SAND2007-7724C

Terahertz semiconductor lasers, receivers and metamaterials

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Sandia National Laboratories

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.

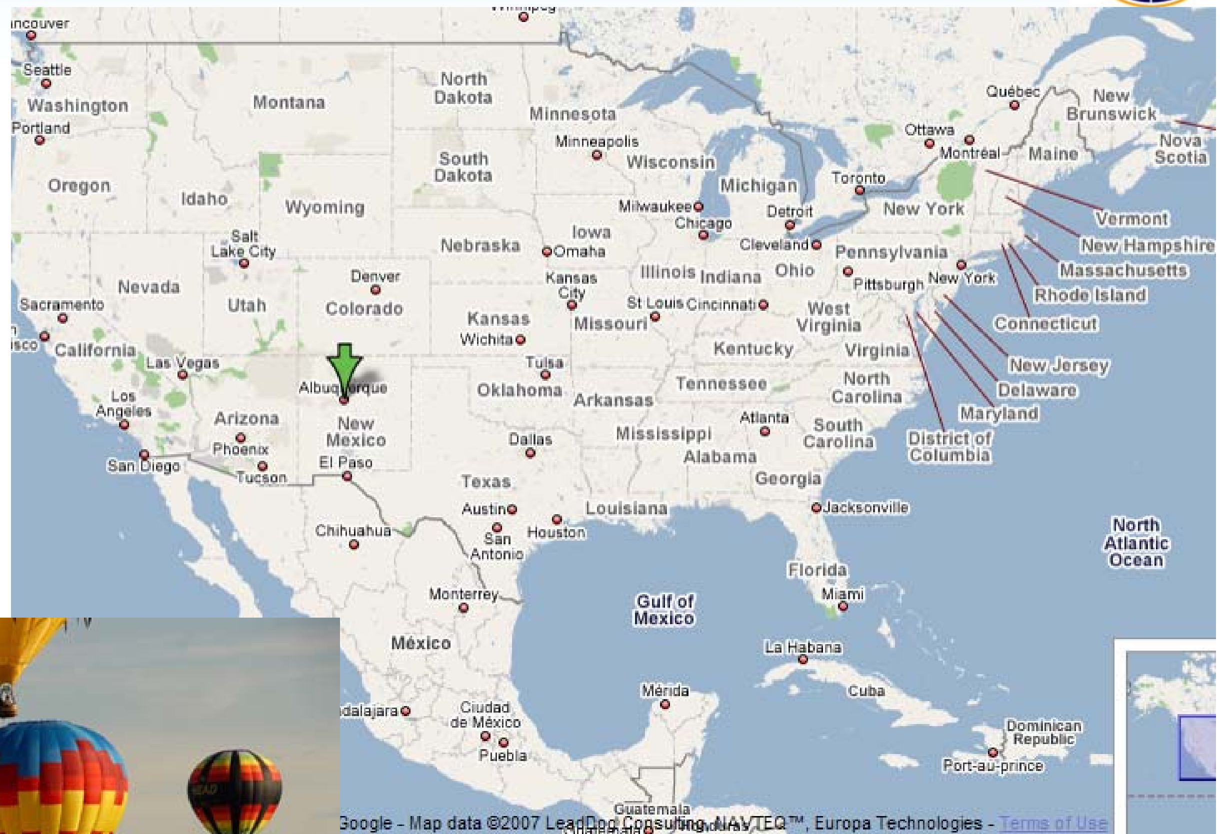
Outline

- Intro: Sandia, CINT, etc.
- Terahertz (THz) – General
- THz Quantum Cascade Lasers
- Waveguide, beam issues
- The THz QCL + Schottky receiver
- THz metamaterials

Sandia National Laboratories

Sandia, Albuquerque, NM…

- **New Mexico houses 2 Department of Energy (DOE) National Labs:**
  - **Los Alamos**
  - **Sandia**
- **Also 1 of 5 Nanotech. Research Centers**



← Balloon fiesta, ~October

Sandia National Laboratories

CINT is one of five U.S. Dept. of Energy Nanoscience Centers

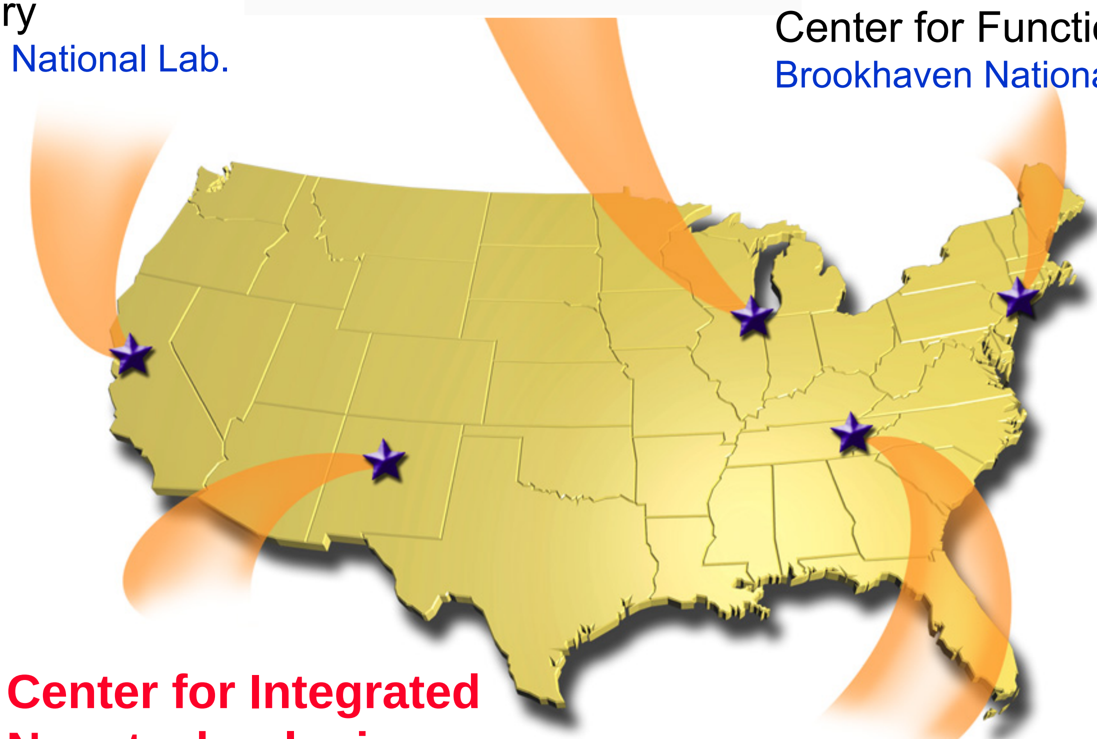
Center for Nanoscale Materials
Argonne National Lab.

Molecular Foundry
Lawrence Berkeley National Lab.

Center for Functional Nanomaterials
Brookhaven National Lab.

Core Facility (Albuquerque)

CINT Gateway to Los Alamos
Nanomaterials / Biosciences



Center for Integrated Nanotechnologies
Sandia National Labs.
Los Alamos National Lab.

Center for Nanophase Materials Sciences
Oak Ridge National Lab.

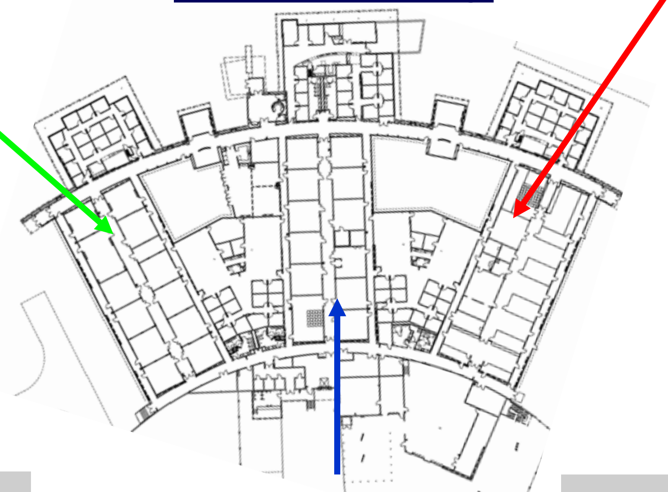
Sandia National Laboratories

CINT laboratories are supported by state-of-art equipment

Characterization Wing

- TEM
- Atom tracking STM
- FTIR, UV-VIS
- Nano-indenter, AFM
- Low Temp Transport
- Ultra-fast Laser Spec.

Core Facility



Integration Lab

- E-beam lithography
- Photolithography
- Thin Film Deposition
- Reactive Ion Etch
- Plasma Etch
- Dual beam SEM

Gateway to Sandia

- Interfacial Force Microscopy
- Low Energy Electron Microscopy
- Chem prep oxide
- LB Film
- microfluidics

Synthesis Wing

- MBE
- P-CVD
- Wet Chemistry
- Bio labs
- Molecular films

Gateway to Los Alamos

- NSOM, AFM
- Environmental SEM
- Nano-indenter
- Pulsed Laser Dep.
- Ultra-fast Laser
- Computer Cluster

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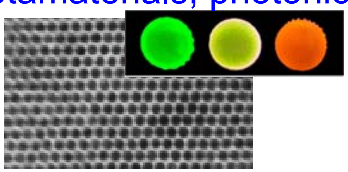
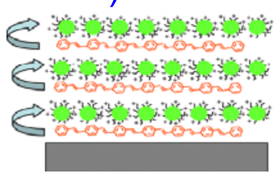
Science Thrusts provide relevant expertise

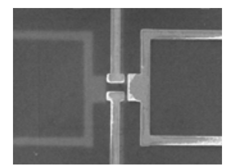
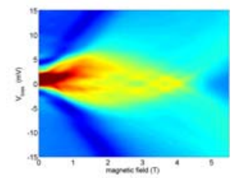
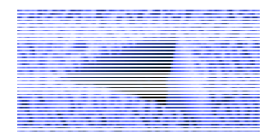
Nanophotonics & Optical Nanomaterials

Synthesis, excitation and energy transformations of optically active nanomaterials and collective or emergent electromagnetic phenomena (plasmonics, metamaterials, photonic lattices)

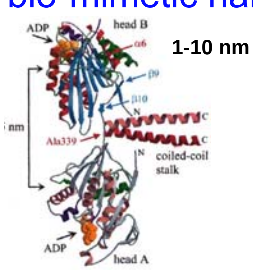

Nanoscale Electronics, Mechanics & Systems

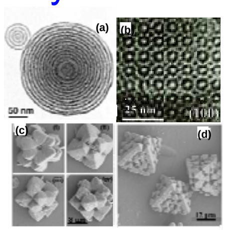
Control of electronic transport and wavefunctions, and mechanical coupling and properties using nanomaterials and integrated nanosystems

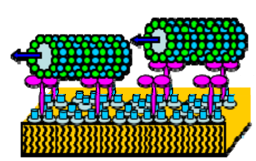




Soft, Biological, & Composite Nanomaterials

Solution-based materials synthesis and assembly of soft, composite and artificial bio-mimetic nanosystems

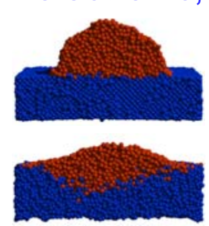
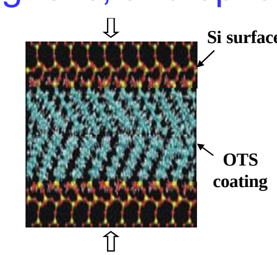


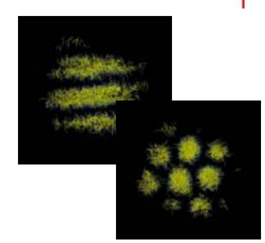




Theory & Simulation of Nanoscale Phenomena

Assembly, interfacial interactions, and emergent properties of nanoscale systems, including their electronic, magnetic, and optical properties



Call for User Proposals: Open now through 1/2008

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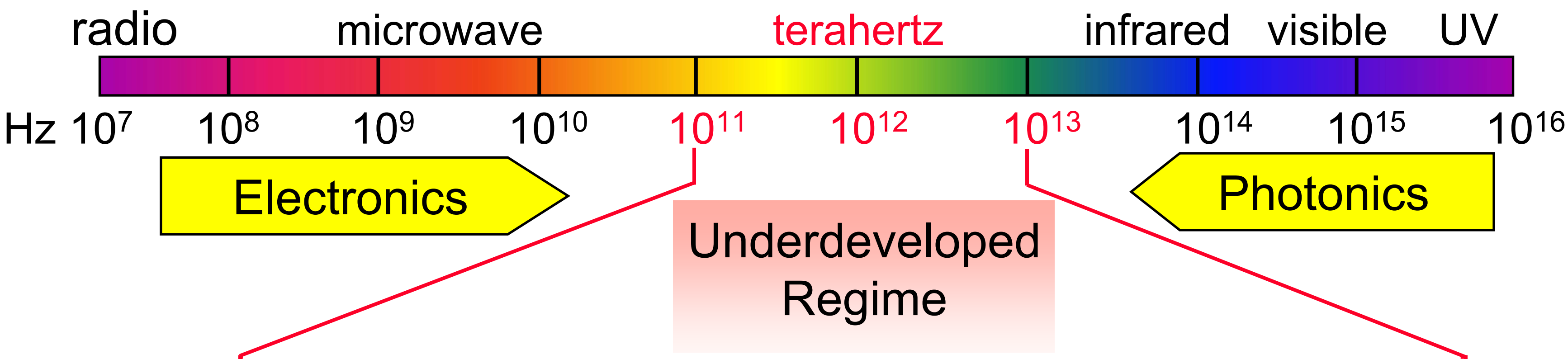
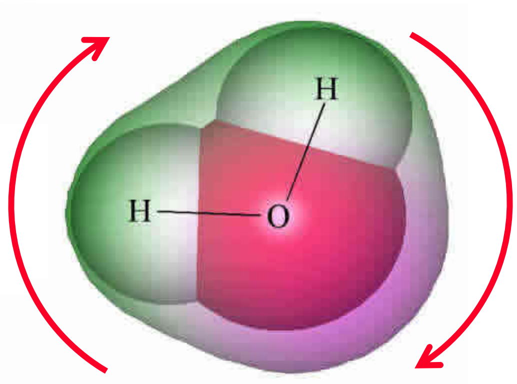
The THz Spectrum

The Electromagnetic Frequency Spectrum



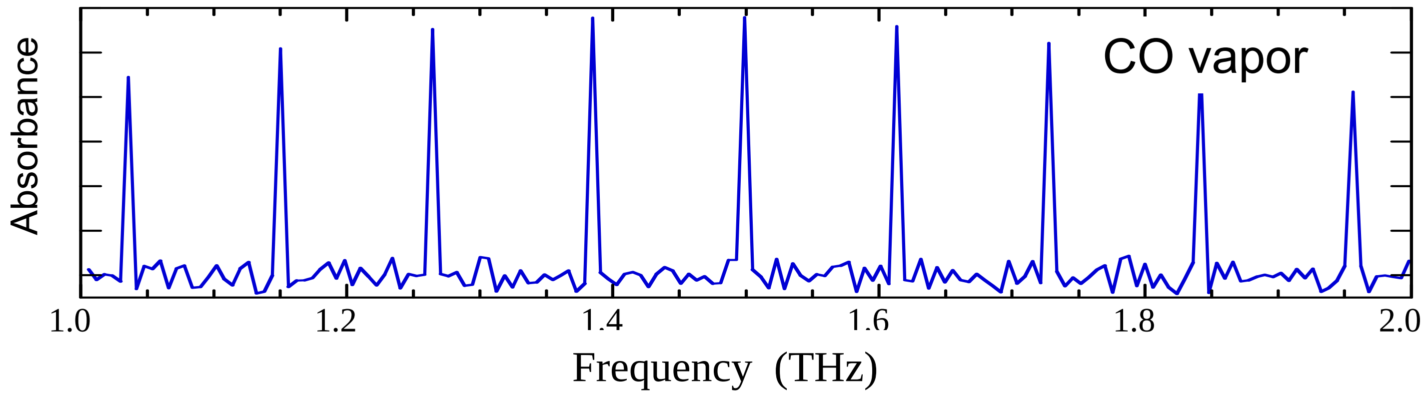
- **Frequency range 10^{11} to 10^{13} Hz**
  - Wavelength range 3 mm to 30 μm
  - Wavenumber range 3.3 to 333 cm^{-1}
  - Photon energy range 0.4 to 40 meV

THz Molecular Signatures



- **Rotational resonances in the THz**
- **<u>Moment-of-Inertia spectroscopy</u>:**
  - Depends on *mass distribution*
  - Many distinctive spectral lines

- ***Better chem detection & ID than using other spectral regions***



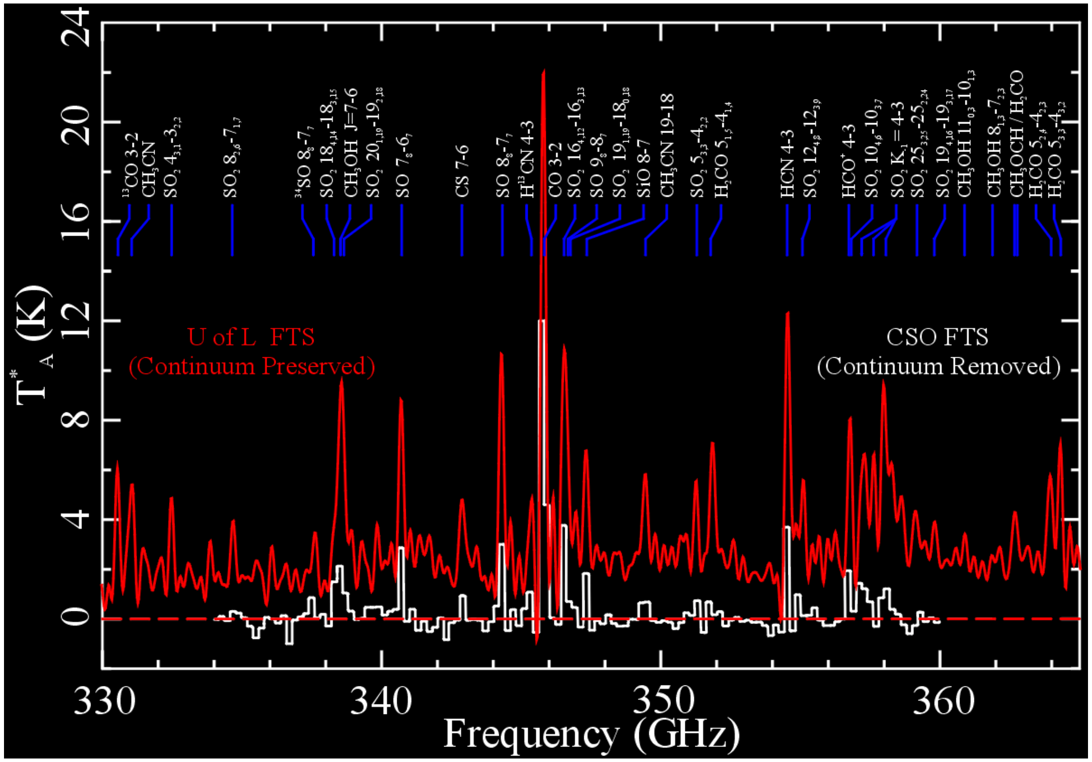
M. Lee
SNL 01123

...But often requires very high resolution

(Extreme) Remote Chem Sensing

Composition of interstellar dust cloud Orion KL

(courtesy D. Naylor, Univ. of Lethbridge)

