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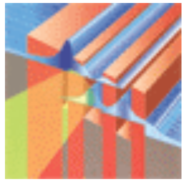

Long Wavelength THz QCL, emitting down to 1.2 THz

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ETH Zürich, Institut for Quantum Electronics, Zürich, Switzerland

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EU project « Teranova »

ITQW 2007

Outline

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- Challenges for low frequency THz QCL
- Bandstructure and waveguide design
- Results on low frequency THz QCL
- Transport and selective injection
- Temperature limits
- Conclusions

Actual frequency coverage

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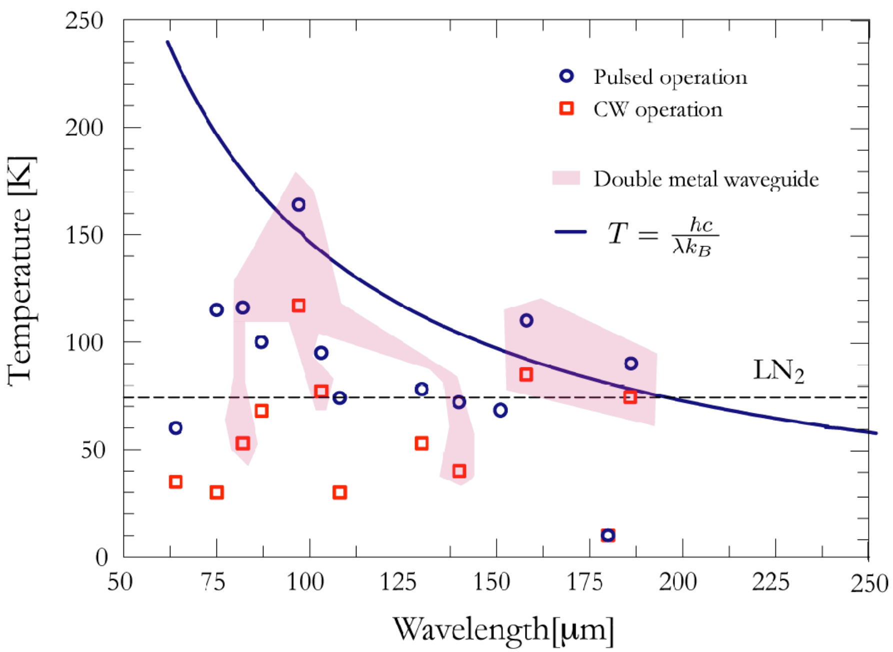
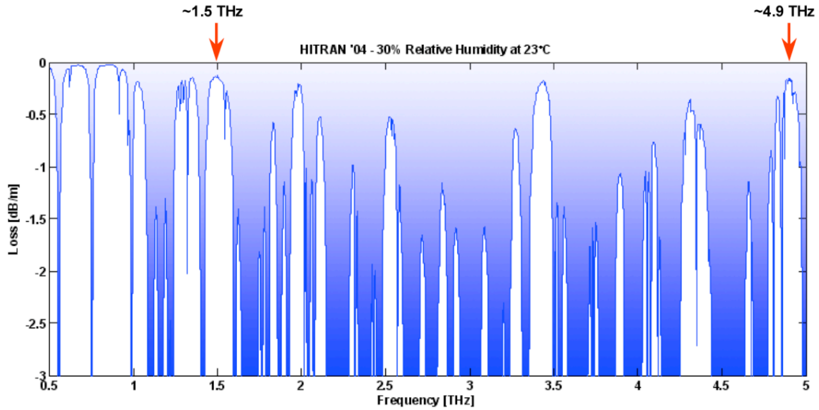
Map of THz QCL's (without magnetic field)



Atmospheric Transmission



- Absorption due to water vapor

- Motivation for low frequency THz QCL: Imaging, earth-based local oscillators

- S. Kumar et al., ITQW 2007 — 1.4 THz without B-field
- G. Scalari et al., ITQW 2007 — 0.83 THz in B-field
- A. Wade et al., ITQW 2007 — < 1 THz in B-field

Challenges for QCL below 2 THz

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Facts:

- Photon energy < 8 meV
- Broadening of quantum states 1-2 meV
- Free carrier absorption scales with λ^2

Challenge is to get:

- Low loss waveguides
- Sufficient population inversion
- Selective injection of carriers

Bandstructure

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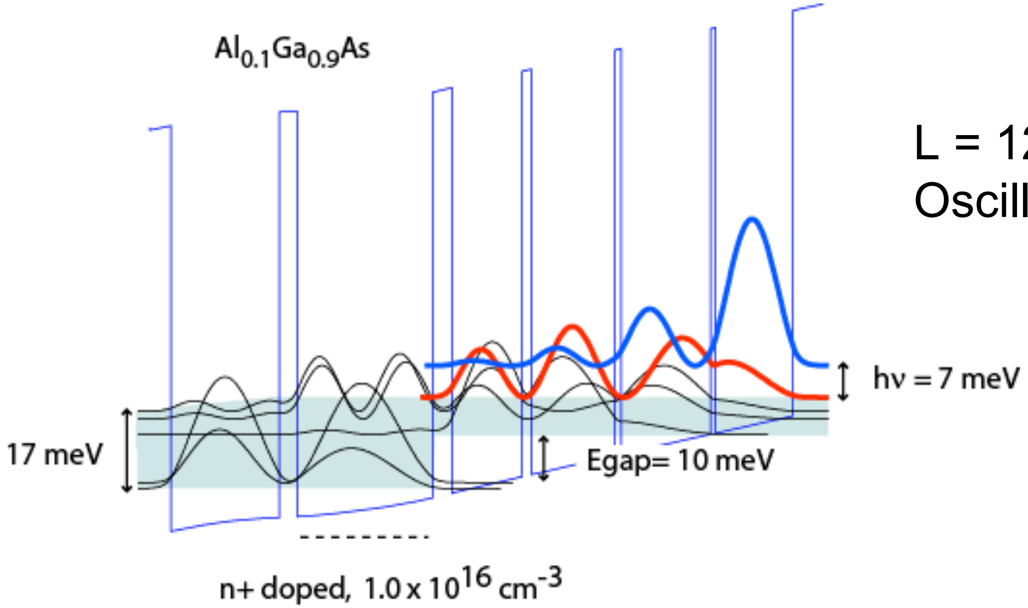
Bound to continuum transition with energy gap

