THz QCL sources for operation above cryogenic temperatures

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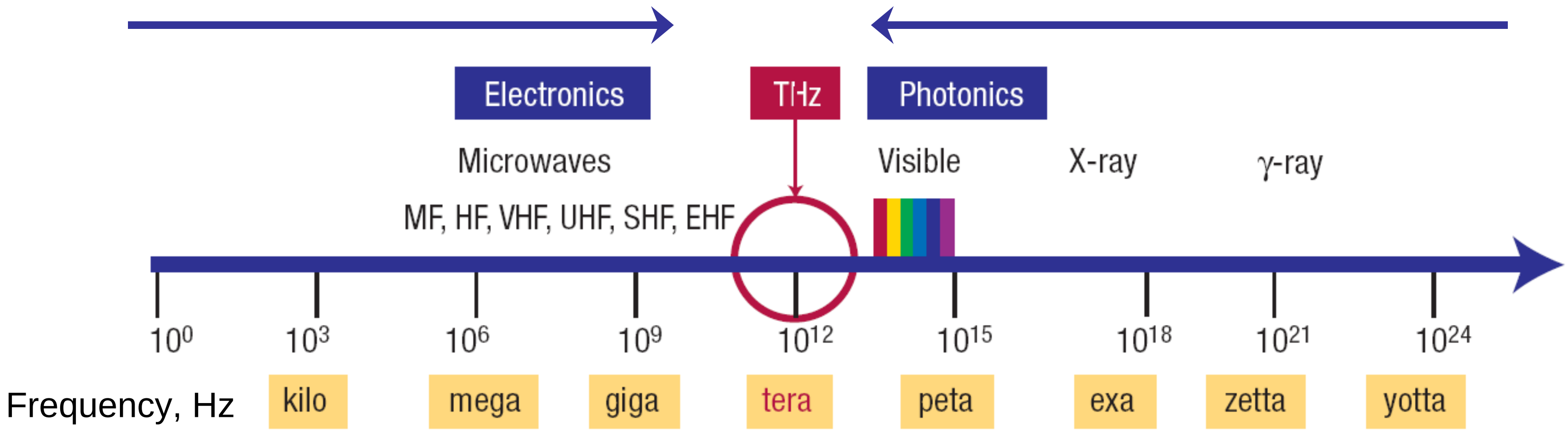
IQCLSW, Monte Verita, Switzerland 2008

Need for semiconductor THz source

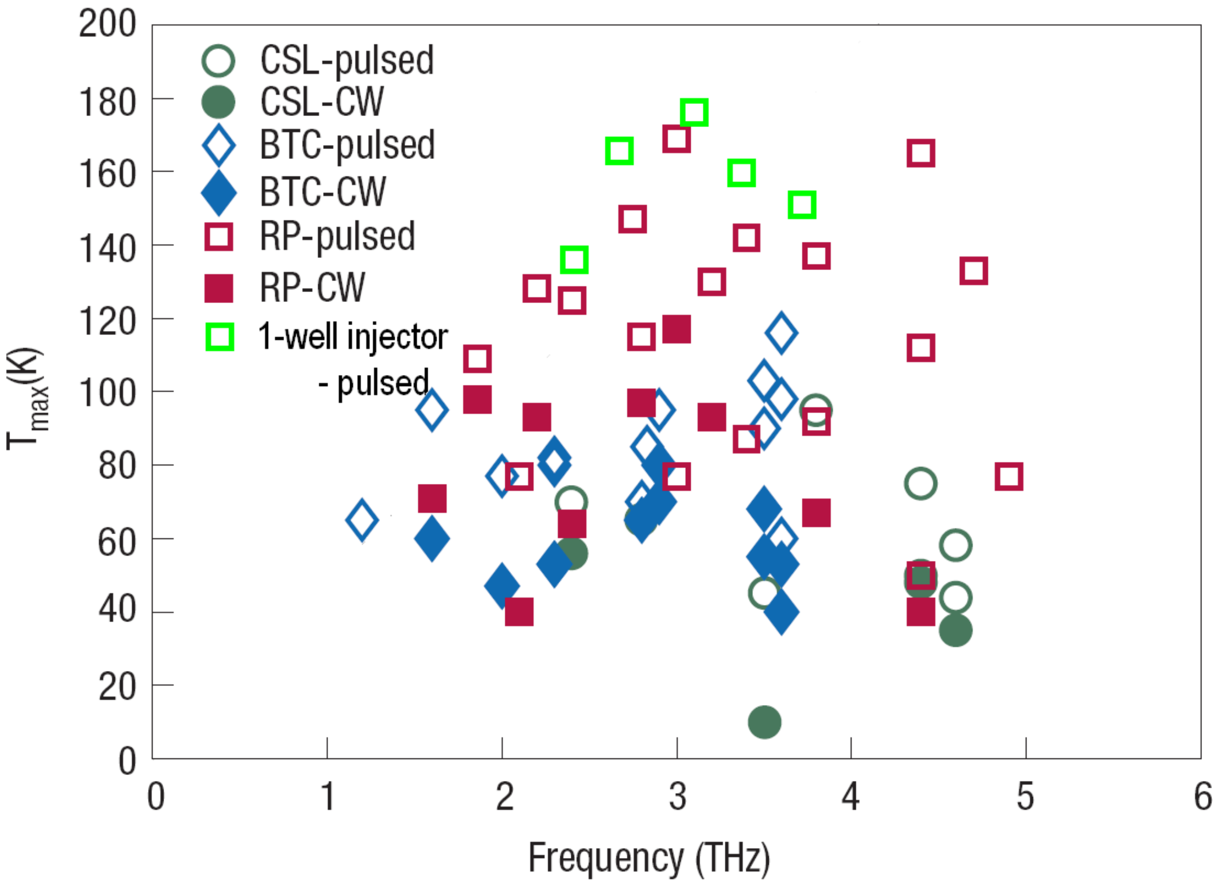


- Spectroscopy
- Local oscillator for THz heterodyning
- Remote sensing, screening, inspection, etc.
- THz frequency amplification

THz Quantum Cascade Lasers

UNIVERSITY OF TEXAS AT AUSTIN

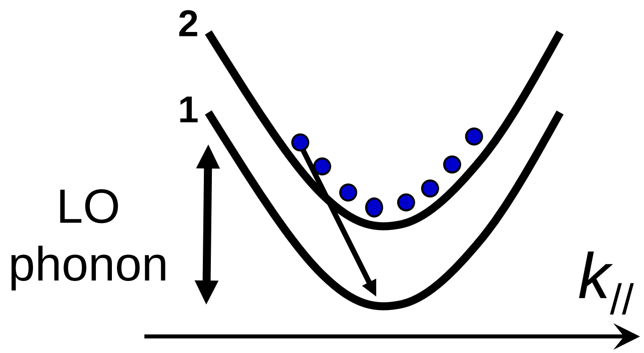
Maximum operating temperature VS frequency



BS Williams, Nature Photonics 1, 517-525 (2007) +

2008 data of Capasso, Colombelli, and Linfield groups

Upper laser state lifetime vs T



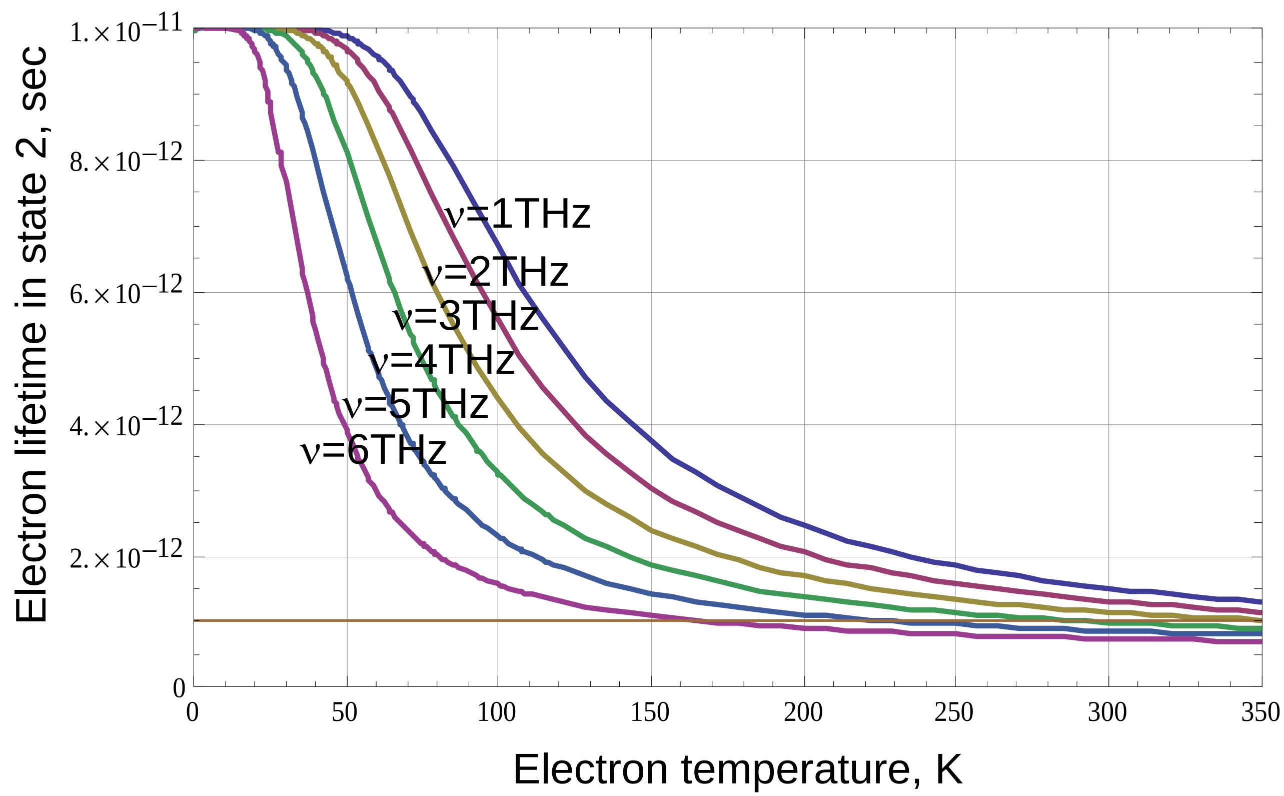
LO phonon scattering of thermal electrons:

$\tau_{upper}(E_{//} < E_{LO} - h\nu) = 10ps$

$\tau_{upper}(E_{//} > E_{LO} - h\nu) = 0.5ps$

Assume 2D Fermi distribution in state 2 and low population in state 1

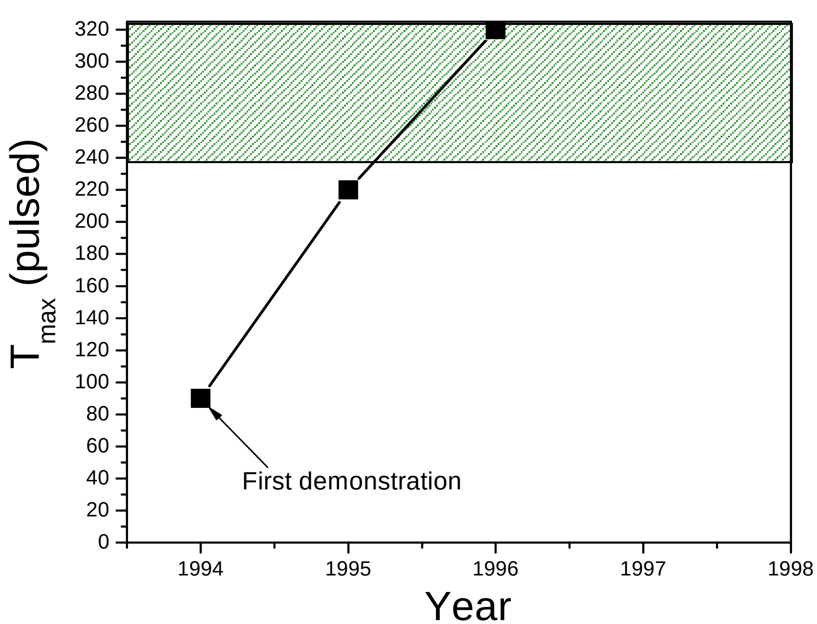
$E_{LO} = 36meV \leftrightarrow 8.7\ THz$