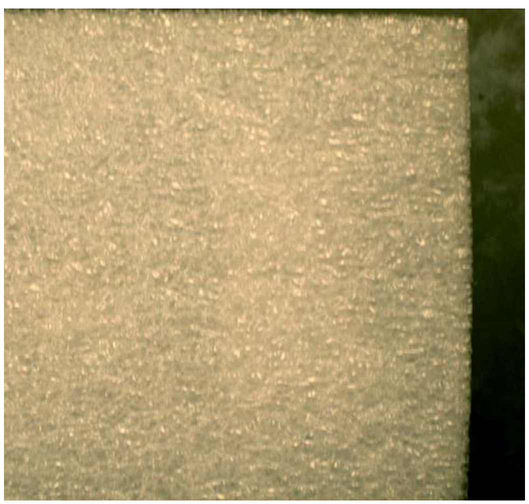


- **From Mauna Kea to <u>interstellar space</u>**
- **Cold body: ~ 100 K**
- **12 chemicals ID'd in 0.33 to 0.37 THz atmospheric window**
- **Fourier spectrometer with ~ 10 hr integration time**

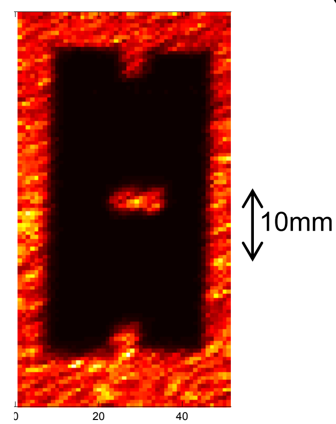
THz "See-through" Imaging

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

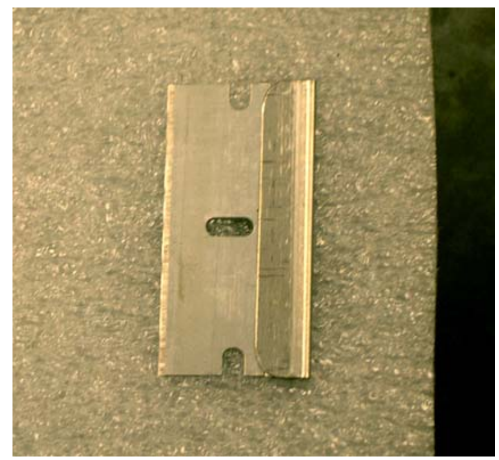
(from X. C. Zhang, RPI) 0.6 THz image



Front of thick packing foam



"See-through" image as seen using a 2.9 THz QCL



(The real object in the back)

Science **316,** 64 (2007)

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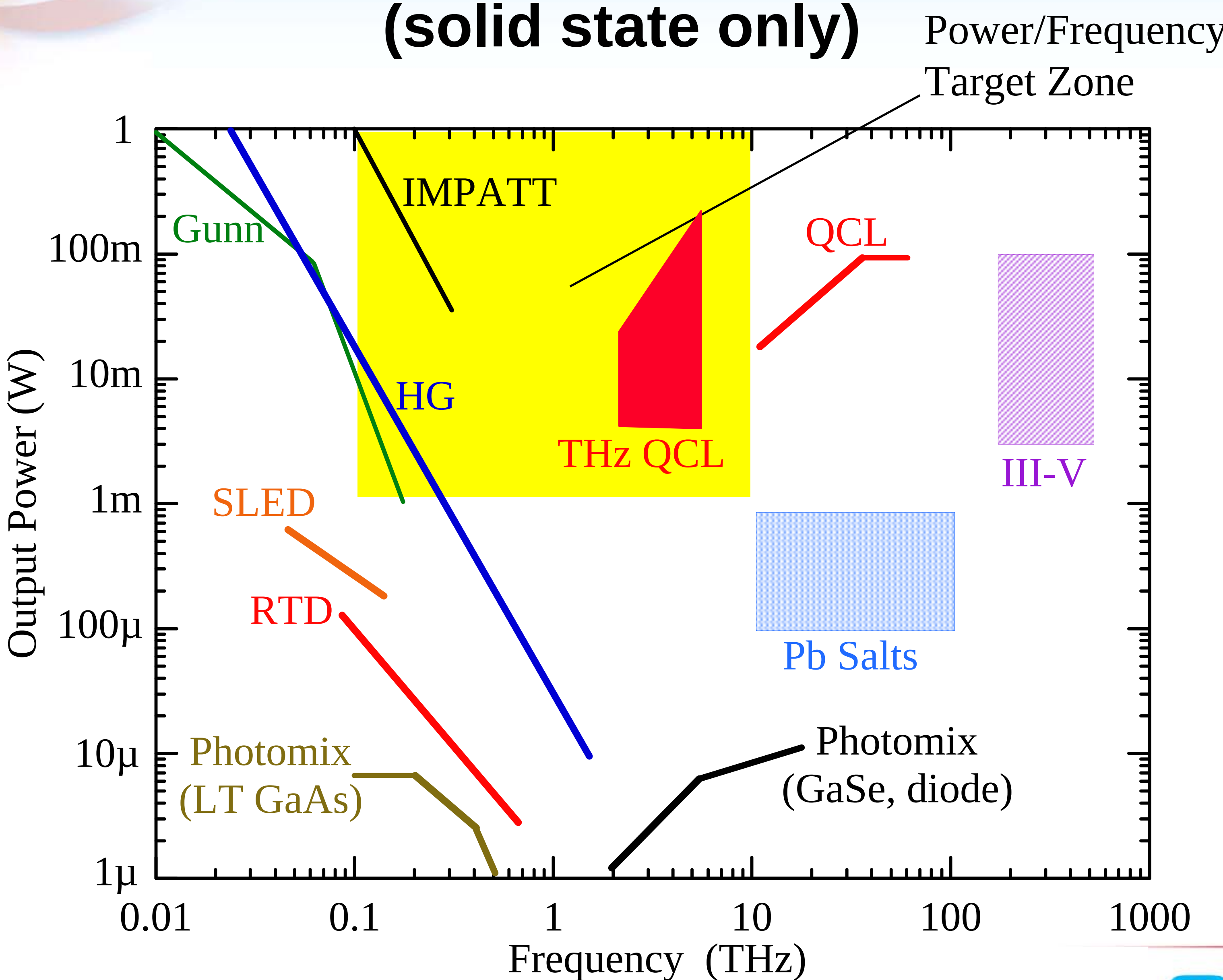
THz Technology Gap (solid state only)



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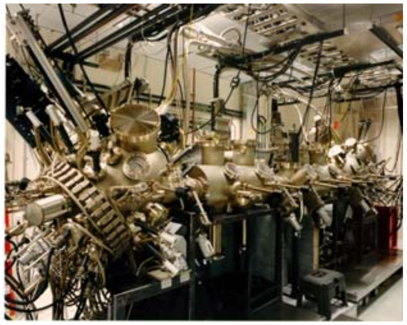
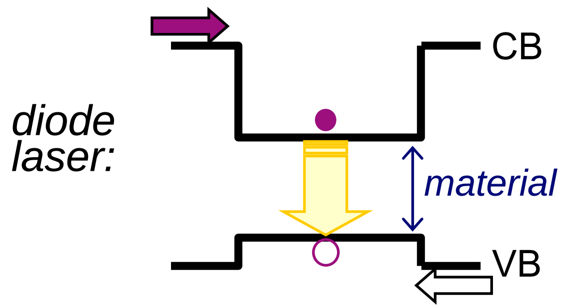
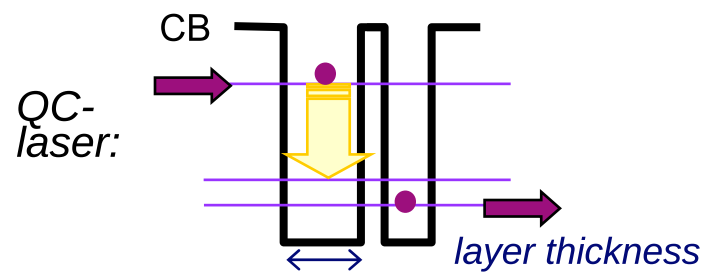


Diode Laser and QCL comparison





$In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$ on InP
first QCL material system

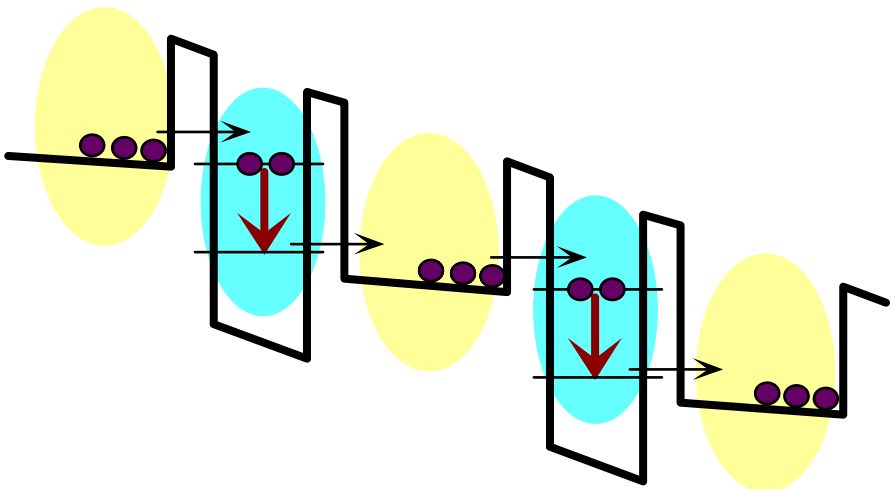
Faist et al. Science 264, 553, (1994)

Interband Transition
- λ defined by material
- immature materials at long λ
- bi-polar (interband)

Intersubband Transition
- λ defined by layer thickness
- mature materials at long λ
- unipolar (intraband)

(Unipolar lasers)

Quantum Cascade Basic Principle

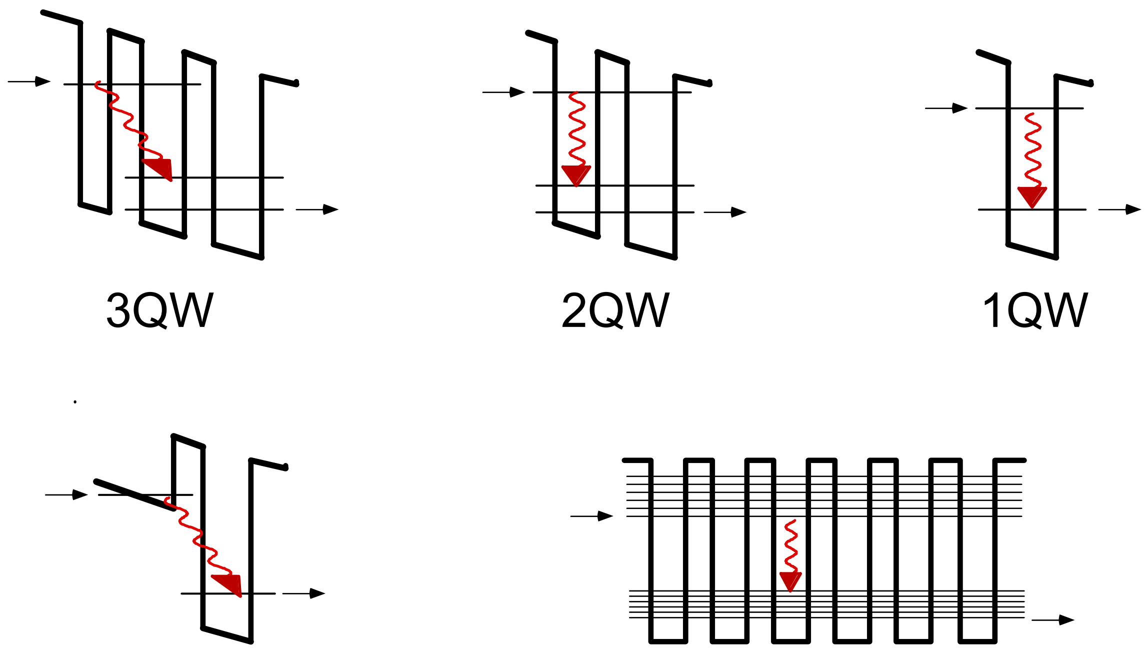


Repeat the unit cell
- **Recycle the electrons**
- **Increase gain**

Key "components" that need to be engineered and optimized:
- **Injector**
- **Active region**

Active Regions
(or fun with particle-in-a-box)

- **Use combination of LO phonon, tunneling, phase space, and non-parabolicity to generate inversion**



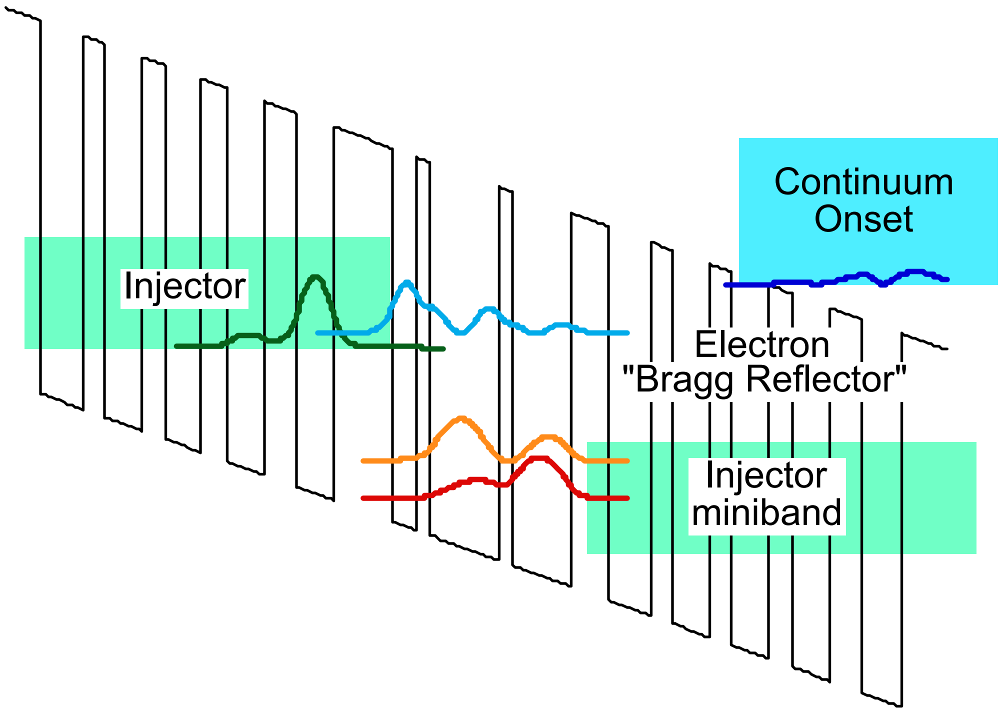
3QW 2QW 1QW (Fixed λ)

Diagonal Superlattice

(Voltage tunable) (high current density)

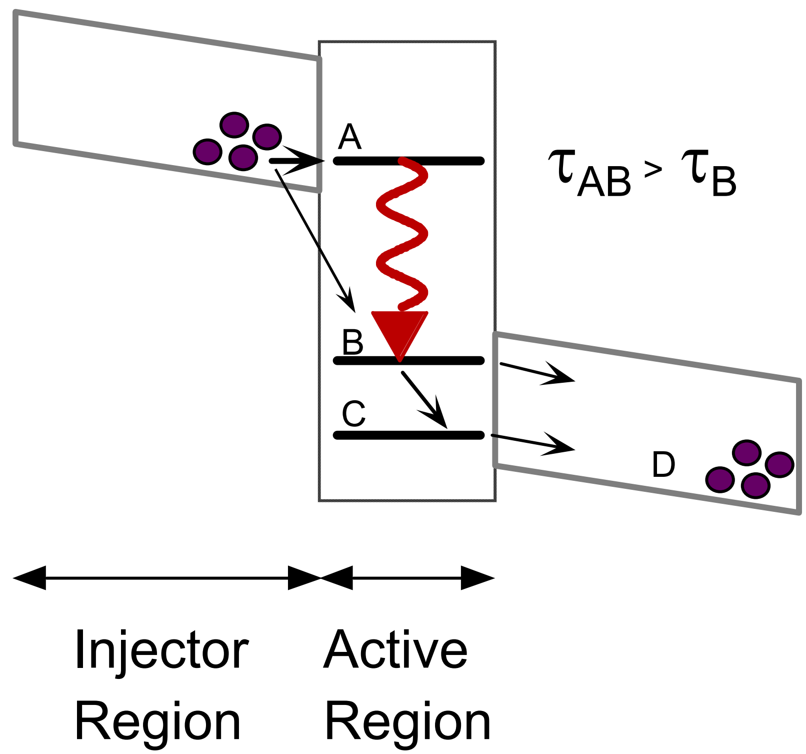
Injectors: more band-engineering

- No intersubband absorption (reabsorption)
- Width / thermal backfilling
- Phonon resonances
- Bragg reflectors
- Ballistic
- Funnel



Very Successful in MIR : Why is THz so much harder?

