Broadly tunable external cavity quantum-cascade lasers

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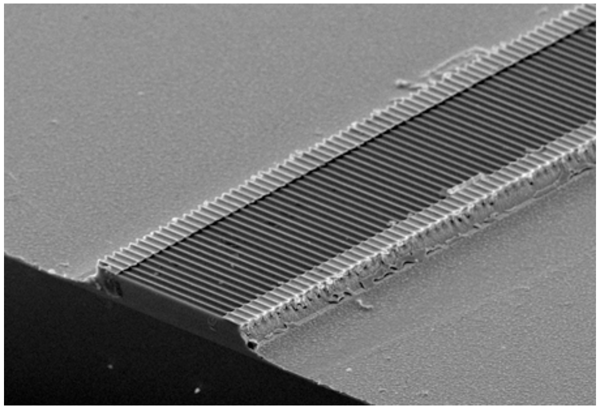
Outline

- ➢ Motivations
- ➢ TE-cooled CW external cavity QCL at 5.2 μm
- ➢ Room temperature CW EC-QCL at 8.4 μm
- ➢ EC-QCLs based on a heterogeneous cascade active region
- ➢ Conclusions

Motivations

Distributed-feedback QCLs:

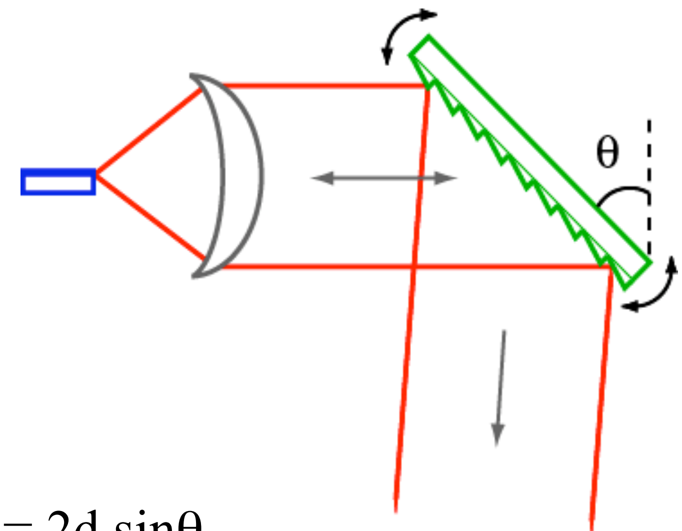


$\lambda = 2n_{eff}\Lambda$

Tuning by thermo-optic effect
$d\nu/dT = -0.05$ to -0.2 cm^{-1}/K
Typical tuning range on TEC: 10 cm^{-1}

Faist et al., APL **70**, 2670 (1997)

External-cavity QCLs:

