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Quantum coherence in quantum cascade lasers: paths to THz generation and correlated photon emission

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Outline

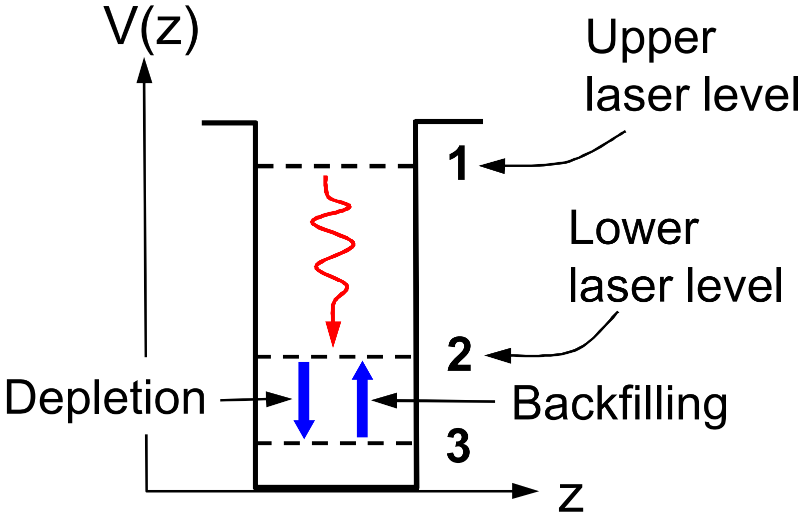
High-temperature THz QCL

Optically-pumped electrically-driven scheme

- Theory
- Numerical results

THz quantum cascade laser (QCL)

Problem



3 THz ≈ 12 meV

$k_B T$ ≈ 25 meV (300K)

THz quantum cascade laser (QCL)

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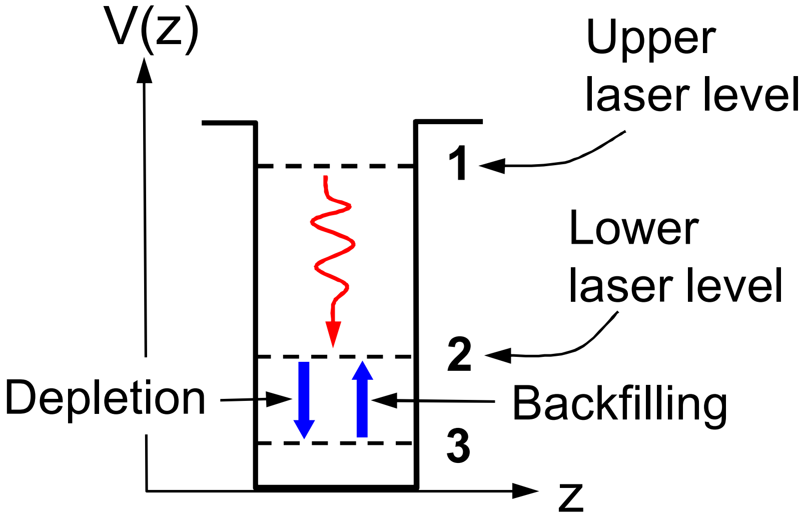
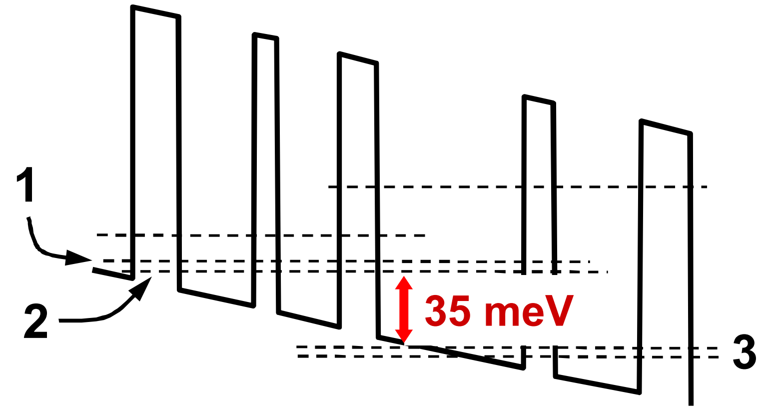


THz QCL gain region



Williams, Kumar, Hu and Reno, Optics Express 13, 3331 (2005)

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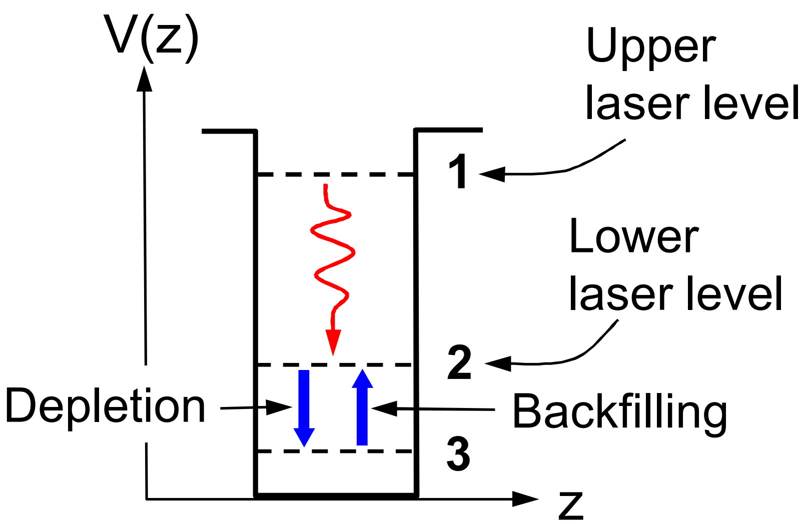
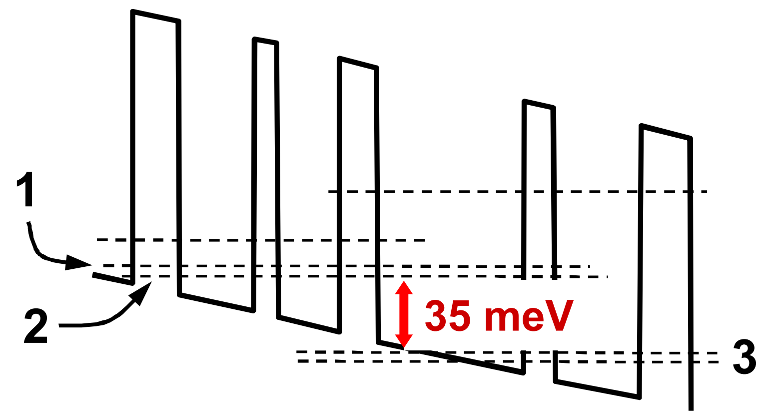