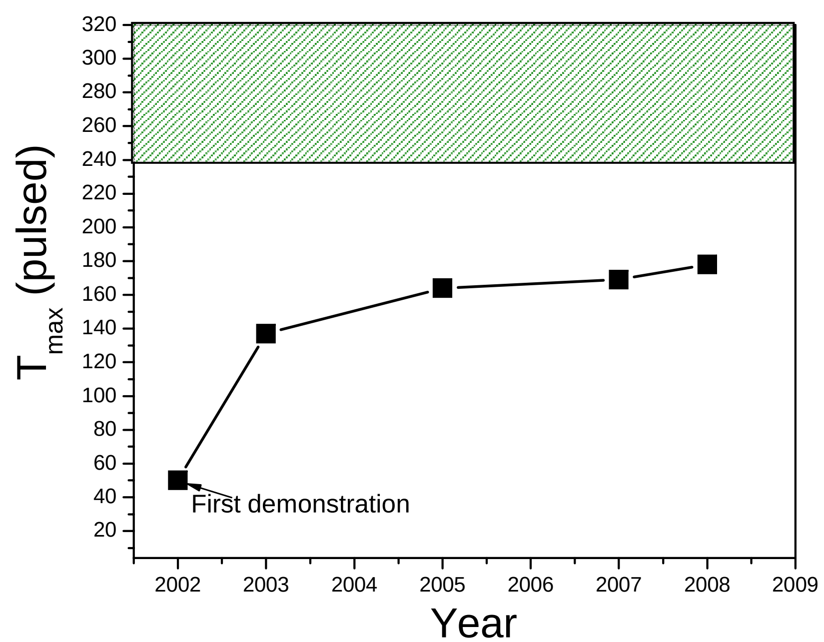
RT THz QCLs: very difficult

Upper state lifetime <2ps for temperature >200K
This lifetime is similar to that in mid-IR QCLs
BUT, THz QCLs have higher w/g losses and smaller injection efficiency

Mid-IR QCLs



THz QCLs



Nevertheless, no fundamental limit on RT operation

Room-temperature THz source?

1. Investigate alternative designs, improve GaAs/AlGaAs quality, try different materials (InGaAs/AlInAs, Si/SiGe, AlGaN/GaN), low-dimensional systems (quantum dots, wires), etc.

2. Develop semiconductor THz sources that do not require population inversion across the THz transition

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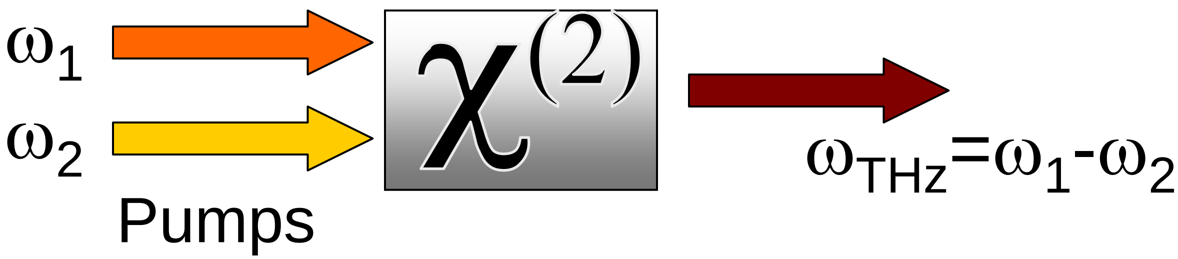
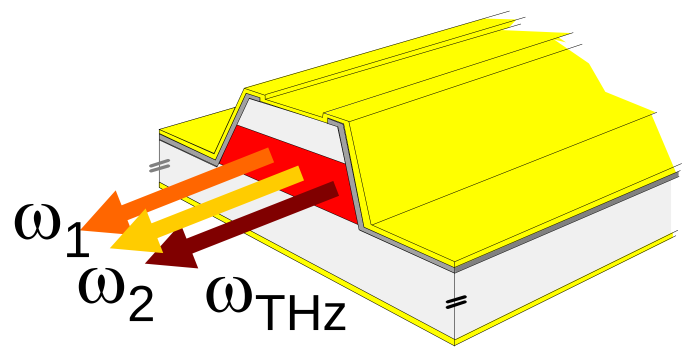
Difference Frequency Generation

Difference-frequency generation (DFG) occurs in a medium with second-order nonlinear susceptibility $\chi^{(2)}$



THz QCL source using intra-cavity DFG

- *Dual-frequency mid-infrared QCLs with $\chi^{(2)}$*
- *THz radiation is generated via intra-cavity DFG*
- *Widely tunable THz source at RT*



Challenges for intra-cavity THz DFG

$$I(\omega_{THz}) \propto \left|\chi^{(2)}\right|^2 I(\omega_1) I(\omega_2) \times l_{coh}^2$$

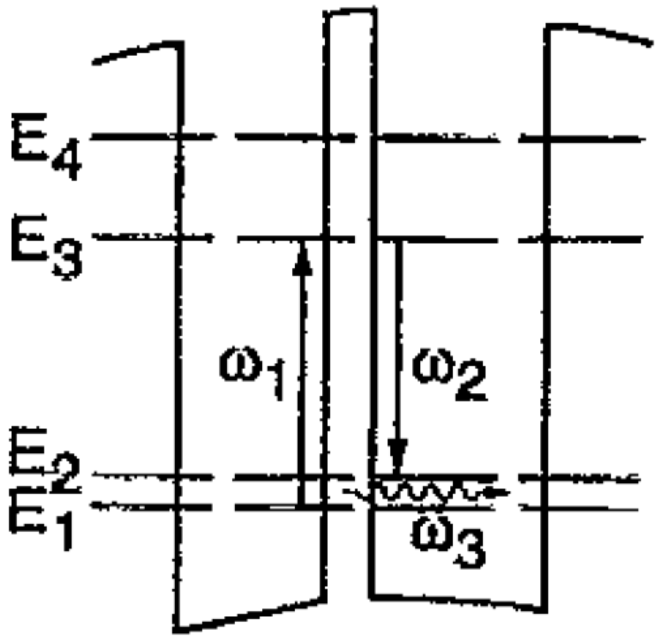
$$l_{coh}^2 = 1 \Big/ \left((k_1 - k_2 - k_{THz})^2 + (\alpha_{THz})^2 \right)$$

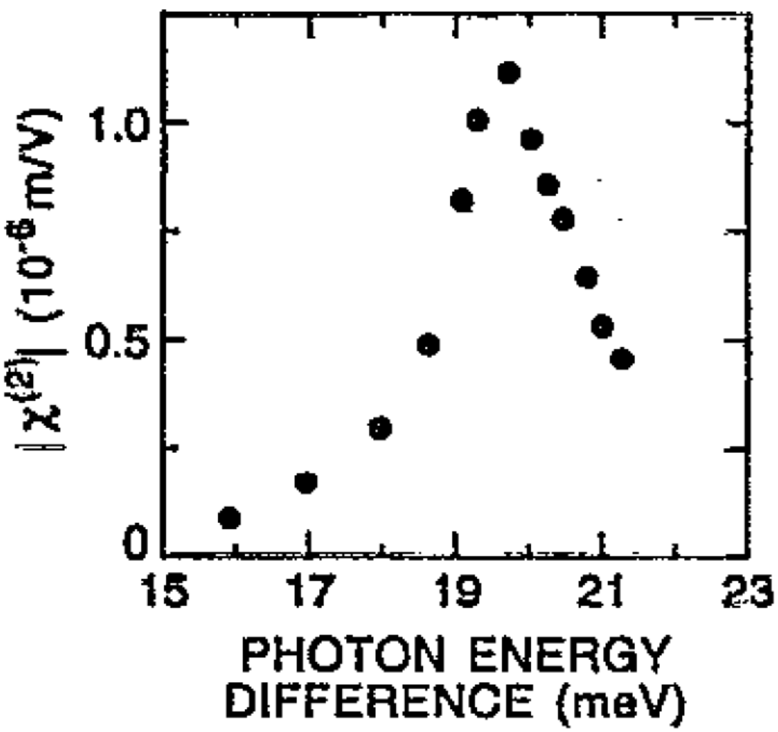
	Solid-state systems	QCLs
$I(\omega_1), I(\omega_2)$	100 -1000 MW/cm^2	1-10 MW/cm^2
l_{coh}	$\gtrsim$10 mm	$\lesssim$0.2mm
$\chi^{(2)}$	~100 pm/V	can be designed

Need giant $\chi^{(2)}$

Giant $\chi^{(2)}$ in quantum wells

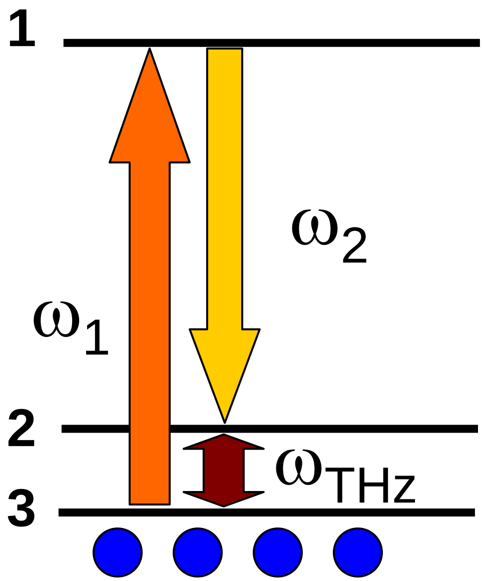
$$\chi^{(2)} = N_e \frac{e^3}{\hbar^2 \varepsilon_0} \times \sum_{n,n'} \frac{z_{1n} z_{nn'} z_{n'1}}{\left(\omega - \omega_{nn'} + i\Gamma_{nn'}\right)} \left(\frac{1}{\left(\omega_1 + \omega_{n'1} + i\Gamma_{n'1}\right)} + \frac{1}{\left(-\omega_2 - \omega_{n1} + i\Gamma_{n1}\right)} \right)$$





Sirtori et al., APL (1994)

Giant $\chi^{(2)}$ in quantum wells



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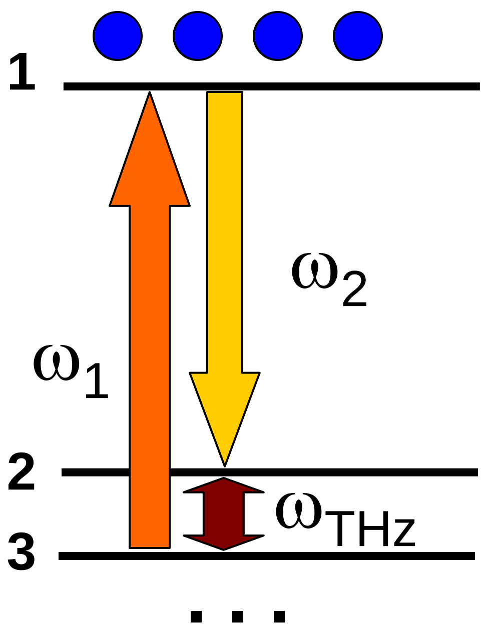
Giant absorption!