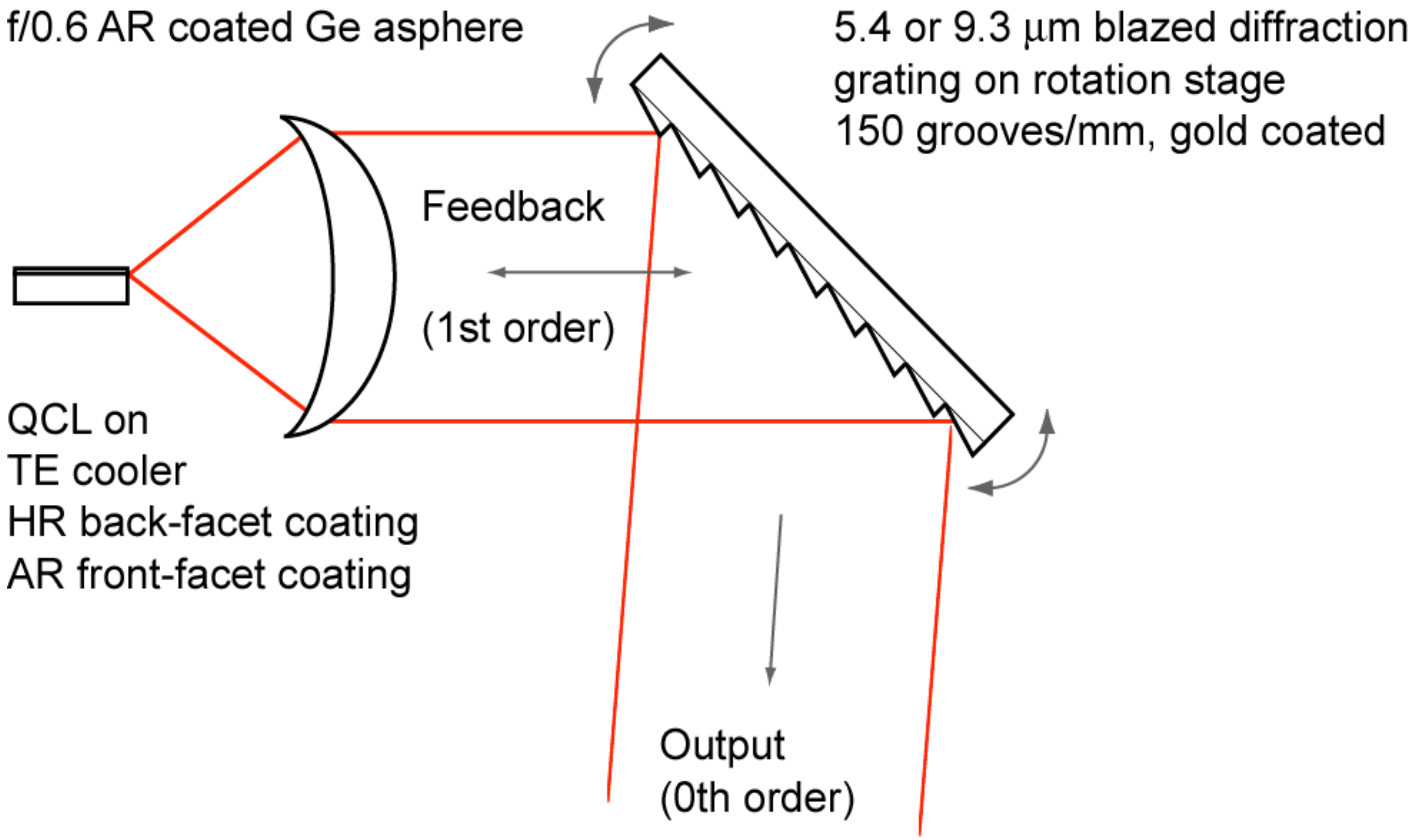


$\lambda = 2d \sin\theta$

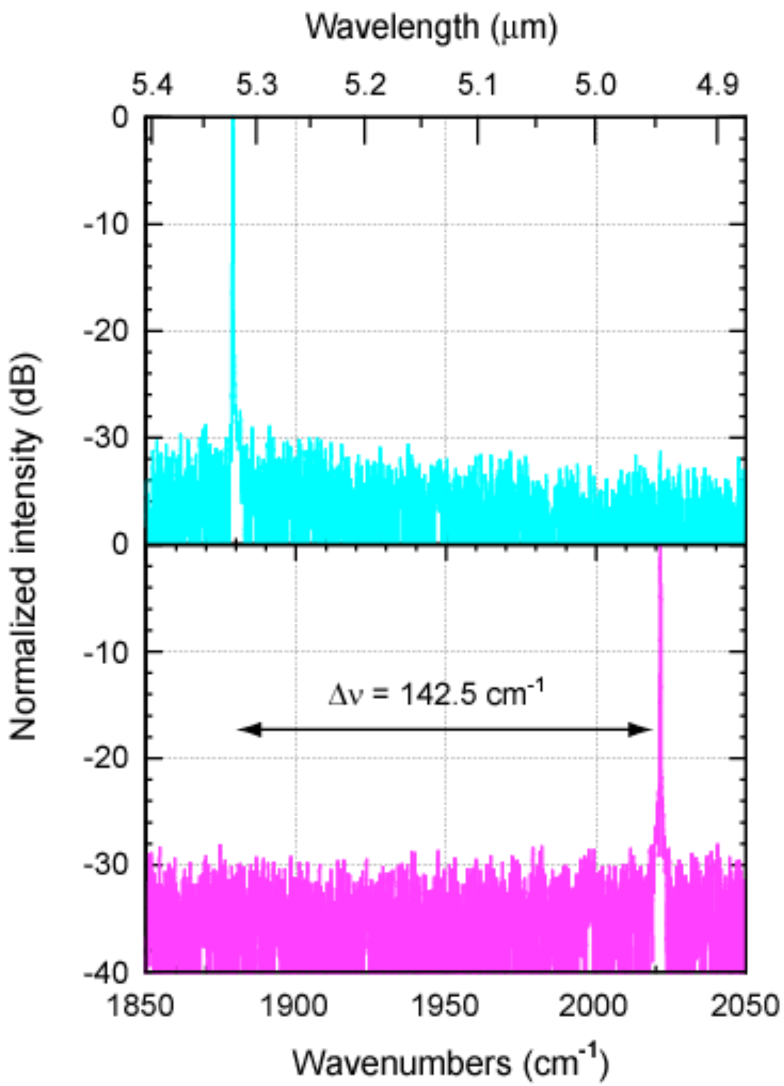
Coarse tuning by varying grating angle
Tuning range limited by gain bandwidth of the QC structure

Luo et al., APL **78**, 2834 (2001)

