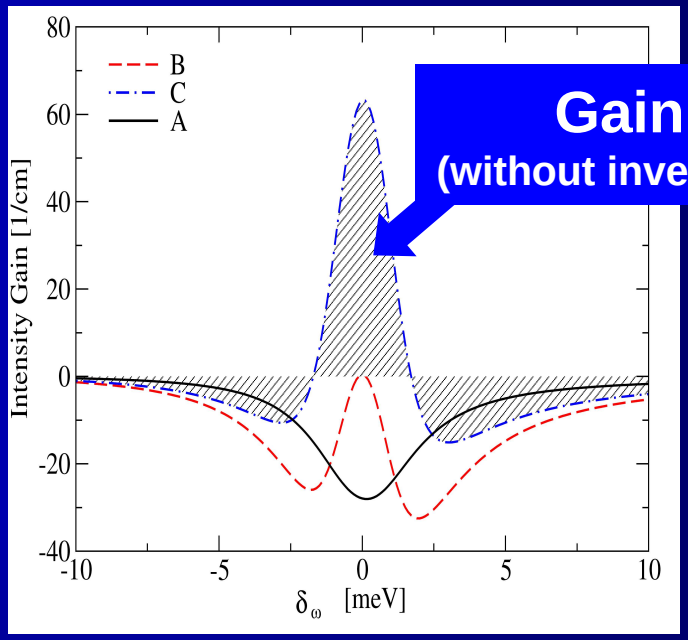
Who needs population inversion?

Automatically phase-matched quantum coherence contributions as a source for THz radiation



Inès Waldmueller, Weng W. Chow and Michael C. Wanke
Sandia National Laboratories

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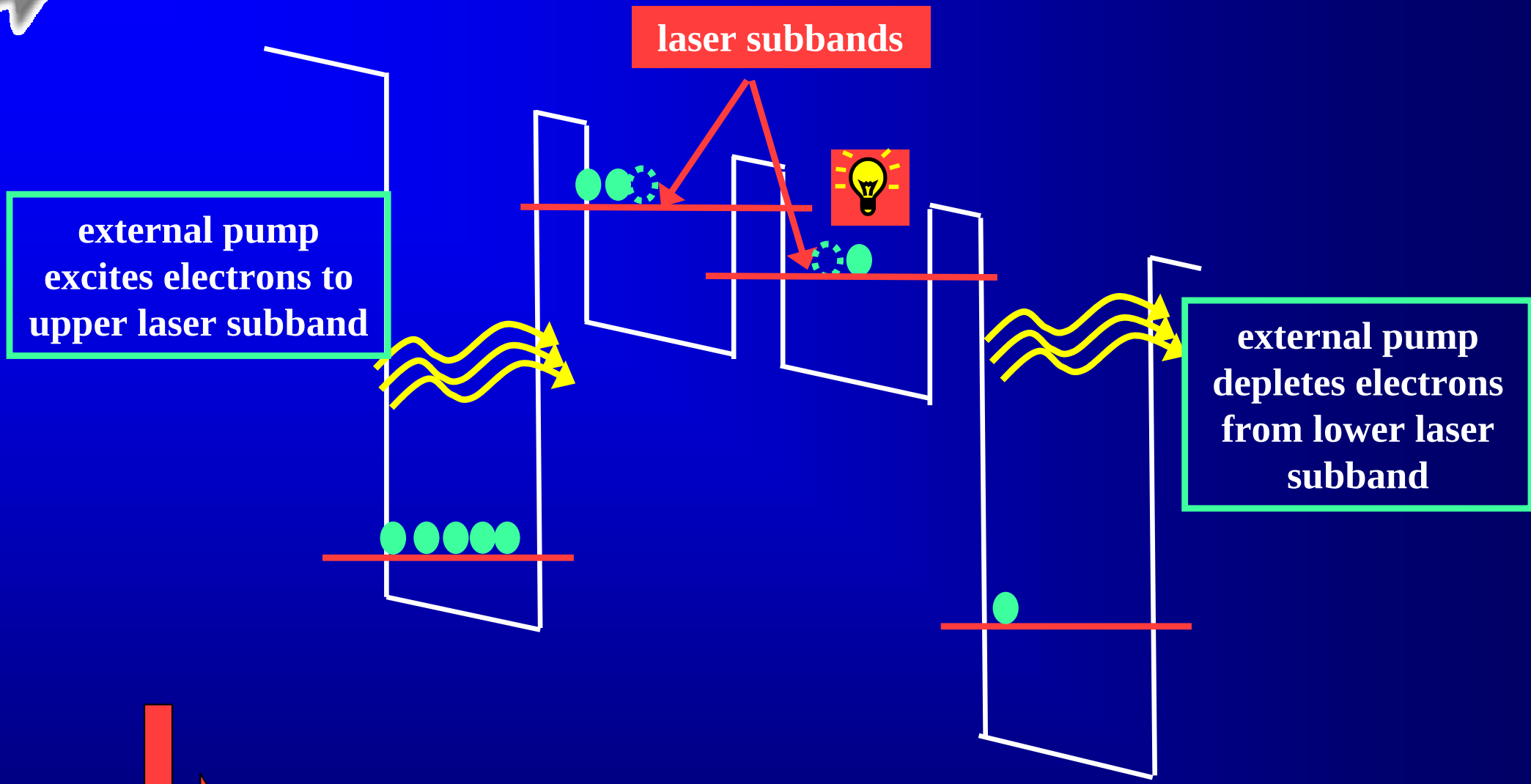
Opt. pumped, electrically driven QCL (OPED)



control population of laser subbands with external pump field

generate THz radiation

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Overview

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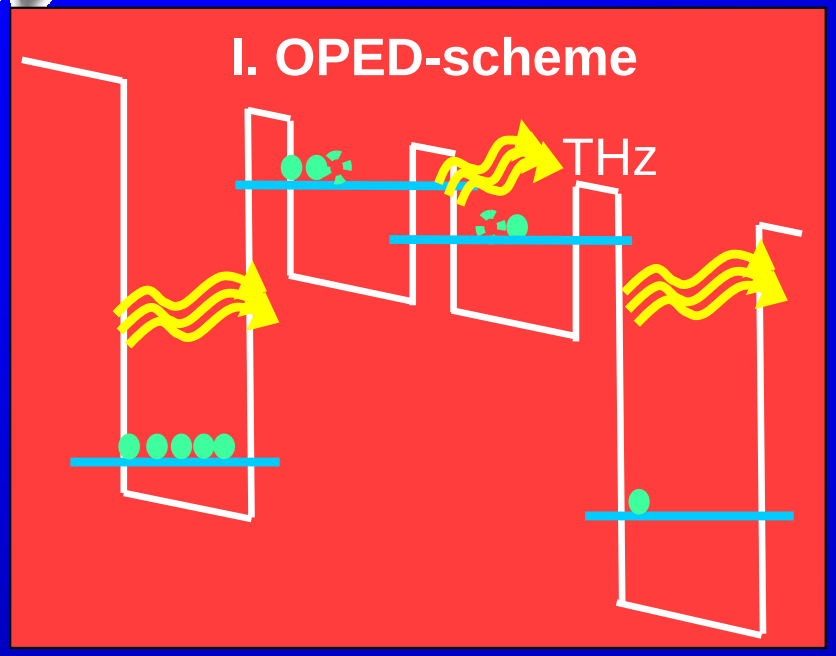

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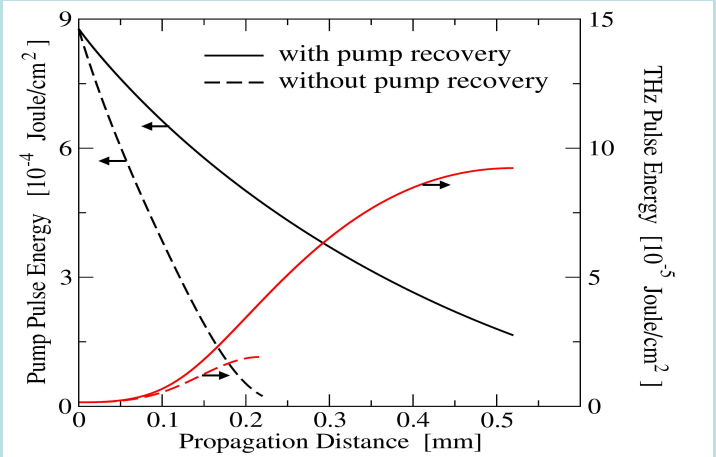
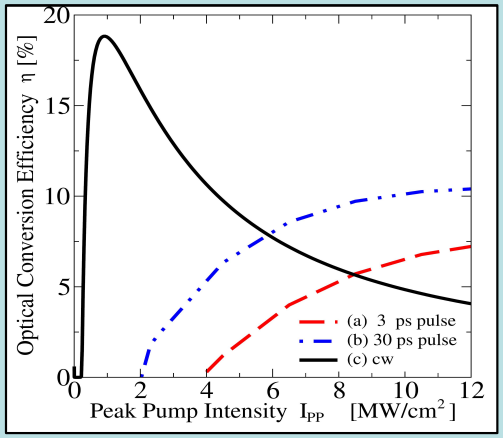
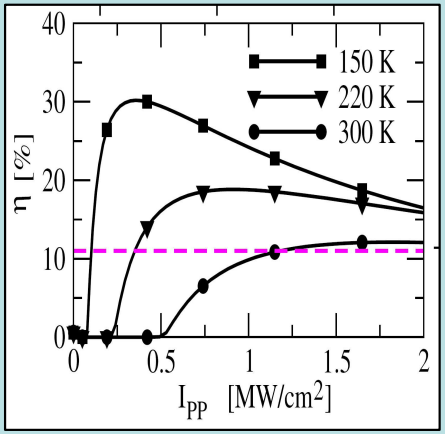


III. Capabilities of OPED

(Dependence of Optical Conversion Efficiency on Pulse Duration and Temperature)





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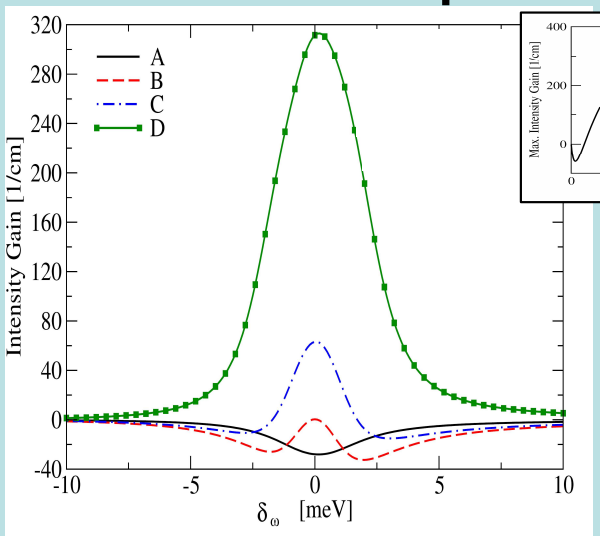

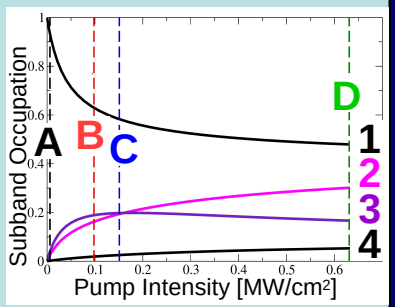

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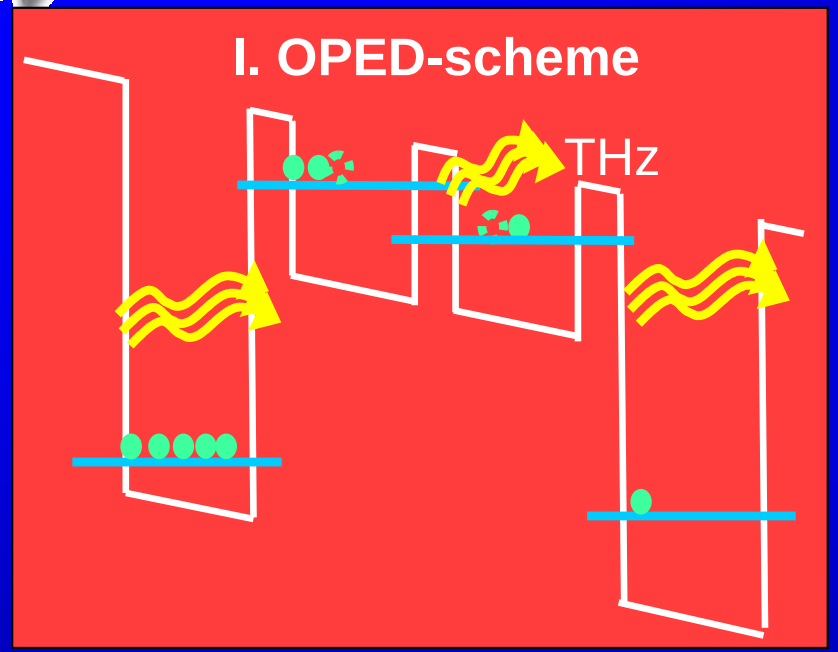

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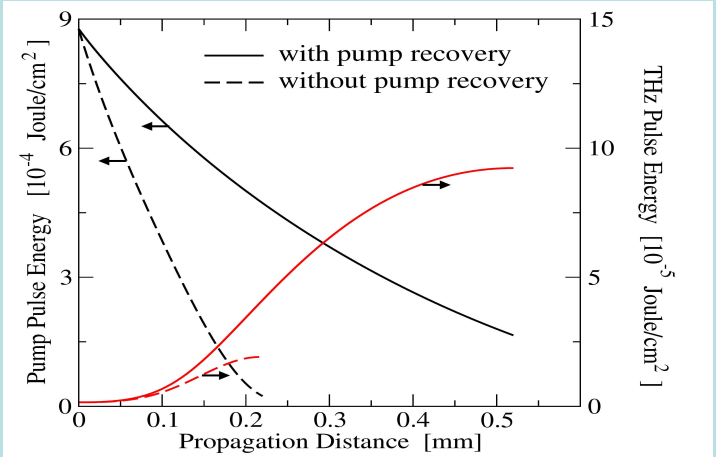

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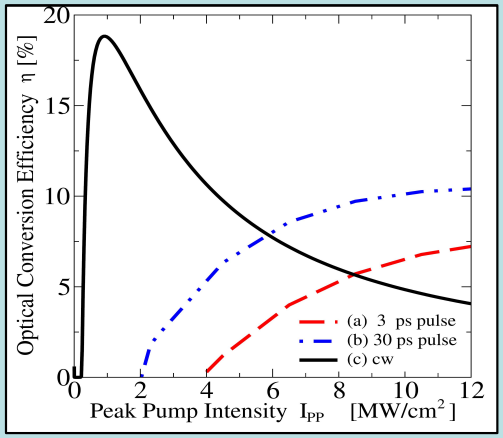

