 1.4 +/- 0.15 dB / mm (.15 dB / λ)
  - 0.15 +/- 0.15 dB / bend
- Observed good far-field beam patterns.



Transmission through various components

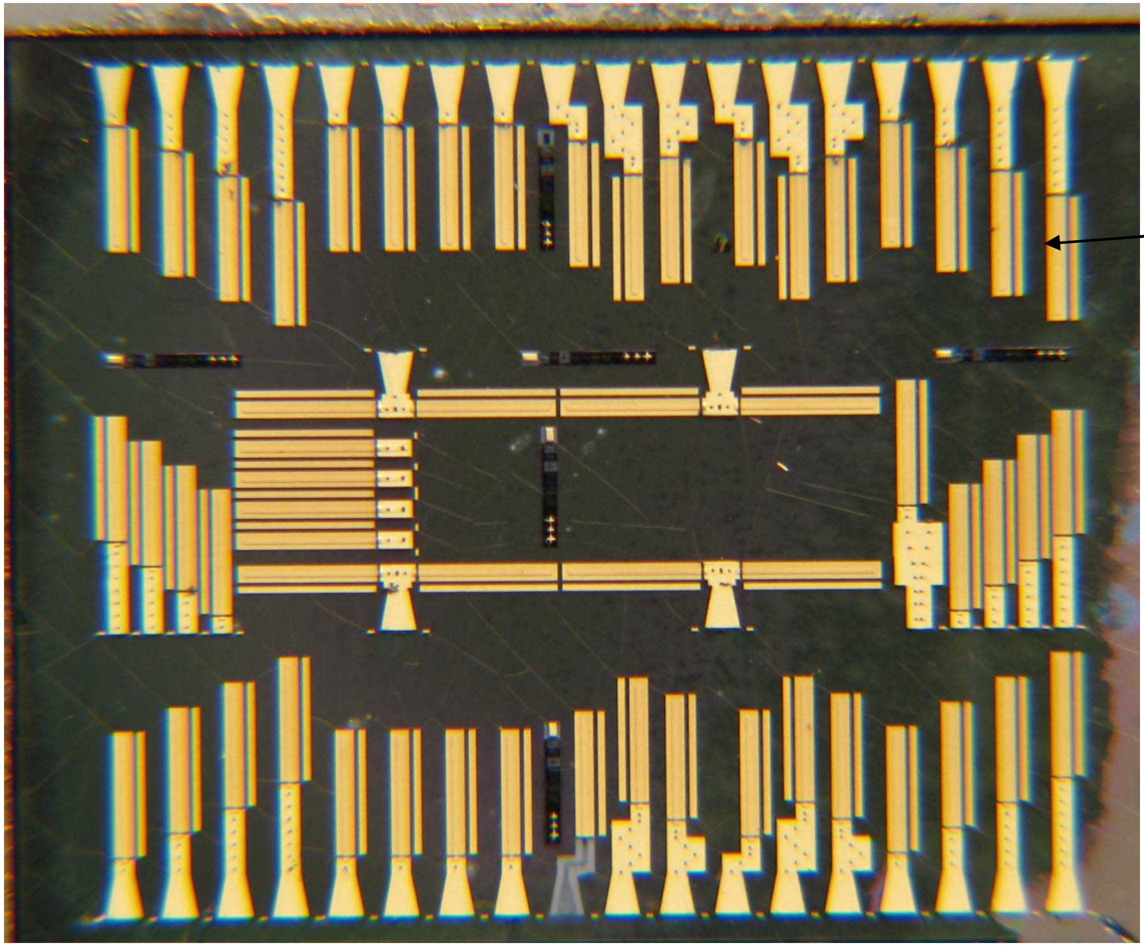


Antenna Beam Pattern



Linear Scale Log Scale

Integrated Lasers with Waveguides



Built waveguides on top of lasers

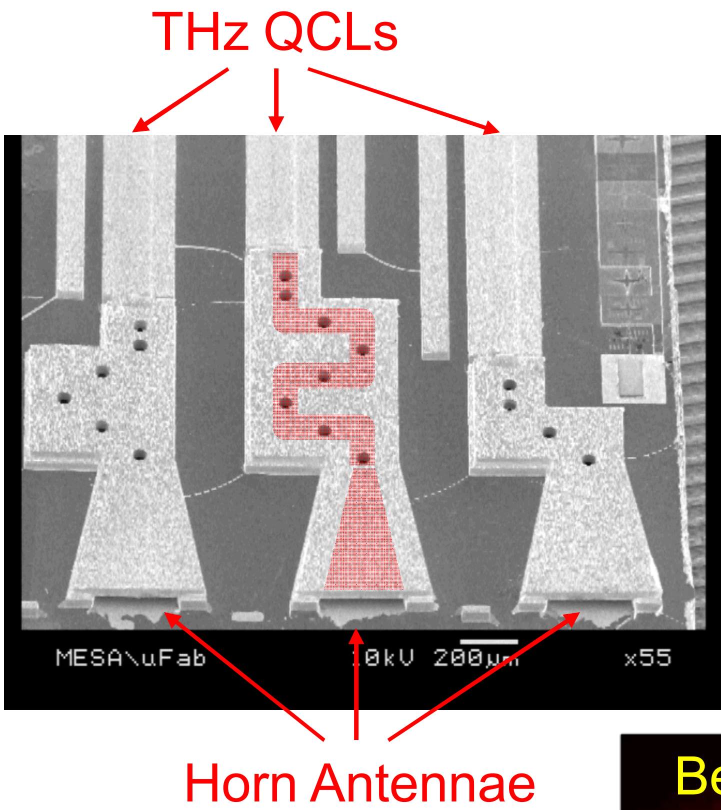
Waveguides include
- H-plane bends
- E-plane bends
- Magic-Tees
- Combiners
- Horns
- Insertion position
- WG length