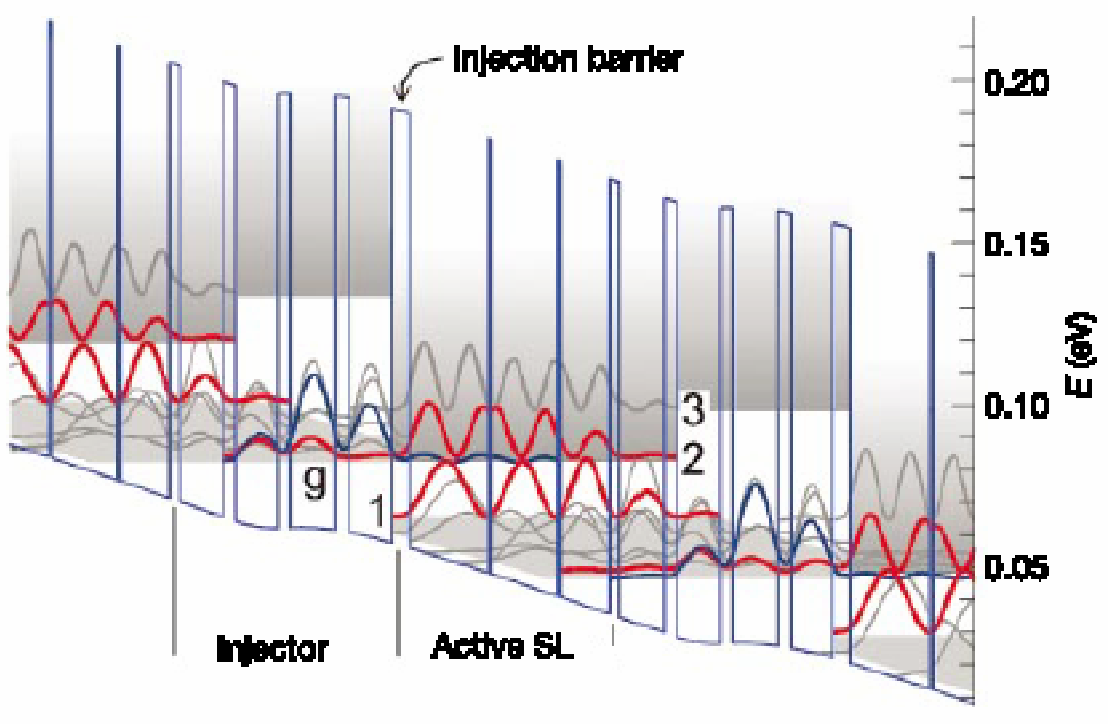
- **Physics:**
  - **Difficult to inject and extract carriers from desired states**
  - **Small energies allow more thermal backfilling**
  - **Shorter non-radiative lifetimes**



- **Engineering:**
  - **High waveguide losses**
  - **Large wavelength reduces overlap (waveguide mode)**
  - **Growth more challenging**

First THz QC

Chirped superlattice design
Kohler, Nature, **417**, May 2002



Getting high performance QCLs depend crucially on good modeling

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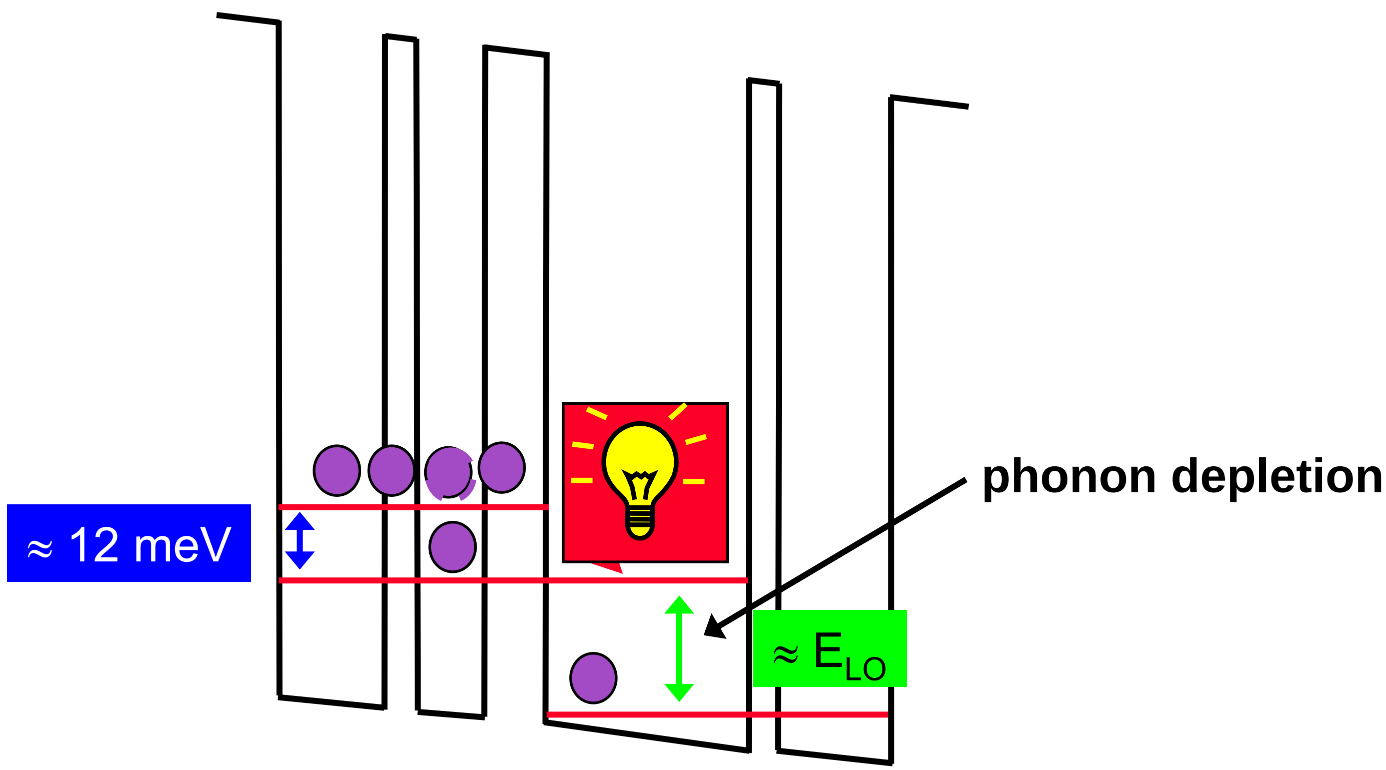
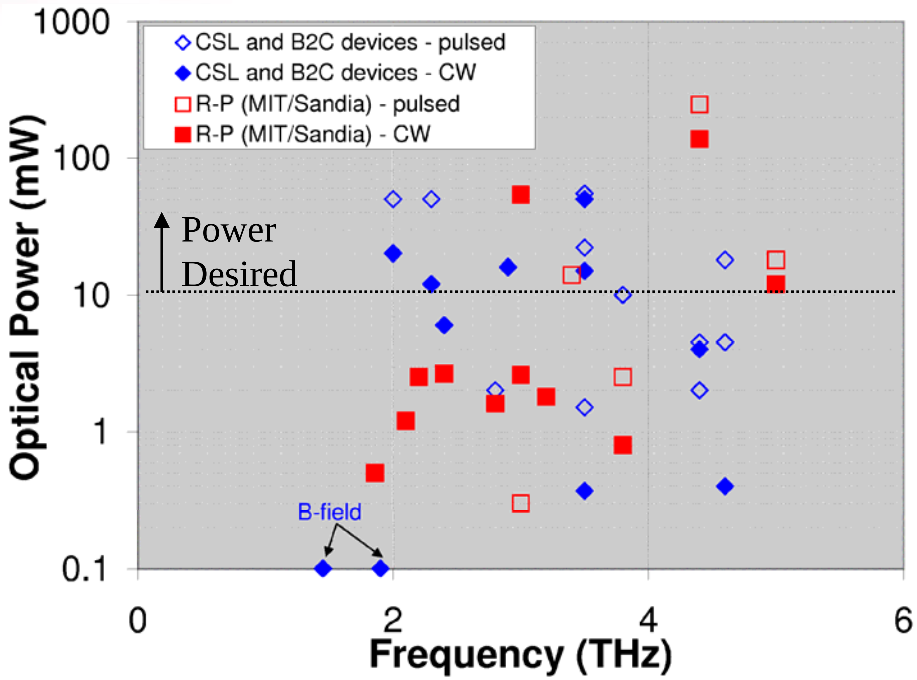
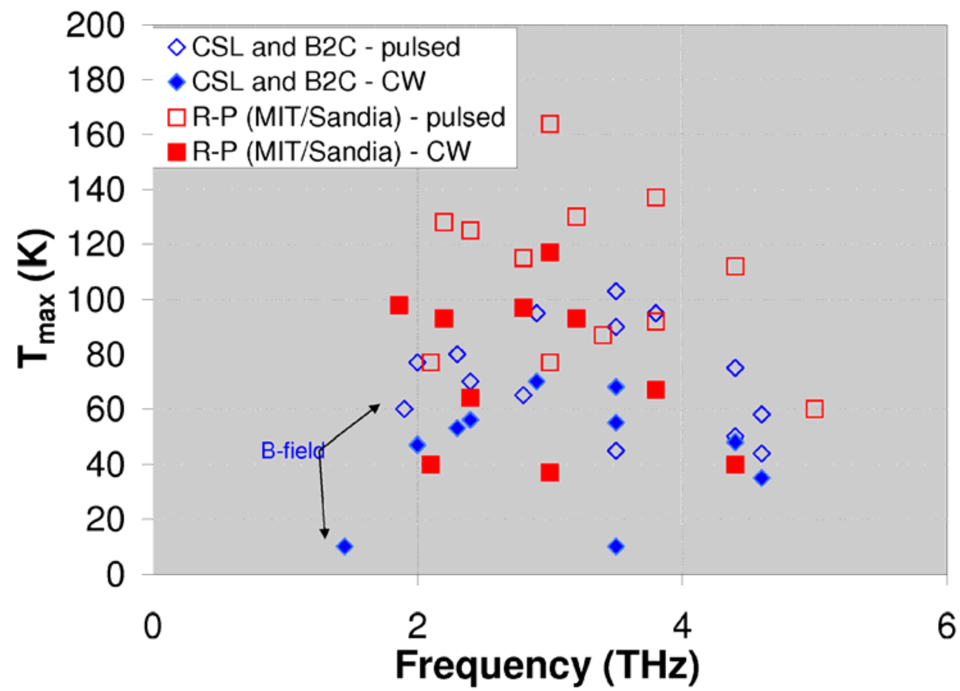
Schematic of phonon-depletion THz-QCL



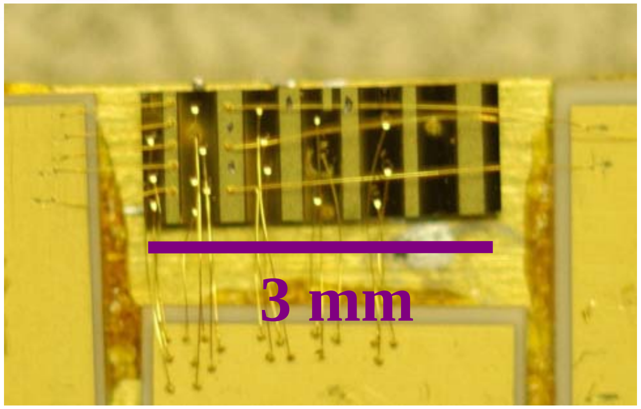
Performance of Terahertz QCLs



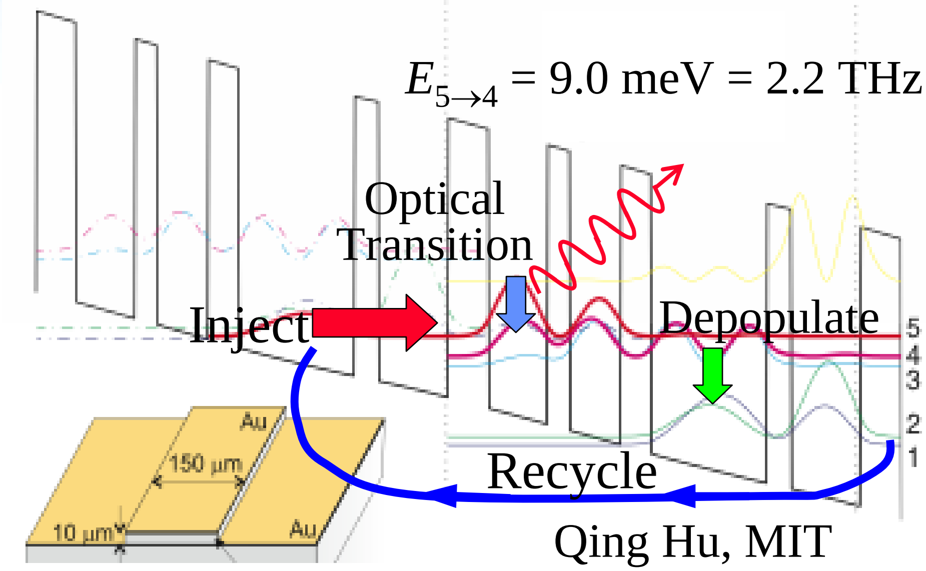


- **Wavelength – 60 μm – 161 μm (1.86 – 5.0 THz)**
- **Temperature – up to 164 K (pulsed), 117 K (cw) (RP)**
- **Power – 248 mW pulsed, 138 mW cw @ 10 K (RP), 1.5 mW cw @ 77 K (RP)**
- **Threshold – J_{th} ~ 50 – 500 A/cm^2 (B2C, CSL)**
- **Linewidth – 20 – 30 kHz (over 3 ms) (CSL, B2C), 65 kHz freq. locked (RP @ 59 K)**
- **DFB structure – single mode (NEST Pisa, Neuchâtel, MIT)**
- **B-field design – J_{th} < 1 A/cm^2, λ~207 μm (1.45 THz) (Neuchâtel)**

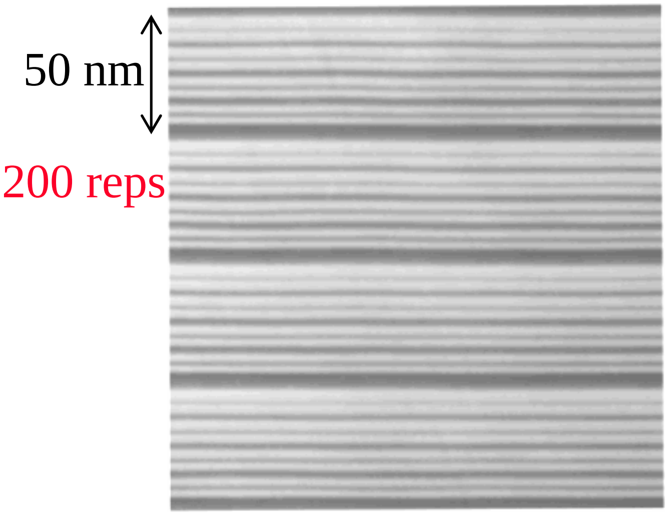
THz Quantum Cascade Lasers



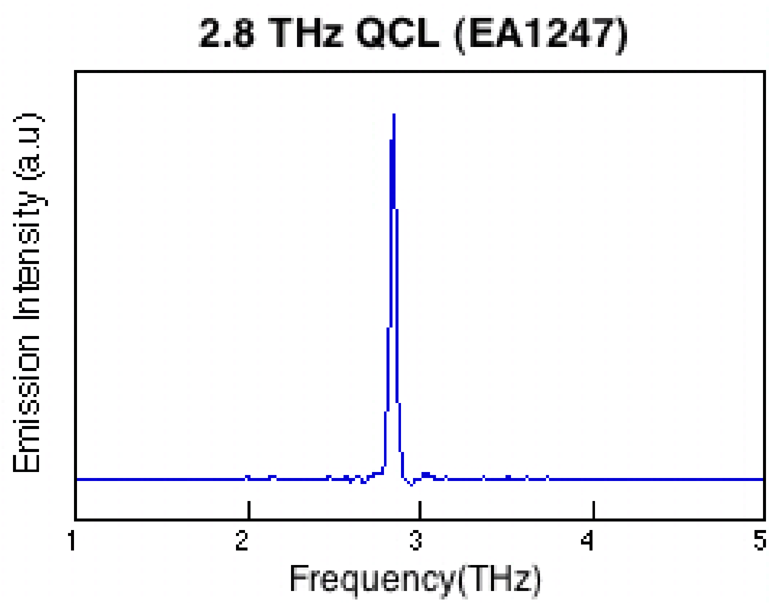
6 QCLs integrated on chip



Qing Hu, MIT

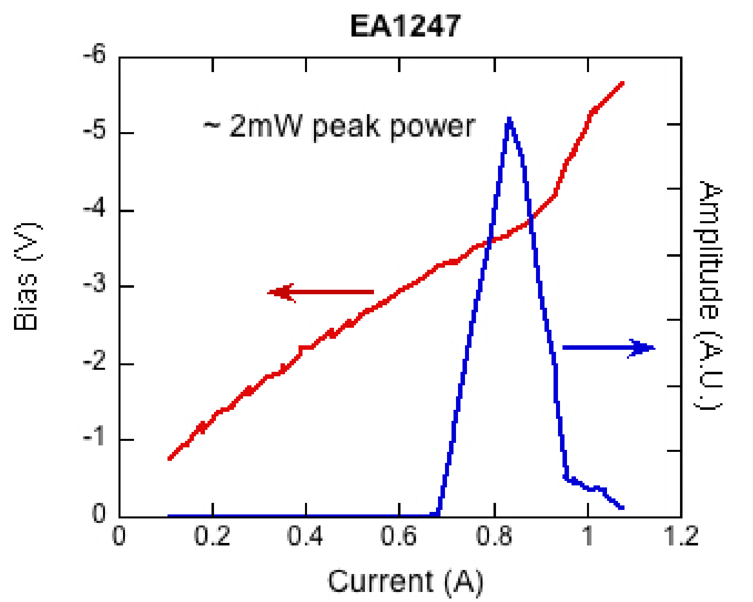


TEM cross-section of QCL stack

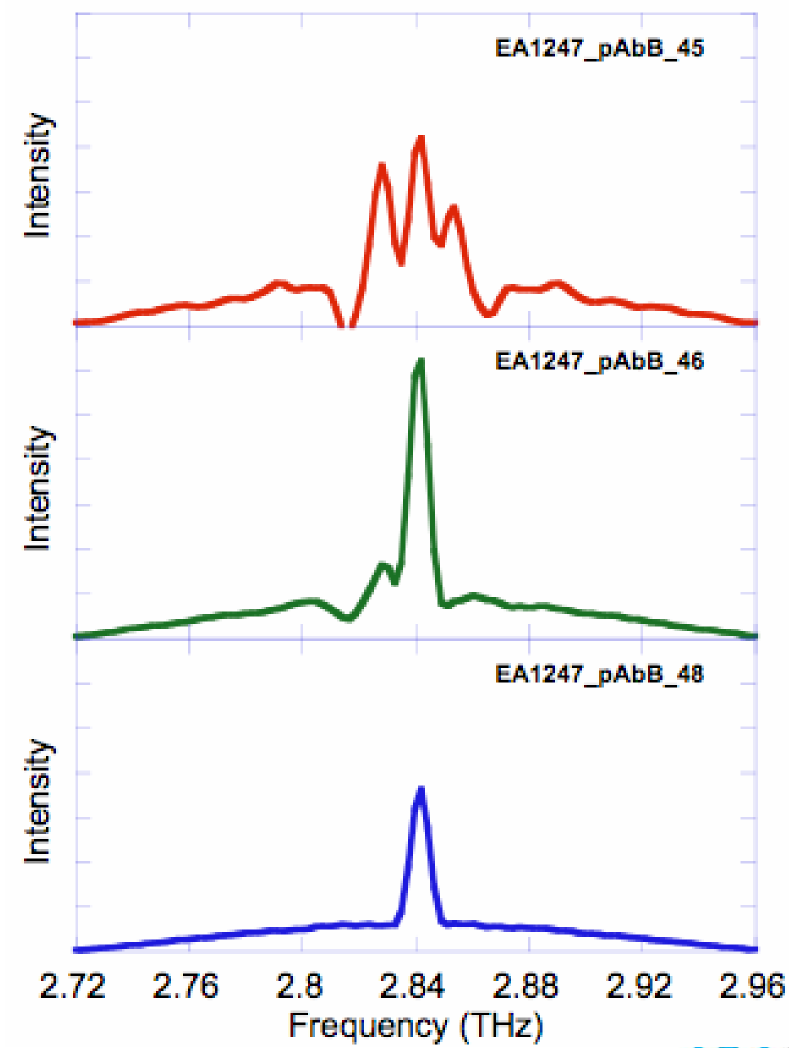


Fabry-Perot 2.8 THz QCLs

(plasmon waveguide)