$\chi^{(2)}$ with population inversion



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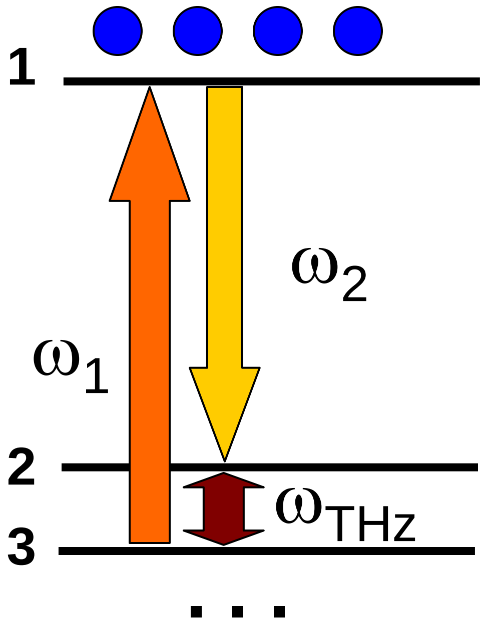
Laser action instead of absorption!

Gmachl, Belyanin, et al., JQE (2003)

$\chi^{(2)}$ with population inversion



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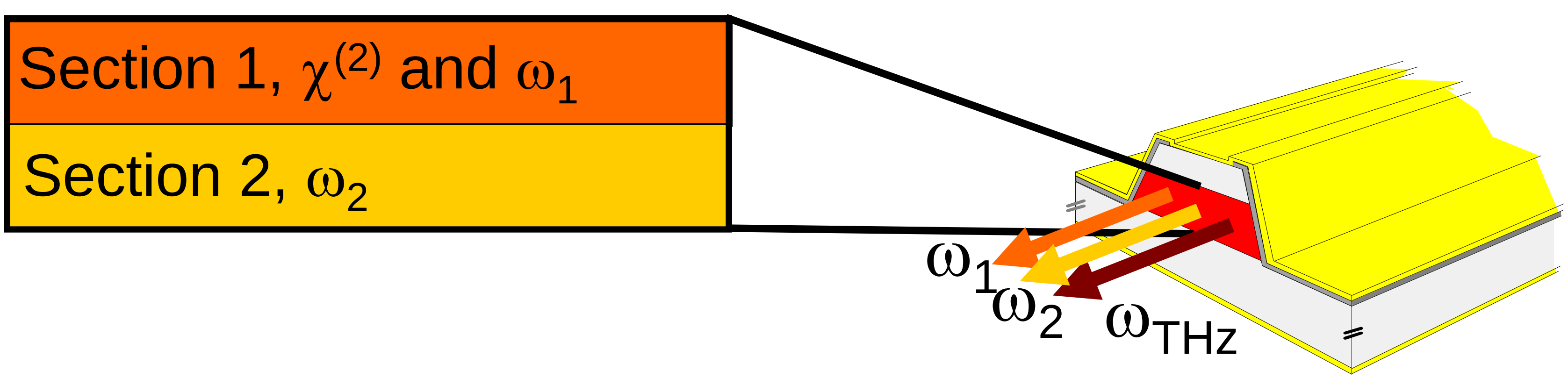
Laser action instead of absorption!

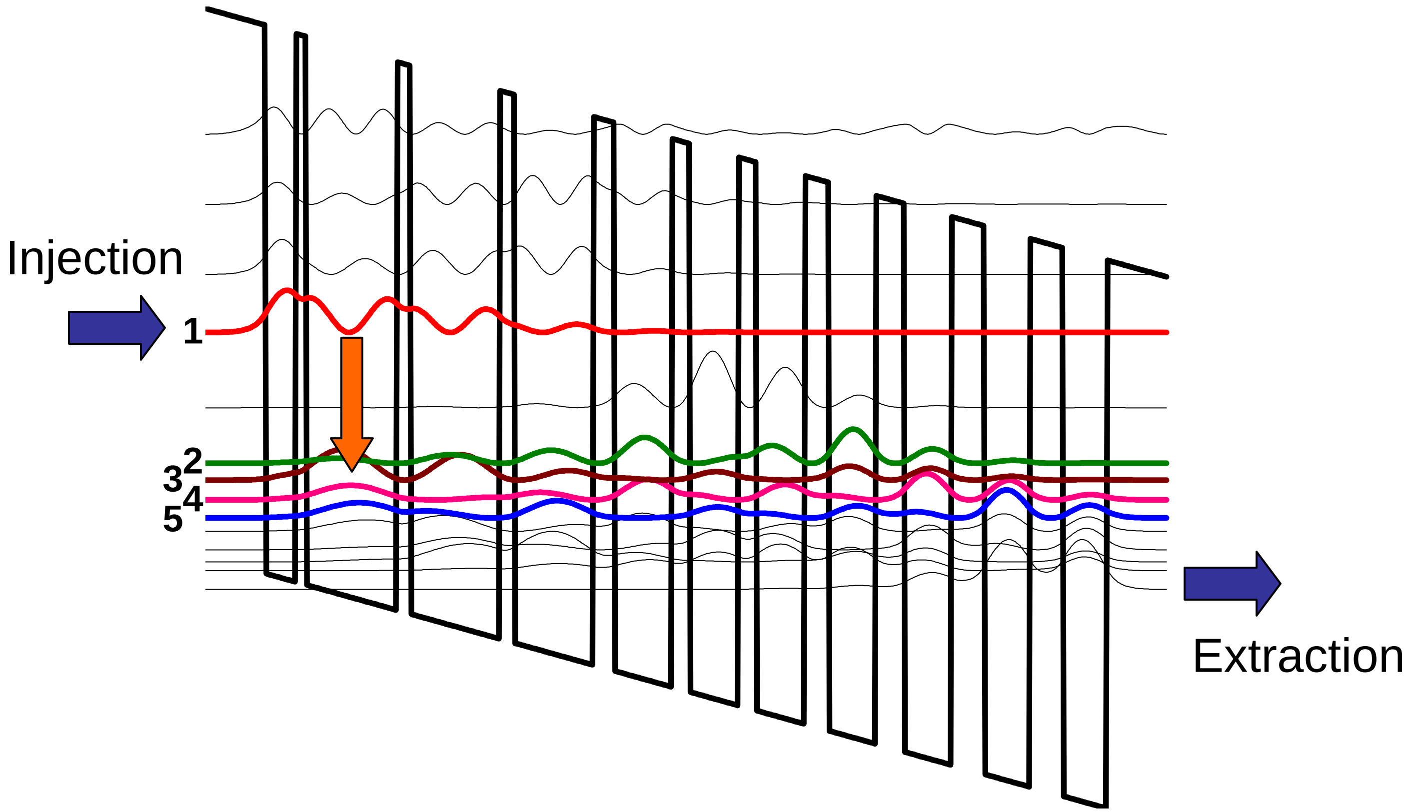
Active region design



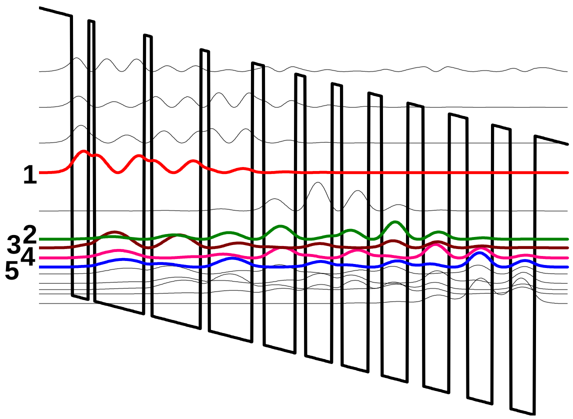
χ(2)-section design

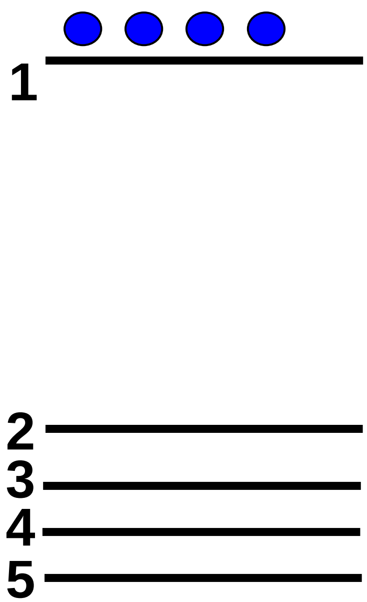
Bound-to-continuum active region for λ≈9μm

[Faist et al. IEEE JQE (2002)]

