Terahertz quantum cascade lasers: recent progress and future challenges

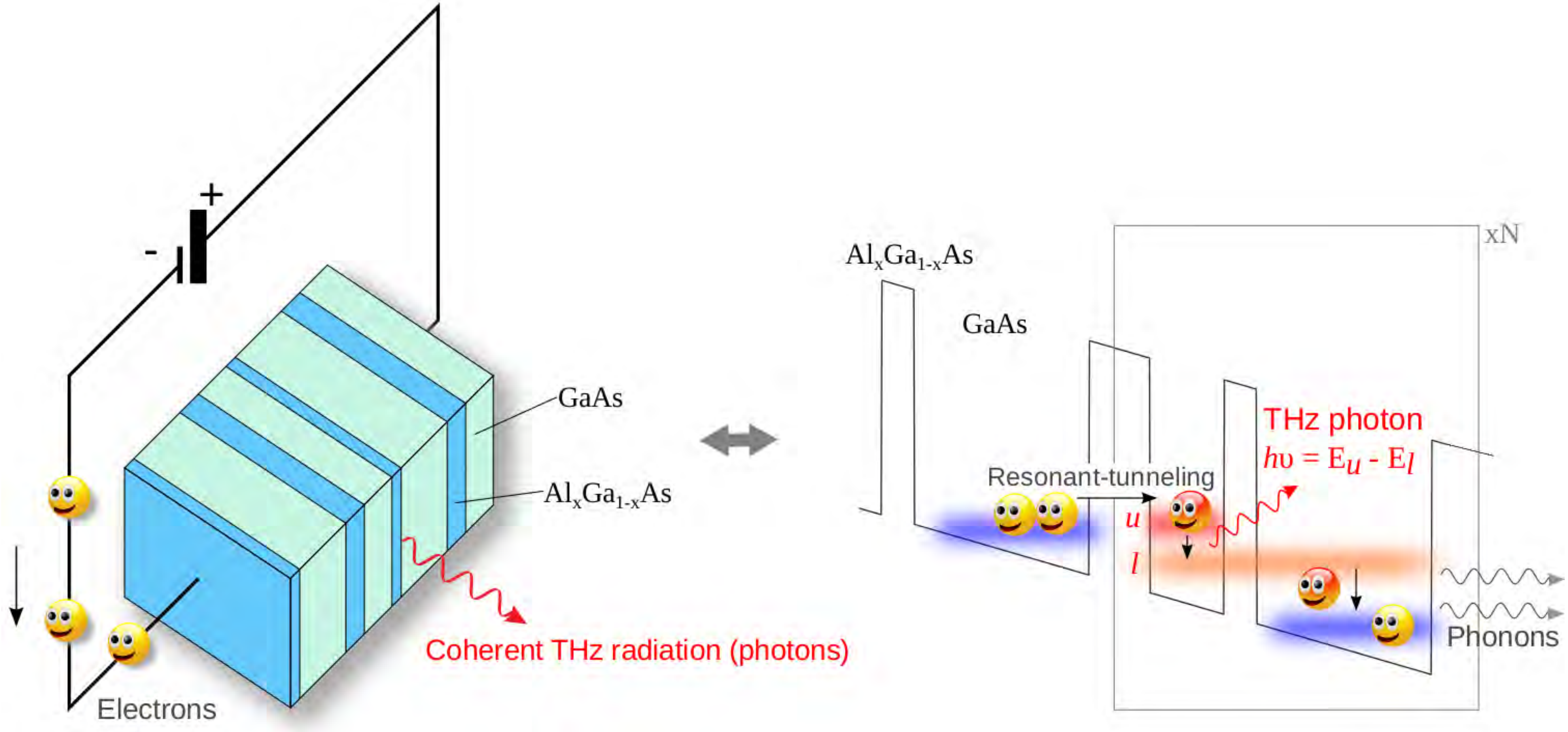
Sushil Kumar

Center for Photonics and Nanoelectronics
Department of Electrical and Computer Engineering
Lehigh University, USA

Outline

- Introduction
- THz Intersubband gain in superlattices
- THz QCL active regions and their performance
- Gain degradation at high temperatures
- Outlook for future

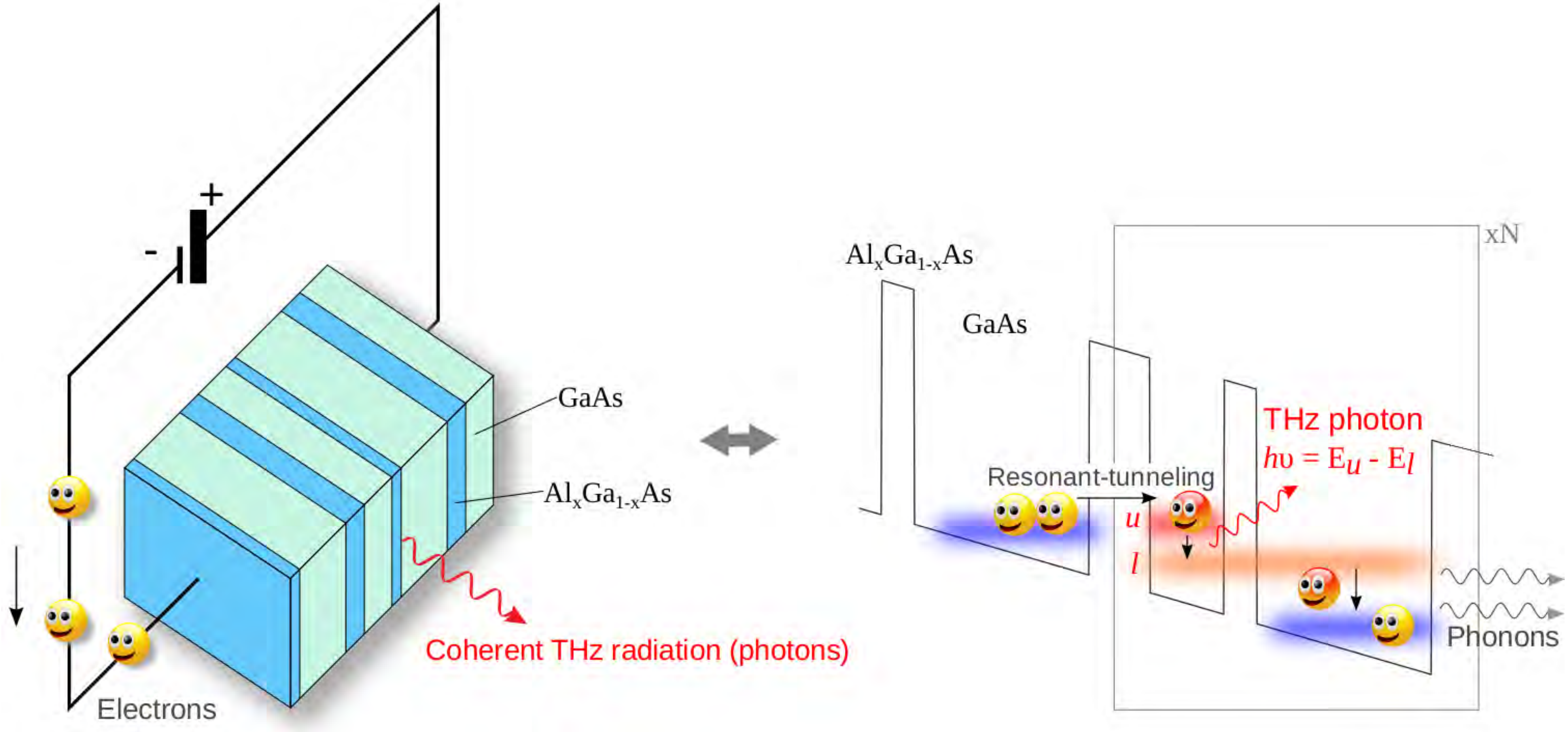
THz QCLs: active region



- Intersubband spontaneous emission is extremely inefficient: $\tau_{ul,\mathrm{rad}} \sim 10\ \mu\mathrm{s}$

$$\tau_{ul,\mathrm{non-rad}} \sim 10\ \mathrm{ps}$$

THz QCLs: active region

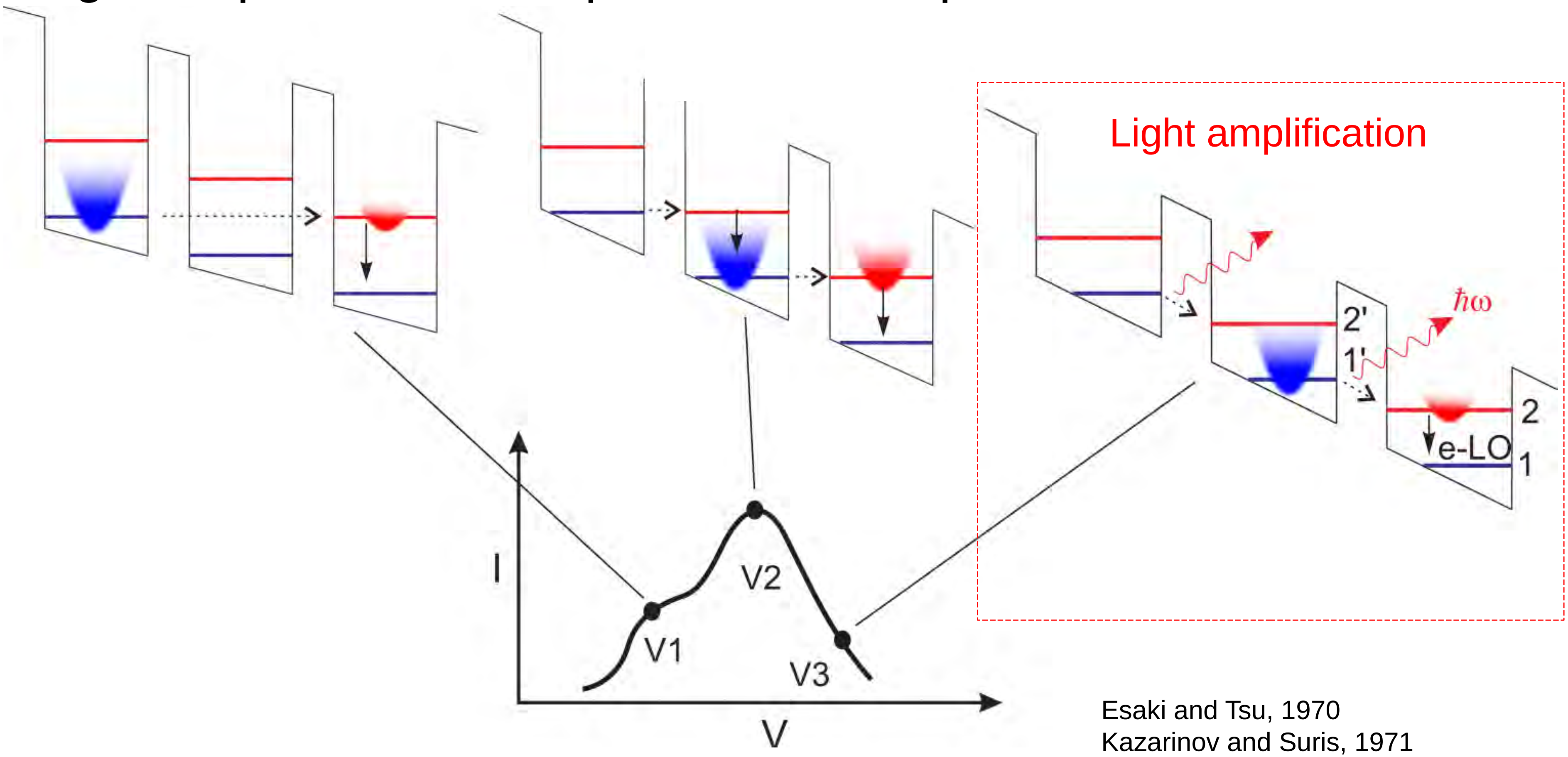


- Intersubband spontaneous emission is extremely inefficient: $\tau_{ul,\mathrm{rad}} \sim 10\ \mu\mathrm{s}$

  $\tau_{ul,\mathrm{non-rad}} \sim 10\ \mathrm{ps}$

- Need intersubband amplification for usable optical power: $\Delta n_{ul} \equiv n_u - n_l > 0$ (population inversion)

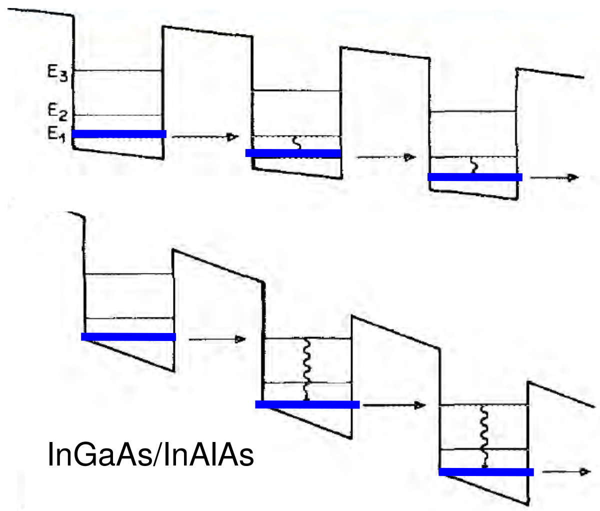
Light amplification in superlattices: Proposed in 1971

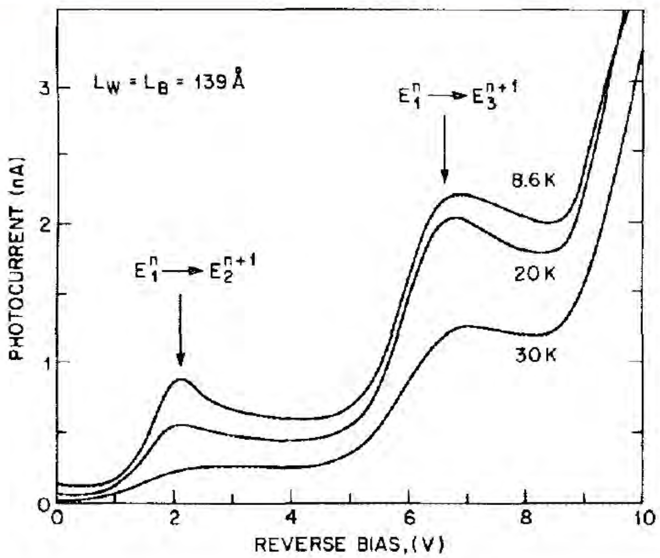


Esaki and Tsu, 1970
Kazarinov and Suris, 1971

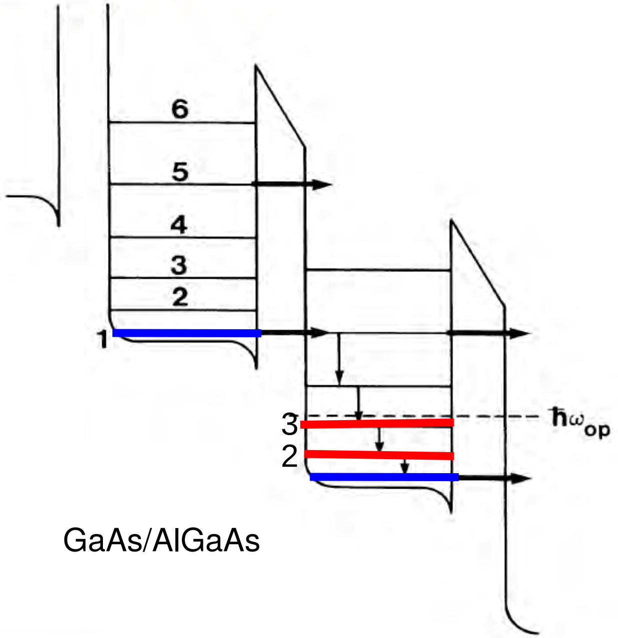
- Population inversion occurs in the negative differential resistance (NDR) region.
- Uniform bias cannot be maintained in a superlattice when biased in the NDR region.

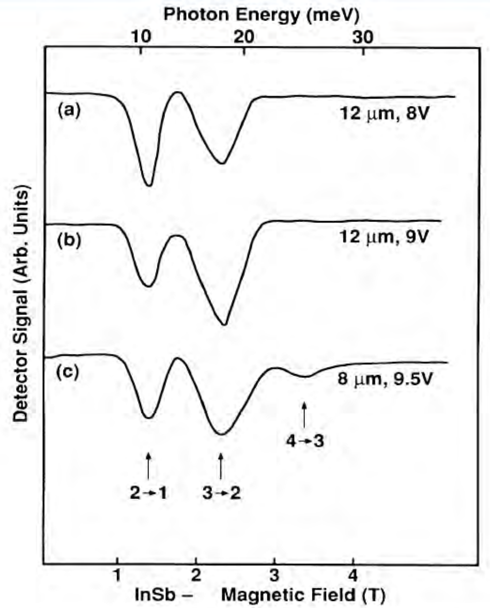
Use of resonant-tunneling to populate high energy subbands





Capasso *et al.*, APL (1986) – first demonstration of sequential resonant-tunneling in superlattices



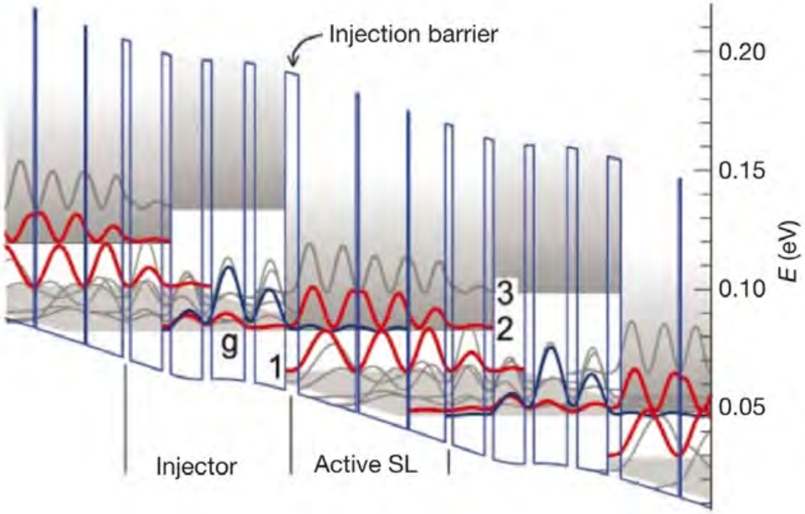


Helm *et al.*, PRL (1989) – first observation of intersubband (THz) light emission in superlattices

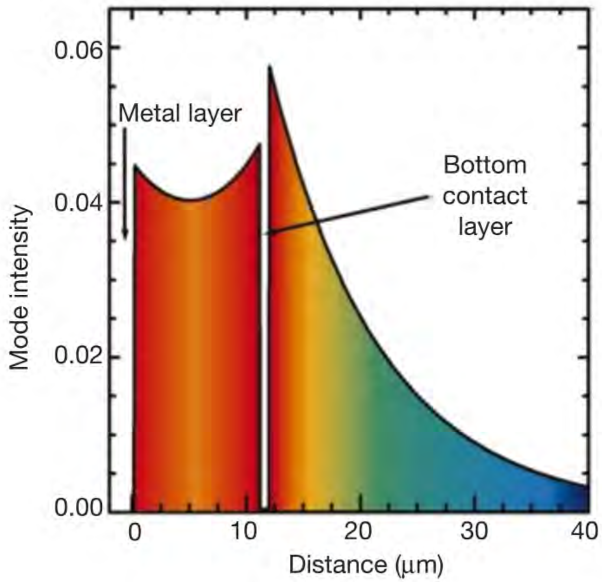
First THz QCL

Chirped-superlattice design

E_{21}~18 meV (4.4 THz)

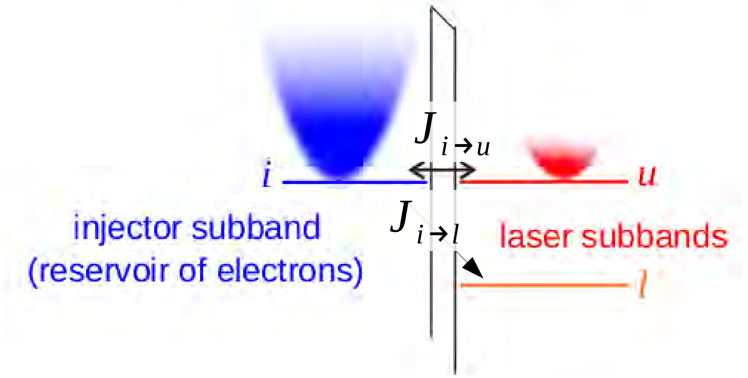


Semi-insulating surface-plasmon waveguide



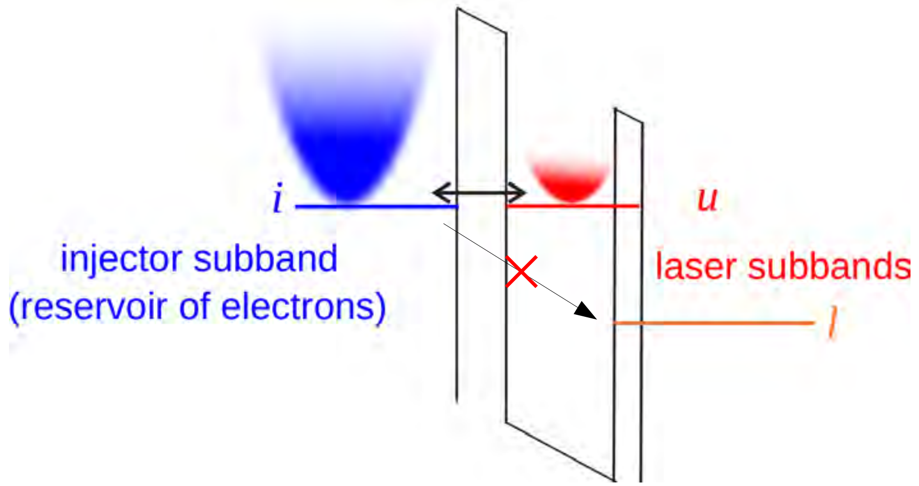
Köhler *et al.* Nature (2002)