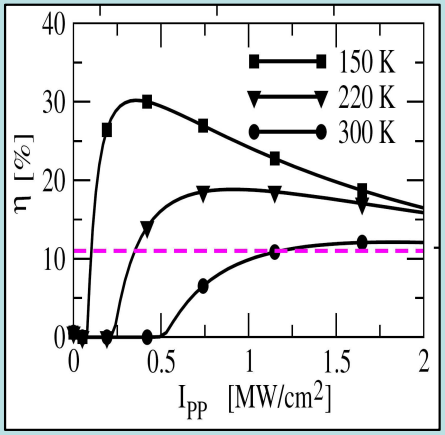

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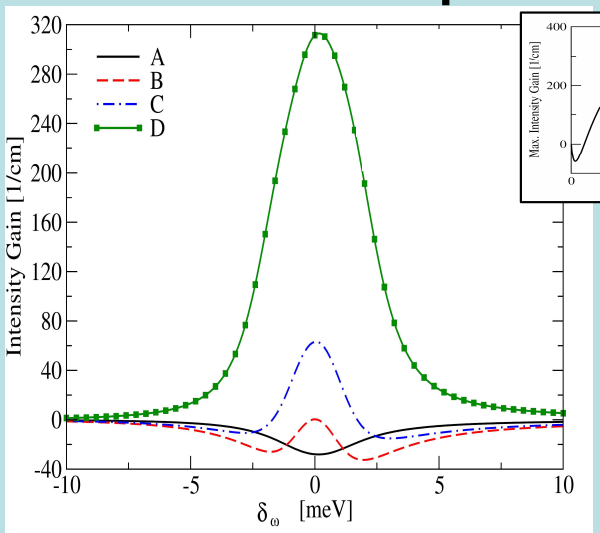
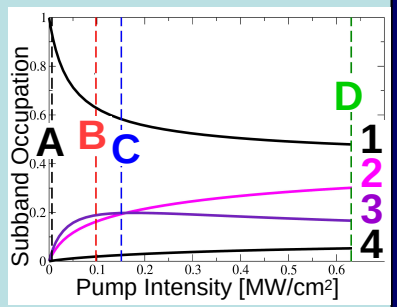
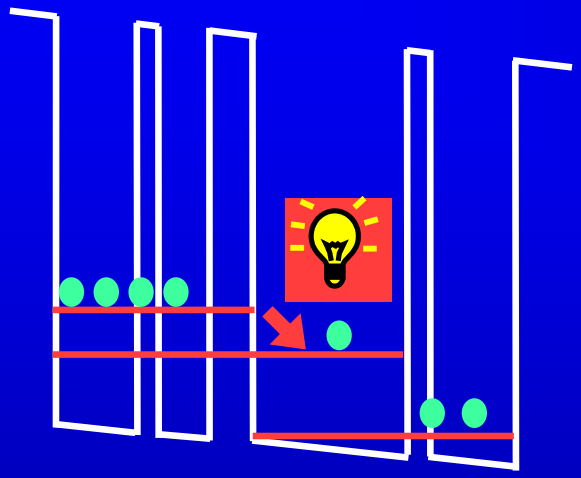
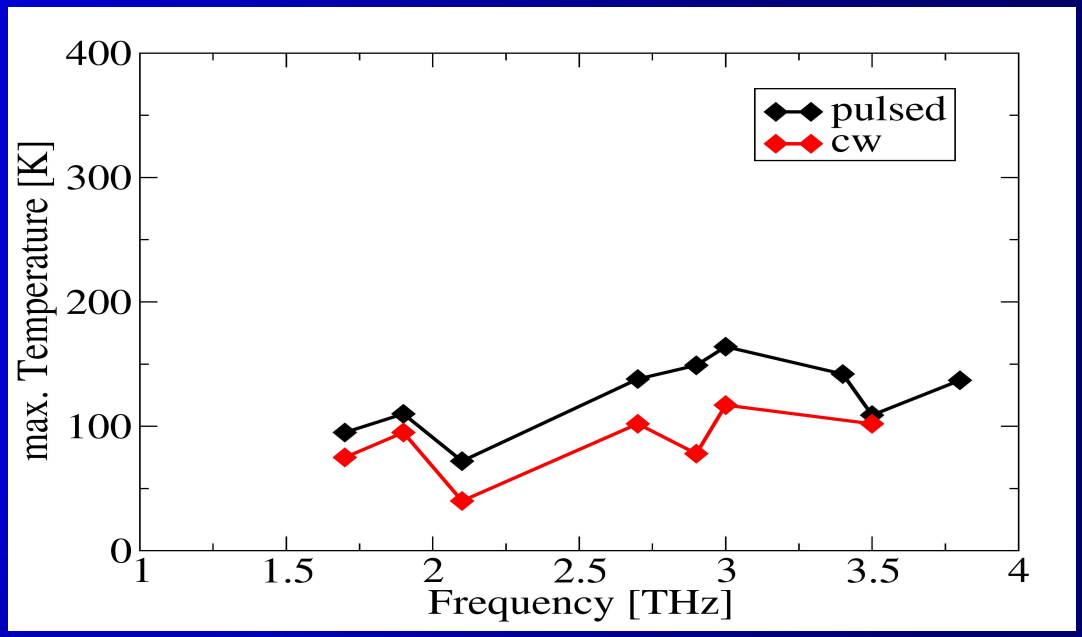




Motivation: Direct (“conventional“) THz-QCL

direct (“conventional”) THz-QCL





for room temperature (and higher)

hard to achieve/maintain population inversion

➡ **efficiency decreases with increasing temperature**

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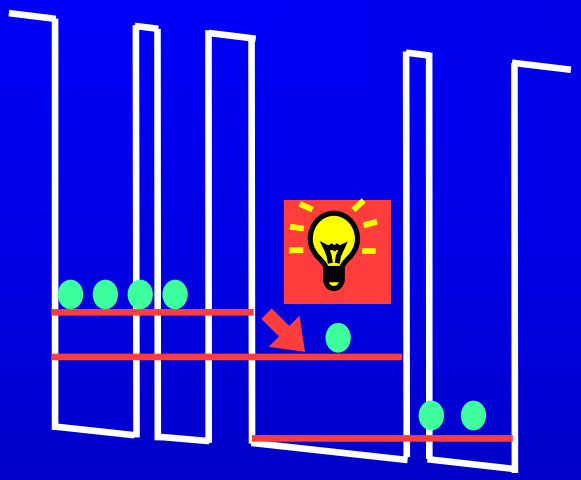

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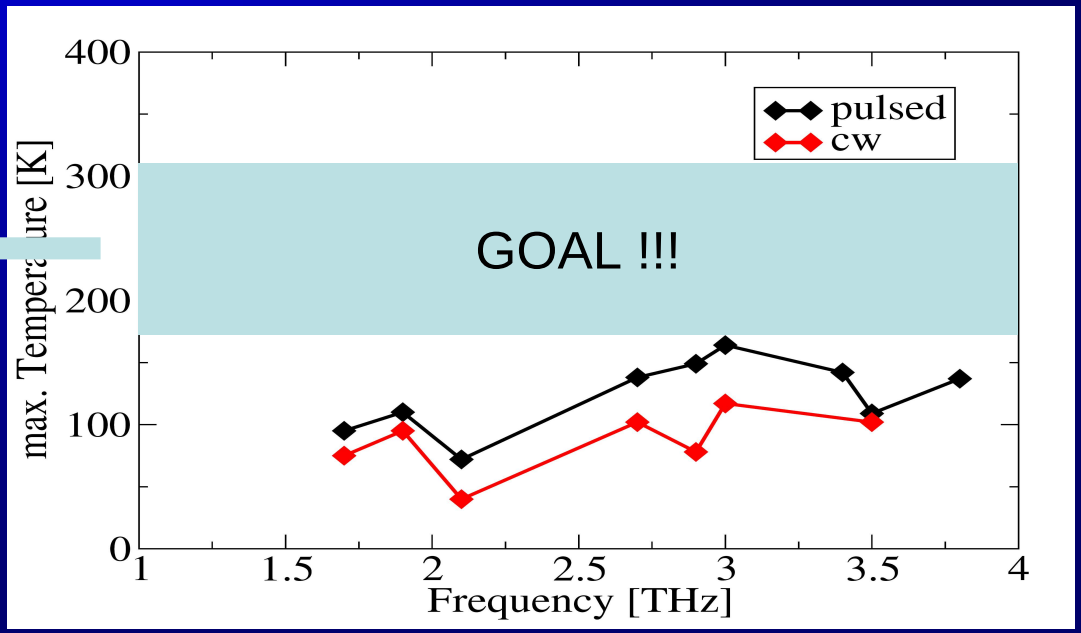
hard to achieve/maintain population inversion

efficiency decreases with increasing temperature

different approach better suited for high temperature operation ?



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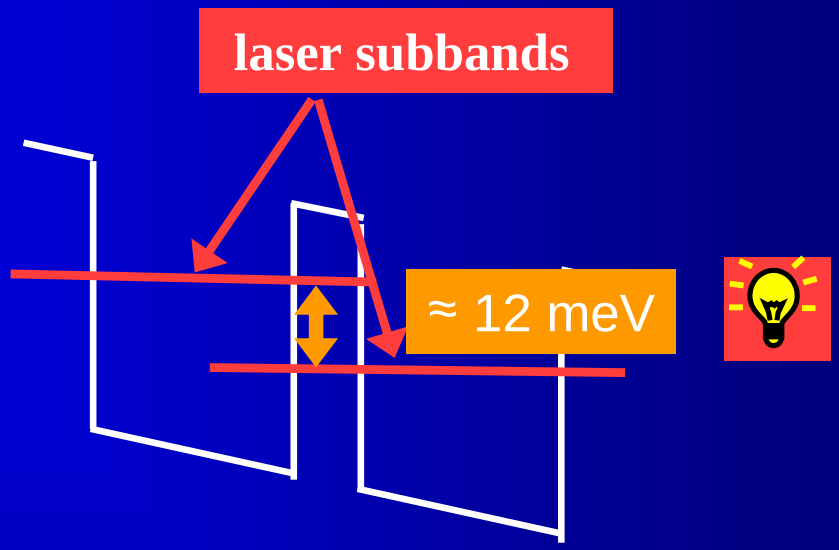

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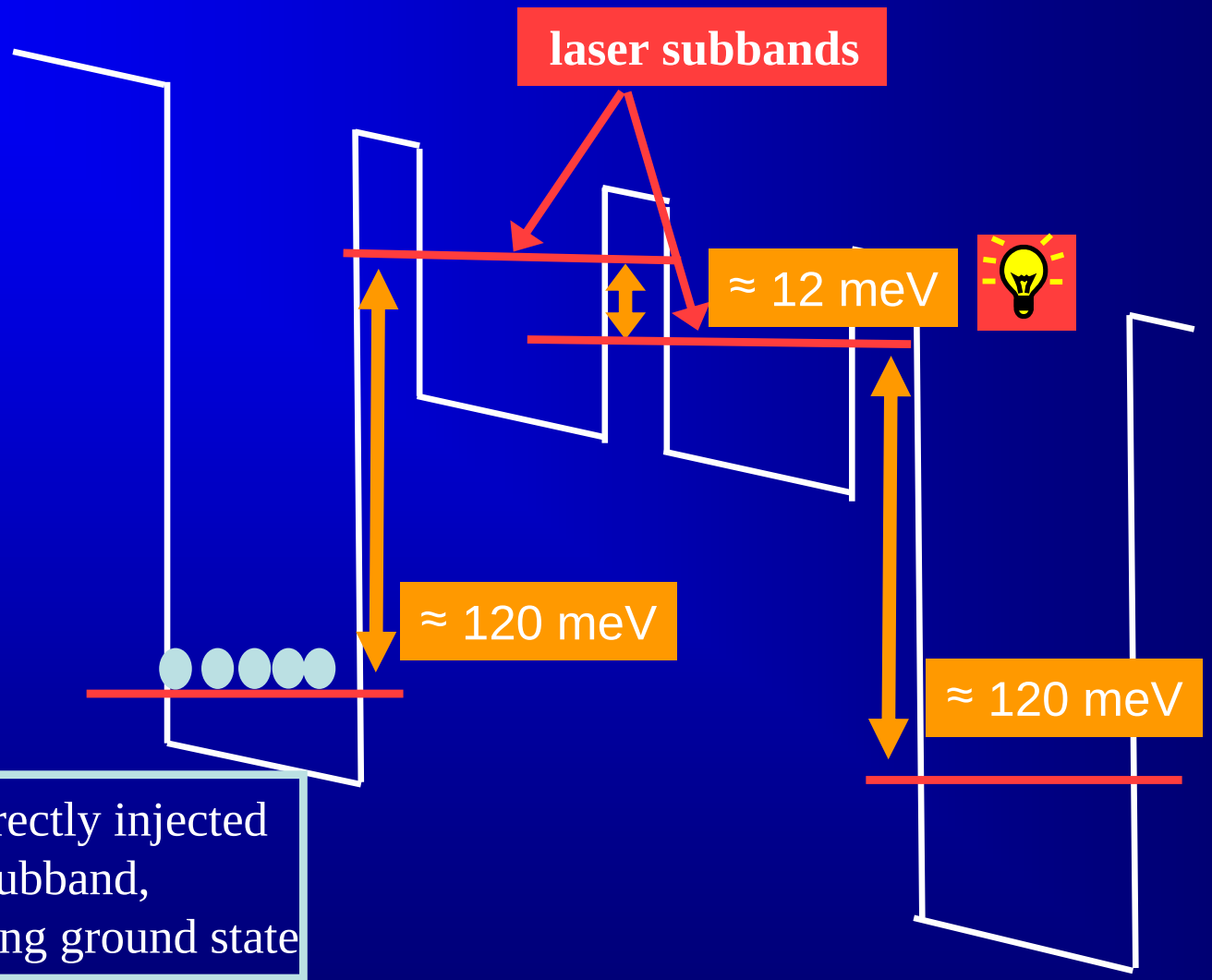

electrons are NOT directly injected
in upper laser subband,
but instead in lower lying ground state

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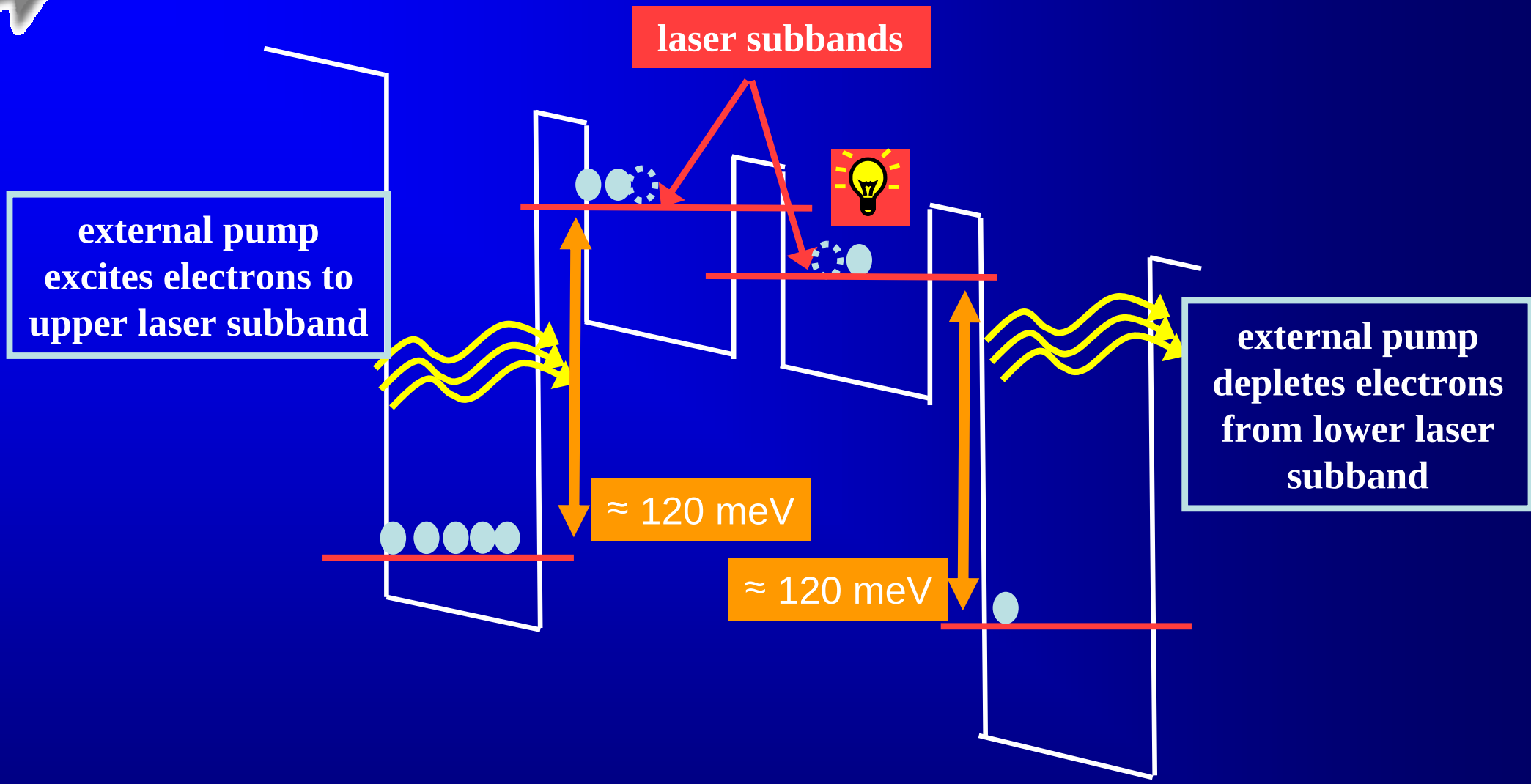