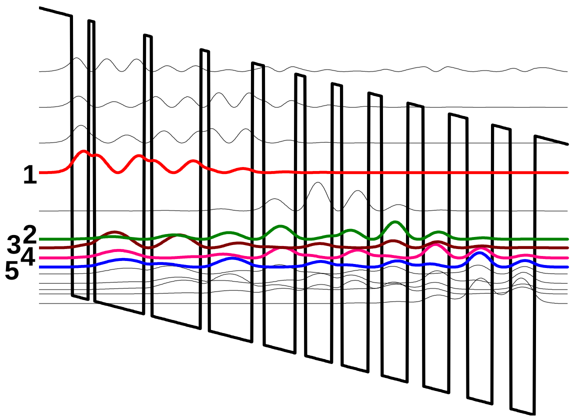


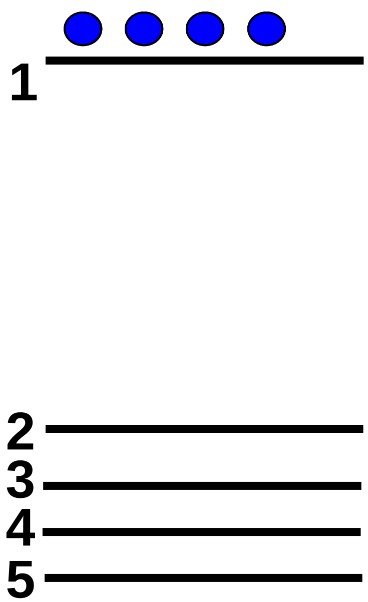
$\chi^{(2)}$-section design

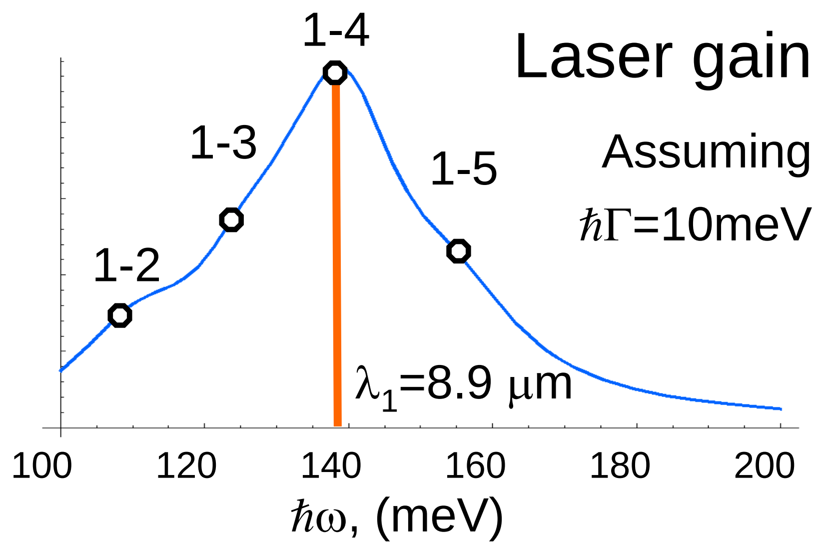




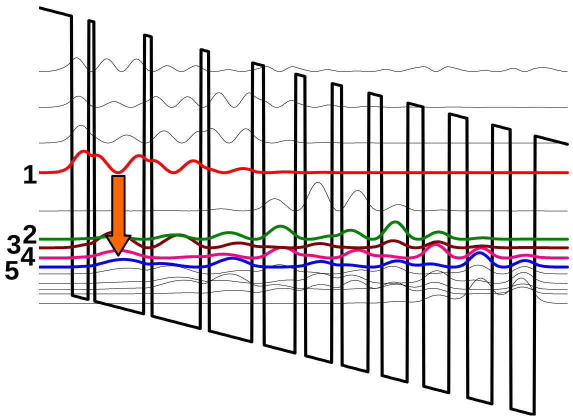
$\chi^{(2)}$-section design

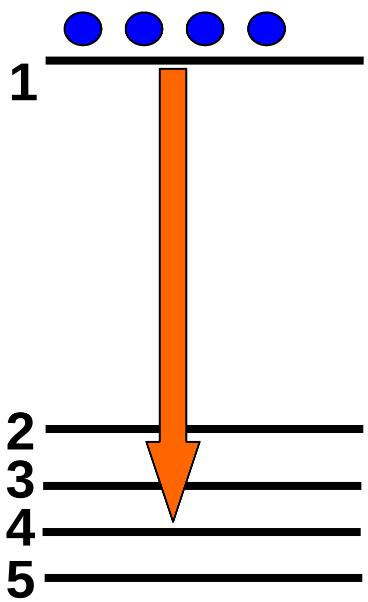


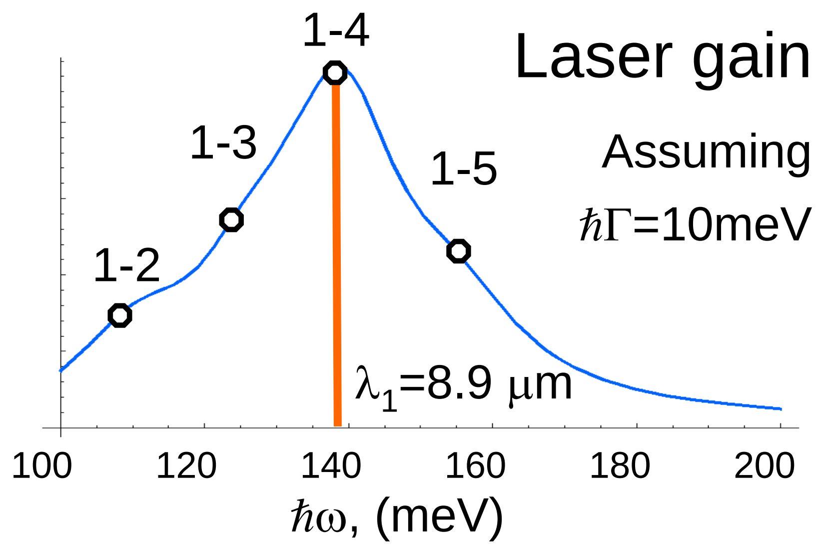




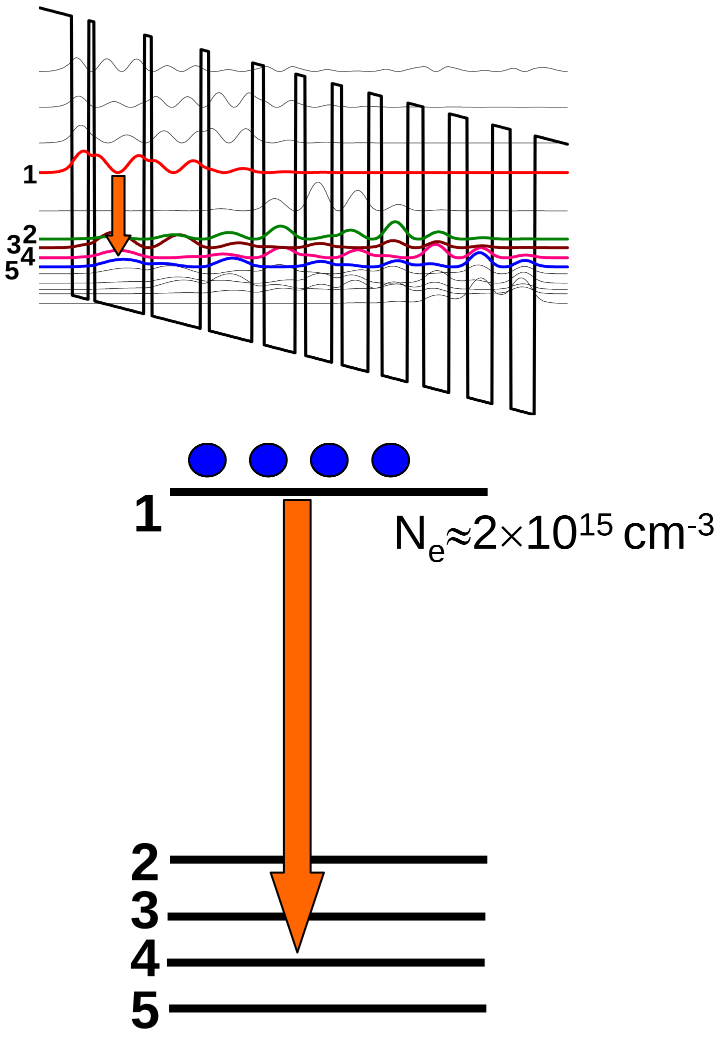
$\chi^{(2)}$-section design

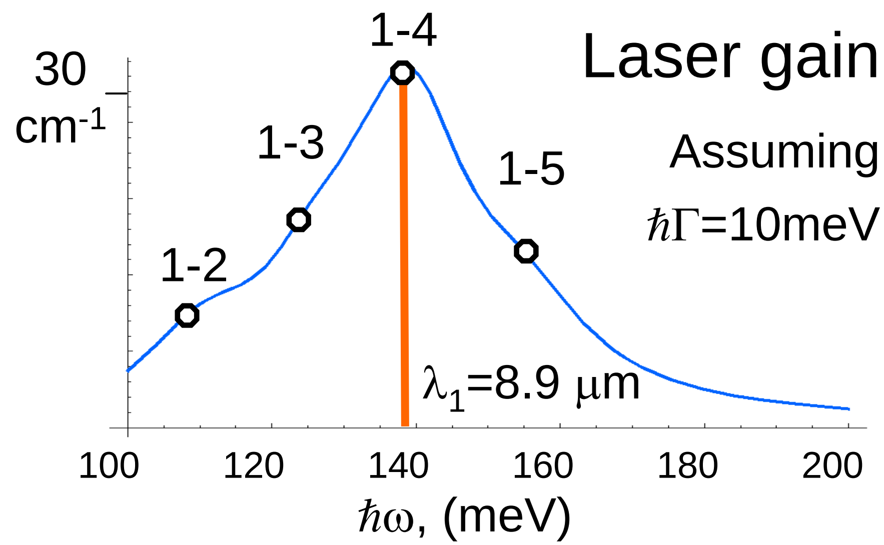




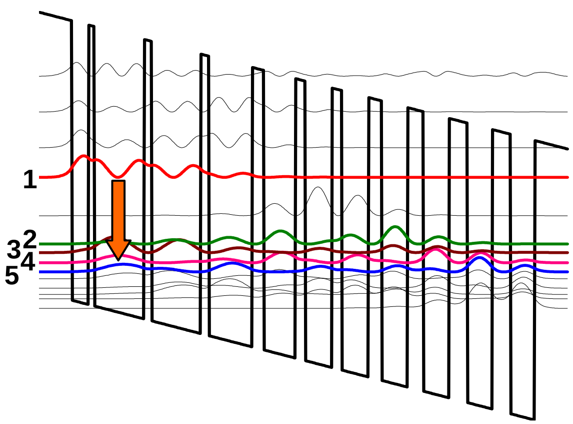


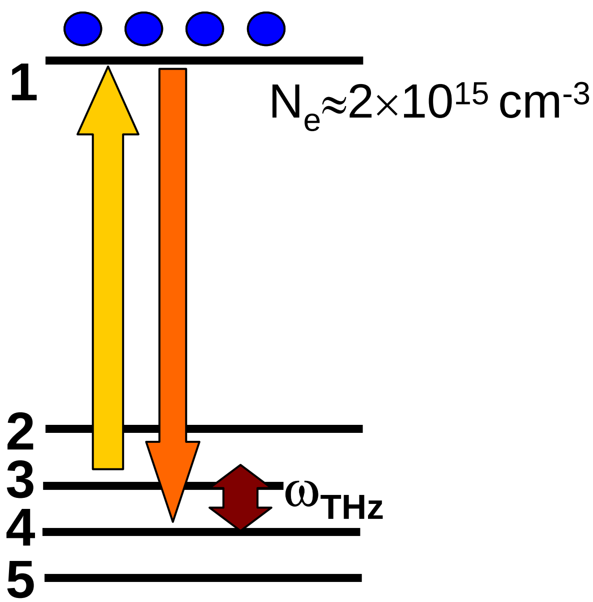
$\chi^{(2)}$-section design

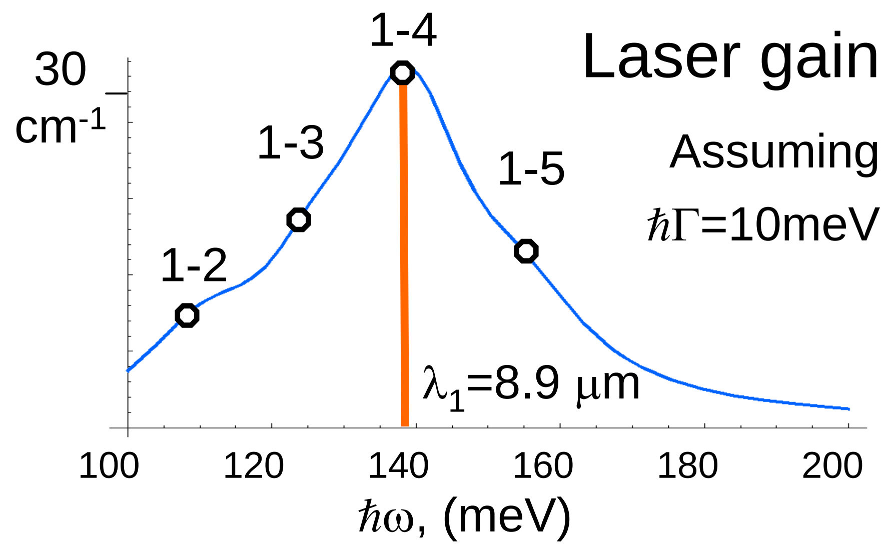




$\chi^{(2)}$-section design







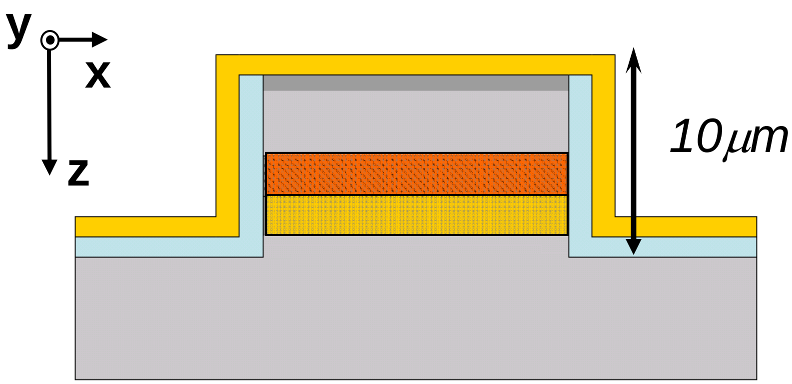
$\lambda_1 = 8.9\ \mu m$

$\lambda_2 = 10.5\mu m$

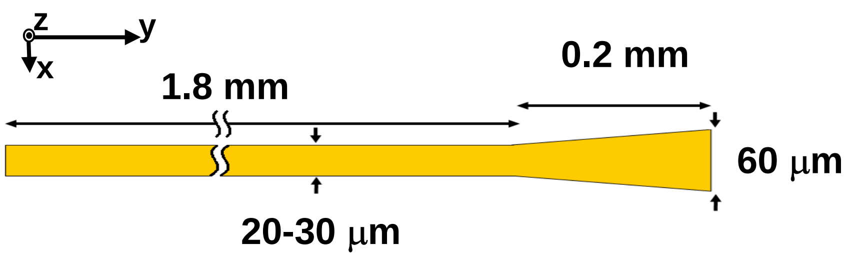
$\Rightarrow$ $\lambda_{THz} = 60\ \mu m$

