Magnetic confinement on THz quantum cascade structures

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teraNova
POISE
quantum photonics
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Fonds national suisse
Swiss National Science Foundation

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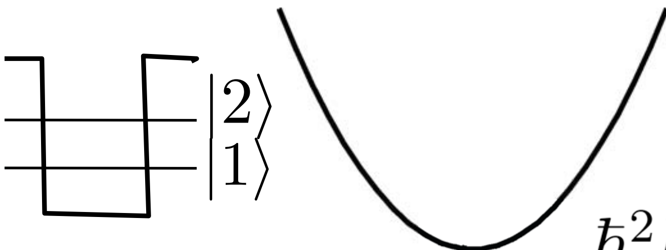
Cavendish Laboratory, University of Cambridge, Cambridge, UK

Outline

- Magnetic confinement on intersubband systems
- Magneto-spectroscopy and population inversion tuning
- Magnetically assisted gain: low frequency/low threshold
- Step well + magnetic confinement: beyond the phenomenological $h\nu = k_B T$
- Conclusions and perspectives

Add perpendicular magnetic field

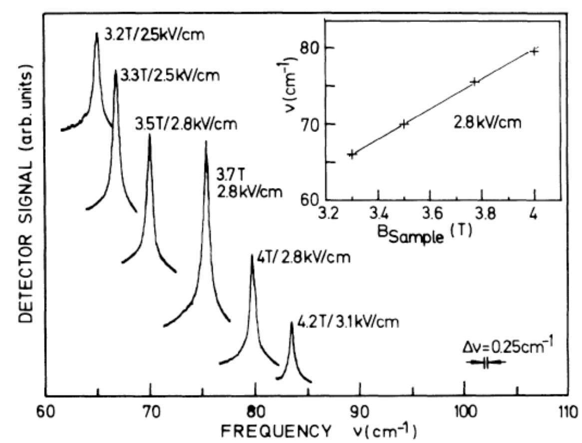


$$E = \frac{\hbar^2 k_{\parallel}^2}{2m^*}$$

Landau levels coupling: radiative transitions

TM polarized (intersubband), selection rule is δn=0 for Landau levels NO tuning of the ISB emission between Landau states (unless different masses…..)

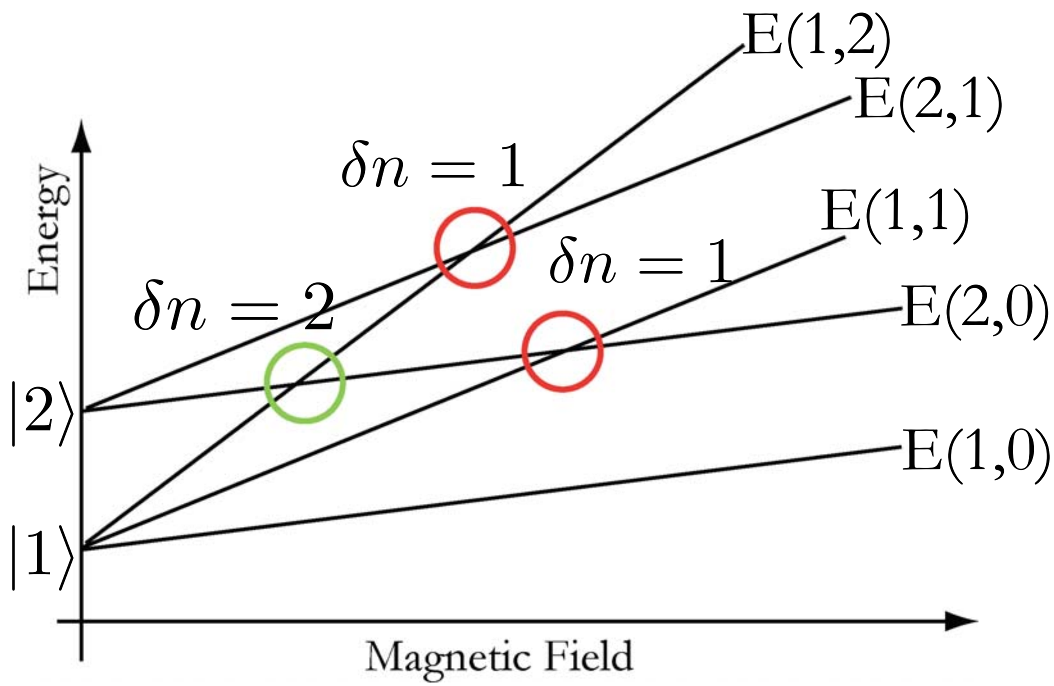
TE polarized: selection rule is is δn=±1, cyclotron resonance and Landau emission



K. Unterrainer et al., *Phys. Rev. Lett.*, **64,** 2277 (1990)

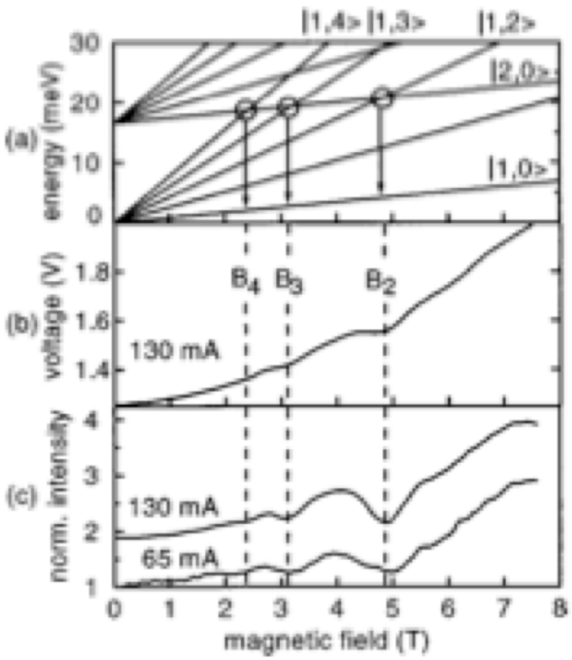
Landau level coupling: non radiative transitions

Elastic: $E_{|up,k\rangle} - E_{|low,j\rangle} = n\hbar\omega_c$



Landau index conservation can be broken due to interface roughness/ impurity scattering. Stark-Cyclotron resonance in SLs, MIS in QCL emitters

Elastic scattering in electroluminescence



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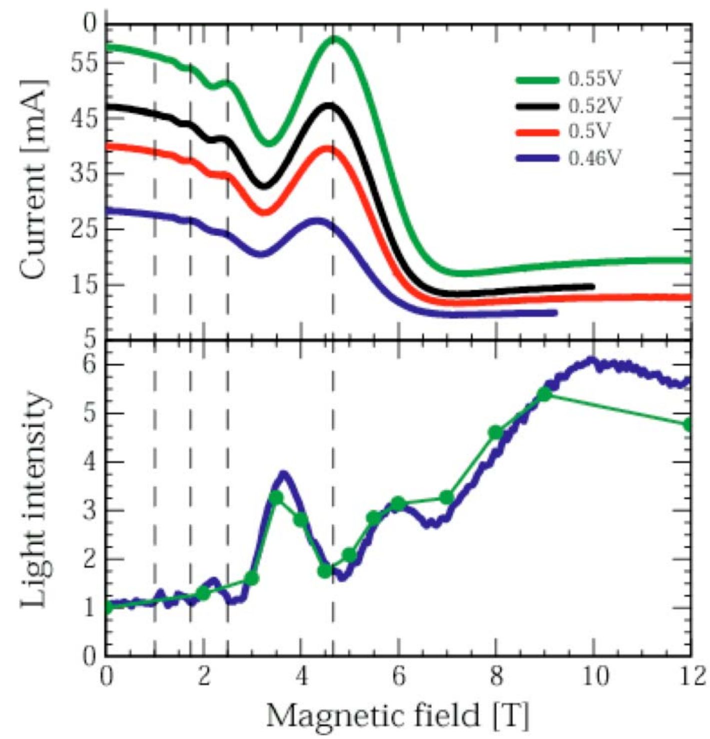
Appl. Phys. Lett., Vol. 76, No. 1, 3 January 2000



Stéphane Blaser,[a),b)] Michel Rochat, Mattias Beck, Daniel Hofstetter, and Jérôme Faist[c)]
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Appl. Phys. Lett., Vol. 81, No. 1, 1 July 2002

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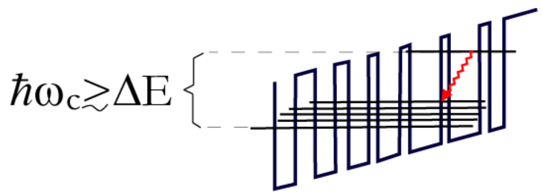
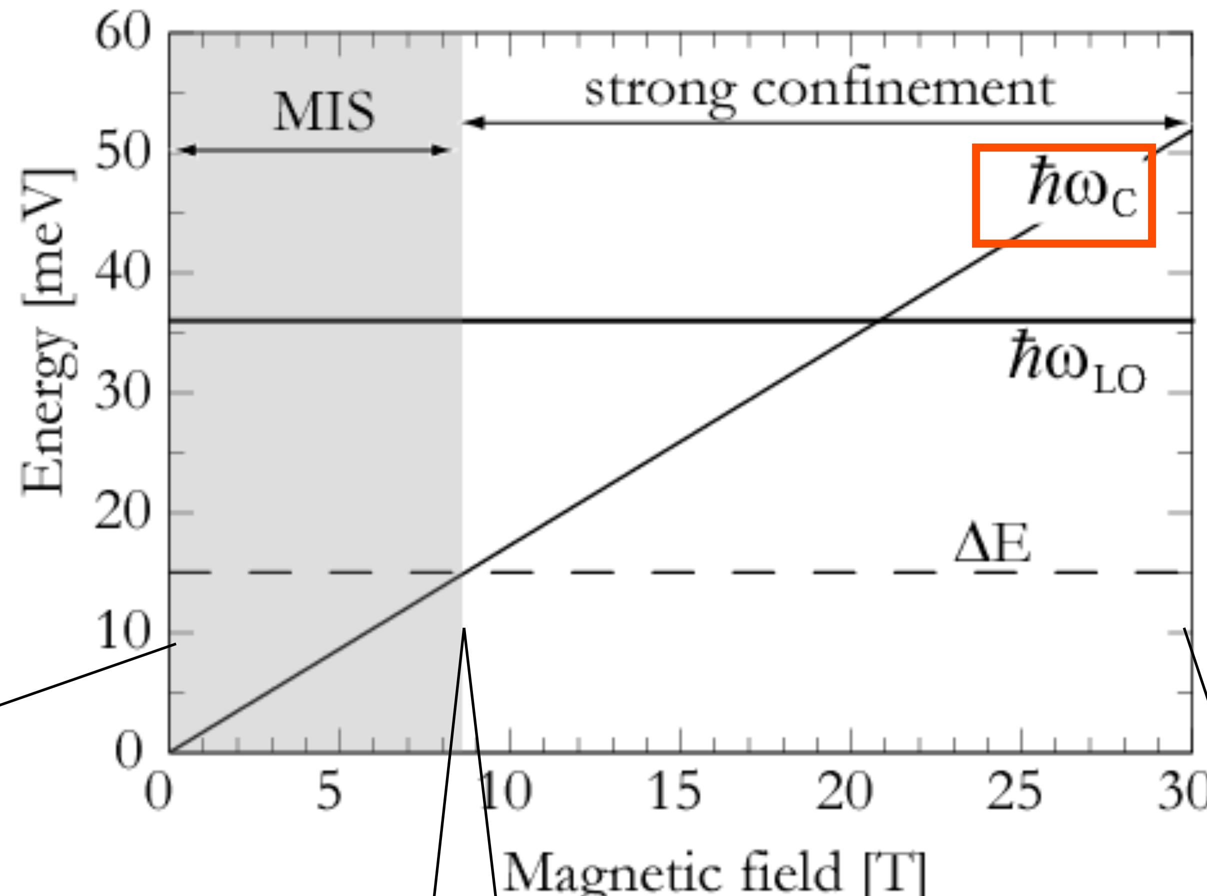
Magnetic confinement: 2 regimes