- 2 mW peak output
- 0.7A/3.4V threshold
- Single mode at lower power
- T_{max}~75K (pulsed)



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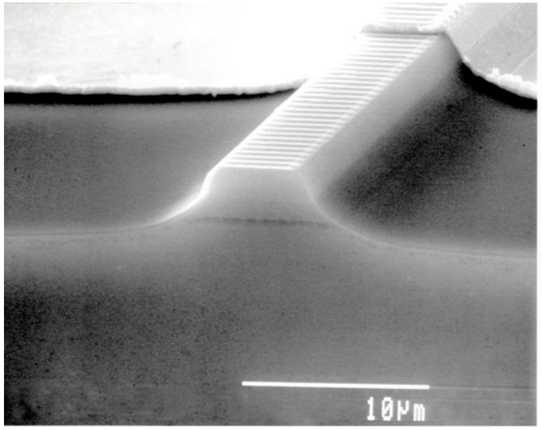
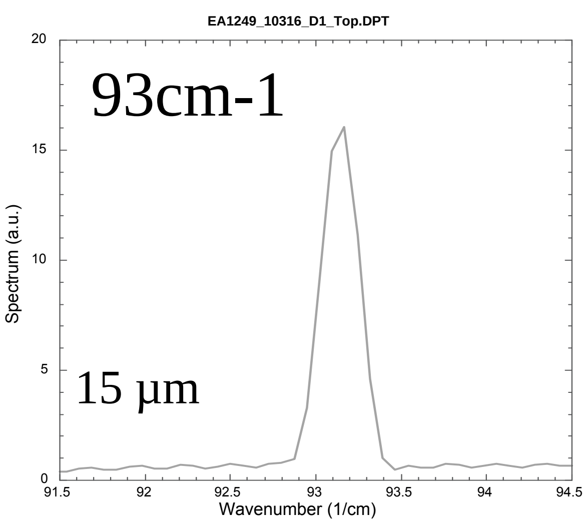
Distributed Feedback (DFB) THZ QCLs

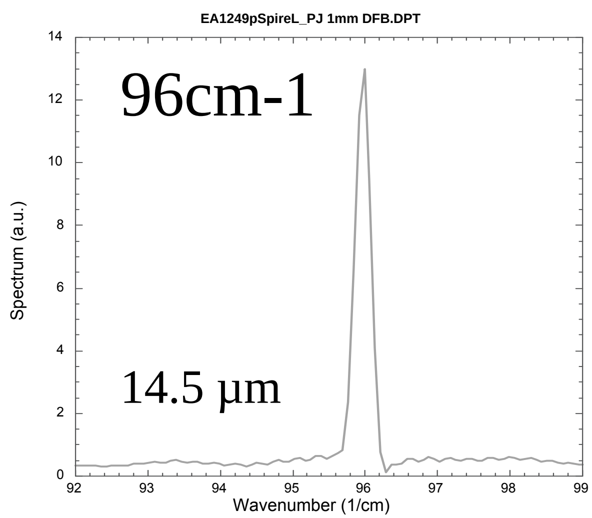


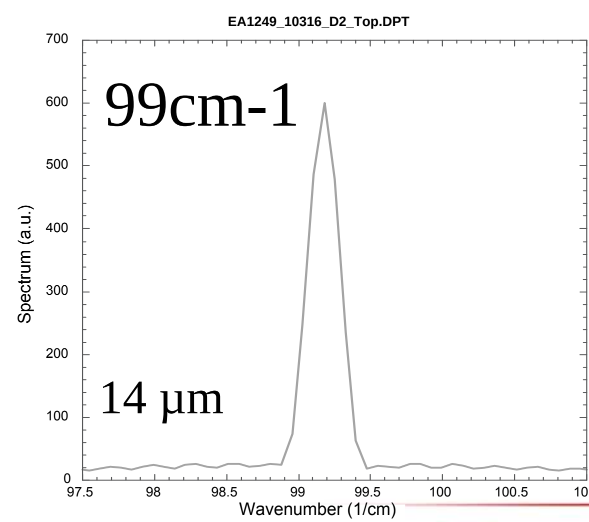
(Example: mid-IR QCL, Princeton)

- Lasing wavelength is determined by grating
- DFB gives single mode behavior
- Tuned by 180 GHz (even outside observed FP range)

  - very sensitive (~18 GHz / 0.1 micron pitch change)







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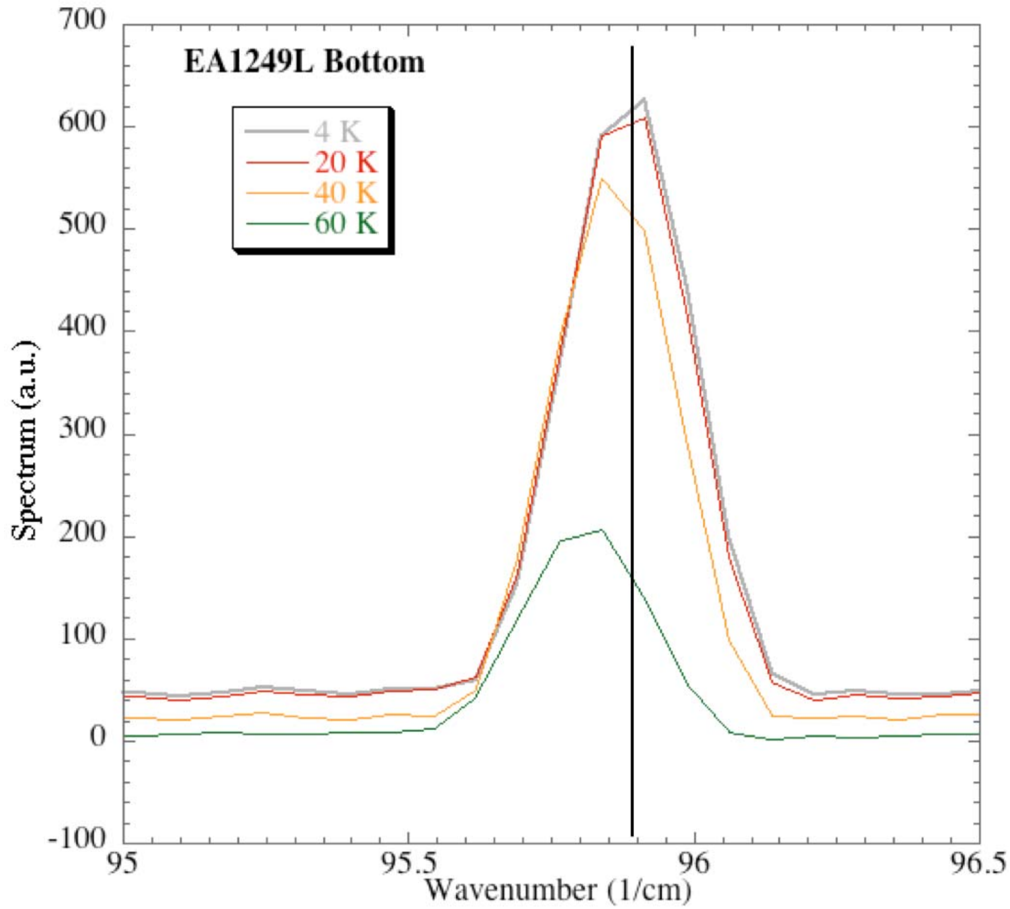
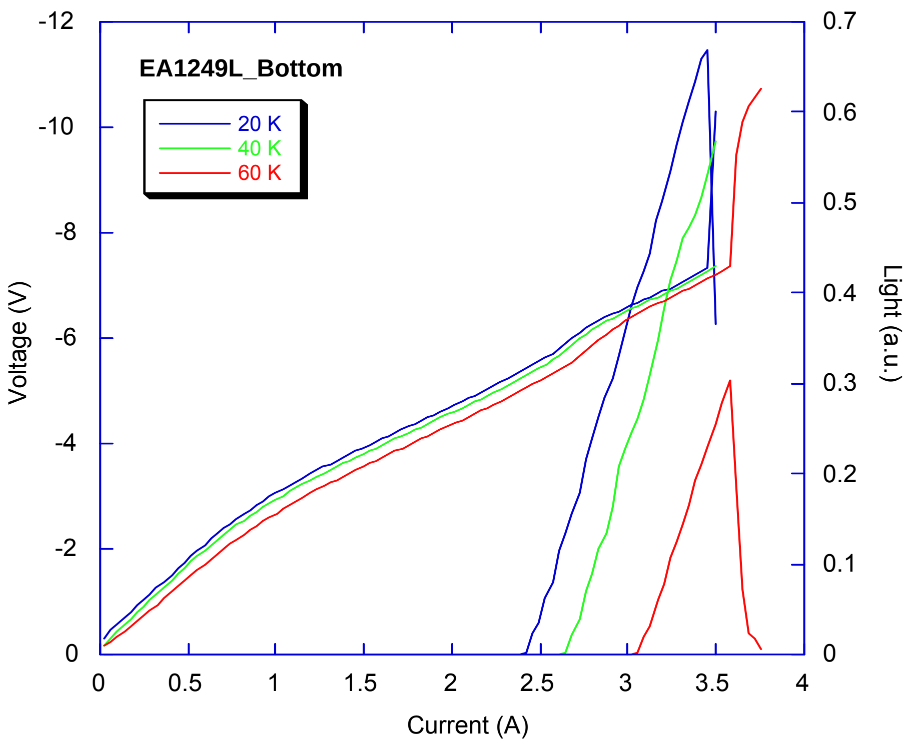
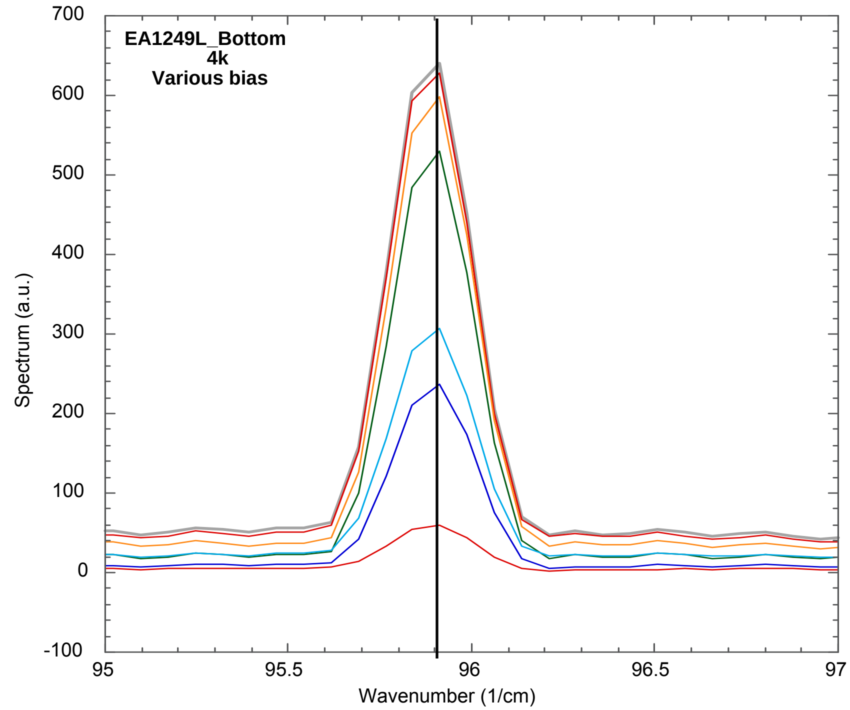
QCL-DFB FrequencyTemperature Dependence



- Slight redshift as the temperature increases

QCL-DFB Frequency Current Dependence





- Slight redshift as the bias increases

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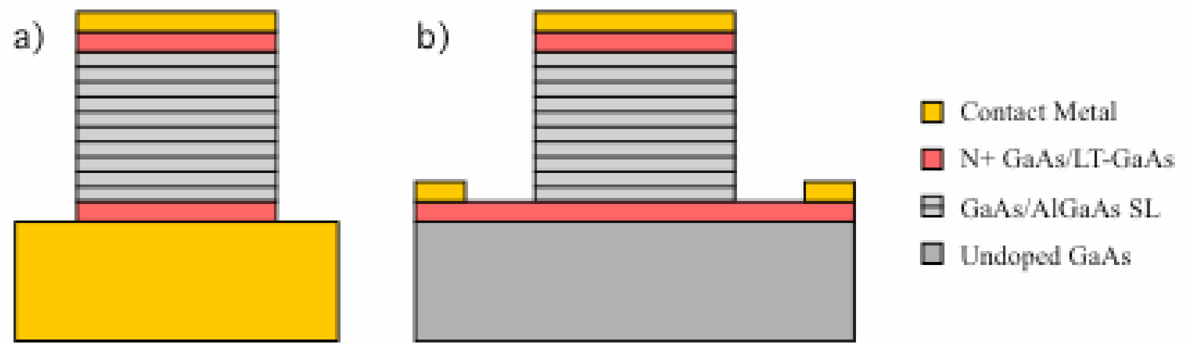
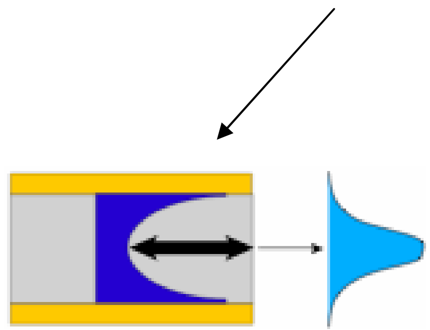
THz Laser Waveguides

QCLs are made using one of these 2 waveguides:

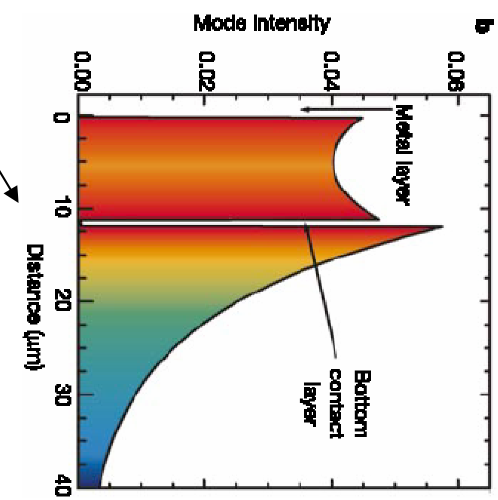
Metal-Metal Waveguide

Surface Plasmon Waveguide





In reality - probably close to top hat mode

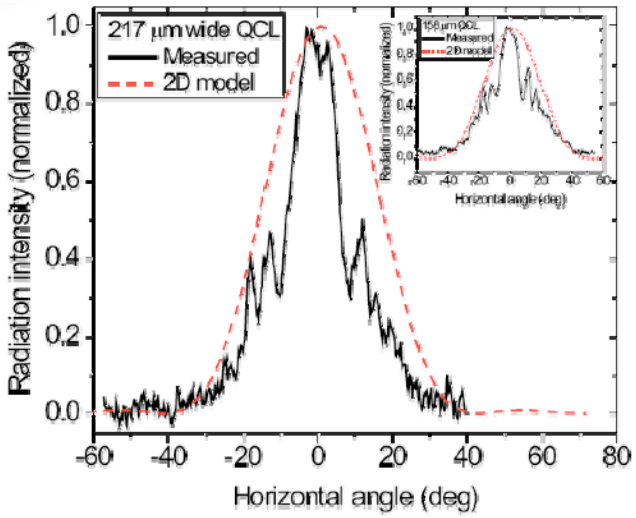


Kohler, Nature, **417**, May 2002

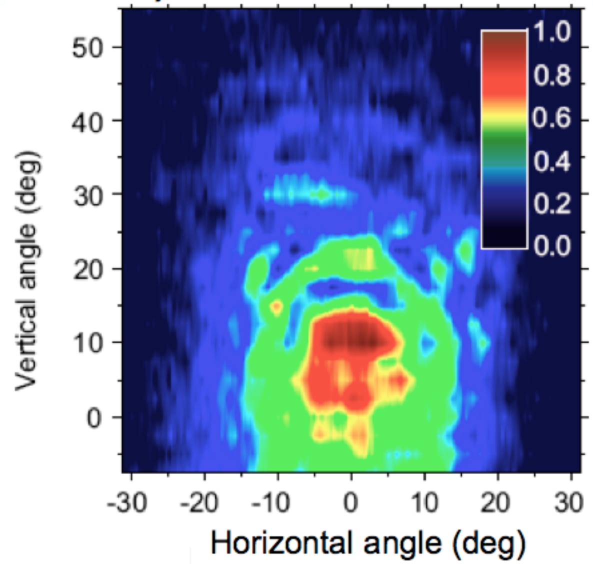
Neither waveguide has ideal mode for free space coupling
but intuitively metal-metal might couple well to empty waveguide