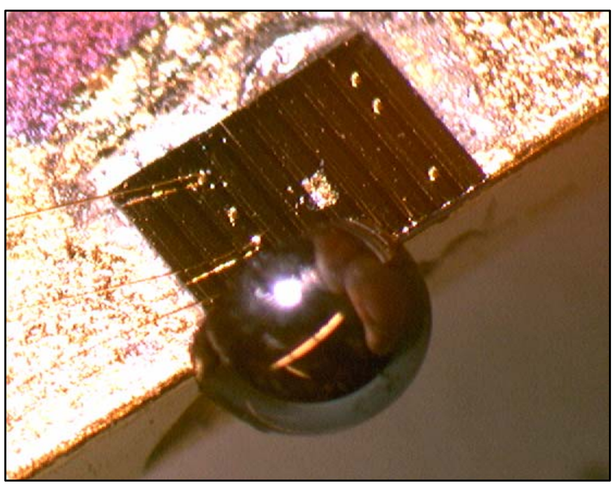
$\chi^{(2)} \approx 3\times10^4\ pm/V$

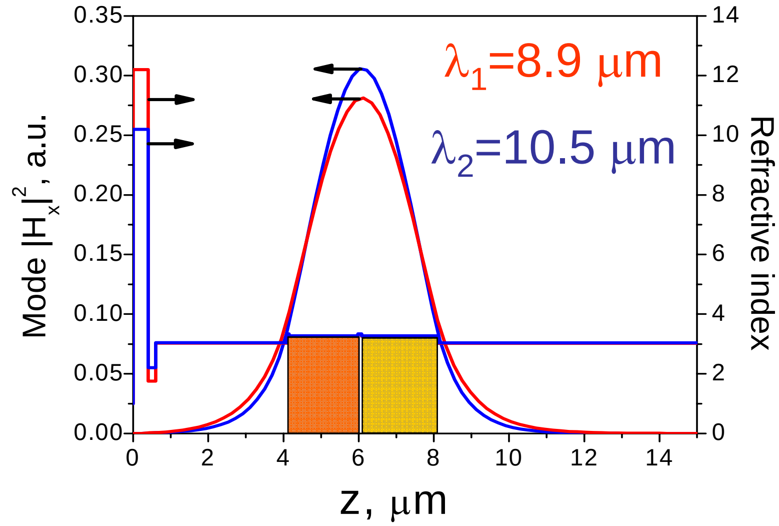
Waveguide design

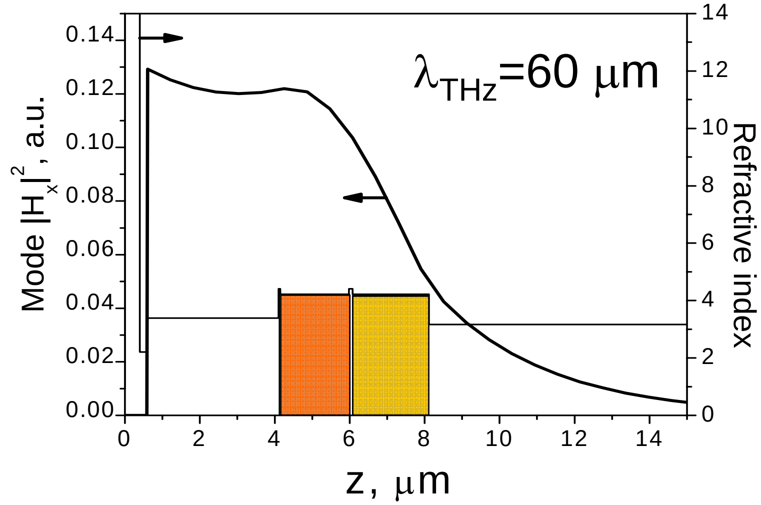


30 stages of each QCL structure





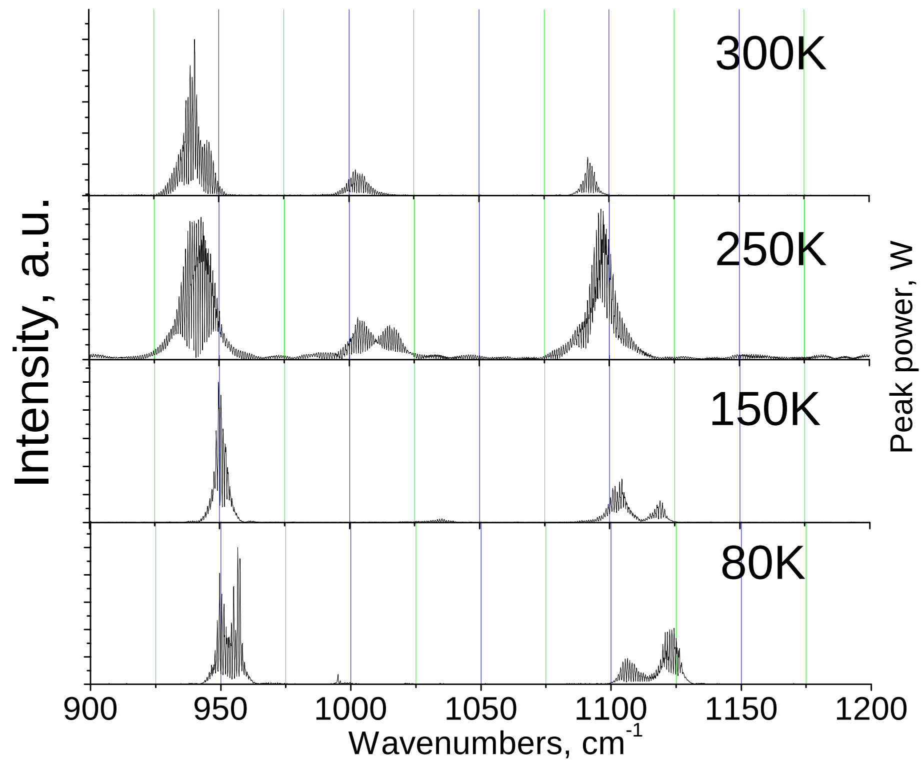




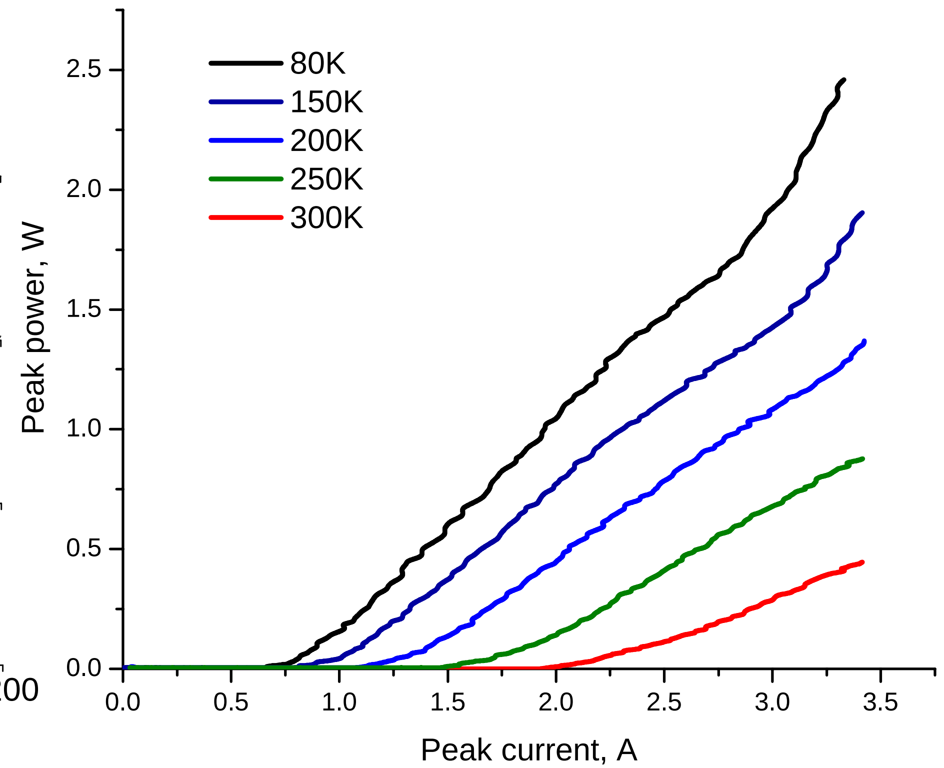
$l_{coh}=70\mu m$

Device performance: mid-IR

Spectra



Power (combined)



25-µm-wide, tapered to 50-µm-wide, 2-mm-long, back facet HR coating.
Testing in pulsed mode (60ns pulses at 250kHz).

Device performance: mid-IR

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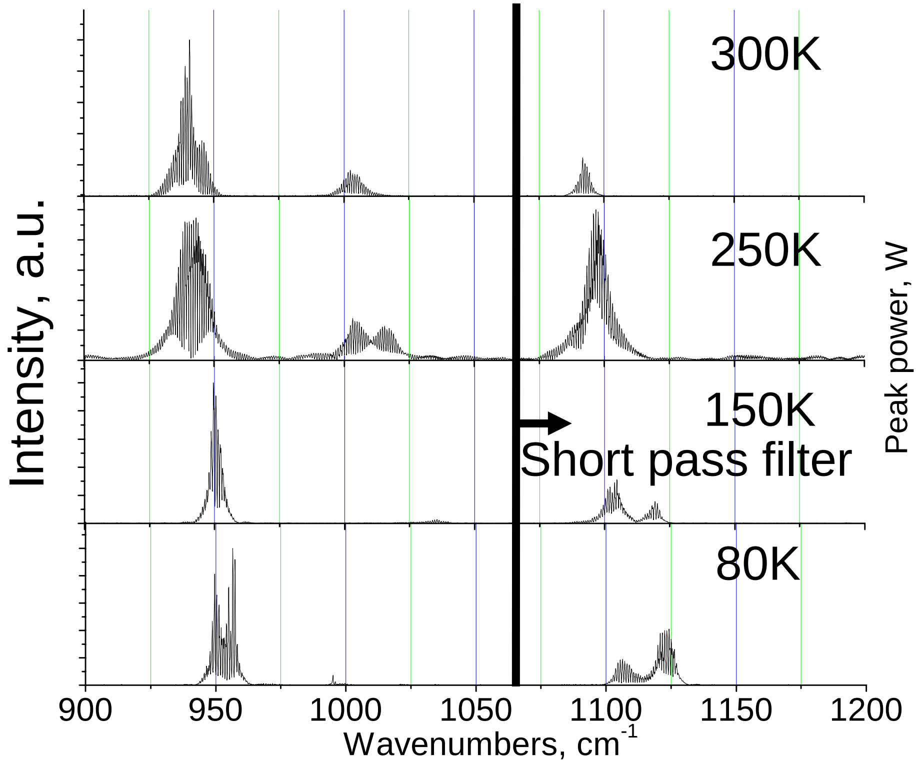