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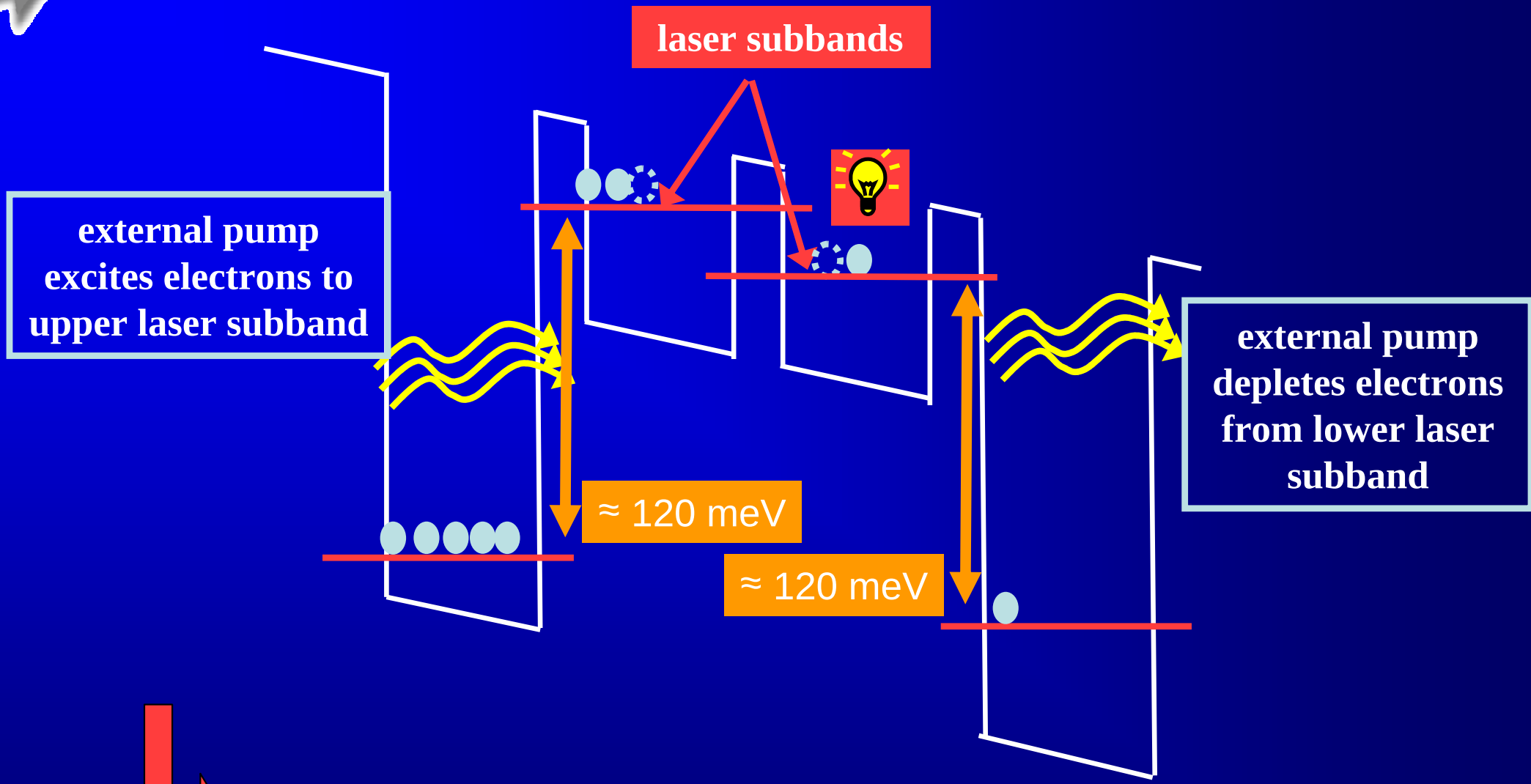

control population of laser subbands with external pump field

generate THz radiation

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Theory: Maxwell's Equations + SBE

Maxwell's wave equations for total field:

$$\frac{\partial E}{\partial t} = -\frac{1}{\epsilon}\nabla \times H - \frac{1}{\epsilon}\frac{\partial P}{\partial t}, \quad \frac{\partial H}{\partial t} = -\frac{1}{\mu}\nabla \times E$$

$$E, H$$

$$P = \sum_{ij} d_{ij} P_{ij}$$

SBE for polarizations P and subband populations N:

$$\frac{d}{dt}P_{ab} = (\frac{i}{\hbar}\epsilon_{ab} - \gamma)P_{ab} + \frac{i}{\hbar}d_{ab}(N_a - N_b)E + \frac{i}{\hbar}\sum_{c\neq a,b}(d_{bc}P_{ac} - d_{ac}P_{cb})E$$

$$\frac{d}{dt}N_a = \frac{i}{2\hbar}\sum_{c\neq a} d_{ac}(P_{ca} - P_{ac})E + \frac{d}{dt}N_a|_s$$

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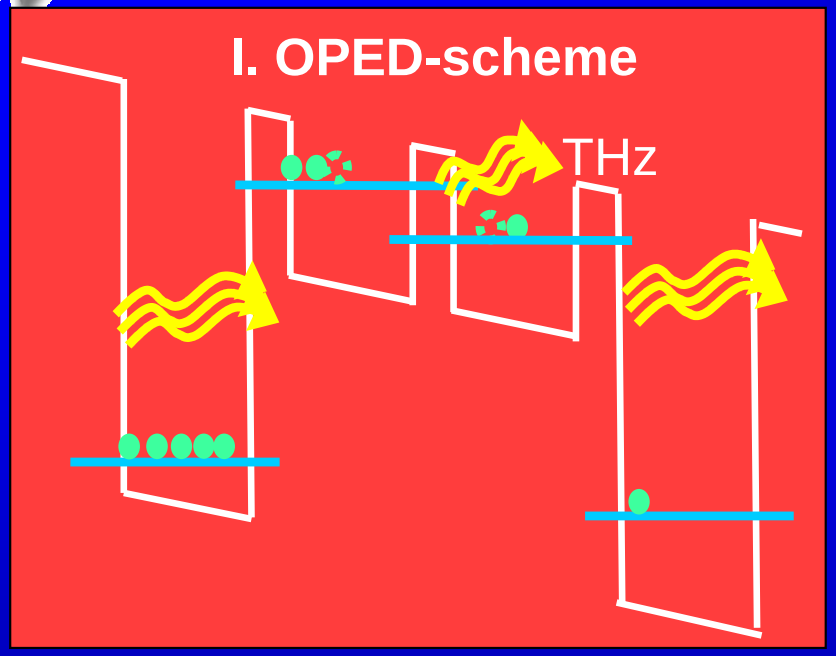

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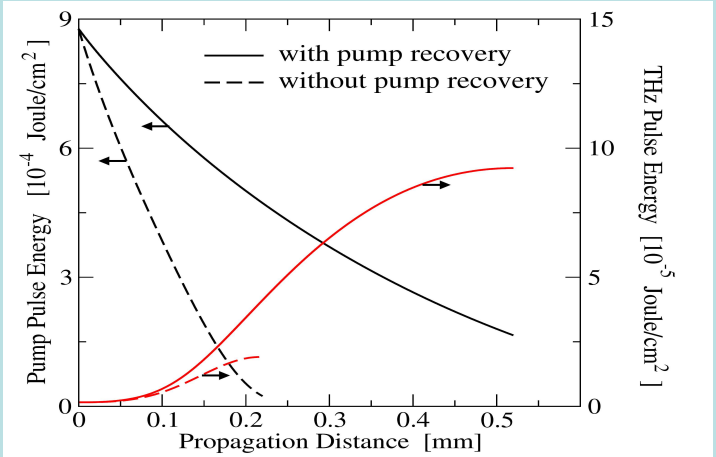

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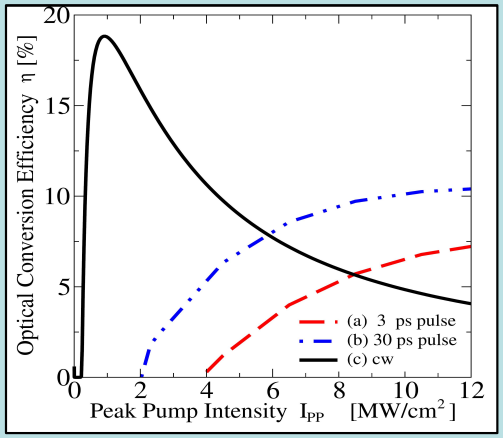

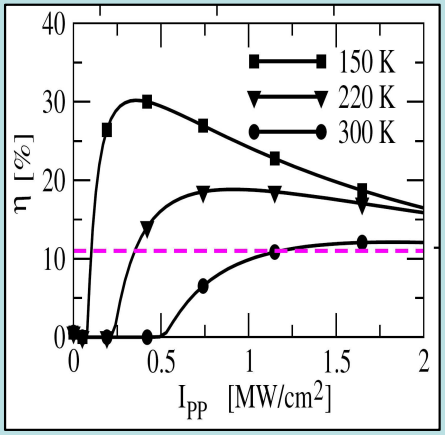

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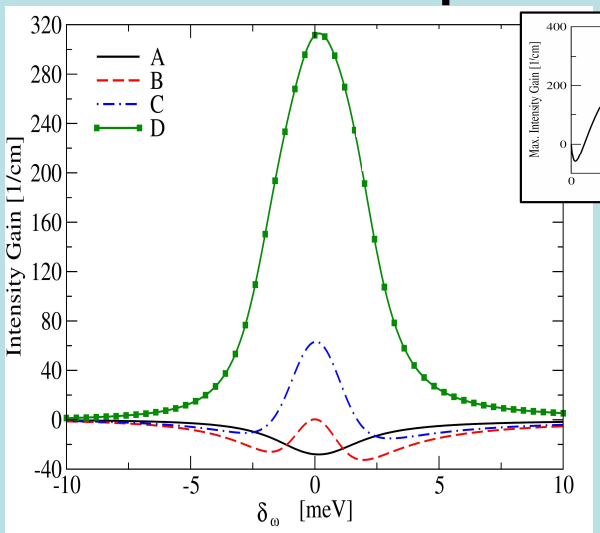

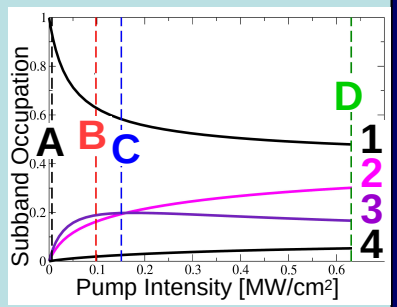

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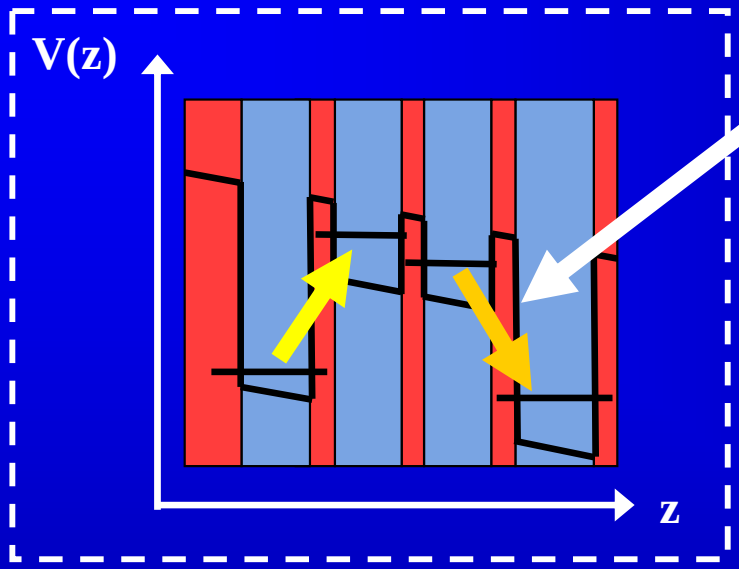
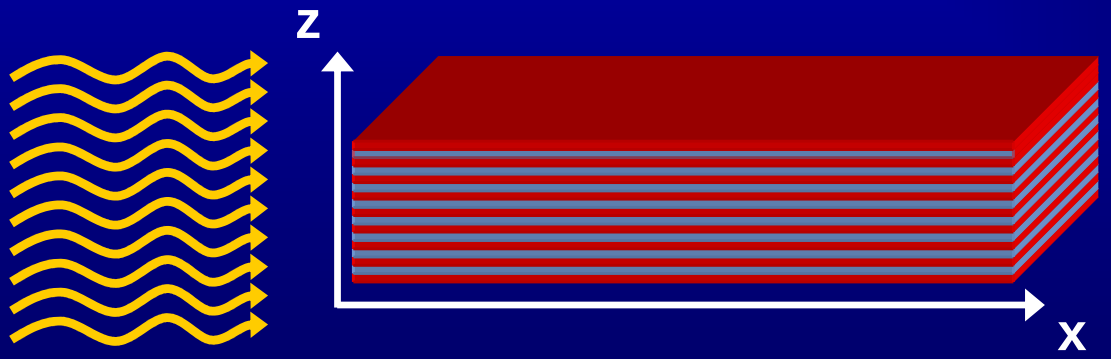


Coherent Pump Recovery !!!

excite structure with Gaussian pulse (propagating in x-direction)



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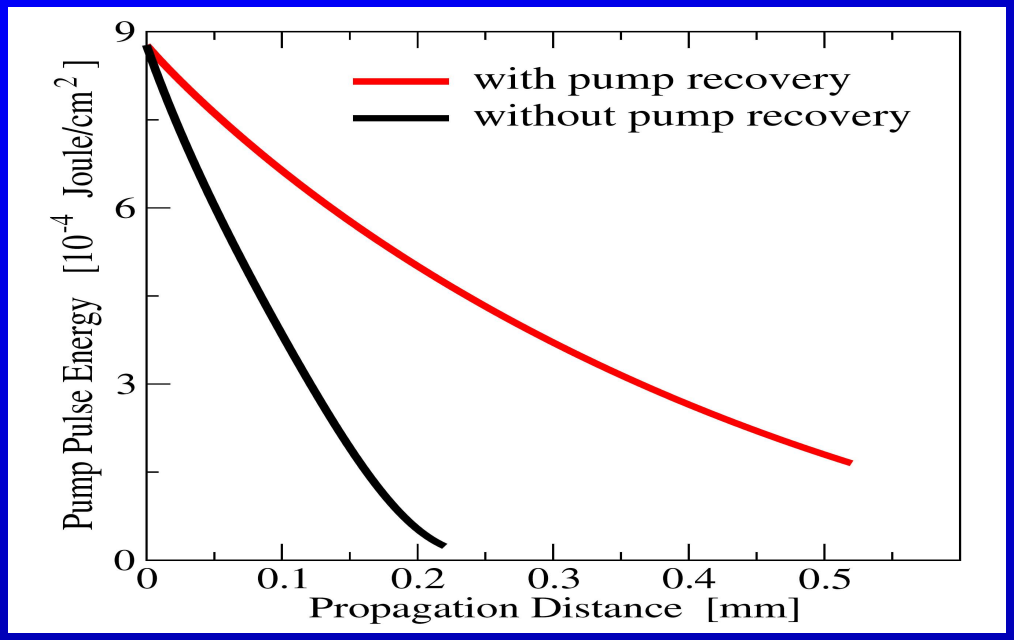

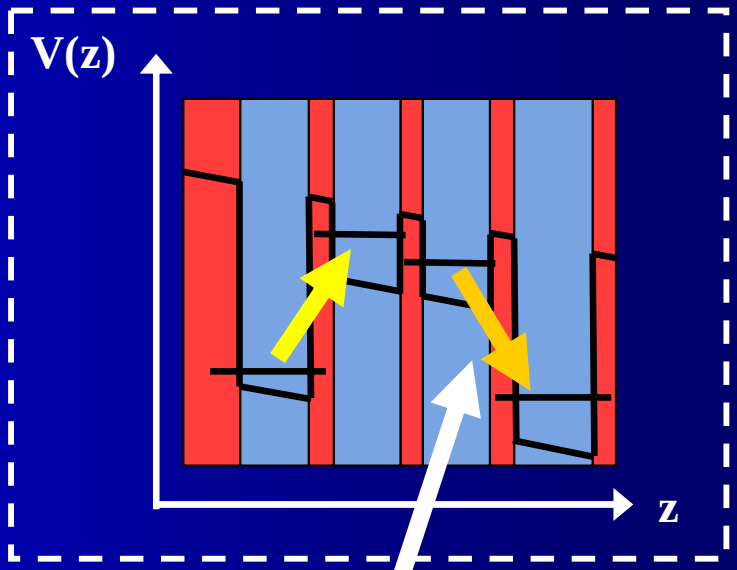

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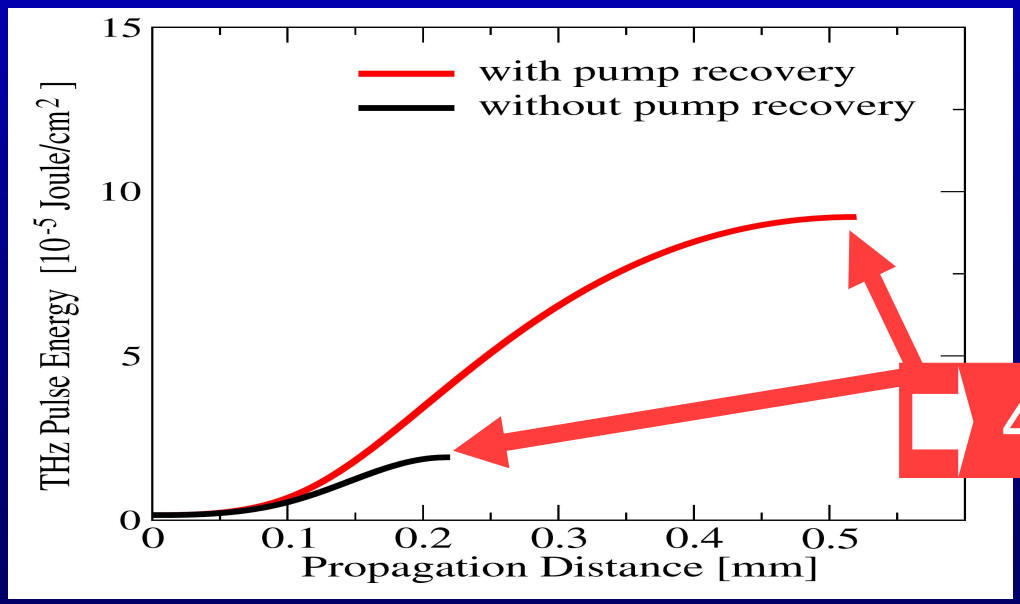