THz intersubband gain: design considerations



- Population inversion density: $$\Delta n_{ul} \propto J_{i\to u}\left(1-\frac{\tau_l}{\tau_{ul}}\right)\tau_u$$
- Gain: $$g \propto \frac{\Delta n_{ul}\cdot f_{ul}}{\Delta\nu}$$
- Design requirements
  - $\tau_{ul} > \tau_l$
  - $J_{i\to l} << J_{i\to u}$
  - NDR shoud not occur prior to bias voltage required for $i\to u$ alignment

THz QCL design considerations: diagonal radiative transition



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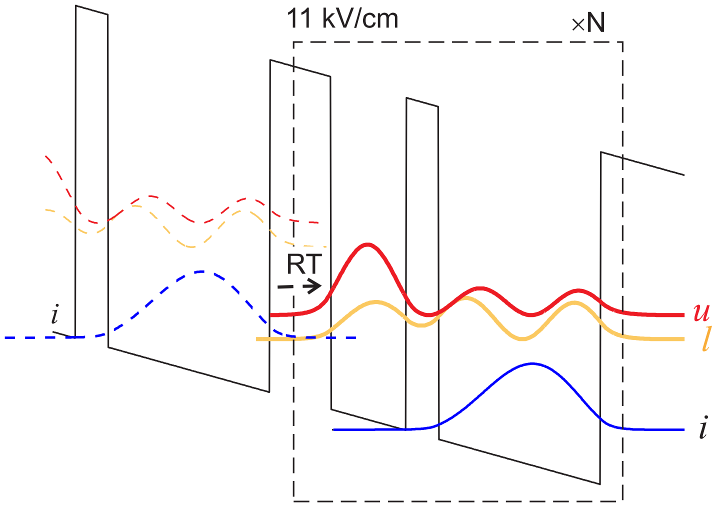
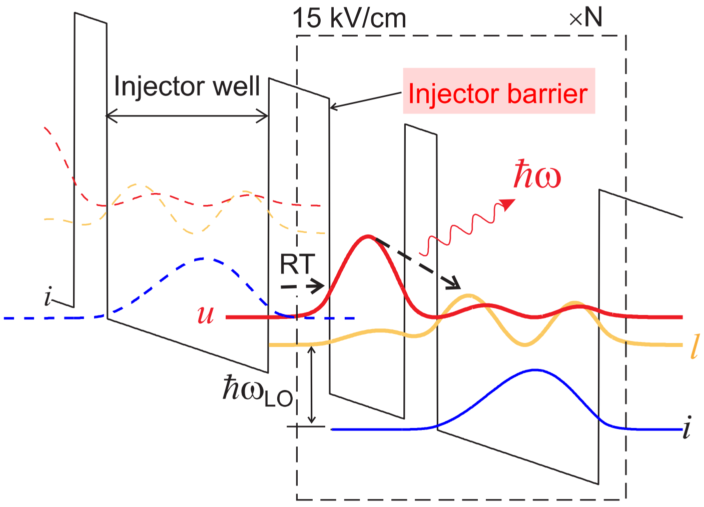
THz QCL design considerations



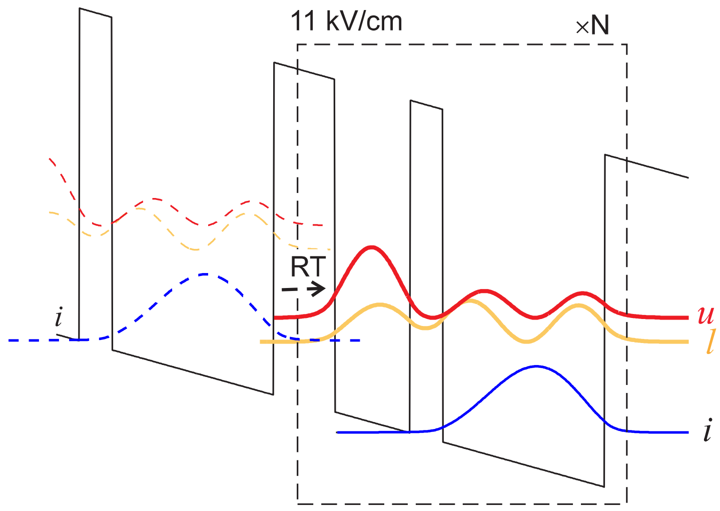


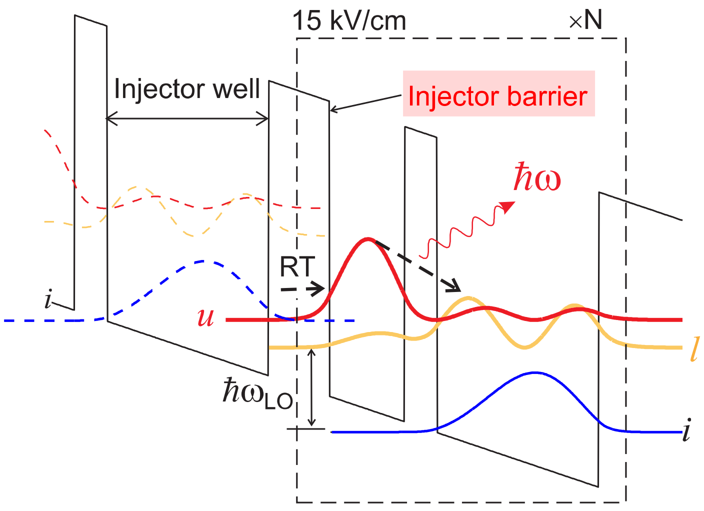
- Low-bias, $i \rightarrow l$ alignment
- Design-bias, $i \rightarrow u$ alignment

Requirement:

$$J_{i\rightarrow l} \propto \frac{1}{\tau_l}\left(1-\frac{1}{4\Omega_{il}^2\tau^*\tau_l+1}\right) < J_{i\rightarrow u} \propto \frac{1}{\tau_u}\left(1-\frac{1}{4\Omega_{iu}^2\tau^*\tau_u+1}\right)$$

THz QCL design considerations: thick injector barrier





- Low-bias, $i \rightarrow l$ alignment
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Requirement:

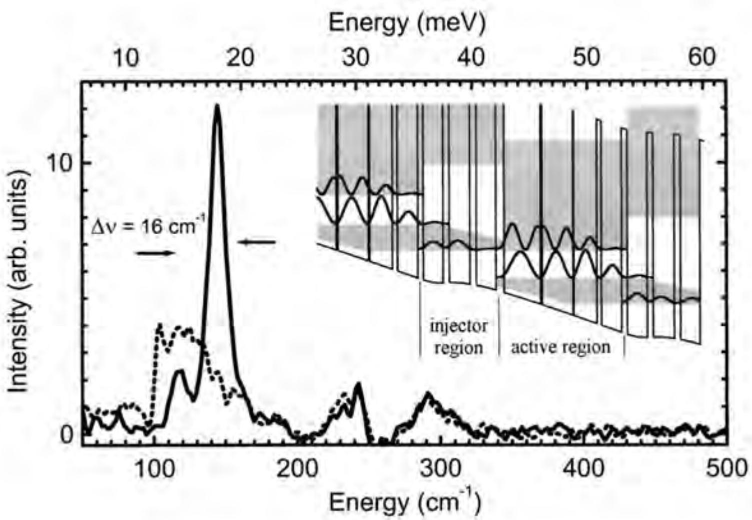
$$J_{i\rightarrow l} \propto \frac{1}{\tau_l}\left(1-\frac{1}{\underline{4\Omega_{il}^2\tau^*\tau_l}+1}\right) < J_{i\rightarrow u} \propto \frac{1}{\tau_u}\left(1-\frac{1}{\underline{4\Omega_{iu}^2\tau^*\tau_u}+1}\right)$$

<<1 ~1 or larger

Thicker barrier reduces coupling term Ω

Early THz QCL designs

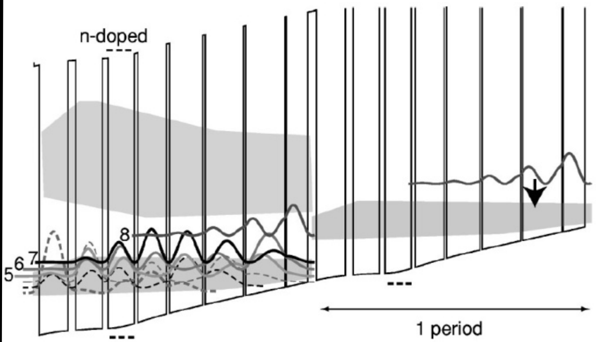
Chirped-superlattice



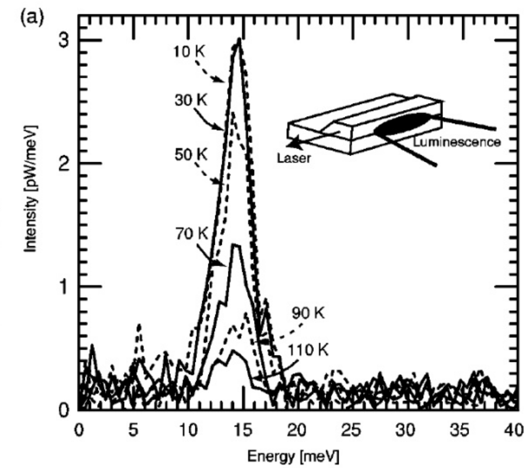
$\Delta\nu \approx 0.5\,\mathrm{THz}$

Köhler *et al.* APL (2002)

Bound-to-continuum

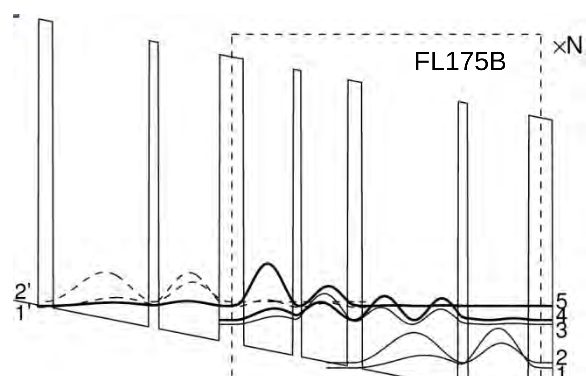


Scalari *et al.* APL (2003)



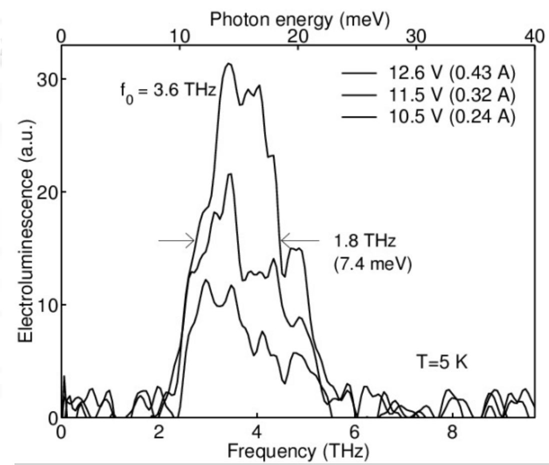
$\Delta\nu \approx 0.8\,\mathrm{THz}$

Resonant-phonon
(resonant-tunneling assisted depopulation)



Williams *Ph.D. Dissertation* (2003)

Williams *et al.* APL (2003)



$\Delta\nu \approx 1.8\,\mathrm{THz}$

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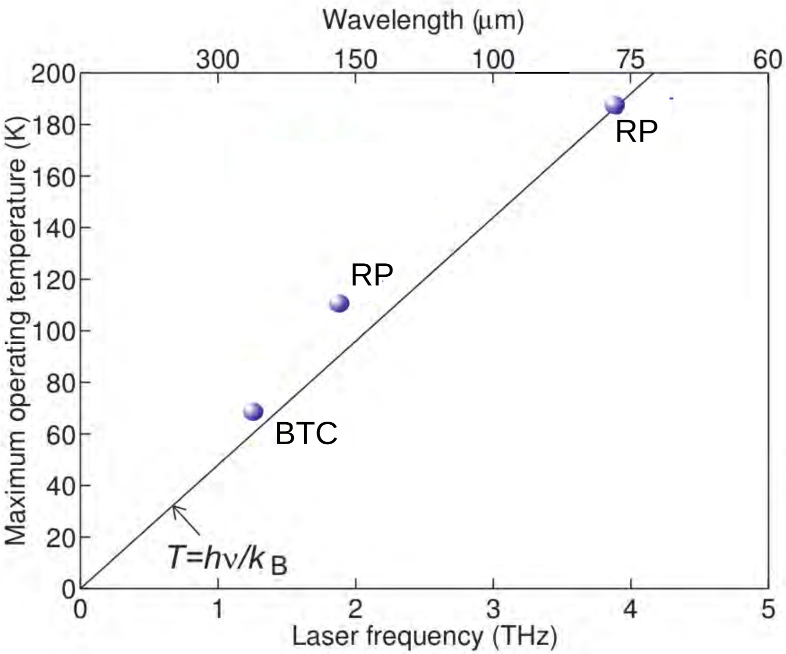
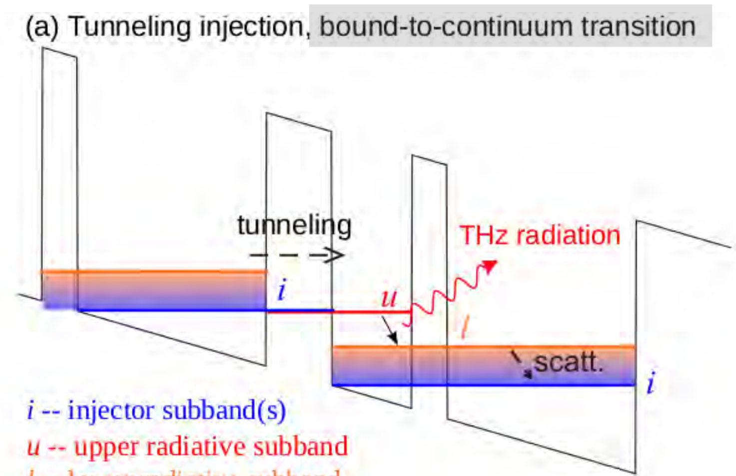
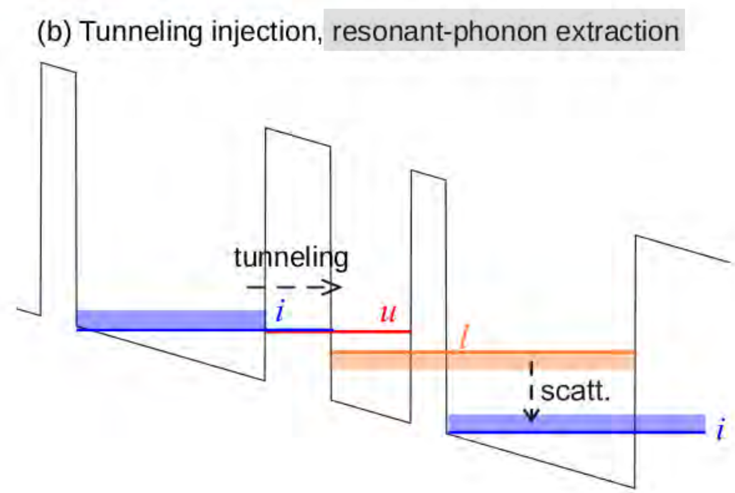
THz QCLs: temperature performance (2002-2011)



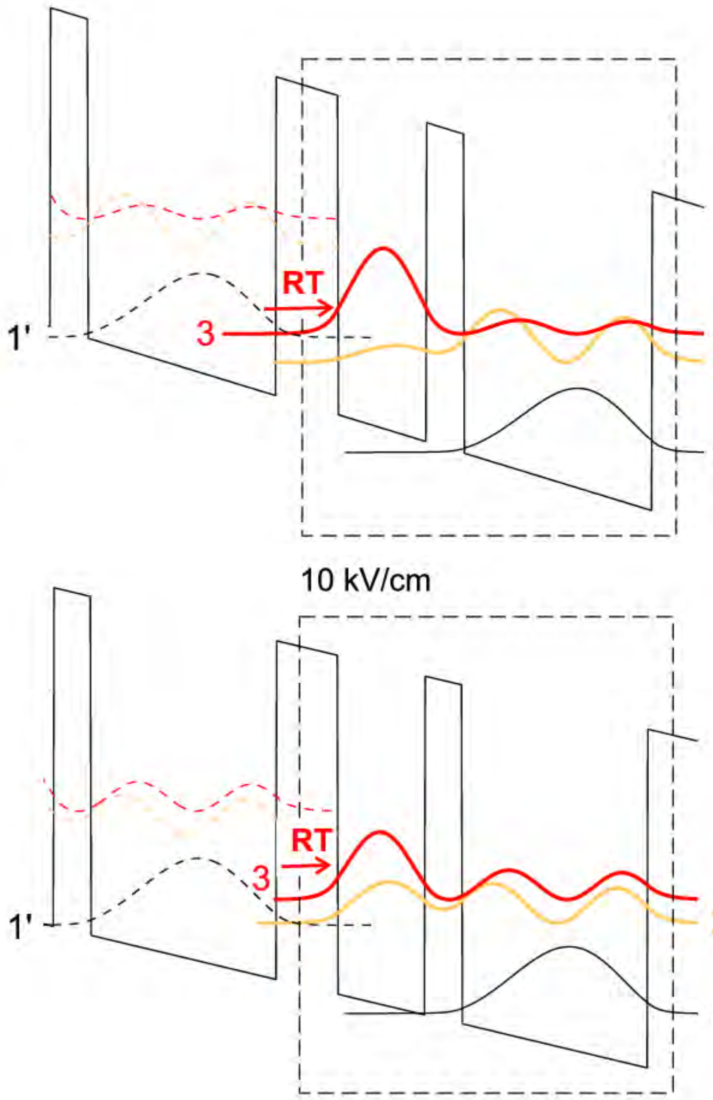


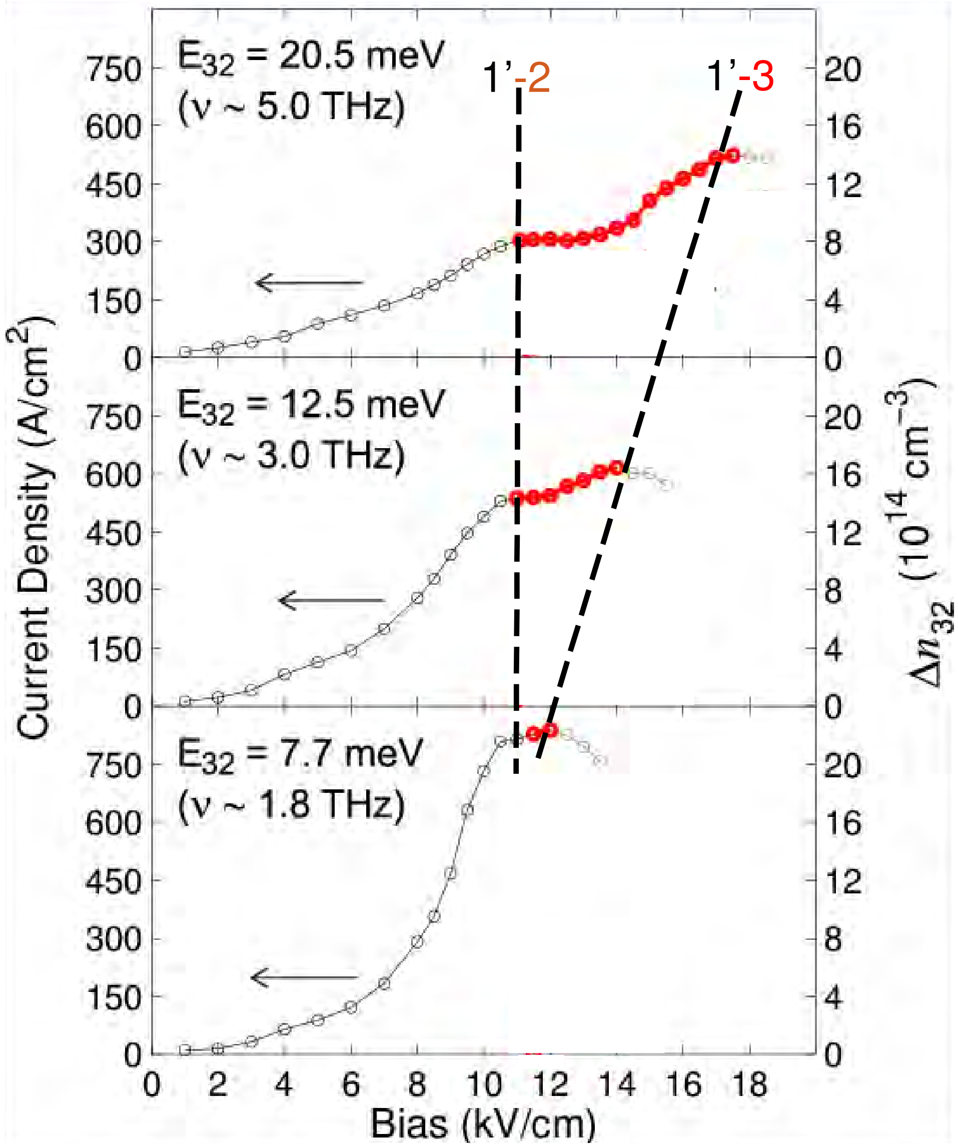
Scalari *et al.* APL (2003)