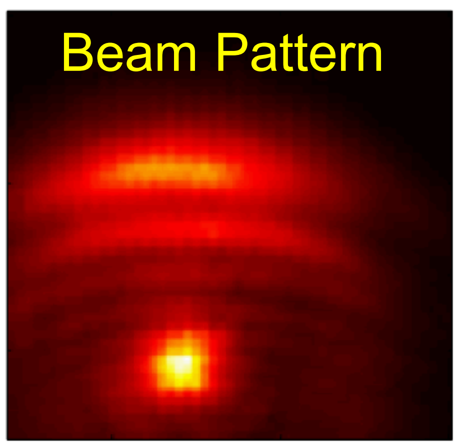
Note: parallel assembly advantage

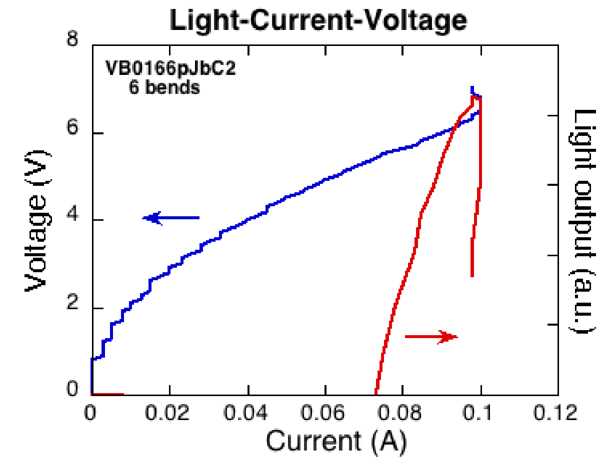
Integrated Waveguide Performance

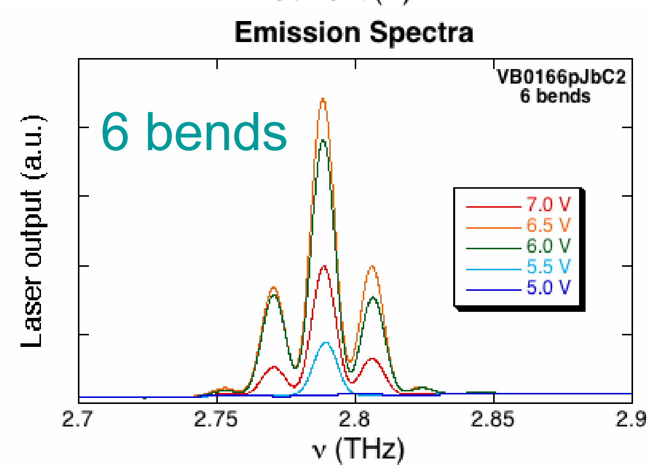
Sandia National Laboratories

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

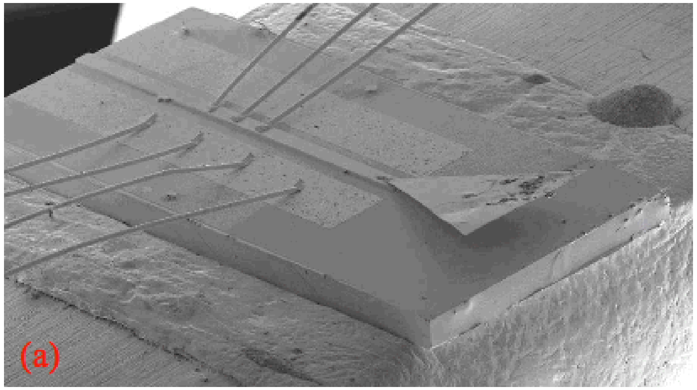




