External Modulation of Terahertz Quantum Cascade Lasers Using Metamaterials

SAND2008-6974C

I. Brener,[1] X. G. Peralta,[1] W. J. Padilla,[2] E. W. Young,[1] A. J. Hoffman,[3] M. J. Cich,[1] R. D. Averitt,[4] M. C. Wanke,[1] J. B. Wright,[1] H.-T. Chen,[5] J. F. O'Hara,[5] A. J. Taylor,[5] J. Waldman,[6] W. D. Goodhue,[6] J. Li[6]

[1]CINT, Sandia National Laboratories
[2]Boston University
[3]Princeton University
[4]Boston College
[5]MPA-CINT, Los Alamos National Laboratory
[6]University of Massachusetts Lowell

October 22, 2008.

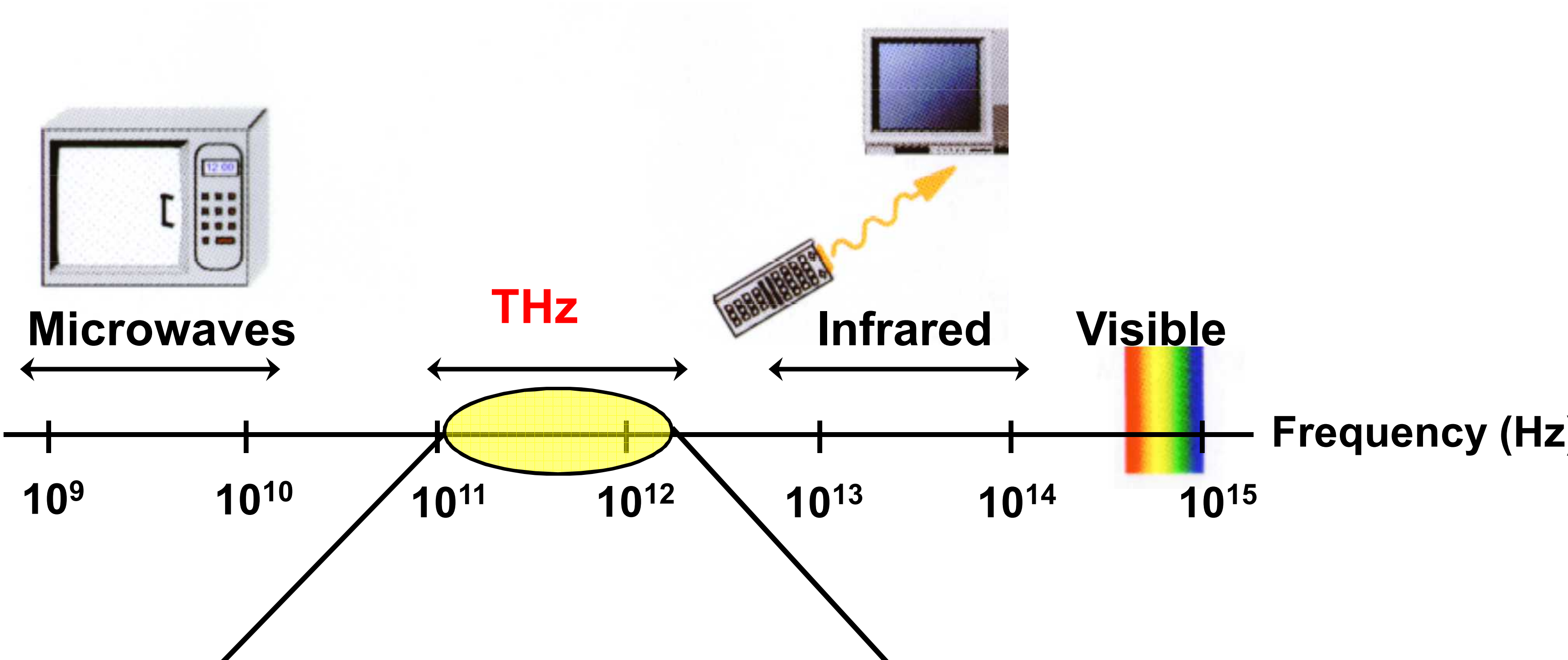
IC Postdoctoral Research Fellowship Program

Research Institutes · National Laboratories · Universities

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US DOE's NNSA under Contract DE-AC04-94AL85000. Los Alamos National Laboratory is operated by Los Alamos National Security, LLC, for the NNSA of the US DOE under contract DE-AC52-06NA25396.

Sandia National Laboratories

The terahertz region



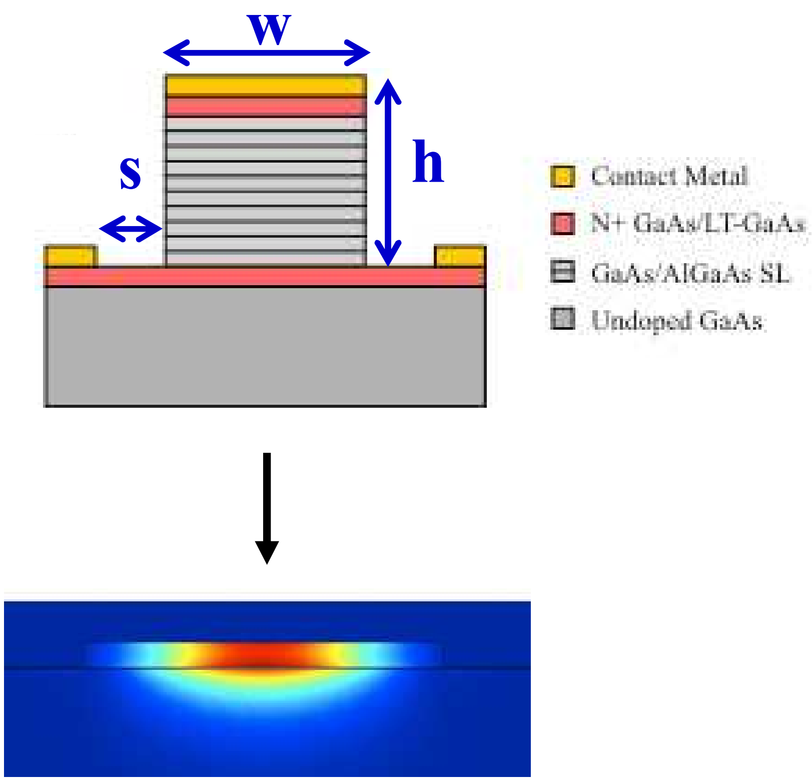
Narrowband THz sources

- Free electron lasers
- Molecular gas lasers
- Quantum cascade lasers

ν = 1 THz; λ = 300μm; wave number = 33cm^{-1}; energy = 4meV

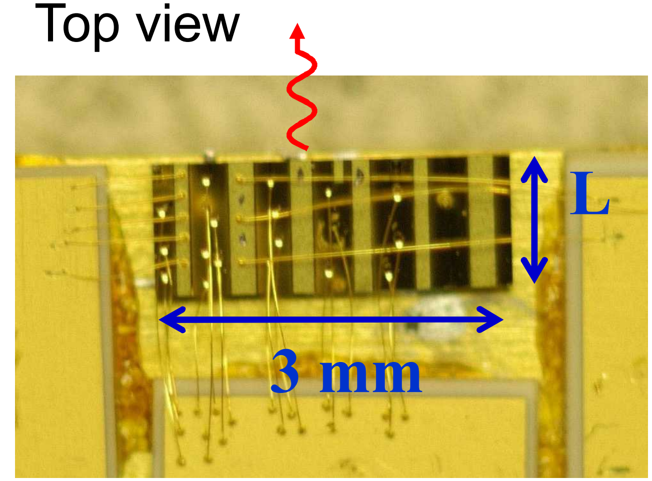
Overview of plasmon waveguide THz quantum cascade lasers (QCL)

