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Operation of a Monolithic Planar Schottky Receiver Using THz Quantum Cascade Lasers

Mike C. Wanke

M. Lee, M. Lerttamrab, A. D. Grine, J. L. Reno

Sandia National Laboratories

P. H. Siegel, R. J. Dengler

Cal Tech and Jet Propulsion Laboratory

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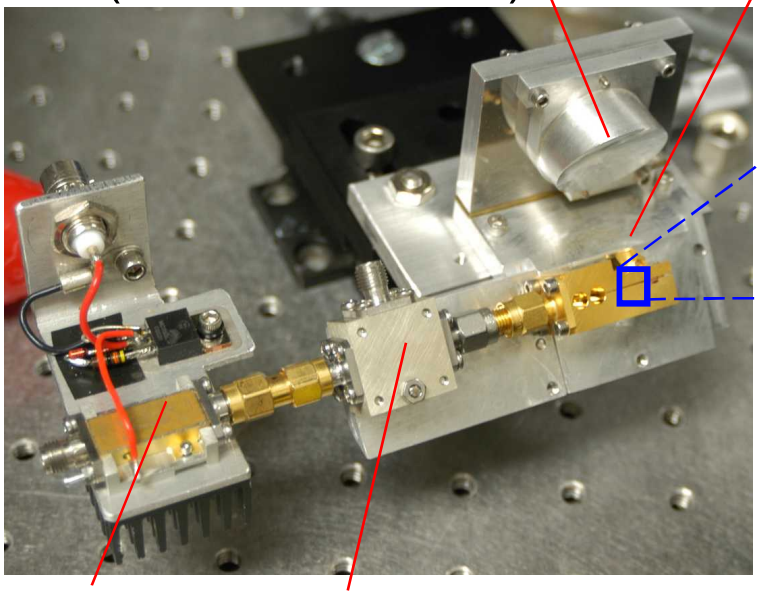
Outline

- A little history & motivation
- The Schottky receiver
- The THz quantum cascade laser
- The THz QCL + Schottky receiver
- Possible mode improvements

(Recent) History and Motivation

- Continuing search for better LO sources > 2 THz
  - FIR molecular gas laser most common
  - Solid-state sources preferable but have power issues
- Quantum cascade lasers in THz demonstrated in 2002
  - Continuous improvements in power, efficiency, frequency coverage, operating temperature
  - 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?

The Schottky Receiver



- 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 ≈ 20,000 K at 2.9 THz with ~ 6 mW FIRL LO power

Duplicate of Aura receiver

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

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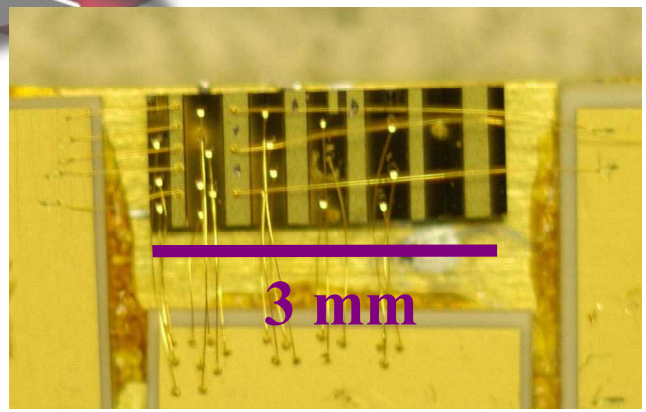
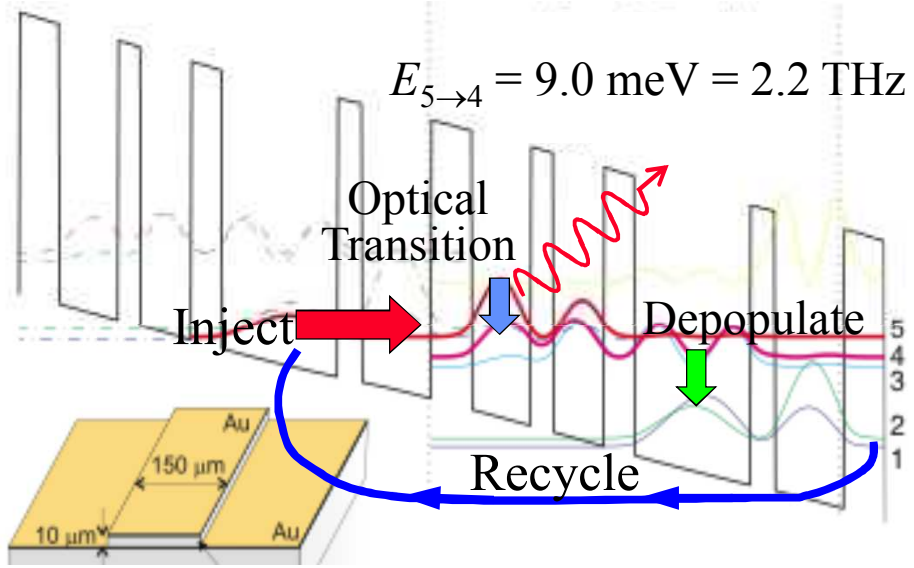
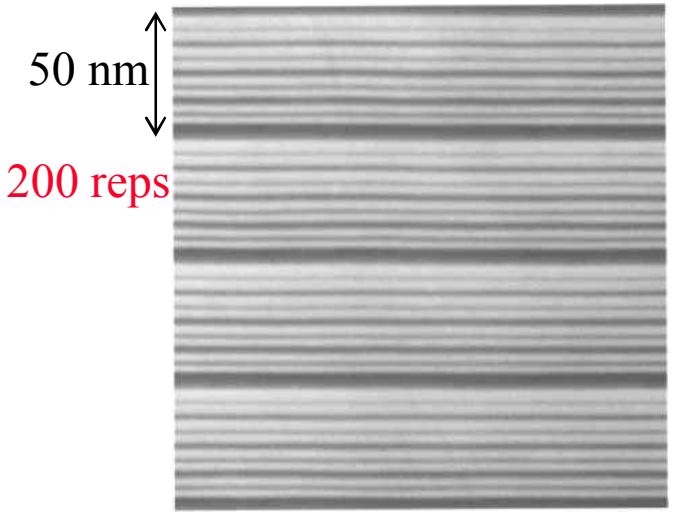
THz Quantum Cascade Lasers



