TECHNISCHE UNIVERSITÄT WIEN
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THZ quantum cascade structures: time-domain spectroscopy study

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Talk Outline

Interaction of THz-QCL and few-cycle THz pulse

- theory
- technicalities

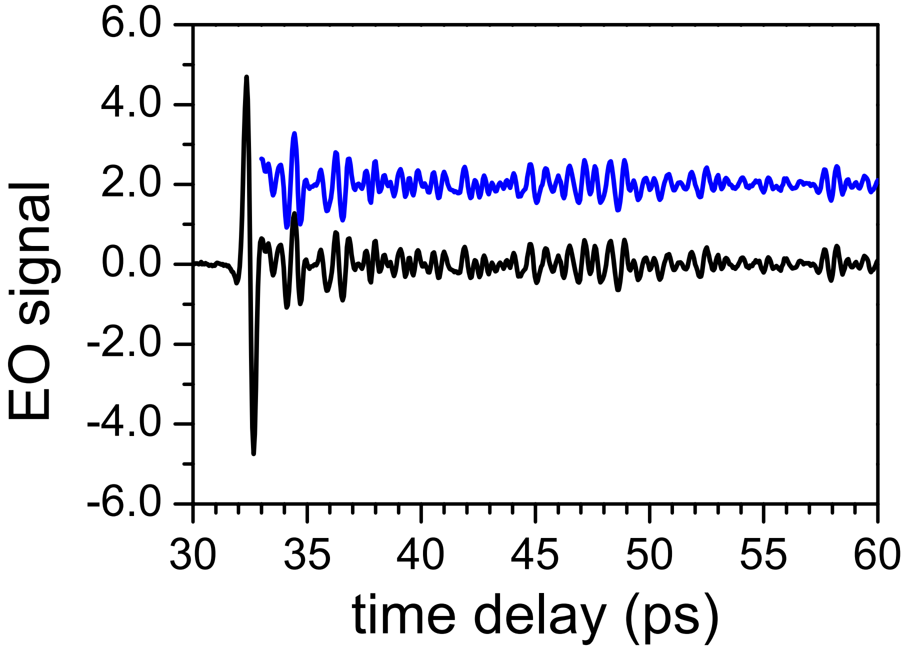
Experiment

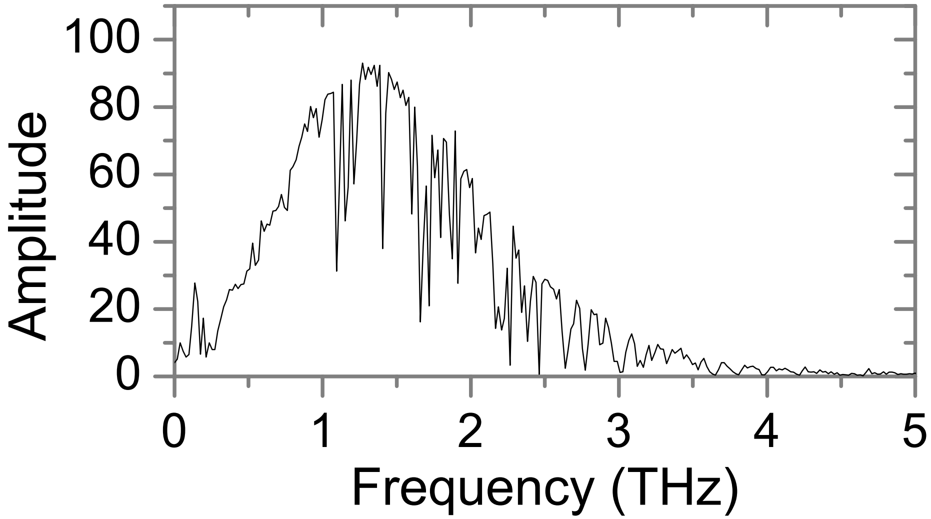
- transmission through THz-QCL (gain)
- longitudinal spatial hole burning in QCL
- thermally activated losses
- optical control of QCL emission

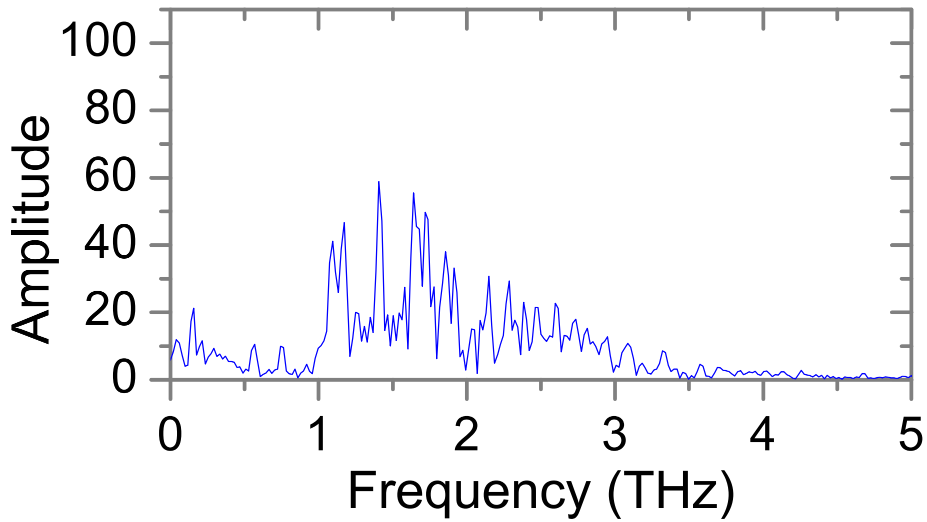
Summary and outlook

THz time-domain spectroscopy

THz time-domain spectroscopy







Free induction decay
of coherently excited H_2O molecules

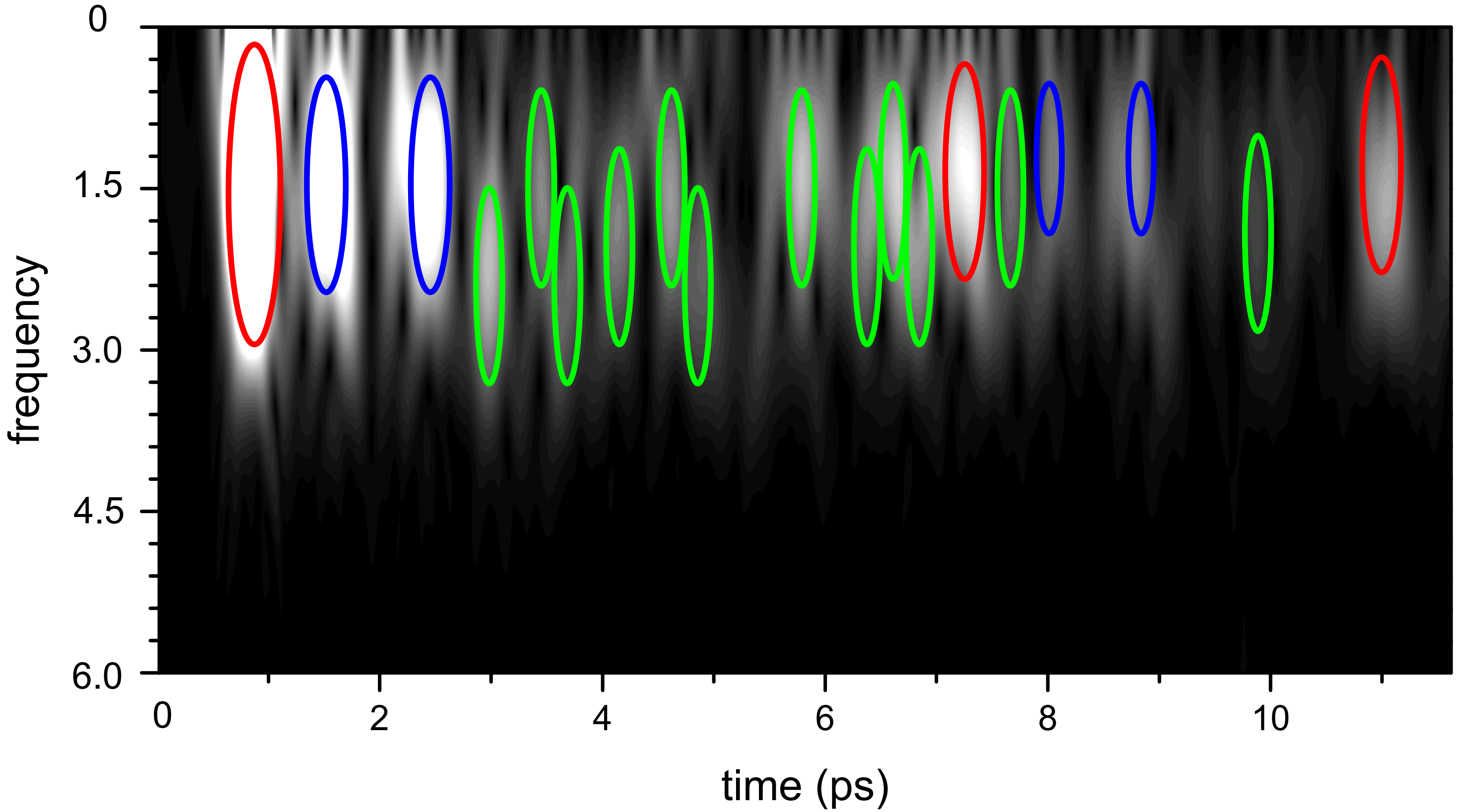
F.I.D. of coherently excited H_2O molecules