4-5 x more THz radiation

total losses for simulations:

$\alpha_{THz} = 140cm^{-1}, \alpha_{FIR} = 50cm^{-1}$

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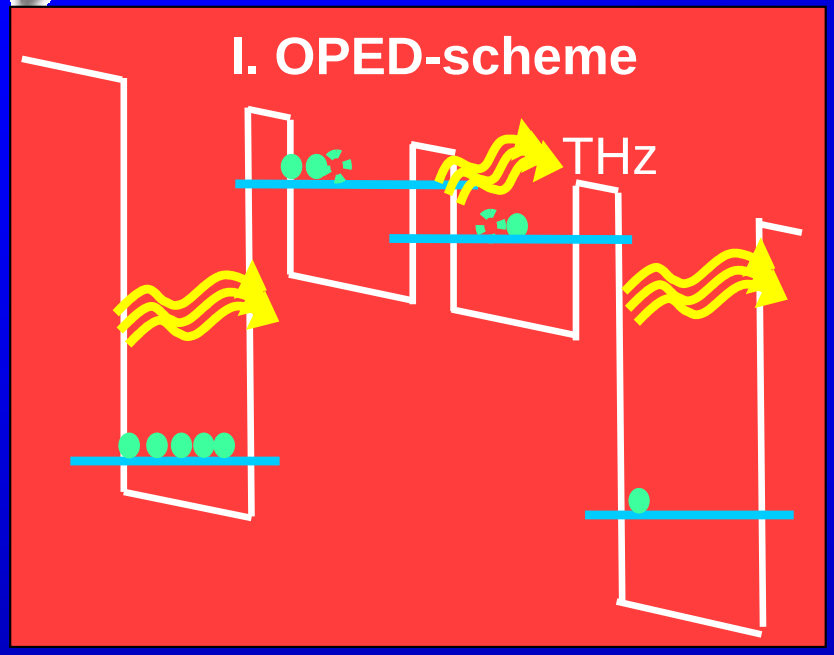

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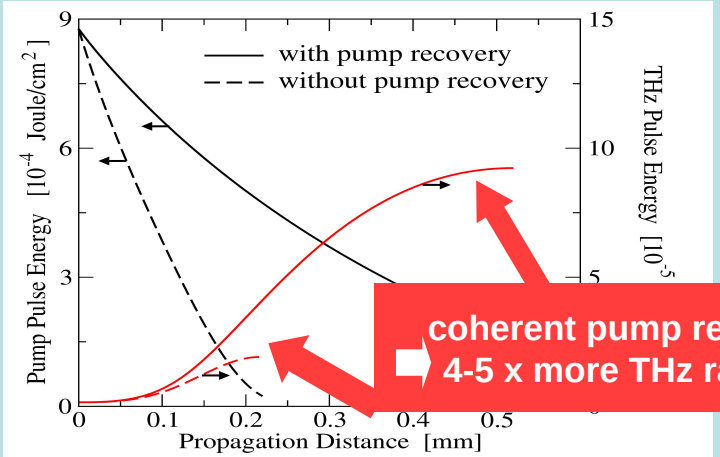

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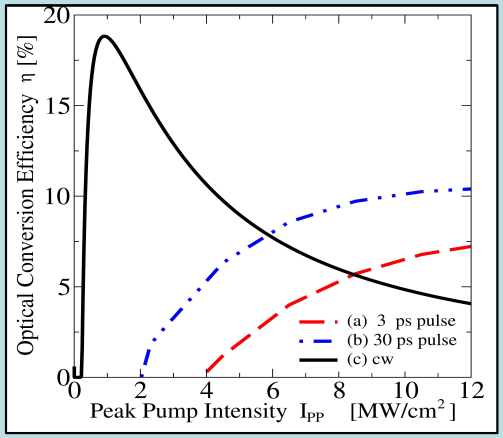

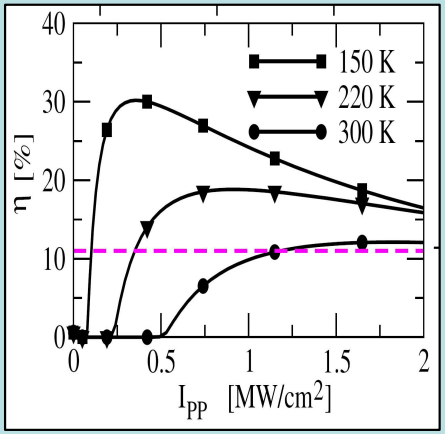

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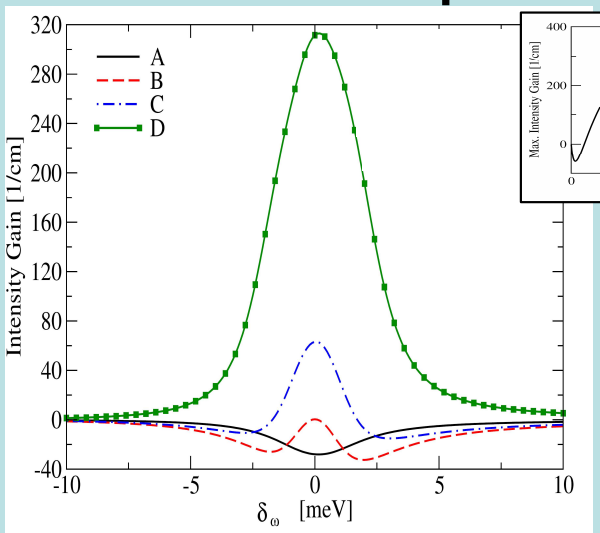
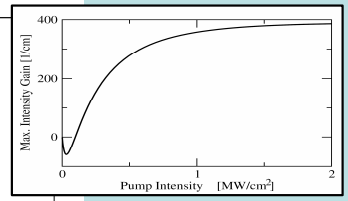
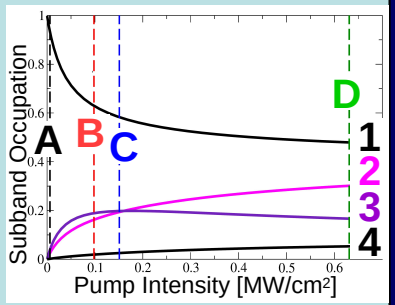






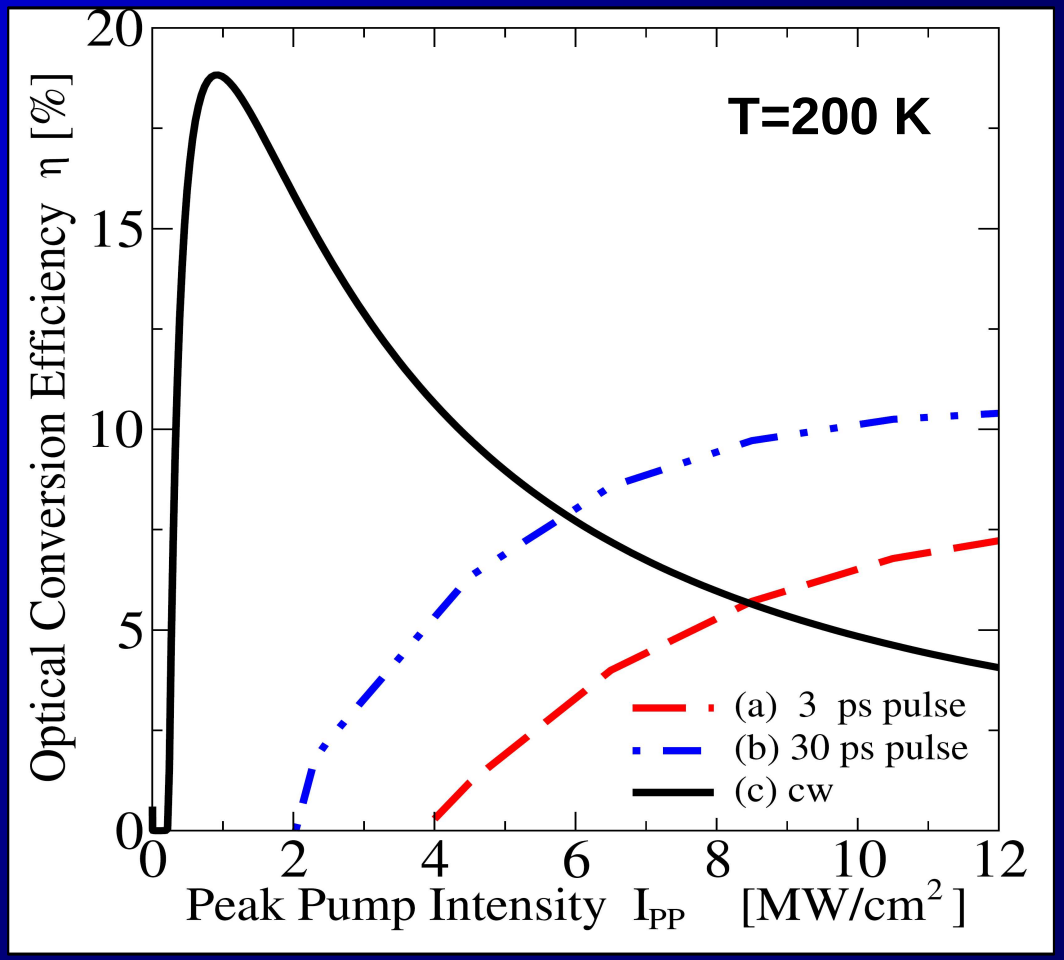
Optical Conversion Efficiency (max. Output/Input)

Dependence of optical conversion efficiency η on pump energy

for (a) excitation with 3 ps pulse
for (b) excitation with 30 ps pulse
for (c) cw excitation

- strong dependence on excitation length and intensity
- saturation of THz gain (optical Stark effect and pump-induced population redistribution)

window for optimal pump excitation



total losses for simulations:
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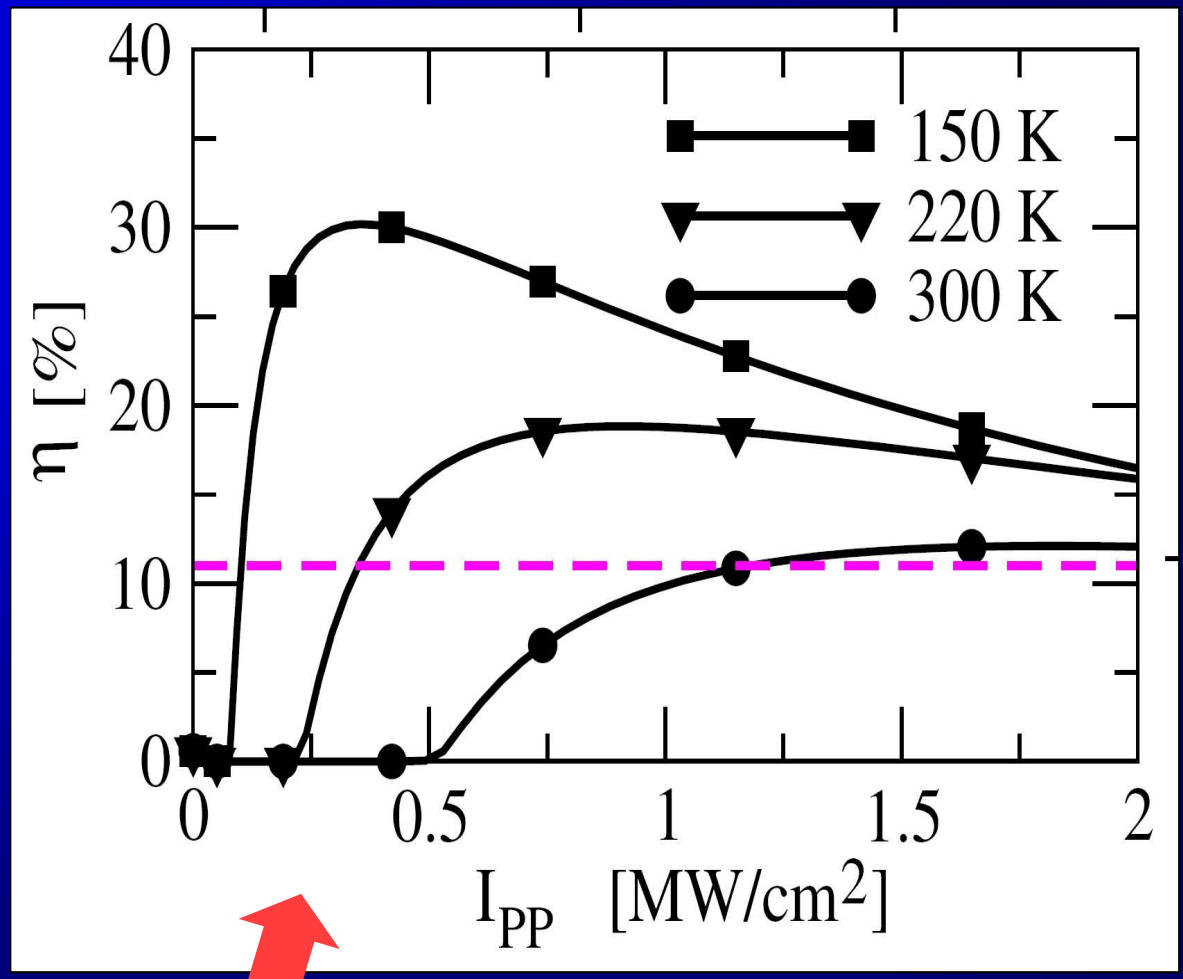
Optical Conversion Efficiency

Dependence of optical conversion efficiency η on pump energy

for cw excitation
at different temperatures



strong temp. dependence due to temp. dependent non-radiative carrier recombination and polarization dephasing

highest achievable η and width of the window for optimal pump excitation are temperature dependent

cw-excitation: pathway to room-temp operation

total losses for simulations:
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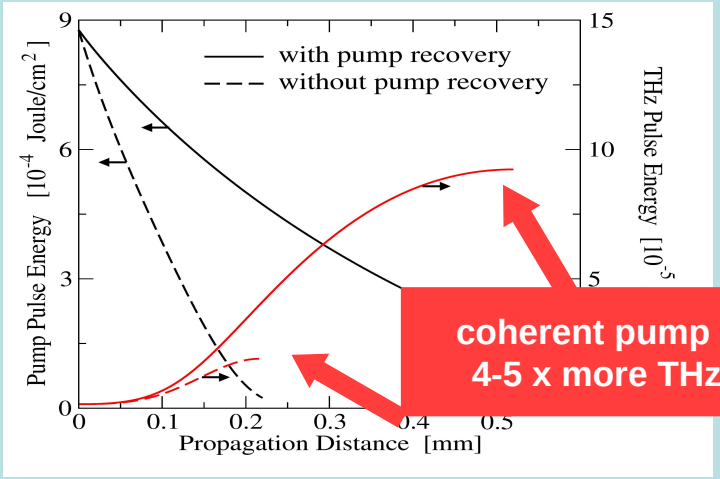
Promising Results for Pulse- and CW-Excitation:

II. Benefits of Pump Recovery



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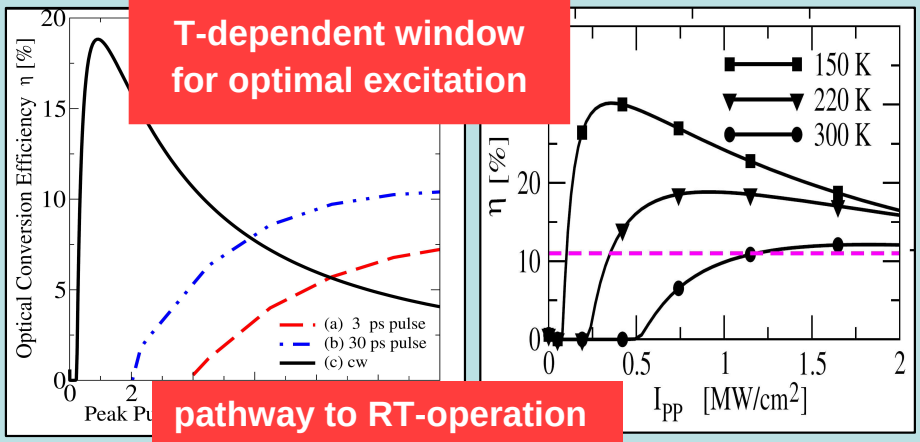

T-dependent window for optimal excitation

pathway to RT-operation

promising conversion effiencies for different lattice temperatures

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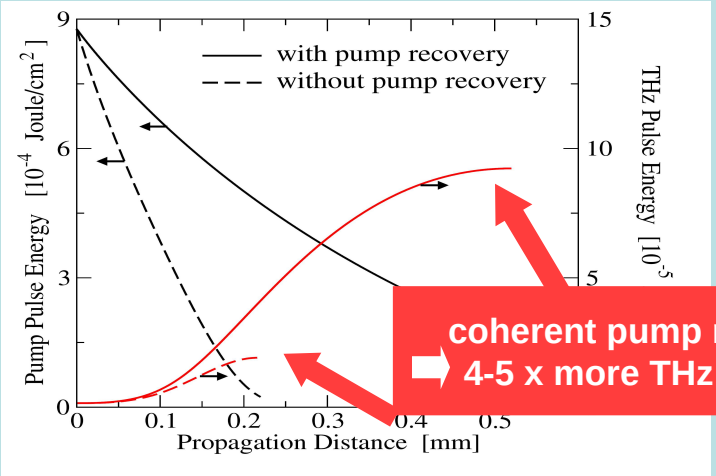

coherent pump recovery
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This means that our approach works -
- theoretically -
like we thought it would!
Or does it?