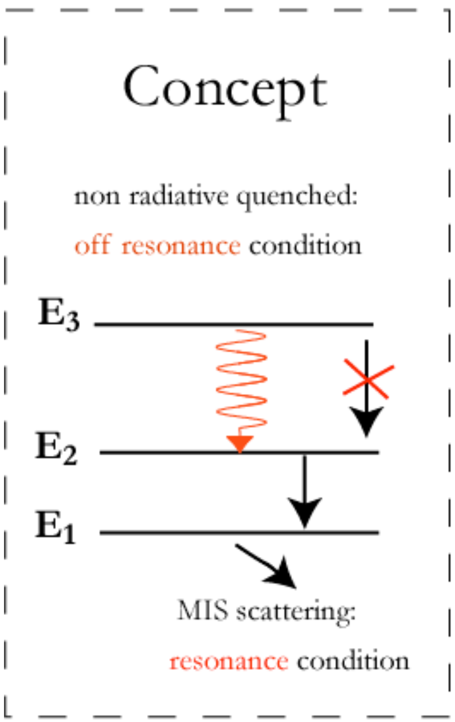


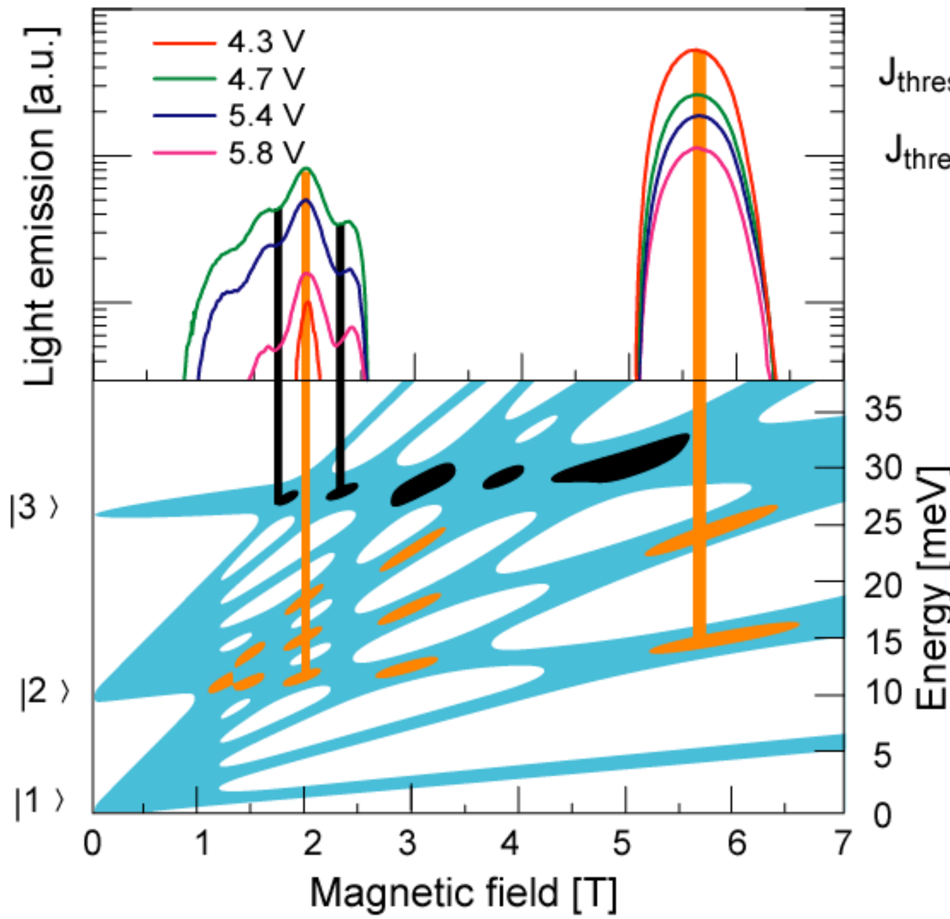


Elastic scattering: lifetimes modulation

Scattering quenching: long lifetimes

Engineering of elastic inter-Landau scattering

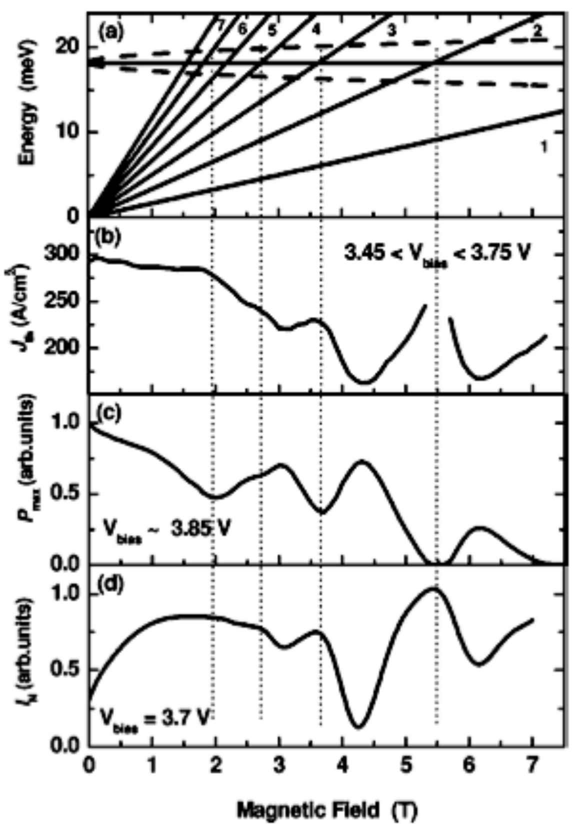


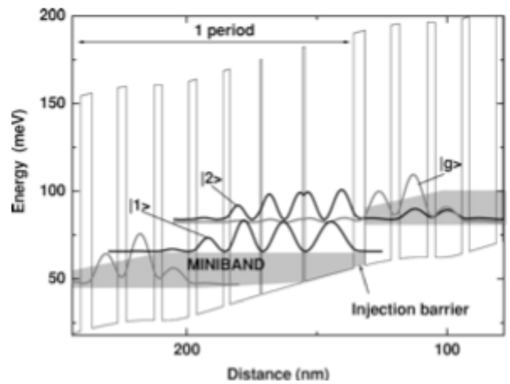


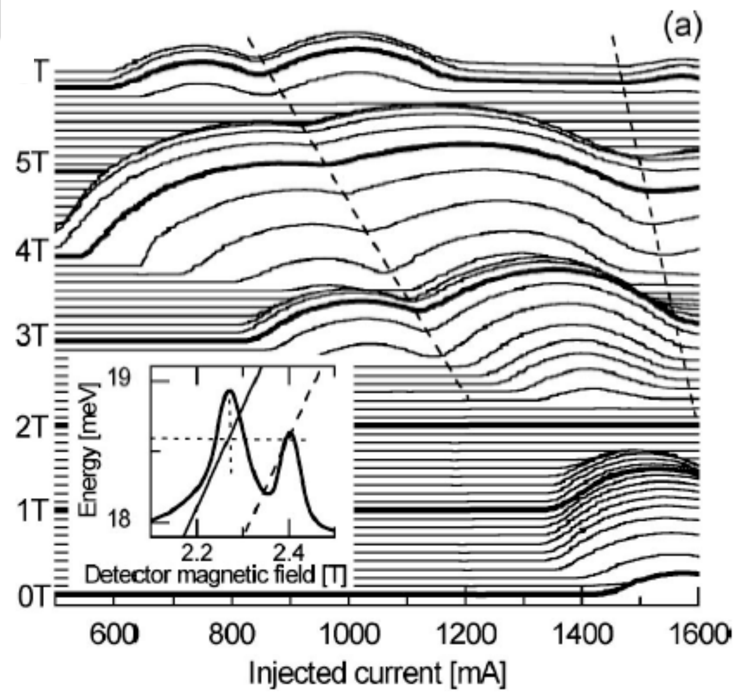
J_{thresh}=22 A/cm^2 at 4.2 K

J_{thresh}=34 A/cm^2 at 60 K

Elastic scattering to tune population inversion



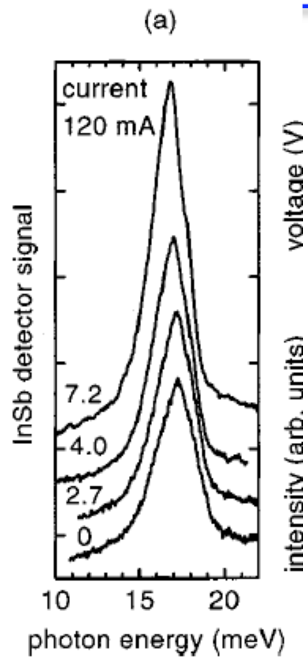




J. Alton et al., *Phys. Rev. B*, **68**, 081303 (2003)

V. Tamosiunas et al., *Appl. Phys. Lett*, **68**, 081303 (2003)