Free induction decay of coherently excited H_2O molecules

Main pulse

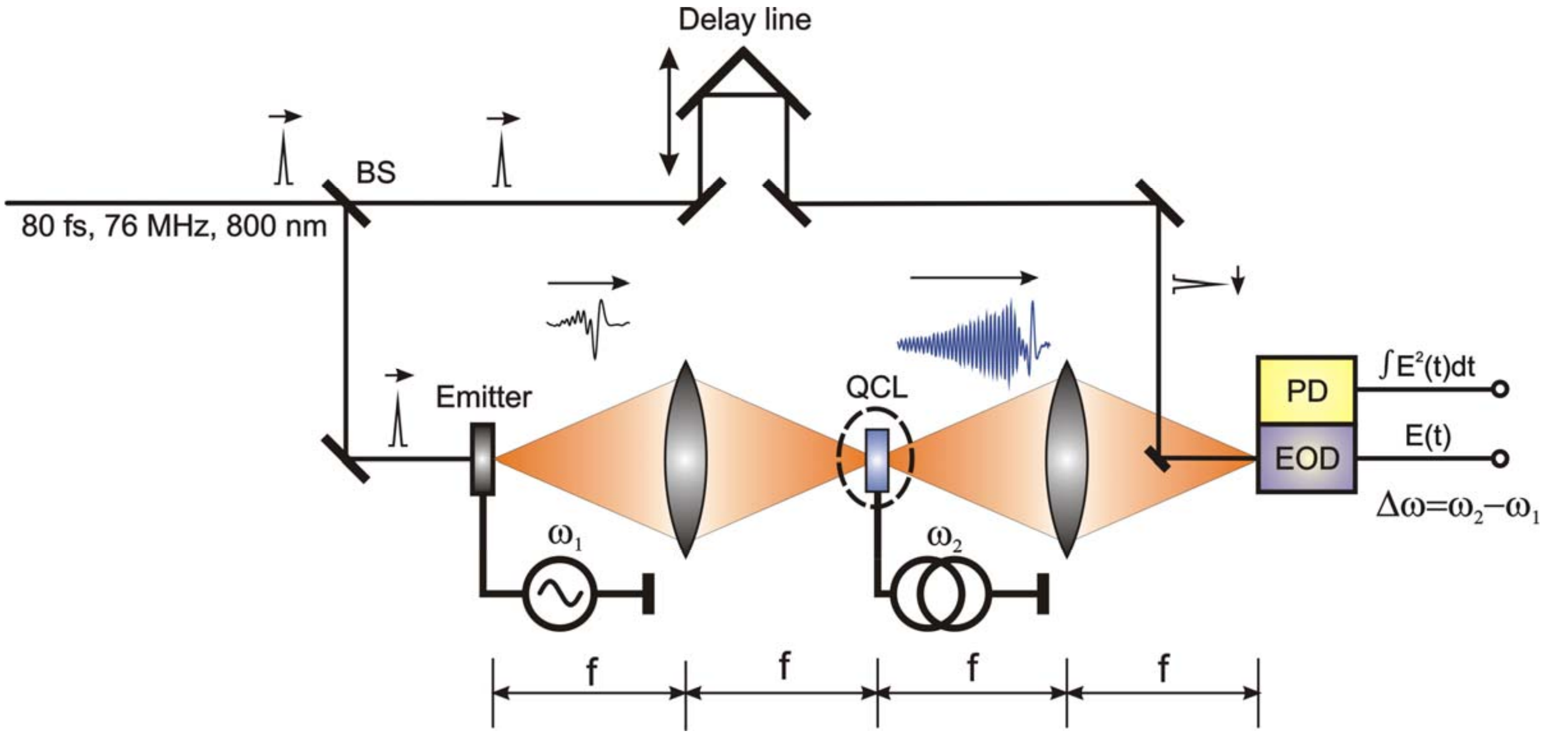
First coherences

Parasitic reflections



Time-domain response of gain medium

Coherent Detection of THz QCL Emission



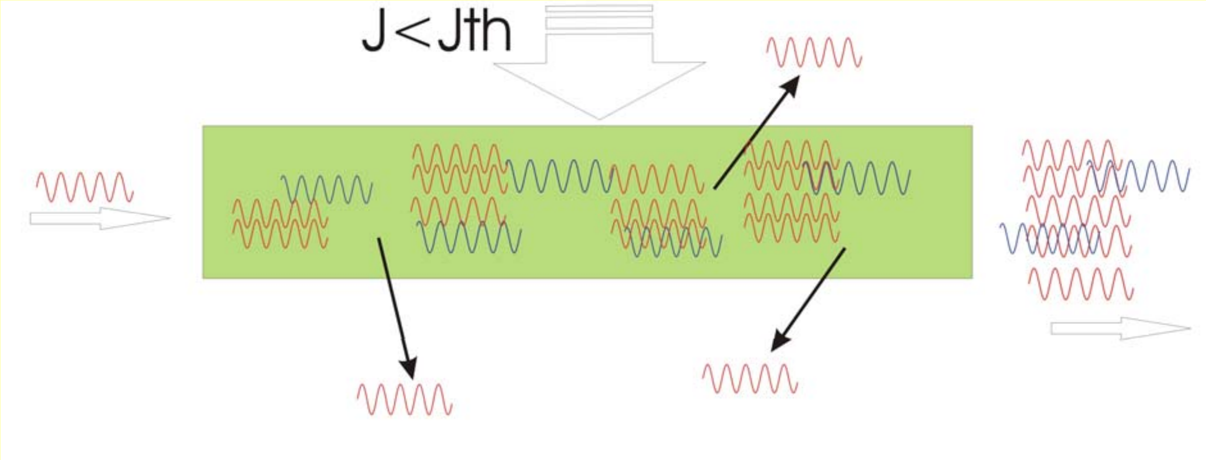
High repetition fs-system (80 MHz):
Ti:sapphire at 800 nm, < 80 fs pulses

Photoconductive THz emitter

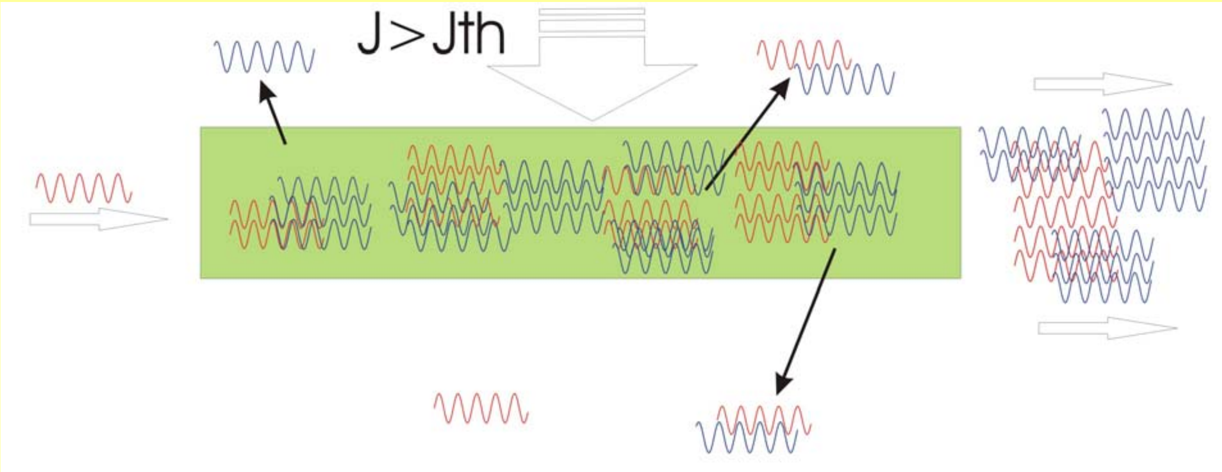
Electro-optic detection:
- gated detection
- detection bandwidth of 7 THz
(300 um GaP)