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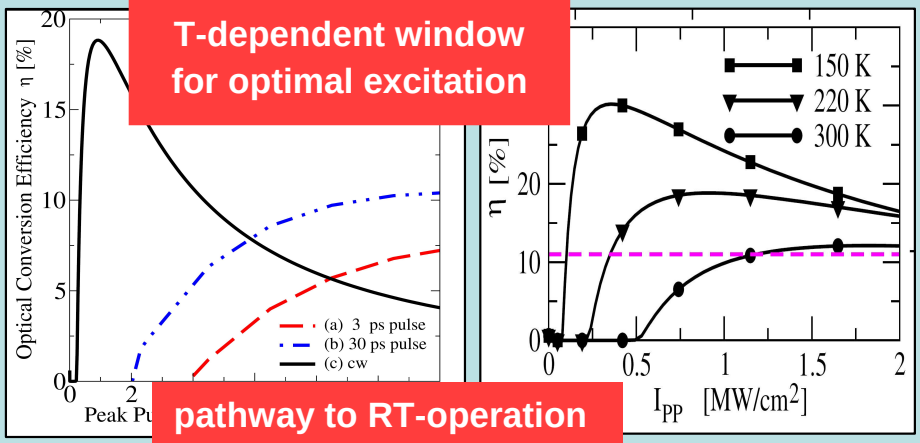

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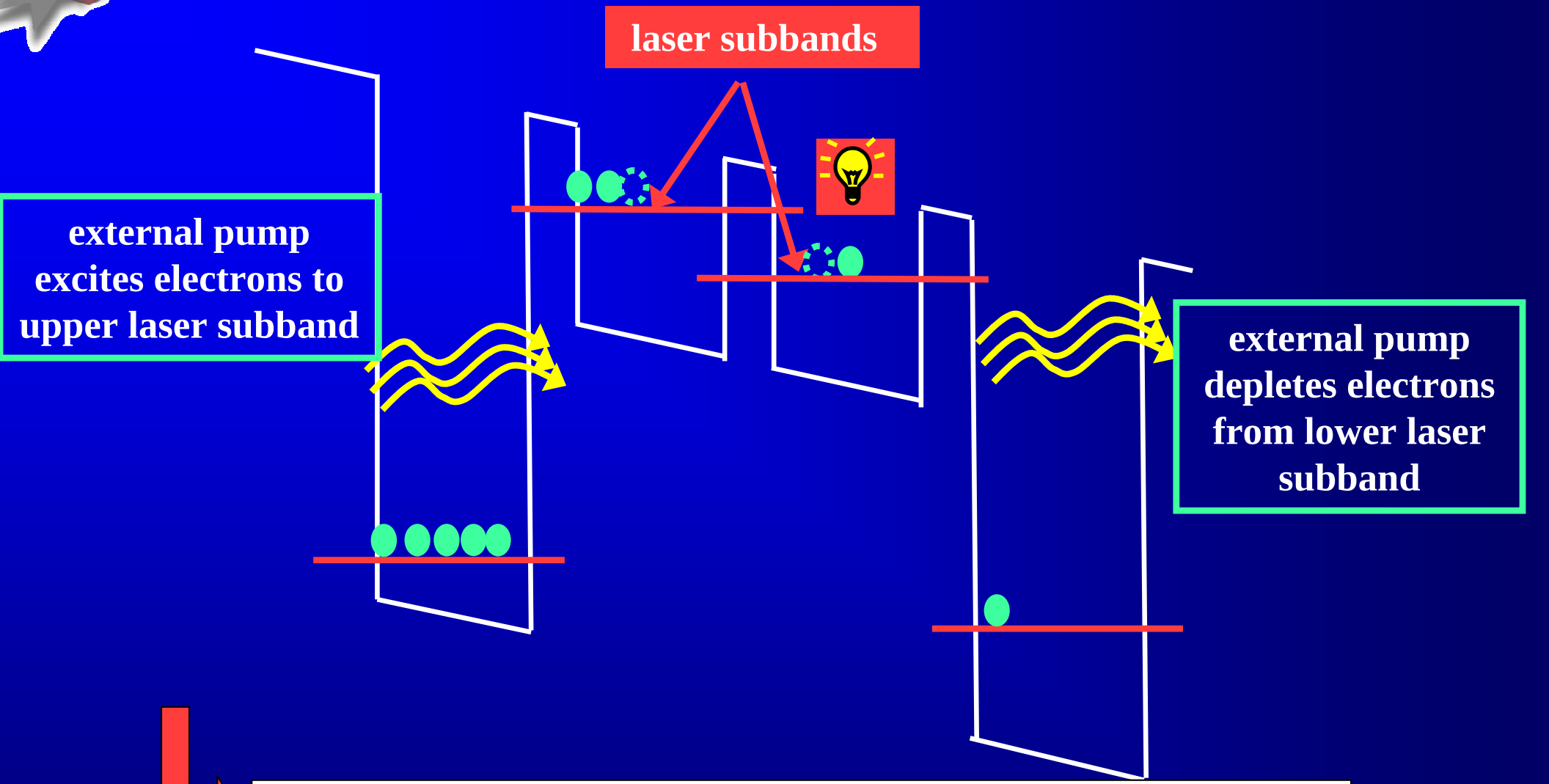

control population of laser subbands with external pump field

➡ generate THz radiation via stimulated emission

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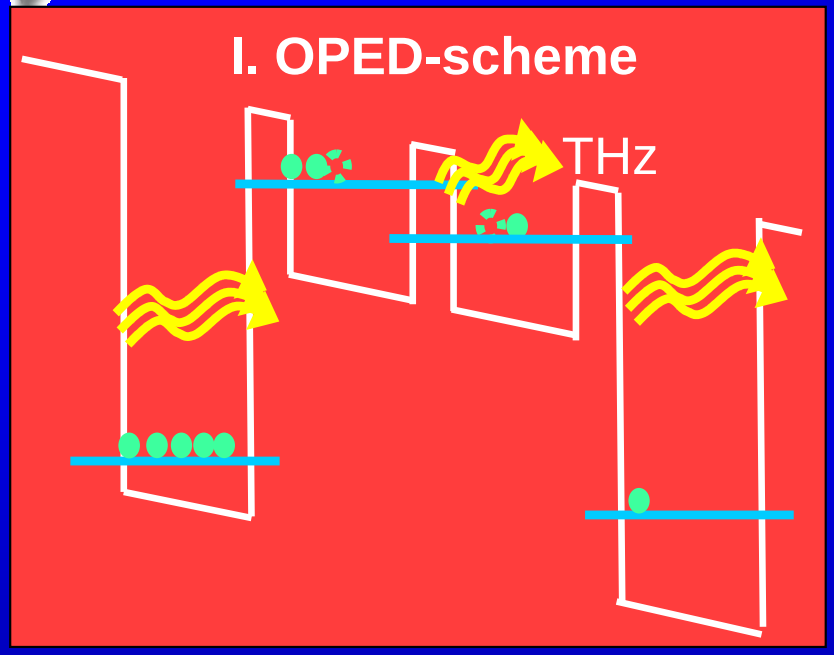

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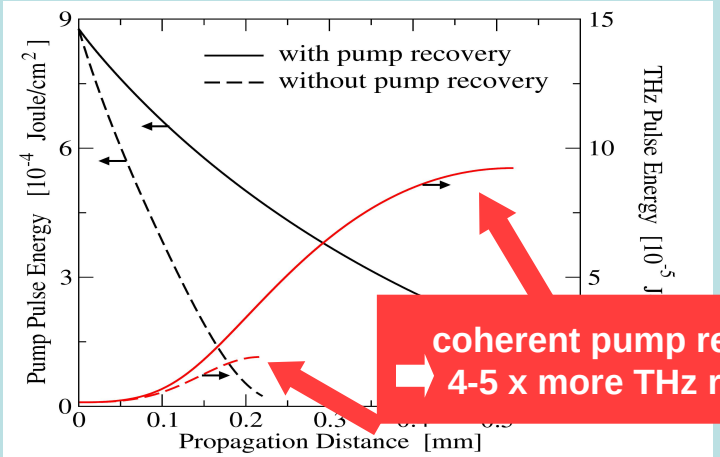

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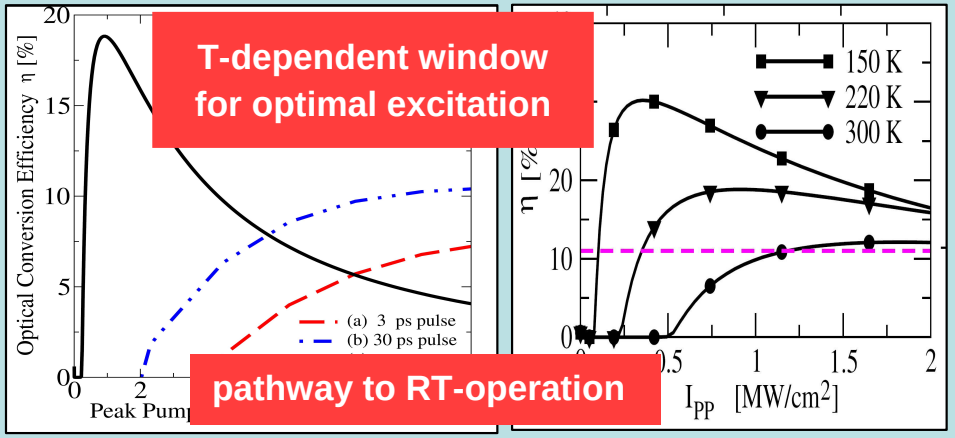
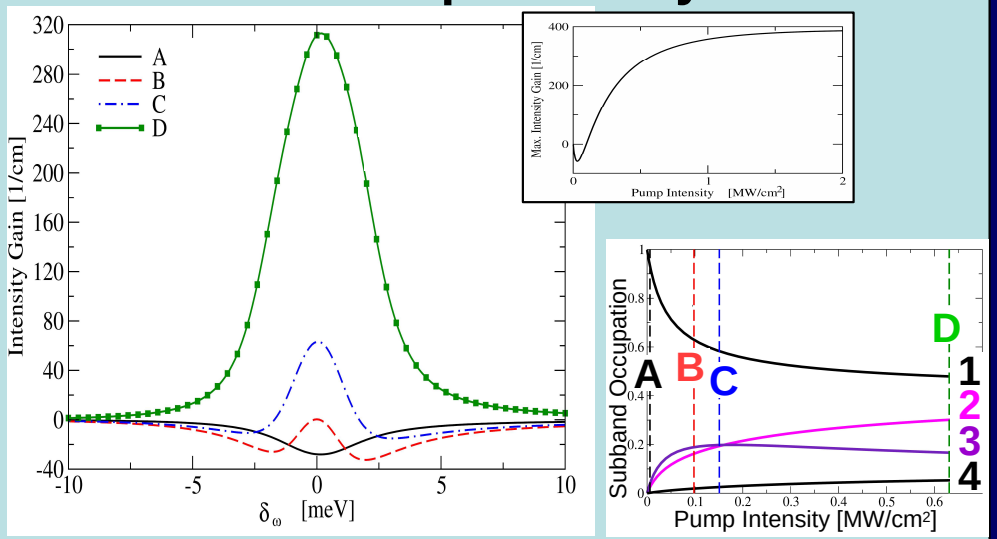
(Dependence of Optical Conversion Efficiency on Pulse Duration and Temperature)



T-dependent window for optimal excitation

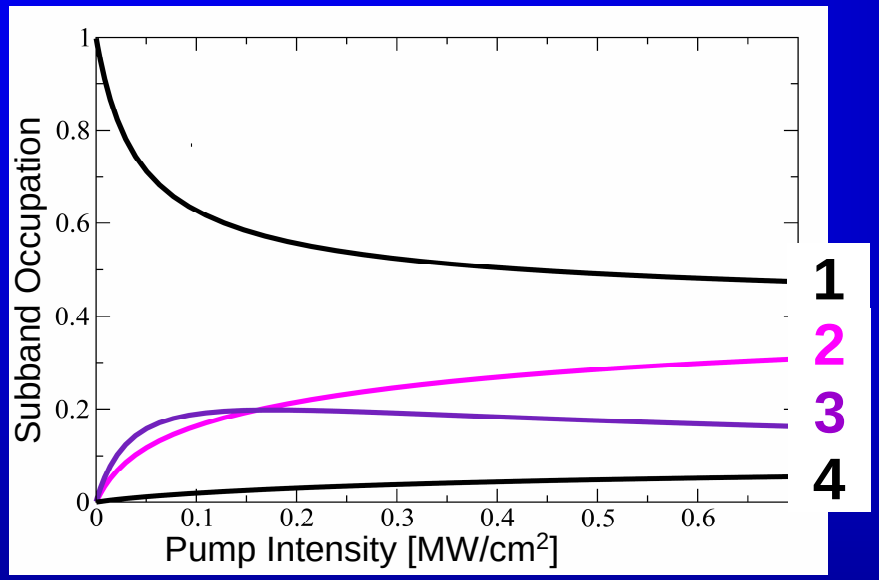
pathway to RT-operation

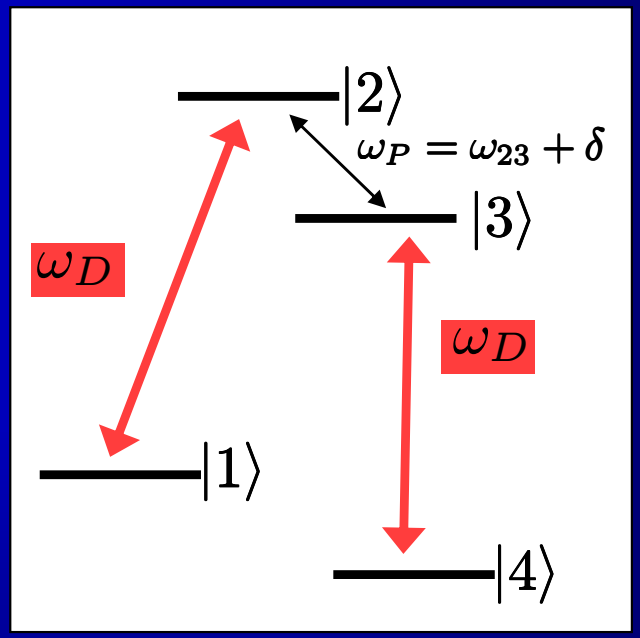
IV. Dependence of Small Signal Gain on Pump Intensity



Let's look at the linear gain for different pump intensities

- excite OPED with pump field
  (redistribute carriers between subbands)