Rescaling of LO-phonon extraction design



L = 129 nm
Oscillator strength = 19

- Good injection efficiency
- Low intersubband absorption

C. Walther *et al.*, Appl. Phys. Lett., **89**, 231121 (2006)

G. Scalari *et al.*, Appl. Phys. Lett., **86**, 181101 (2005)

Calculated intersubband absorption

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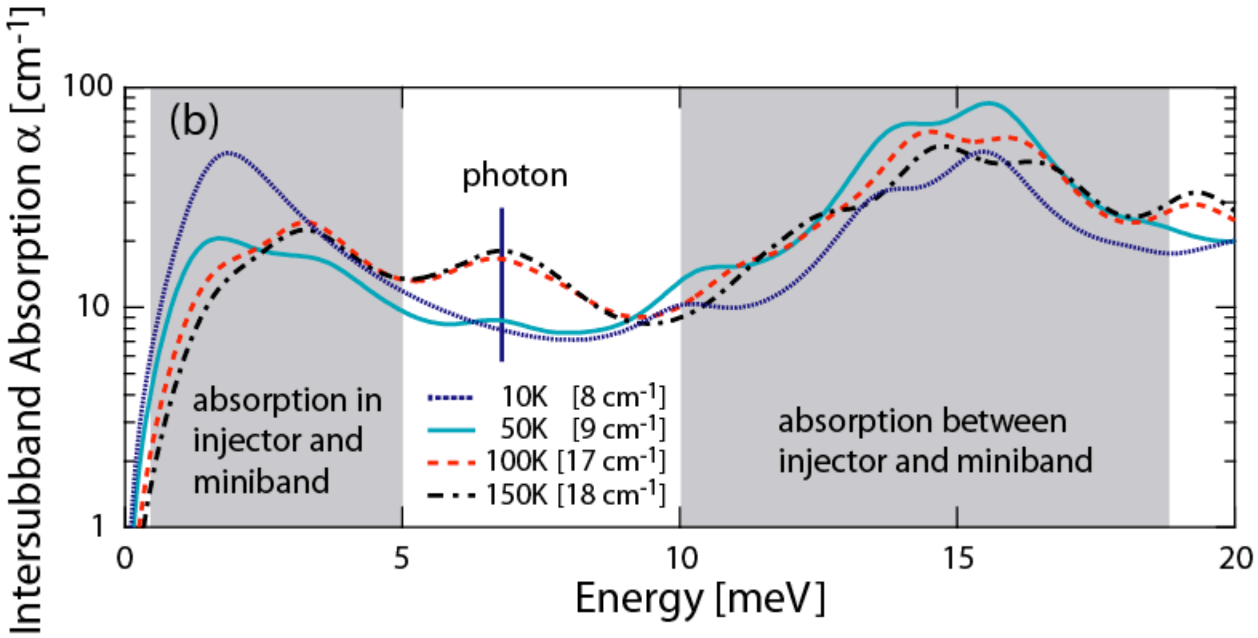

Using a thermal equilibrium model for electron distribution

- Low intersubband absorption at photon energy (7 meV)

Double-metal waveguide : loss calculation

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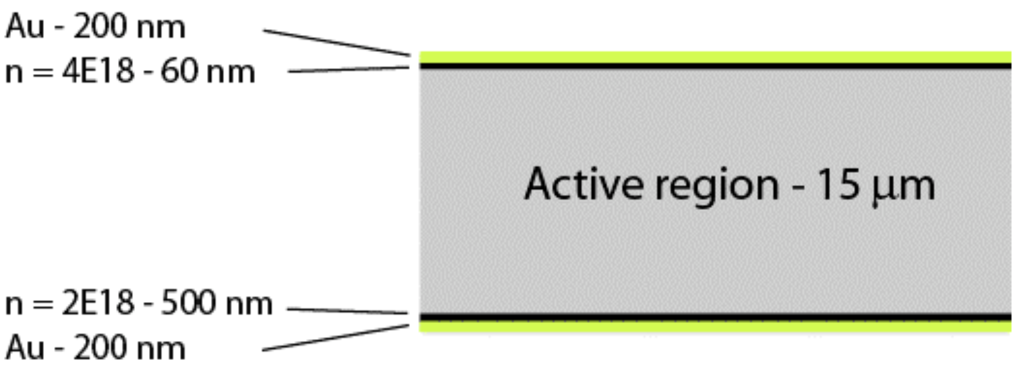
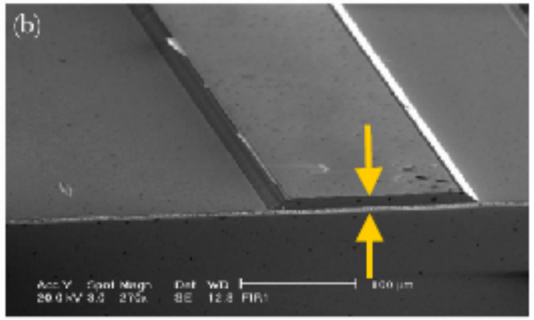
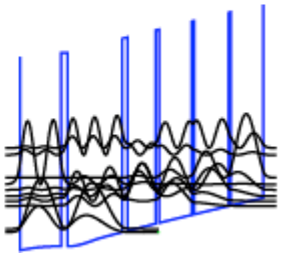