Coupling optics

THz-TDS in QCL: Travel-wave amplification

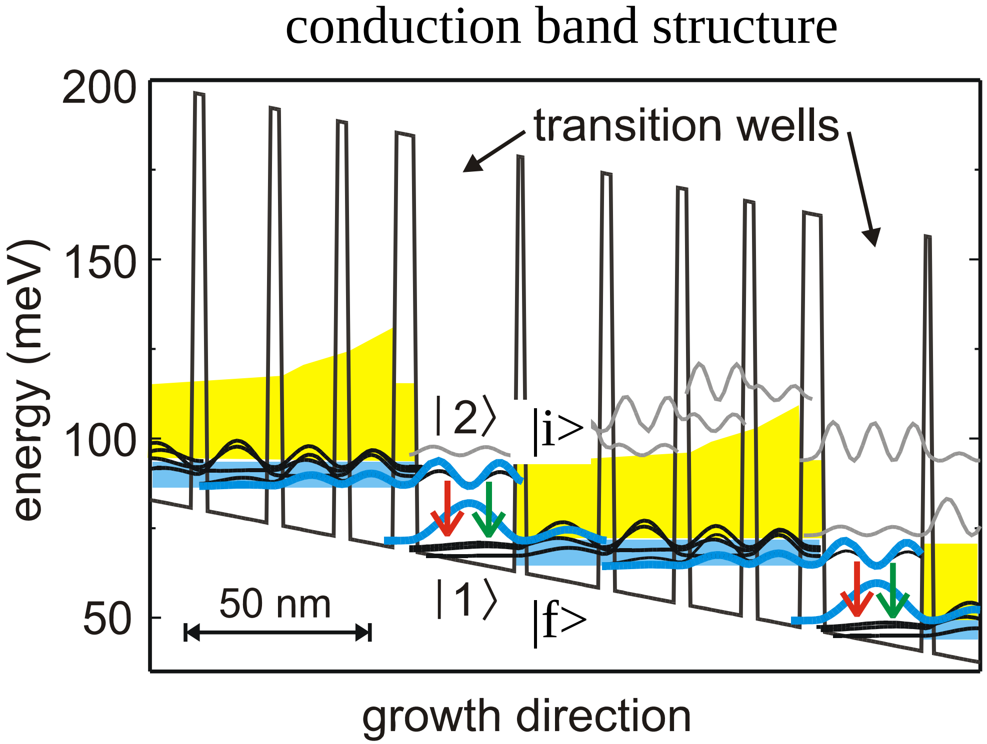


Spontaneously emitted photons:
random phase and timing
stimulated photons: in-phase



Strong stimulated emission, but photons with wrong phase …

(THz) QCL – principle of operation



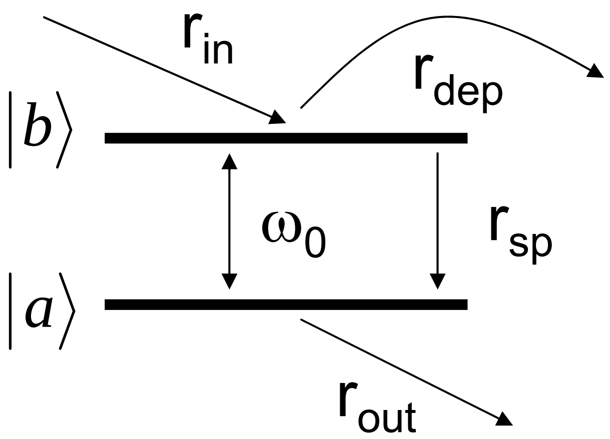
- energy transition within sub-band structure
- quantum cascade (one charge carrier passes multiple cascades)

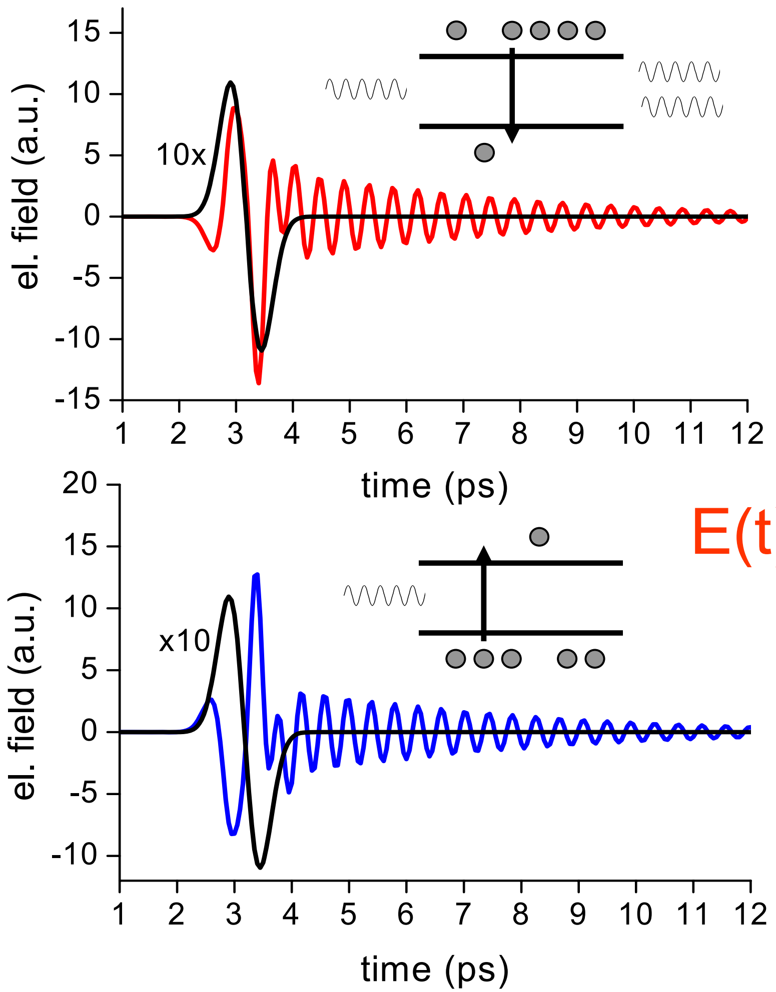
Operation conditions:

- pulsed/ CW
- current driven
- temperature: up to 160 K (>90 K for CW mode)

Two-level system: time domain response

(standard spectroscopy – sensitive to probe intensity changes ($\int E^2 dt \sim \rho_{aa}-\rho_{bb}$))





$E(t) \sim \rho_{ab}$

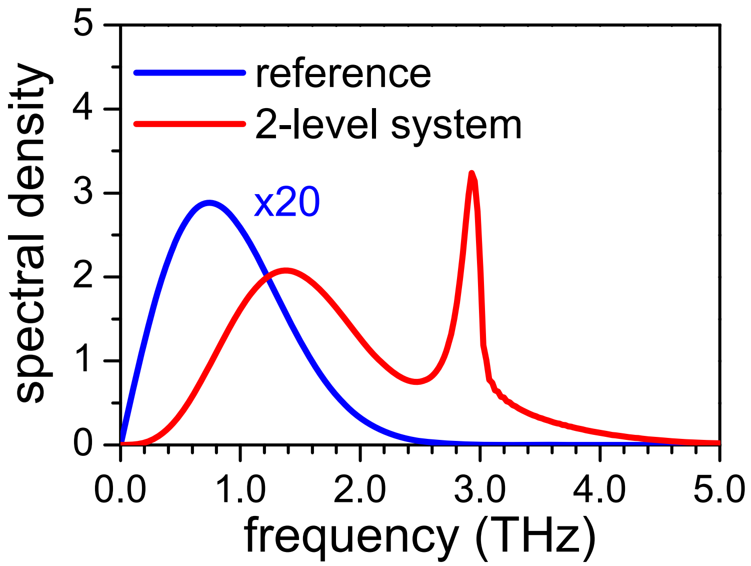
Density matrix

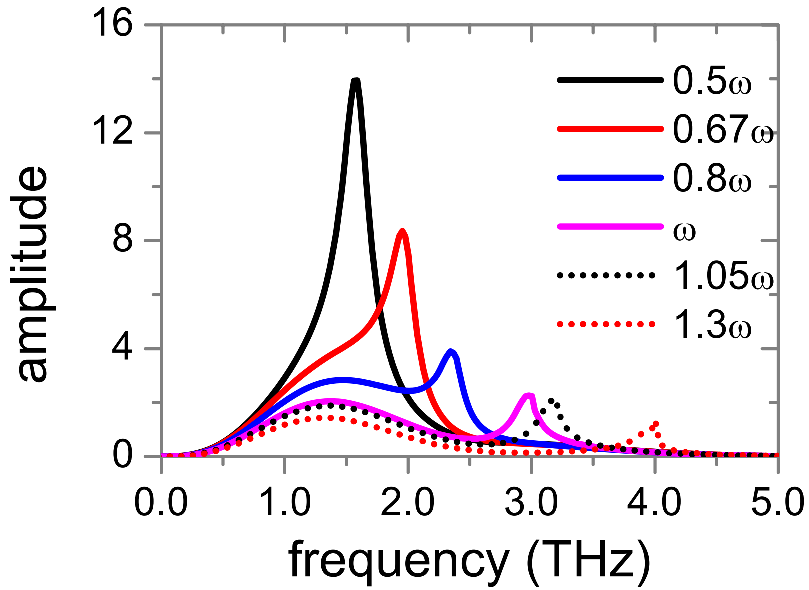
$$\begin{pmatrix} \rho_{aa} & \rho_{ab} \\ \rho_{ba} & \rho_{bb} \end{pmatrix}$$