$3\ \text{THz} \approx 12\ \text{meV}$

$k_BT \approx 25\ \text{meV (300K)}$

THz QCL gain region



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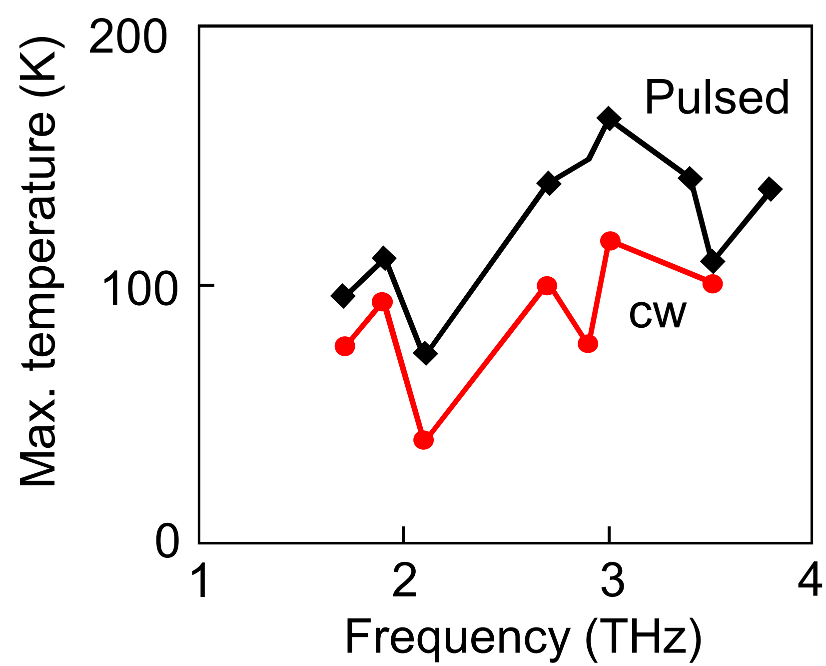
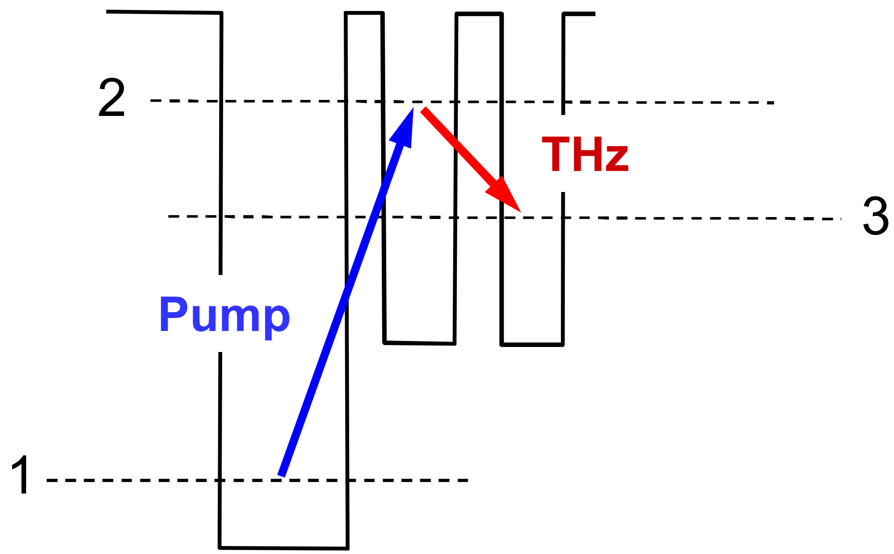