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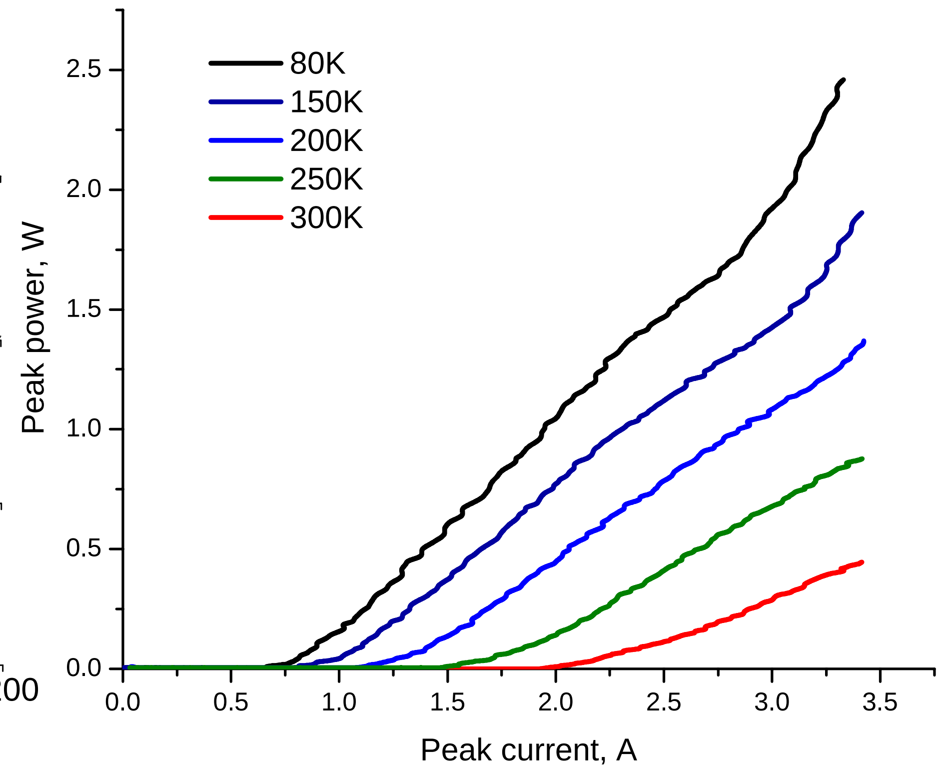
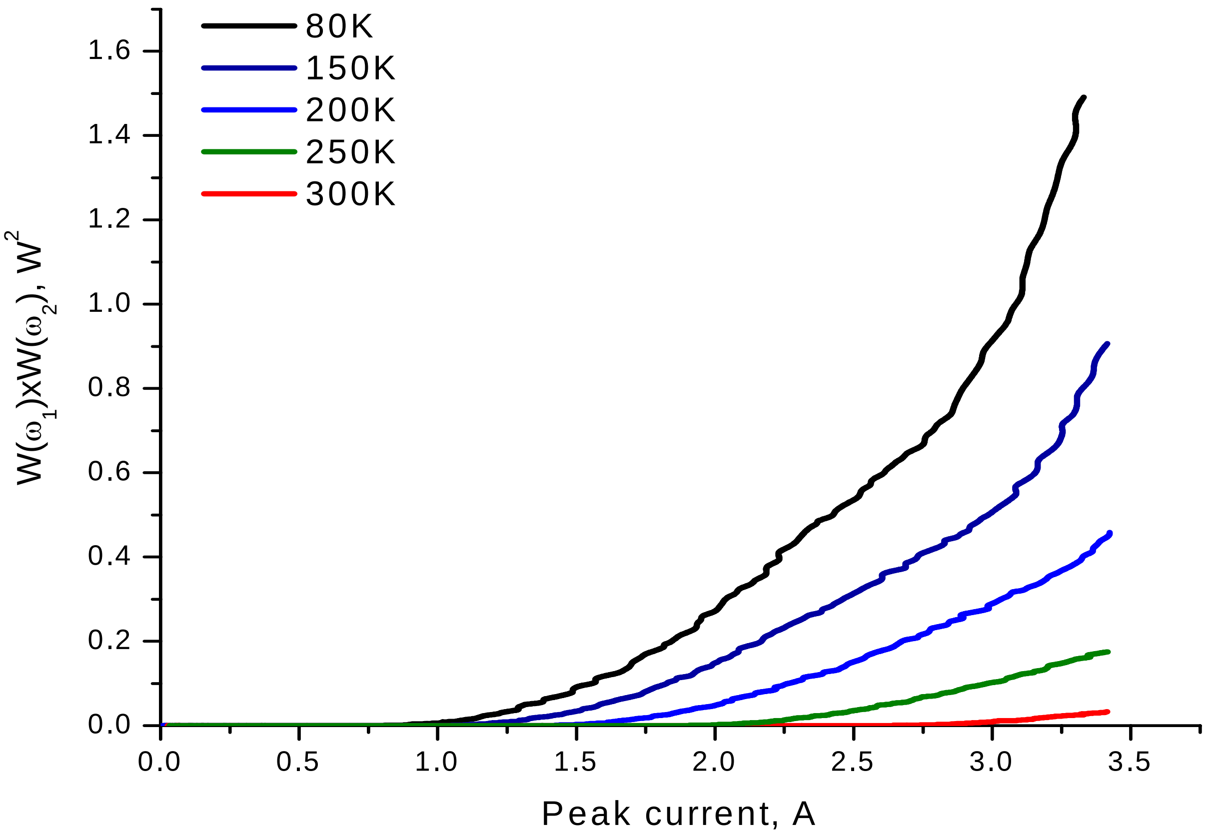


25-µm-wide, tapered to 50-µm-wide, 2-mm-long, back facet HR coating.
Testing in pulsed mode (60ns pulses at 250kHz).

Product of the pump powers

$$W(\omega_{THz}) \propto \left|\chi^{(2)}\right|^2 W(\omega_1) W(\omega_2) \times l_{eff}^2$$



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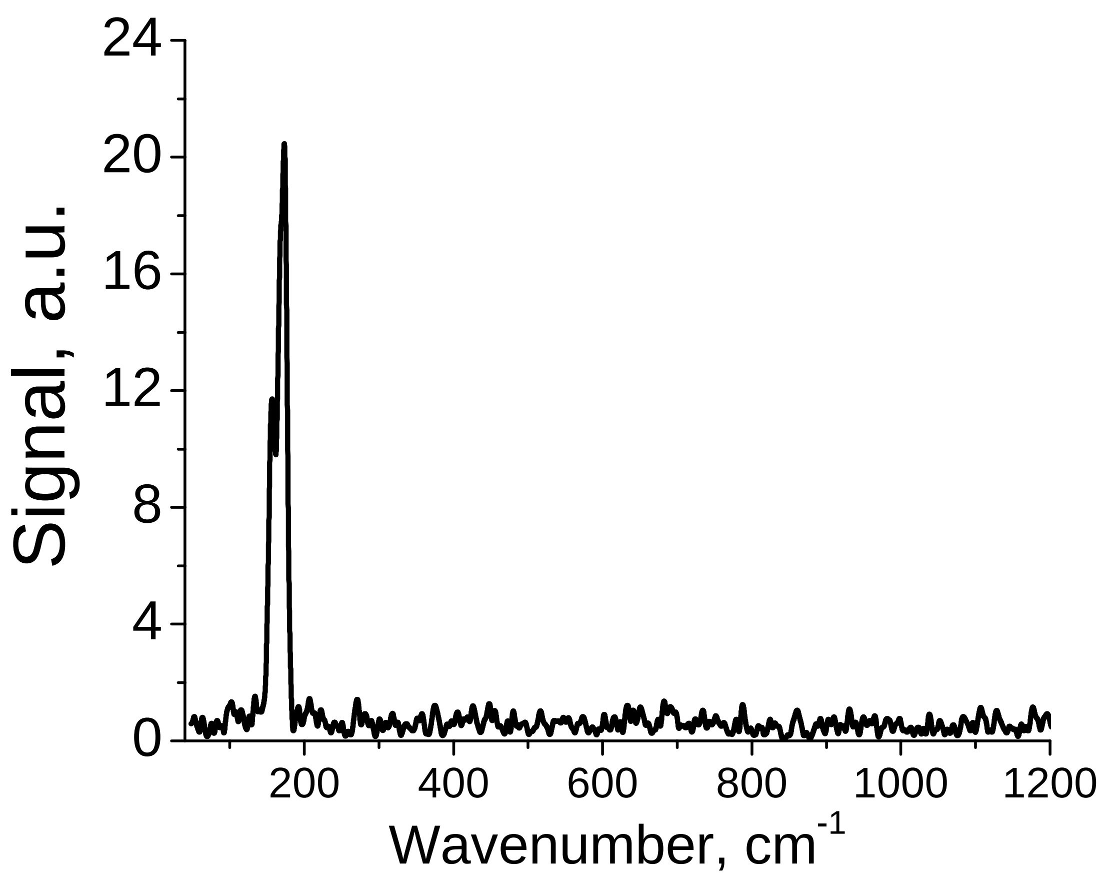
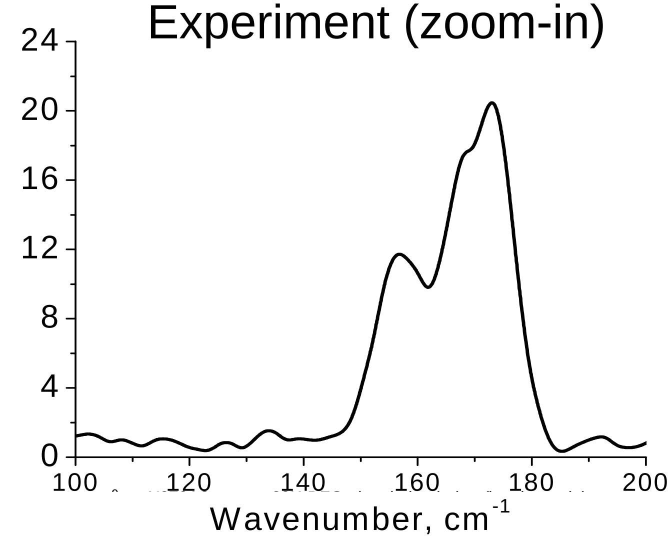
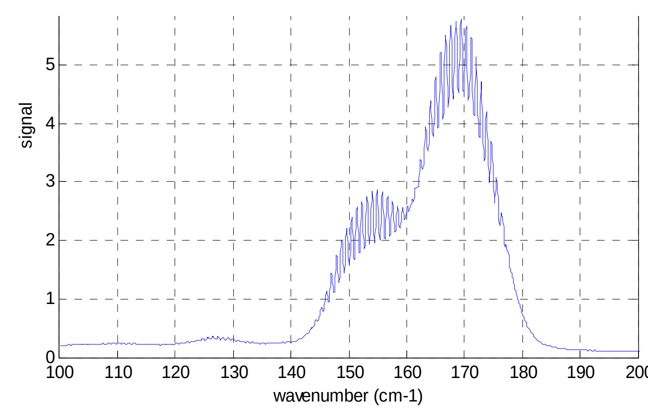
Terahertz emission 80K