Side view



Demichel, *Opt. Exp.*, **14**, 5335, 2006

Top view



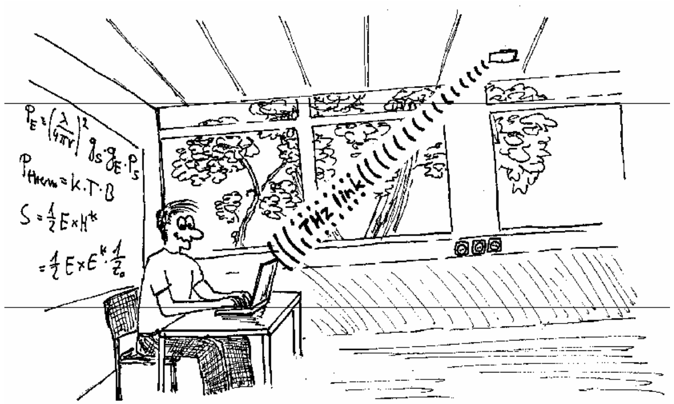
6 QCLs integrated on chip

QCLs provided by UMass Lowell and processed at SNL.

Sandia National Laboratories

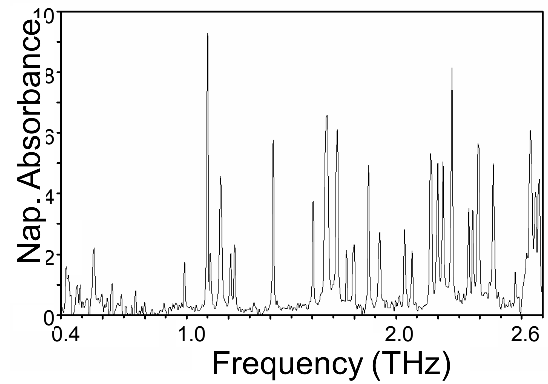
Emerging applications of THz QCLs

Communications



www.cpmoh.cnrs.fr/html/UserFiles/File/Bombannes/Frankreich-Koch.pdf

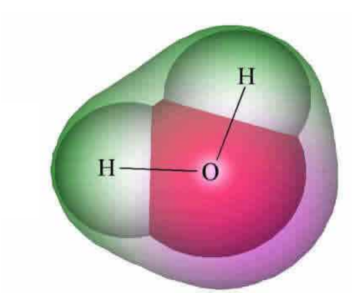
Spectroscopy



R. J. Foltynowicz, Sandia report 2005-5709.

Sensing

Chemical



Biological

Imaging

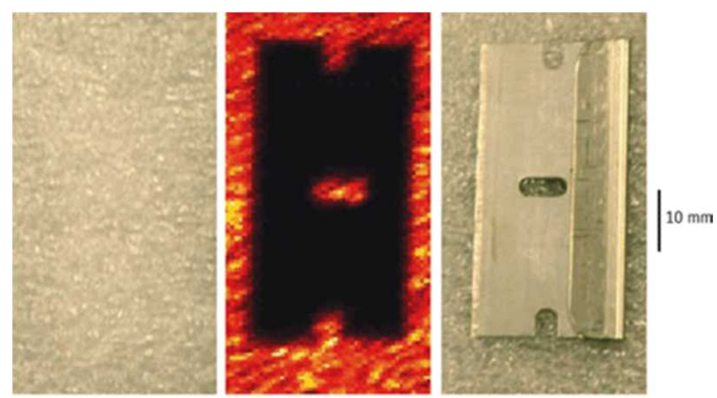
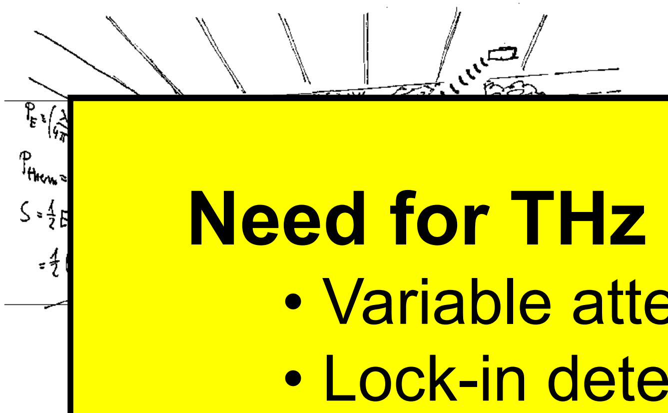


Image taken by I. Brener at SNL.

Emerging applications of THz quantum cascade lasers

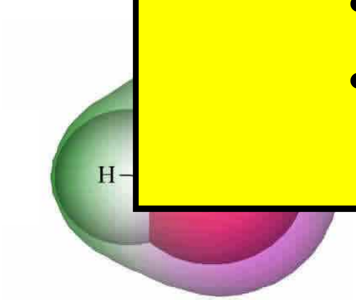
Communications



www.cpmoh.c

Spectroscopy

Ch



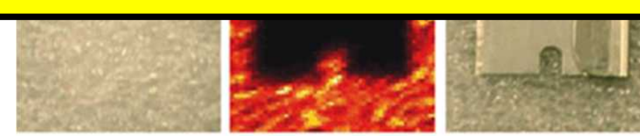
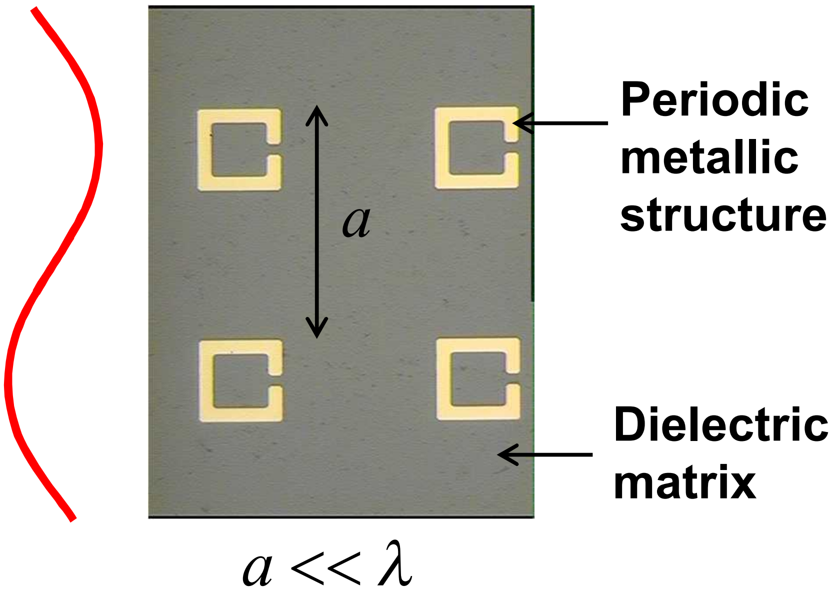


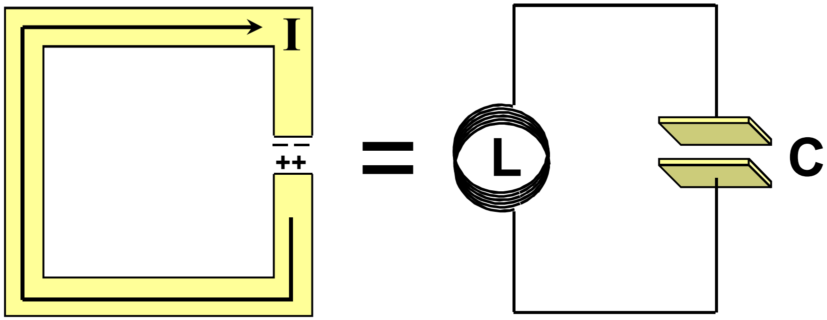
Image taken by I. Brener at SNL.