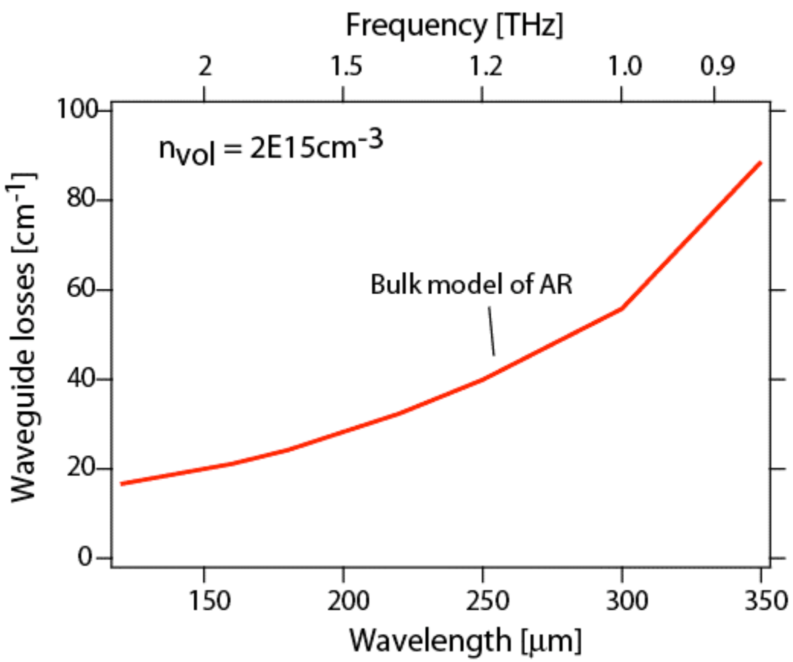


2 Models

Active region = bulk with average doping n=2E15cm^{-3} — free carrier absorption

Active region =  — Intersubband absorption

Waveguide losses: Bulk model



Bulk model :

λ [µm]	160	180	220	250	350
α [cm^{-1}]	21	24	32	40	87

For λ > 150 µm, the waveguide losses increase with λ^2.

This model predicts to high losses for lasing at long wavelength. But is the model adequate?

W’guide losses: ISB Model

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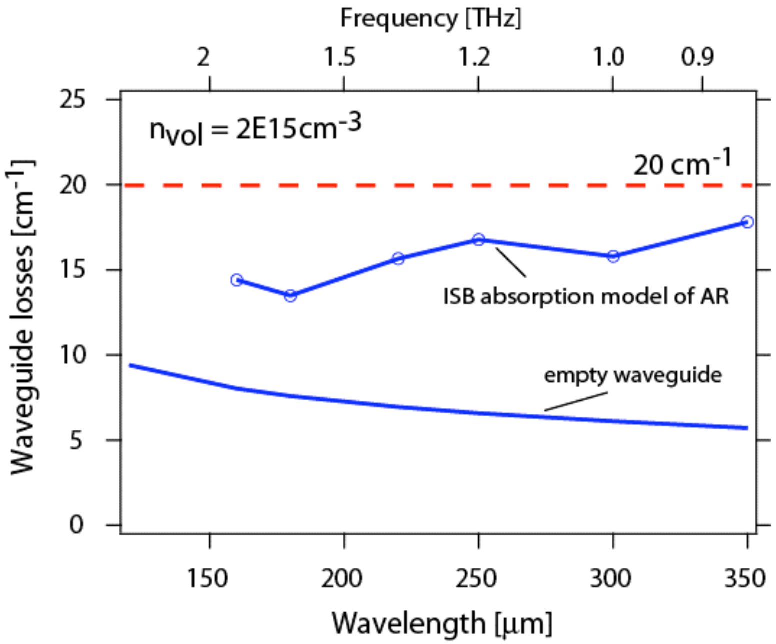

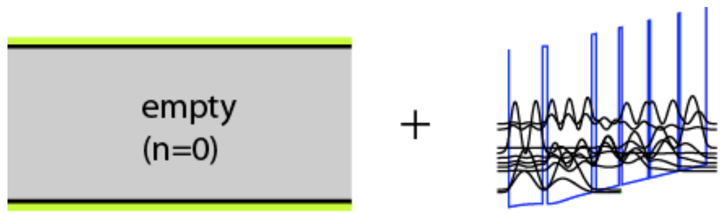

< 10 cm $^{-1}$ ~ 10 cm $^{-1}$ (B2C)

λ [µm]	160	180	220	250	300	350
α [cm^{-1}]	14	14	16	17	16	18

ISB absorption depends on the specific Bandstructure.

Bound-to-continuum design with energy gap allows to get waveguide losses below 20 cm^{-1} for n=2E15cm^{-3}.

Structure N891 (150-170um)