ρ_{aa},ρ_{bb} ~ population

ρ_{ab}, ρ_{ba} ~ coherence

Two-level system: time domain response

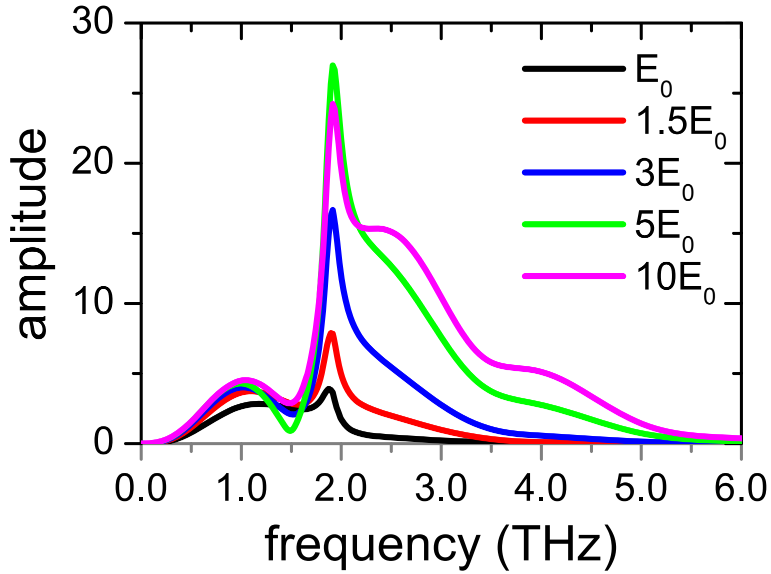




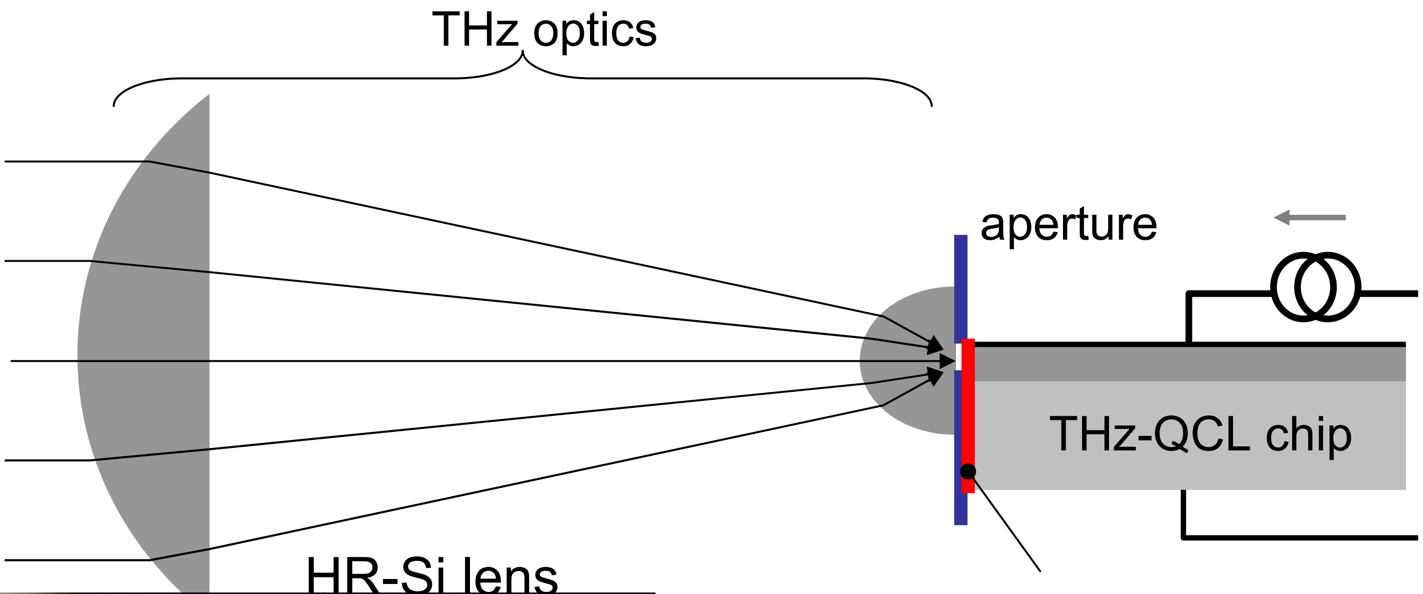
Two response components
- instant & resonant

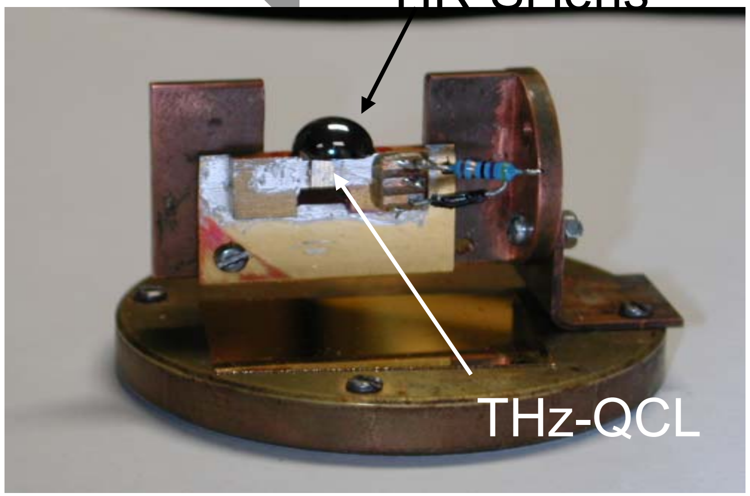
- stronger for higher frequency overlap

- effect of strong driving field
(partial Rabi oscillations)



Optics: Coupling of THz Waves into WG





- near diffraction limited focus
- leaky laser cavity
- low coupling efficiency (<10%)

1. THZ gain of QCL
2. Spatial hole burning in QCL
3. Temperature effect

THz QCL – Design & Parameters

Design:
- GaAs/AlGaAs system
- band-to-continuum
- transition energy:

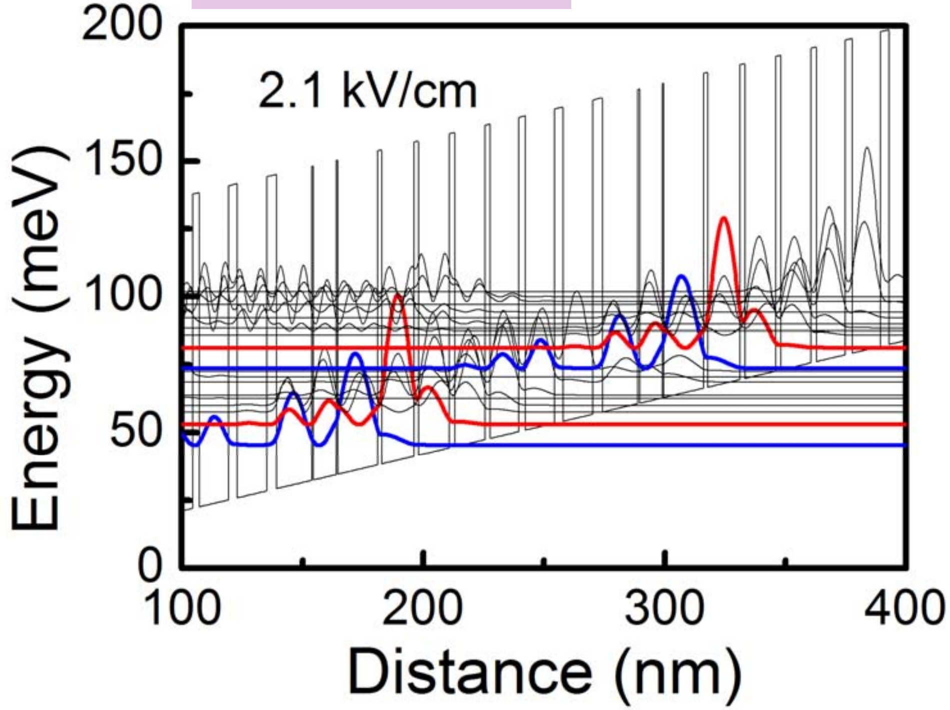
2.00, 2.9 THz and 3.4 THz

Waveguide:
- surface plasmon

(n^+-GaAs buried confinement layer)
- ridge type

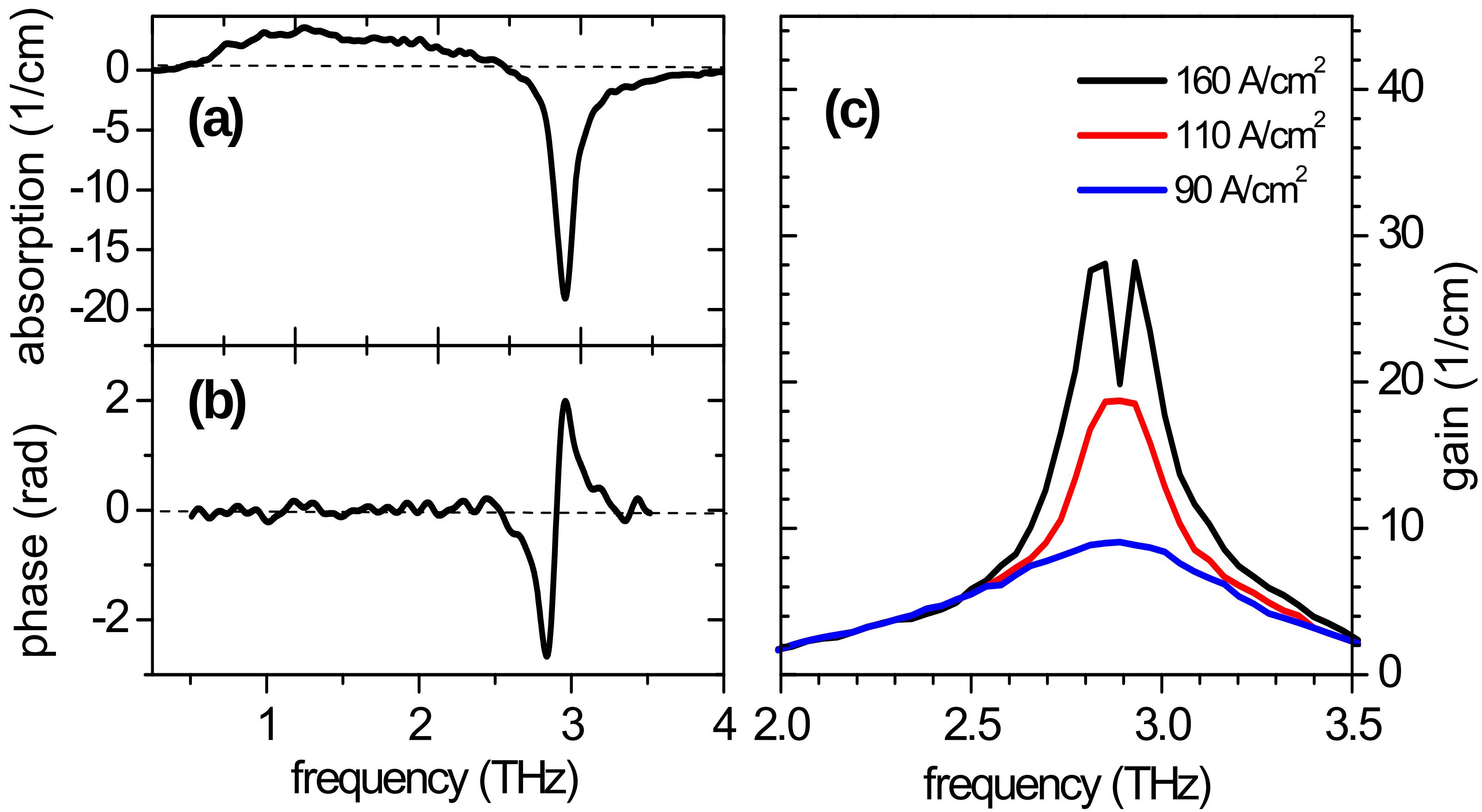
(110 – 200 μm wide)

band structure



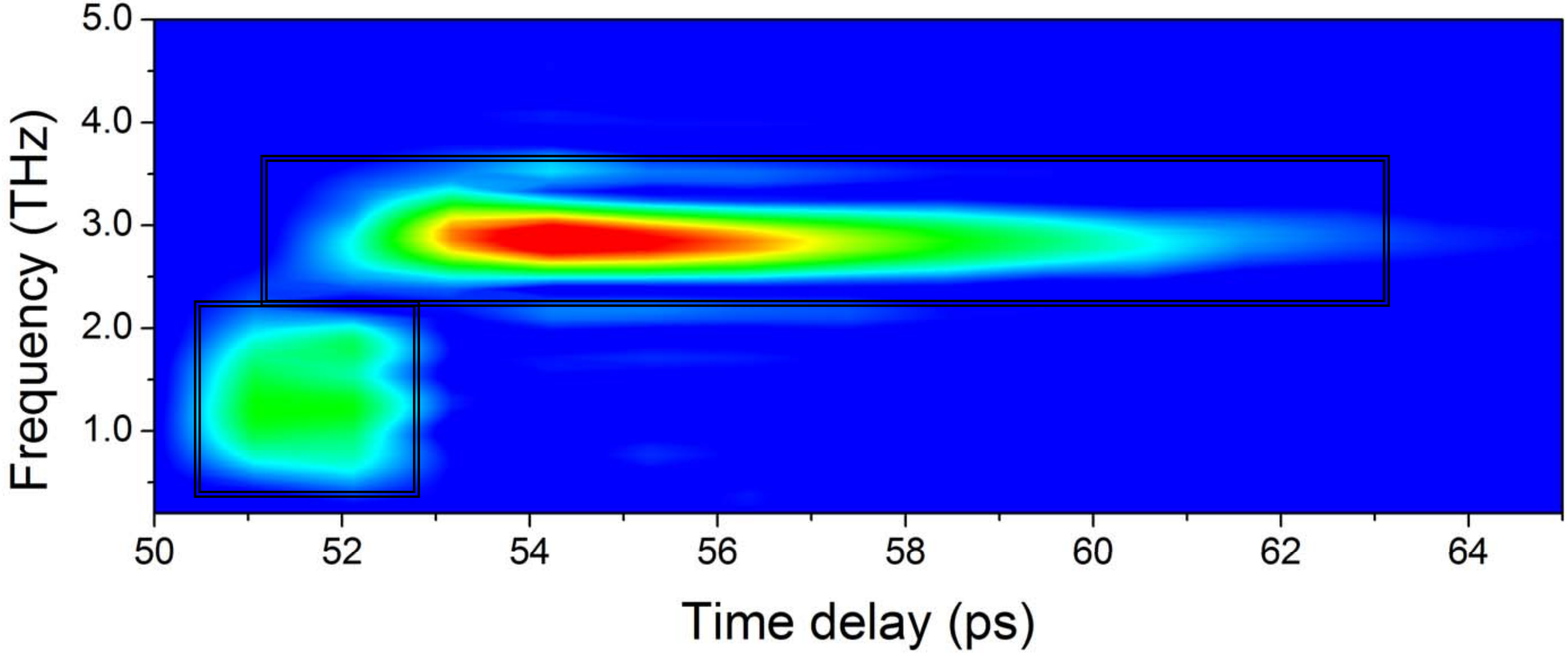
S: Barbieri et al., APL85(10), 2004
Ch. Worral et al., OE14(1), 2005
B. Williams et al., EL40, 2004

Gain spectrum: 2.9 THz-QCL



- gain region centred at 2.9 THz (resonant part of signal)
- evolution of dip (spectral gain hole) in spectrum above threshold

Dynamics of Spectral Features (2.9 THz)



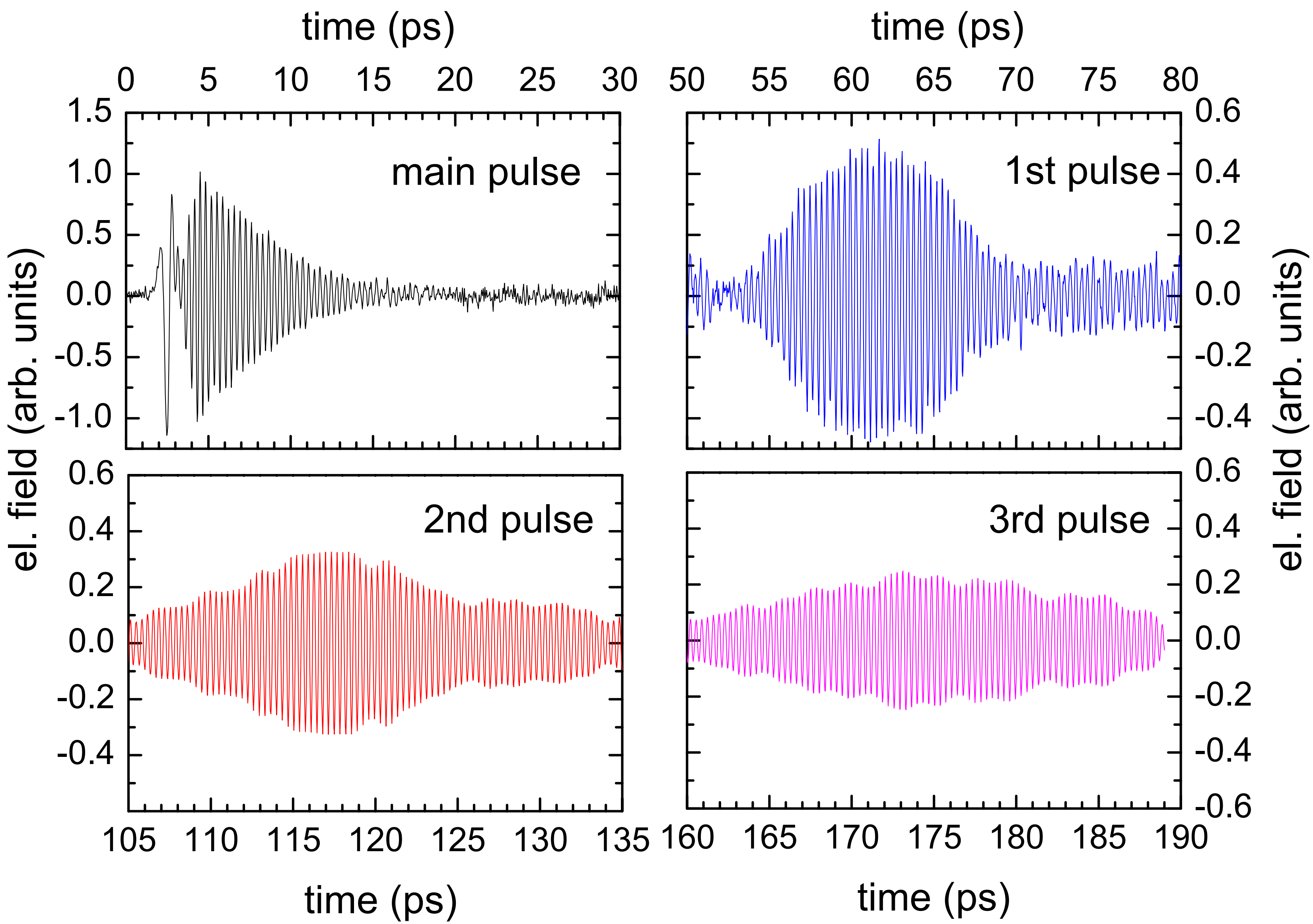
- Dynamics of spectral features separated by FFT windowing
- Instant response → reduced losses @ 0.8-2.0 THz
- Delayed oscillatory response → Gain @ 2.75-3.05 THz
- No spectral shift