Narrowing of the ISB linewidth



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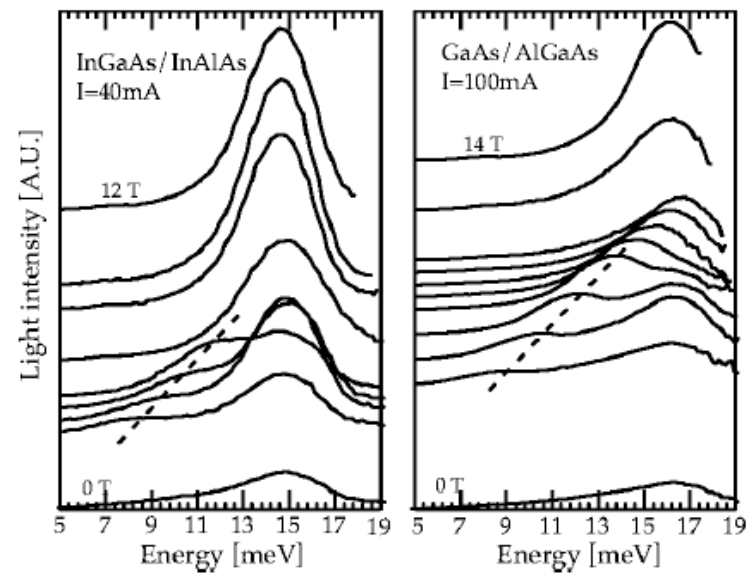

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Attributed to quenching of the intra-subband dephasing

$$\gamma_{ij} \simeq \frac{\hbar}{\tau_{\perp}}$$

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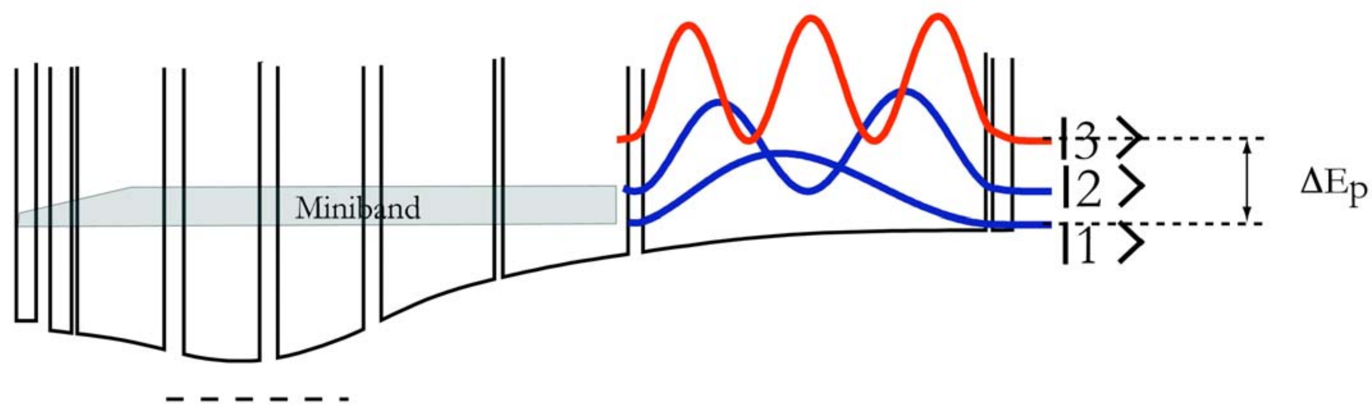
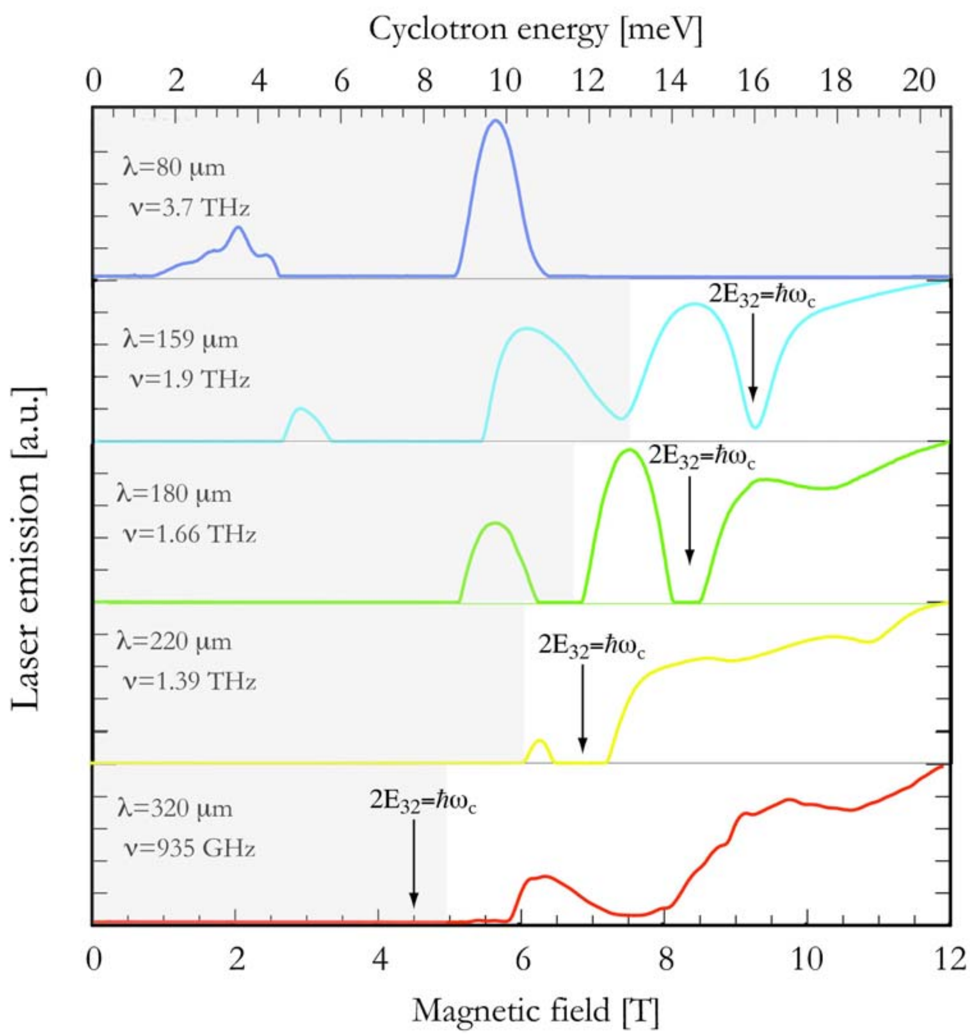
"Big well" concept



- Simple arrangement of levels
- High oscillator strength
- Narrow linewidth
- Low couplings: low current densities (20-40 A/cm^2)

Scalable down to 950 GHz



Big Well width (Å)