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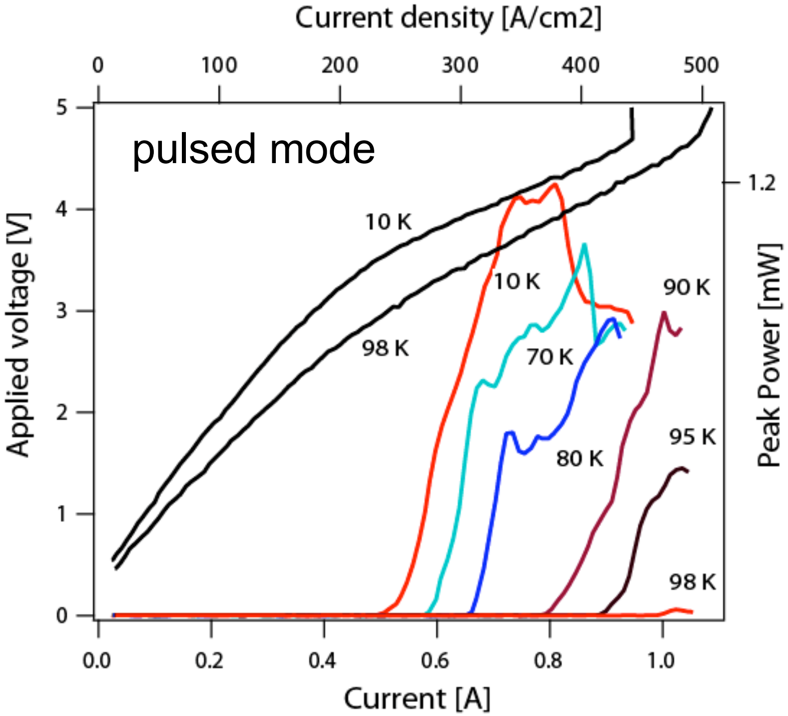
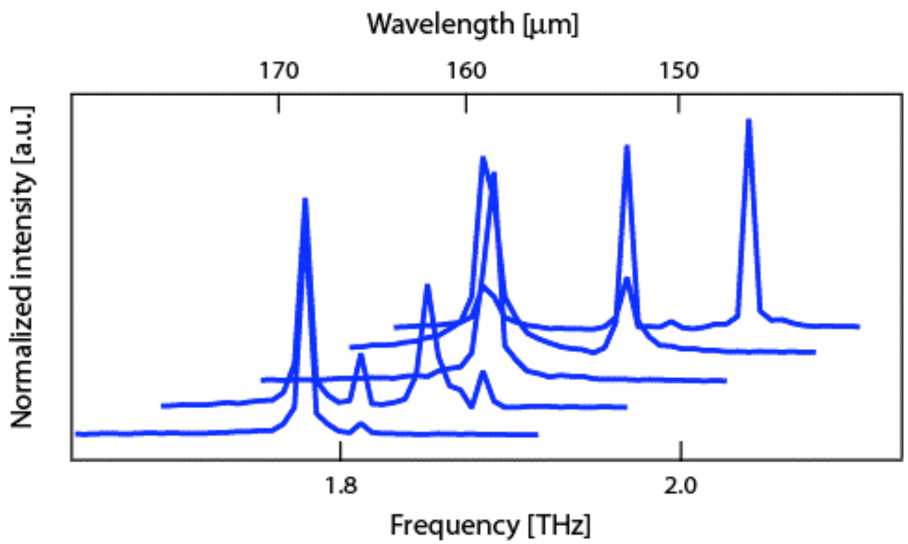
Overview:



cw spectra at 10 K



- Peak power at 10K: 1.2 mW
- Pulsed mode operation up to 98 K for this sample

- Strong Stark-shift with increasing voltage

Structure N899 (170-190um)

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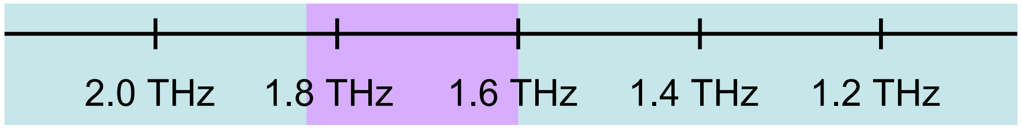
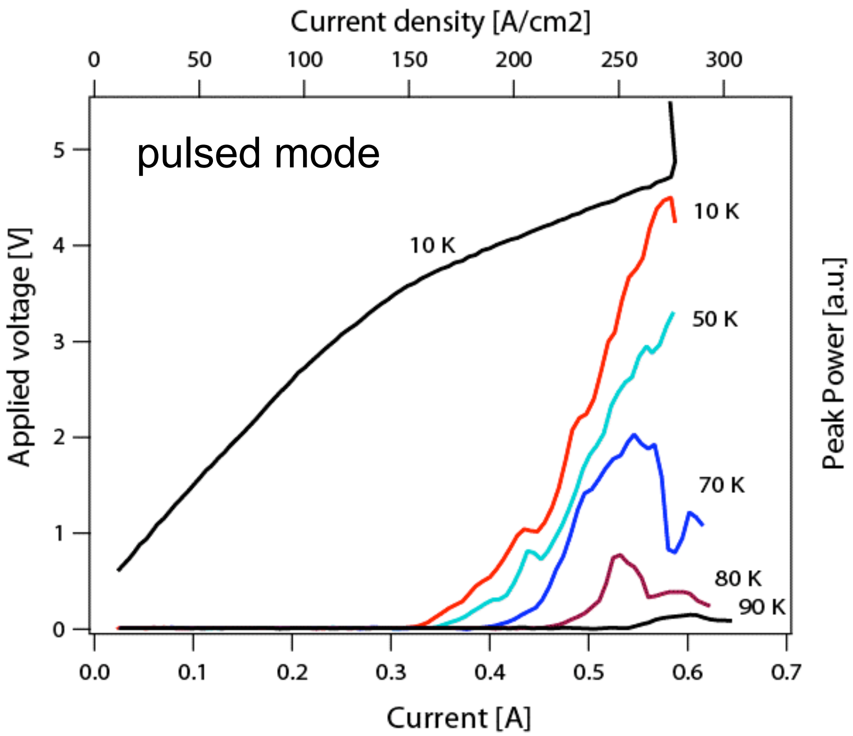
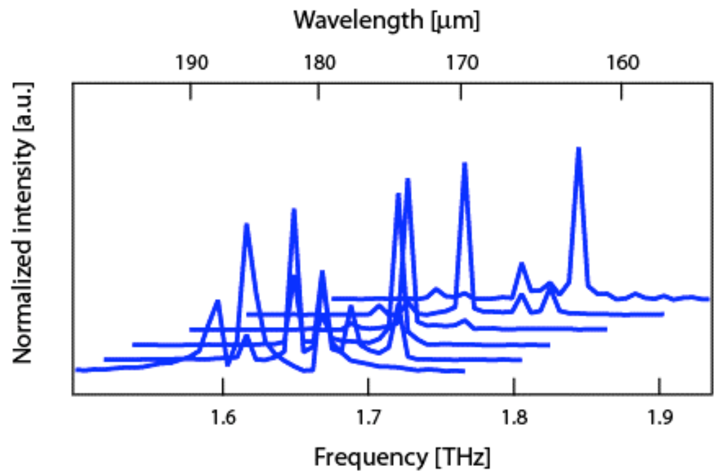
Overview:





cw spectra at 10 K



- Pulsed mode operation up to 90 K for this sample
- Strong Stark-shift with increasing voltage