1. THZ gain of QCL

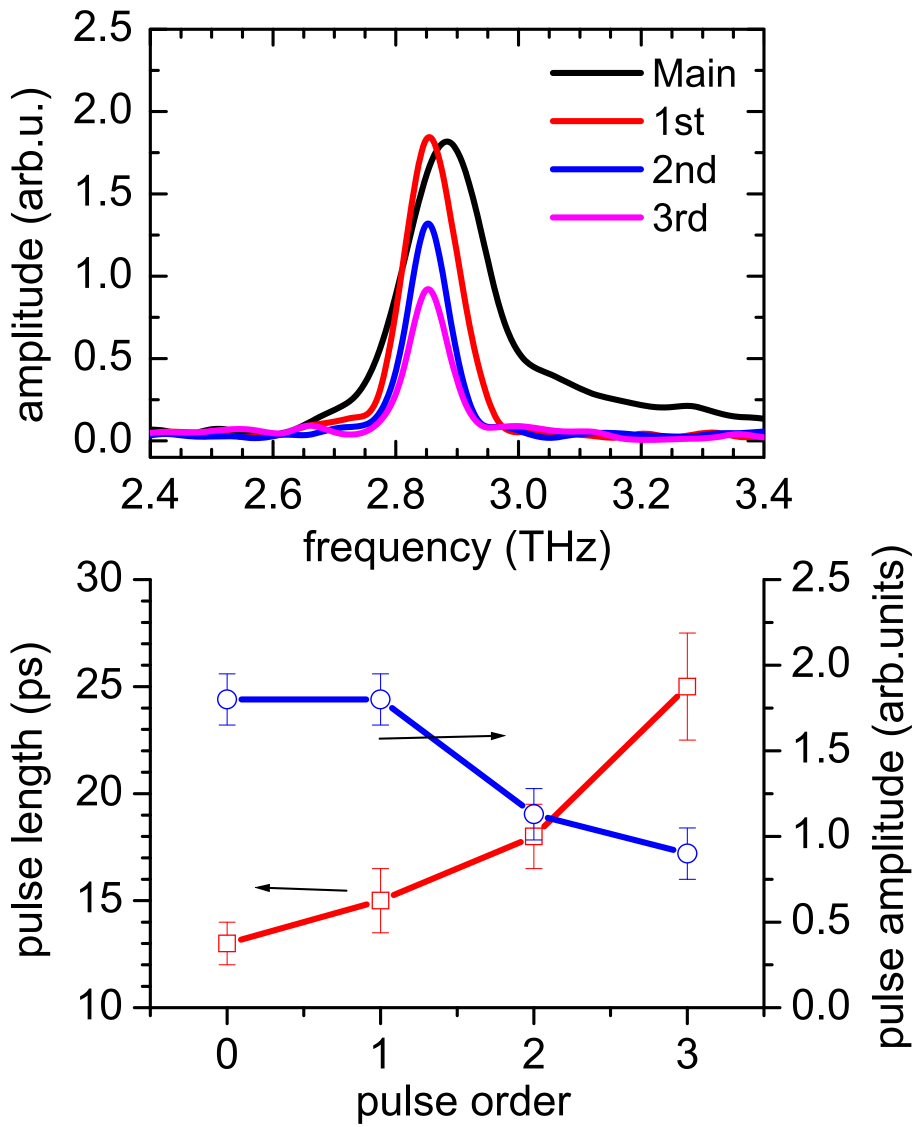
2. Spatial hole burning in QCL

3. Temperature effect

THz QCL – delayed pulses



Delayed pulses: parameters I.

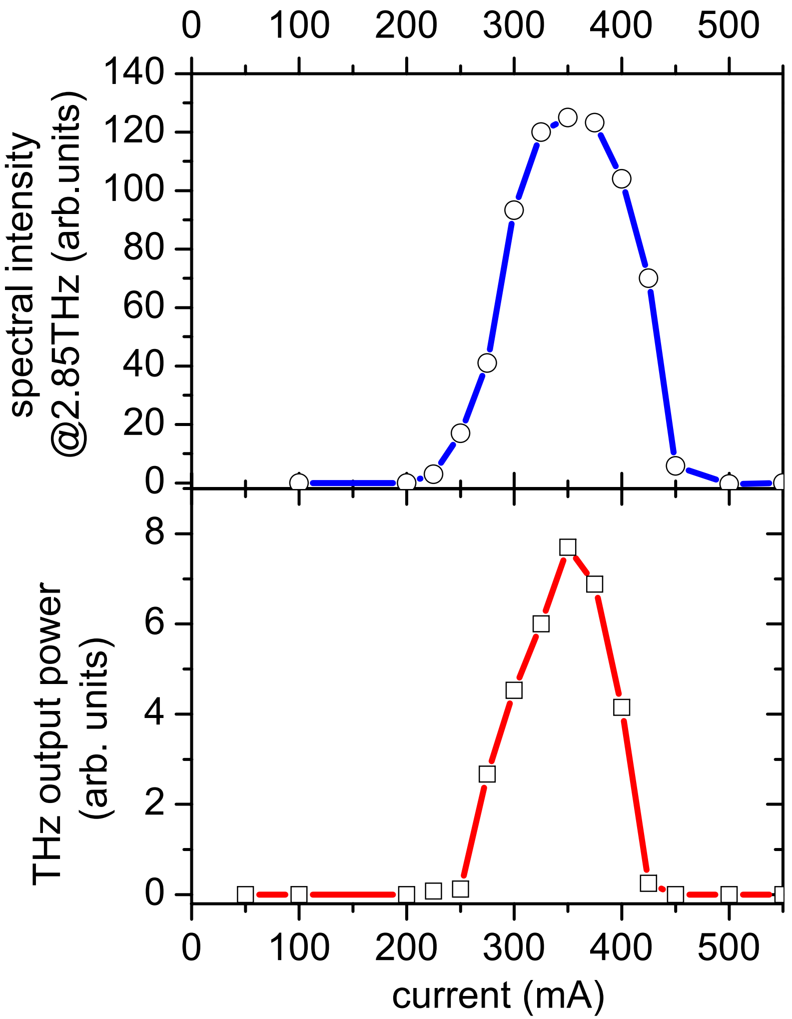


1. Spectral filtering effect
- gain medium provides wider bandwidth than seen in the pulses (frequency selection)

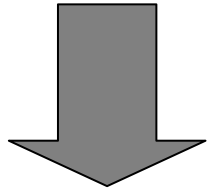
2. Central frequency of pulses equal to laser line

3. Power carried by pulses is decreasing (losses)

Delayed pulses: parameters II.