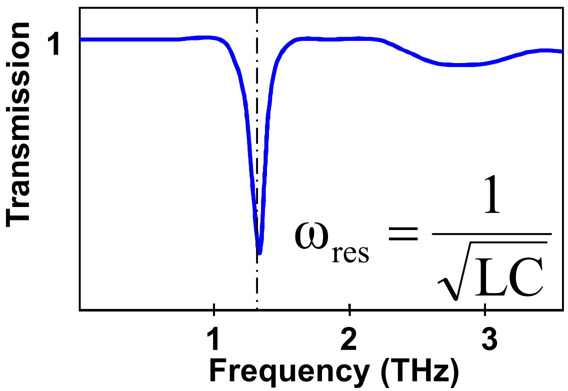
Need for THz modulators

- Variable attenuators
- Lock-in detection at high frequencies for high resolution spectroscopy
- Pulse picking applications
- Active mode locking
- Sideband generation

Active metamaterials can be used as THz modulators



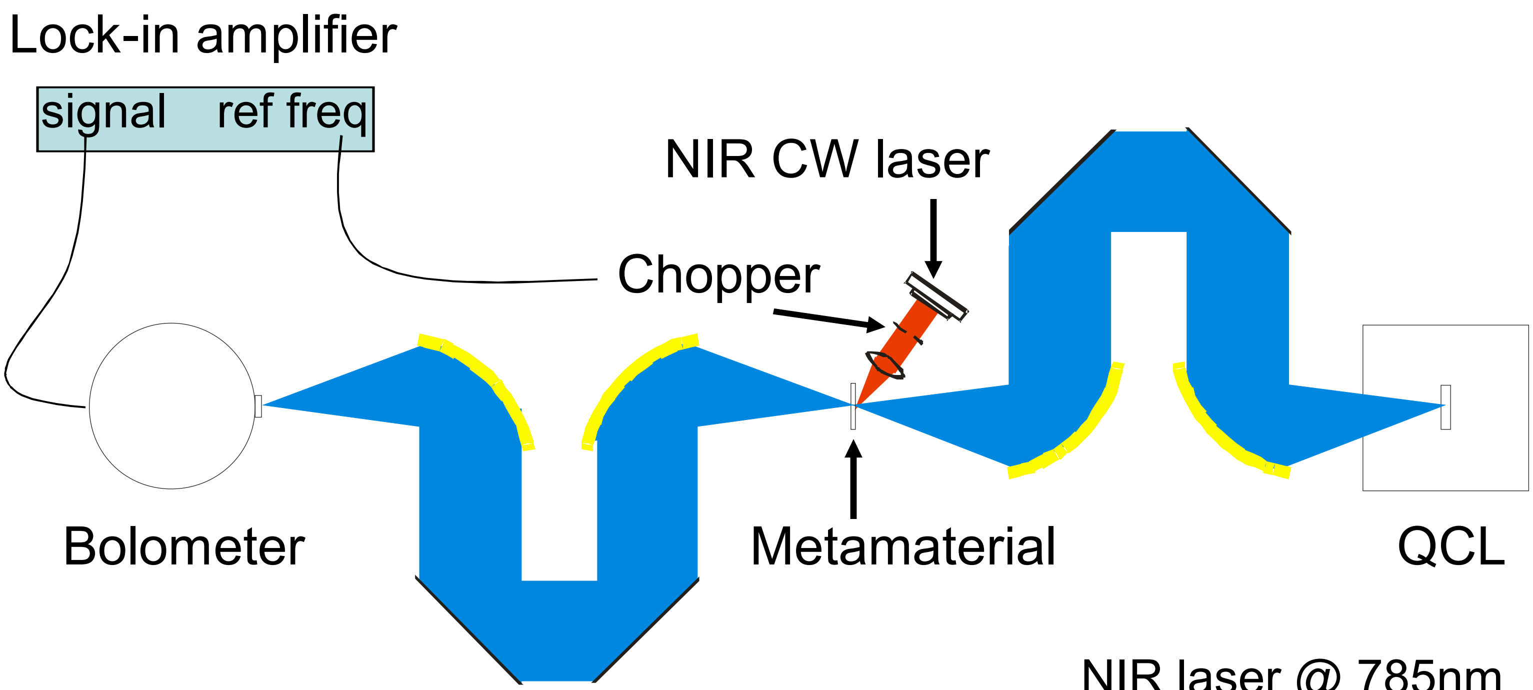




The individual units are designed to have specific electromagnetic properties.