6 QCLs integrated on chip





TEM cross-section of QCL stack

- *Tour-de-Force of Bandgap Engineering*
  - Requires ultra-precise, clean MBE growth
  - Many designs successfully grown at Sandia
- Can output > 1 mW CW power
  - Beam profile problematic
- Ongoing research into:
  - Higher power & operating temperature
  - Expanded frequency coverage

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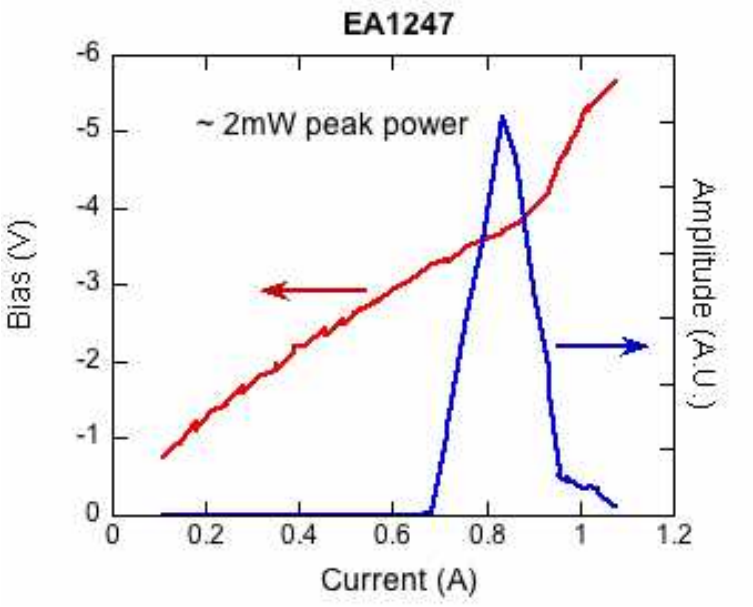
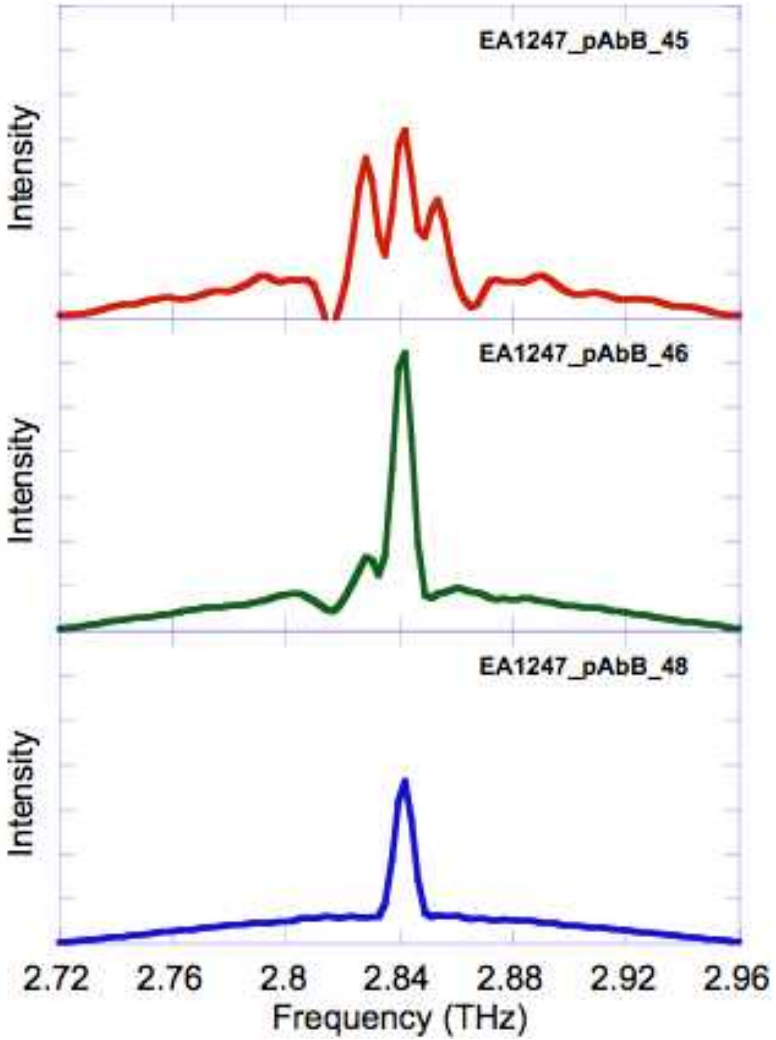
The QCL