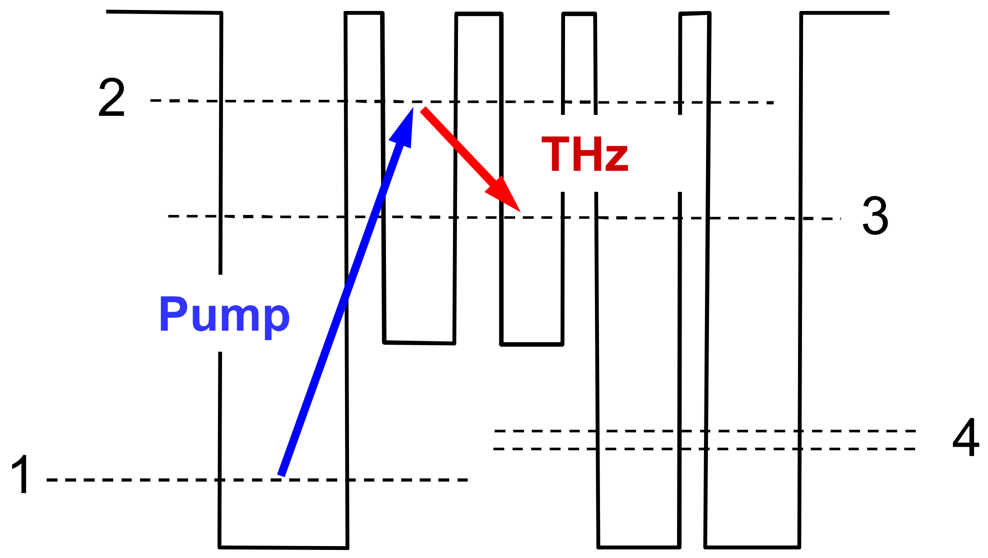
Optical pumping



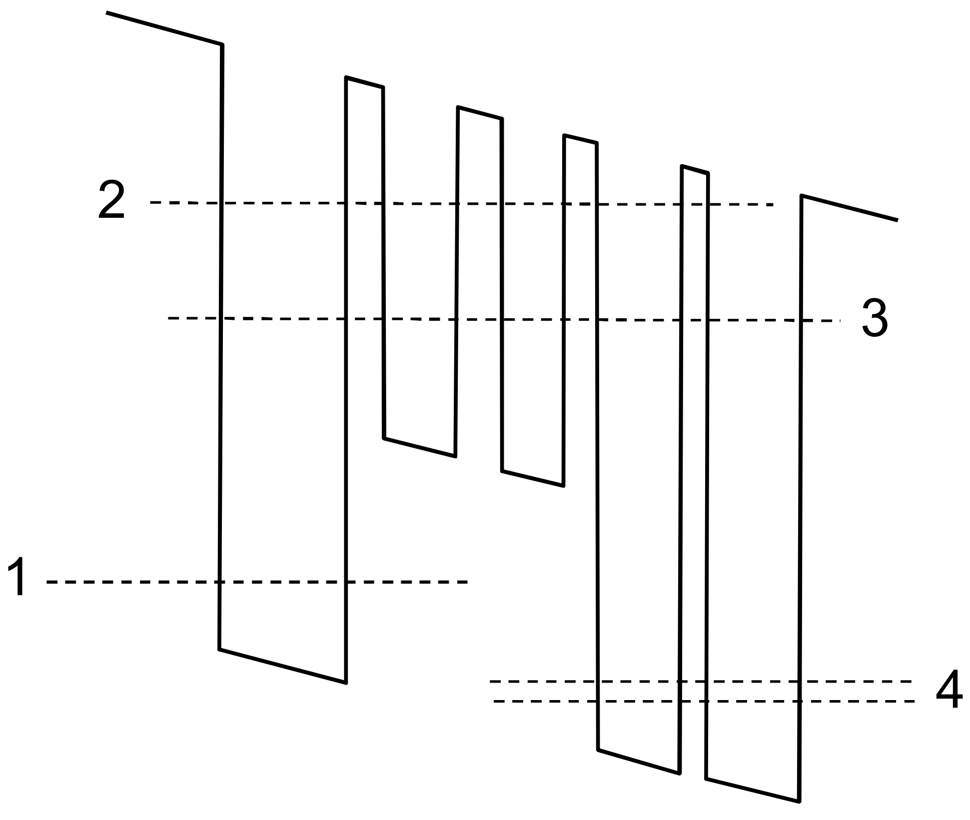
Manley-Rowe limit

$$\eta = \frac{\hbar\omega_{Thz}}{\hbar\omega_{Pump}} \simeq 0.105$$

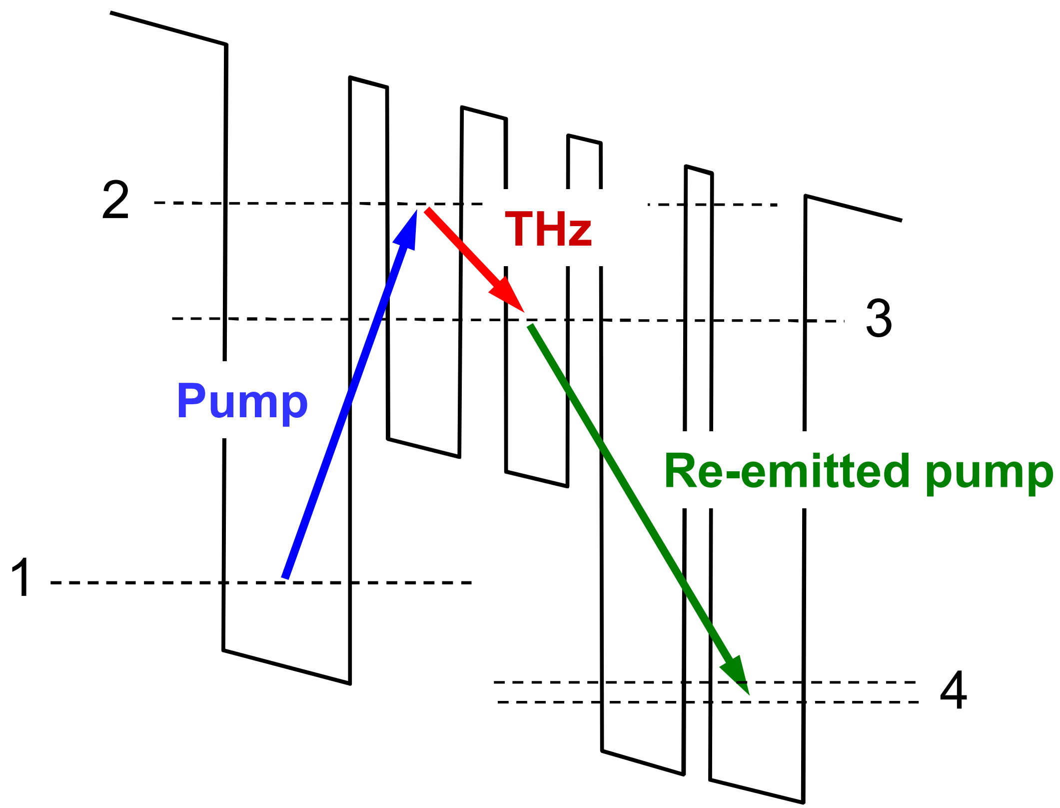
Optically-pumped



Optically-pumped electrically-driven



Optically-pumped electrically-driven (OPED) QCL



Band structure calculation

k·p theory, 8x8 Luttinger Hamiltonian, envelop approximation

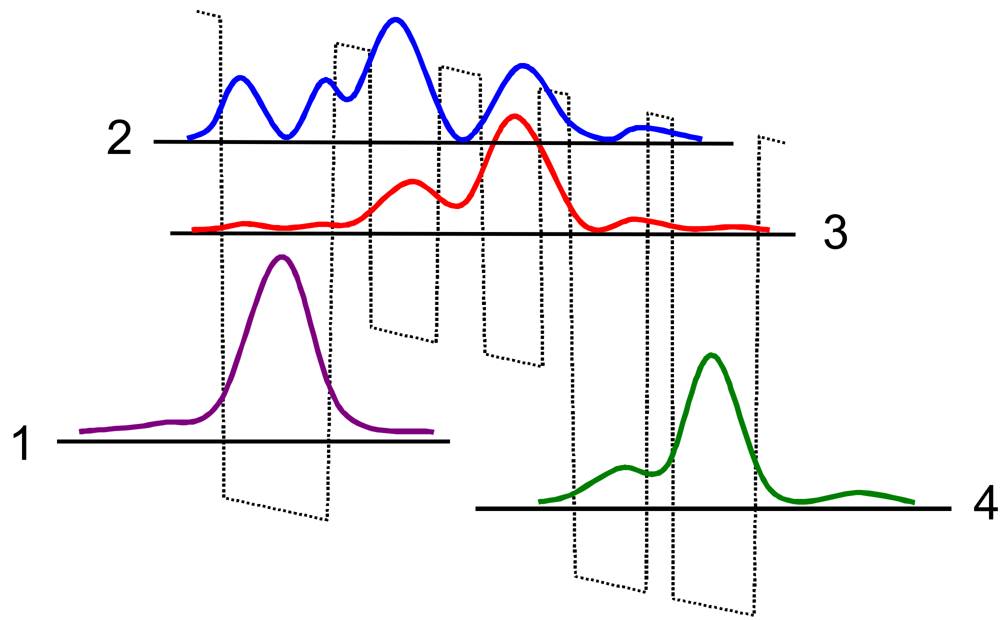
Growth sheet

Composition	Width (Å)
$Al_{0:4}Ga_{0:6}As$	17:2
GaAs	70
$Al_{0:4}Ga_{0:6}As$	22
$Al_{0:15}Ga_{0:85}As$	45
$Al_{0:4}Ga_{0:6}As$	27
$Al_{0:15}Ga_{0:85}As$	41
$Al_{0:4}Ga_{0:6}As$	17:2
GaAs	49
$Al_{0:4}Ga_{0:6}As$	14:3
GaAs	54

Doping density

1.9£ 10^{16} cm¡ ^{3}

Forward bias = 25kV/cm