-probe with small THz field with different detunings

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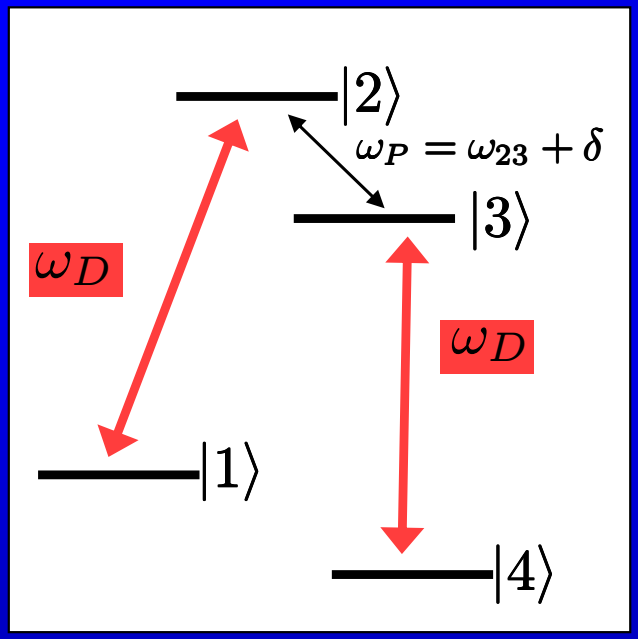
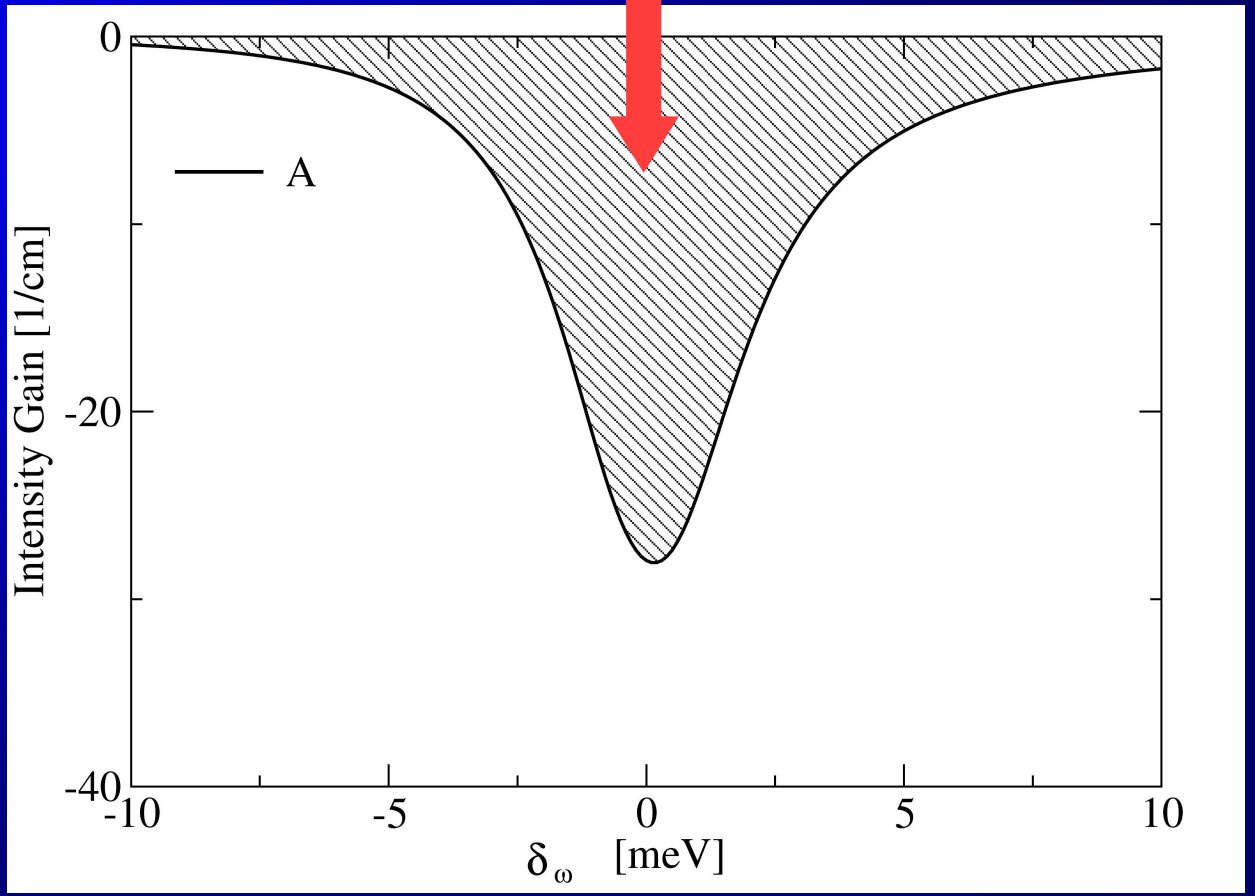
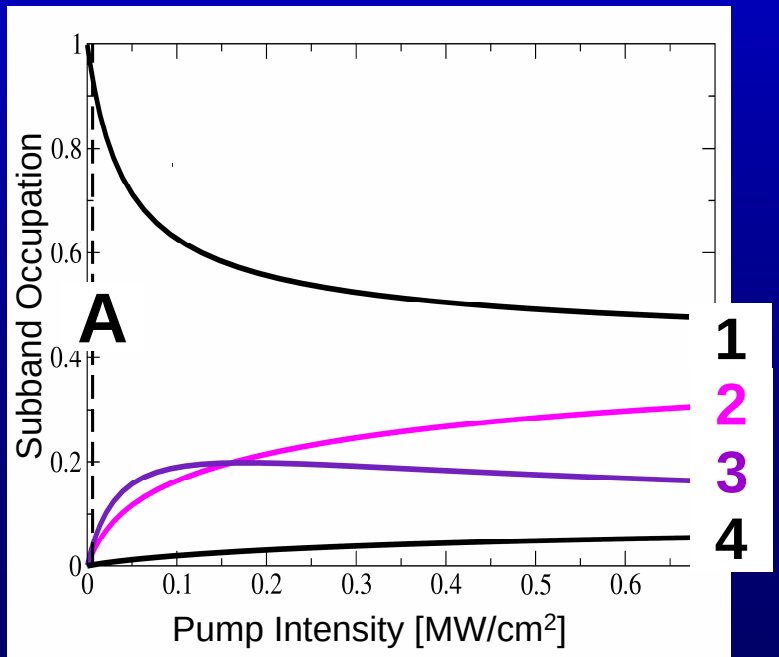
Let's look at the linear gain for different drive intensities



absorption





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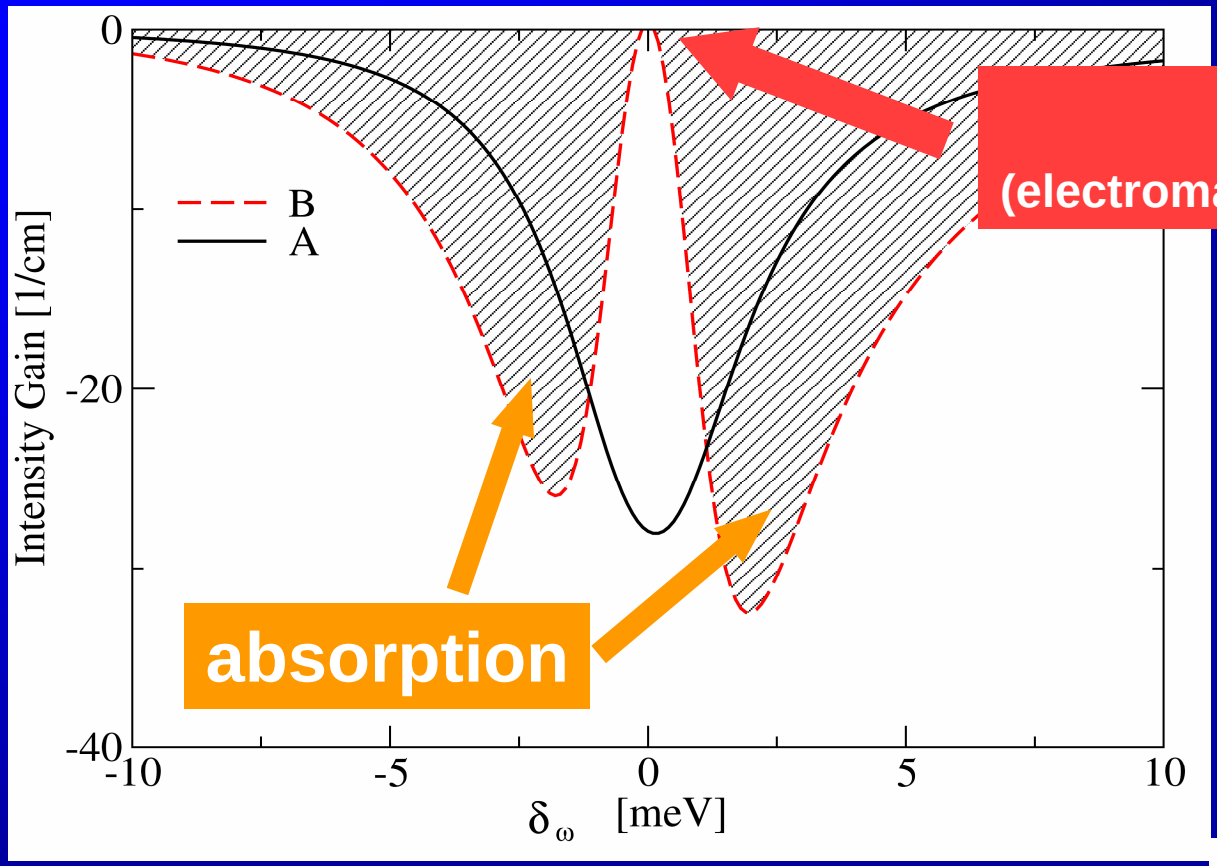
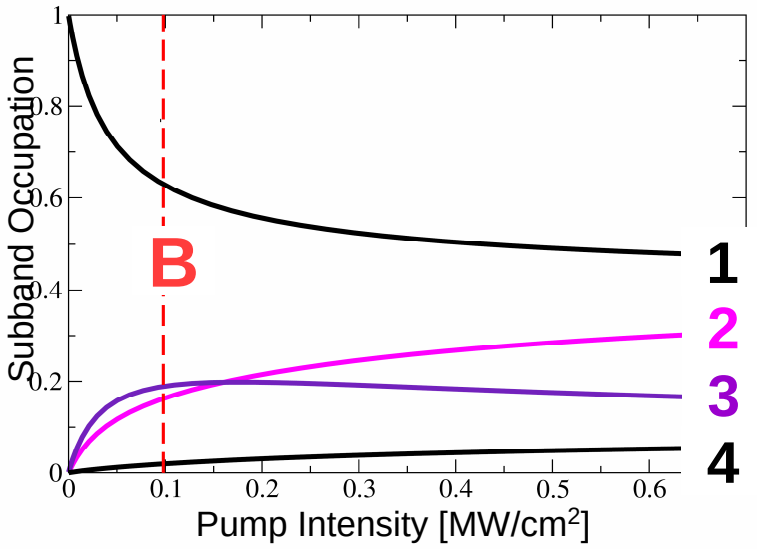
Let's look at the linear gain for different drive intensities

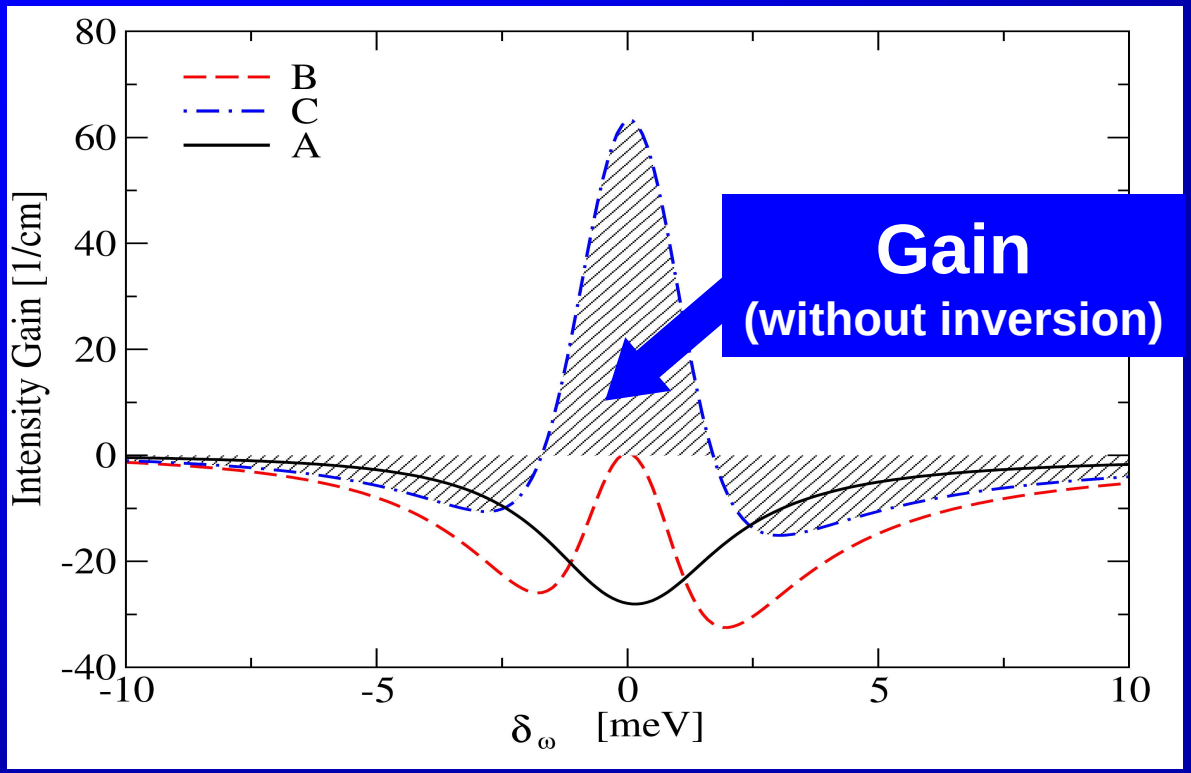


EIT
(electromagentically induced transparency)

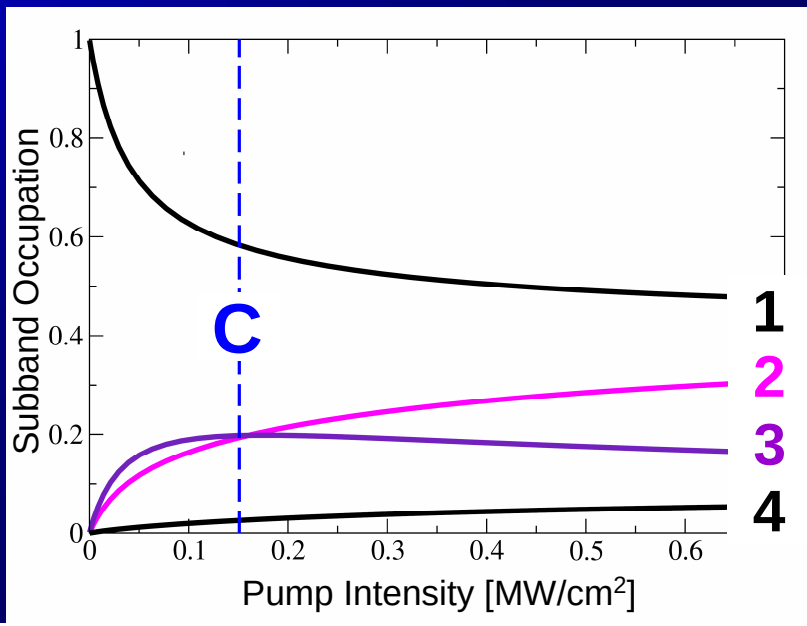
SIGN OF QUANTUM COHERENCE!!!



Let's look at the linear gain for different drive intensities

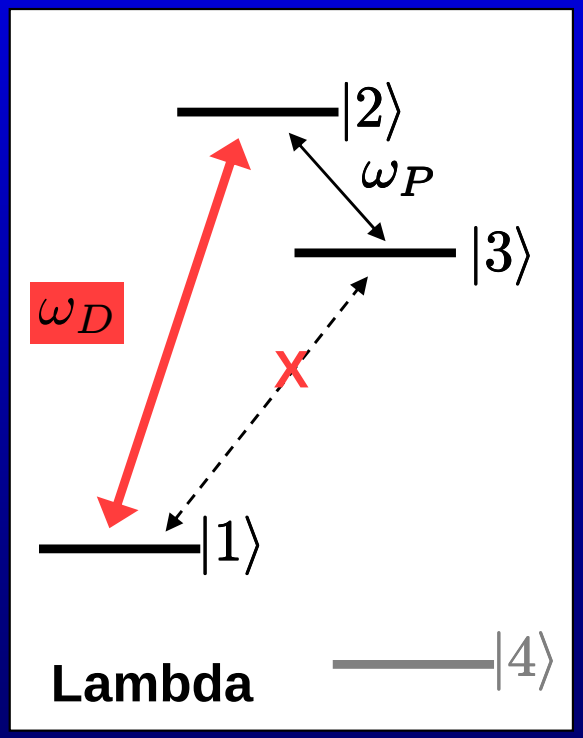


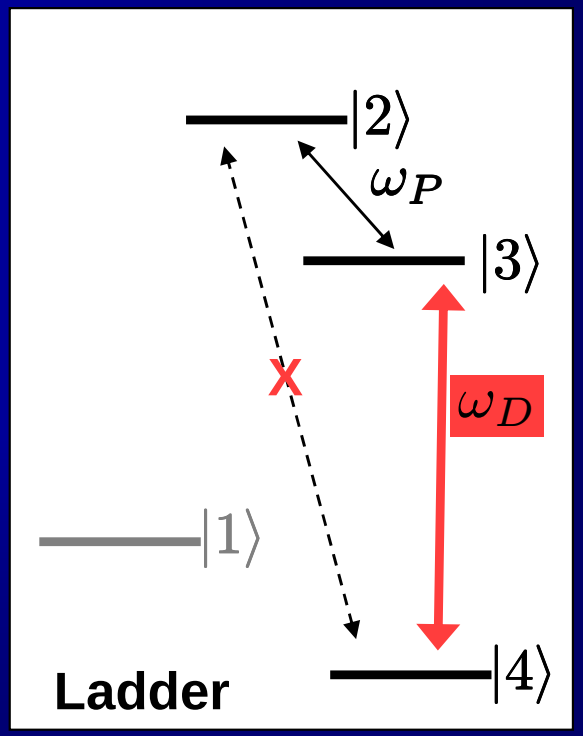
SIGN OF QUANTUM COHERENCE!!!