Williams *et al.* APL (2003)

Linear reduction in operating bias range with QCL frequency





Need even thicker injector barrier for low-frequency designs

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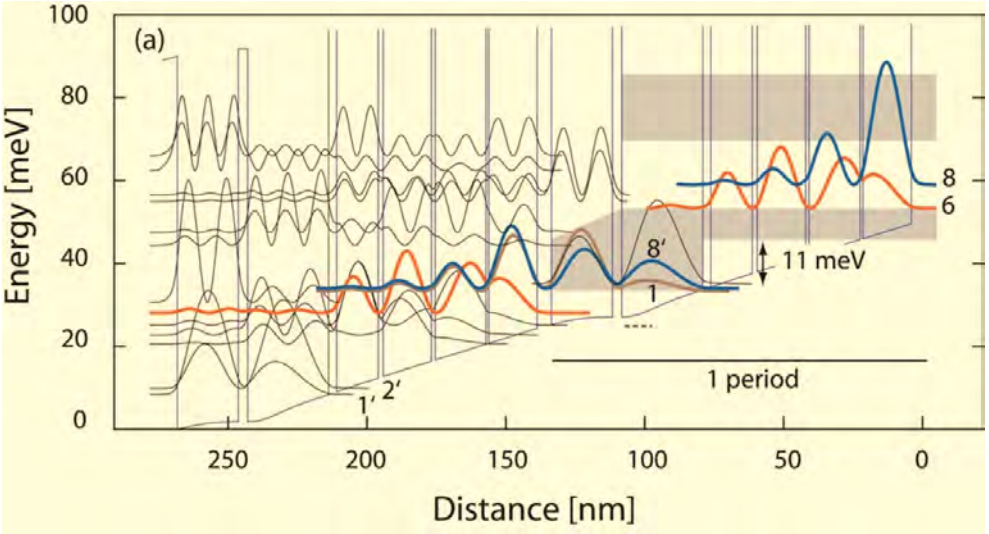
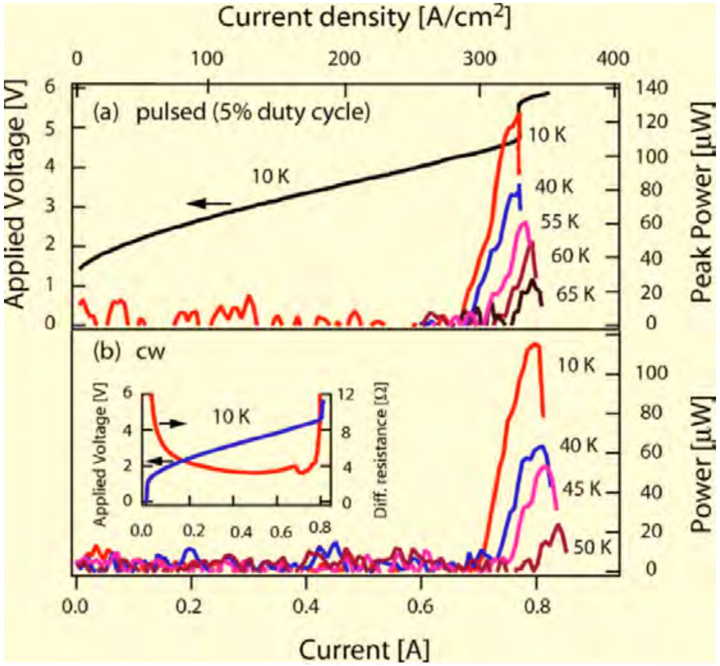
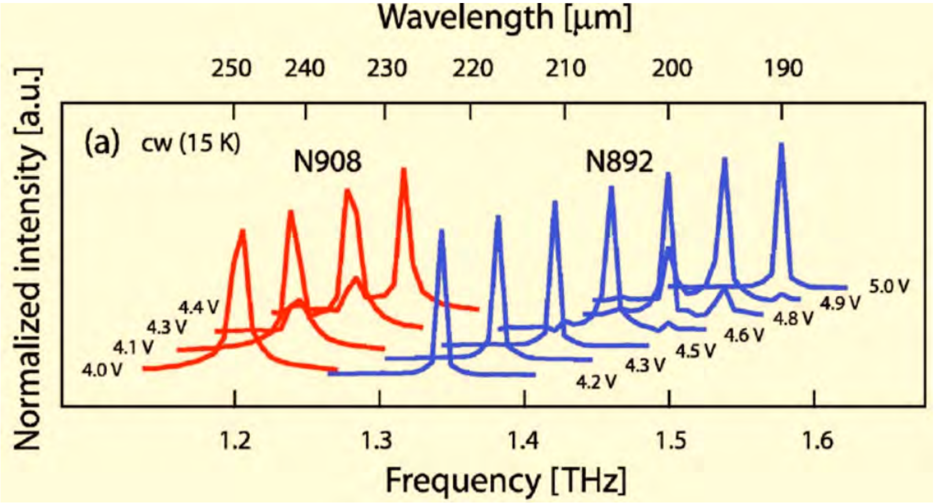
BTC design: lowest frequency THz QCL (without mag. field)

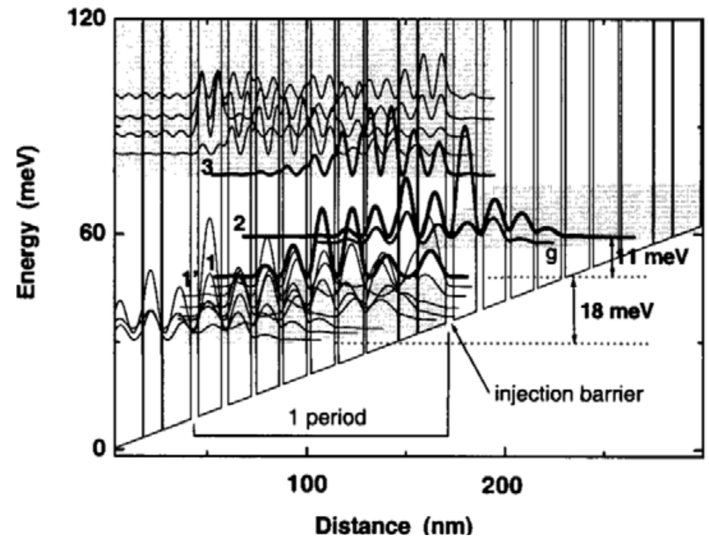


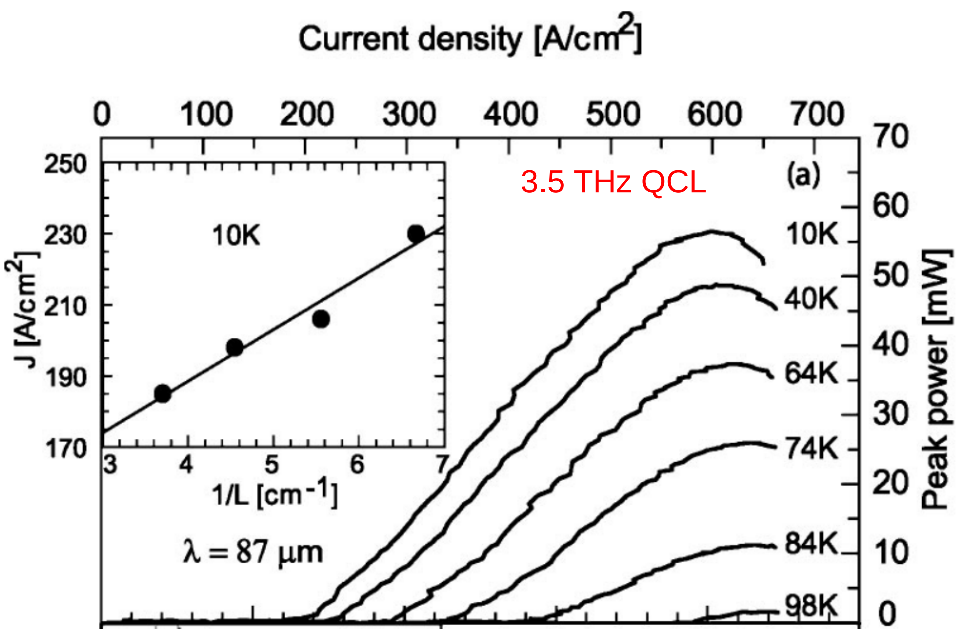




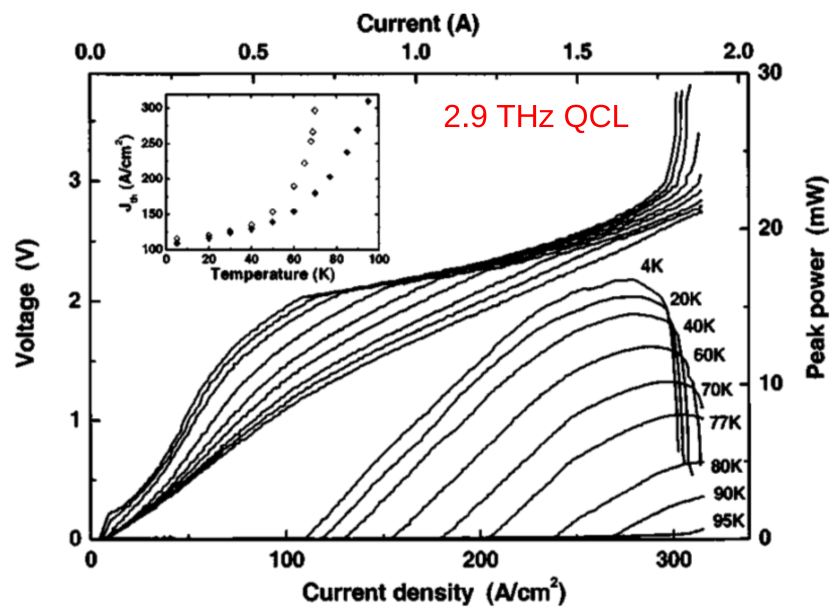
Walther *et al.* APL (2007)

Bound-to-continuum THz QCLs: low operating current densities



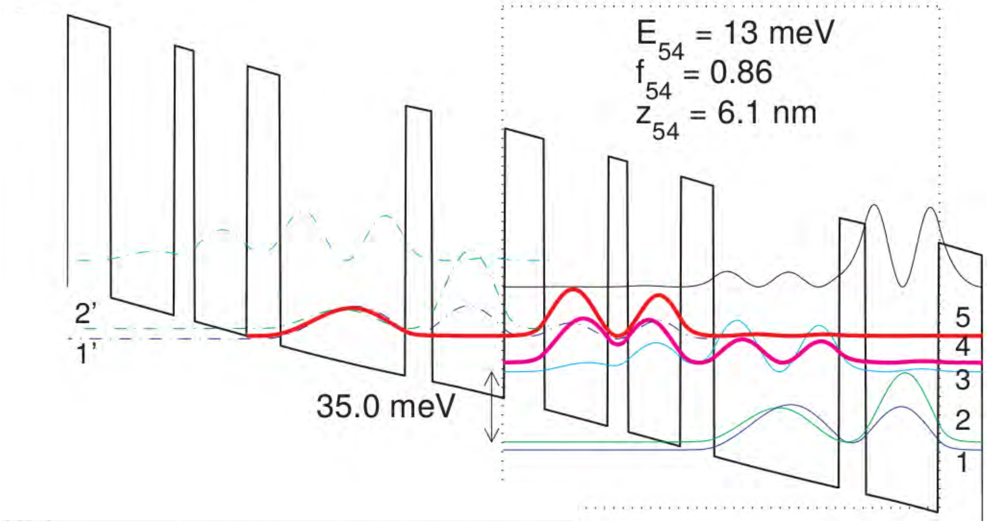


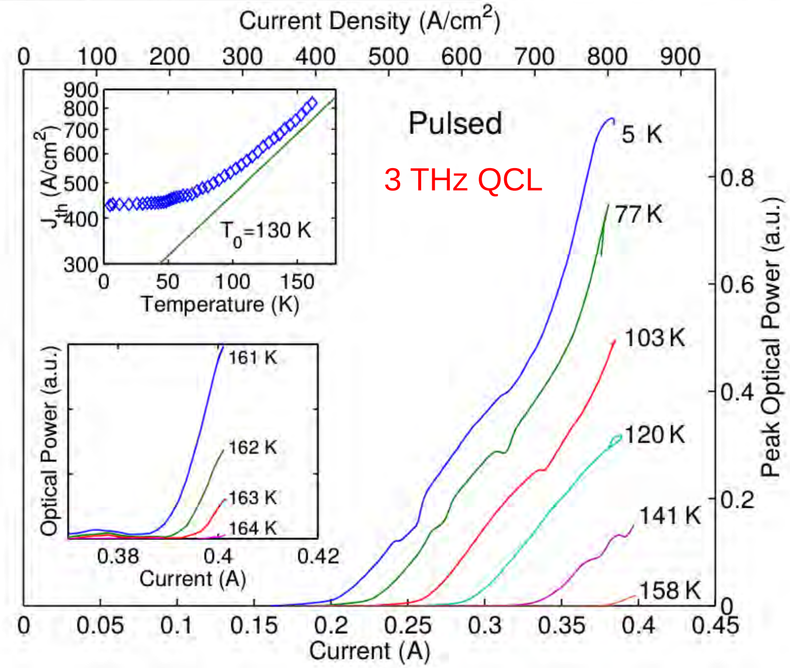
Ajili *et al.* APL (2004)



Barbieri *et al.* APL (2004)

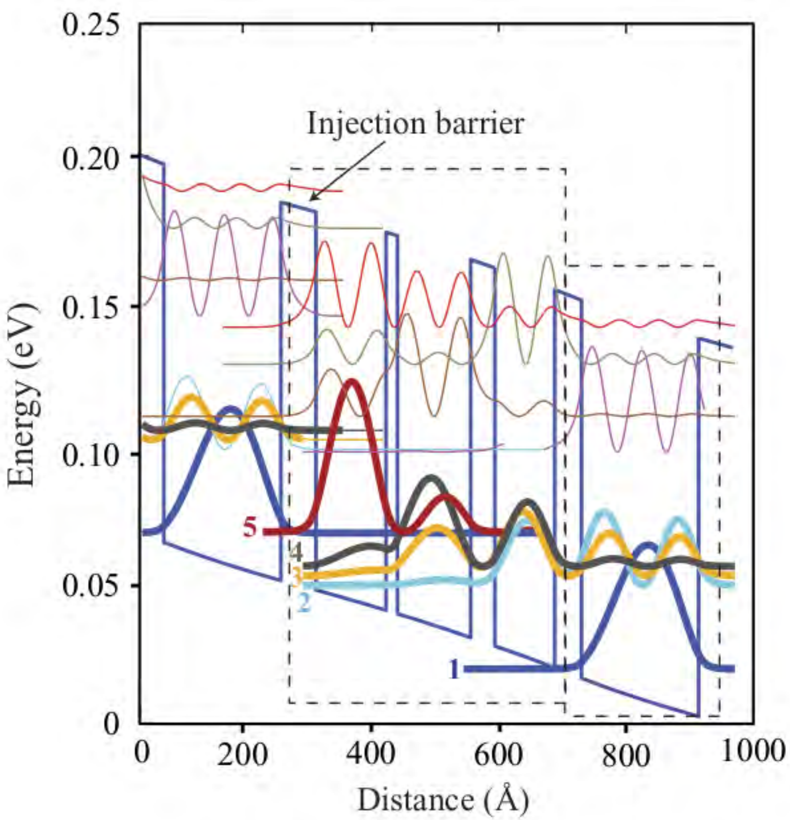
Resonant-phonon THz QCLs: high-temperature operation

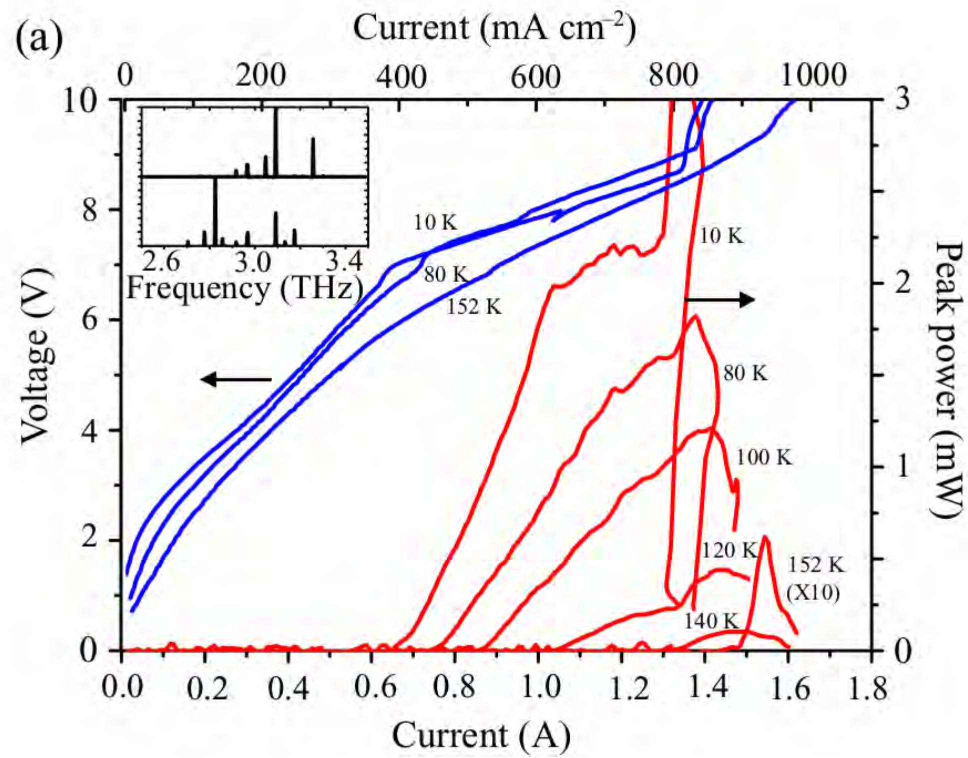




Williams *et al.* Opt. Exp. (2005)

Hybrid designs: bound-to-continuum transition + phonon depopulation

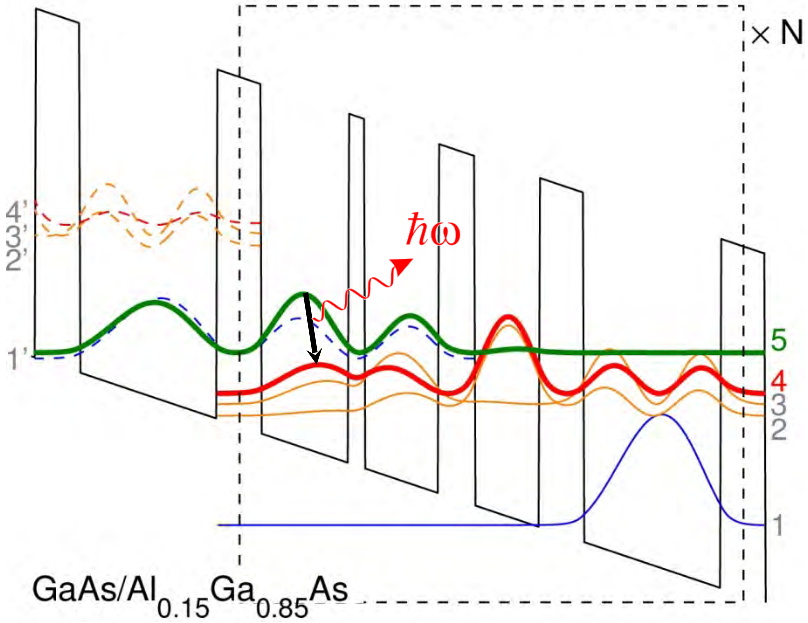


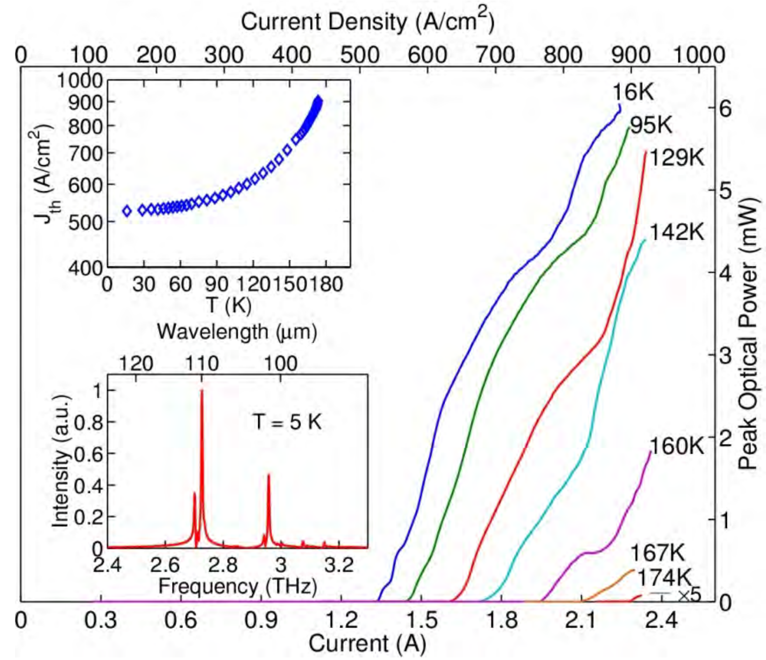


Amanti *et al.* New J. Phys. (2009)
Fischer *et al.* APL (2010)

- More tolerant to growth variations, grown with MOCVD
- Transport not limited by resonant-tunneling
- Grown in InGaAs/InAlAs material system (T_{max}~122 K)

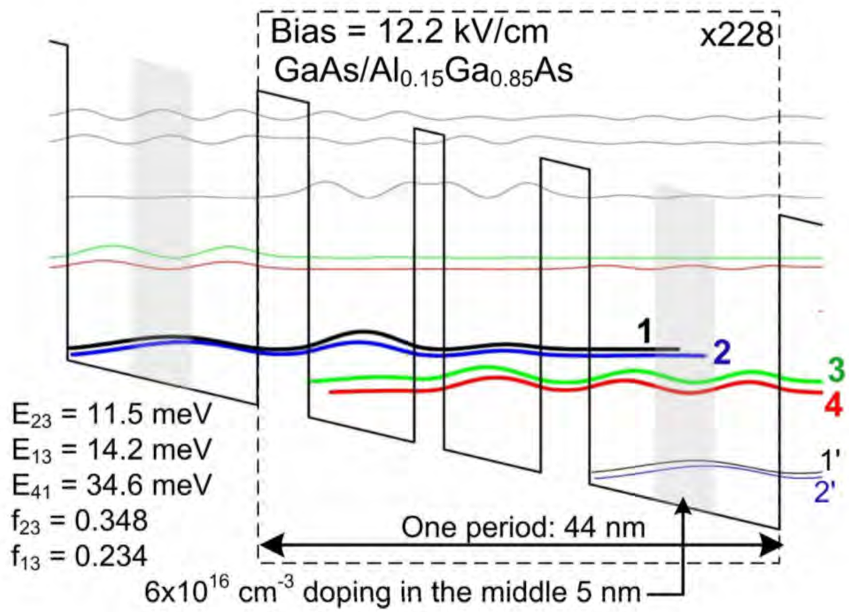
Hybrid designs (contd.)