Structure N892 (200-220 um)

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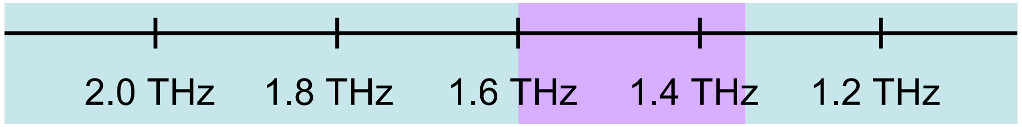
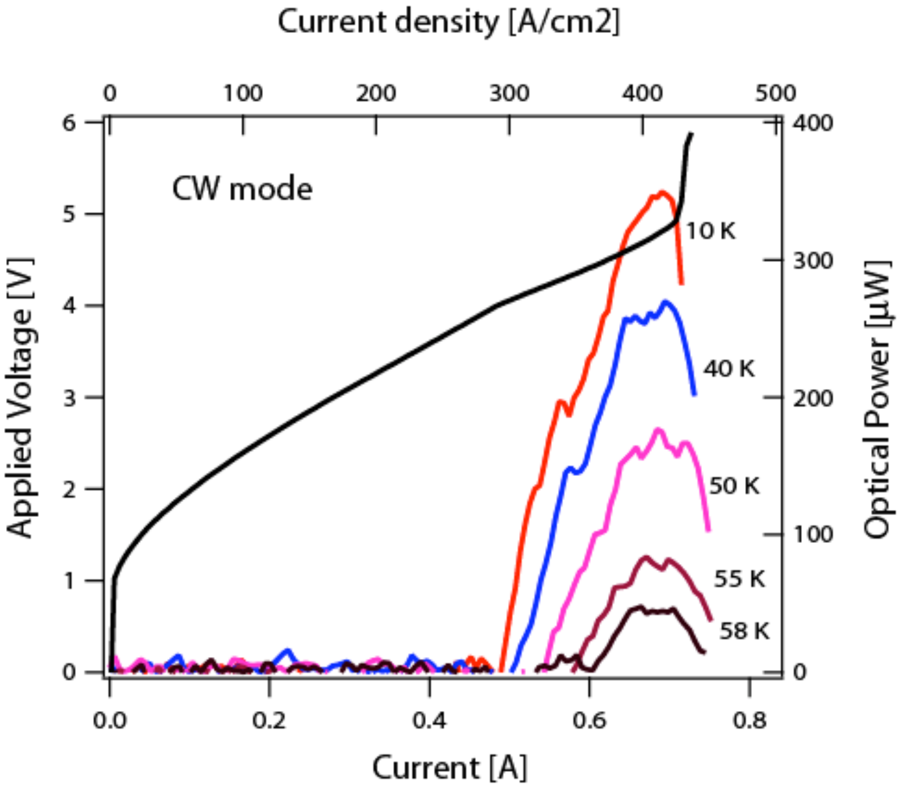
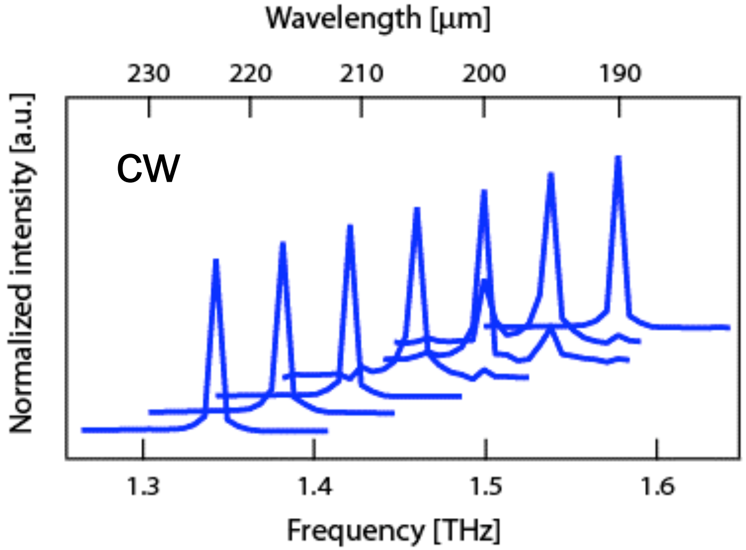
Overview:







- T_{max} in cw: 58K (pulsed 84K)
- Max optical power at 10K: 0.35 mW

- Strong Stark shift of gain curve, 16% of center frequency
- Lasing on Fabry-Pérot modes of the cavity (1mm x 165µm)

In press Appl. Phys. Lett.