Quantum Coherence Contributions

Quantum coherence contributions are usually observed in atomic model system, such as … e.g. lambda and ladder systems





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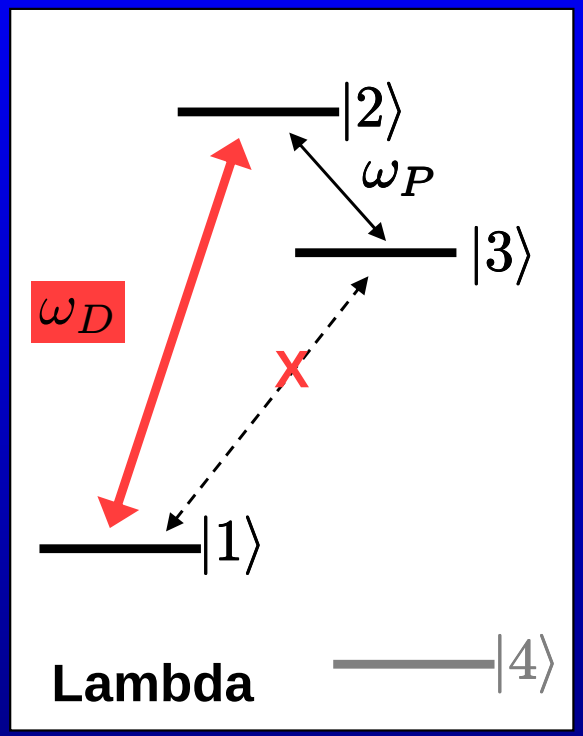
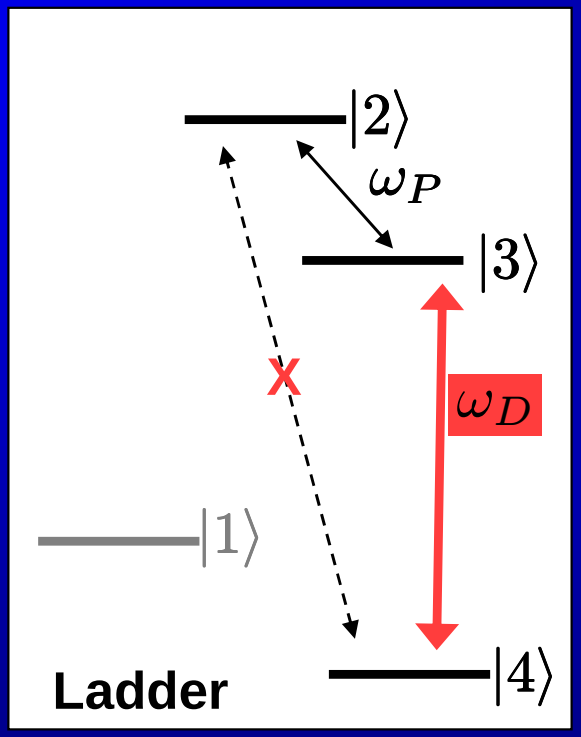
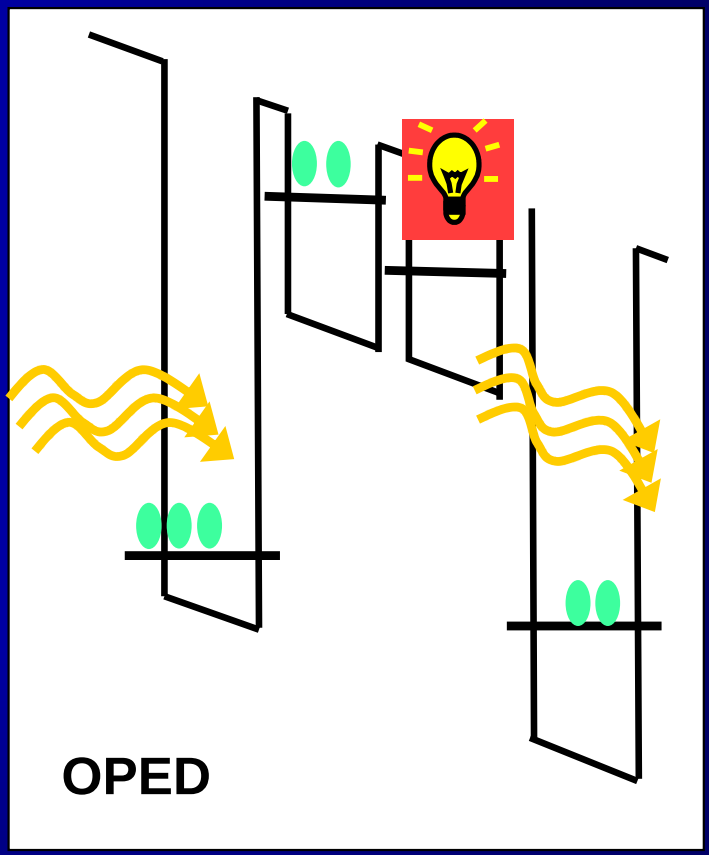
Lambda + Ladder = OPED



+



=



model systems for quantum coherence effects
(LWI, EIT)
should see signs of q. c. in gain spectra

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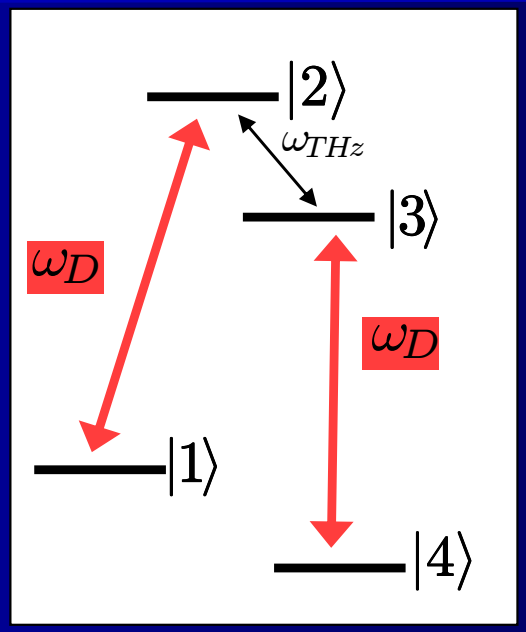
Analytical Results:

possible to generate THz radiation
with/without population inversion due to:
- stimulated emission
- quantum coherence contributions



linear stimulated emission

automatically phase-matched quantum coherence effects

auto-correlation

cross-correlation

$$\frac{d}{dt}E_{THz} \propto d_{THz}^2 E_{THz} \frac{(N_2 - N_3)4\hbar^2\gamma^2 + (N_2 - N_3)d_{THz}^2|E_{THz}|^2 + (N_1 + N_2 - N_3 - N_4)d_D^2|E_D|^2}{2\hbar\gamma(4d_D^2|E_D|^2 + d_{THz}^2|E_{THz}|^2 + 4\hbar^2\gamma^2)}$$

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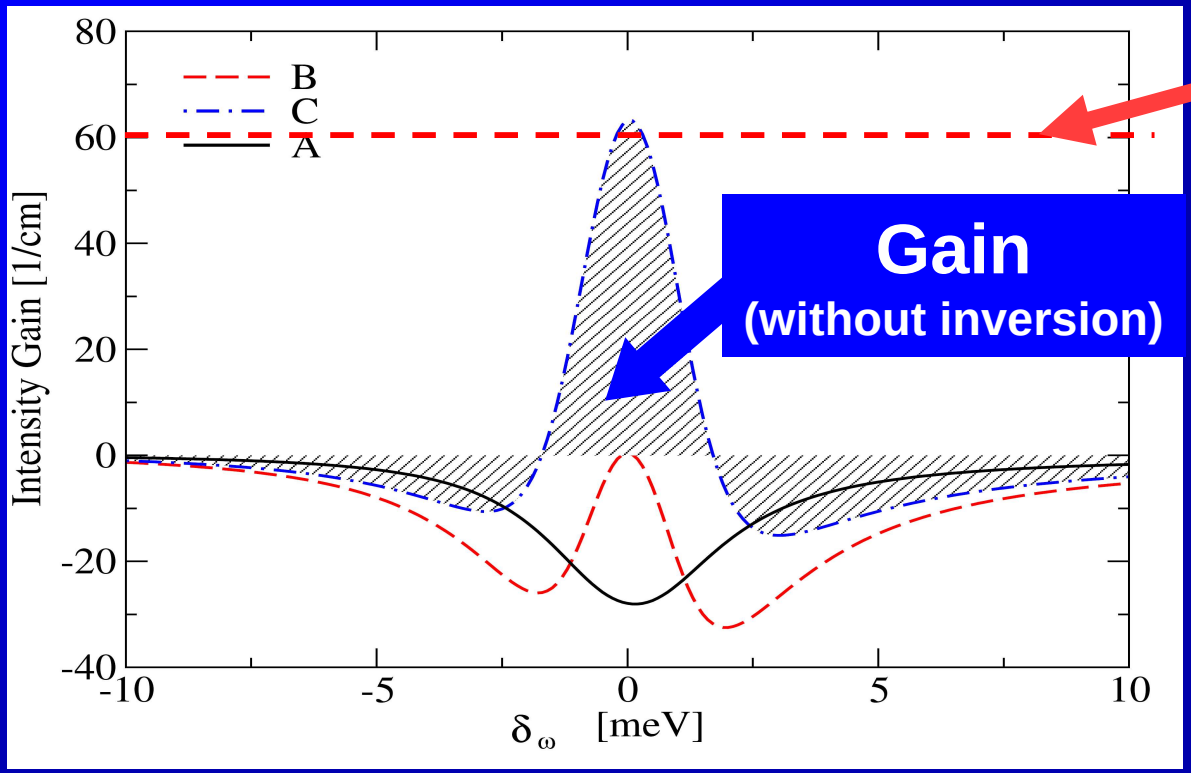
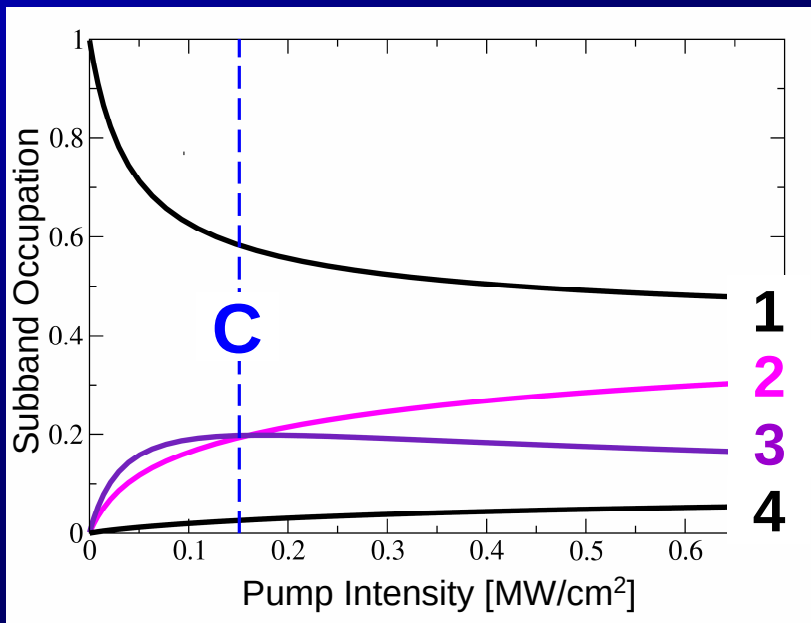
Let's look at the linear gain for different drive intensities



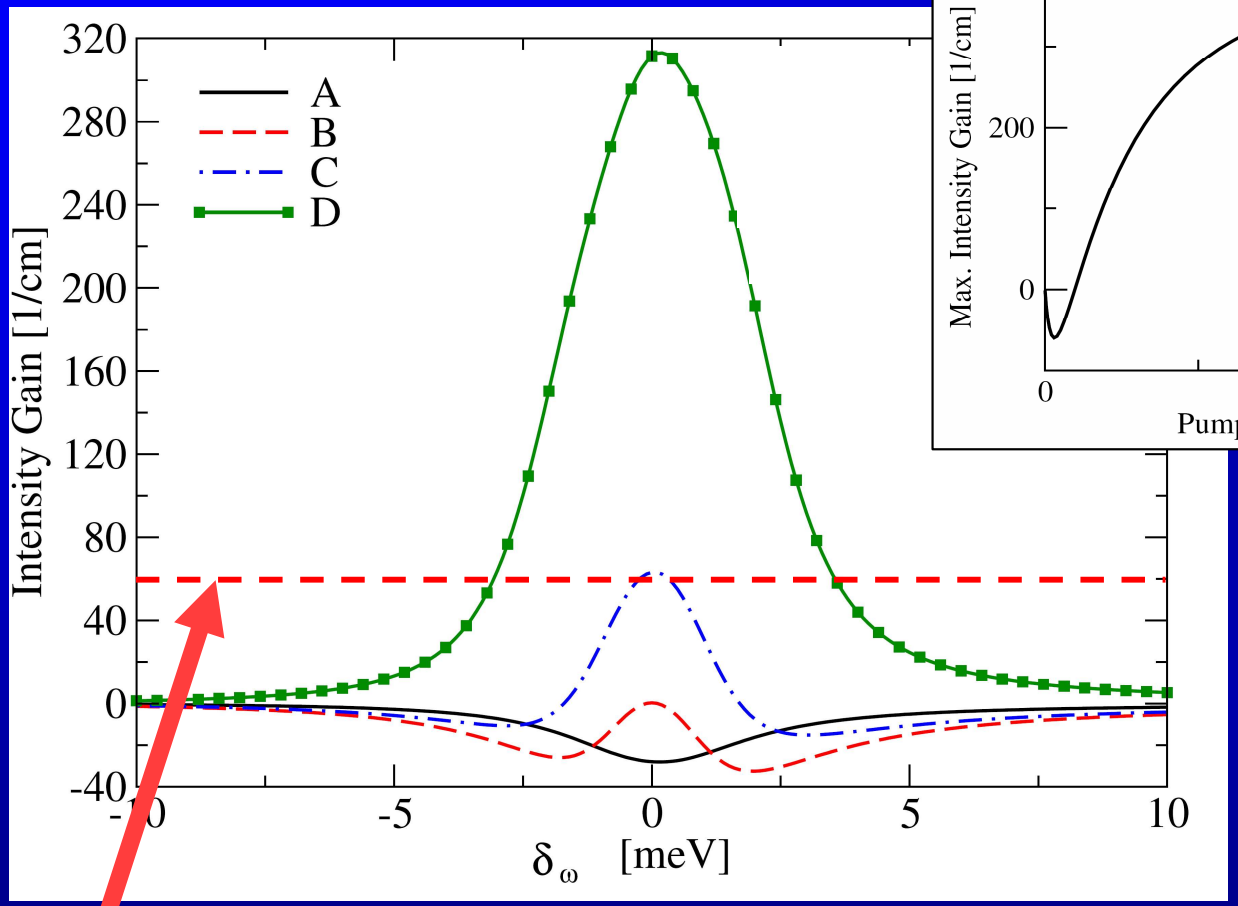
$$\alpha_{THz} = \alpha_{WG} + \alpha_M + \alpha_{FCL} \geq 60 cm^{-1}$$

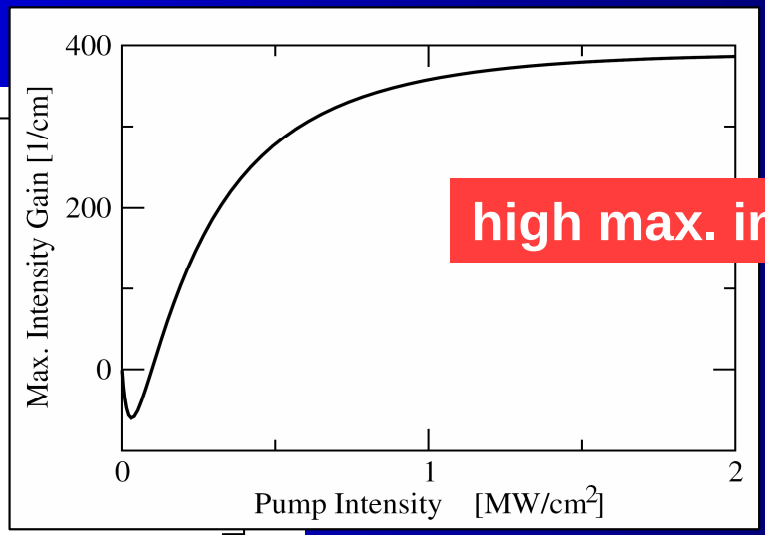
Gain
(without inversion)

SIGN OF QUANTUM COHERENCE!!!