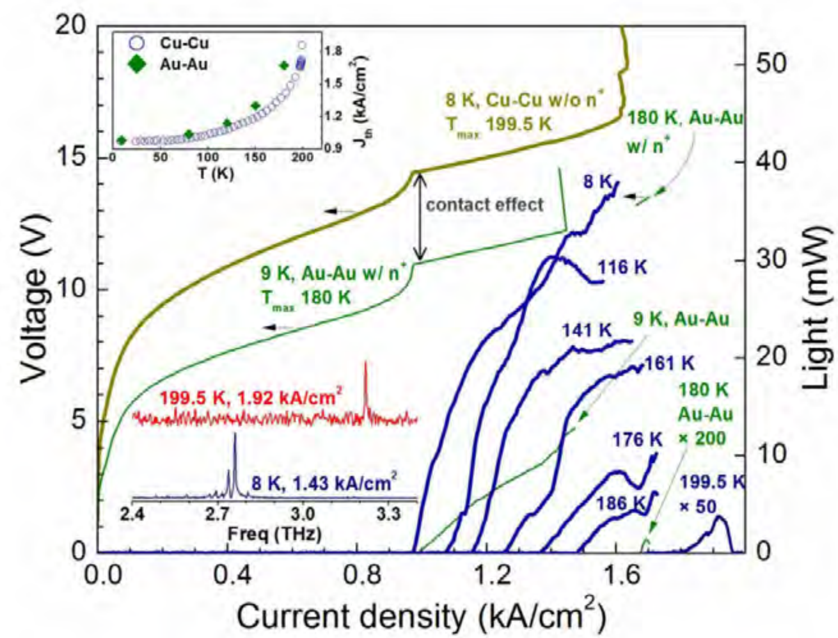




Kumar *et al.* CLEO conference (2009)

Three-well resonant-phonon design: Highest T_{max}~200 K

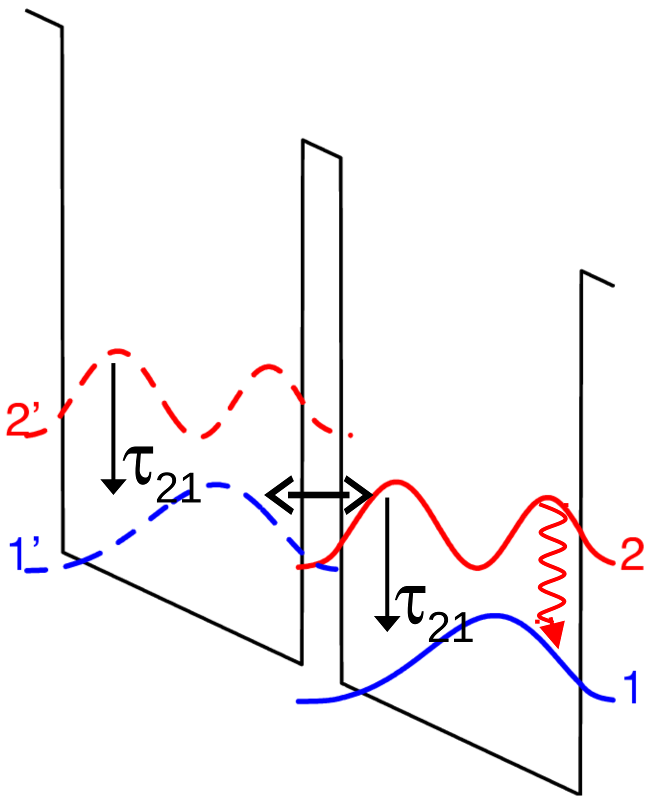


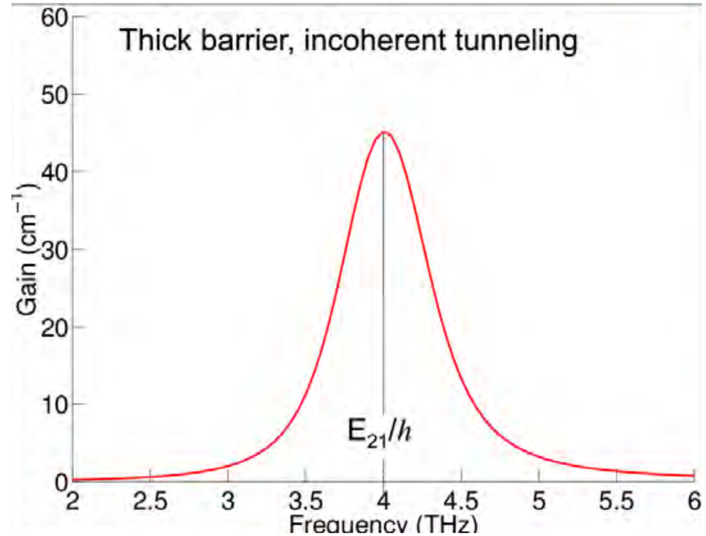


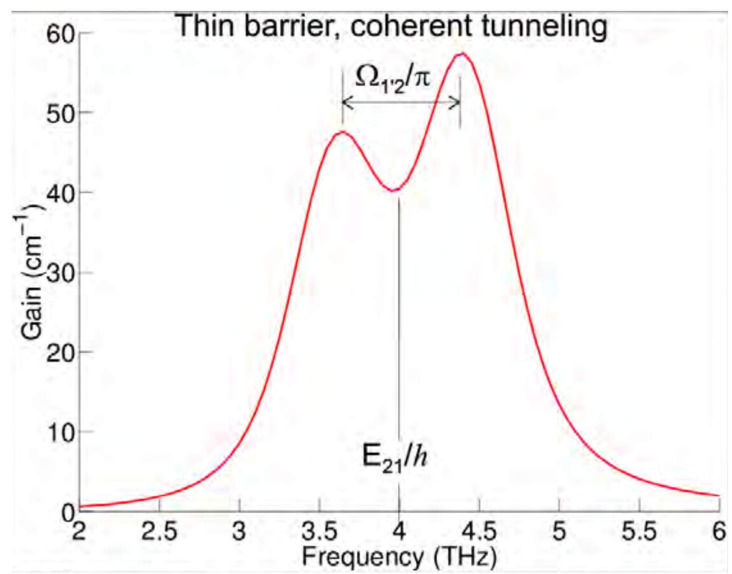
Luo *et al.* APL (2007)

Fathololoumi *et al.* Opt. Exp. (2012)

Resonant-phonon designs: large gain bandwidth



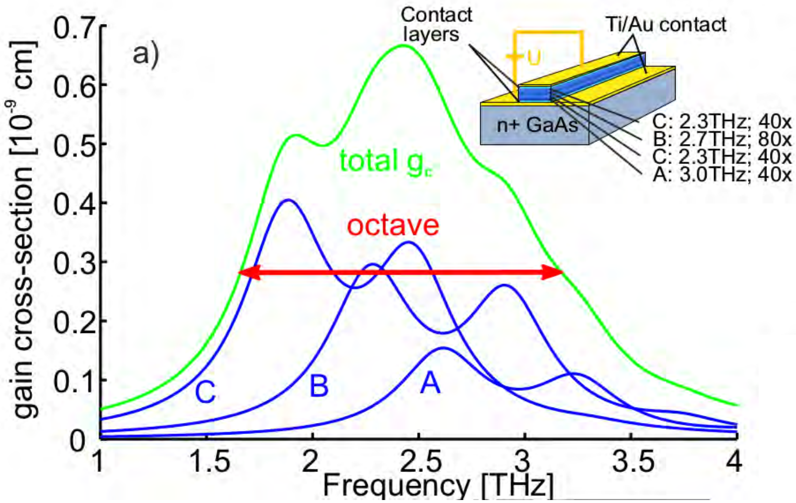


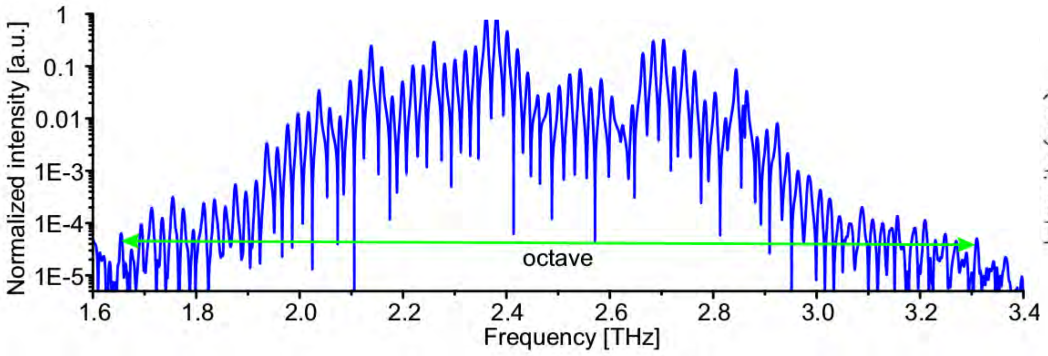


- Coherent 1'-2 resonant-tunneling ($\frac{\Omega_{1'2}}{\pi} > \Delta\nu_{21}$) causes additional gain broadening

THz QCLs with large gain bandwidths, frequency comb generation

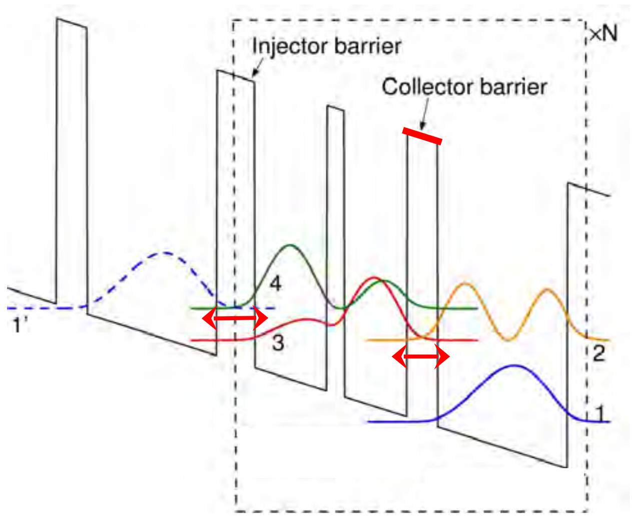
- Heterogeneous cascade region for very large gain bandwidth

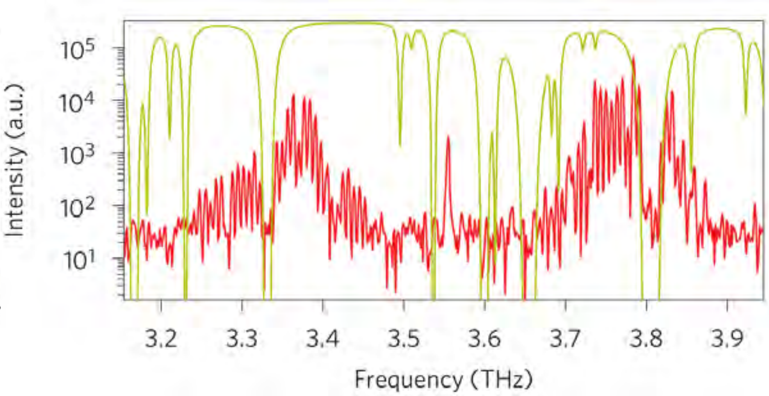




Rösch *et al.* Arxiv (2014)

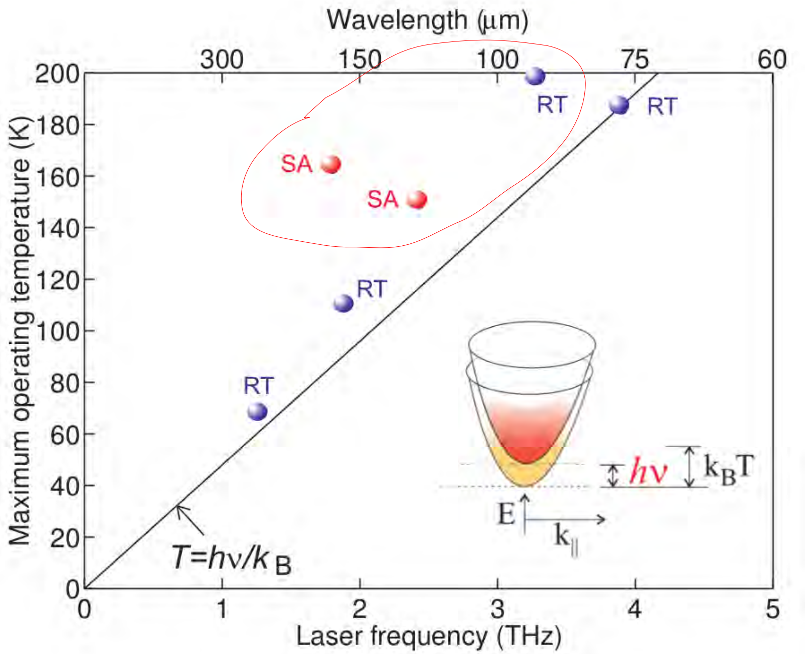
- Coherent tunneling for extraction broadens gain curve



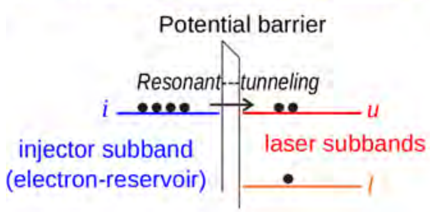


Burghoff *et al.* Nat. Photon. (2014)

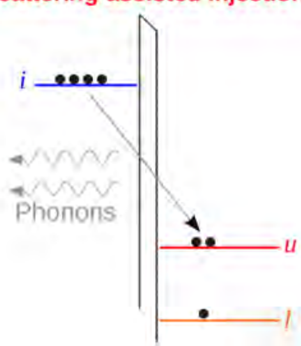
THz QCLs: temperature performance (2011-2014)



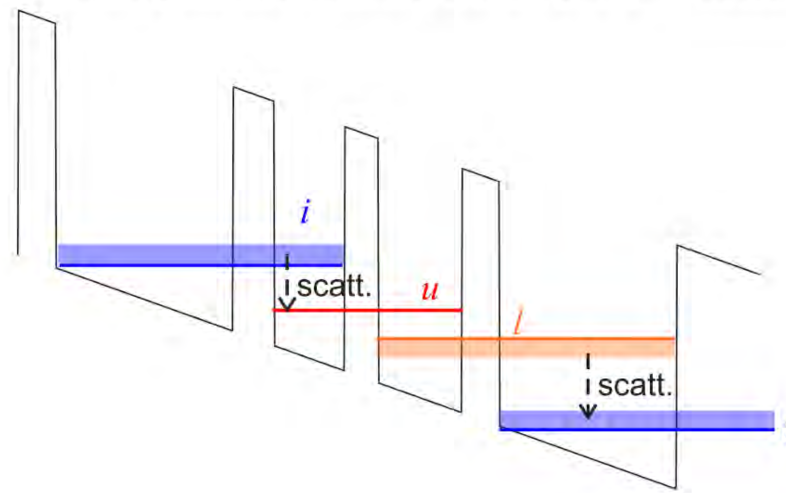
RT - Resonant-tunneling injection



SA - Scattering-assisted injection



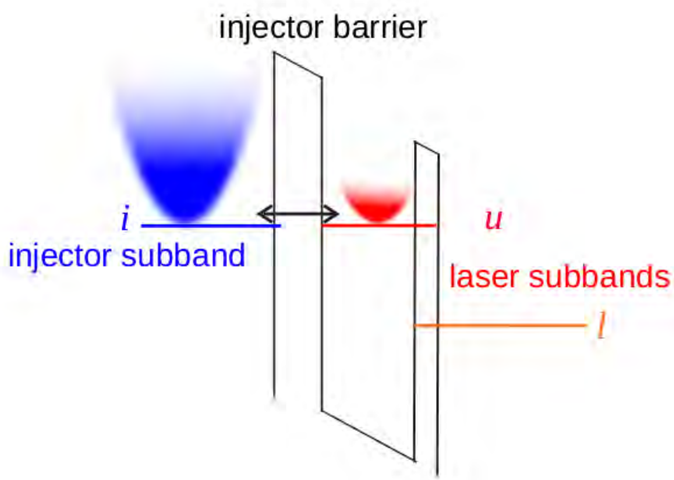
Scattering-assisted injection, resonant-phonon extraction



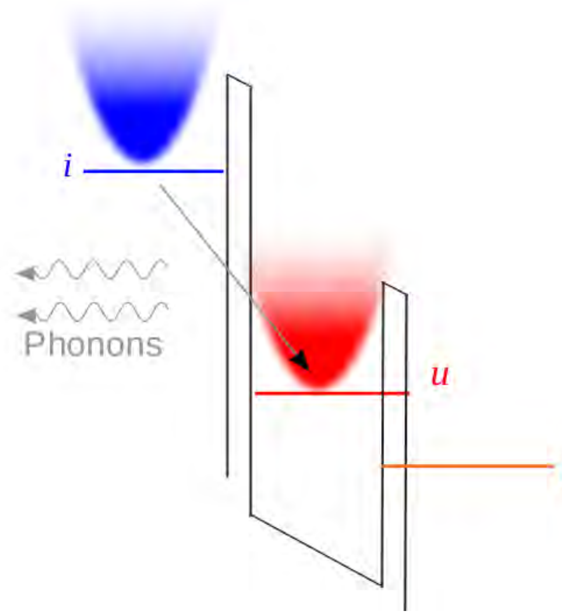
Kumar *et al.* Nature Phys. (2011)

Scattering-assisted injection for low-frequency THz QCLs

Resonant-tunneling injection:
requires thick injector barrier



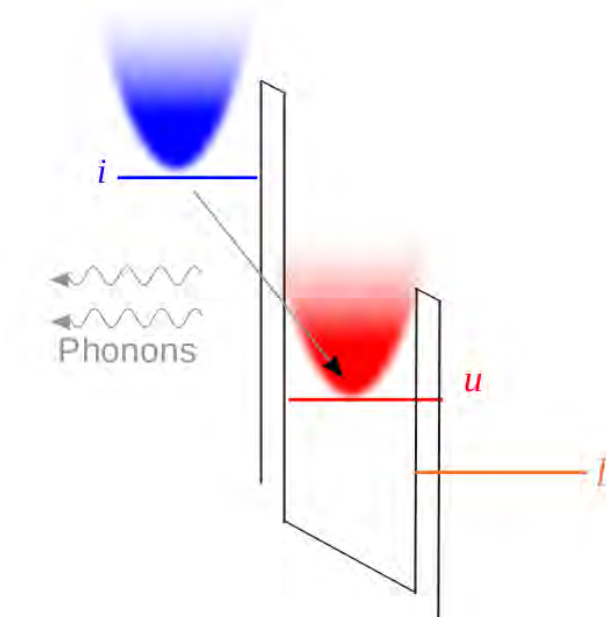
Scattering-assisted injection:
works with thin barriers



$$\Delta n_{ul} \downarrow = \frac{J_{i\to u}}{eL_{\mathrm{mod}}} \tau_u \downarrow \left(1 - \frac{\tau_l}{\tau_{ul}}\right)$$

$$J_{i\to u} \downarrow \propto \frac{1}{\tau_u} \left(1 - \frac{1}{4\Omega_{iu}^2 \downarrow \tau^* \tau_u + 1}\right)$$

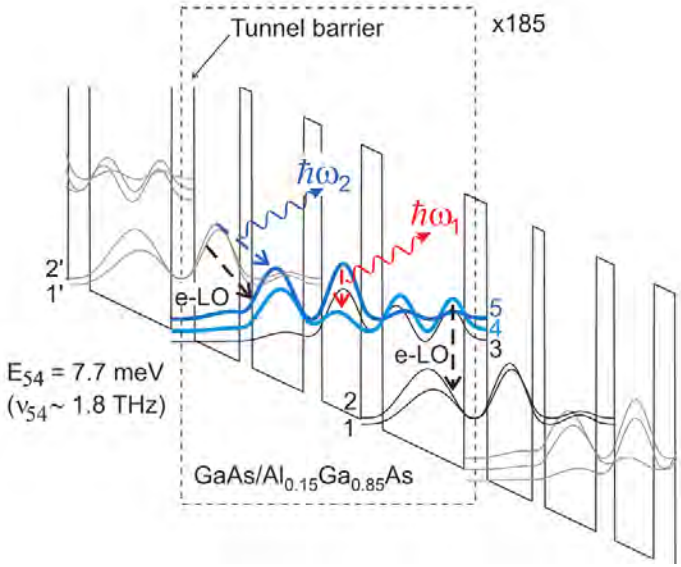
Scattering-assisted injection for high-frequency THz QCLs?