- **2 mW peak output**
- **0.7A/3.4V threshold**
- **Single mode at lower power**

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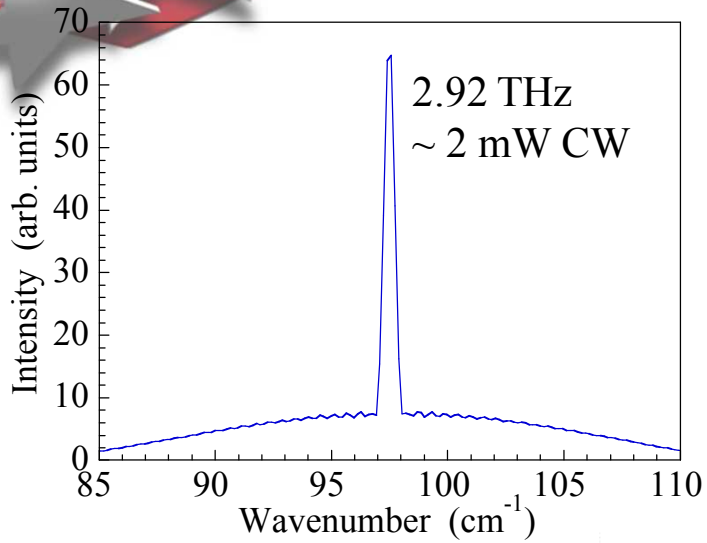
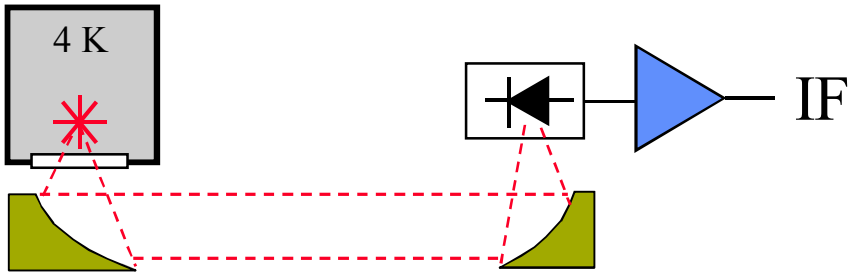
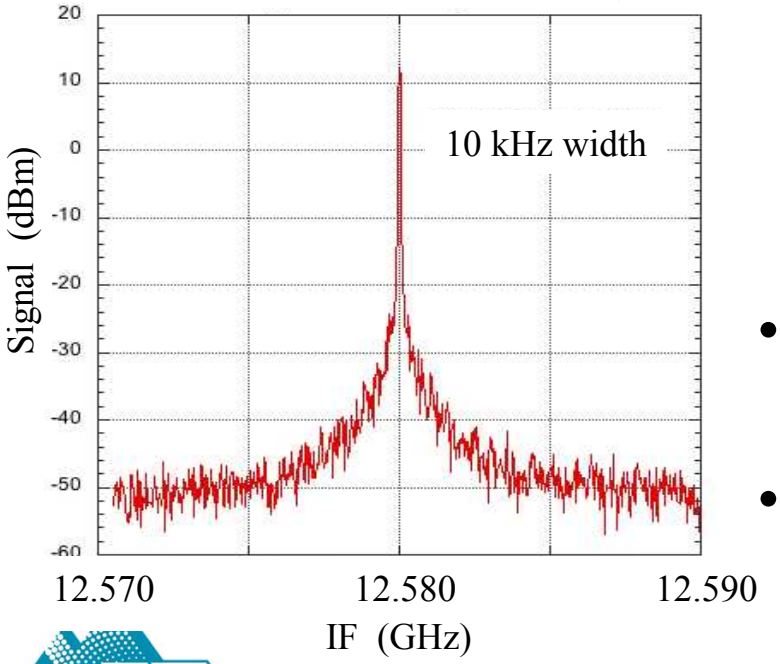
QCL Dual-mode Mixing