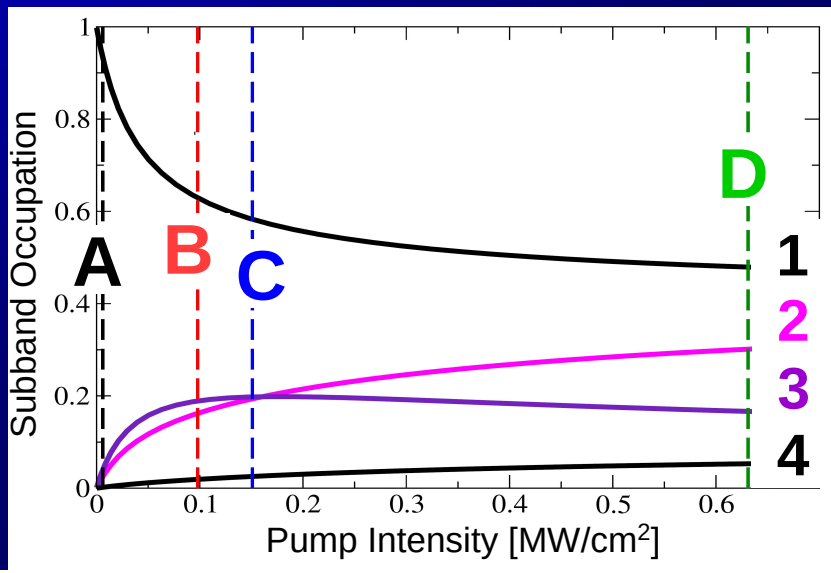
Let's look at the linear gain for different drive intensities





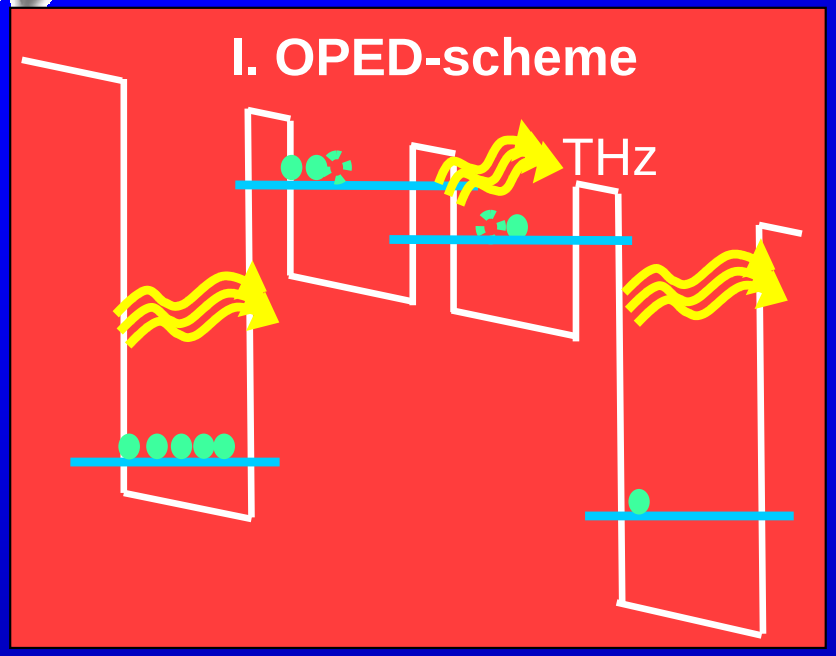
high max. intensity gain

$$\alpha_{THz} = \alpha_{WG} + \alpha_M + \alpha_{FCL} \geq 60cm^{-1}$$

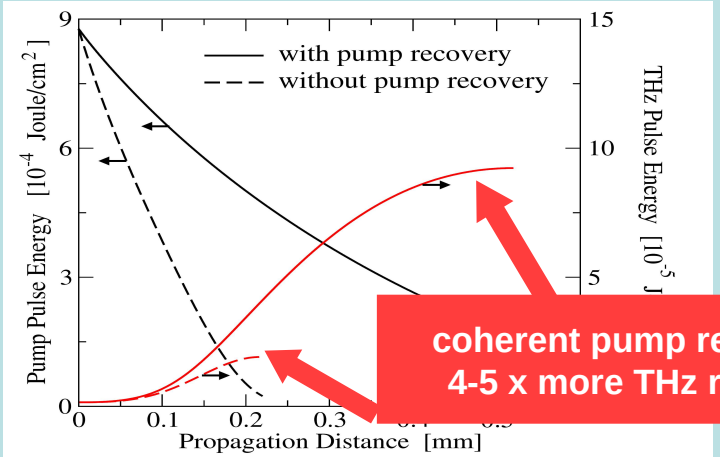


Summary: more information in PRL (Sept. 2007)

I. OPED-scheme



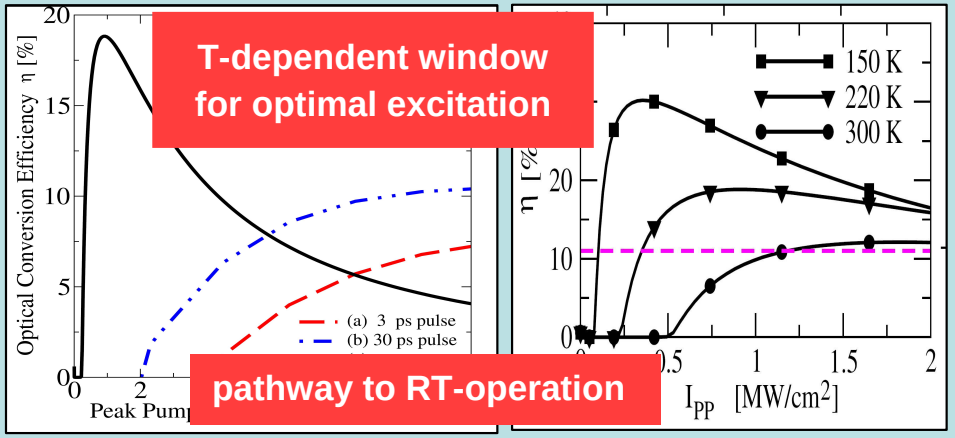
II. Benefits of Pump Recovery



coherent pump recovery
4-5 x more THz radiation

III. Capabilities of OPED

(Dependence of Optical Conversion Efficiency on Pulse Duration and Temperature)



T-dependent window
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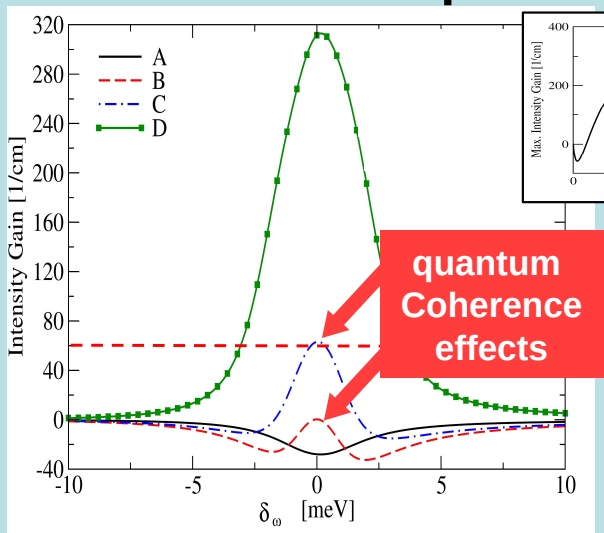
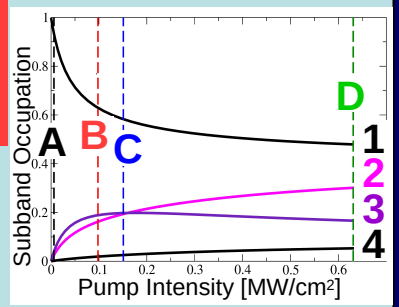
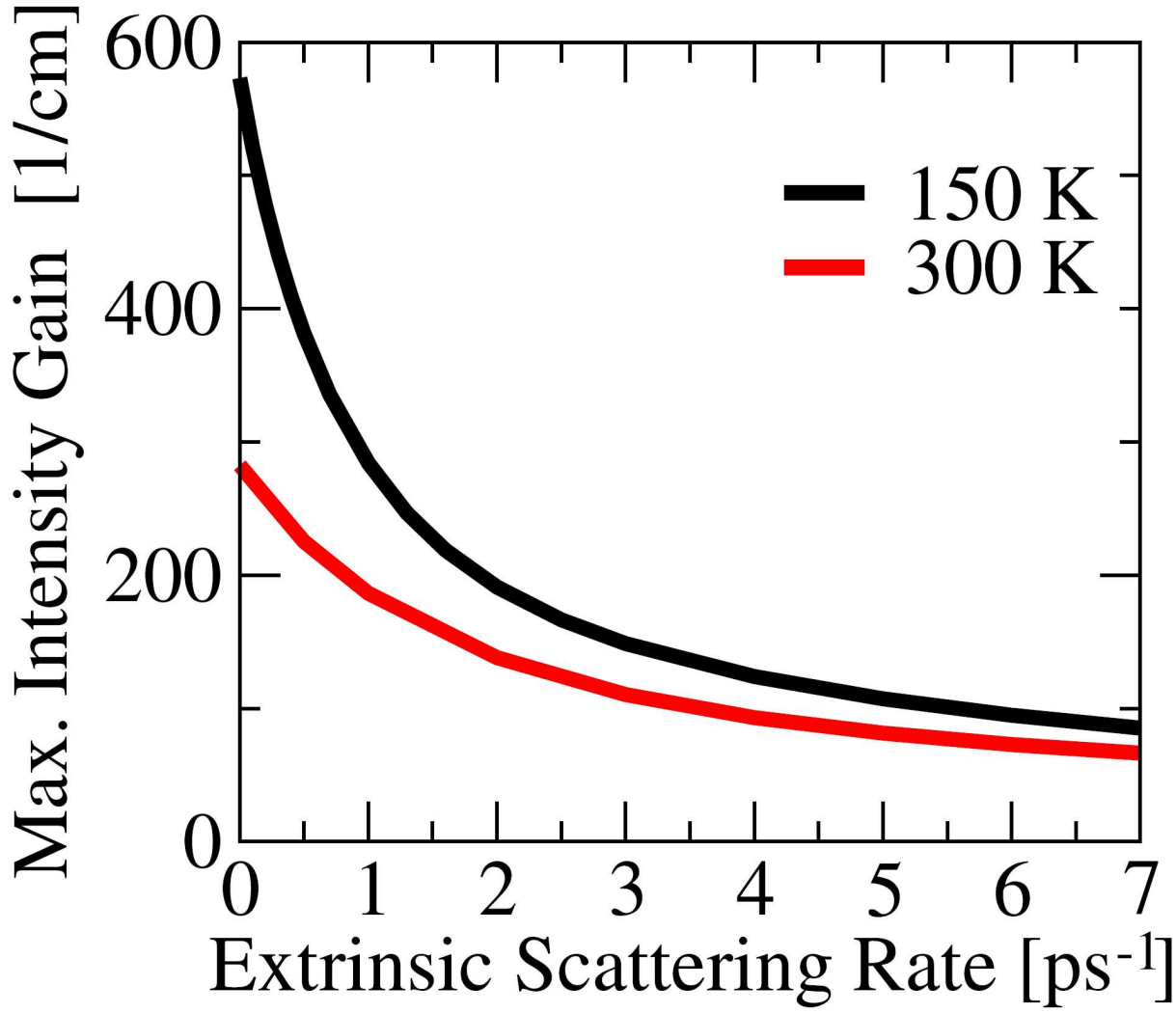
IV. Dependence of Small Signal Gain on Pump Intensity



high max.
intensity gain

quantum
Coherence
effects





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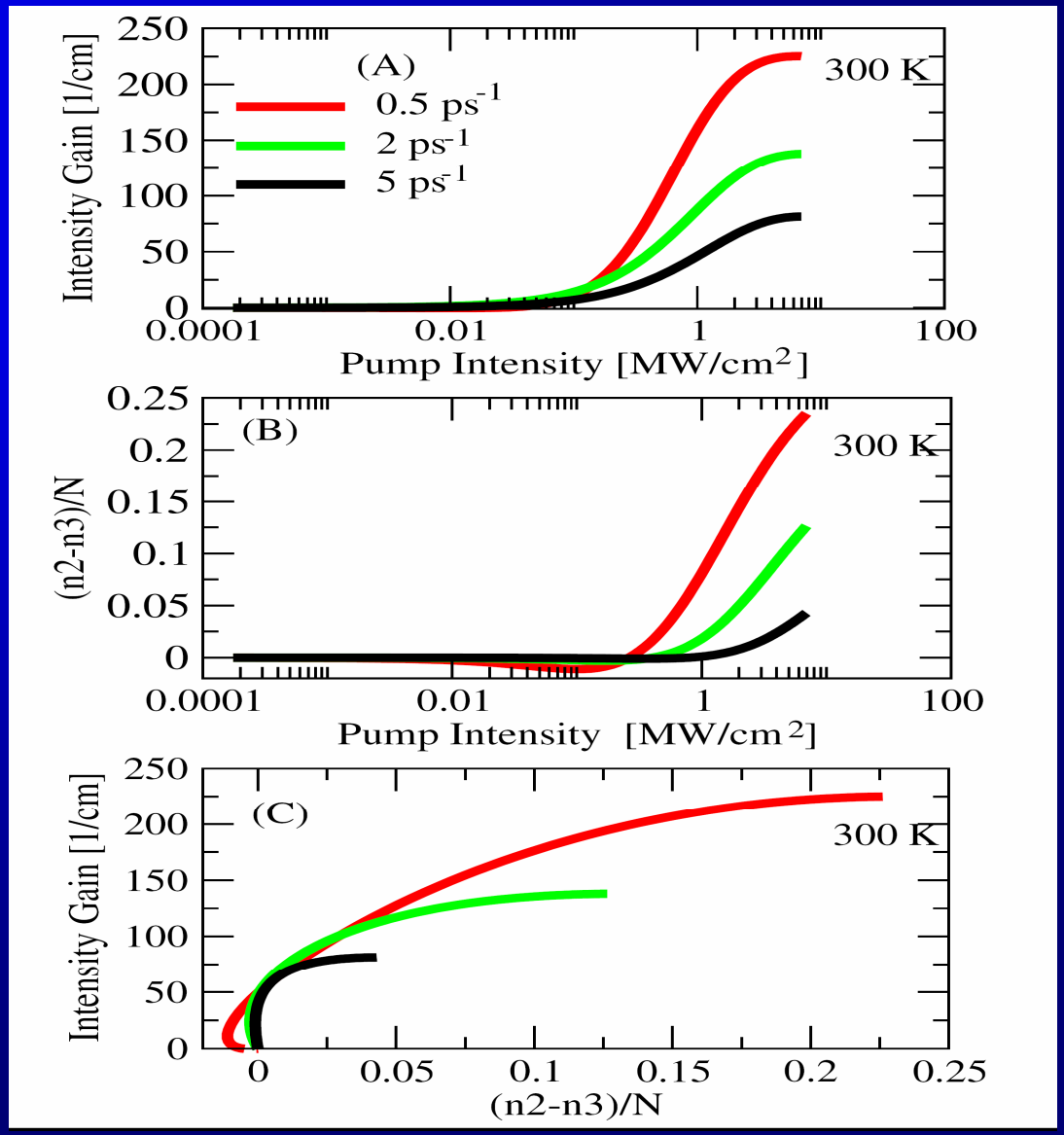
(A)
300 K
0.5 ps-1
2 ps-1
5 ps-1
Intensity Gain [1/cm]
Pump Intensity [MW/cm2]
(B)
300 K
(n2-n3)/N
Pump Intensity [MW/cm2]
(C)
300 K
Intensity Gain [1/cm]
(n2-n3)/N