QCL Beam Pattern Issues

(Courtesy J. R. Gao, TU Delft)

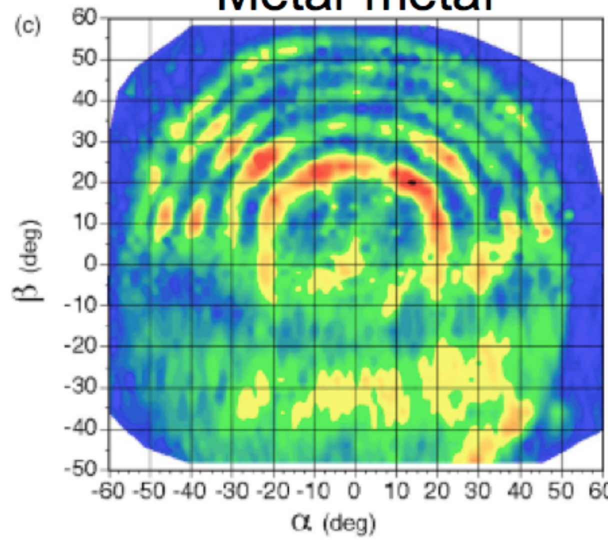


Surface Plasmon

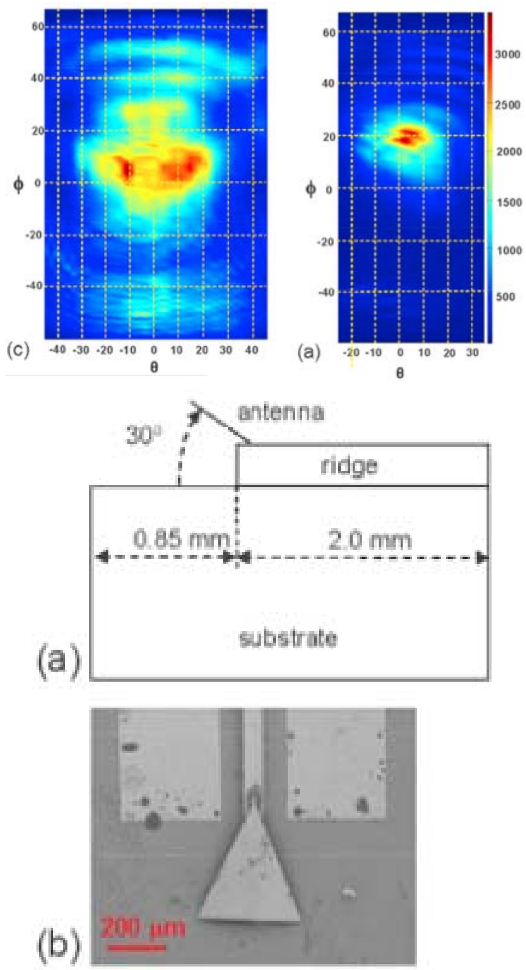


- Beam envelope close to Gaussian
- Fringes superposed on envelope
  - Rings of nulls in metal-metal
  - Rings of minima in plasmon
  - Decrease Gaussian content of beam
- Maximum coupling thru lens ~ 6%

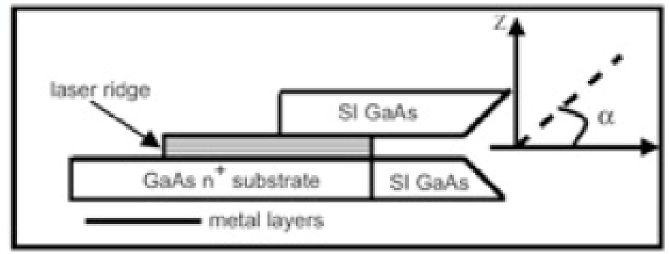
Metal-metal



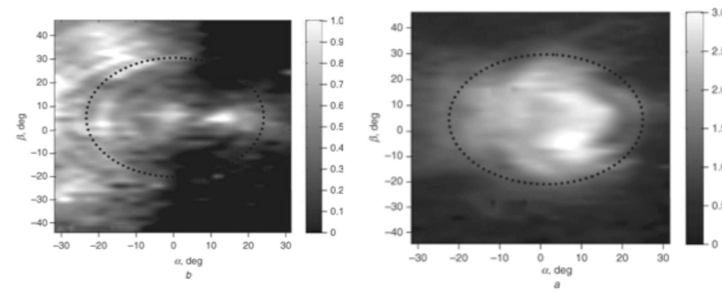
Attempts to fix the beam

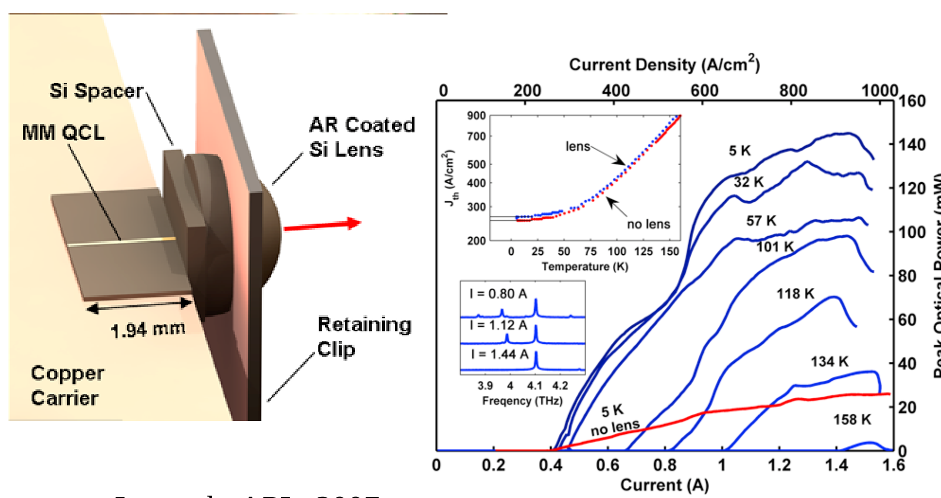


Barbieri, CLEO CWP4



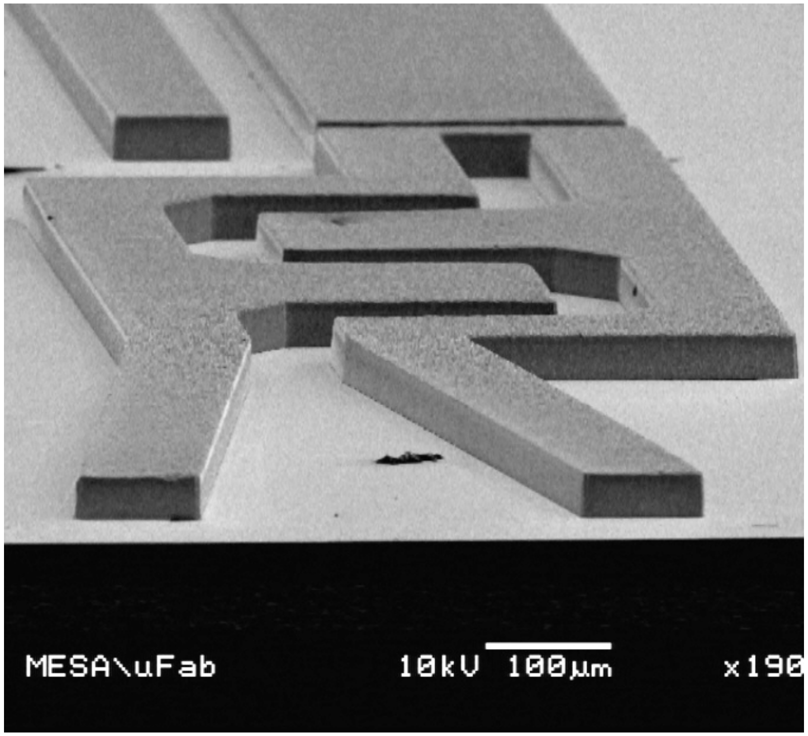
Amanti, *Elec. Lett.*, **43**, p573, 2007

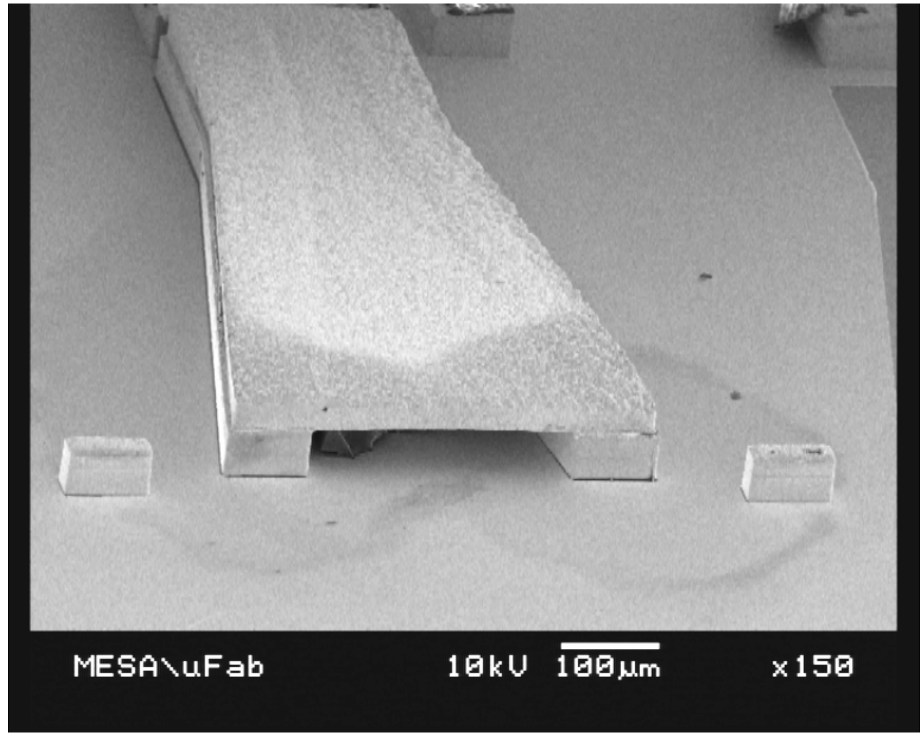




Lee, sub. APL, 2007

QCLs in Rectangular Waveguide



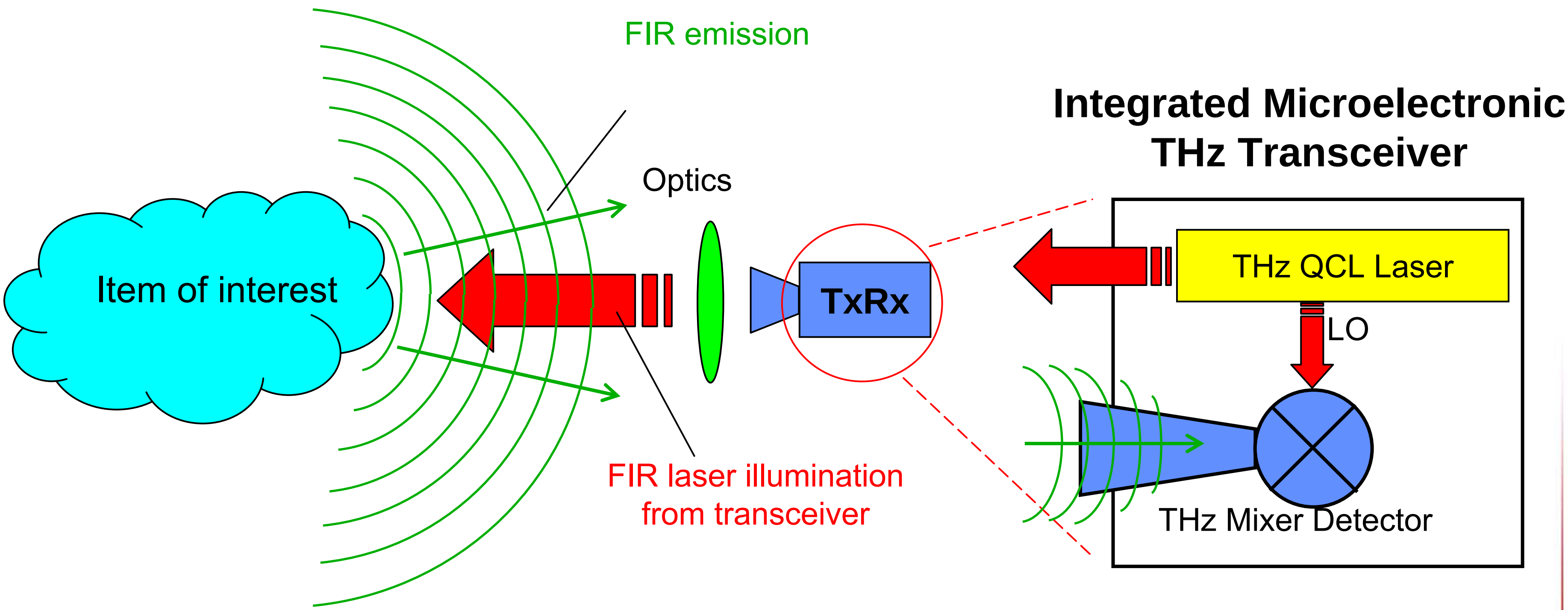


- LIGA process
- Gold walled rectangular waveguides

Outline

- Intro: Sandia, CINT, etc.
- Terahertz (THz) – General
- THz Quantum Cascade Lasers
- Waveguide, beam issues
- **The THz QCL + Schottky receiver**
- THz metamaterials

Essential THz Transceiver Makeup

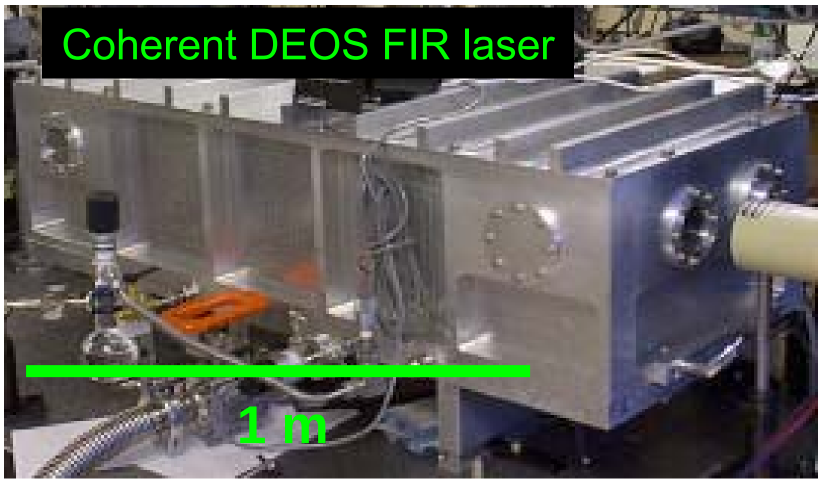


Signature of interest
- Emission/absorption
- Reflection
- ...

Integration of:
- QCL
- Schottky Mixer

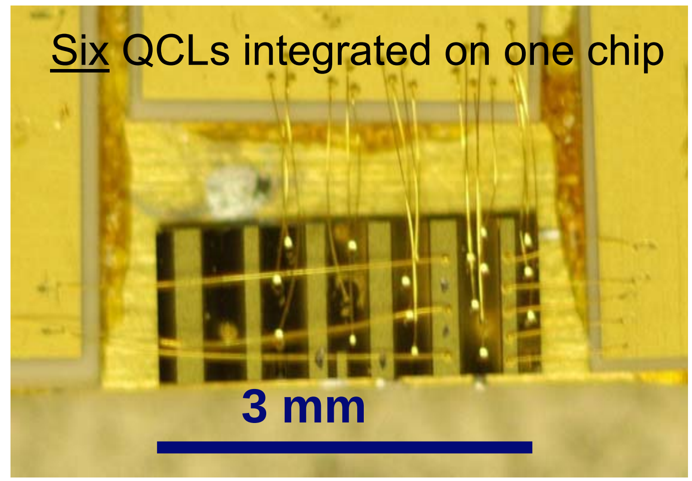
Heterodyne receiver…..

Replace this….



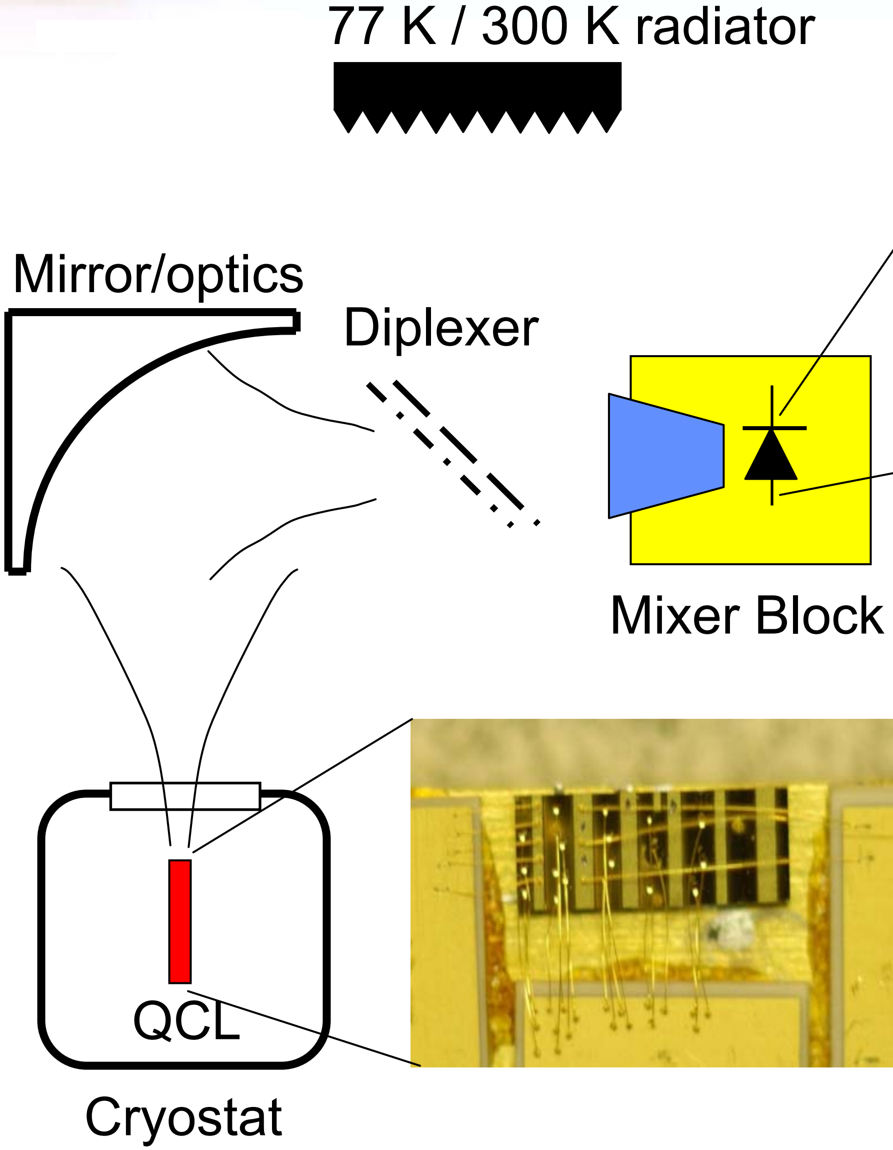
- 2.52 THz Molecular gas laser heterodyne transceiver
- 1 m x 0.3 m
- 50 kgs
- One fixed wavelength
- 40 mW LO power
- Space-qualified

With this !