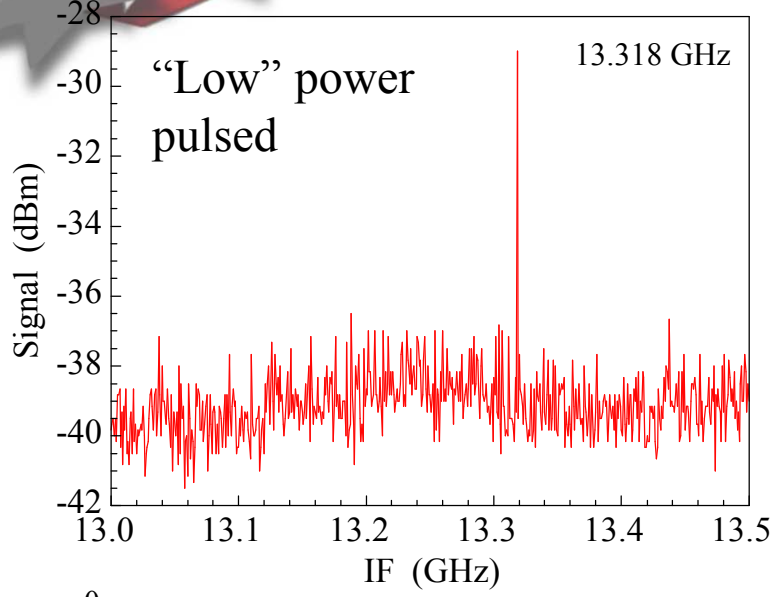


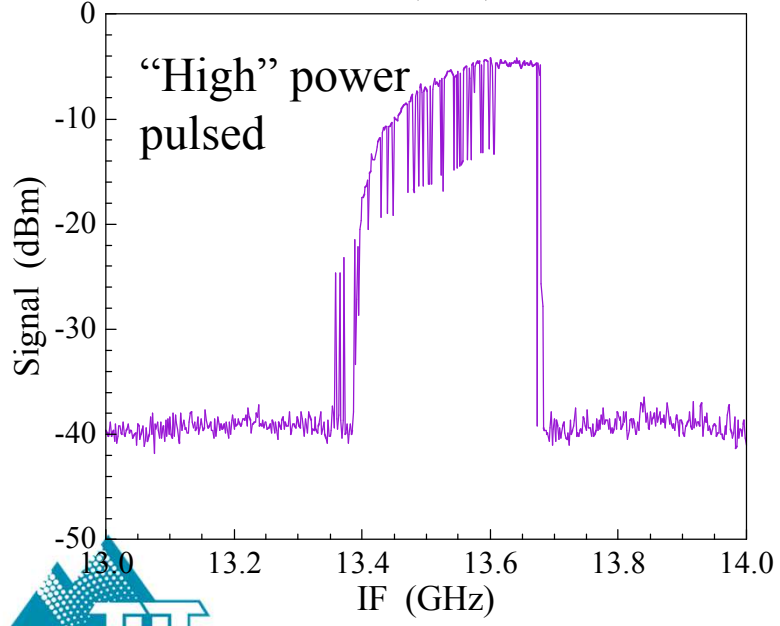


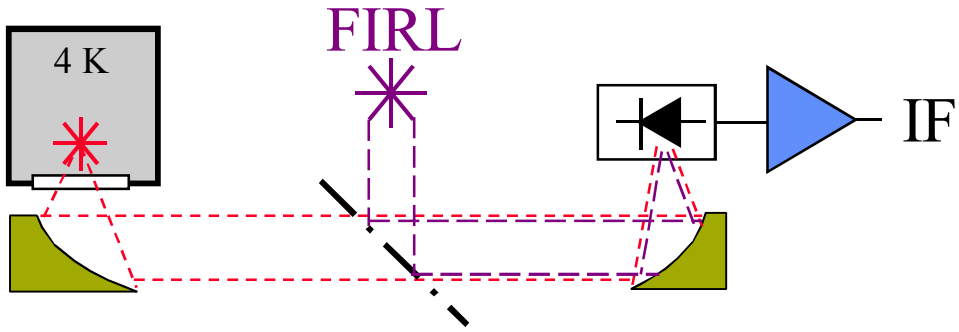


- 2.92 THz free running cw QCL
- ~ 2 mW total CW power in non-Gaussian divergent beam
  - Estimate ≤ 0.2 mW coupled to receiver (≥ 10 dB coupling loss)
  - Insufficient to measure noise temp.
- Above threshold bias, dual Fabry-Perot modes split by 12.58 GHz
- Difference frequency linewidth ≤ 10 kHz (common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