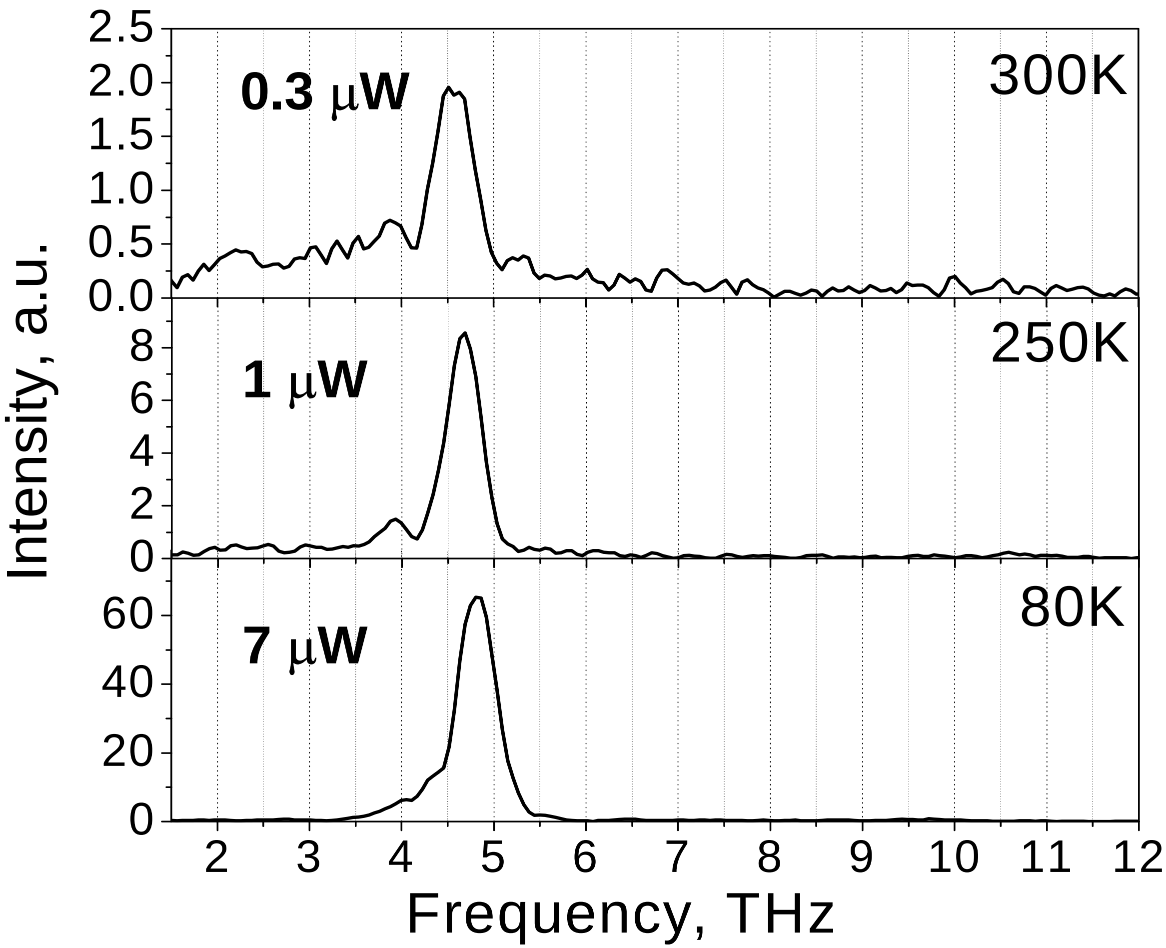






25-µm-wide, tapered to 50-µm-wide, 2-mm-long, back facet HR coating.
Testing in pulsed mode (60ns pulses at 250kHz).

Terahertz output at different T

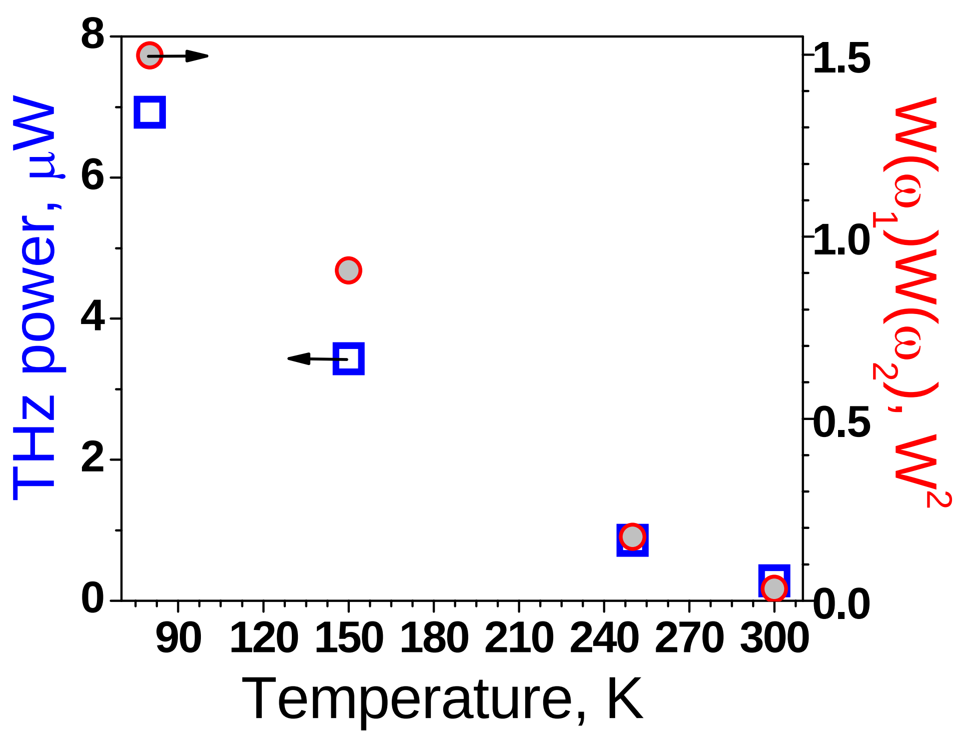


- Peak positions agree with mid-IR data
- Red-shift with temperature can also be observed in mid-IR data
- THz DFG signal observed up to room temperature

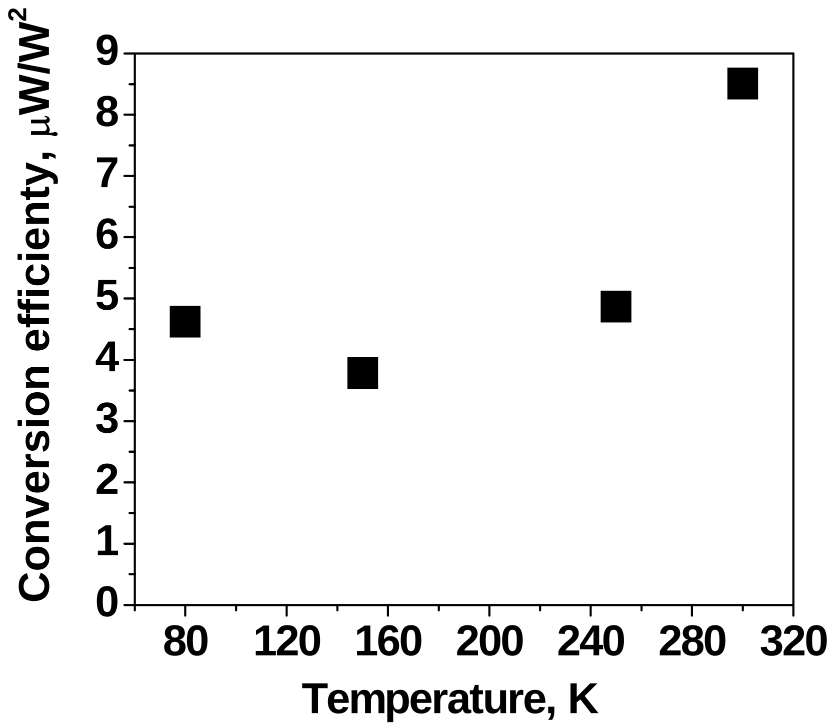
25-µm-wide, tapered to 50-µm-wide, 2-mm-long, back facet HR coating, + Silicon lens
Testing in pulsed mode (60ns pulses at 250kHz).

Conversion efficiency at different T

Peak THz and mid-IR power *vs* T



Conversion efficiency *vs* T



Conversion efficiency ~5 $\mu W/W^2$

Conversion efficiency: analysis

$$W_{THz} \approx \frac{\omega^2}{8\varepsilon_0 c^3 n_{eff}^{\omega} n_{eff}^{\omega_1} n_{eff}^{\omega_2}} \times \frac{\left|\chi^{(2)}\right|^2}{S_{eff}} W_1 W_2 \times l_{eff}^2$$

S_{eff}, l_{eff}, refractive indices are known from waveguide calculations:

$n_{eff} \approx 3$, $l_{eff} \approx 70\ \mu m$, $S_{eff} \approx 1800\ \mu m^2$

Estimate $\chi^{(2)}$ using electron density in upper laser state from gain=loss condition:

$\chi^{(2)} \approx 3 \times 10^4$ pm/V

Uncertain parameters:

Mid-IR lasing in higher order lateral modes

THz wave out-coupling efficiency from QCL waveguide (~30%?)

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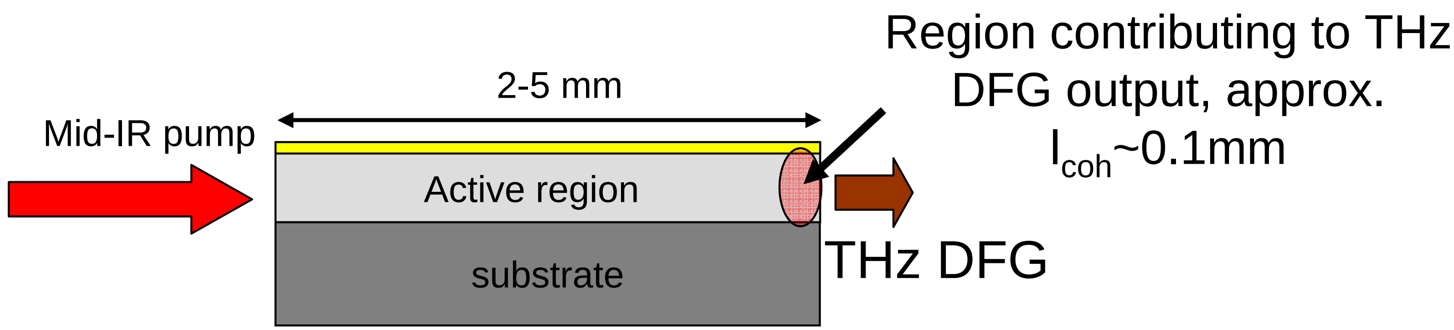
THz wave out-coupling efficiency from QCL waveguide (~30%?)

Theoretical efficiency: $W_{THz}/(W_1 \times W_2)$ ~ 30 $\mu W/W^2$

Experiment (corrected for the collection efficiency): ~ 5 $\mu W/W^2$

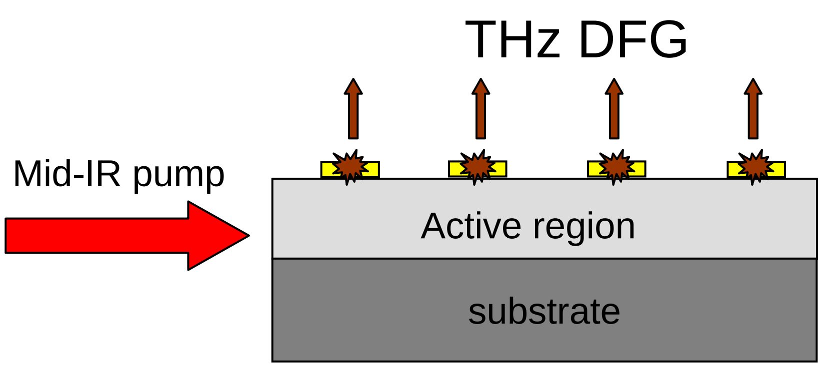
Need for surface extraction of DFG

Edge emitting THz DFG is not efficient



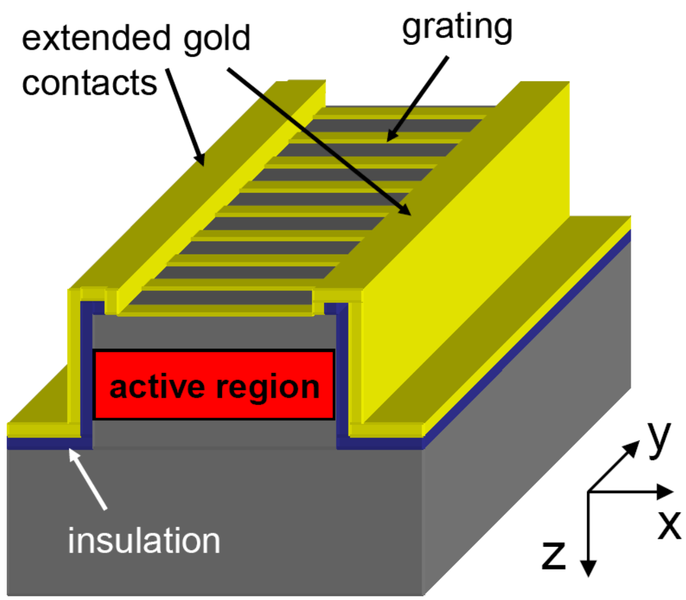
Only a small section ~l_{coh} contributes to THz DFG output