- QC Laser heterodyne transceiver
- 2 mm x 0.1 mm,
- 1 g
- Multiple wavelengths
- 10 mW LO power
- Scalable to mass production

Goal :Compact THz Receiver



JPL Schottky Mixer

- **Quantum cascade lasers in THz demonstrated in 2002**
  - **Only solid-state source capable of > 1 mW CW above 2 THz**
- **2.5 THz QCL used successfully as LO for Nb HEB mixer**
  - **~ 10 μW LO power to mixer [Hübers, *et al.*, Optics Exp. (2005)]**
- **Dual-mode mixing of THz QCL with point-contact Schottky**
  - **Low conversion gain [Barbieri, *et al.*, Optics Lett. (2004)]**
- **Planar Schottky mixer has more stringent LO requirements**
  - **Need 5 to 10 mW CW coupled into mixer**
- **Can a THz QCL be used successfully with a planar Schottky receiver?**

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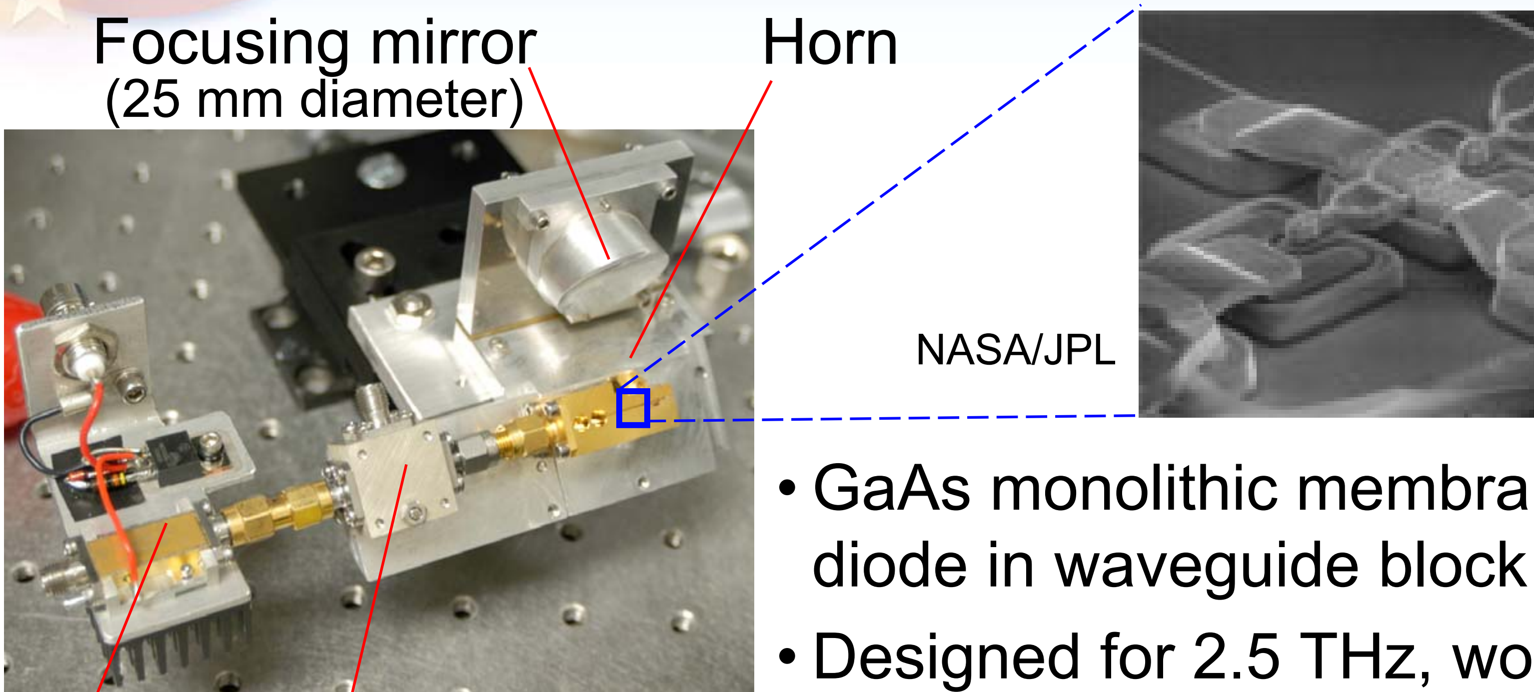
The Schottky Receiver

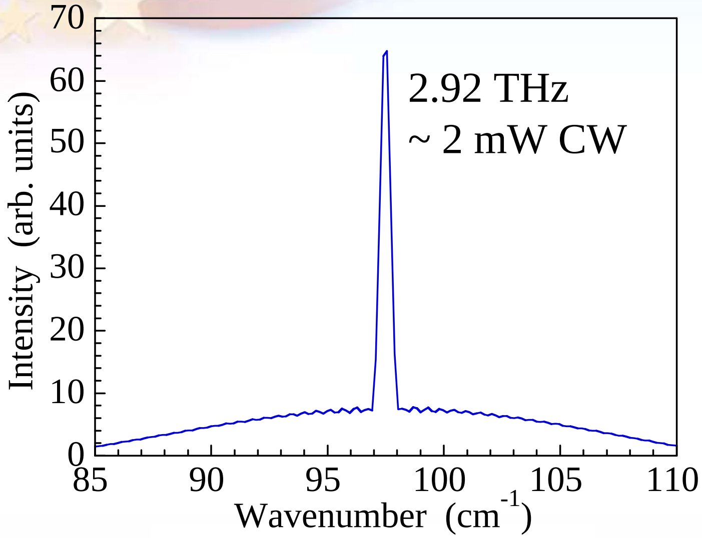


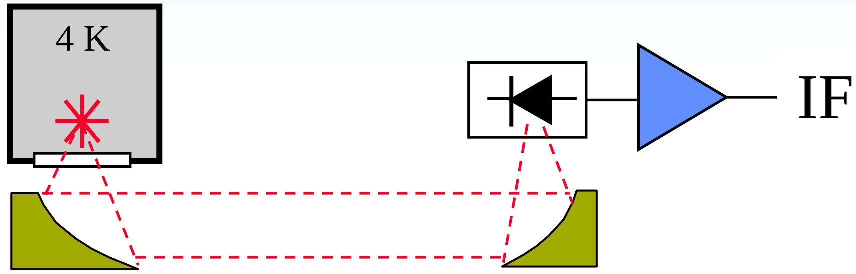
<u>Duplicate of Aura receiver</u>

Siegel, *et al*., IEEE Trans. Microw Th. Tech (1999)
Gaidis, *et al*., IEEE Trans. Microw Th. & Tech. (2000)

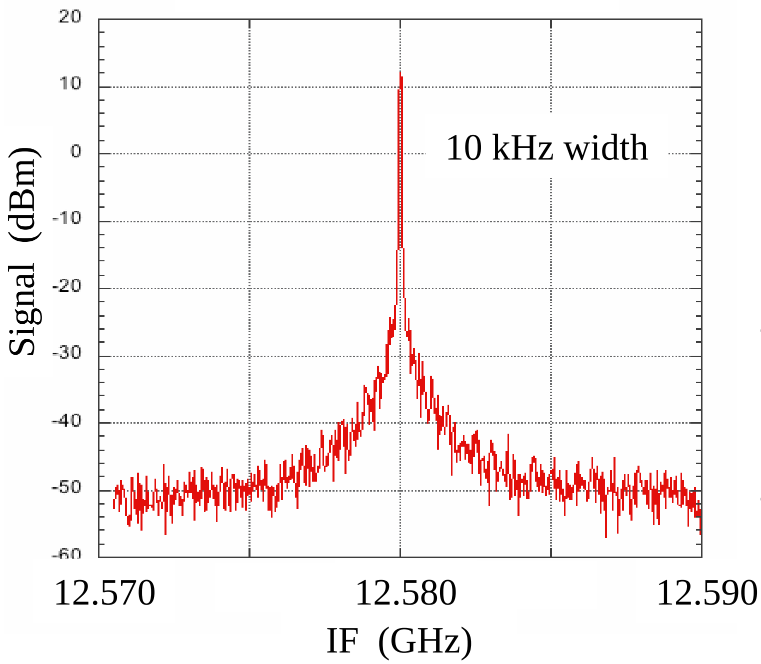
- GaAs monolithic membrane diode in waveguide block
- Designed for 2.5 THz, works to ≥ 3.1 THz
- 20 GHz IF BW (LNA limited)
- T_N = 11,000 K at 2.5 THz with ~ 5 mW FIRL LO power
- $T_N \approx$ 20,000 K at 2.9 THz with ~ 6 mW FIRL LO power

QCL Dual-mode Mixing

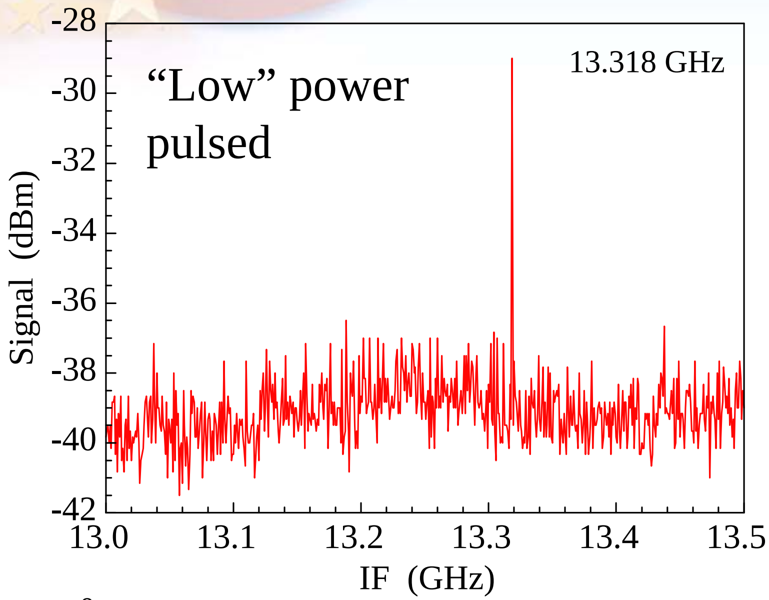


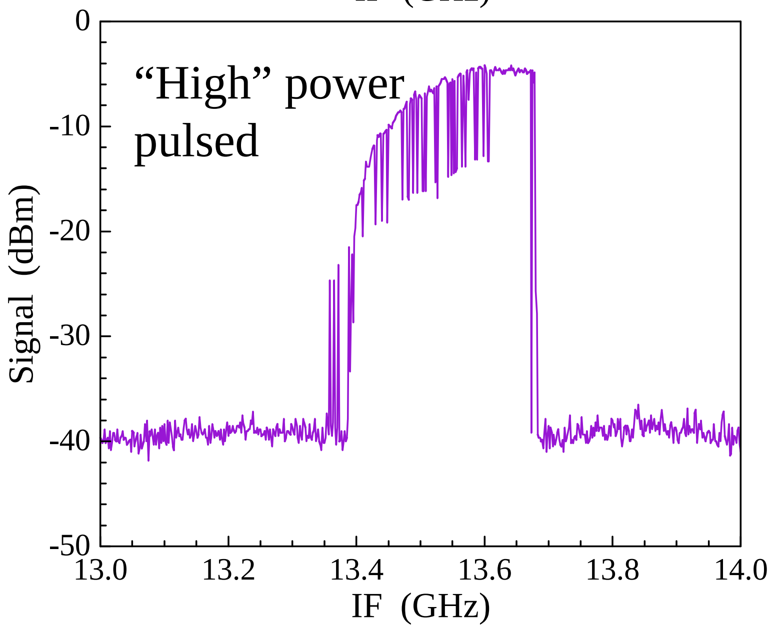


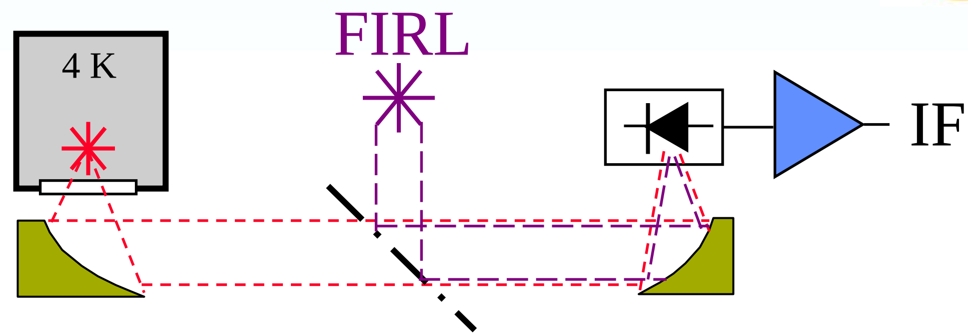
- 2.92 THz <u>free running</u> CW QCL
- ~ 2 mW total CW power in non-Gaussian divergent beam
  - Estimate ≤ 0.2 mW coupled to receiver (≥ 10 dB coupling loss)
  - Insufficient to measure noise temp.
- Above threshold bias, dual Fabry-Perot modes split by 12.58 GHz
- Difference frequency linewidth ≤ 10 kHz (common mode)



QCL Mixing Against FIR Laser







- Mix <u>free-running</u> QCL with 2.9070889 THz D-methanol line
  - High precision measurement of QCL frequency = 2.920406 THz
- QCL pulsed, current biased
  - 0.4 ms/20ms duty cycle
- Single-mode at "low" QCL power (steady-state)
- Frequency unstable (chirping?) at "high" QCL power (transient)

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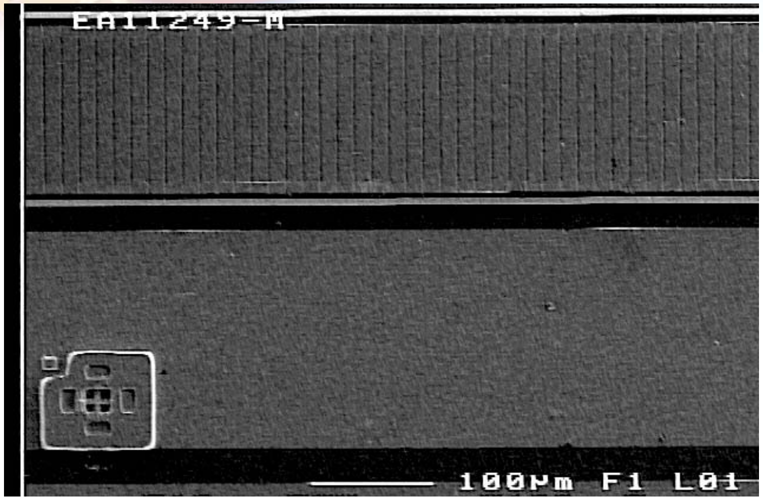
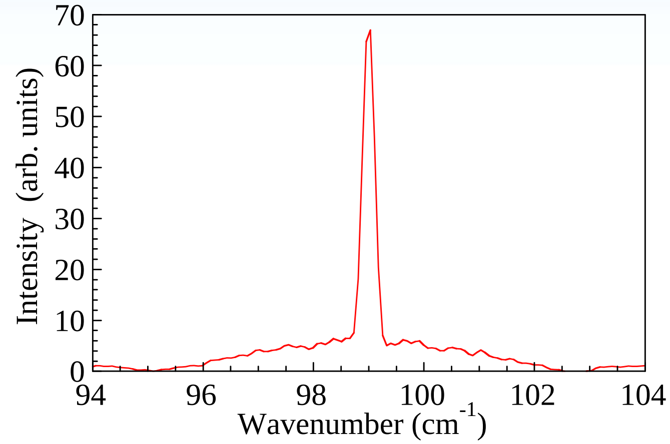
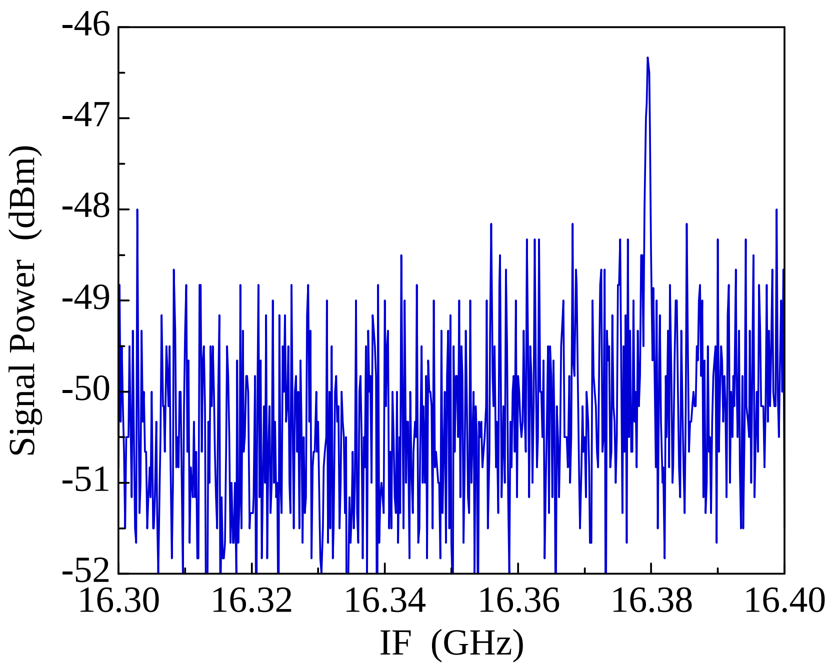
DFB QCL Mixing Against FIR Laser

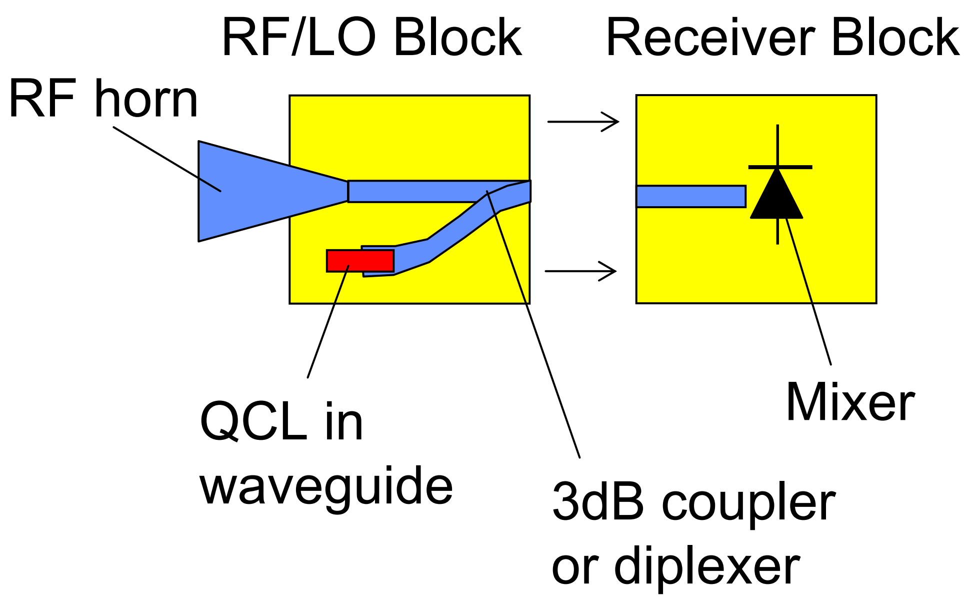






- $\lambda/2$ grating on top of QCL to force single-mode behavior
- Mixed with 2.951 THz D-methanol line
  - QCL frequency = 2.967 THz
- QCL pulsed, 0.2 ms/20 ms
- Only single-mode behavior
- Atmospheric absorption ~ 1.5 dB/in, can't properly align

The future?