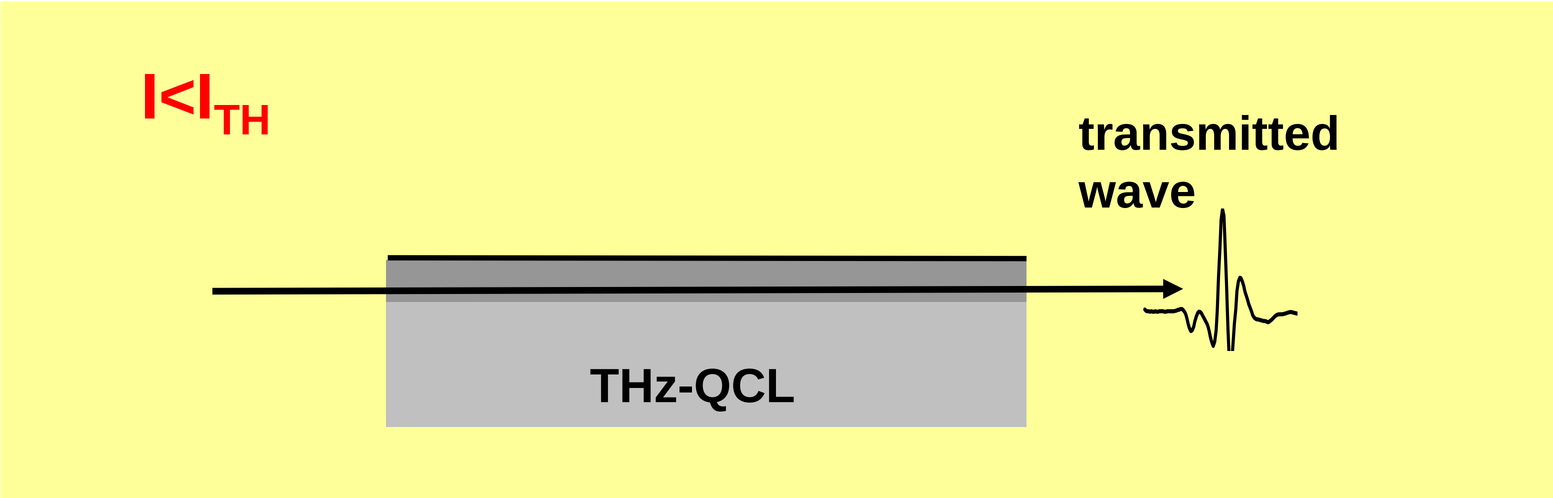


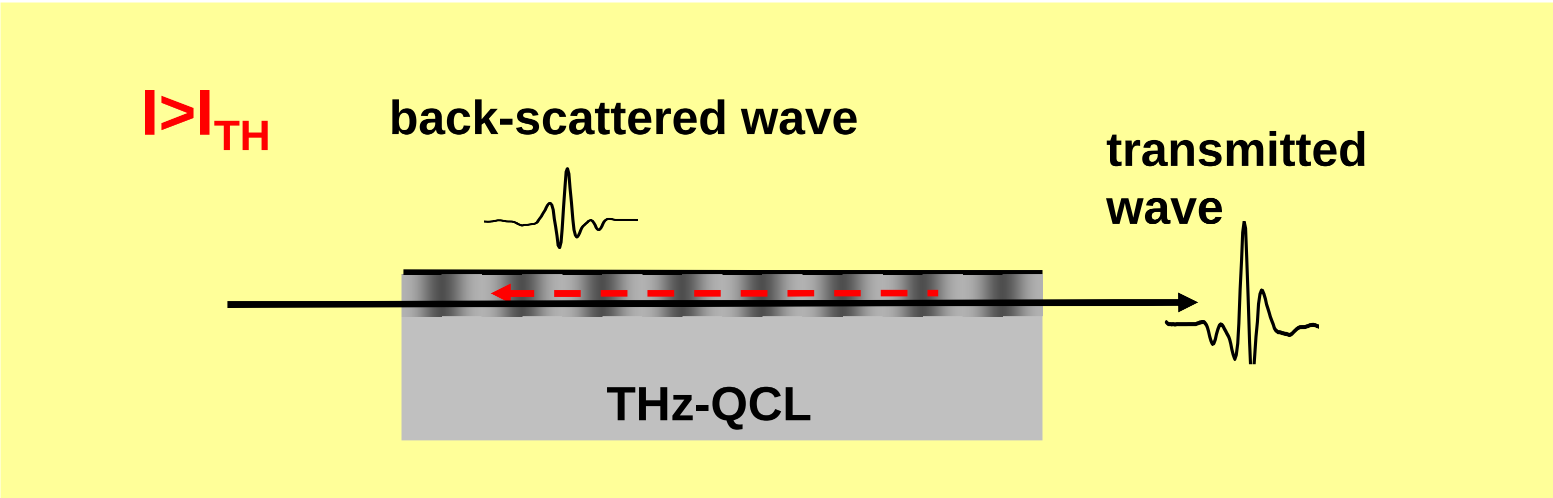
4. Appearance of pulses is correlated with lasing operation



What phenomena control the appearance and parameters of observed pulses ?

THz QCL – longitudinal spatial hole burning





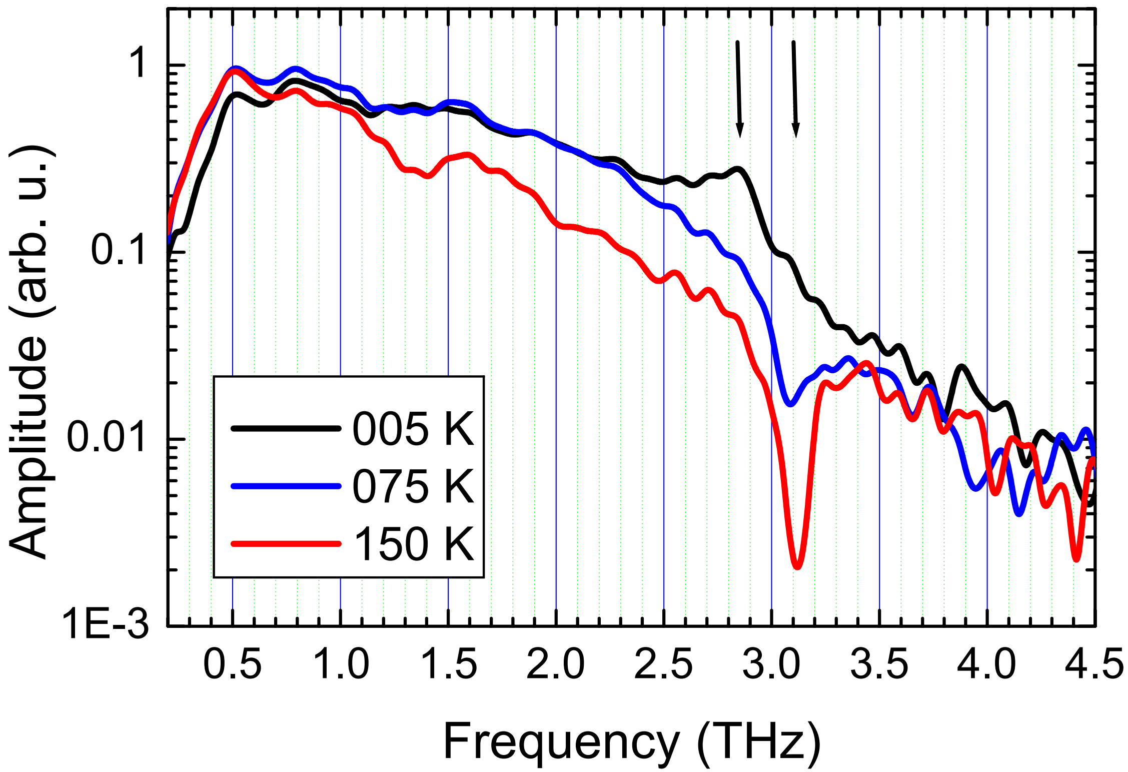
1. THZ gain of QCL

2. Spatial hole burning in QCL

➡ 3. **Temperature effect**

THz-QCL Transmission Spectra

Change of device transmission with temperature

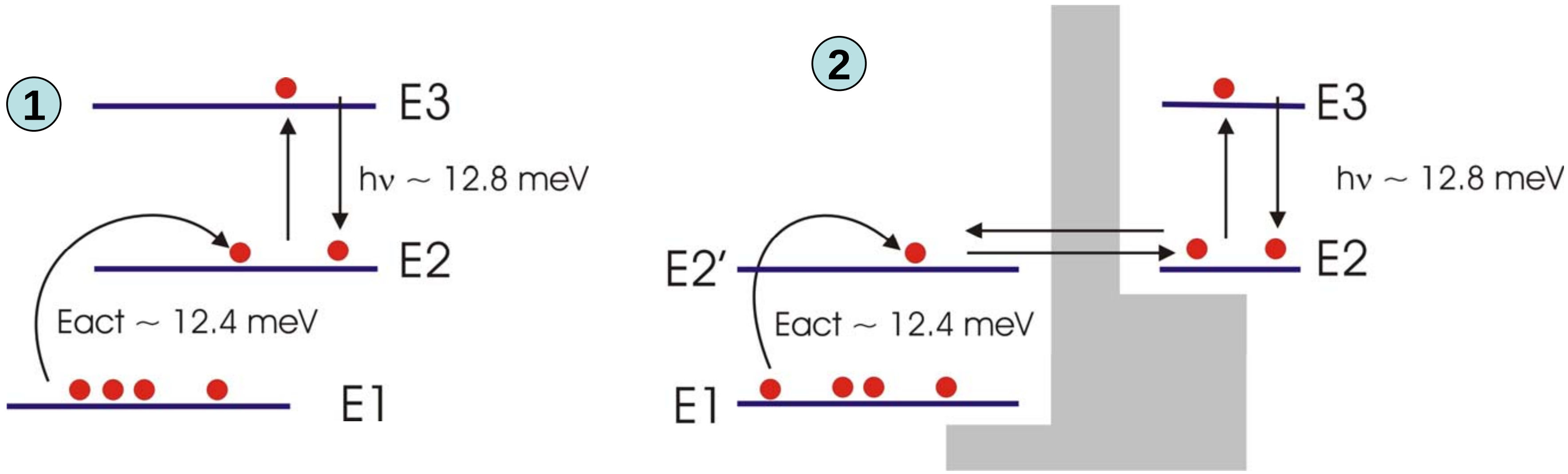


Low Joule-heat load conditions (DC~0.1%)