Sandia National Laboratories

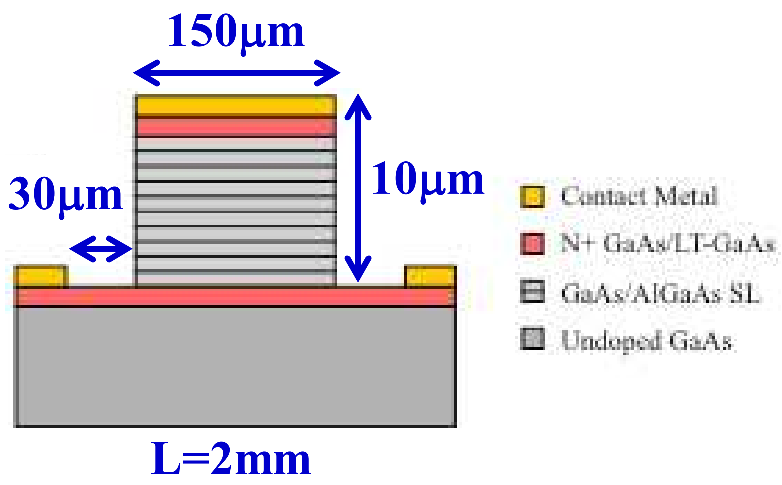
Scheme for optical modulation

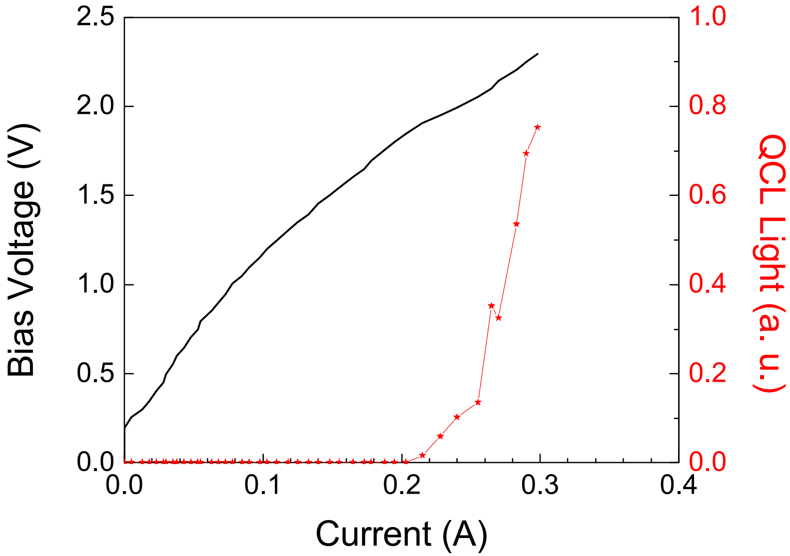


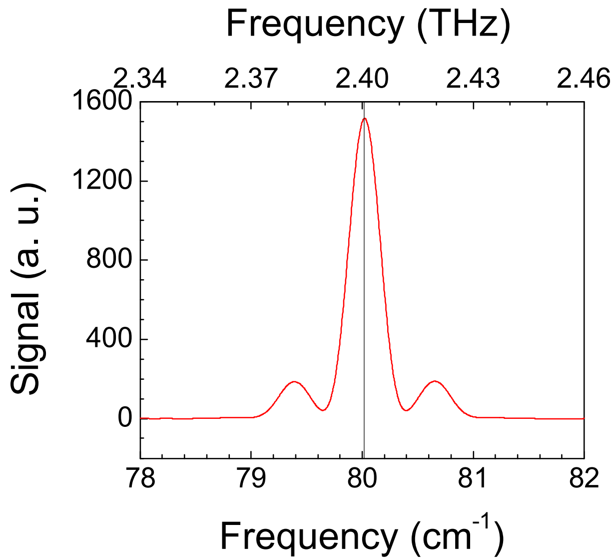
NIR laser @ 785nm
Liquid He cooled Si bolometer