QCL Mixing Against FIR Laser

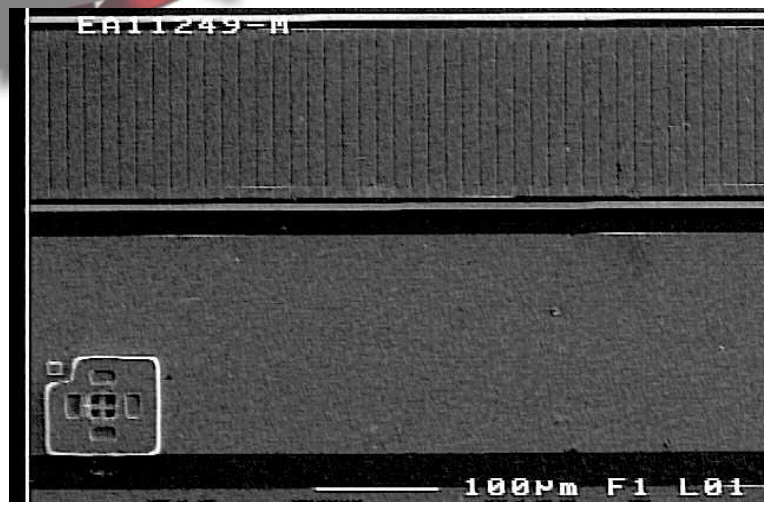


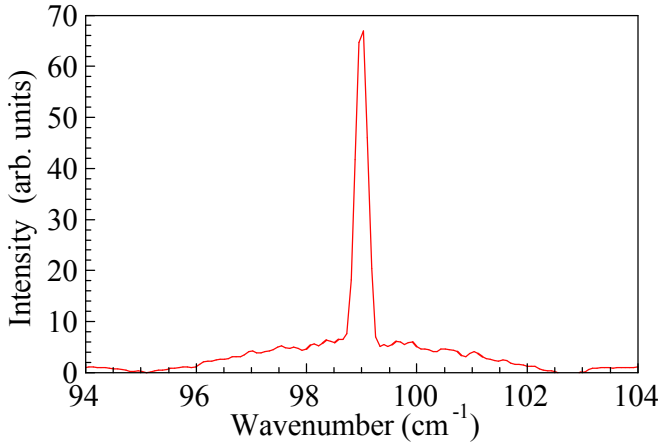


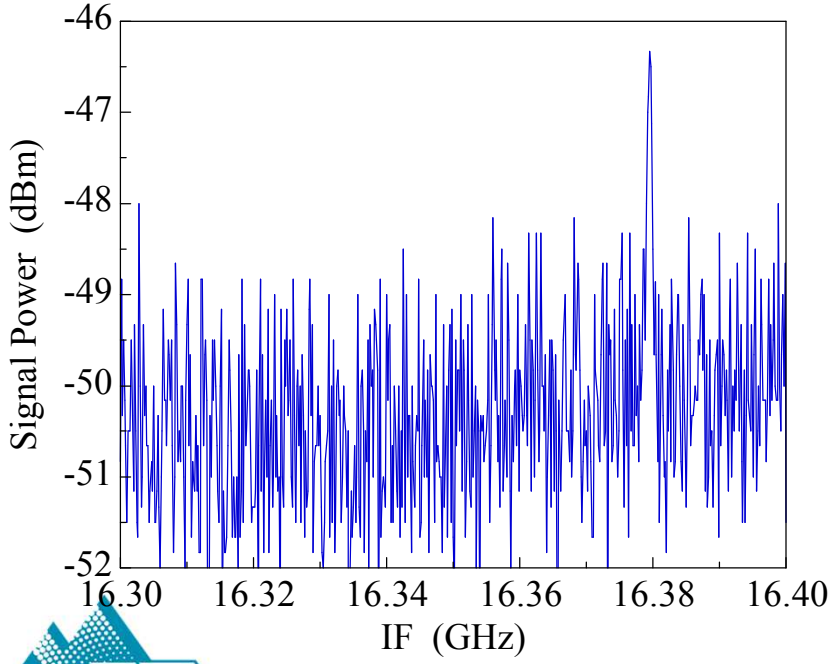


- Mix free-running QCL with 2.9070889 THz D-methanol line
  - High precision measurement of QCL frequency = 2.920406 THz
- QCL pulsed, current biased
  - 0.4 ms/20ms duty cycle
- Single-mode at "low" QCL power (steady-state)
- Frequency unstable (chirping?) at "high" QCL power (transient)

DFB QCL Mixing Against FIR Laser







- λ/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

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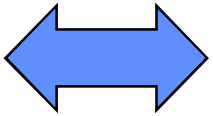
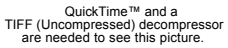
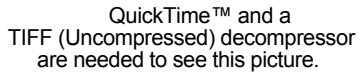
QCL Beam Pattern Issues

(Courtesy J. R. Gao, TU Delft)