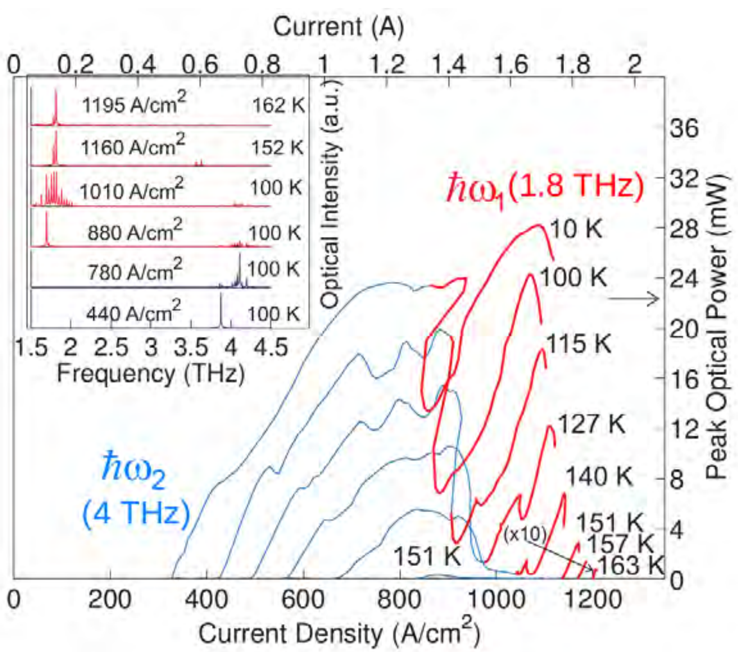


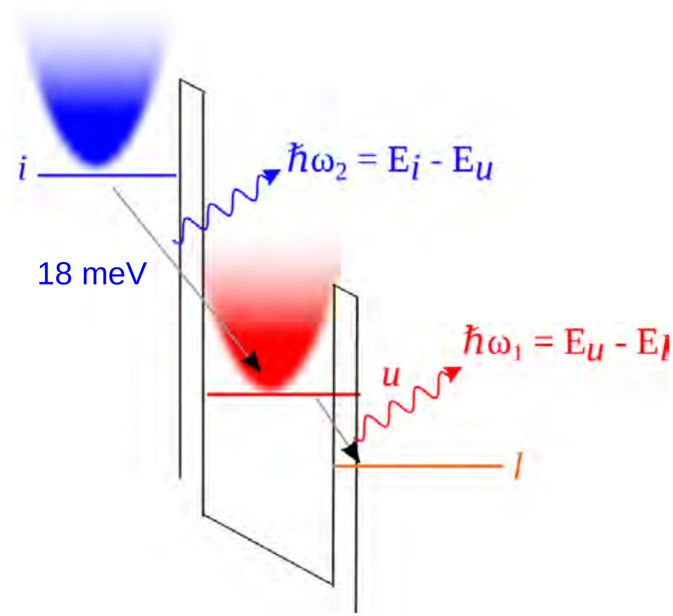
Challenges:

- Poor injection selectivity
- High leakage current
- Large voltage drop per module

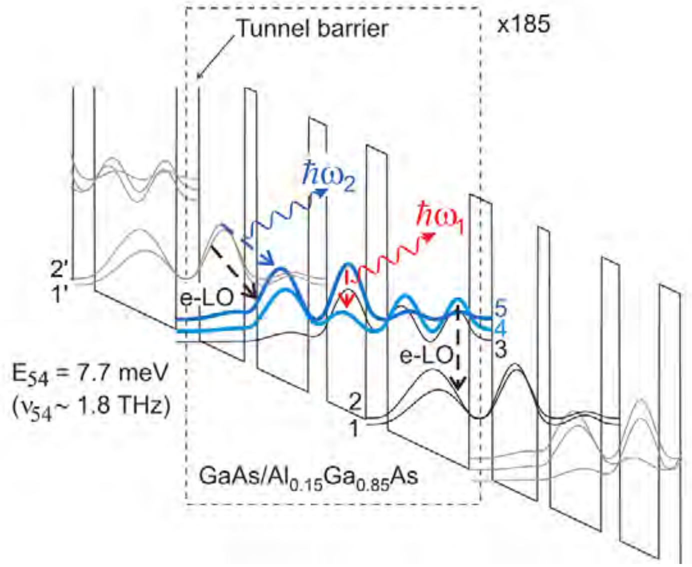
Low-frequency THz QCLs with scattering-assisted injection

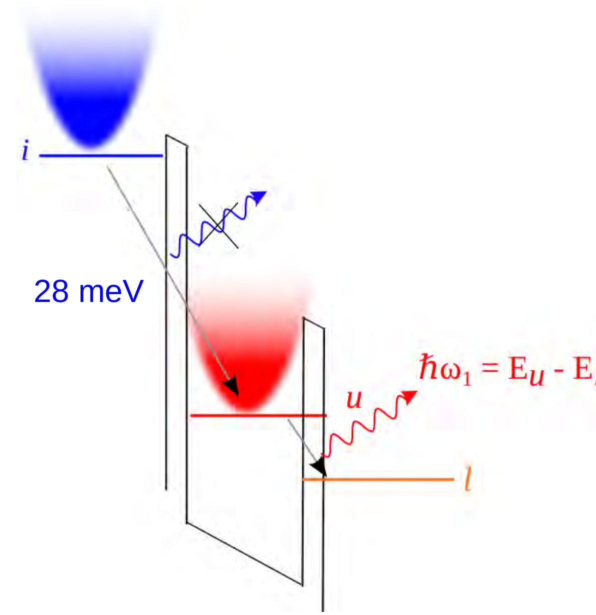


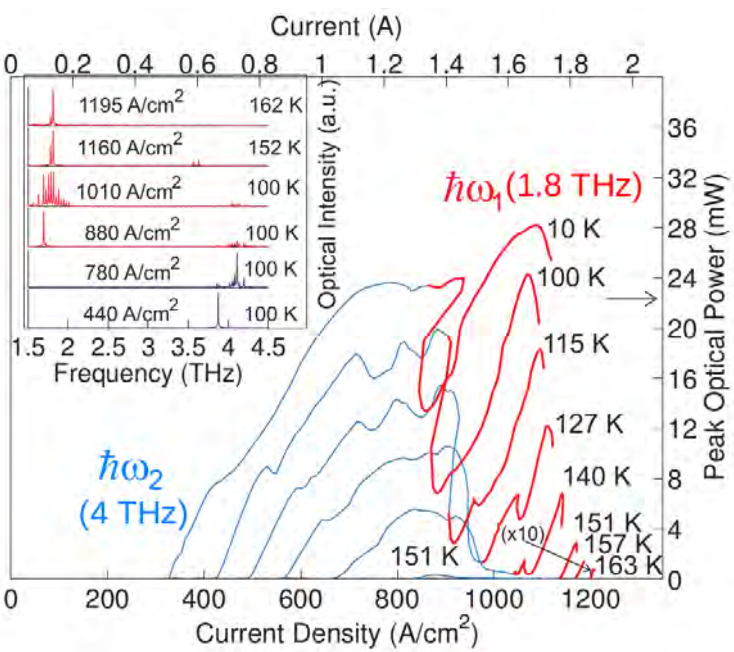


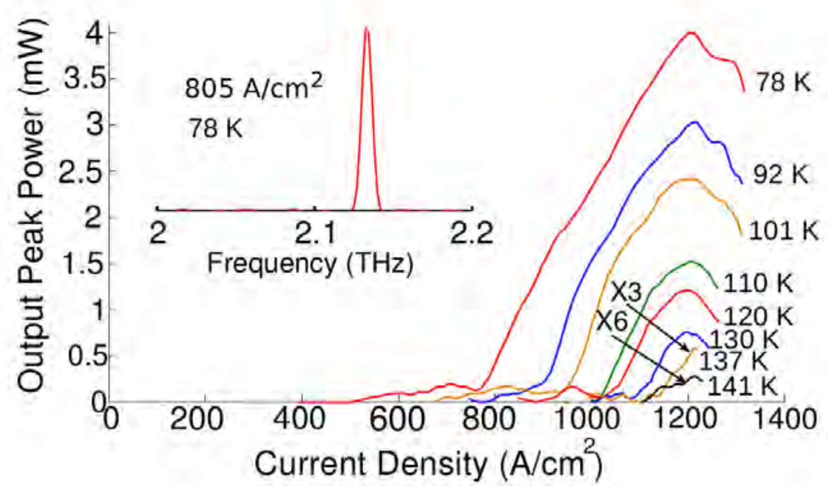


Low-frequency THz QCLs with scattering-assisted injection



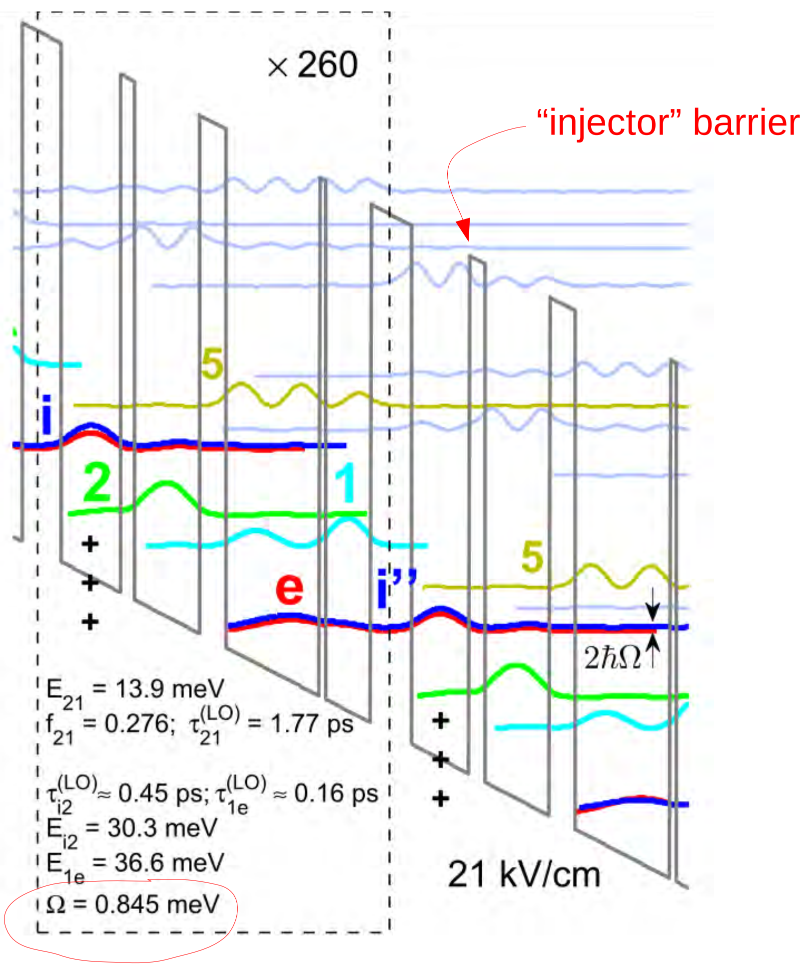




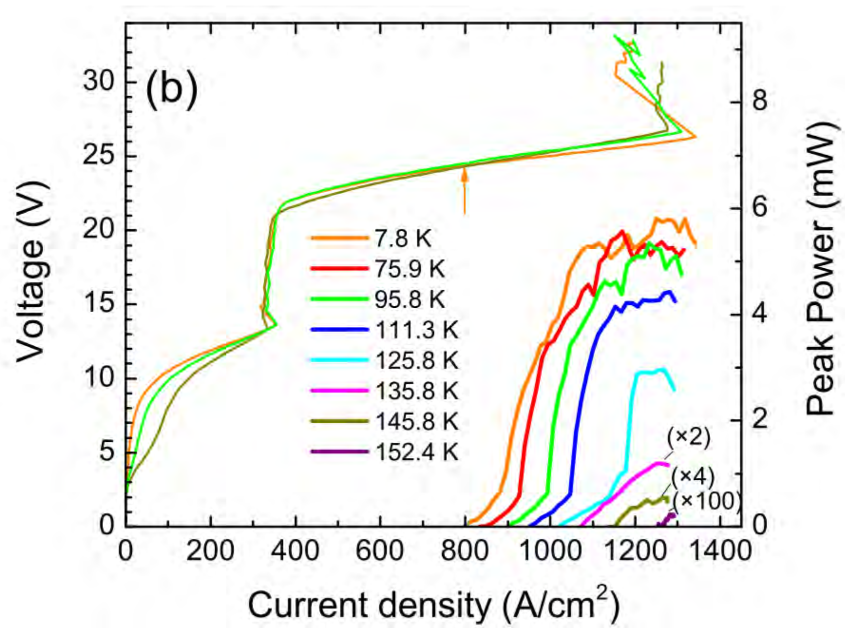


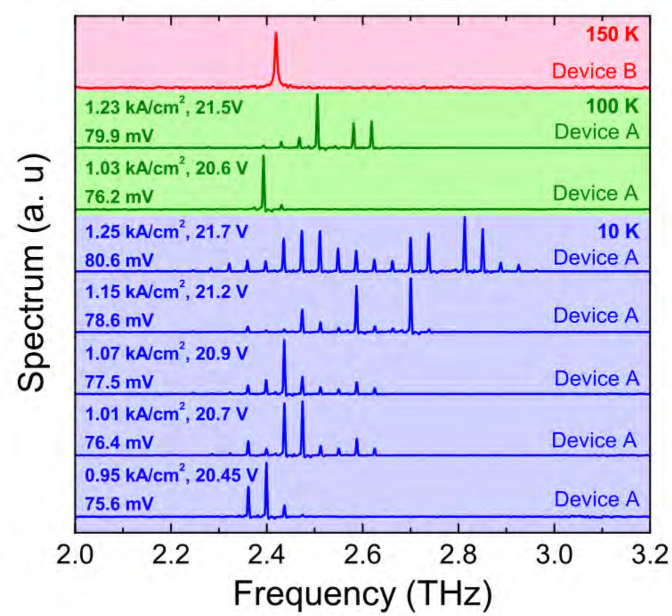
(unpublished result)

Low-frequency THz QCLs with scattering-assisted injection



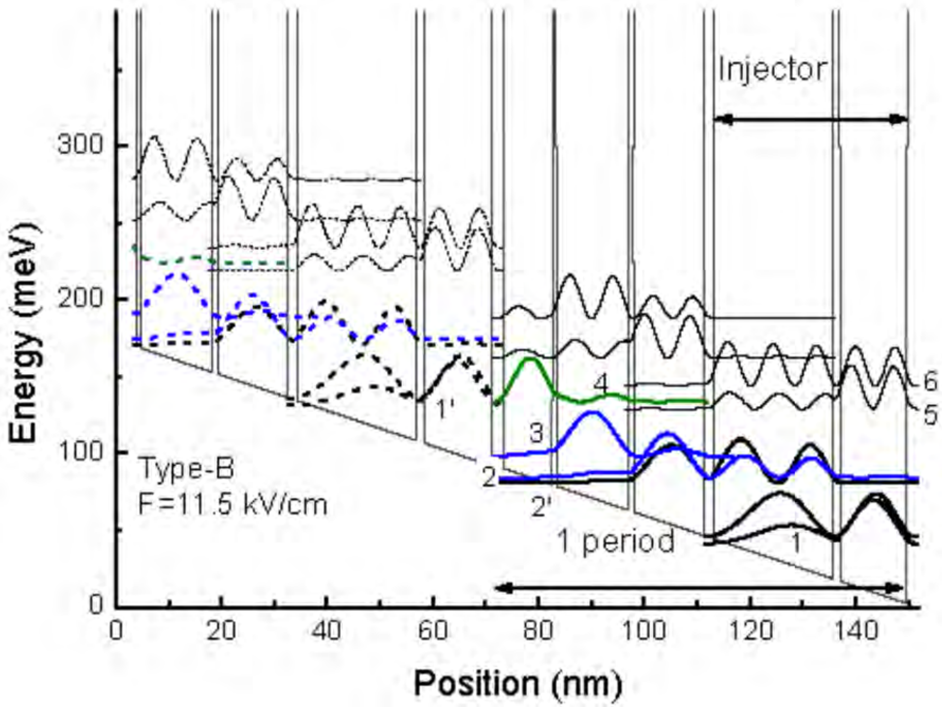
Razavipour *et al.* JAP (2013)