Energy levels: ε_1, ε_2, ε_3, ε_4

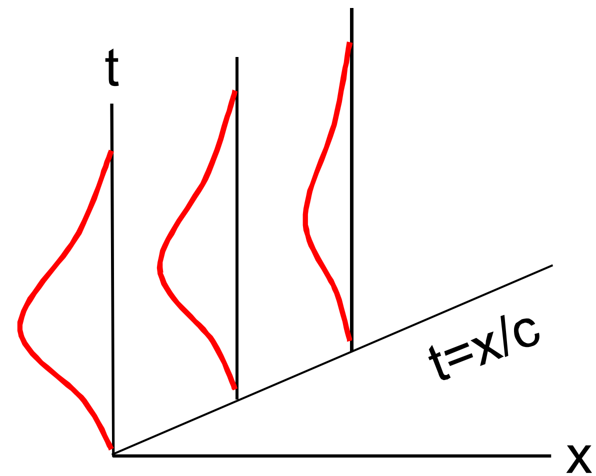
Subband dispersions: m_{e1}, m_{e2}, m_{e3}, m_{e4}

Dipole matrix elements: μ_{12}, μ_{23}, μ_{24}

Laser calculation

Laser fields

$$\frac{d}{dx}E_\alpha = -\frac{\omega_\alpha}{2\epsilon_0 n c}\frac{1}{V}\,\mathrm{Im}\left[\sum_k \mu_{ab;k}\, p_{ab;k}\right]$$



Pump or THz

Polarizations

$$\frac{dp_{ab;k}}{dt} = (i\omega_{ab;k} - \gamma)\, p_{ab;k} + \frac{i}{\hbar}\mu_{ab;k}(n_{a;k} - n_{b;k})E + \frac{i}{\hbar}\sum_{c\neq a;b}(\mu_{bc;k}\, p_{ac;k} - \mu_{ac;k}\, p_{cb;k})E$$

Dephasing rate

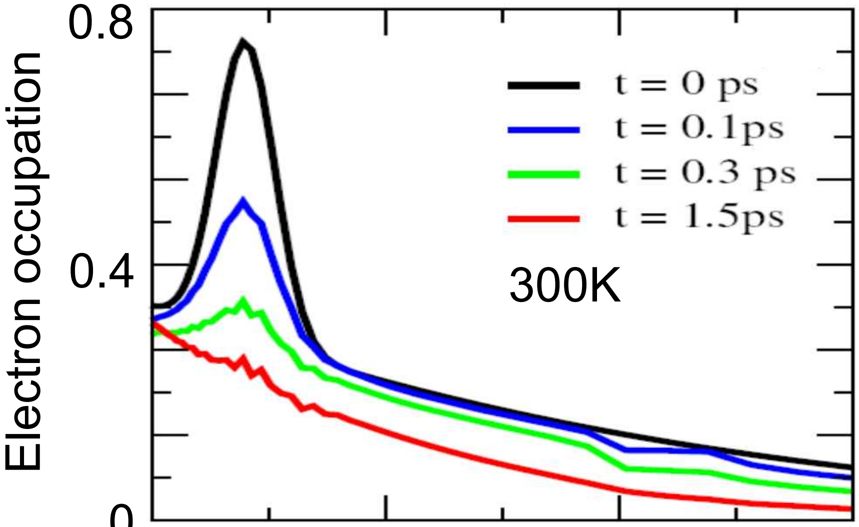
$$E = E_{Pump} + E_{THz}$$

Populations

$$\frac{d}{dt}n_{a;k} = \frac{i}{2\hbar}\sum_{c\neq a}\mu_{ac;k}(p_{ca;k} - p_{ac;k})E + \left.\frac{dn_{a;k}}{dt}\right|_{scat}$$