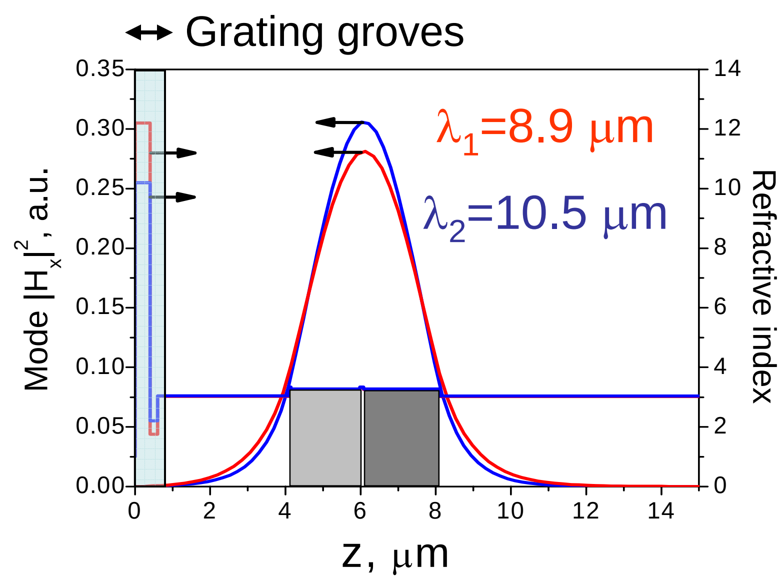
Surface-emitting scheme to boost THz power



The whole device contributes to THz DFG

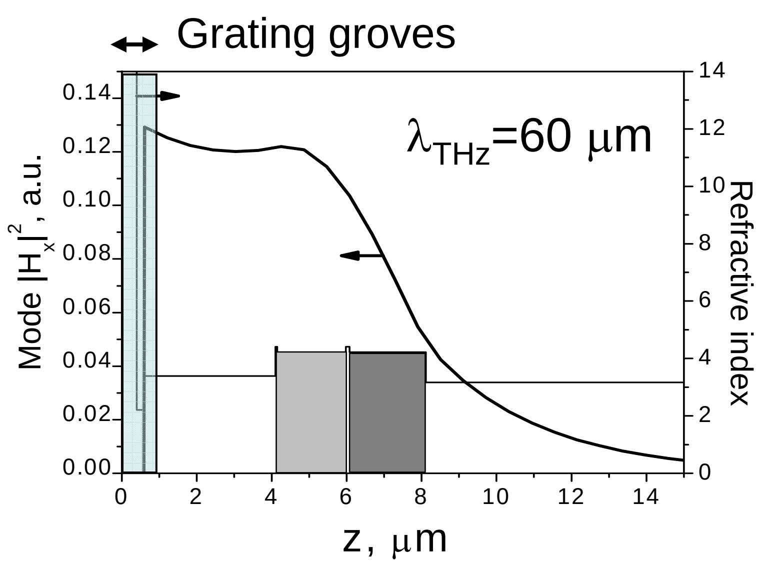
Device design for surface emission





THz radiation is produced by $P^{(2)}$

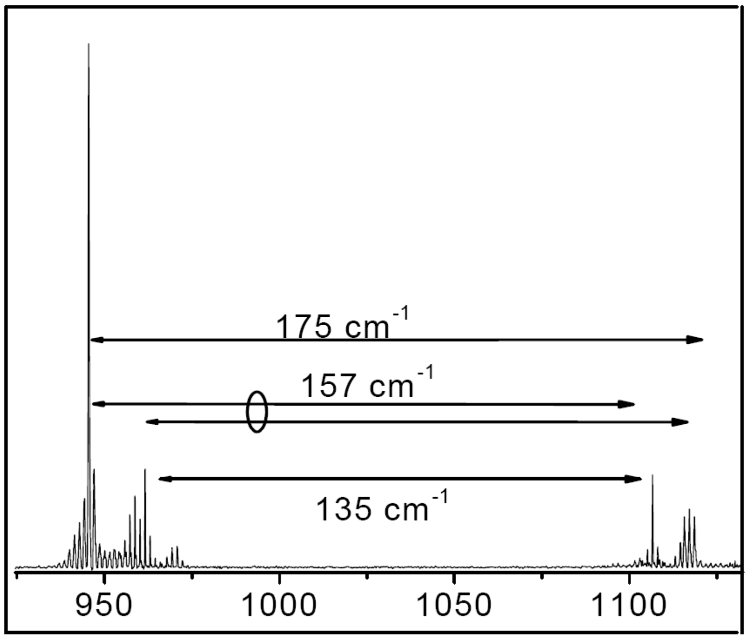
$$P^{(2)}(\omega_{THz}=\omega_1-\omega_2)\sim\chi^{(2)}E(\omega_1)E(\omega_2)e^{i(k_1-k_2)y}$$



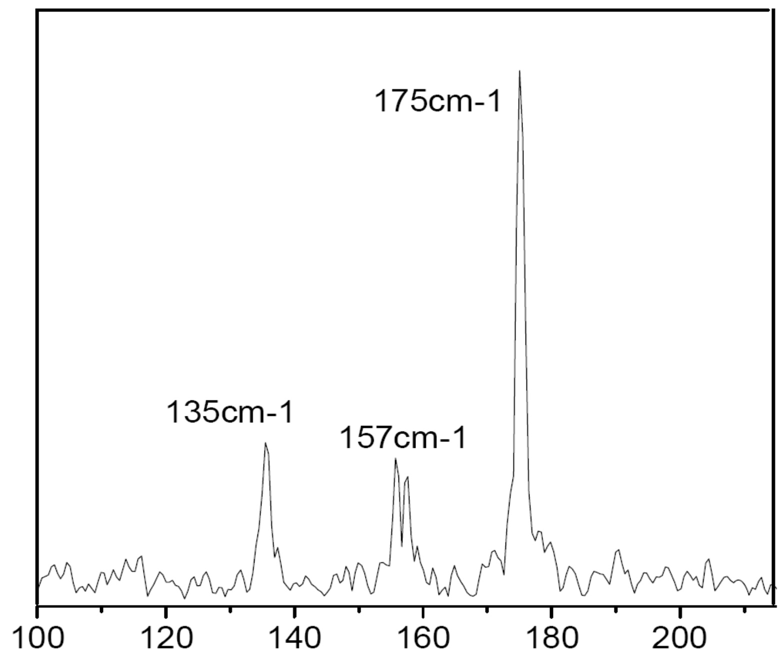
For efficient vertical outcoupling, we need the grating k-vector $k_{gr}=k_1-k_2$

Surface emission

Edge-emission mid-IR spectrum



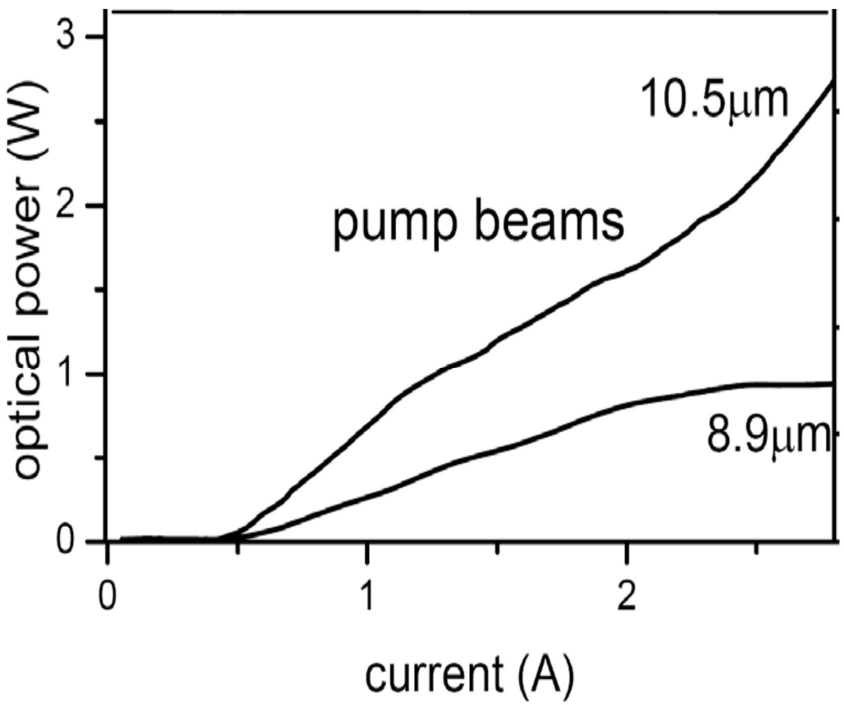
Surface-emission THz spectrum



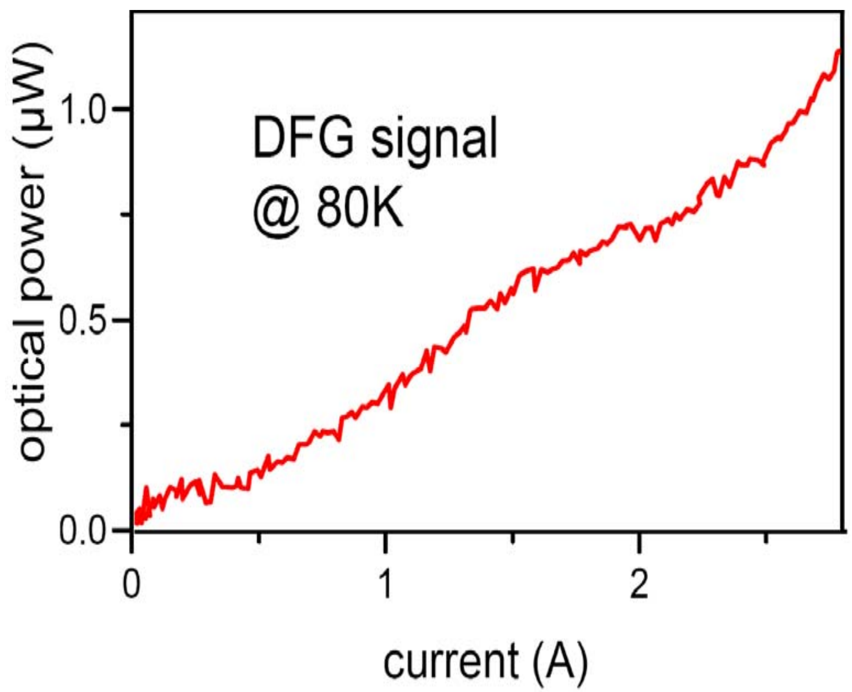
25-µm-wide,with second order grating for THz DFG, 1-mm-long, back facet HR coating. Testing in pulsed mode (60ns pulses at 250kHz) with 3.5A current pulses at 80K.

Power output

Edge emission mid-IR power



Surface emission THz power



25-μm-wide,with second order grating for THz DFG, 1-mm-long, back facet HR coating. Testing in pulsed mode (60ns pulses at 250kHz) with 3.5A current pulses at 80K.

Future improvements

- *Improve waveguide designs for larger l_{coh}*
- *Improve active region designs for higher $\chi^{(2)}$*
- *Improved surface emission for more outcoupling*
- *Mode-locking for higher peak intensity*

mW-level THz DFG QCL sources

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