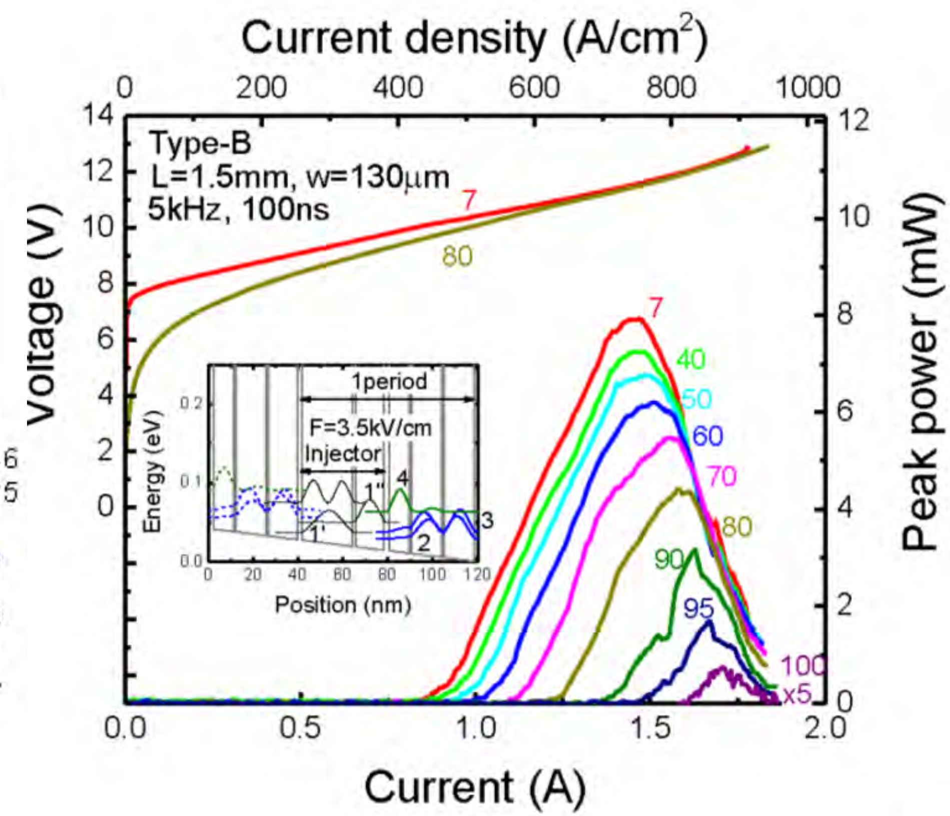




High frequency operation in InGaAs/InAlAs material system, grown by MOVPE

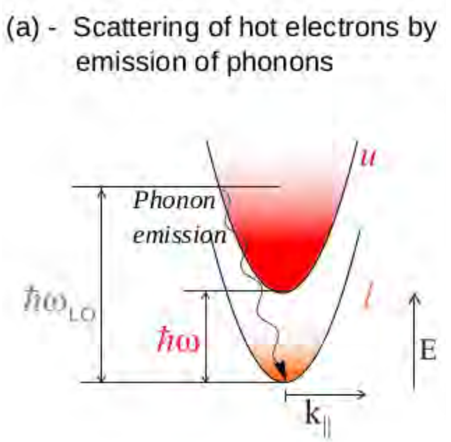
3.7 THz QCL

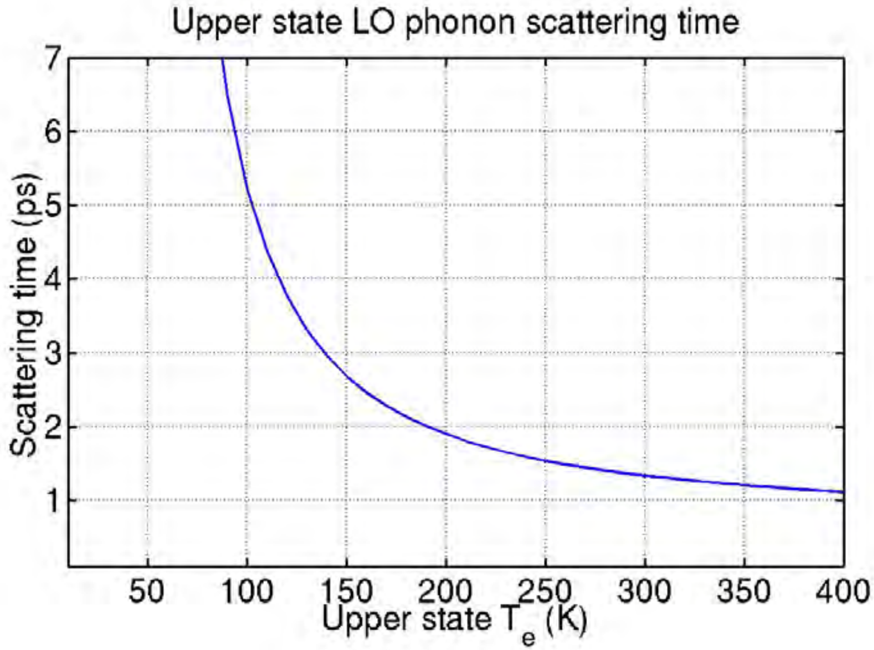




Fujita *et al.* Opt. Exp. (2012)

High temperature effects in THz QCLs

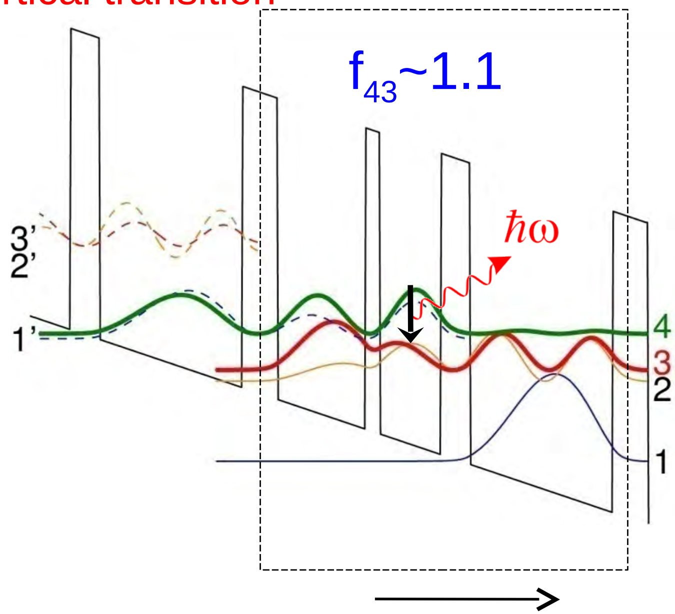




$$\tau_{u\to l} \propto \exp\left(\frac{\hbar\omega_{\rm LO} - E_{ul}}{k_{\rm B}T_{\rm e}}\right)$$

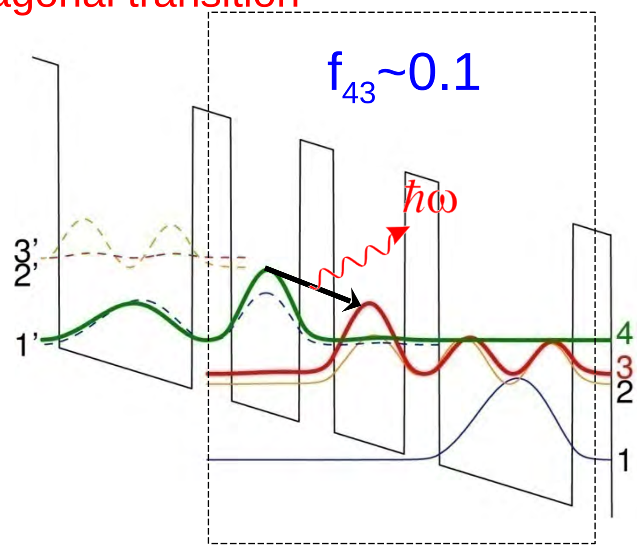
Diagonality of radiative transition (resonant-phonon design)

Vertical transition



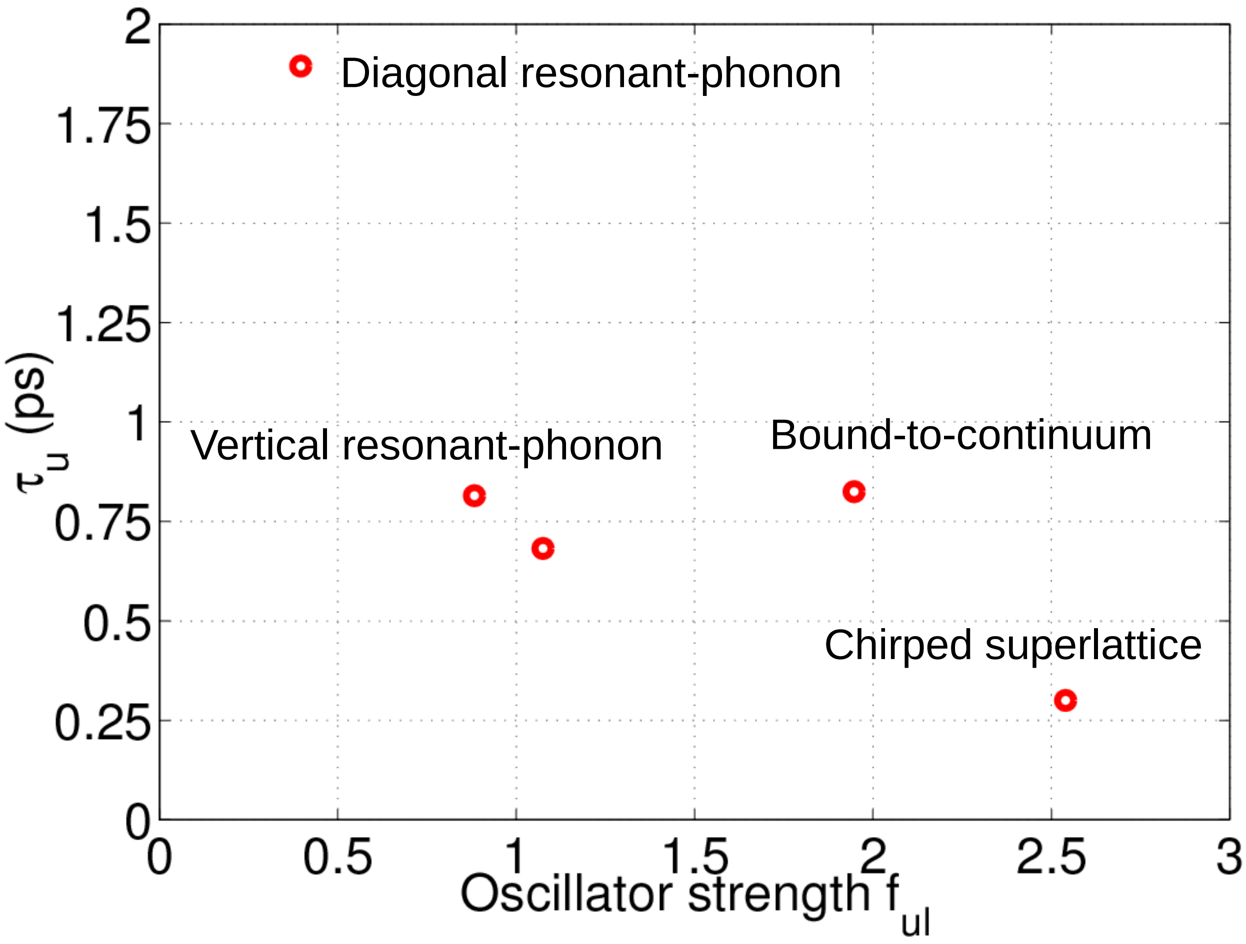
Growth direction ($\hat{z}$)

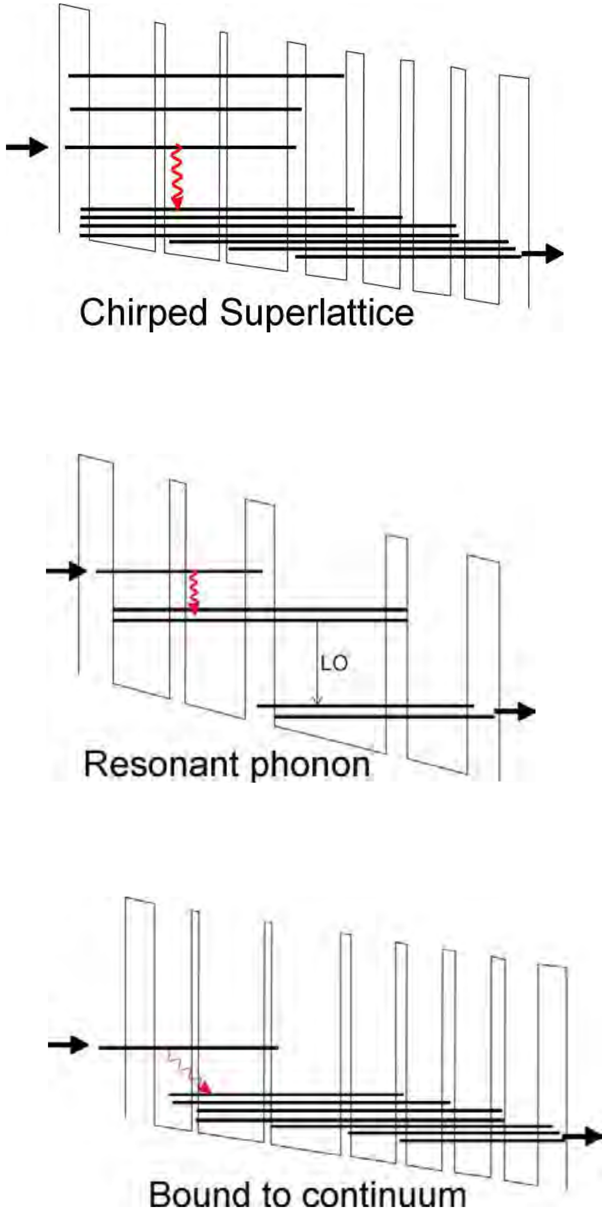
Diagonal transition



Oscillator strength: $f_{43} \mu \left|z_{43}\right|^2, \quad z_{43} \equiv \langle 4|\hat{z}|3\rangle$

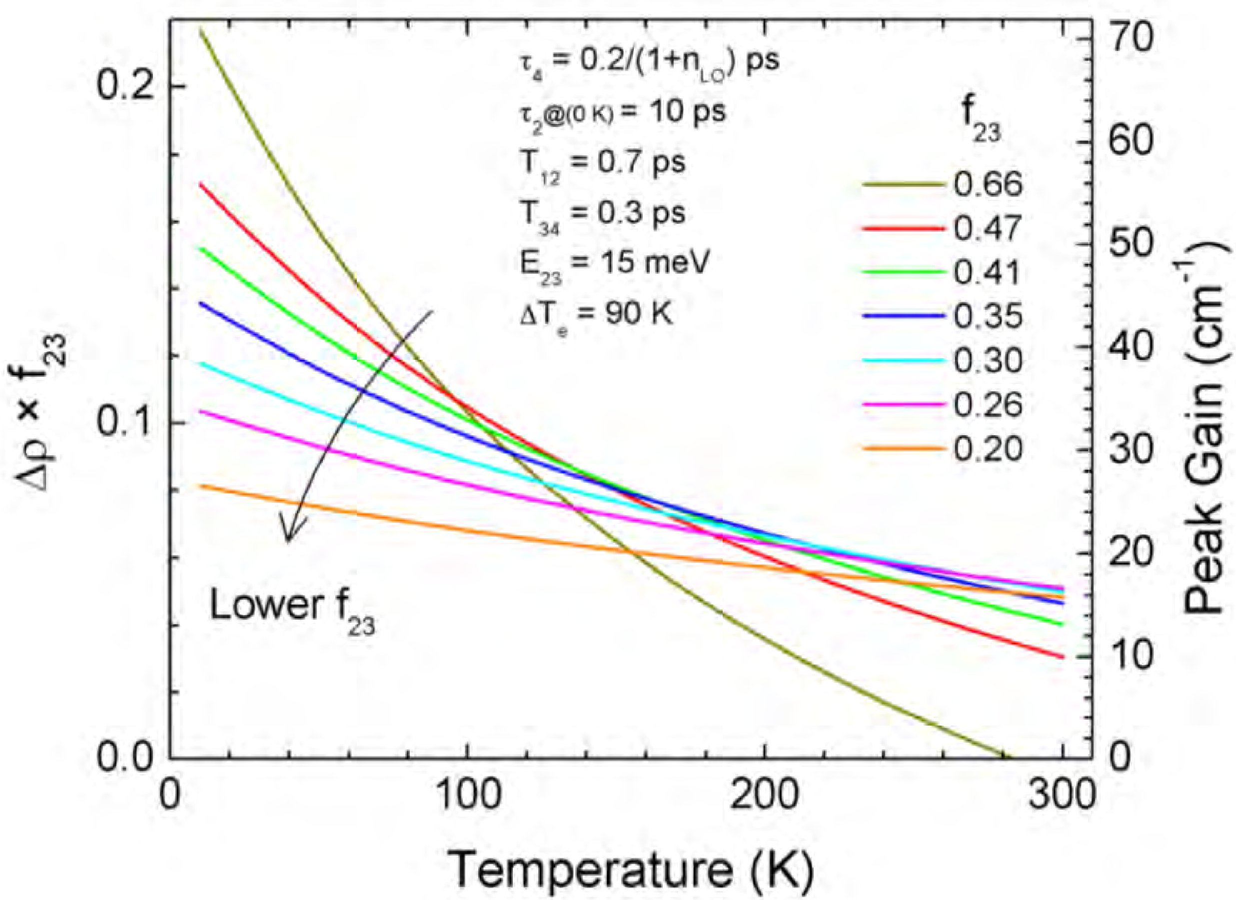
Is oscillator strength a good measure of diagonality?





(τ_u calculated for T_e=200 K)

Resonant-phonon designs: diagonality not an independent design parameter

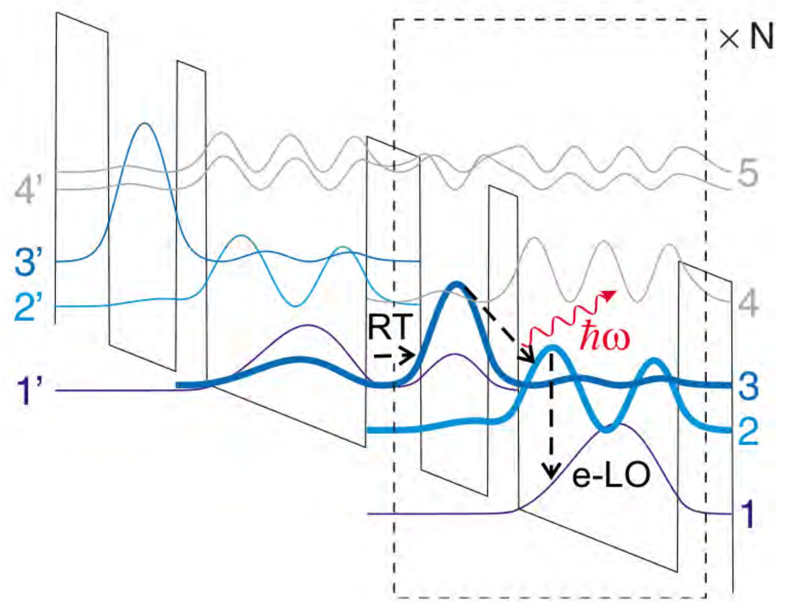


Oscillator strength (f_{23}) (grown wafer ID)	0.47 (V775)	0.41 (V813-14)	0.35 (V774)	0.30 (V812)	0.26 (V773)
$T_{\text{max,exp Cu}}$ (K)	199.5	187	197	199.3	184

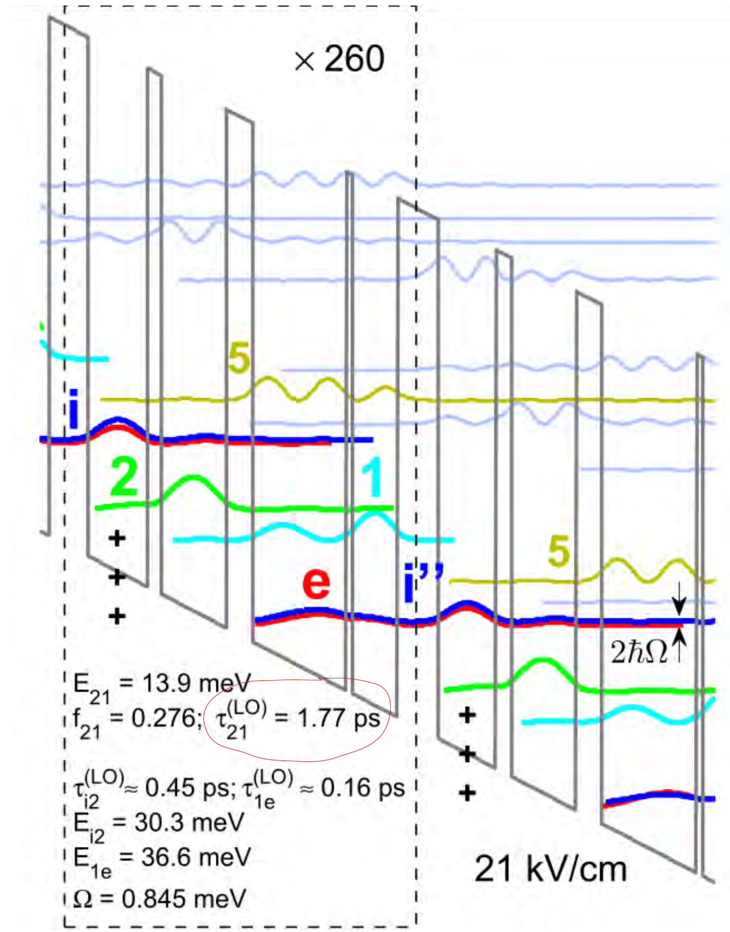
Fathololoumi *et al.* JAP (2013)

Direct phonon depopulation designs: large τ_{ul}/τ_l (>5)

$$\Delta n_{ul} \propto \left(1 - \frac{1}{\tau_{ul}/\tau_l}\right)\tau_u$$



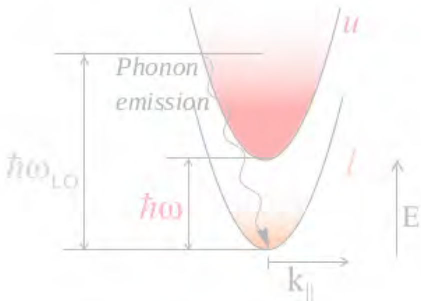
Kumar *et al.* APL (2009)



Razavipour *et al.* JAP (2013)

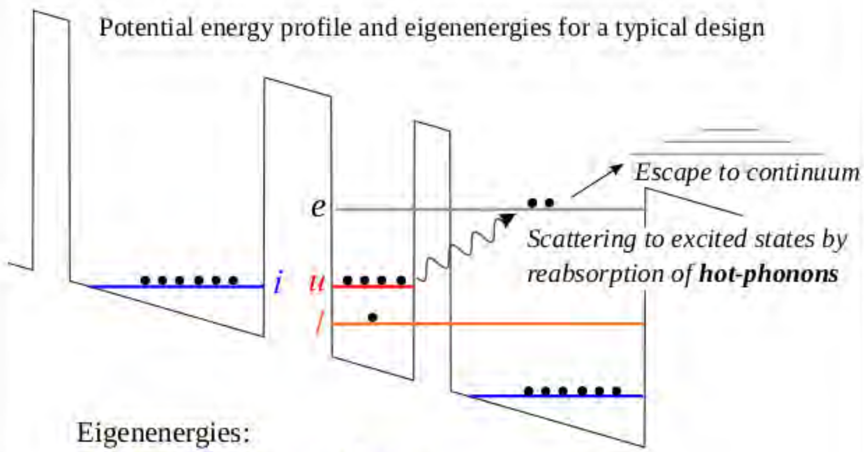
High temperature effects in THz QCLs

(a) - Scattering of hot electrons by emission of phonons



$$\tau_{u\to l} \propto \exp\left(\frac{\hbar\omega_{LO} - E_{ul}}{k_B T_e}\right)$$