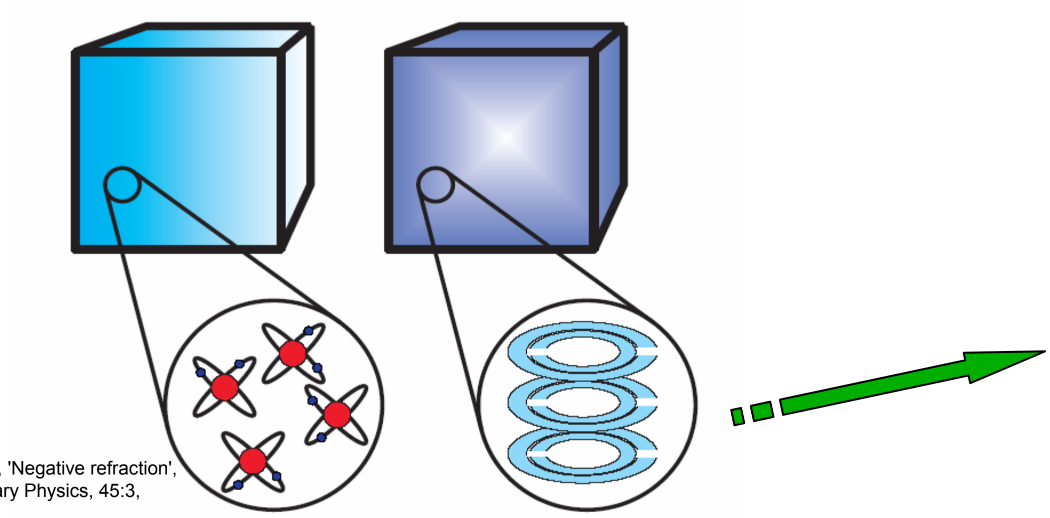
Possibly no free space beam required at all !

Outline

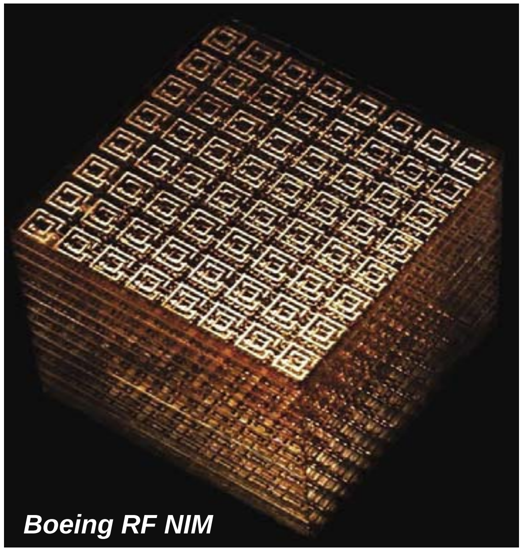
- Intro: Sandia, CINT, etc.
- Terahertz (THz) – General
- THz Quantum Cascade Lasers
- Waveguide, beam issues
- The THz QCL + Schottky receiver
- **THz metamaterials**

Metamaterials

- "Metamaterials":



Pendry, JB , 'Negative refraction', Contemporary Physics, 45:3, 191 - 202



In a conventional material, ε, & μ are derived from the constituent atoms

In a metamaterial, ε_{eff}, μ_{eff} are derived from "meta-units" (bigger than atoms, << λ)

Absolute local control of ε and μ

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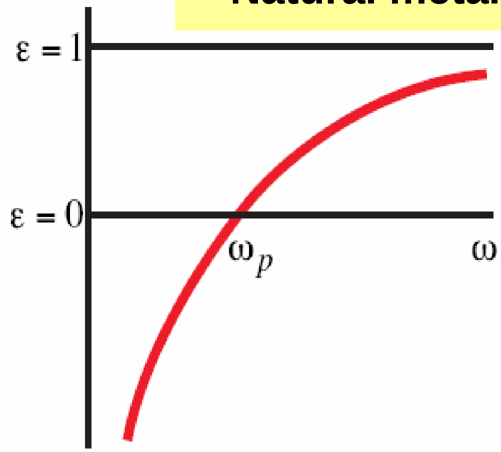
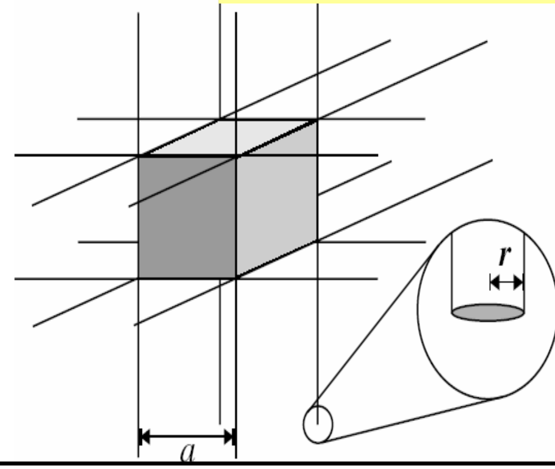
How is this done? ➔ Local control of ε & μ

Natural metals



"Synthetic" metals: control ε

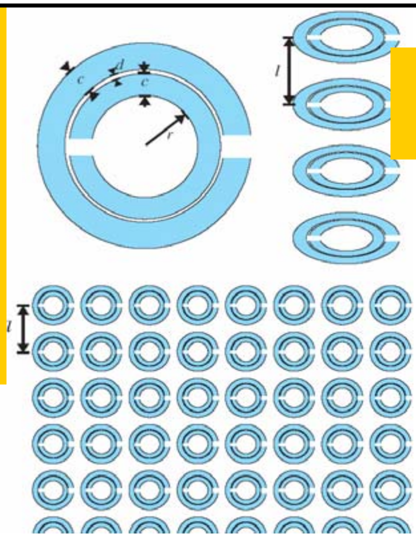


Controlling ε: "Plasmonics"

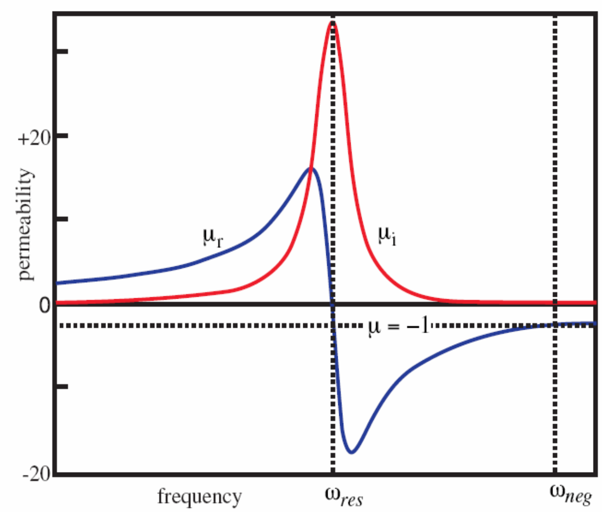
If: $\varepsilon = \varepsilon_1 + \iota\, \varepsilon_2$ then any metal below the plasma frequency will show $\varepsilon_1 < 0$

Metal grids shift the plasma frequency by diluting the electron density and also varying the electron effective mass

Split-ring resonators (SRR): control μ using microscopic LCs



No natural free magnetic monopoles ➔ create and use magnetic dipoles: control μ

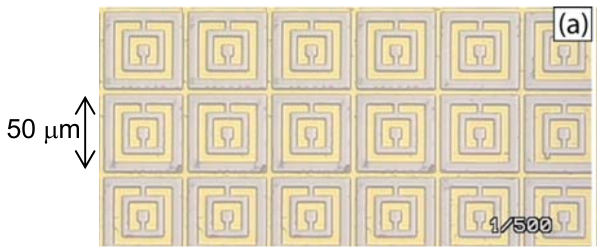


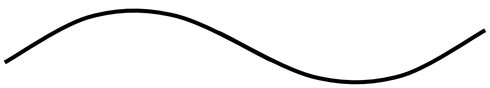
a<<λ

Example: THz Metamaterials

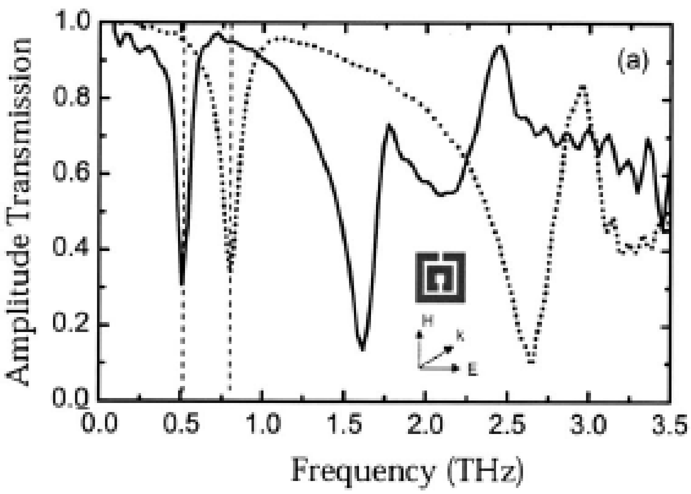
- ***Why THz MMs?*** **Easi(er) to fabricate; good behavior & agreement with modeling; test ground for higher frequencies; *lack of common devices (filters, polarizers, etc)***

"Magnetic"





1 THz ~ 300 μm

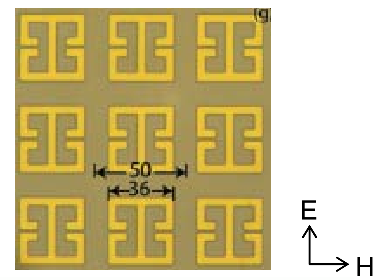


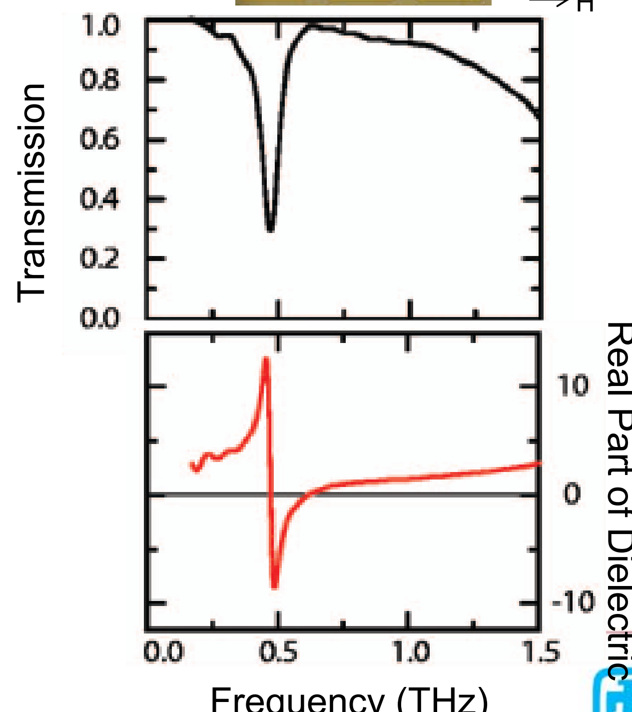
__ Silicon
--- Quartz

Azad, A. K., et al., *Opt. Lett.*, 31 (2006) 634.
First devices fabricated by Clark Highstrete & Mark Lee

At THz frequencies, unit cell ~ 10's of μm

"Electric"





Padilla W. J., et al., *PRB* 75 (2007) 041102.

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Chirality and Metamaterials, Polarization Sensitive Metamaterials

- **Motivation**

  Develop polarization sensitive and (maybe) non-reciprocal devices for manipulating light.

- **Objective**

  Develop a metamaterial that is sensitive to the polarization of the incident THz radiation, (ex: polarization multiplexing)

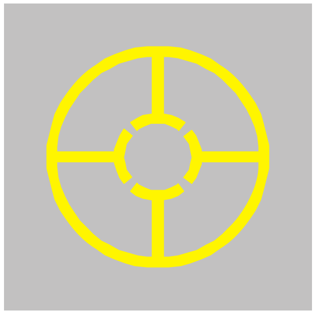
- **Implementation Strategy**

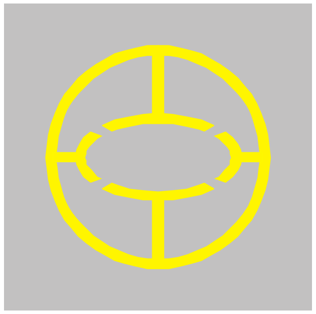
  –Start out with a symmetric resonator

  Circular Split Ring Resonator

  –Modify the unit cell to break the circular symmetry

  Elliptical Split Ring Resonator



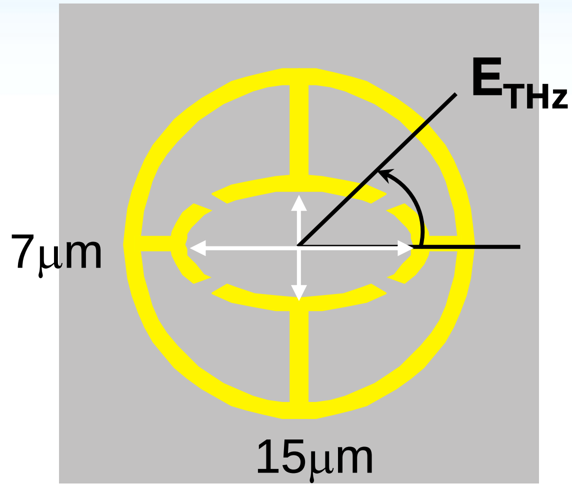


(Lord Kelvin)

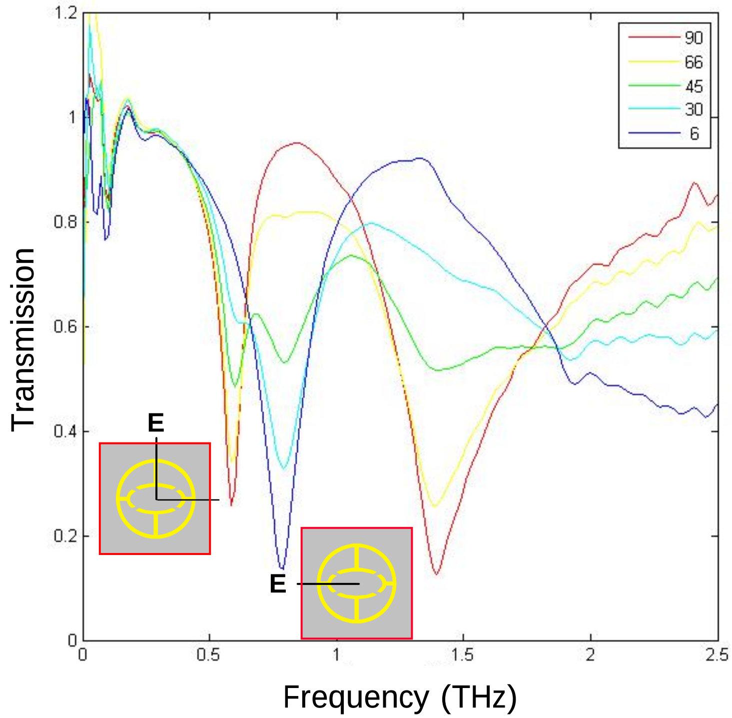
(X. Peralta (SNL) & J. O'Hara, E. Smirnova, A. Azad, T. Taylor LANL & CINT)