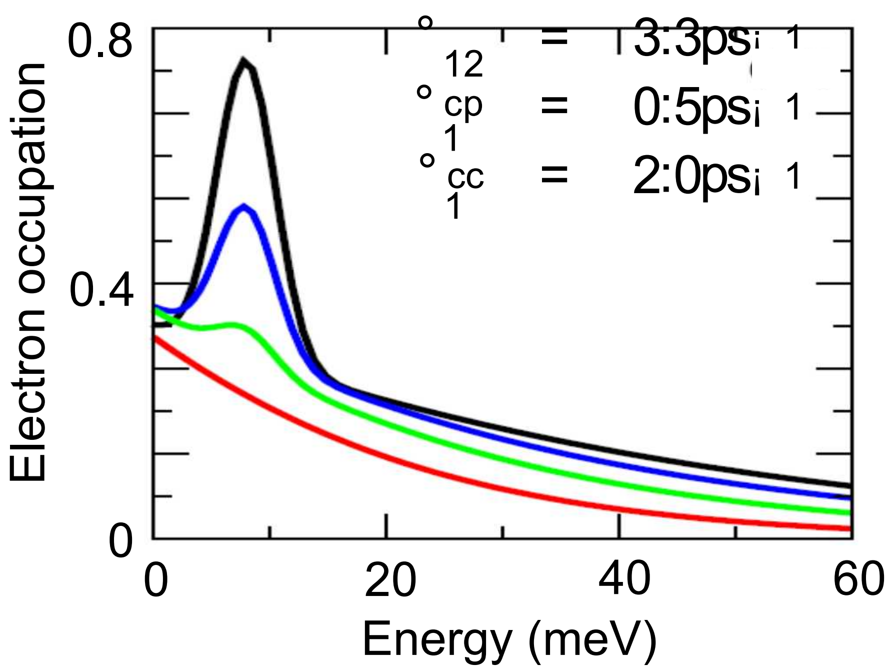
Carrier relaxation and nonradiative losses

Carrier population relaxation



Microscopic calculation

Quantum Boltzmann scattering integrals for carrier-carrier and carrier-LO phonon scattering

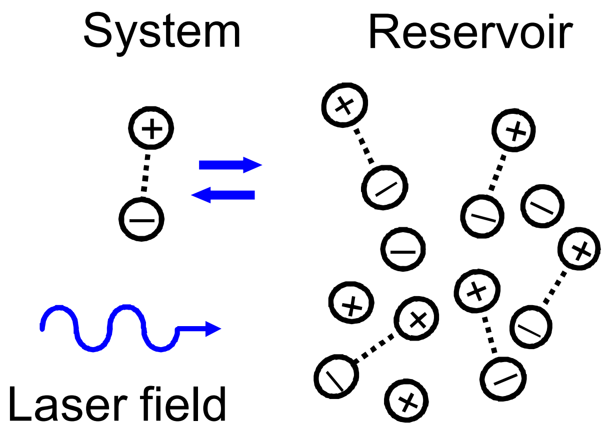


Rate equation approximation

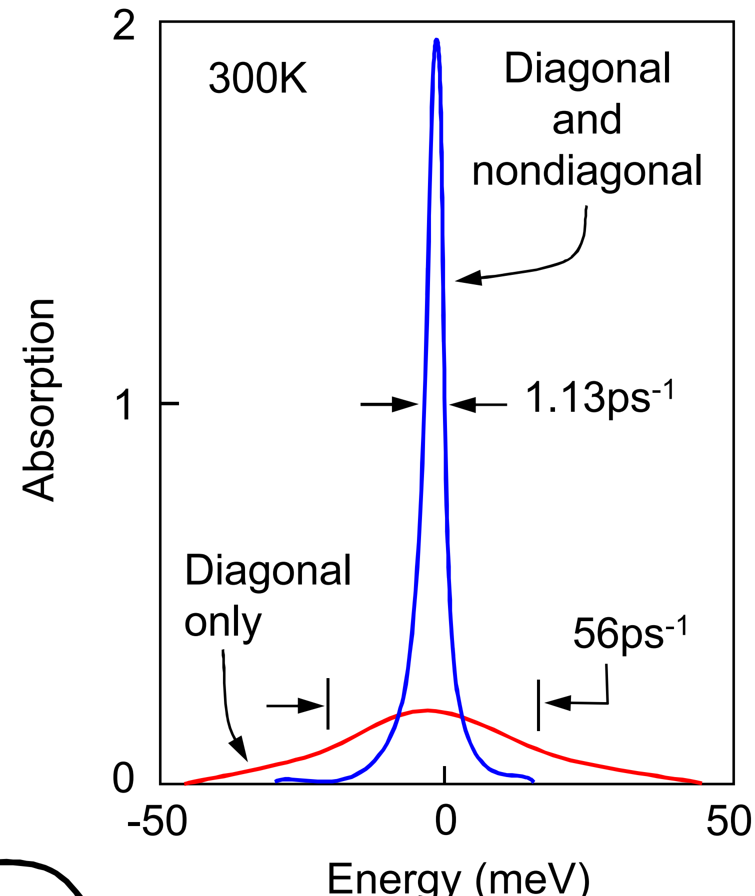
$$\left.\frac{dn_{a,k}}{dt}\right|_{scat} = -\gamma_{ab}\left[n_{a,k} - f_{a,k}(\mu_{ab}, T_l)\right] - \gamma^{cp}_{a}\left[n_{a,k} - f_{a,k}(\mu^{l}_{a}, T_l)\right] - \gamma^{cc}_{a}\left[n_{a,k} - f_{a,k}(\mu^{pl}_{a}, T_{pl})\right]$$

IEEE JQE **42**, 292 (2006)

Dephasing in semiconductors



System is its own reservoir



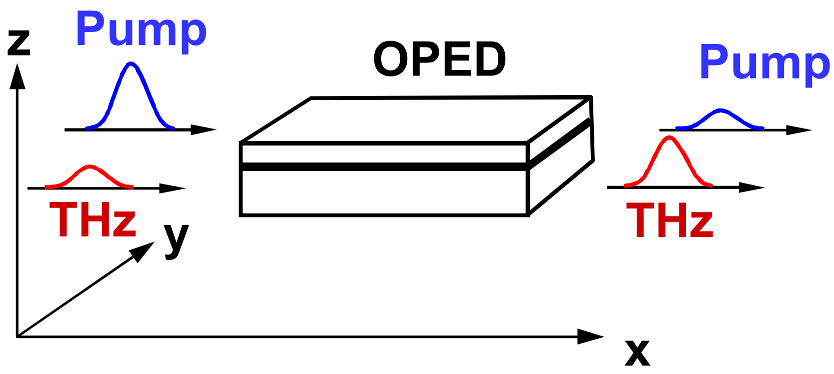
$$\left.\frac{\partial p_k}{\partial t}\right|_{col} = -\overbrace{\sigma^{d}_{k} p_k}^{\text{Diagonal}} + \overbrace{\sum_{k'} \sigma^{nd}_{k,k'} p_{k'}}^{\text{Nondiagonal}}$$