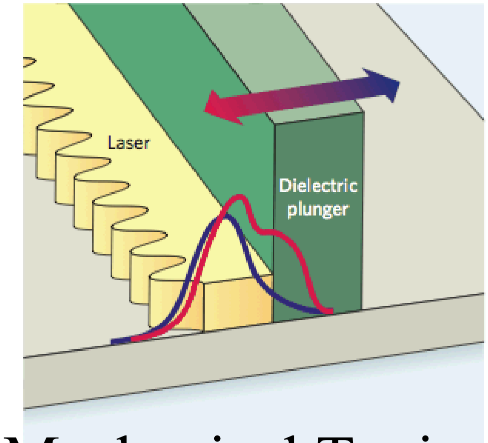




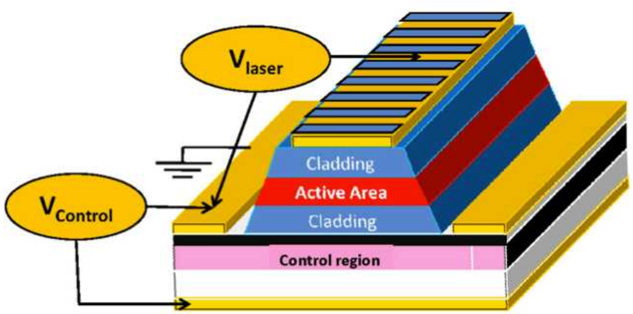
Other THz QCL Integration Examples



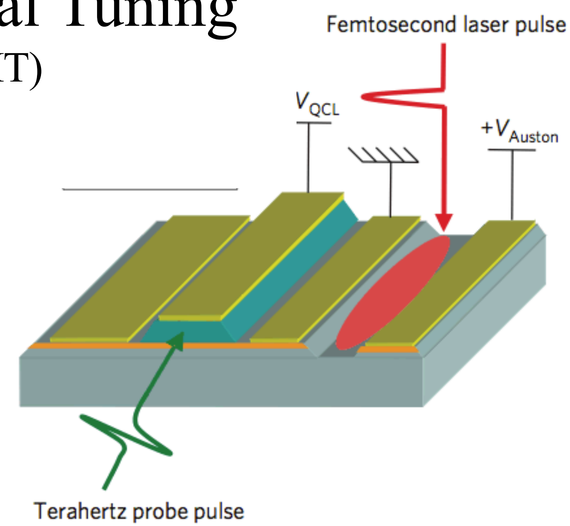
Antenna Coupling
(IEMN/CNRS)



Mechanical Tuning
(MIT)



Modulator
(U. Paris 7)



Pulse Amplifier
(Ecole Normale Sup.)