- low T:
  gain @ 2.9 THz *
- mid T:
  no gain, loss @ 3.1 THz
- high T:
  large loss @ 3.1 THz,
  loss in 1.0-2.5 THz range

for unbiased THz-QCL: frequency flat WG loss ~ 11 cm^{-1}

Model for thermally activated losses

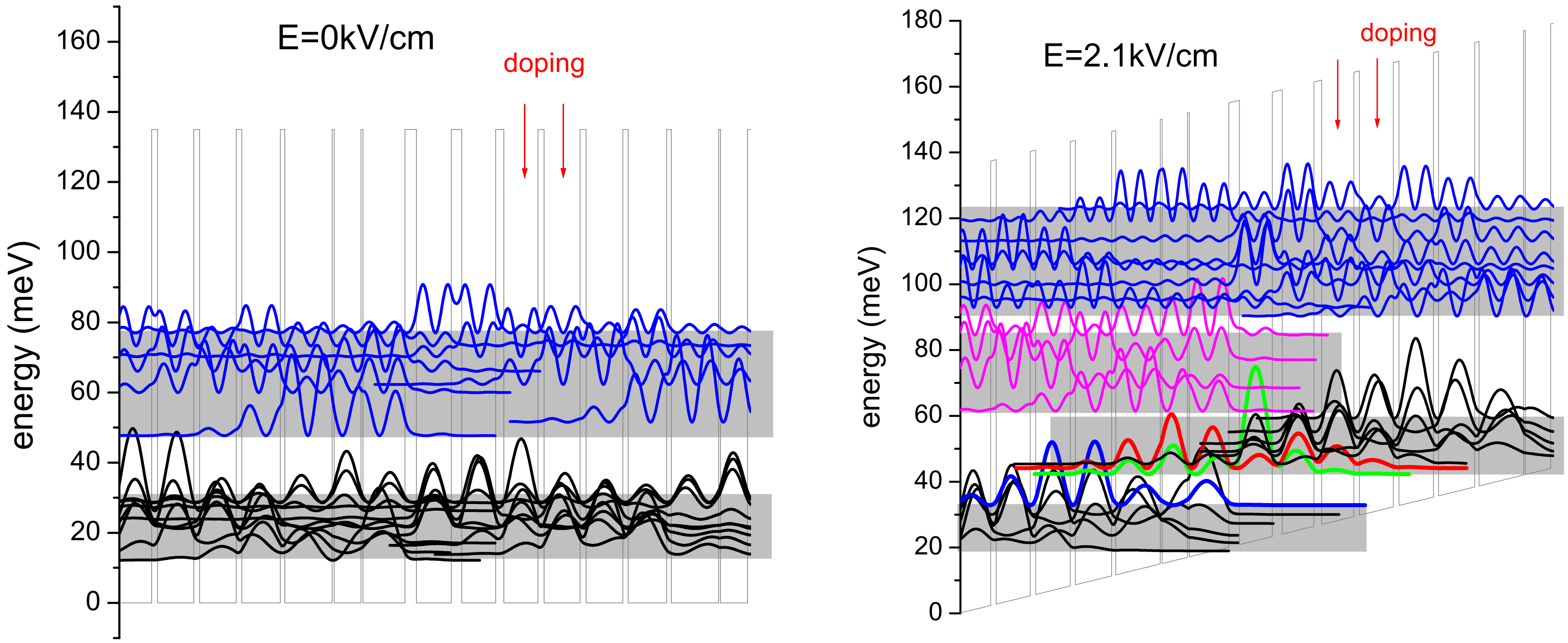


- simple 3-level model for thermally activated absorption

Possible origin: Intersubband absorption ?

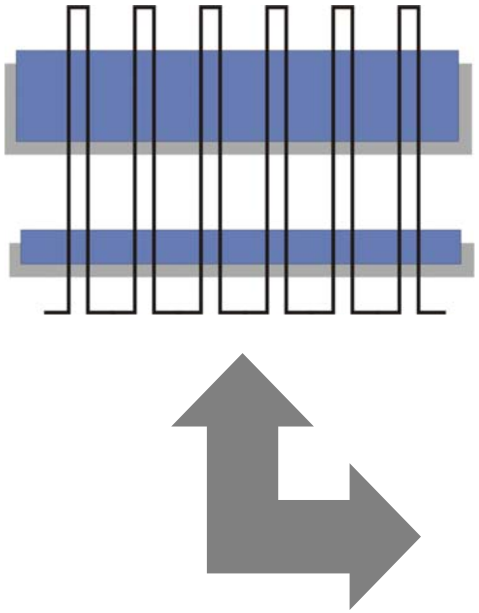
Silicon donors related ?

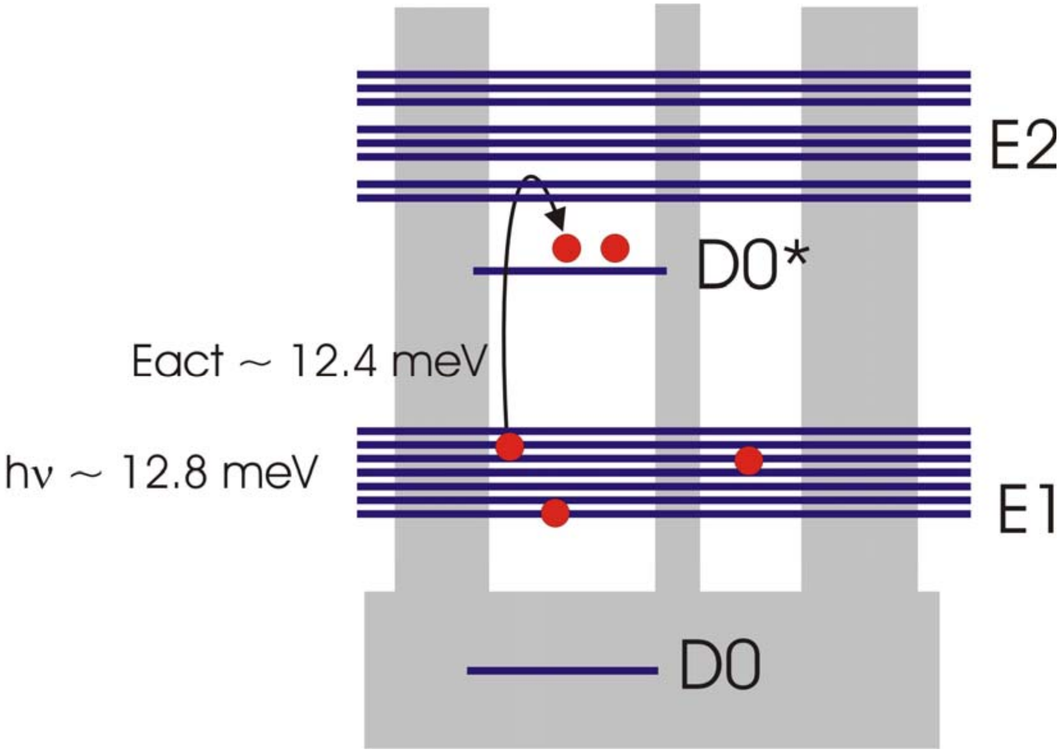
Models for thermally activated losses



Band structure cannot completely explain the absorption feature
(bias dependence ?)
- recently observed in 2 THz BTC laser, but at lower energies (2.9 THz)
- not seen in 3.4 THz BTC laser (?) and 2.8 THz RPD laser

Models for thermally activated losses





- absorption fits with an energetic position of Si donors in GaAs QW
- impurity related split-off states (semiconductor superlattice)
  (M. Helm, Dresden: PRB43, PRB48, PRL95)

Summary & Outlook

- ☑ THZ TDS measurement of an active THz-QCL

  - direct measurement of the laser gain bandwidth

  - first direct observation of L-SBH in gain medium

  - evidences for phase-locking to external source

- ☑ measurement of the saturation and gain dynamics

- ☑ optical coherent control of injector electron states occupation

- ☑ effort towards broadband THz amplifier