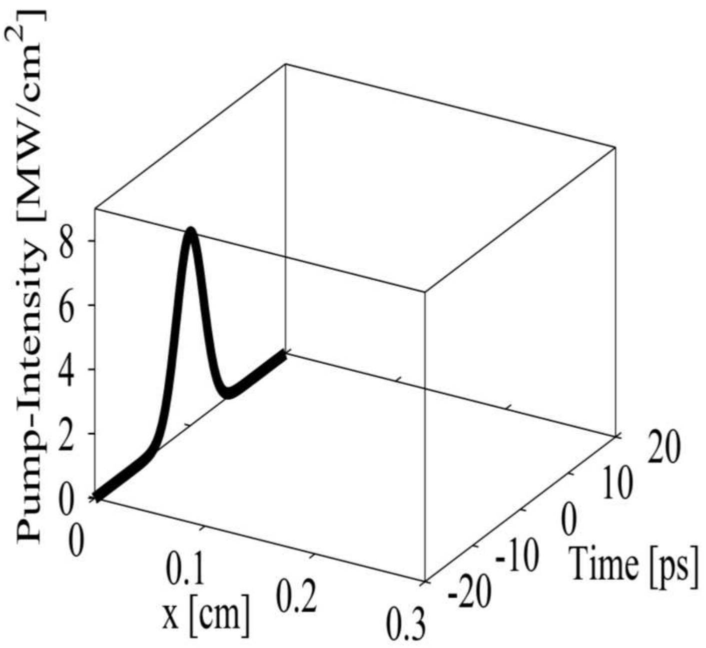
← actual

$$\simeq \gamma_{eff}\, p_k$$

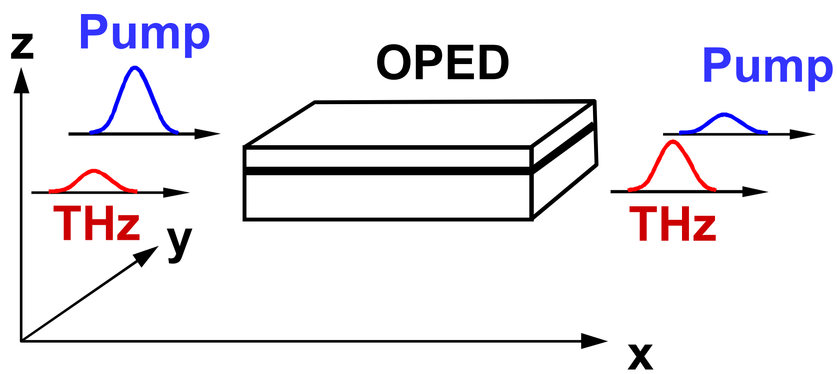
← in laser calculation

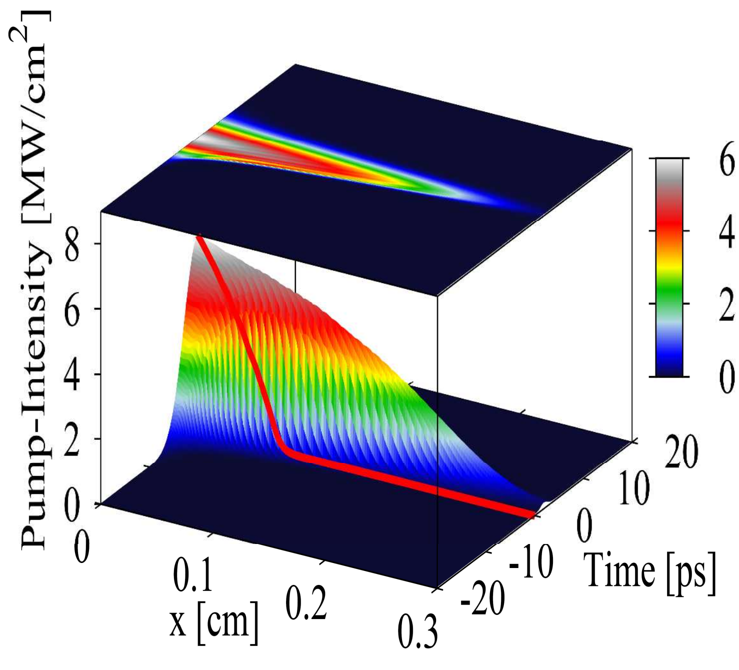
Pulsed excitation simulations





Pulsed excitation simulations





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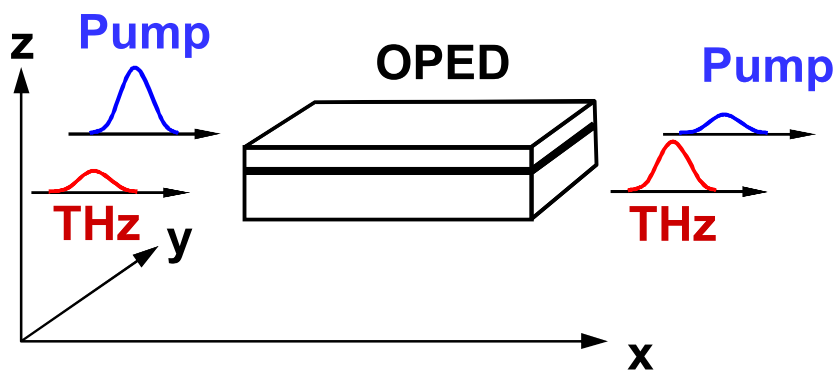