NIR laser → ↑N_e photocarriers → shorts gap → ↑T

Characteristics of the 2.4THz QCL

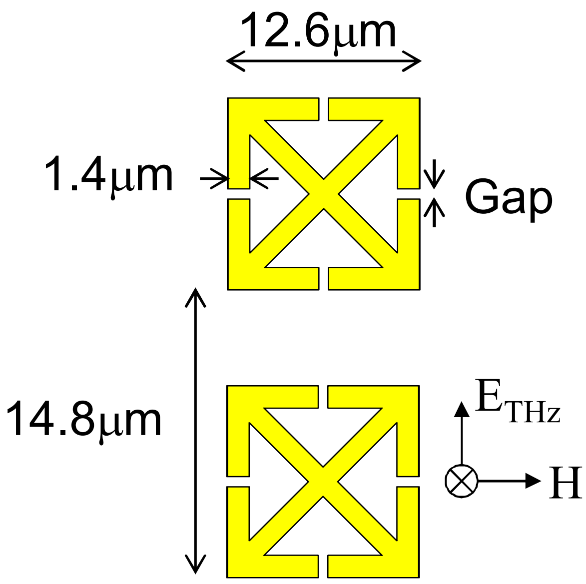




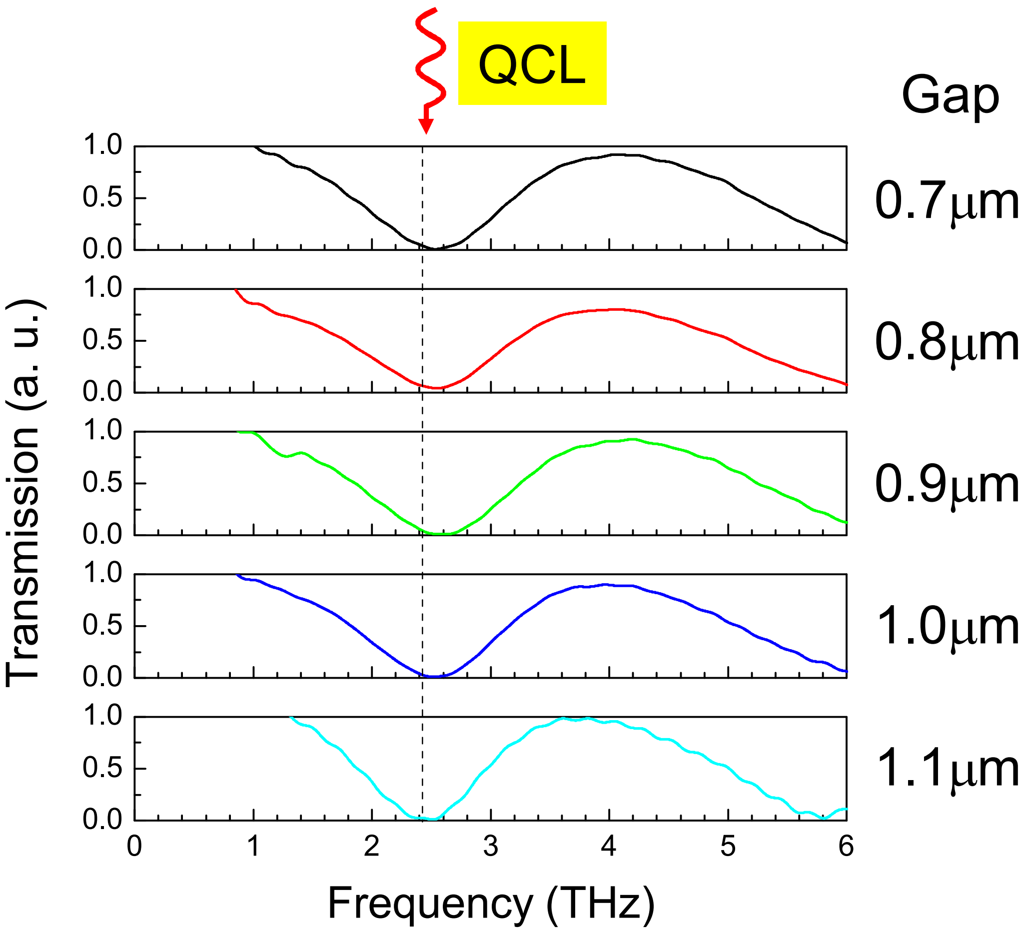


T = 4.4K
Bias V = 2.22V
I = 290 mA

Gap size dependence of E2 metamaterial transmission spectra



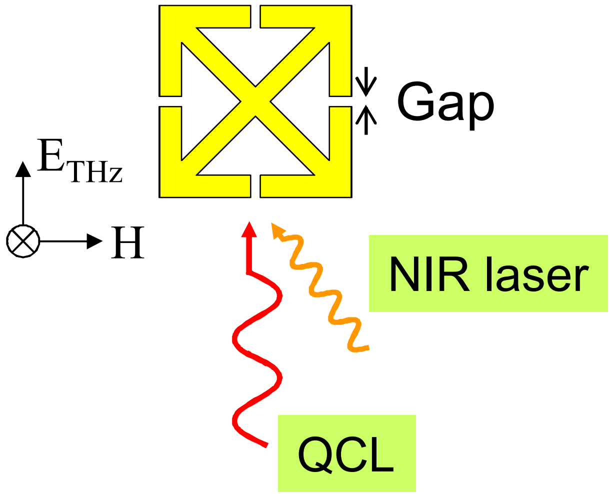
Substrate SI-GaAs
Ti 100Å, Au 2000Å

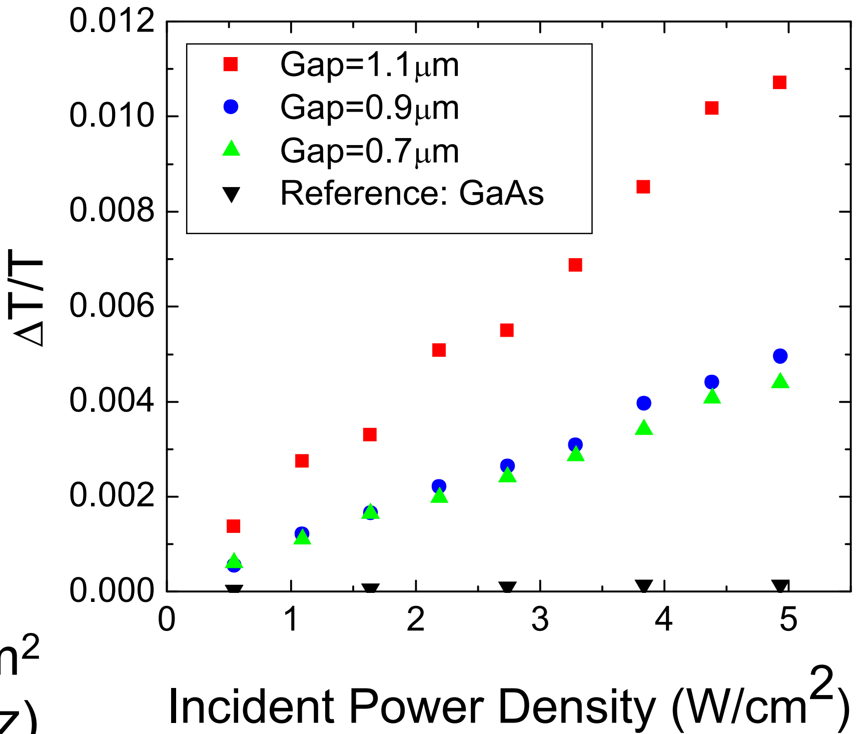


CHECK Ne

Reference SI-GaAs substrate

Optical modulation of a 2.4THz QCL using E2 metamaterials of varying gap sizes

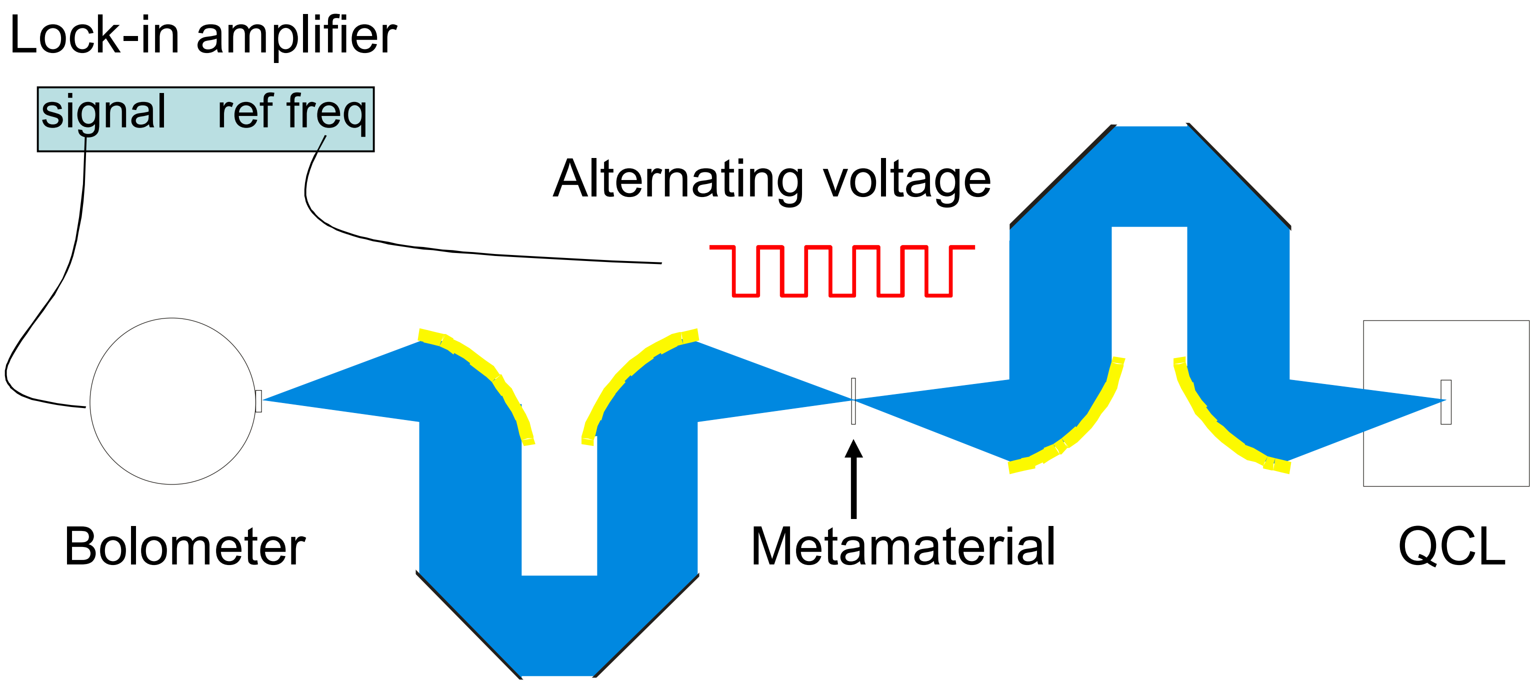


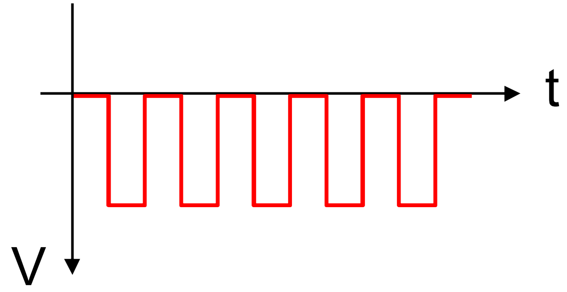


Max. power density of 4.93 W/cm^2 gives $N_e \sim 10^{14}$ cm^{-3} ($\omega_p \sim$ 0.3THz)

Change the substrate to increase N_e and reduce carrier lifetime to improve the modulation depth.