Structure N908 (230 – 250 um)

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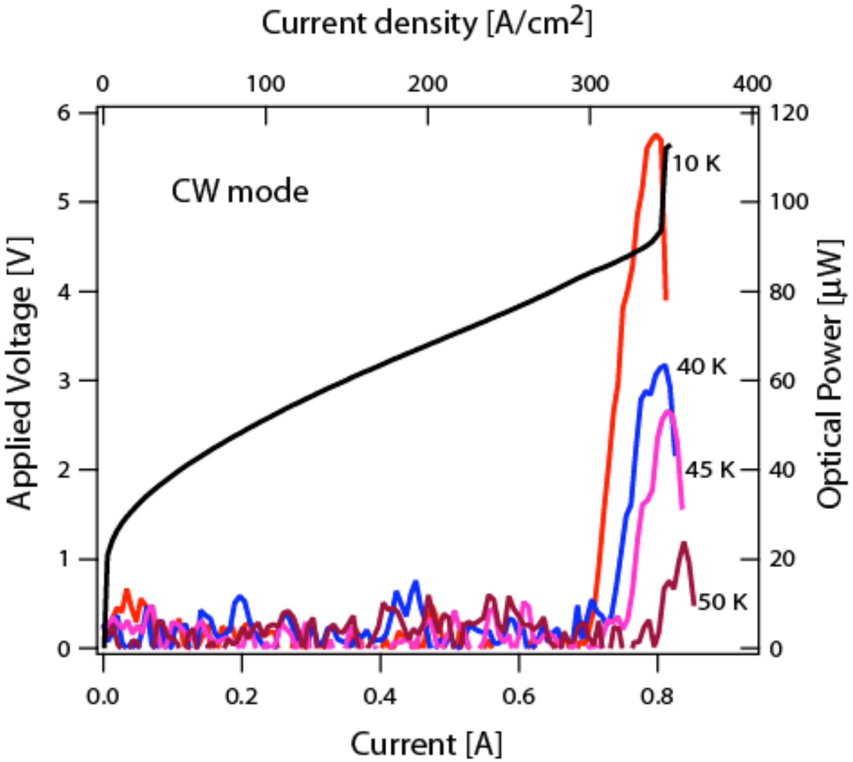
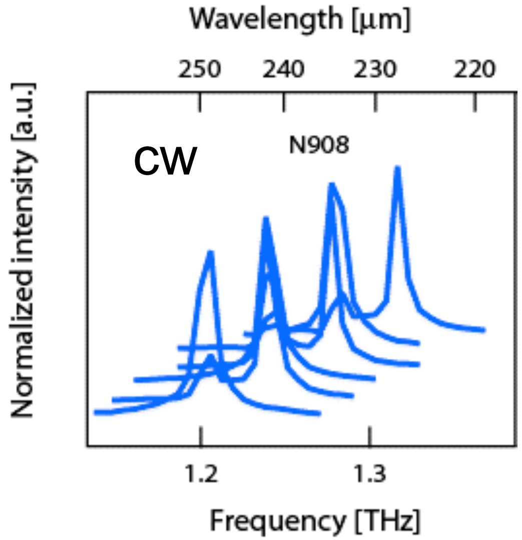
Overview:





- T_{max} in cw: 50K (pulsed 69K)
- Max optical power at 10 K : 117µW

- Stark-shift of gain curve (10% of center frequency)
- Lasing on Fabry-Pérot modes of the cavity (1mm x 165µm)

In press Appl. Phys. Lett.

Selective injection (N891, 160um)

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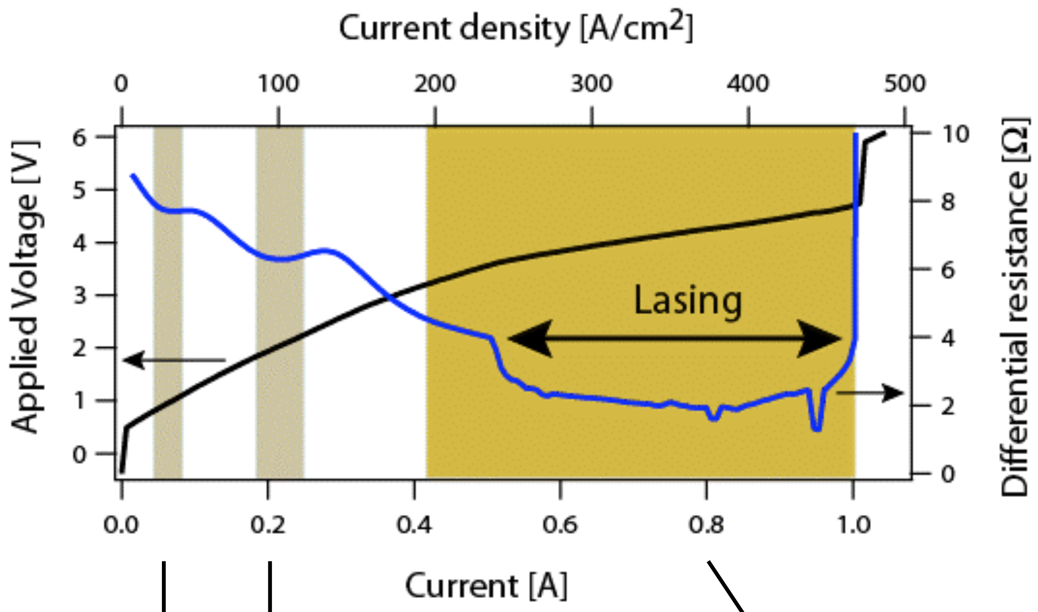
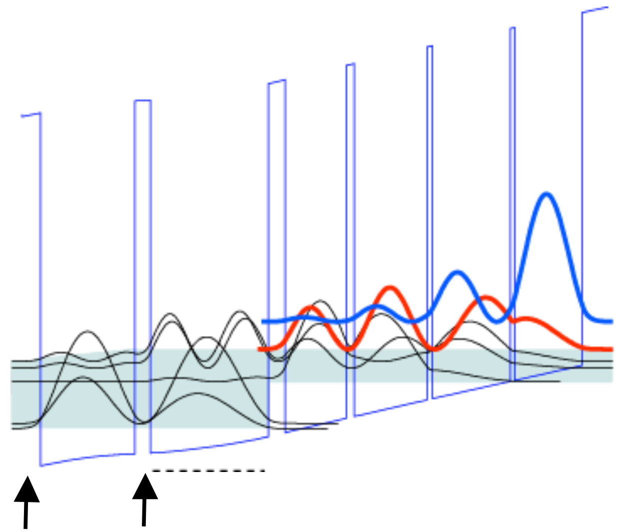
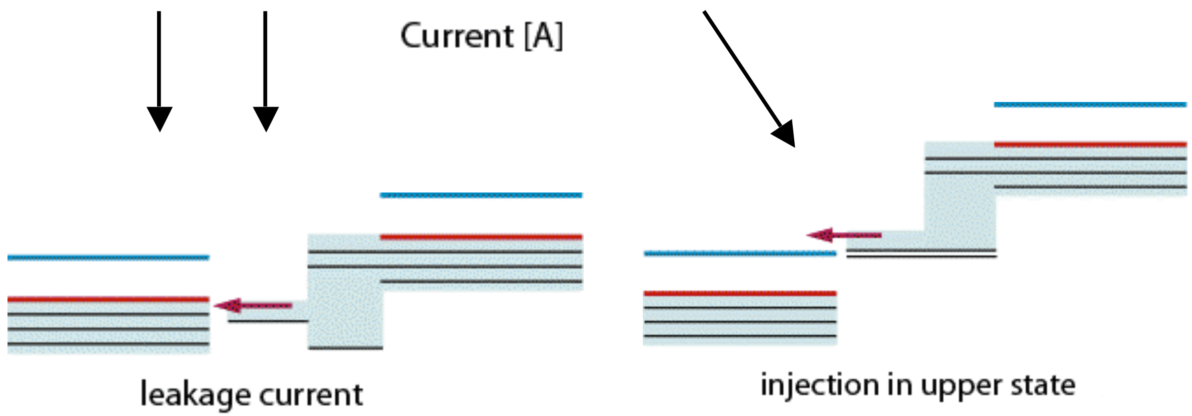