360

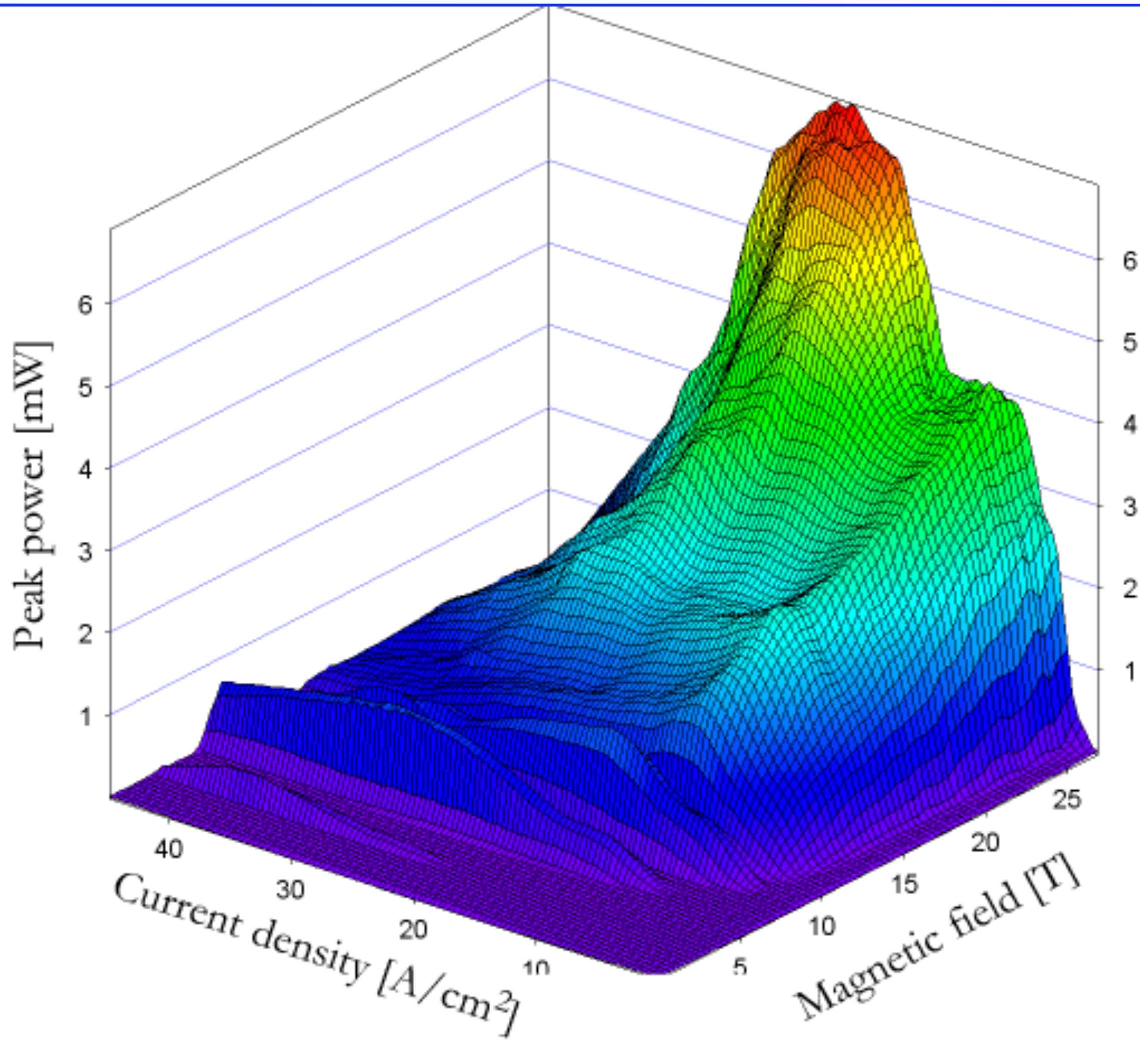
550

570

607

765

Laser emission in very high magnetic field

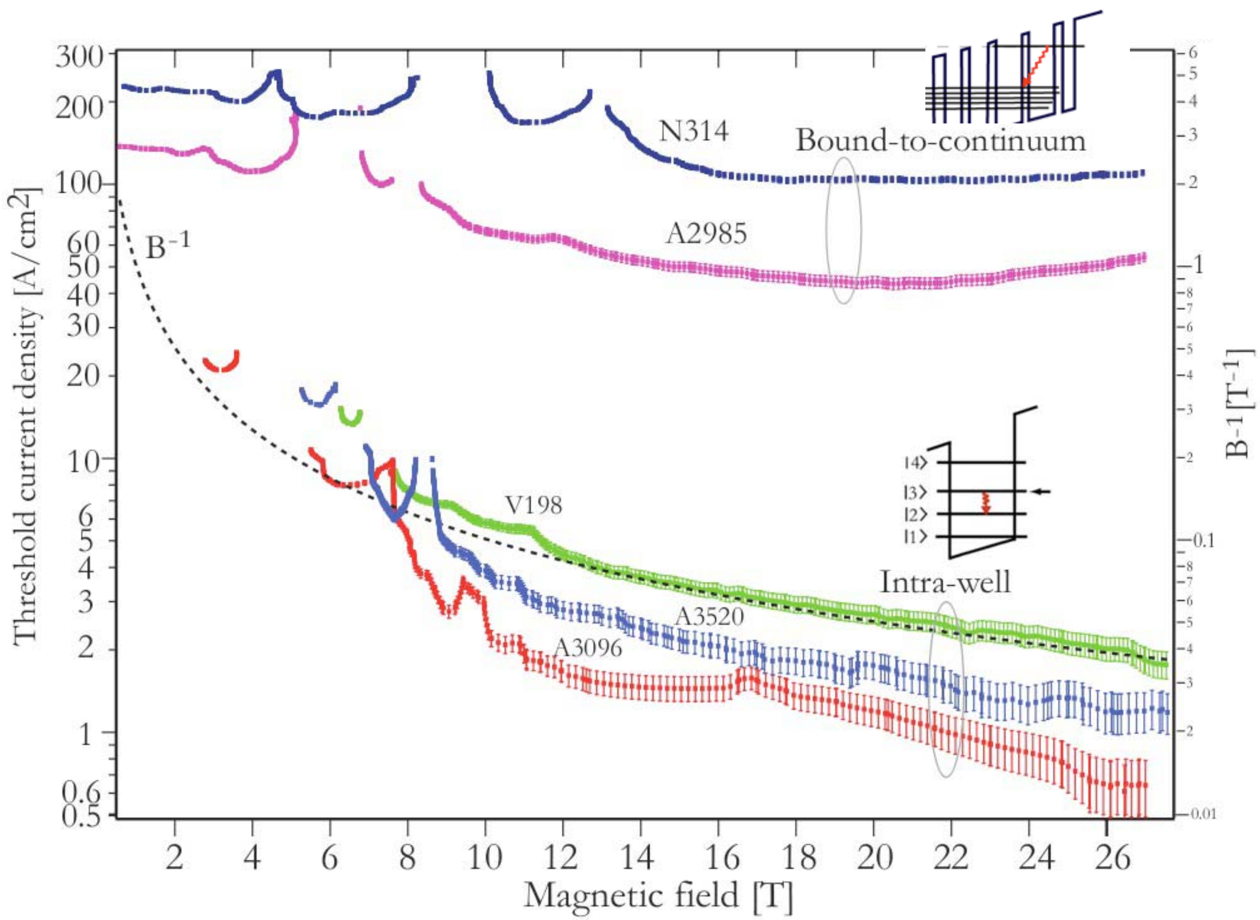


$$\hbar\omega_c >> \Delta E$$

J_{thresh}=0.65 A/cm^2

G. Scalari et al., *Phys. Rev. B*, 76, 115305(2007)

The kind of transition matters…



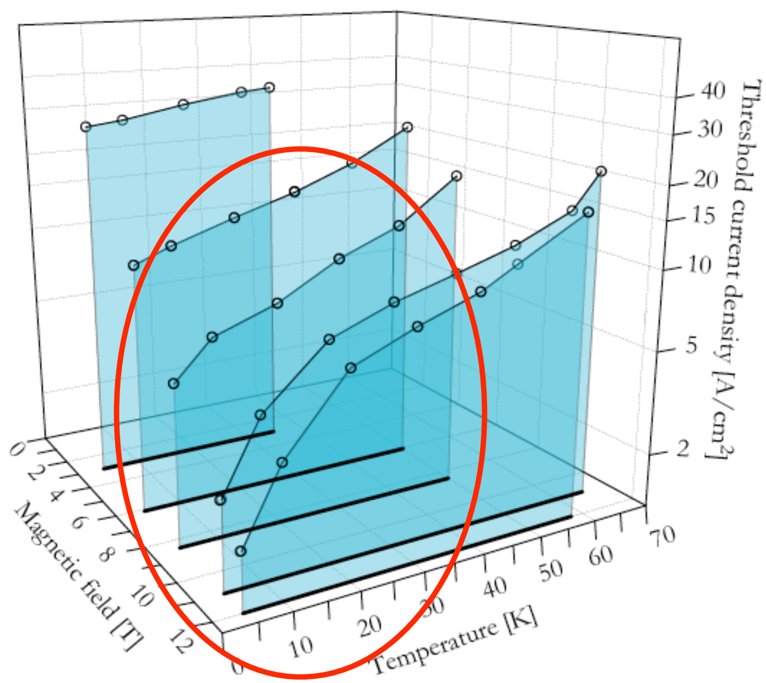
Strong threshold reduction only in “Big well” structures

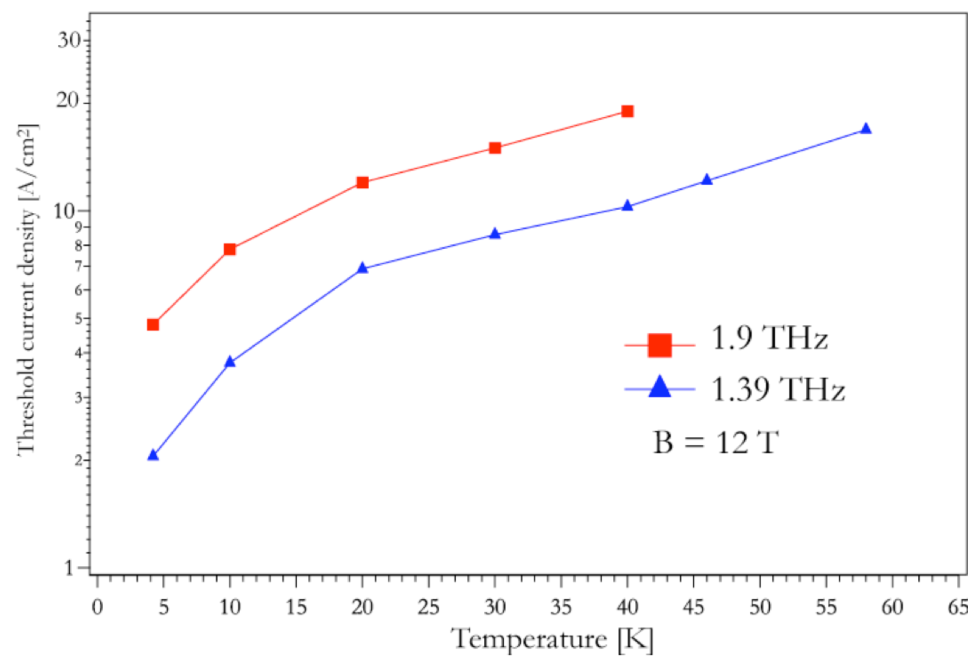
G. Scalari et al., Phys. Rev. B, 76, 115305(2007)