Scheme for electrical modulation

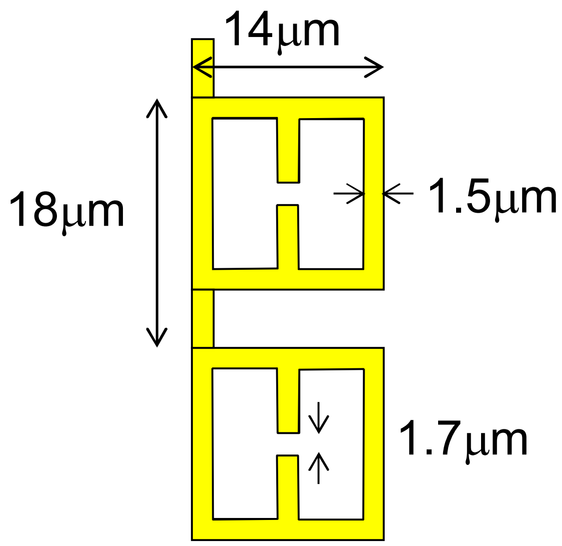


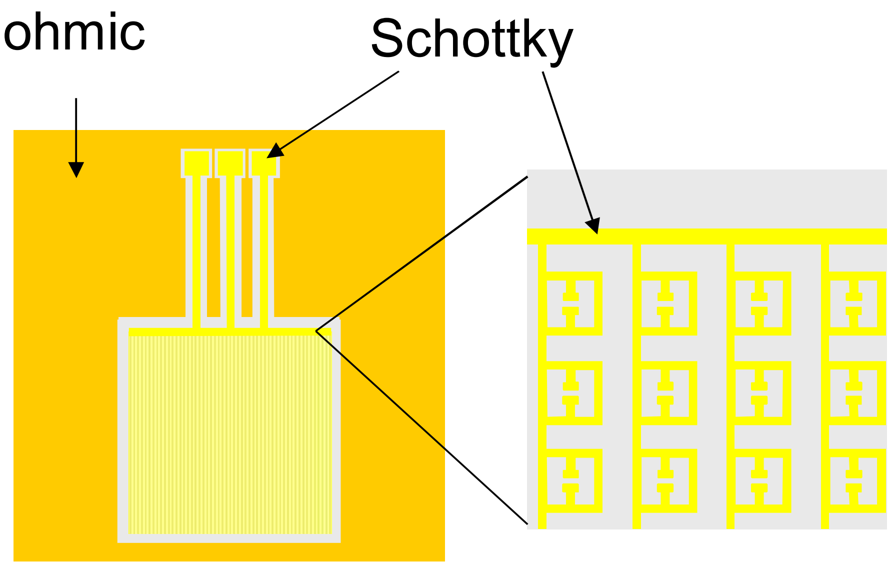


Apply $-V_{gate}$ → ↓N_e → reduces conductivity near the gap → ↓T

Sandia National Laboratories

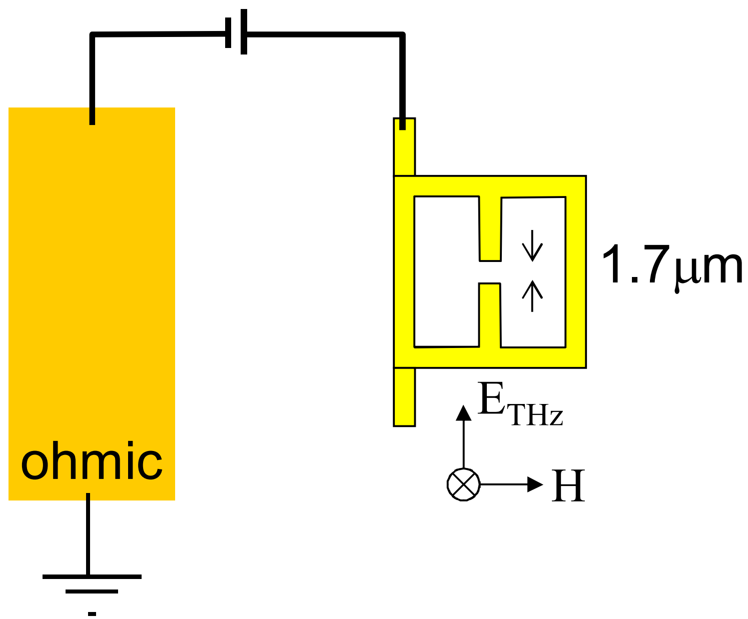
Metamaterial design for electrical modulation



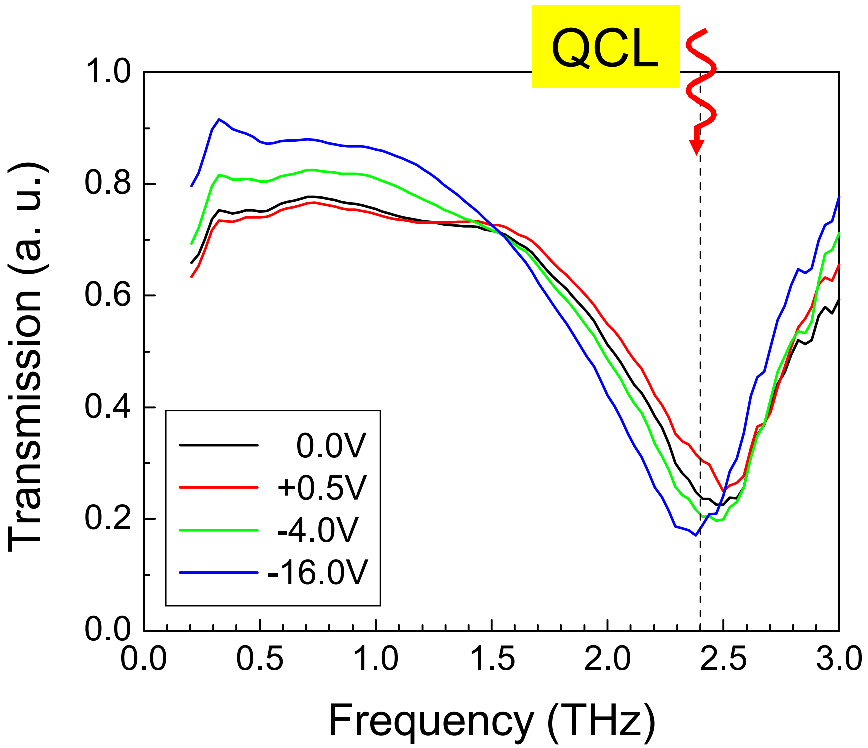


Substrate SI-GaAs
$N_e = 2 \times 10^{16}\ cm^{-3}$
Gate: Ti 100Å, Au 2000Å
Ohmic: Ge 260Å, Au 540Å, Ni 150Å, Au 2000Å

Gate bias dependence of 1.7μm gap E4 metamaterial transmission spectra

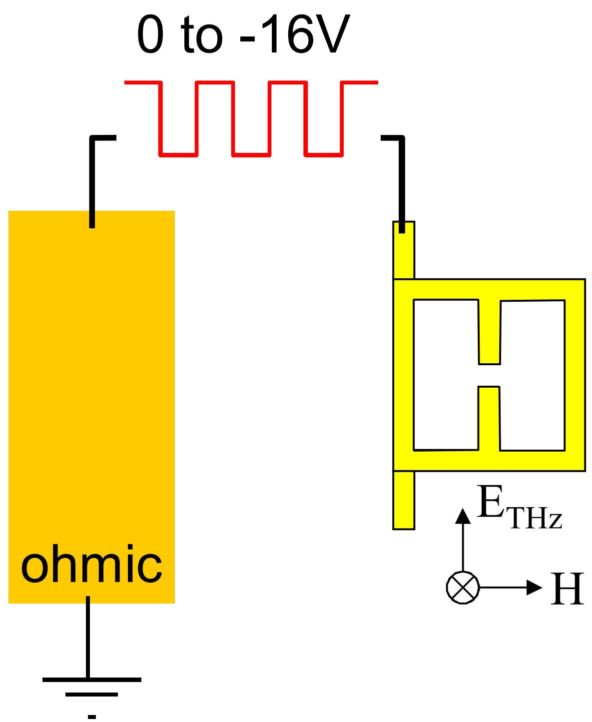


Applied constant gate voltage.