Surface Plasmon



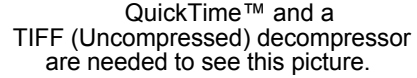




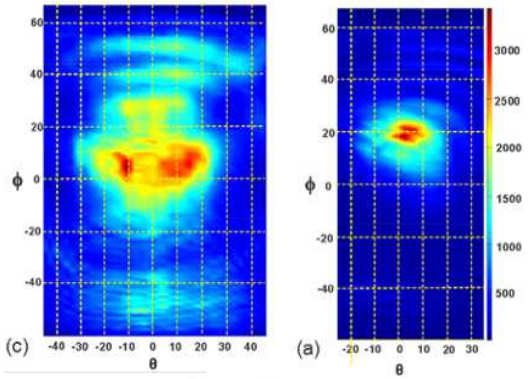
- Beam envelope close to Gaussian
- Fringes superposed on envelope
  - Rings of nulls in metal-metal
  - Rings of minima in plasmon
  - Decrease Gaussian content of beam
- Maximum coupling thru lens ~ 6%

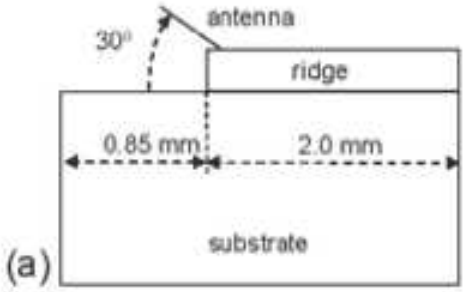
Horizontal angle (deg)