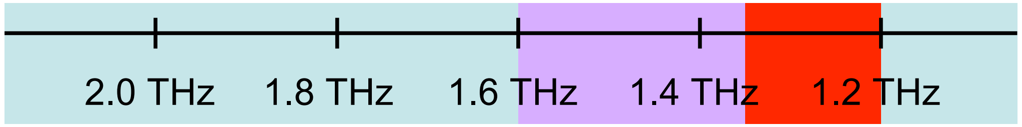


Dynamic range:

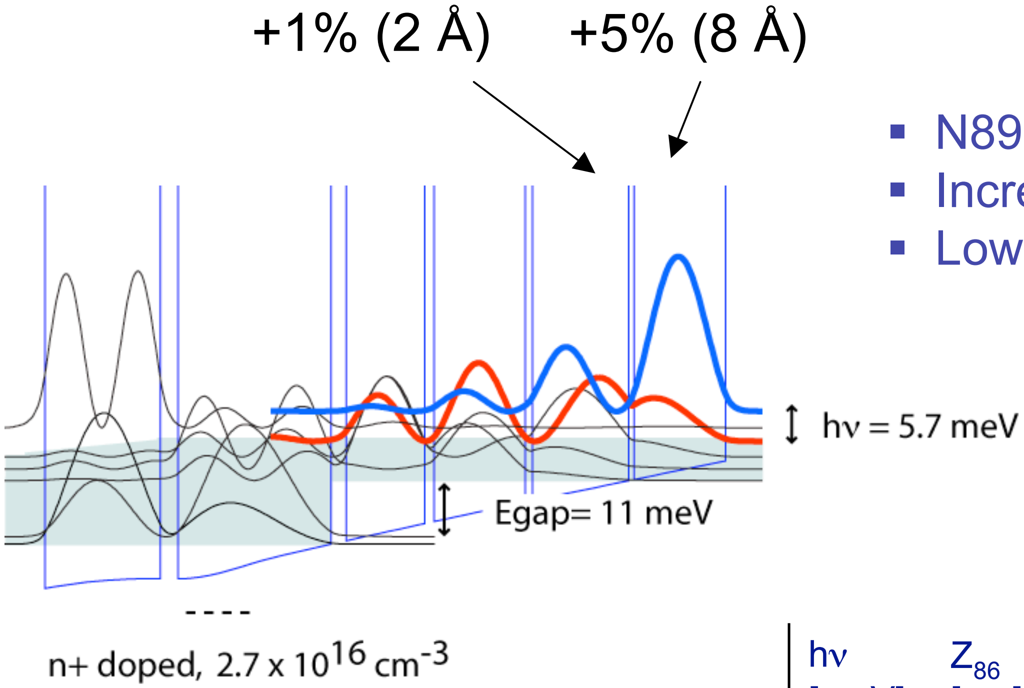
$$Dr = \frac{j_{Max} - j_{th}}{j_{Max}}$$

The dynamic range is determined by the coupling between injector states and upper state. Very sensible!