(b) - Carrier leakage due to reabsorption of hot (nonequilibrium) phonons



Eigenenergies:

i -- injector (reservoir) state

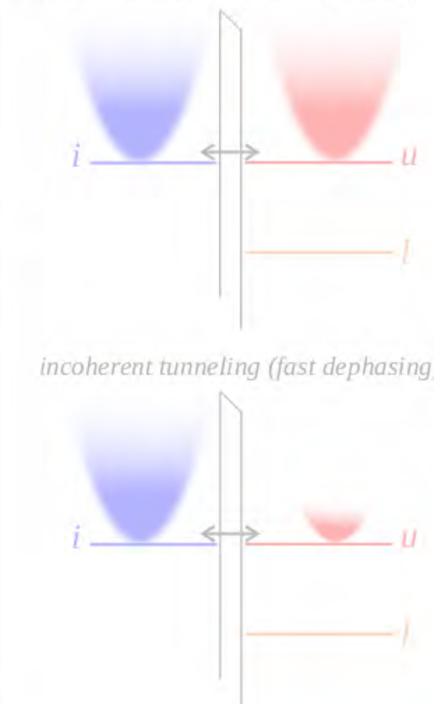
u -- upper laser state

l -- lower laser state

$$\tau_{u\to e} \propto \frac{1}{n_{LO}}$$

$$(n_{LO}^{eq} \sim 0.14 \text{ at } T = 200 \text{ K})$$

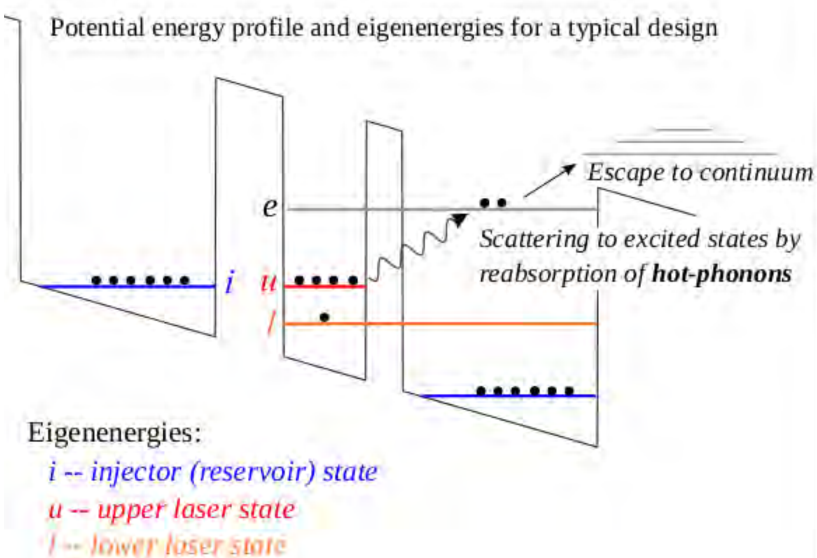
(c) - Incoherent resonant-tunneling transport at high temperatures

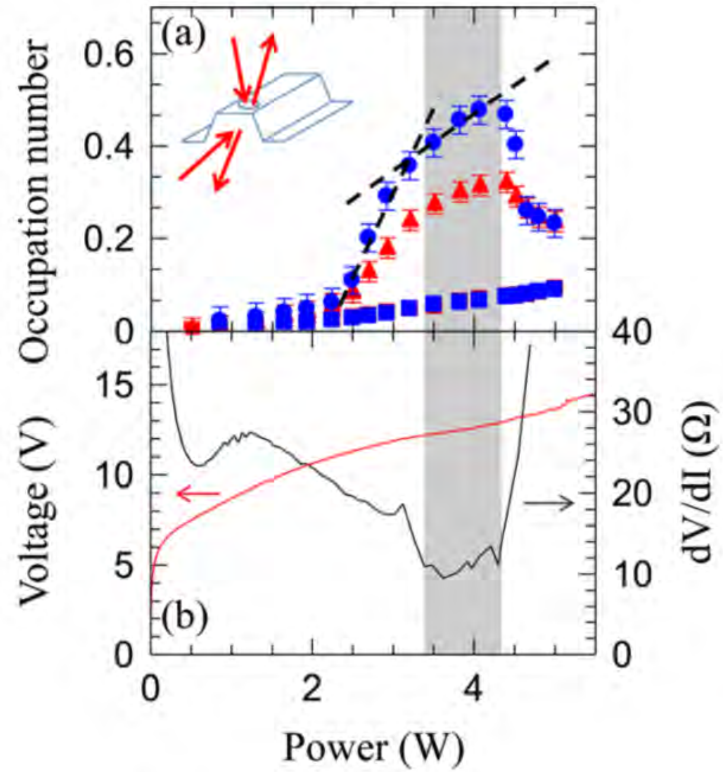


$$J_{i\to u} \propto \frac{1}{\tau_u}\left(1 - \frac{1}{4\Omega_{iu}^2 \tau^* \tau_u + 1}\right)$$

High temperature effects in THz QCLs

(b) - Carrier leakage due to reabsorption of hot (nonequilibrium) phonons





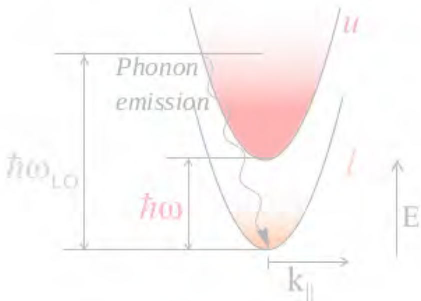
Vitiello *et al.* APL (2012)

$$\tau_{u\to e} \propto \frac{1}{n_{\mathrm{LO}}}$$

$(n_{\mathrm{LO}}^{\mathrm{eq}} \sim 0.14 \text{ at } T = 200 \text{ K})$

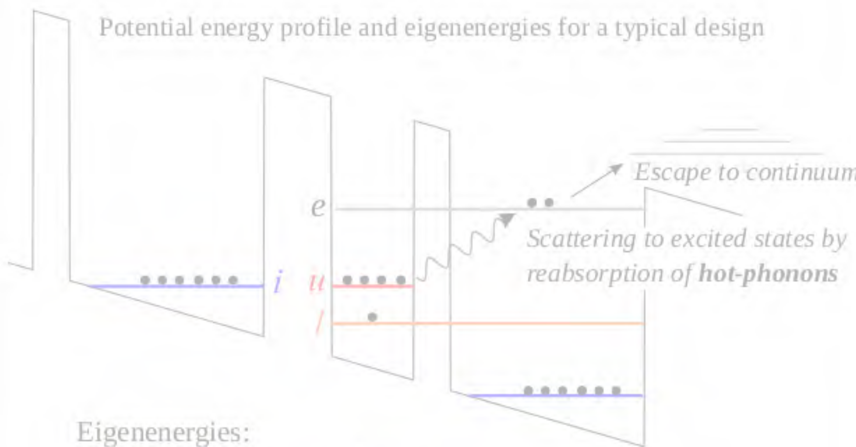
High temperature effects in THz QCLs

(a) - Scattering of hot electrons by emission of phonons



$$\tau_{u\to l} \propto \exp\left(\frac{\hbar\omega_{\rm LO} - E_{ul}}{k_{\rm B}T_{\rm e}}\right)$$

(b) - Carrier leakage due to reabsorption of hot (nonequilibrium) phonons



Eigenenergies:

i -- injector (reservoir) state

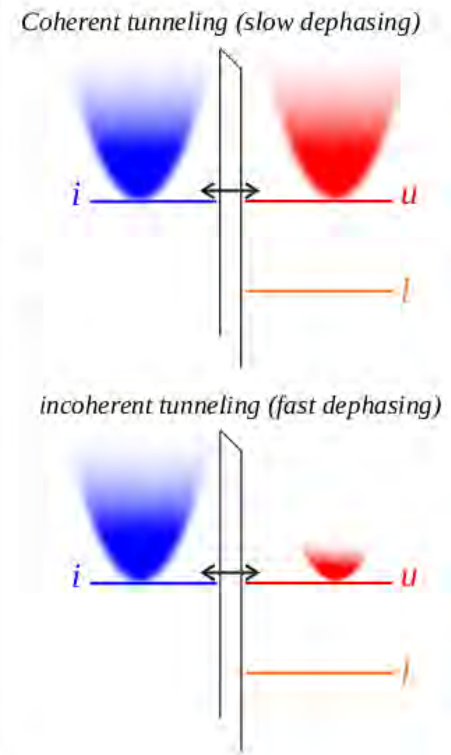
u -- upper laser state

l -- lower laser state

$$\tau_{u\to e} \propto \frac{1}{n_{\rm LO}}$$

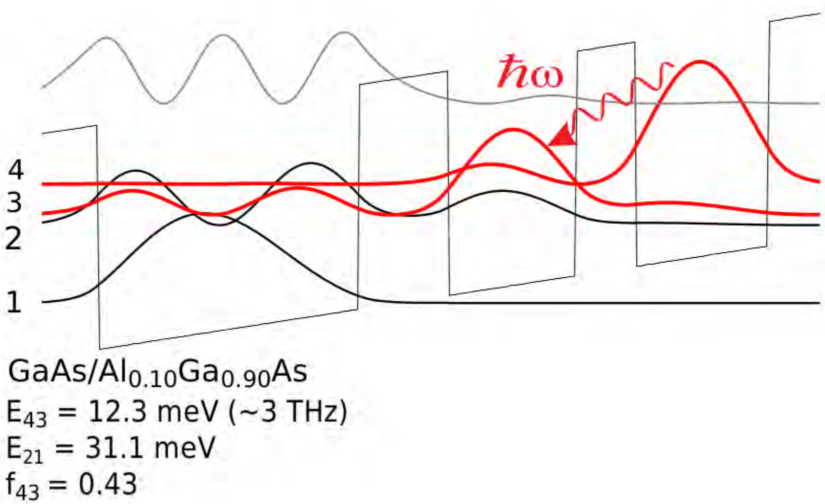
$$(n_{\rm LO}^{\rm eq} \sim 0.14 \text{ at } T = 200 \text{ K})$$

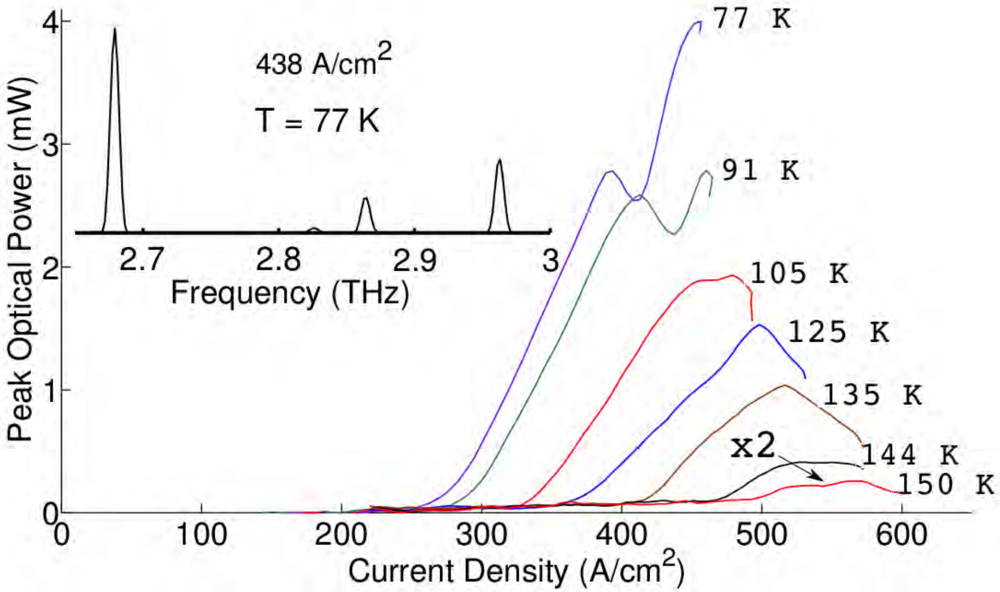
(c) - Incoherent resonant-tunneling transport at high temperatures



$$J_{i\to u} \propto \frac{1}{\tau_u}\left(1 - \frac{1}{4\Omega_{iu}^2\tau^*\tau_u + 1}\right)$$

Role of interface-roughness scattering: THz QCLs with shallow barriers





Design	$\tau_{\mathrm{IR},4\to3}$	$\tau_{\mathrm{IR},4\to2}$	$\tau_{\mathrm{IR},4\to3,2}$	$\tau_{\mathrm{LO},4\to3,2}$	$\tau_{4\to3,2}$
10 % Al barrier design (shown above)	9.4 ps	24.7 ps	6.8 ps	3.6 ps	2.3 ps
15 % Al barrier design (reference design)	5.3 ps	5.4 ps	2.7 ps	1.9 ps	1.1 ps

Khanal *et al.* ITQW Conf. (2013)

Interface roughness scattering is not dominant at high-temperatures

THz QCLs in different material systems

Material gain in intersubband transitions

$$G = gJ = \frac{4\pi e^2}{\varepsilon_0 n\, c}\;\frac{1}{2\gamma_{if} L_p} E_{if}\,|\mu_{if}|^2\,\tau_{if}\,J$$

For a fixed energy and current we obtain:

$|\mu_{if}|^2$

Dipole matrix element of the transition
Probability of making the transition *i* - *f*

τ_i

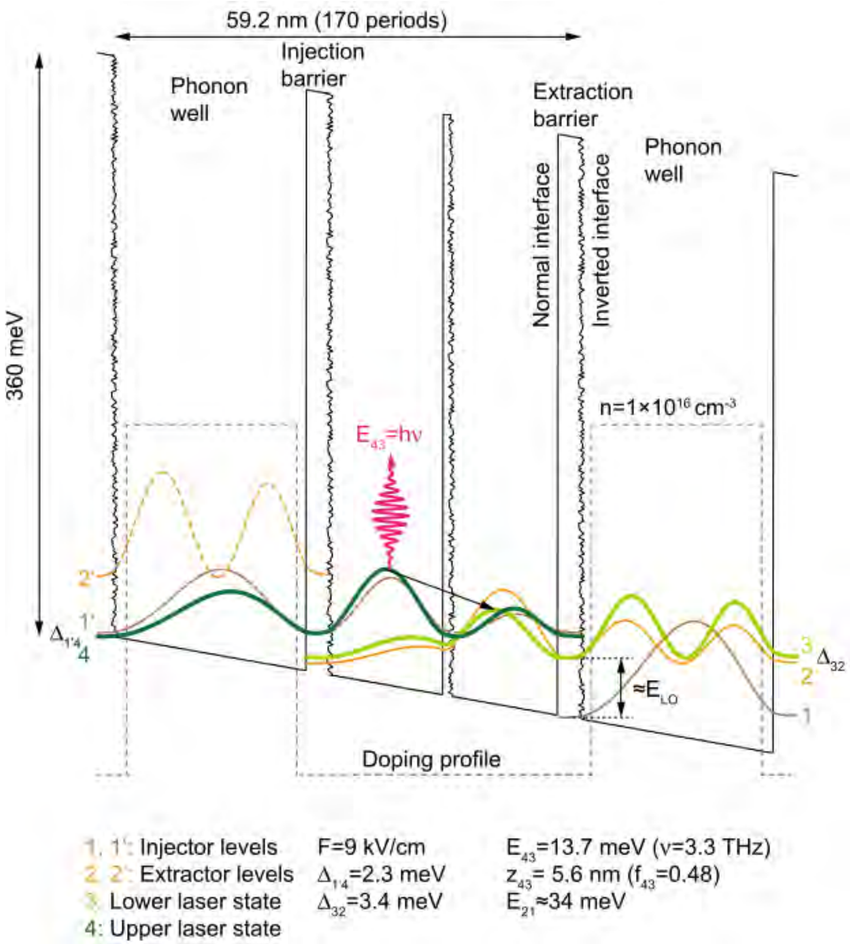
Lifetime of the upper state
Inverse of the probability for an electron to leave the upper state

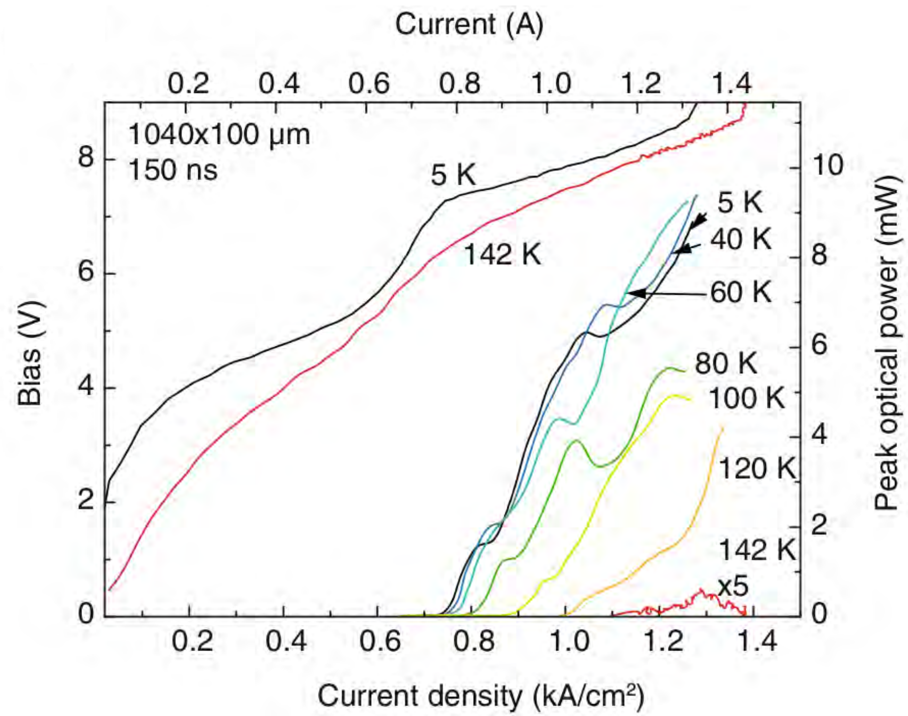
$$G \propto |\mu_{if}|^2\,\tau_i \propto \frac{1}{m^*\,(m^*)^{1/2}} = \frac{1}{(m^*)^{3/2}}$$

(C. Sirtori, 2006)

THz QCLs in different material systems

Material system	E_{CBO} (meV)	m^*_{Well}/m_0	$m^*_{Barrier}/m_0$	Substrate	THz QCL: injection barrier width (nm)
$GaAs/Al_{0.15}Ga_{0.85}As$	120	0.067	0.08	GaAs	4.6
$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$	520	0.043	0.075	InP	1.8
$In_{0.53}Ga_{0.47}As/GaAs_{0.51}Sb_{0.49}$	360	0.043	0.045	InP	3
$GaAs/Al_{0.4}Ga_{0.6}As$	360	0.067	0.104	GaAs	2

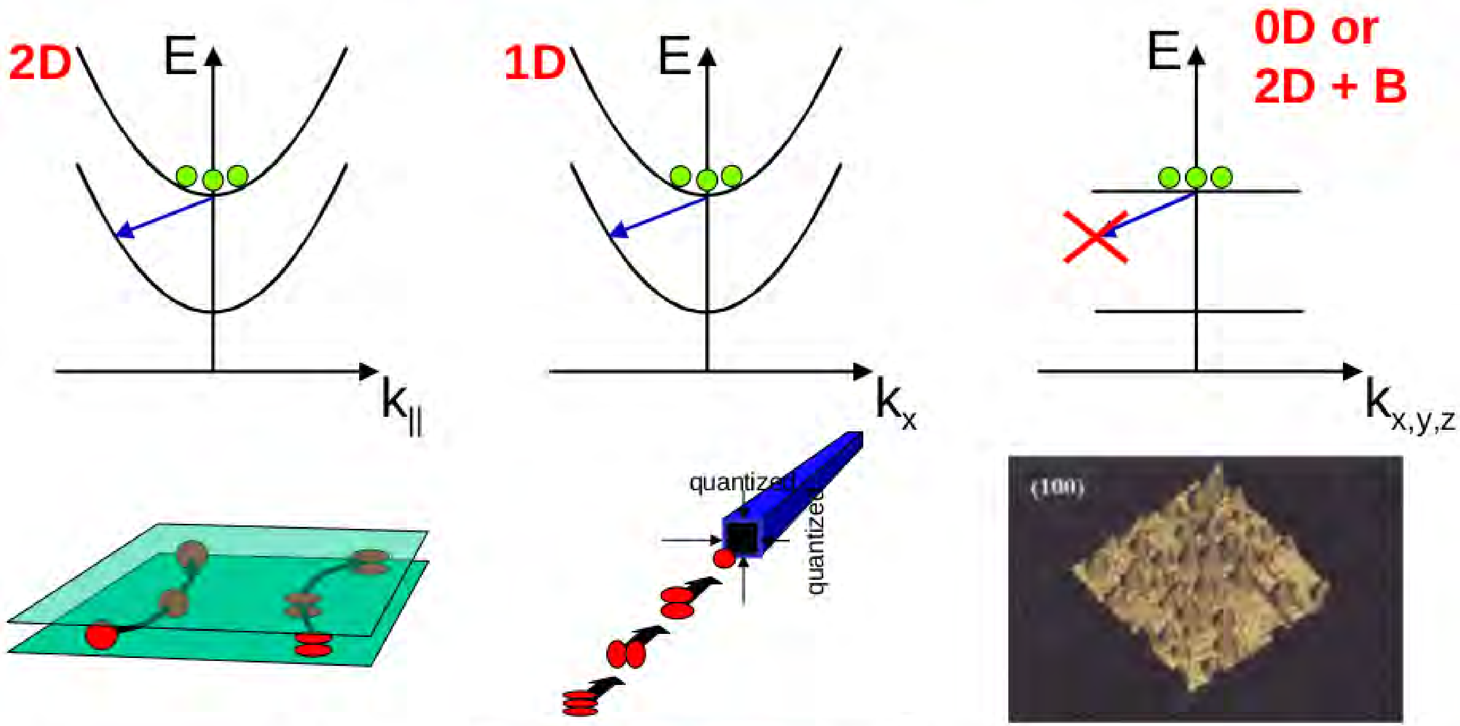




Deutsch *et al.* J.Inf.Milli.Tera.Waves (2013)