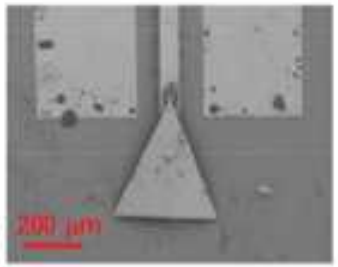
Metal-metal



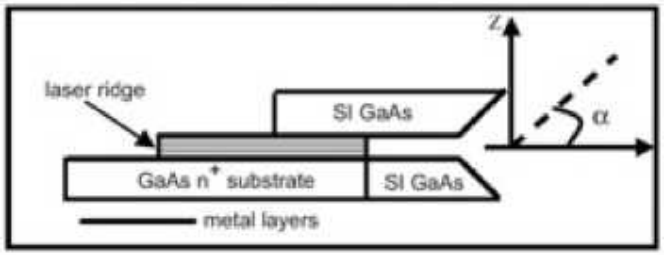
Attempts to fix the beam



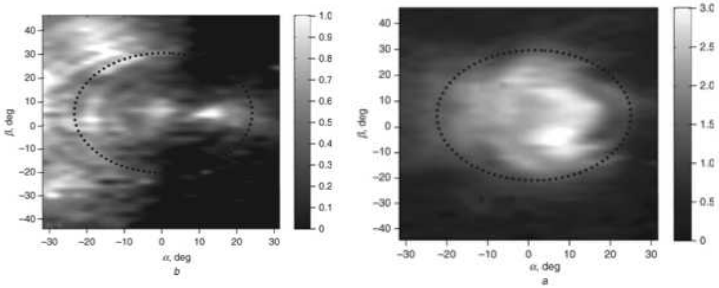


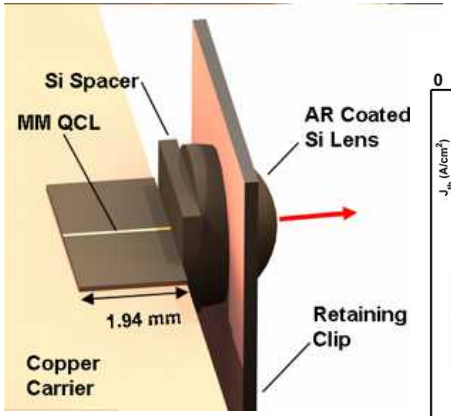


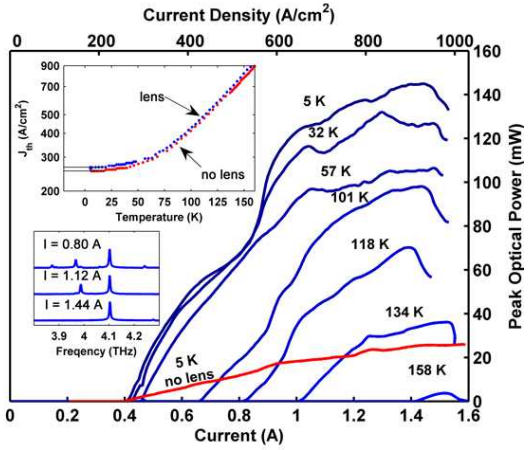
Barbieri, CLEO CWP4



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

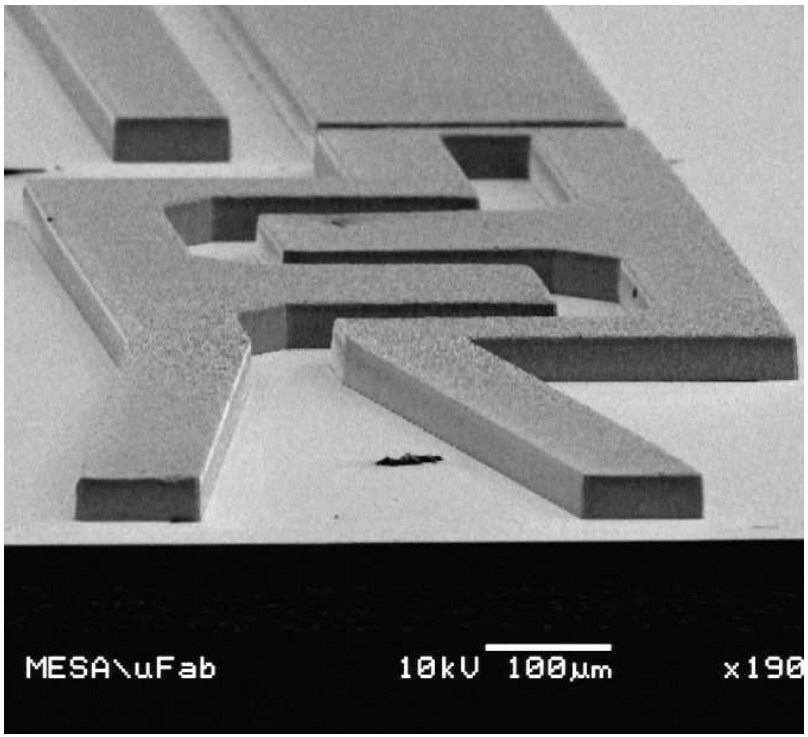


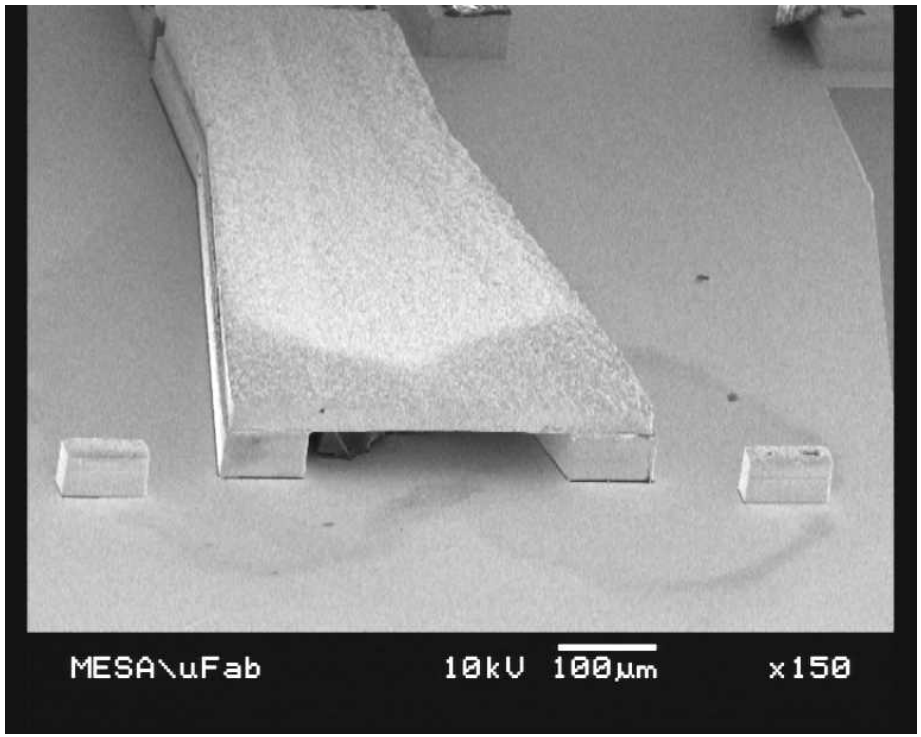




Lee, sub. APL, 2007

QCLs in Rectangular Waveguide





- LIGA process
- Gold walled rectangular waveguides

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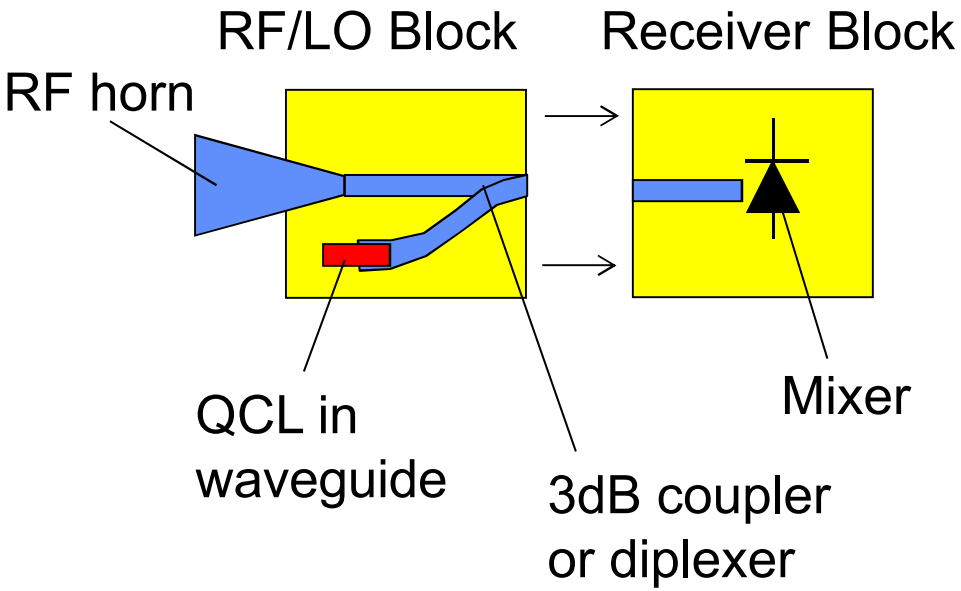
The future?