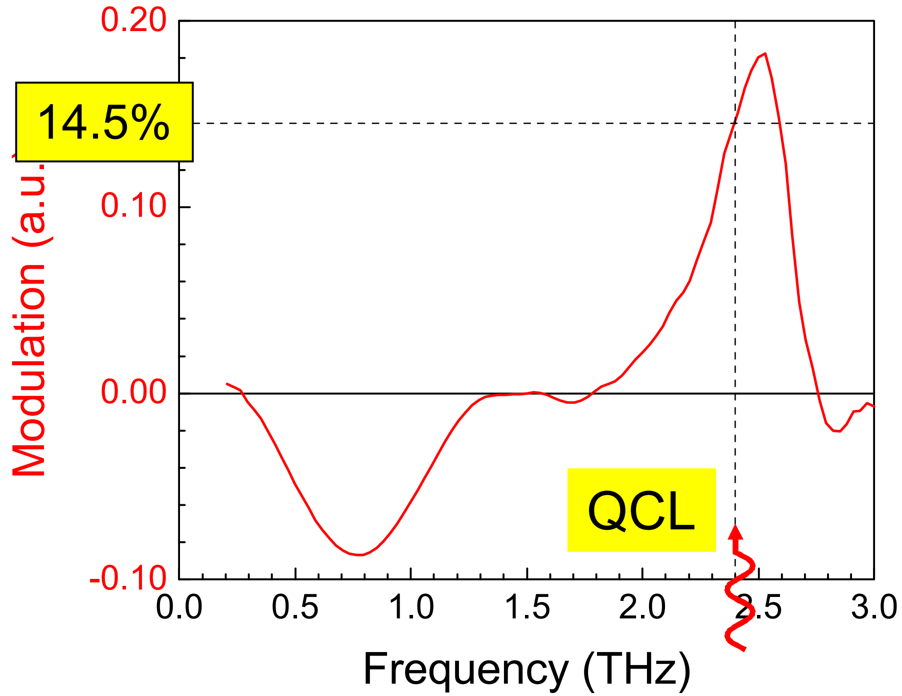


Reference SI-GaAs substrate

Electrical modulation of the metamaterial transmission measured using THz-TDS

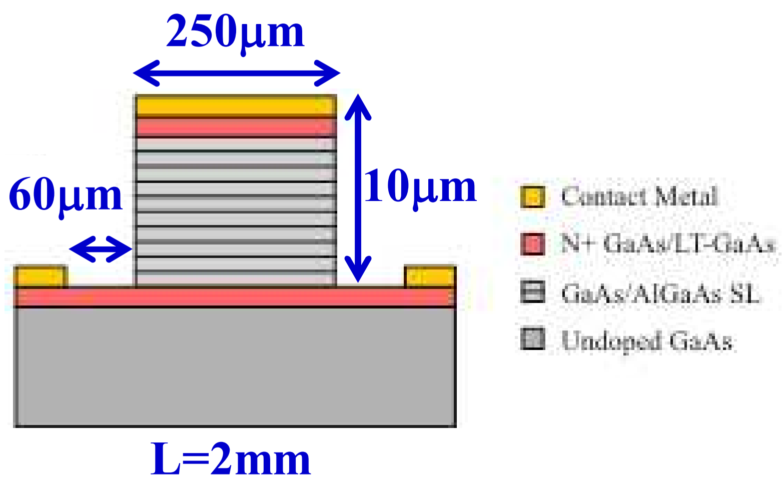


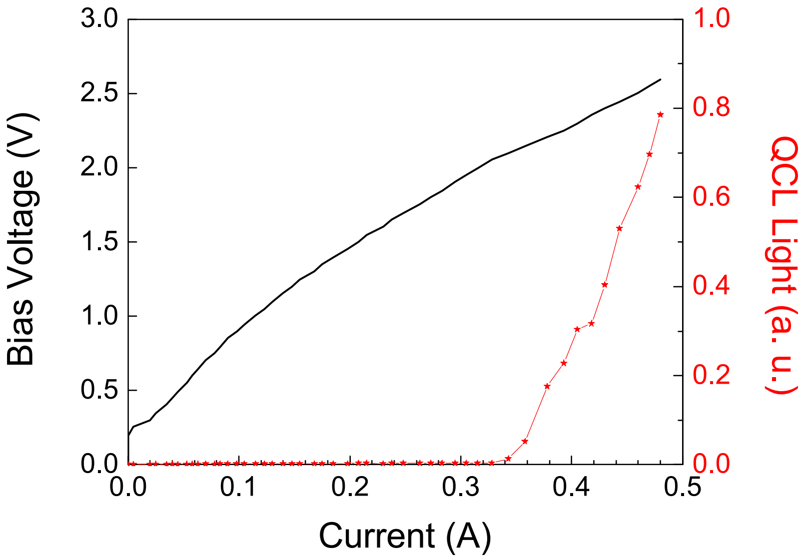
Applied alternating gate voltage.