Threshold current: B and T dependence

T < 20 K, B> 7 T

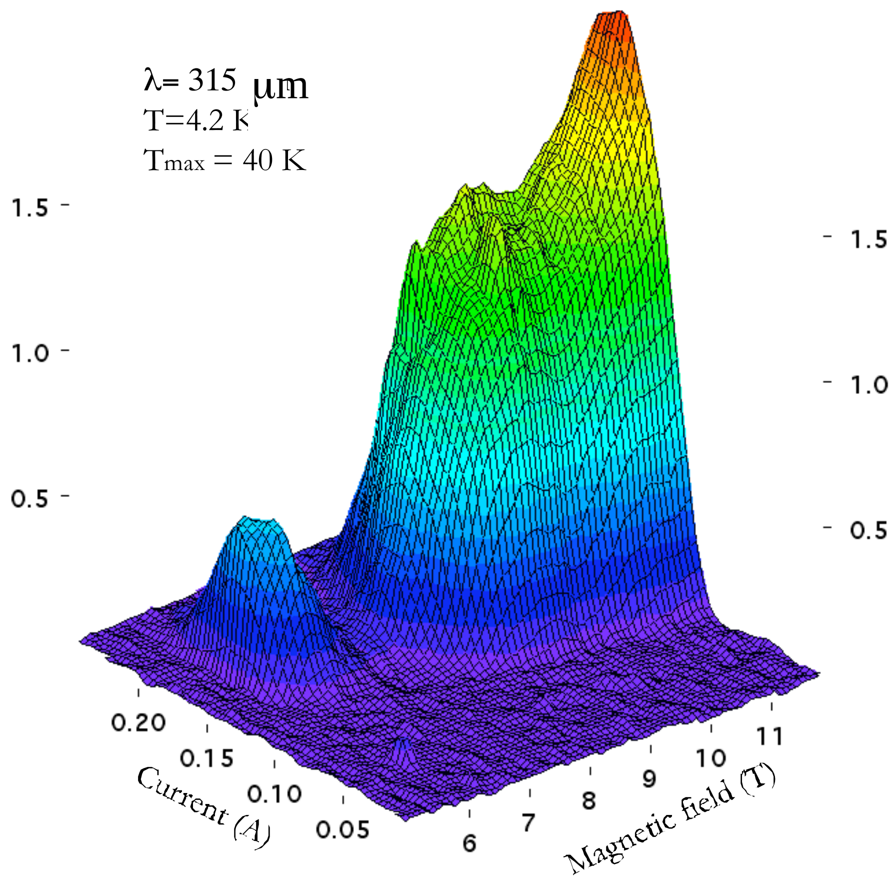
Activated behavior

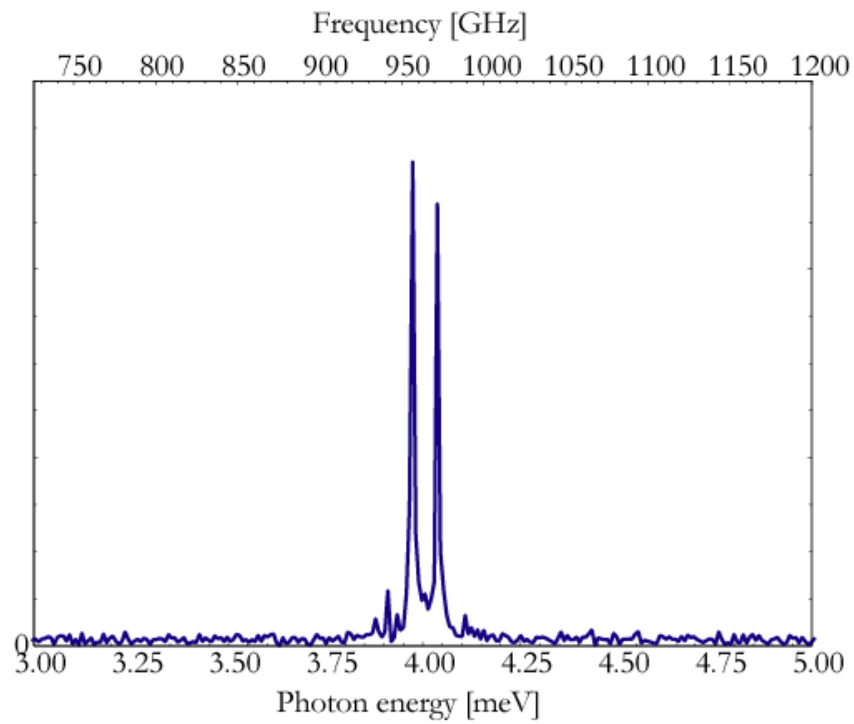




G. Scalari et al. , *Phys. Rev. Lett.*, **93** 237403 (2004)

950 GHz QCL



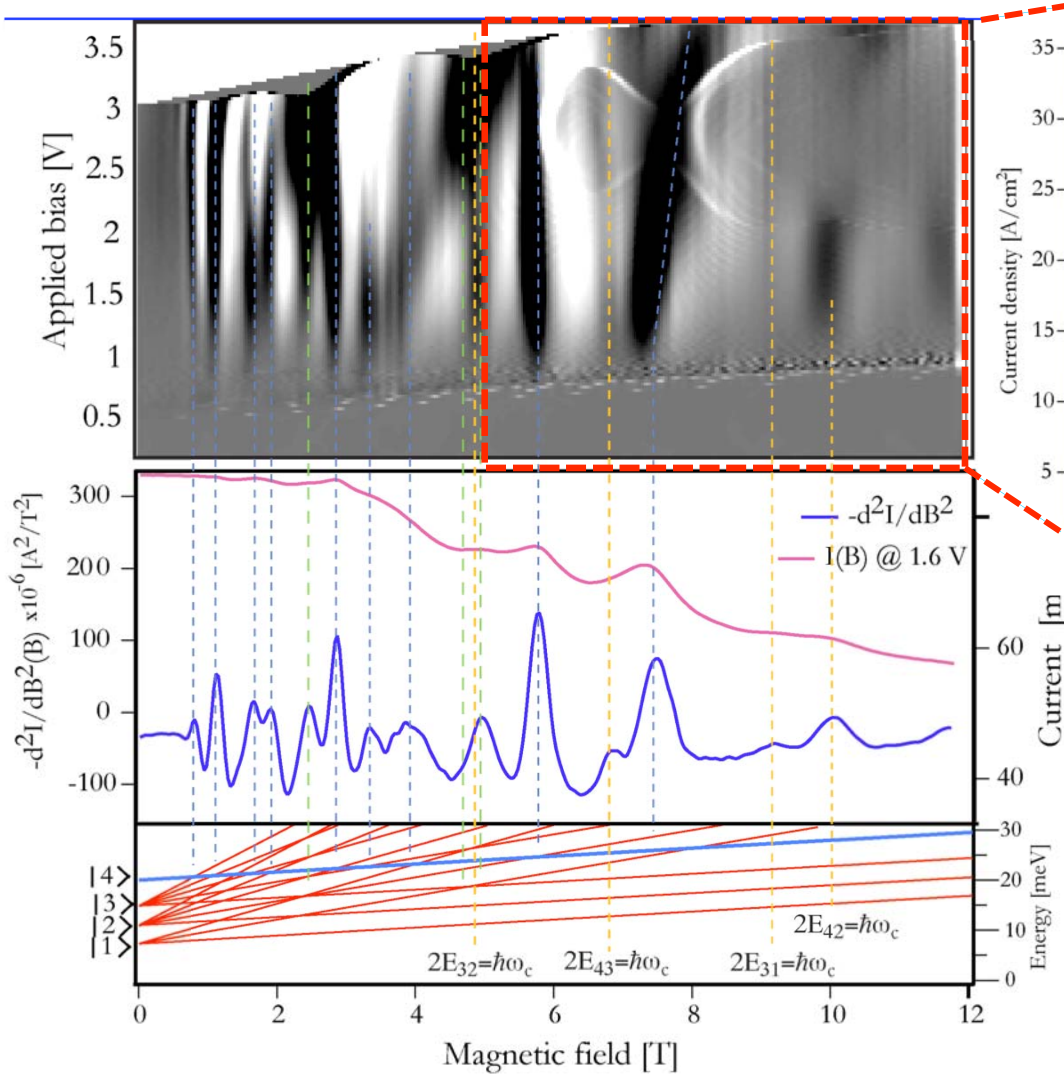


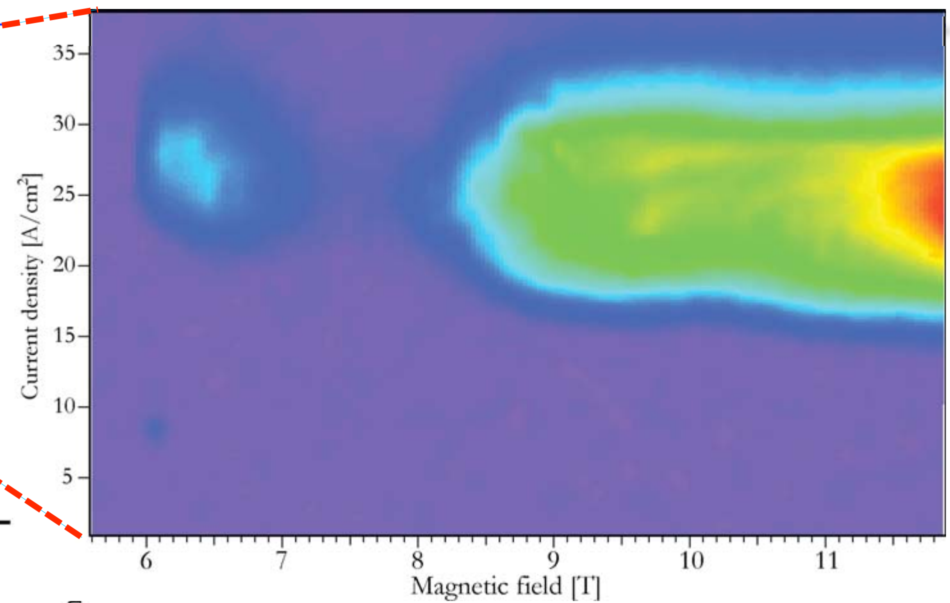
$$J_{thresh}(12\ \mathrm{T}) = 10\ \mathrm{A}/cm^2$$

1.5 mm long, 400 µm wide DM ridge

G. Scalar, C. Walther *et al.*, *Lasers and Photonics Reviews*, in press (2008)

Magnetotransport: elastic resonances and narrow levels





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Magnetic field summary: effects on the gain

$$G_p \propto \frac{4\pi e^2}{\epsilon_0 n_{eff}\,\lambda\,2\gamma_{ij}\,L_p} z_{ij}^2 \tau_{eff}$$

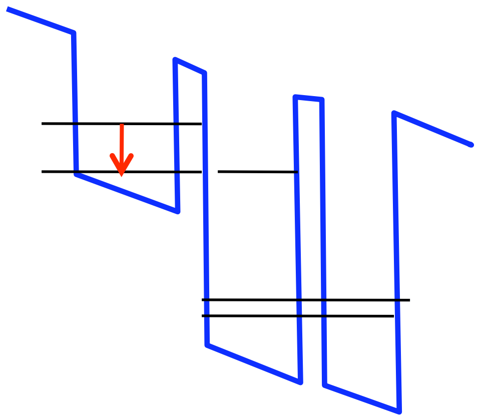
Gain enhancement in B field:

•Longer lifetimes due to phase space reduction: improves population inversion

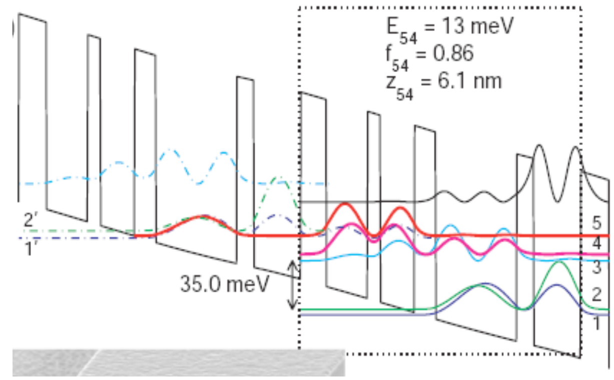
•Narrowing of the ISB linewidth:

positive effect on gain and on waveguide losses (reduces cross absorption from the tails of ISB transitions)