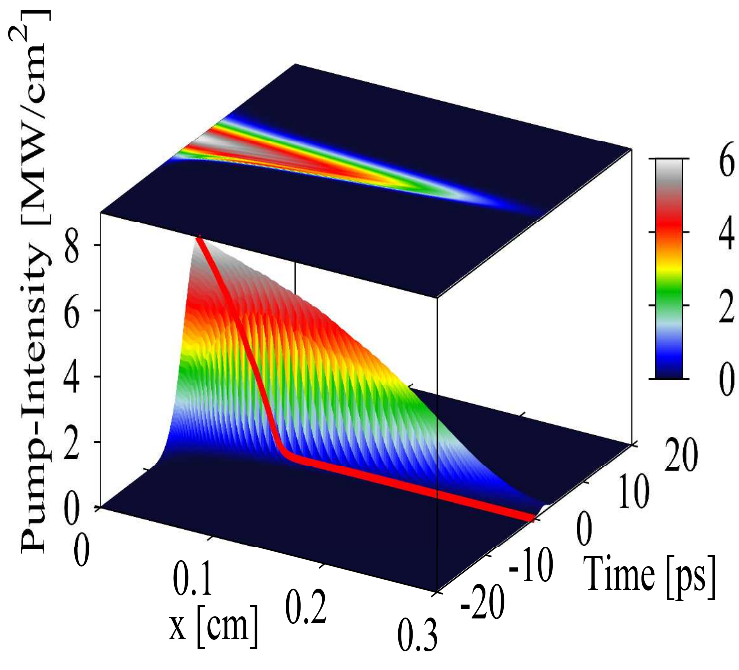
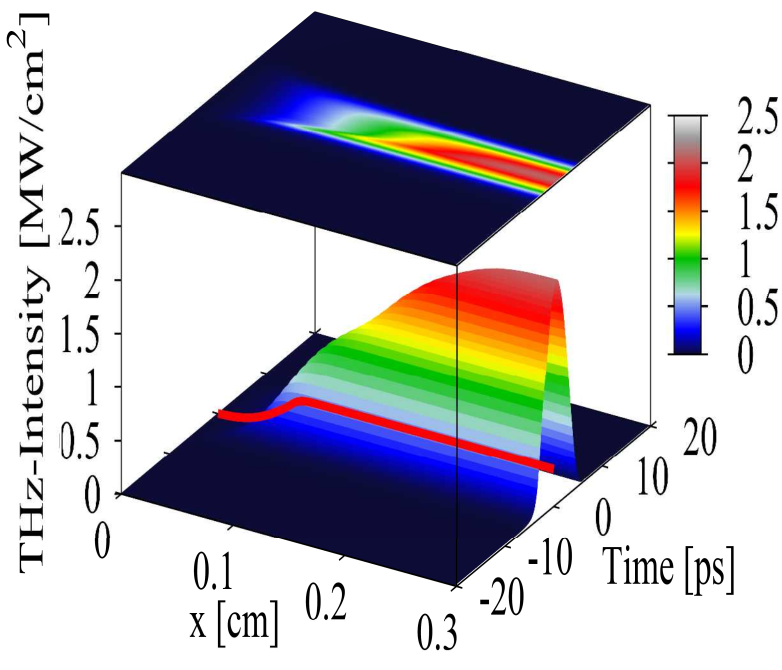
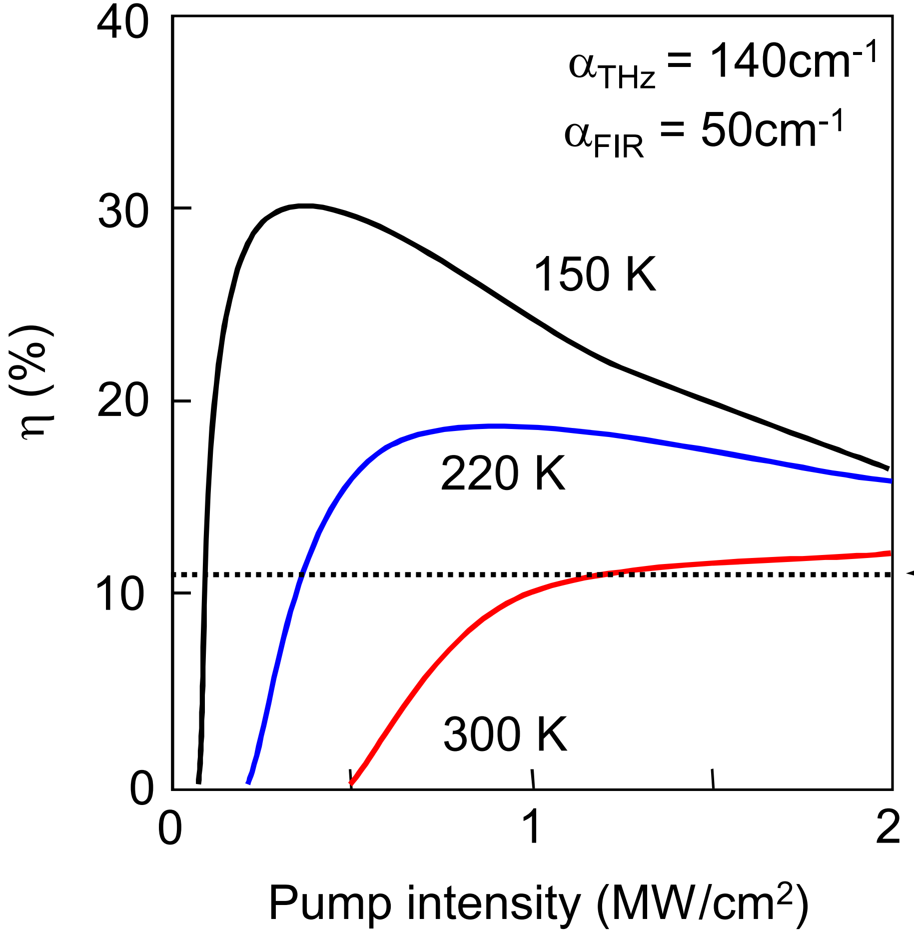






Steady state conversion efficiency

$$´ = \frac{\text{THz Intensity}}{\text{Pump Intensity}}$$



For purely optical pumping

$$´ = \frac{\text{~!}_{Thz}}{\text{~!}_{Pump}} \; ' \; 0{:}105$$

(Manley-Rowe limit)