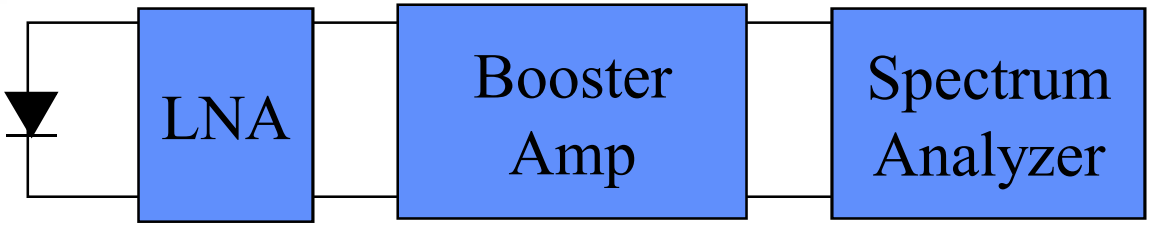
Possibly no free space beam required at all !

Summary & Future Directions

- **Using a planar Schottky receiver with THz QCLs**
  - **Divergent, non-Gaussian beam from QCL causes low coupling efficiency to receiver**
  - **Clearly observe QCL dual-mode mixing and mixing of QCL against known molecular gas FIRL lines**
  - **Good way to do high-frequency-resolution characterization of QCL emission**
- **Currently have insufficient QCL power to do noise temperature measurements**
  - **Schottky needs 5 to 6 mW coupled into receiver at 2.5 to 3 THz**
  - **Coupling losses of –7 dB from collimating divergent beam, –3 dB from beam splitter**
  - **Estimate need QCL with 50 to 60 mW total CW power output to properly pump Schottky**
- **Mode control is important for future work.**

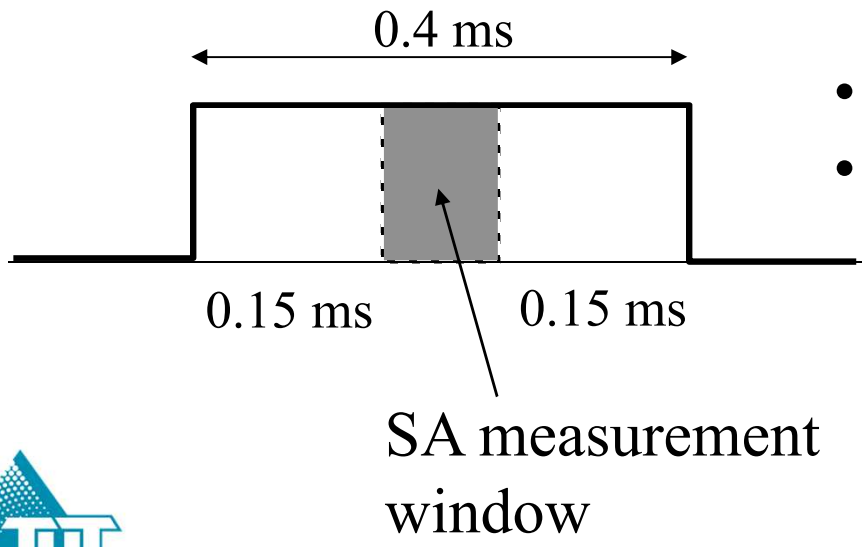
Thank You

Pulsed measurements



0.5 μA
0.69 V

- Measures spectrum in1 MHz BW during 0.1 ms
- Steps center frequency 1 MHz each pulse
- 20 ms period
- (601 points/ 12 sec) per scan



Motivation

- Schottky receiver of choice for many applications
  - – Room temperature operation (& coolable)
  - – Fast / wide IF bandwidth (> 20 GHz)
  - – Usefully low noise (T_N ~ 10,000 K)
  - – Needs 5 - 10 mW stable LO power
- "Zeroth order" integration: Replace FIRL with solid-state LO above ~ 2 THz
- THz QCLs only solid-state source capable of milliWatts CW power above 2 THz
- 2.5 THz QCL used successfully as LO for superconducting HEB mixer
  - – < 10 μW LO power [DLR group, Optics Exp. (2005)]
  - – < 1 μW LO power [Delft group, APL (2005)]
- *QCL LO for Schottky is much more difficult*

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Goal :Compact THz Receiver