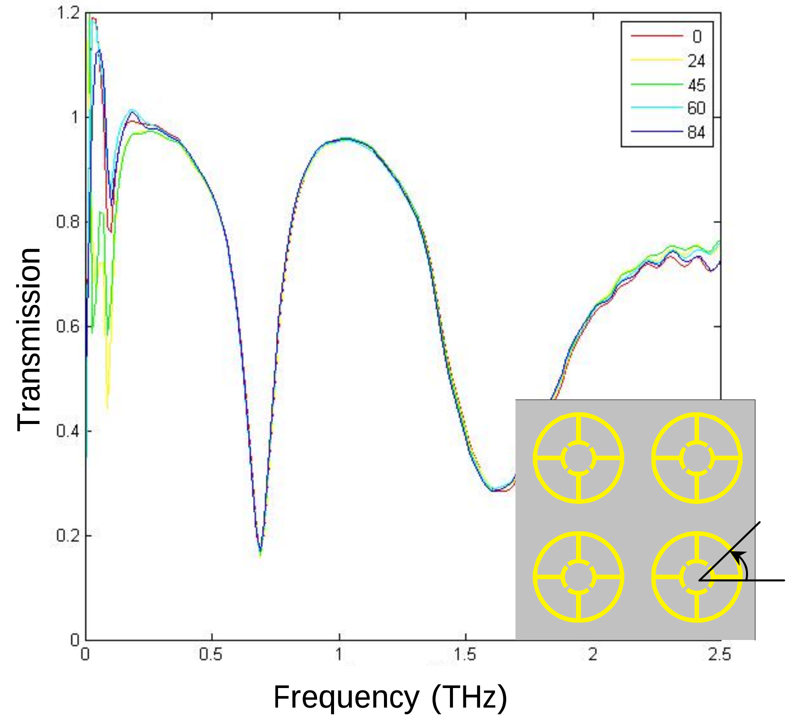
Samples & THz transmission measurements

- **Substrate SI GaAs**
- **Metal 100Å Ti / 2000Å Au**
- **Gap 2μm**

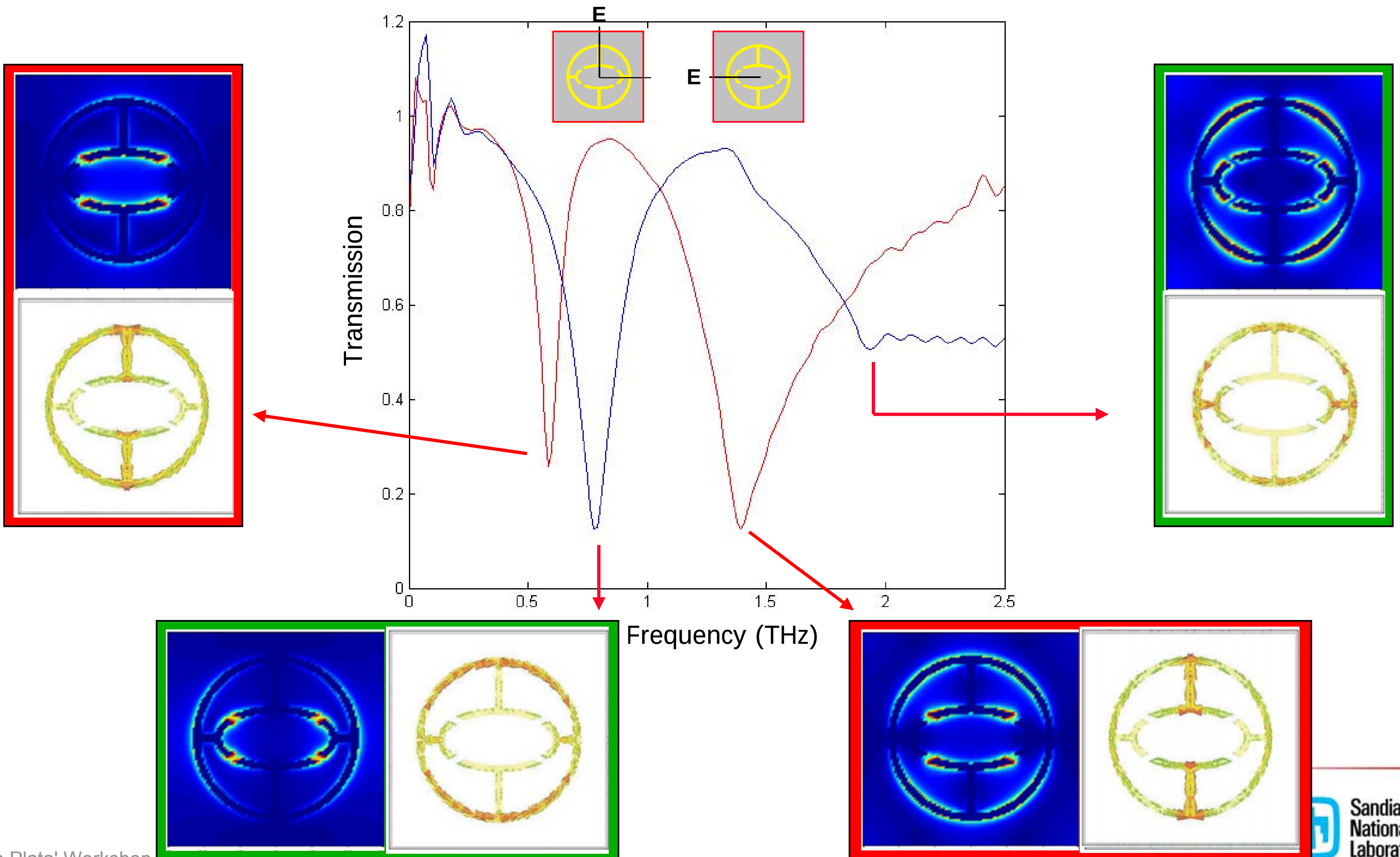


- **Line thickness 2μm**
- **Outer radius 21μm**
- **Period 60μm**

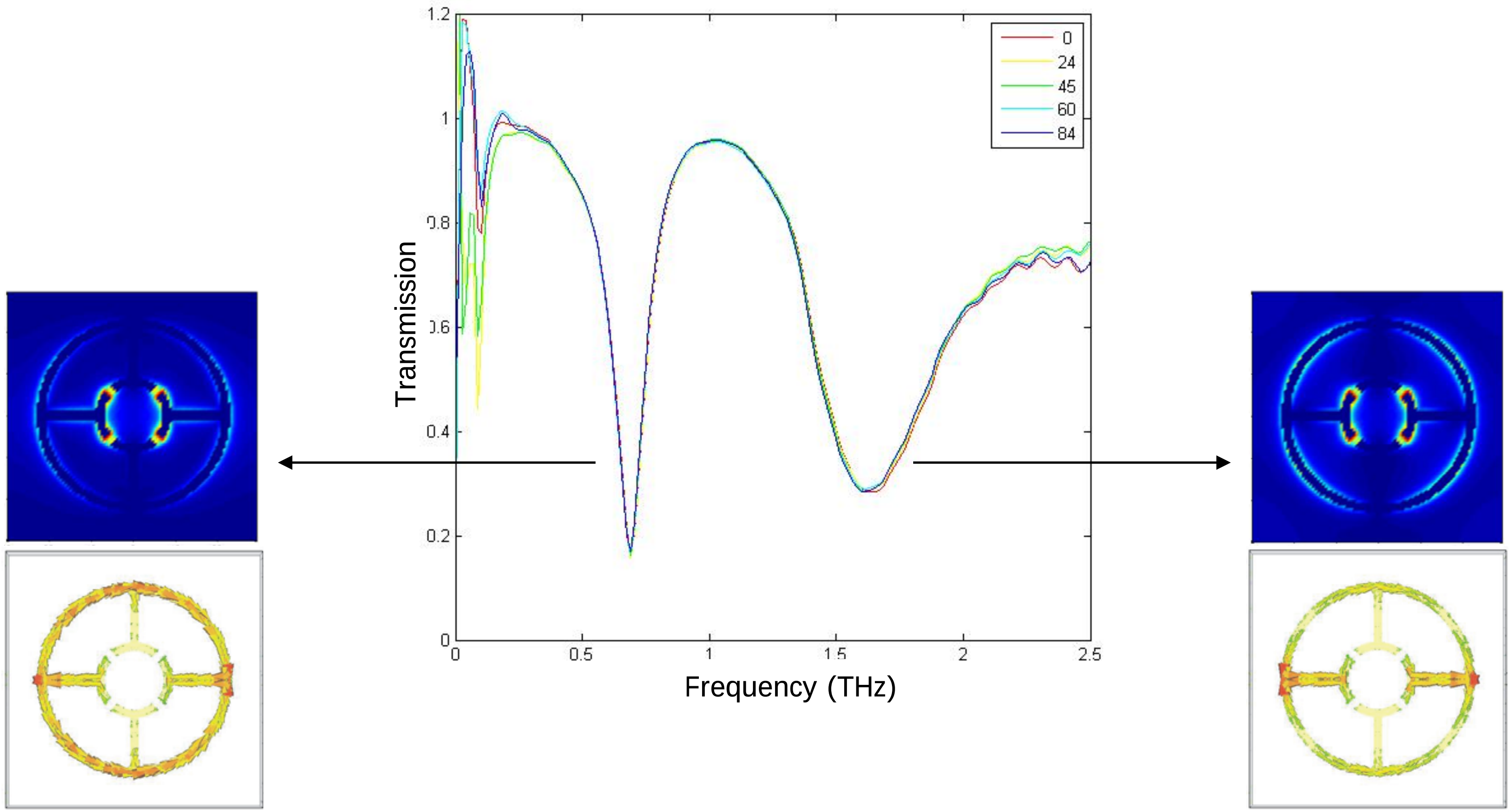




ESRR Electric Fields and Surface Current Densities



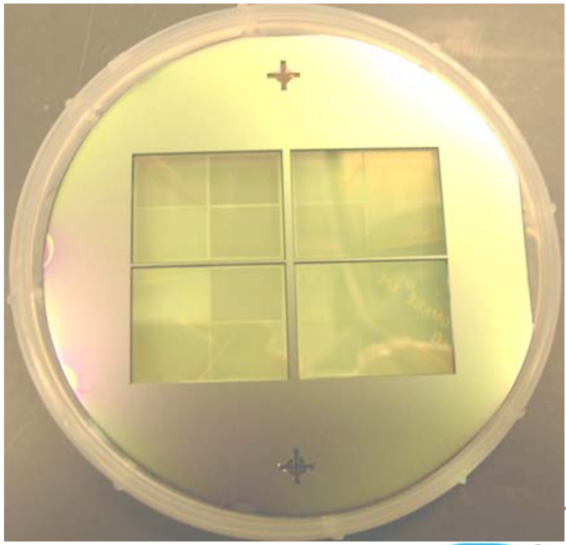
CSRR Electric Fields and Surface Current Densities



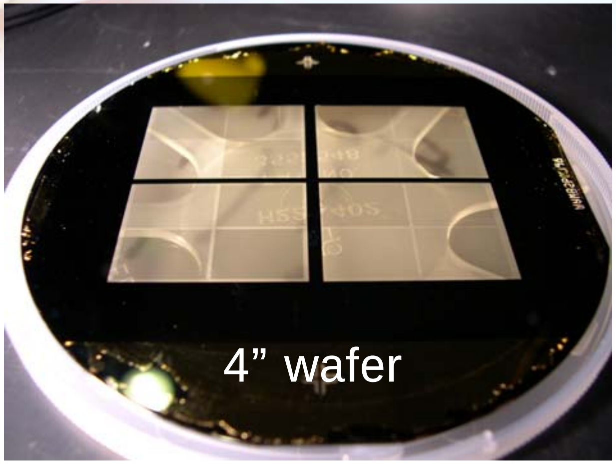
Metamaterials on Si_2N_3 Membranes

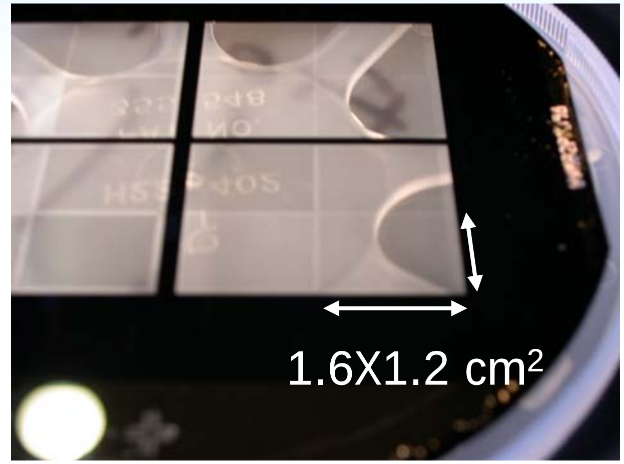
- **Motivation**
  - –**Increase our understanding of dielectric losses, and resonances.**
  - –**Show a path towards fabricating 3D THz metamaterials.**
- **Objective**

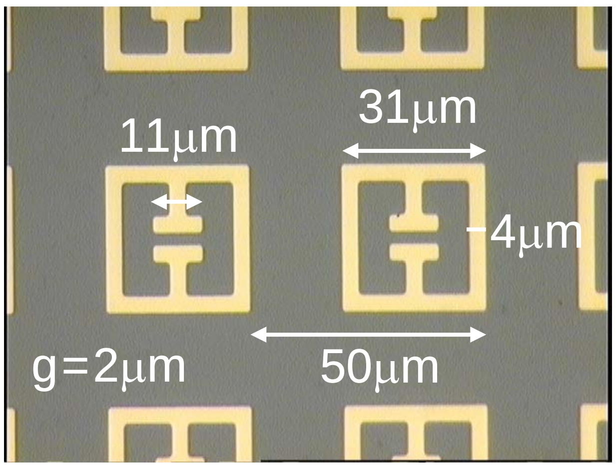
  Fabricate THz metamaterials on very thin (<<λ) membranes.



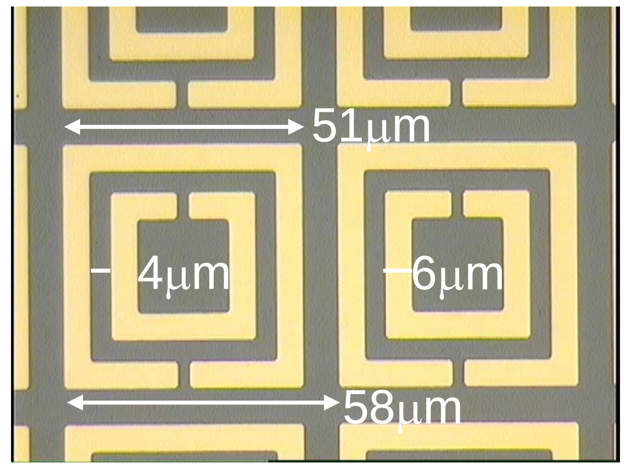
Samples







1.49THz

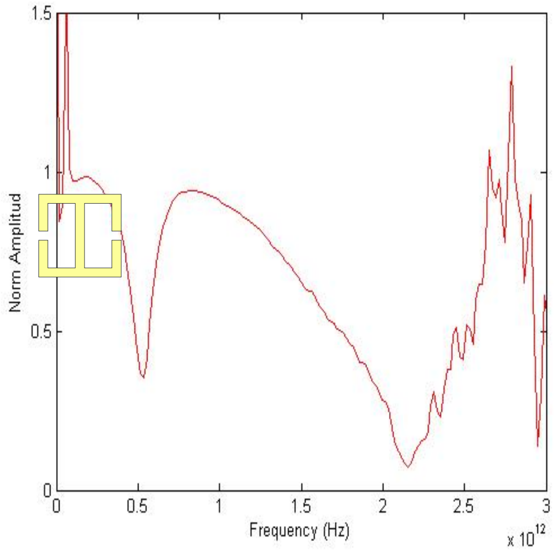


0.50THz

- **Membrane thickness 1μm**
- **Metal 200Å Ti / 500Å Au**
- **4 windows**
  - **window size ~(3.2 x 2.4) cm^2**
  - **4 metamaterial designs per window**

MMs on membranes: THz Transmission

Transmission

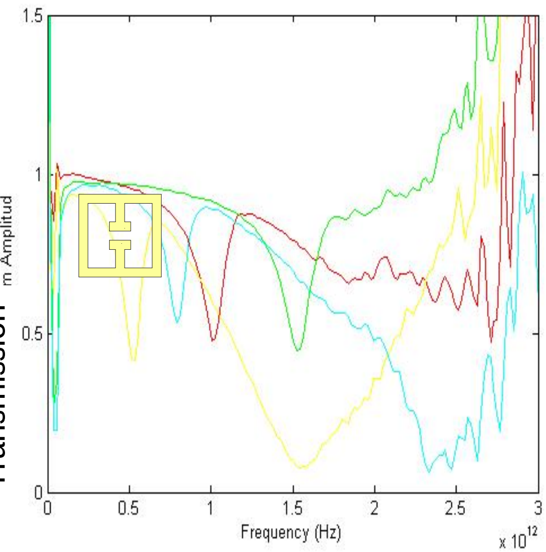


Frequency (THz)

0.5 Thz

0.5 THz
0.76 THz
1.0 THz
1.49 THz

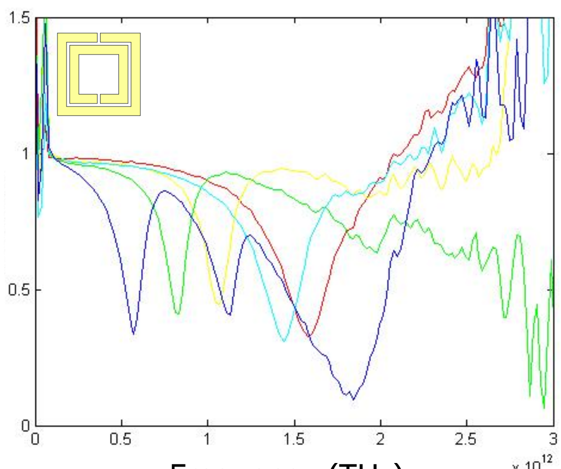
Transmission



Frequency (THz)

0.5 Thz
0.76 Thz
1.0 Thz
1.39 Thz
1.51 Thz

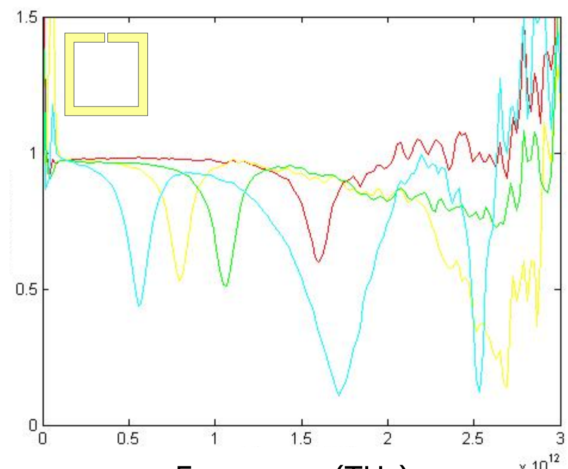
Transmission



Frequency (THz)

0.5 Thz
0.75 Thz
1.0 THz
1.5 THz

Transmission



Frequency (THz)

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Acknowledgements

M. Wanke, M. Lee, M. Lerttamrab, A. D. Grine, J. L. Reno, X. Peralta, C. Fuller

Sandia National Laboratories

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Cal Tech and Jet Propulsion Laboratory