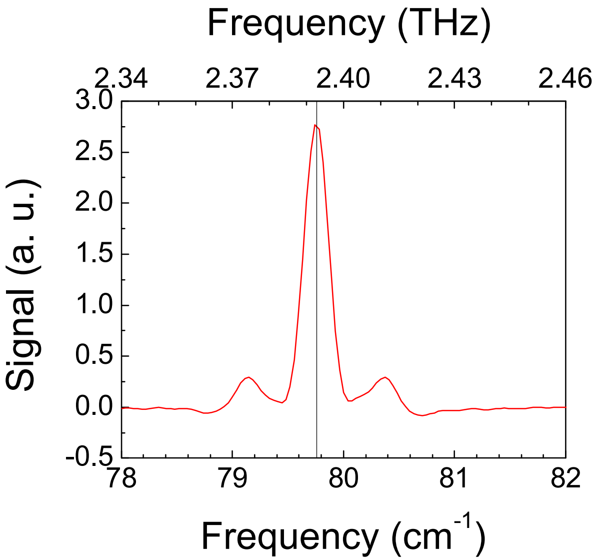


Reference metamaterial @ 0V

Characteristics of the 2.39THz QCL



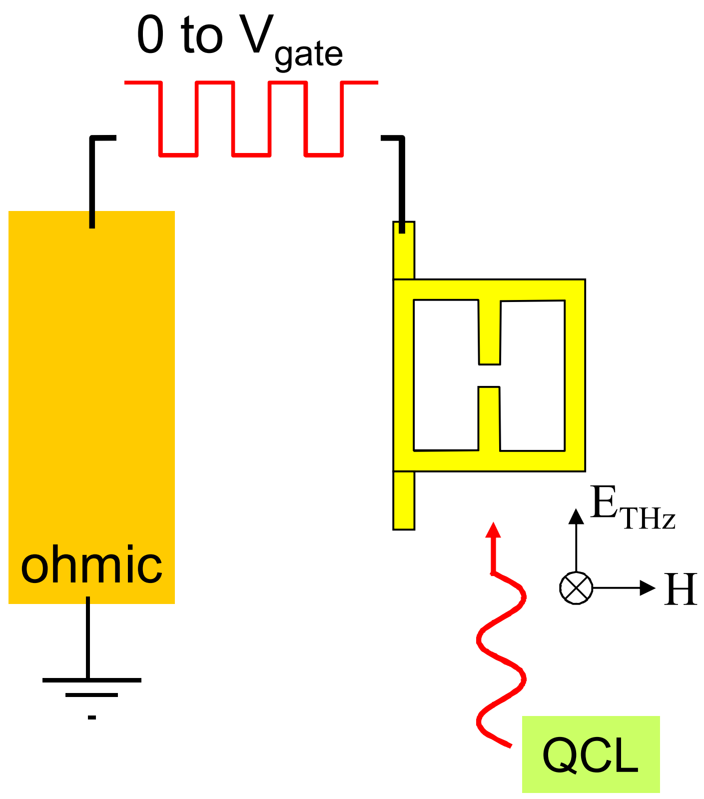


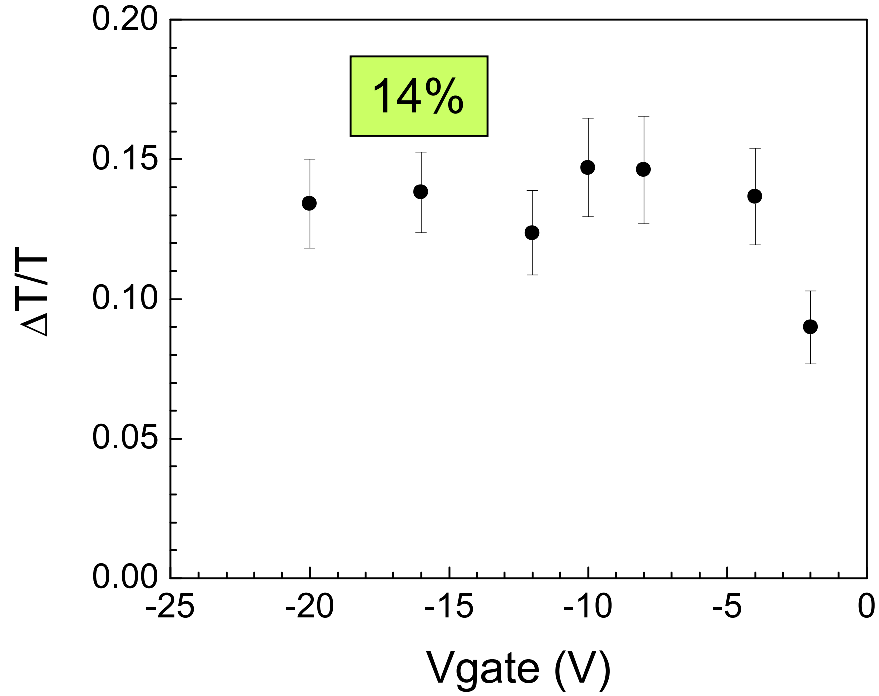


T = 4.4K
Bias V = 2.6V
I = 460 mA

Sandia National Laboratories

Electrical modulation of a 2.39THz QCL with a 1.7μm gap E4 metamaterial



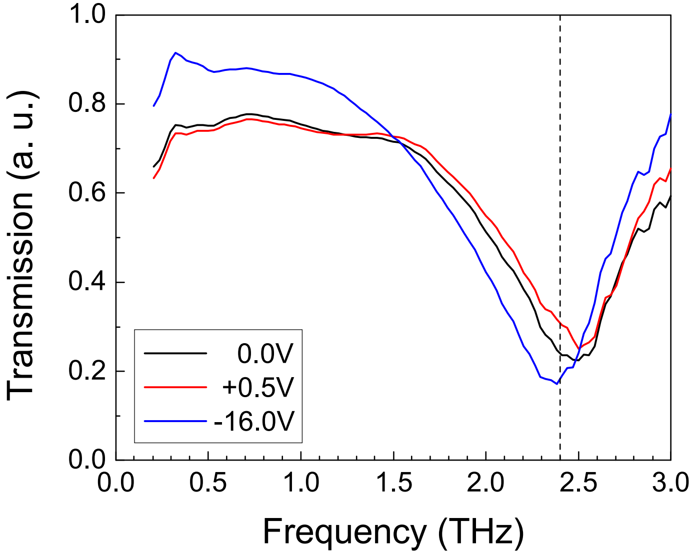


Estimated modulation speed is $f_c=(2\pi RC)^{-1}$ = 2.5MHz.

Sandia National Laboratories

Can improve the performance by biasing between +0.5V and -16V

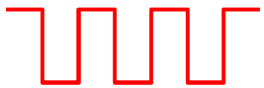
V_{gate} constant



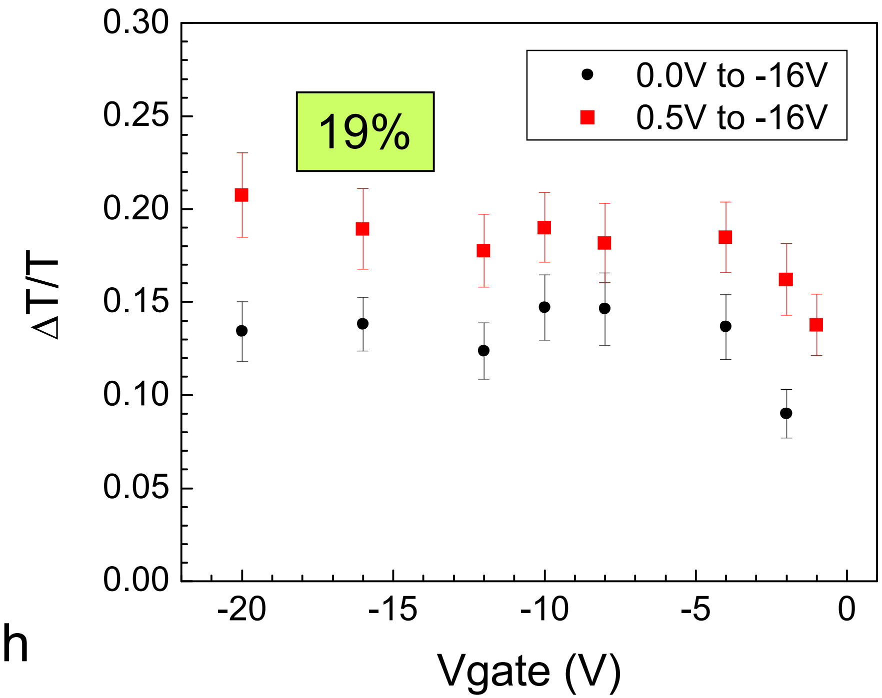
Reference SI-GaAs substrate

Initial $N_e = 2 \times 10^{16}$ cm^{-3} ($\omega_p \sim 1.34$THz) is not high enough to efficiently short circuit the gap.

+0.5V to V_{gate}



$+V_{gate} \rightarrow \uparrow N_e \rightarrow \uparrow$modulation depth

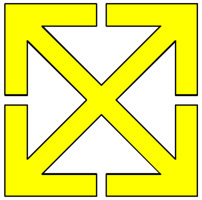


Summary and potential improvements

Accomplishments

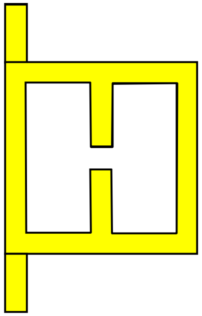
Optical Modulation at 2.4THz

– Modulation depth of 1%



Electrical Modulation at 2.39THz

– Modulation depth of 19%



Improvements

– Change the substrate to increase N_e

– Change the substrate to reduce carrier lifetime

– Increase N_e (minimum to 7×10^{16} cm^3, then $\omega_p \sim 2.5$THz)

– Reduce area to increase modulation speed

Acknowledgements

- Sandia LDRD Program
- LANL LDRD program
- IC Postdoctoral Fellowship Program
- CINT

IC Postdoctoral Research Fellowship Program

Research Institutes • National Laboratories • Universities

Sandia National Laboratories