Optical phonon with step well



Population inversion:
Optical phonon resonance and resonant tunneling

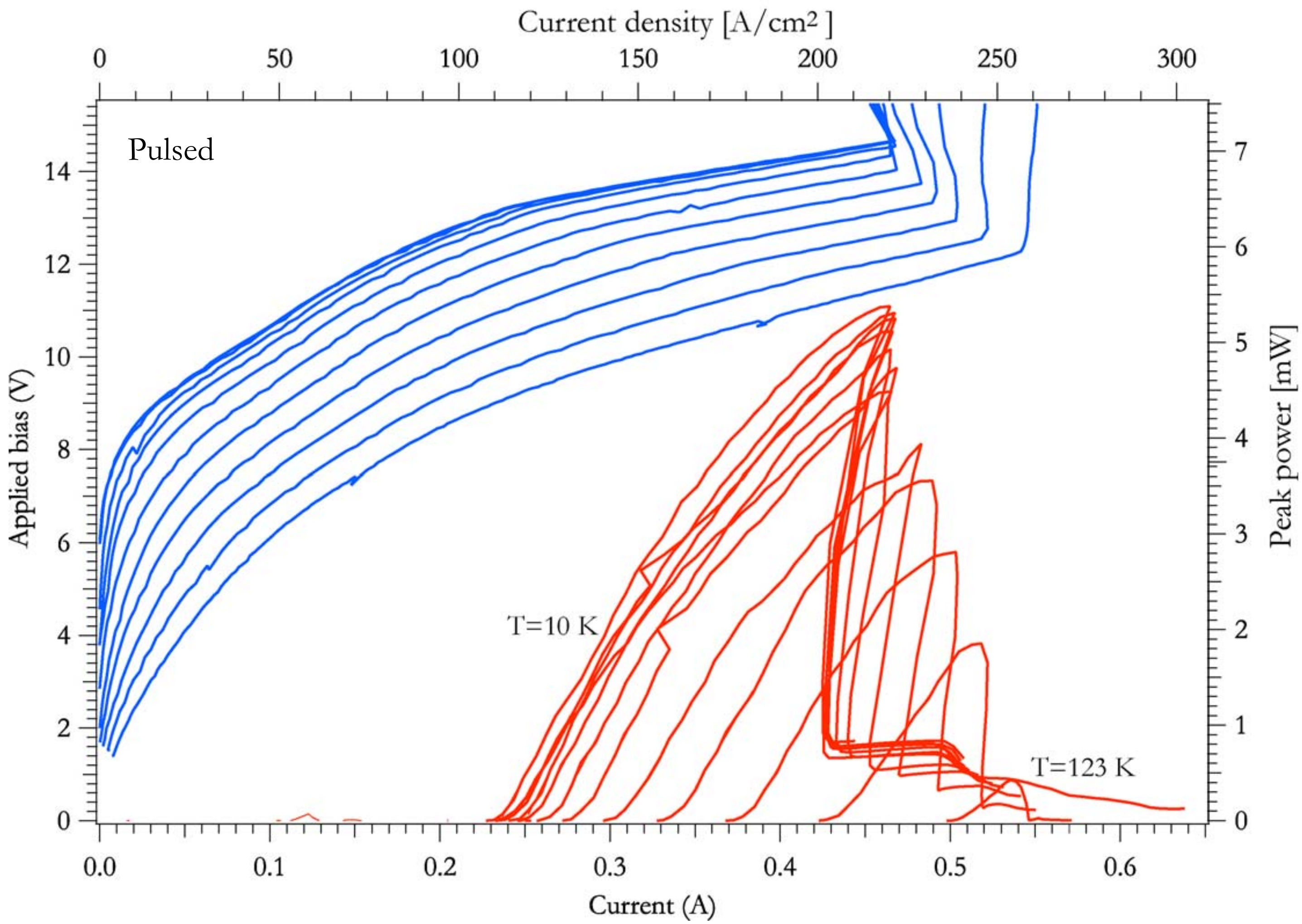


2 May 2005 / Vol. 13, No. 9 / OPTICS EXPRESS 3331

Similar to "MIT/H.C. Liu" phonon extraction scheme

- Limit the leakage current from the injector
- Intra-well transition
- "Big well" + LO phonon

Step well: performance at B=0



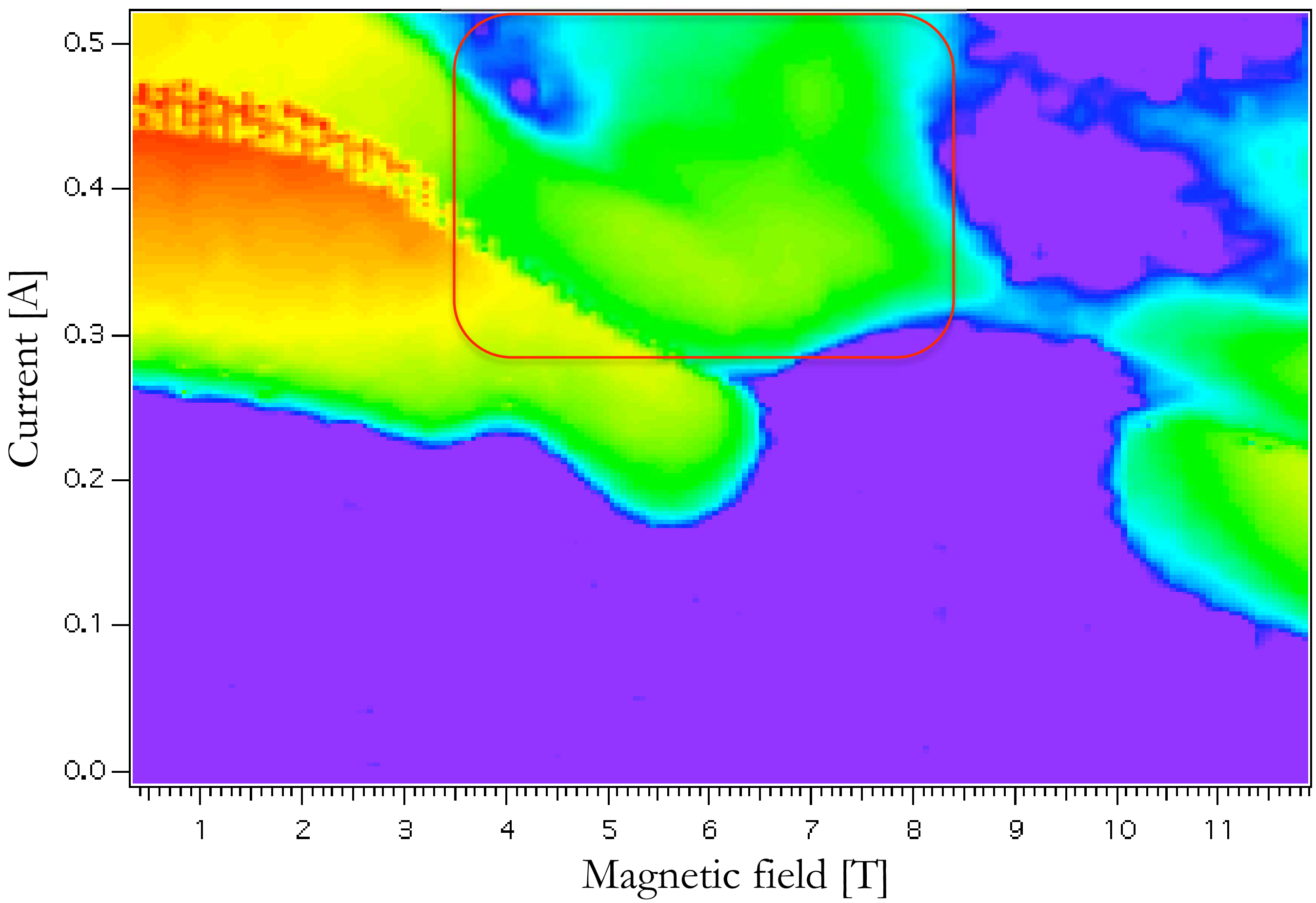
$$\frac{dP}{dI} \approx 30mW/A$$

J_{thresh}^{10K}=110 A/cm^2
Low for a phonon-based design
N_p=180
T_{max}=123 K

Double metal waveguide
1.5 mm x 150 µm
slightly underdoped
(n_s=1.2 x 10^{10} cm^{-2})