Dephasing rate

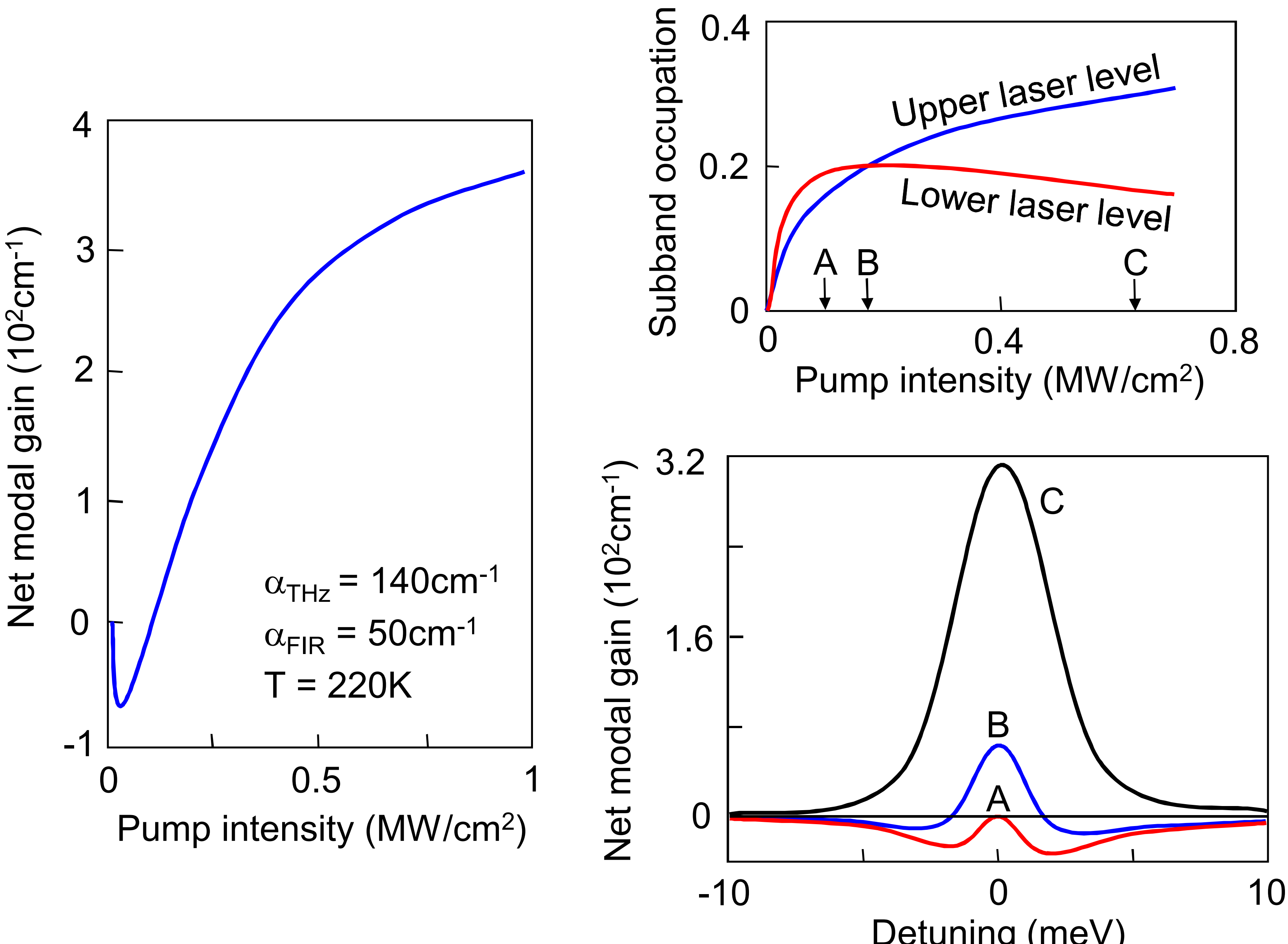
γ = 1.6 ps^{-1} (150K)

2.5 ps^{-1} (220K)

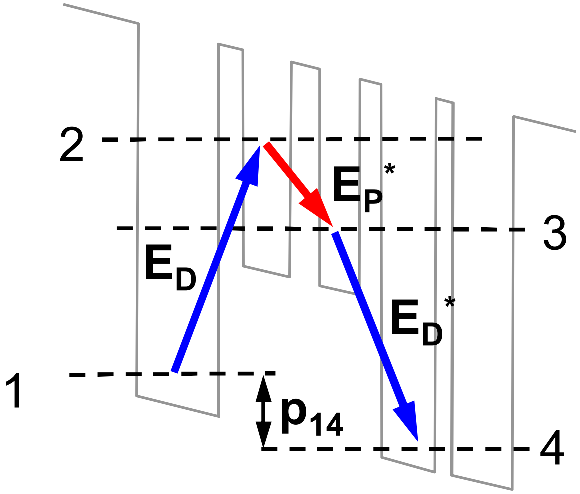
3.3 ps^{-1} (300K)

Waldmueller, et al, PRL 99, 117401 (2007)

Gain and gain mechanisms



Summary



THz laser

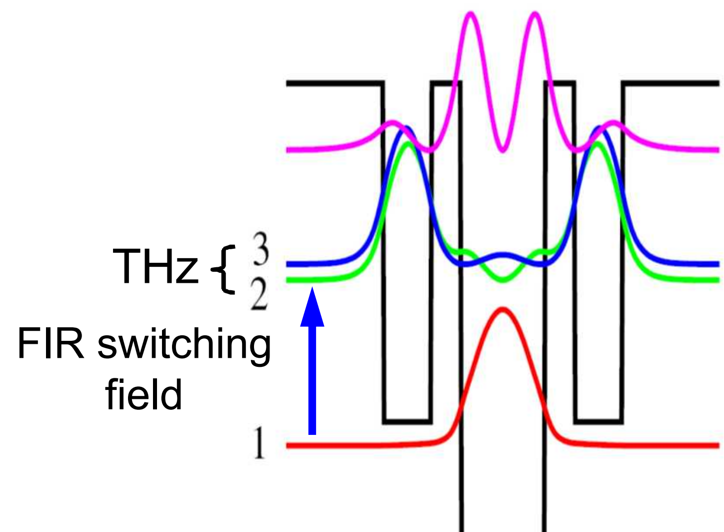
Optical pumping with coherent pump recovery

High temperature THz lasing

> Manley-Rowe limit

Automatically phase-matched

All-optical THz switch



Spontaneous emission properties