Towards intersubband lasing in lower dimensions

Phonon bottleneck



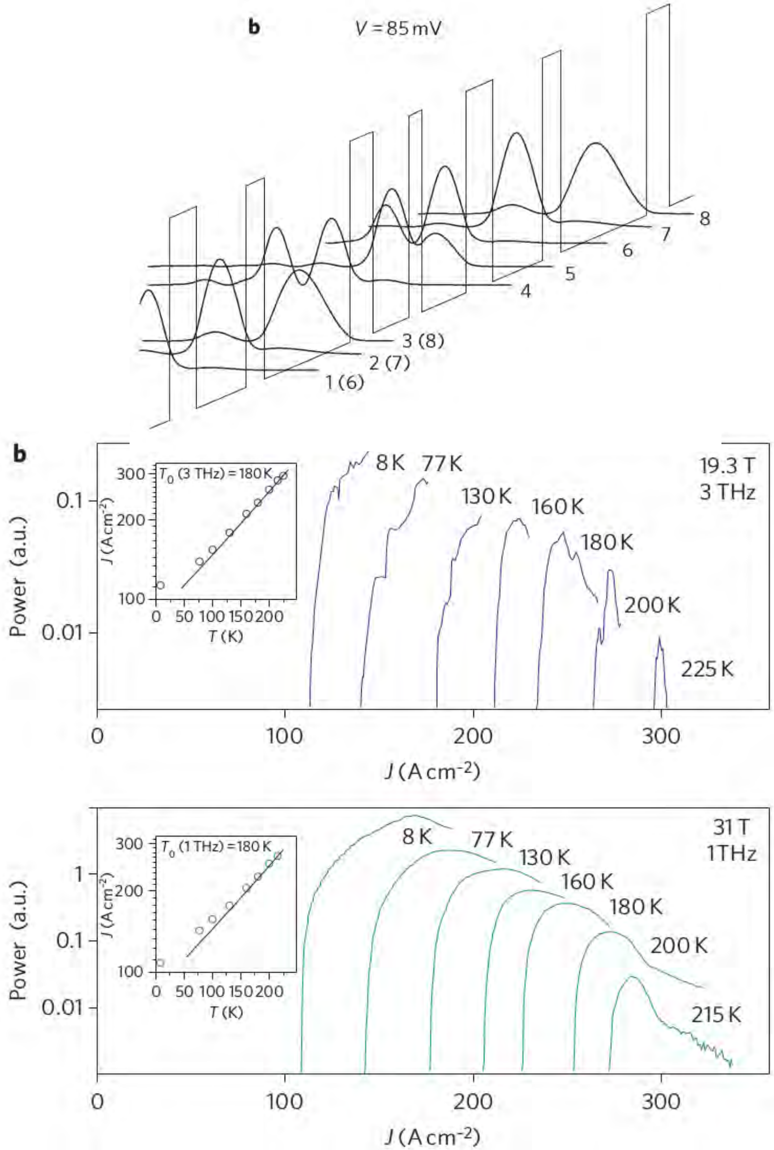
$\tau_{phonon} \cong 1ps$

$\tau_{1D} = 2\pi\,\tau_{2D}$
lift of the degeneracy

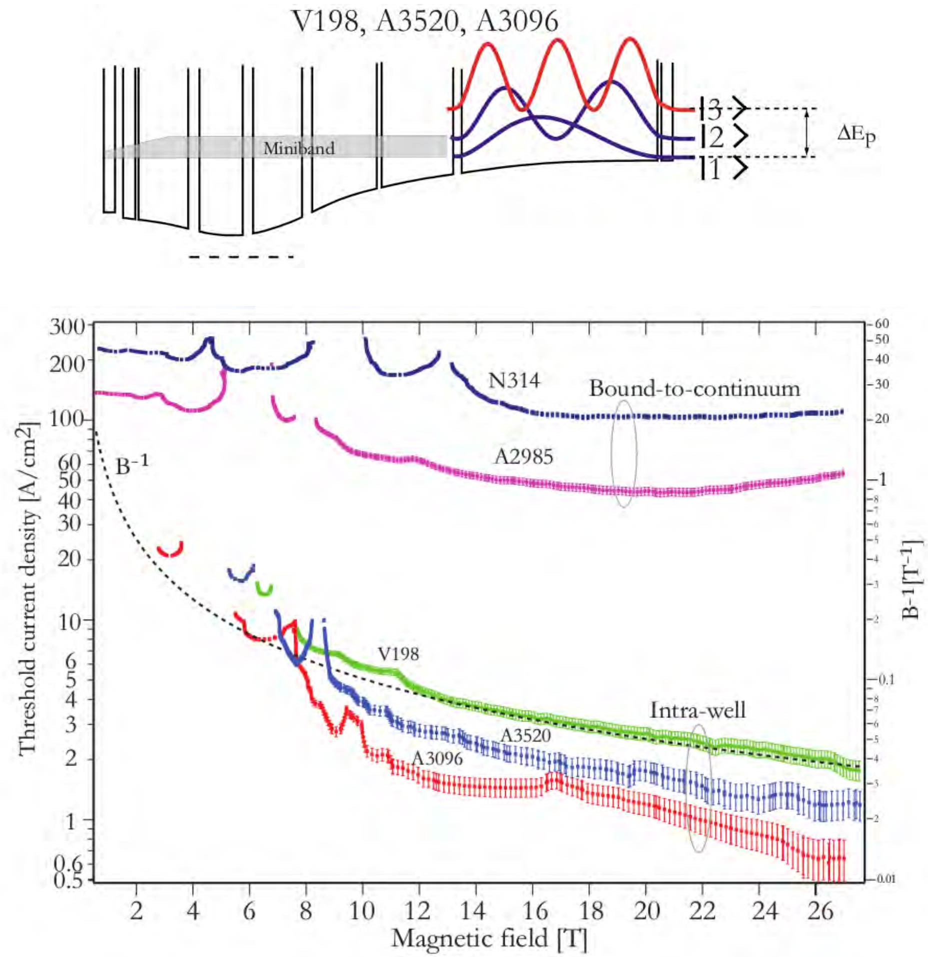
$\tau_{1D} = \infty$
Phonon bottleneck

(C. Sirtori, 2006)

THz QCL operation in high magnetic field

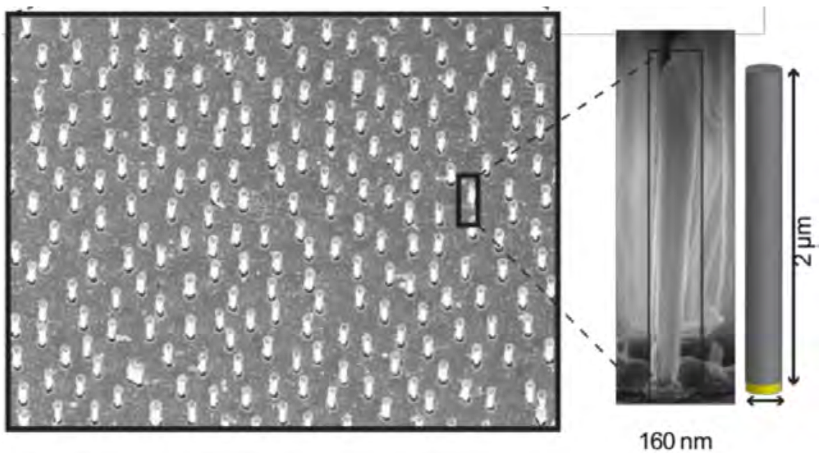


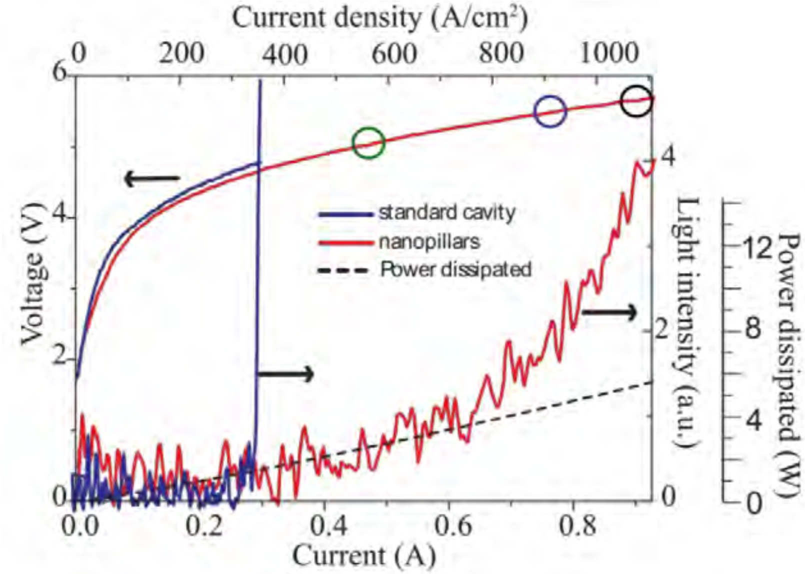
Wade *et al.* Nat. Photon. (2008)

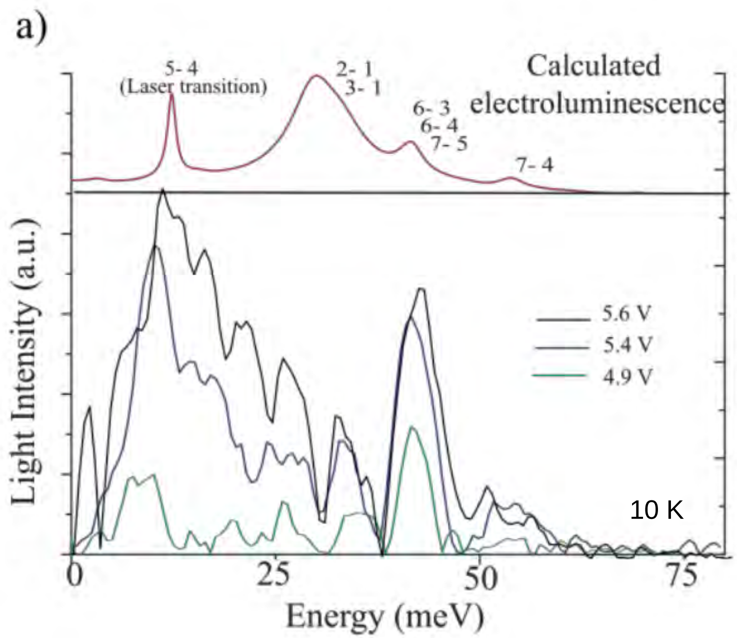


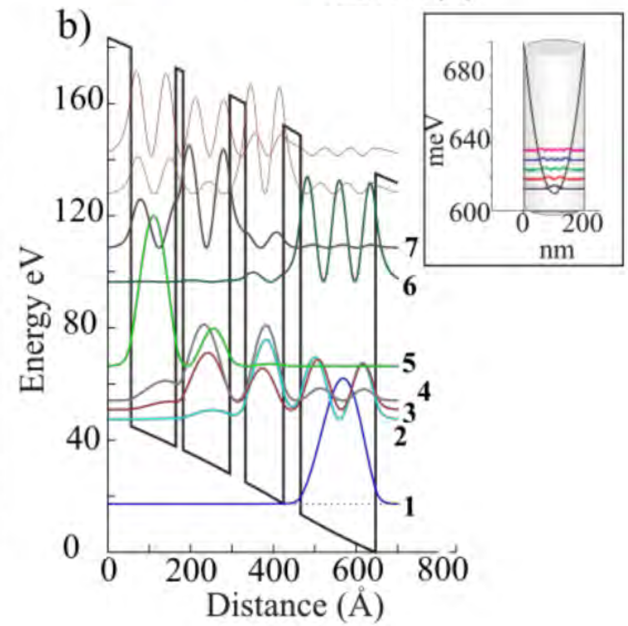
Scalari *et al.* PRB (2007)

Towards intersubband lasing in lower dimensions: nanopillars



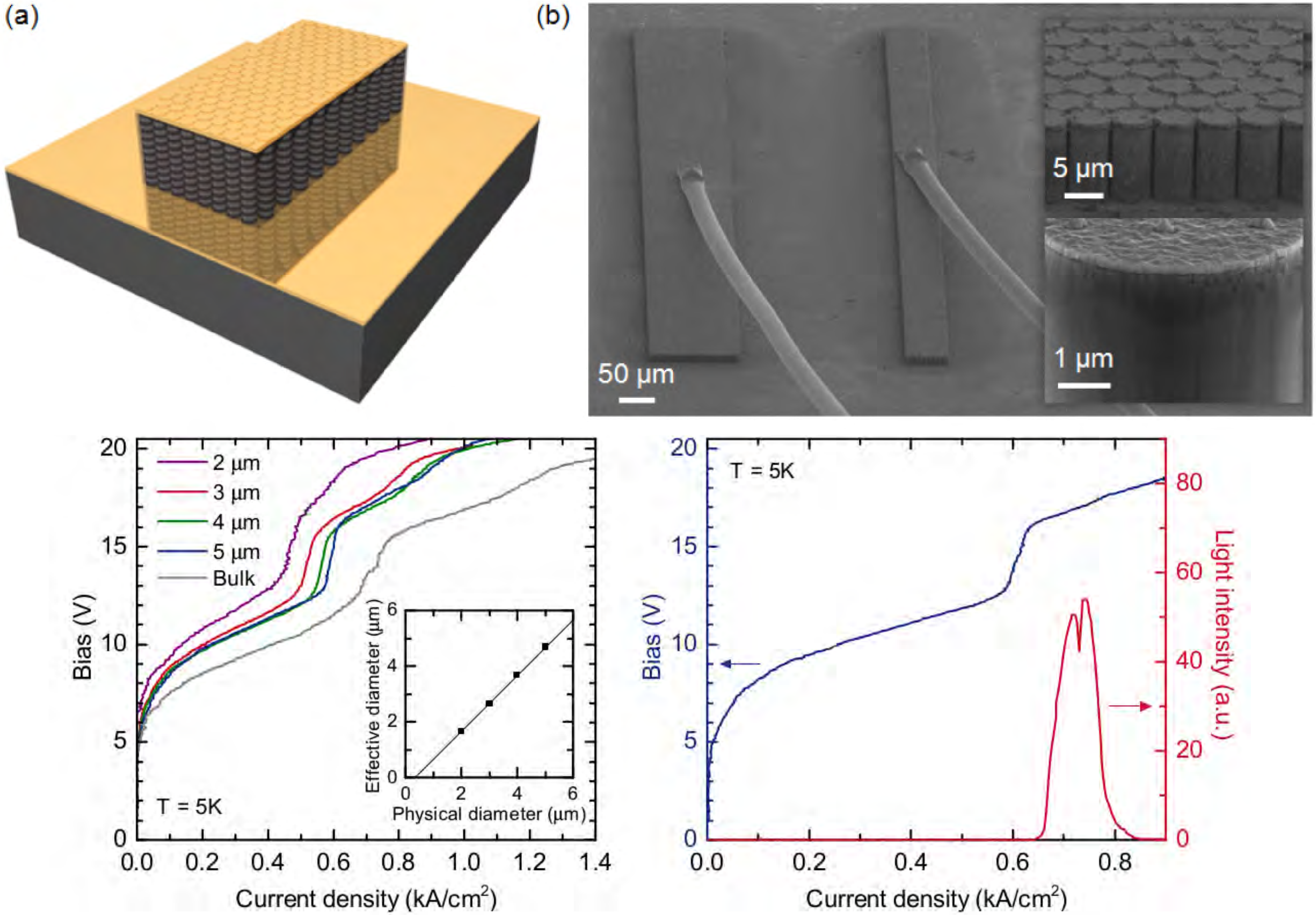






Amanti *et al.* Opt. Exp. (2013)

Micropillar array THz QCLs



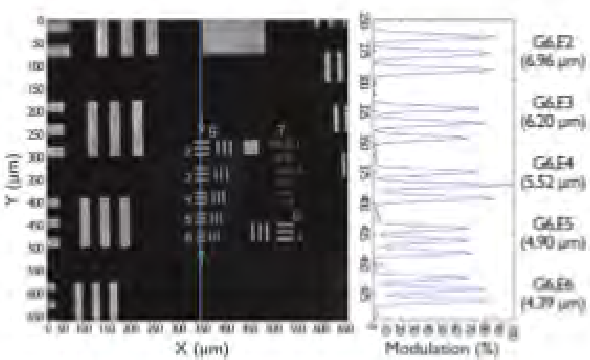
Krall *et al.* Opt. Exp. (2014)

Future: A QCL based THz microscope similar to...

Spero™

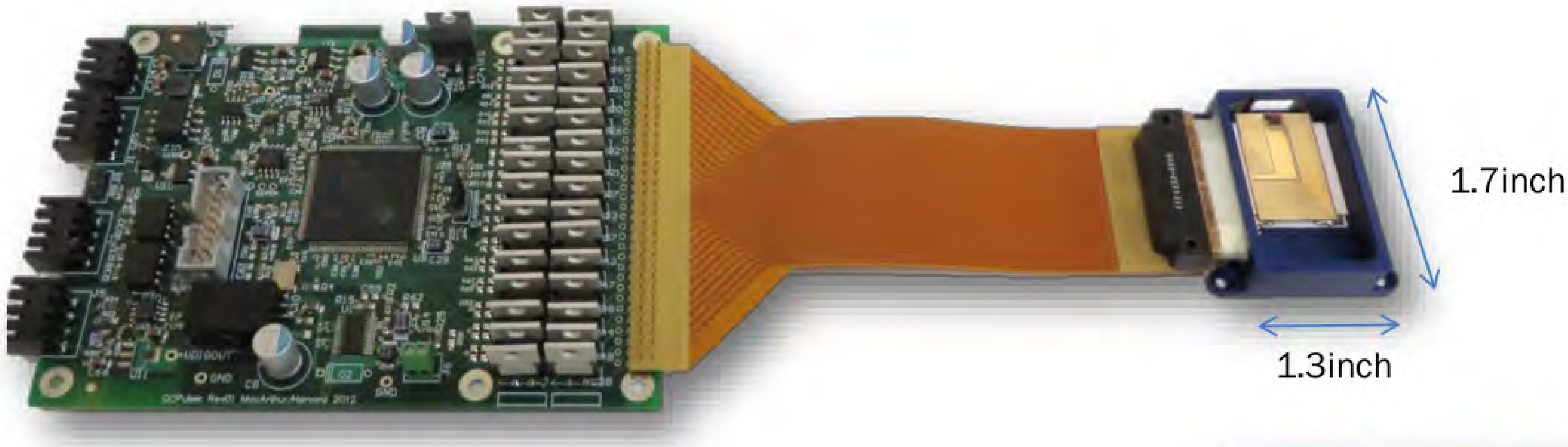
Shining a New Light on Infrared Imaging™

- Designed specifically for mid-infrared spectral imaging analysis of biomedical and materials research samples
- High-brightness tunable laser source
- Spectral coverage across the entire mid-infrared "fingerprint region"
- Rapid acquisition of full spectrum hyperspectral datacubes
- 2 infrared objectives and 1 visible objective
- Transmission and reflection modes
- Large format uncooled focal plane array
- Real-time discrete frequency IR imaging at video frame rates
- Fully automated stage
- Instrument control and data display via Ethernet to PC
- Small instrument footprint



High-resolution, wide-field IR image illuminated at 1555 cm⁻¹ demonstrating diffraction-limited resolution below 5 µm and a pixel resolution of 1.4 µm.

Future: THz QCL arrays, similar to...



The Matchbox 100: A MIR QCL array from EOS photonics
(32 DFB lasers, 100 cm^{-1} discrete tunability)

End of presentation