Laser emission as a function of current and B field

1THz and below emission



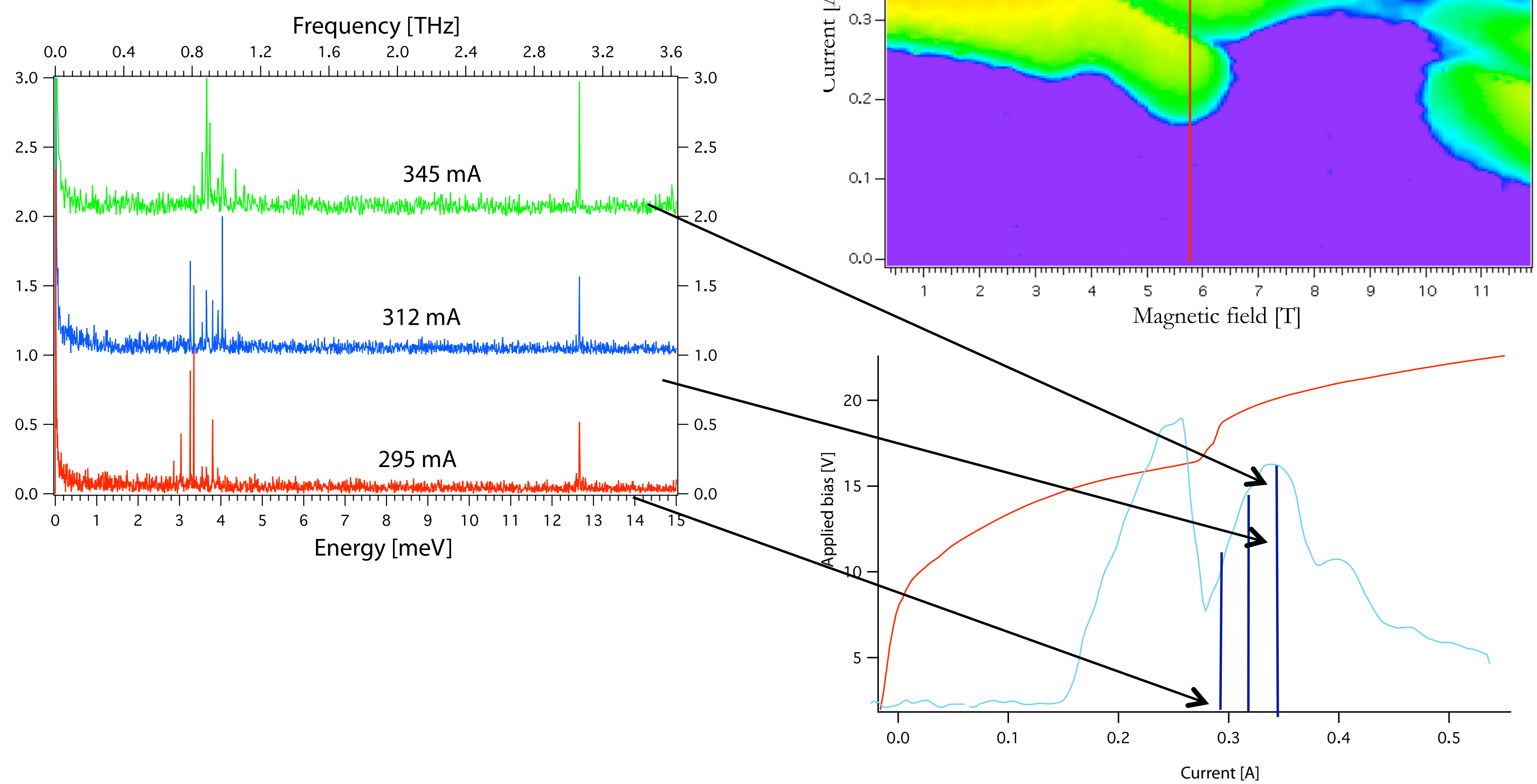
$J_{thresh}(12T)=40\ A/cm^2$

$J(12)/J(0)=1/3$

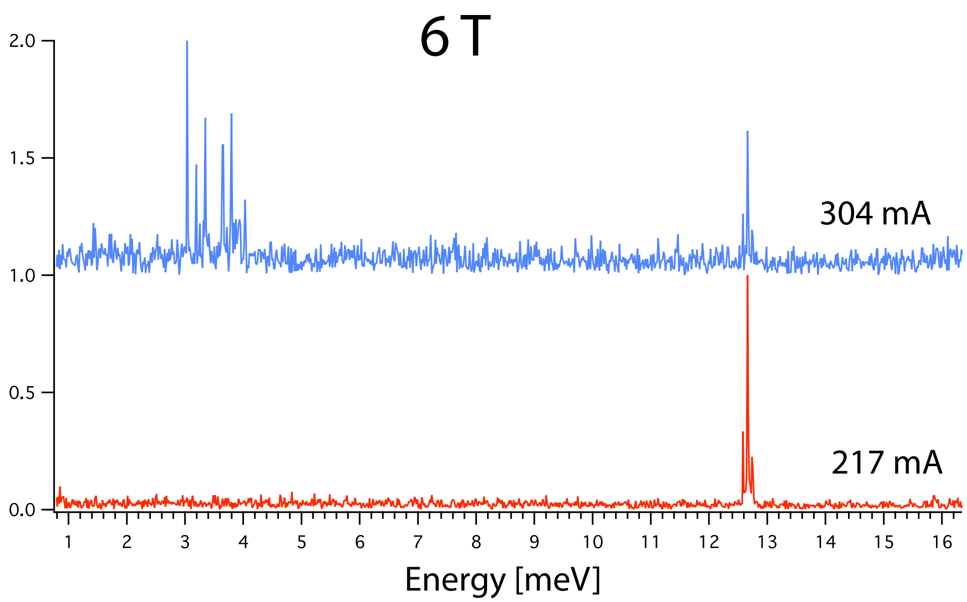
Effect of the intra-well

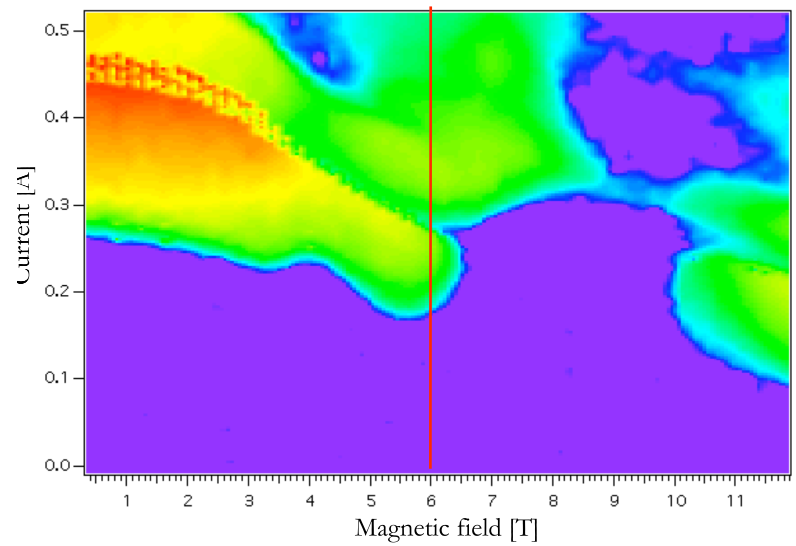
Spectra as a function of B and I

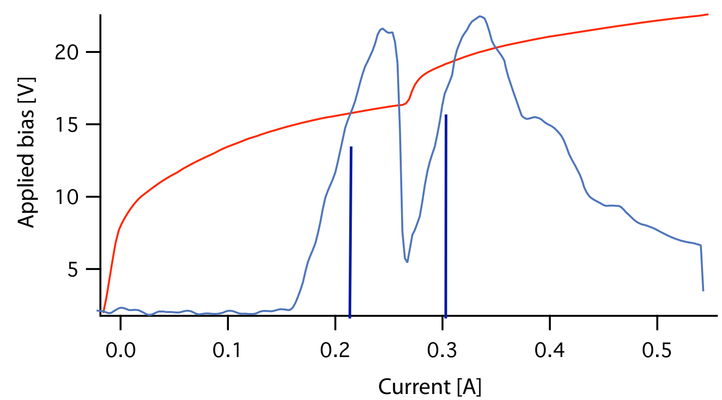
5.7 T



Spectra as a function of B and I







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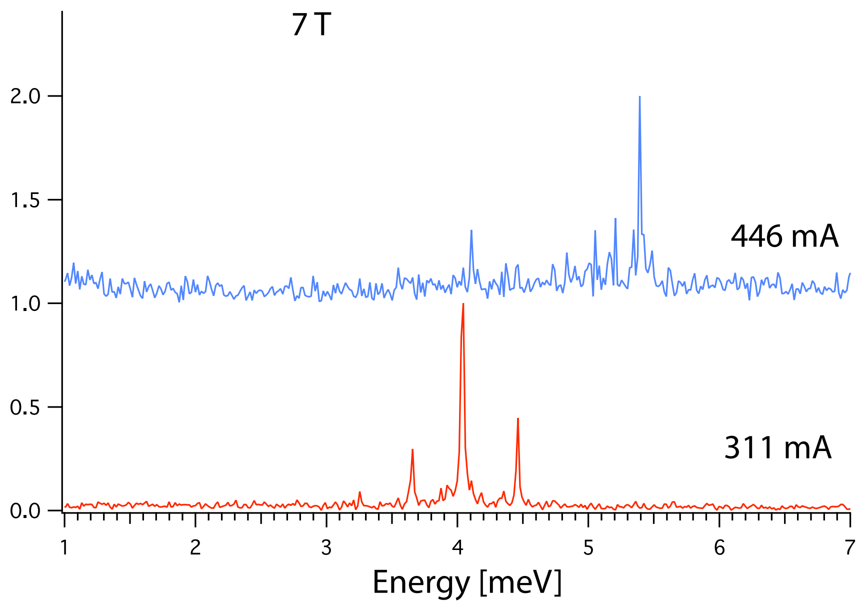

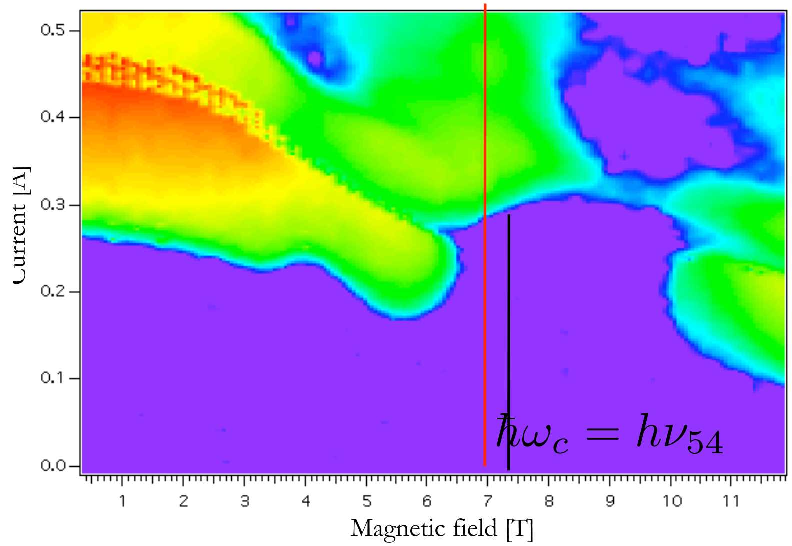

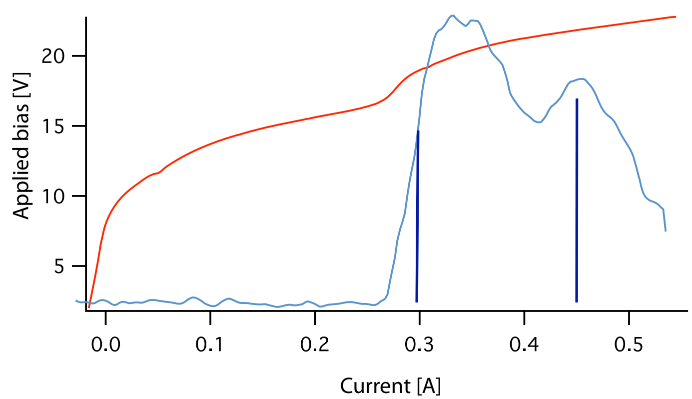

Was somewhat predicted

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 13 29 SEPTEMBER 2003

Theoretical analysis of spectral gain in a terahertz quantum-cascade laser: Prospects for gain at 1 THz