Going from 1.34 to 1.2 THz



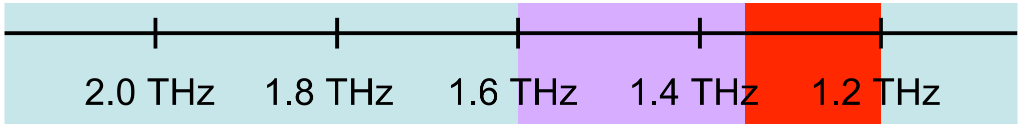
Bandstructure

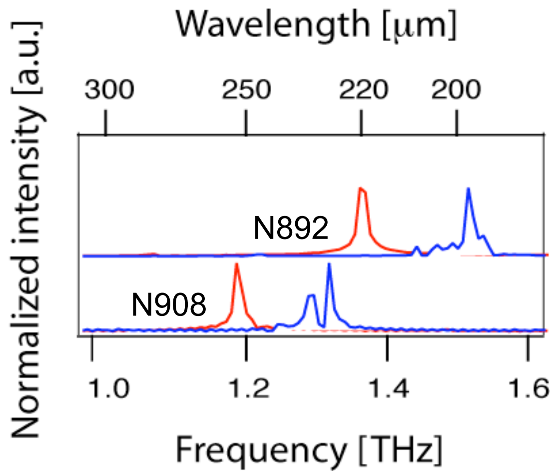


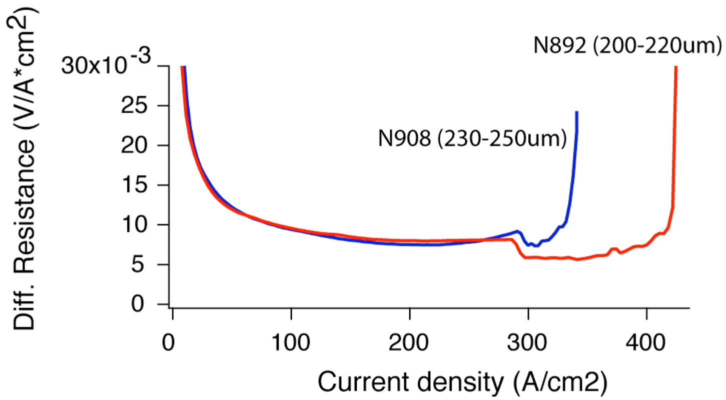
- N892 → N908 (1.34 → 1.2 THz)
- Increasing well width (1. and 2.)
- Lower upper state energy

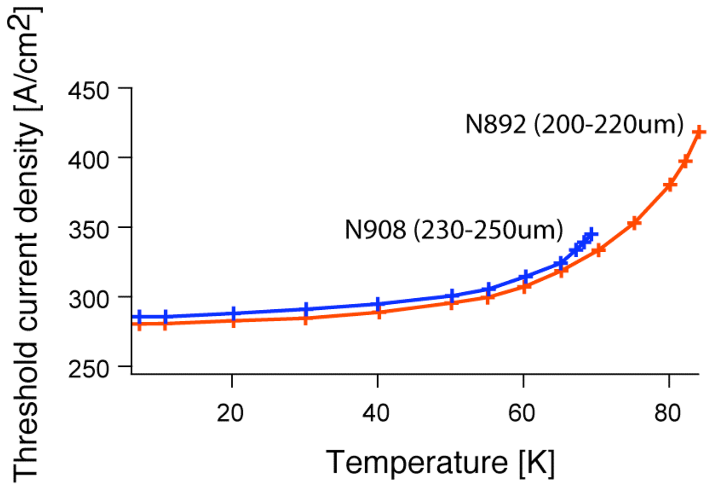
	$h\nu$ [meV]	Z_{86} [nm]	ΔE_{inj} [meV]	α_{ISB} [cm^{-1}]	α_{tot} [cm^{-1}]	f_{86}
N892	5.7	10.8	0.63	8.7	19	17.3
N908	4.9	11.3	0.54	10.2	19.7	16.6

Comparison N892 and N908









- Lower emission frequency
- Same threshold current density
- Dynamic range decreases from 32% to 15%
- Lower coupling:
  ΔE_{N892}=0.63 meV → ΔE_{N908}=0.54 meV
- Lower T_{max}
- Importance of Injector design

Temperature limits ?

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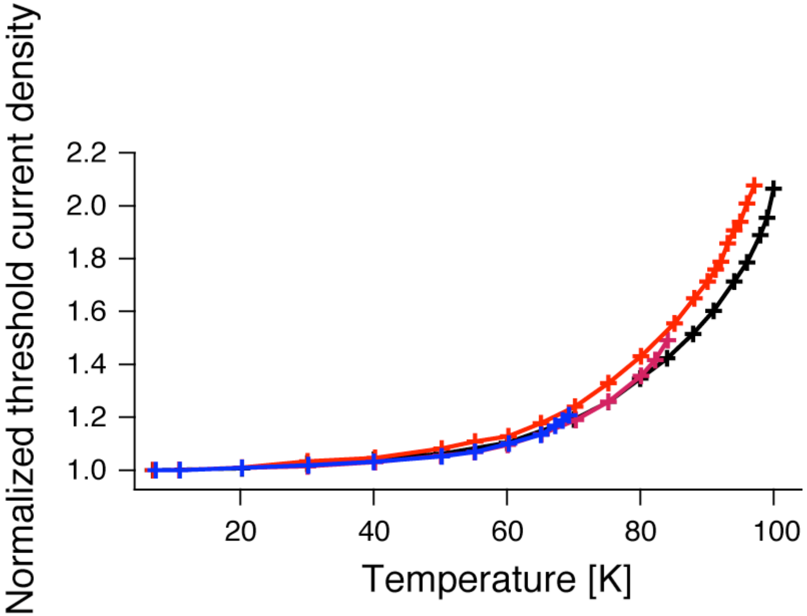
Lasers between 160 μm and 250 μm

Different threshold current densities



	N891 ~160μm	N899 ~190μm	N892 ~210μm	N908 ~240μm
Tmax	100 K	97 K	84 K	69 K

- Same activation with Temperature
- Independent on the photon energy

Comparison suggests:

- A limit at ~ 100 K for this class of lasers
- Dynamic range determines whether laser stops before 100 K

Conclusion

- QCL's covering the range from 2.1 to 1.2 THz
- Injector design is crucial for maximizing dynamic range
- Maximal operation temperature seems to be limited at ~ 100K. Injector has to be optimized to achieve ~ 100K.

Thank you for your attention!