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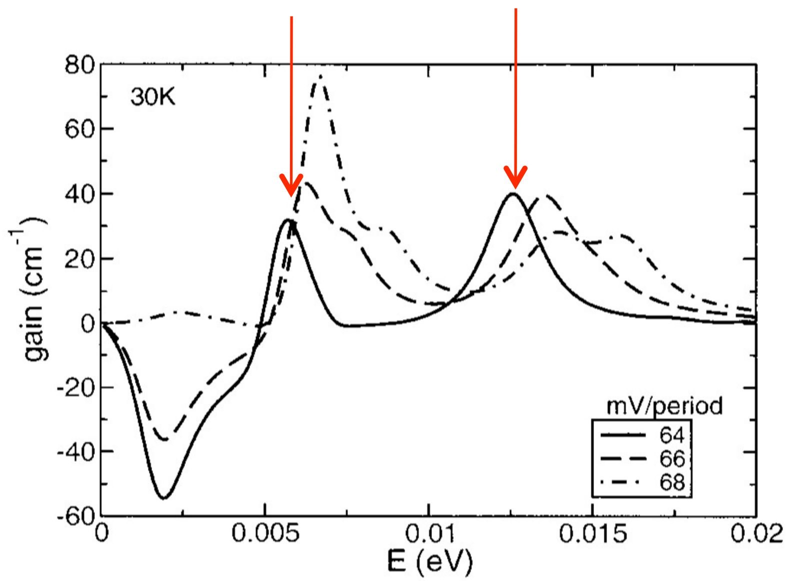
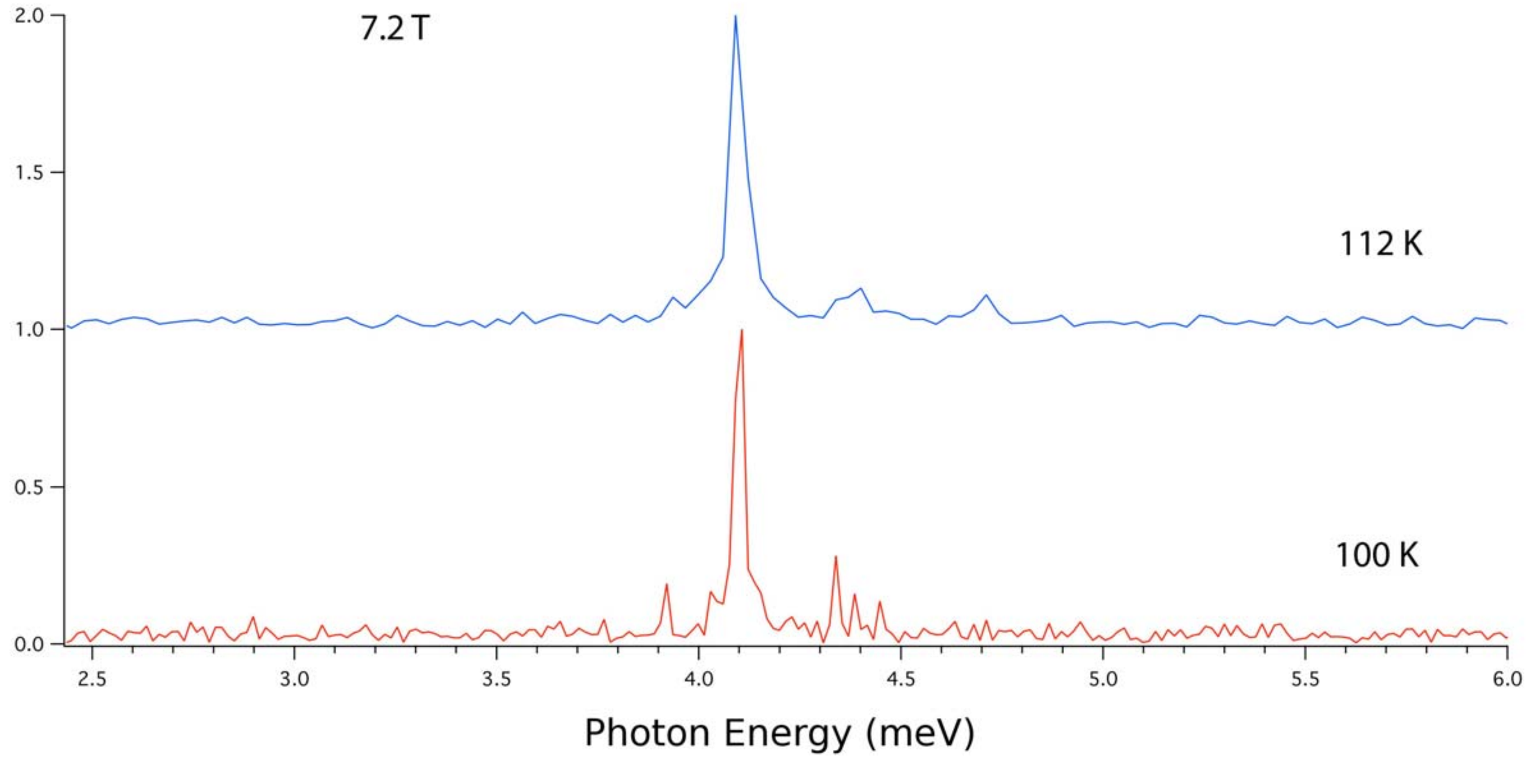


Magneto-spectroscopy on THz QC's

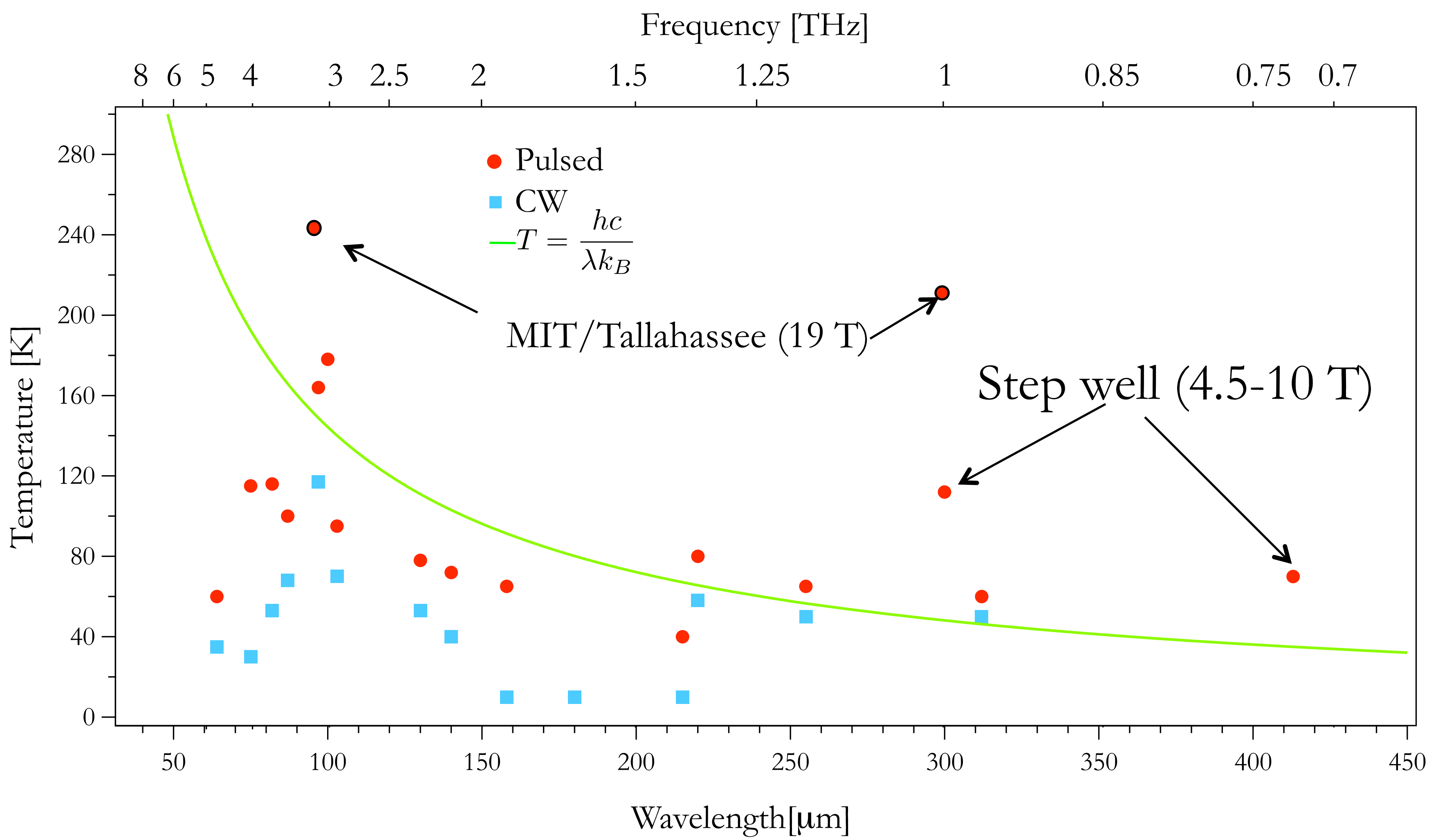
- The combination of a **broad-band** waveguide as the double metal resonator with the **gain enhancement** provided by the field allows the study of different transitions in the same structure
- Intriguing lasing on a "real" diagonal transition, widely tunable (3-5.5 meV !!!)
- …what about temperature?

1 THz operation up to 112K



$$\frac{k_B T}{h\nu} = 2.3$$

Terahertz QCLs performance



Data from: ETHZ, SNS-NEST, MIT, Harvard/Leeds, Cambridge-Teraview, Paris 7-Thales

Conclusions

- Confinement by B-field enables a much larger playground, despites limitations:
  - 0.6 A/cm^2 threshold, 650GHz operation…
- "Parasitic" transition achieves operation at a T with kT>>hν: further study is needed to fully understand the physics. Interesting for application w/out field also!
- In-plane control can be fundamental
- Non-resonant injection: one of the keys for higher temps?