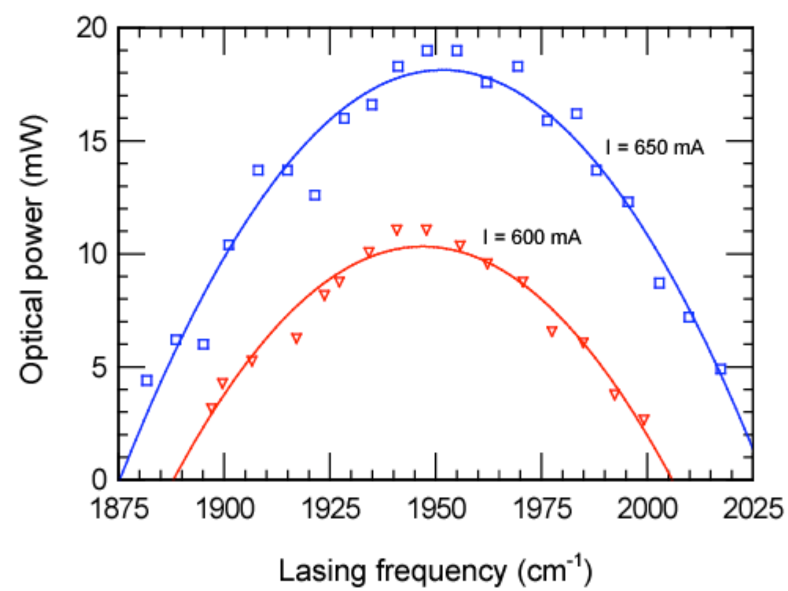
EC setup: Littrow configuration



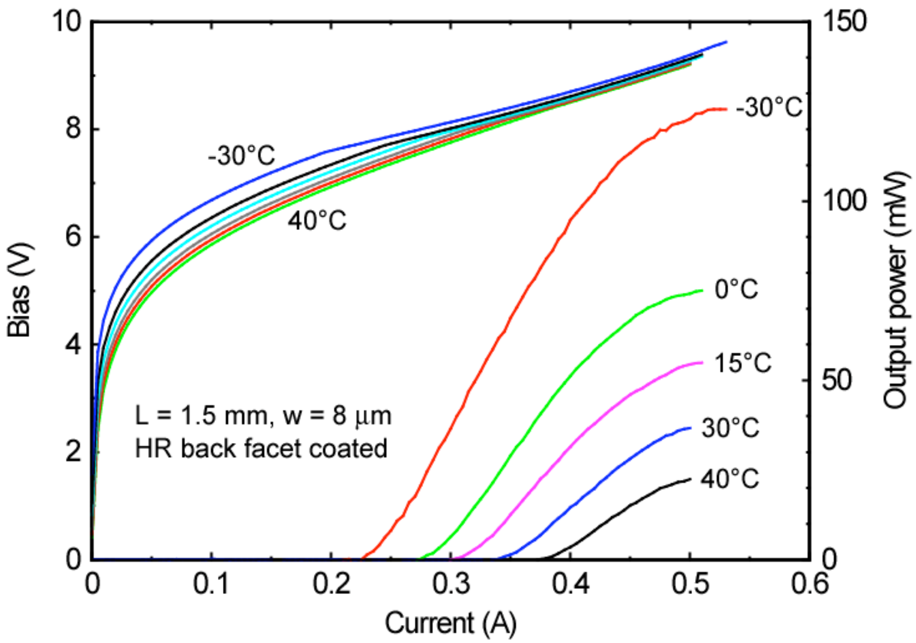
Continuous-wave EC-QCL at 5.2 μm



- Bound-to-continuum active region design
- CW operation on thermoelectric cooler
- Tuning over 174 cm^{-1} (9% of center frequency)
- Single-mode operation over more than 140 cm^{-1}
- Output power > 10 mW over 100 cm^{-1} (T = 243 K)
- Linewidth < 5 MHz

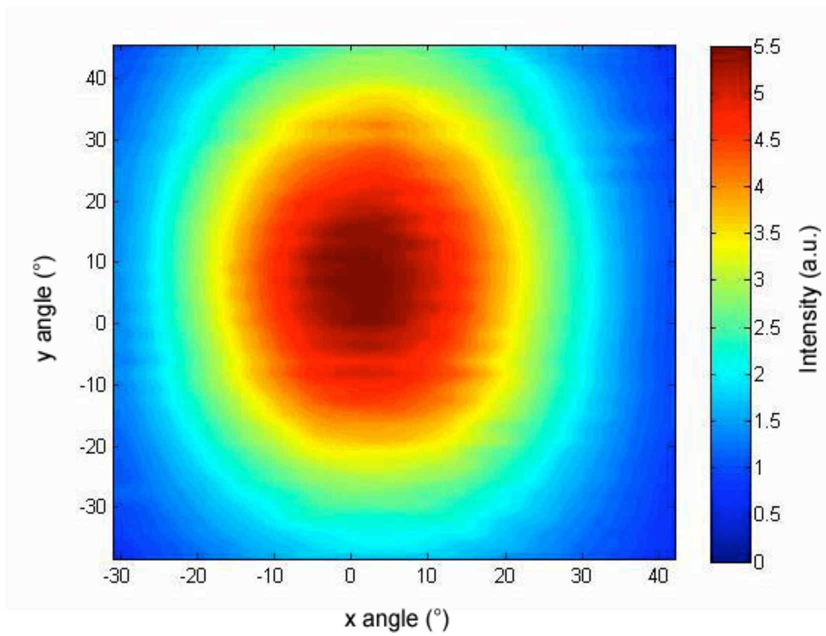


Buried heterostructure at 8.4 μm



Far field measurement:

- x axis: FWHM = 30°
- y axis: FWHM = 44°

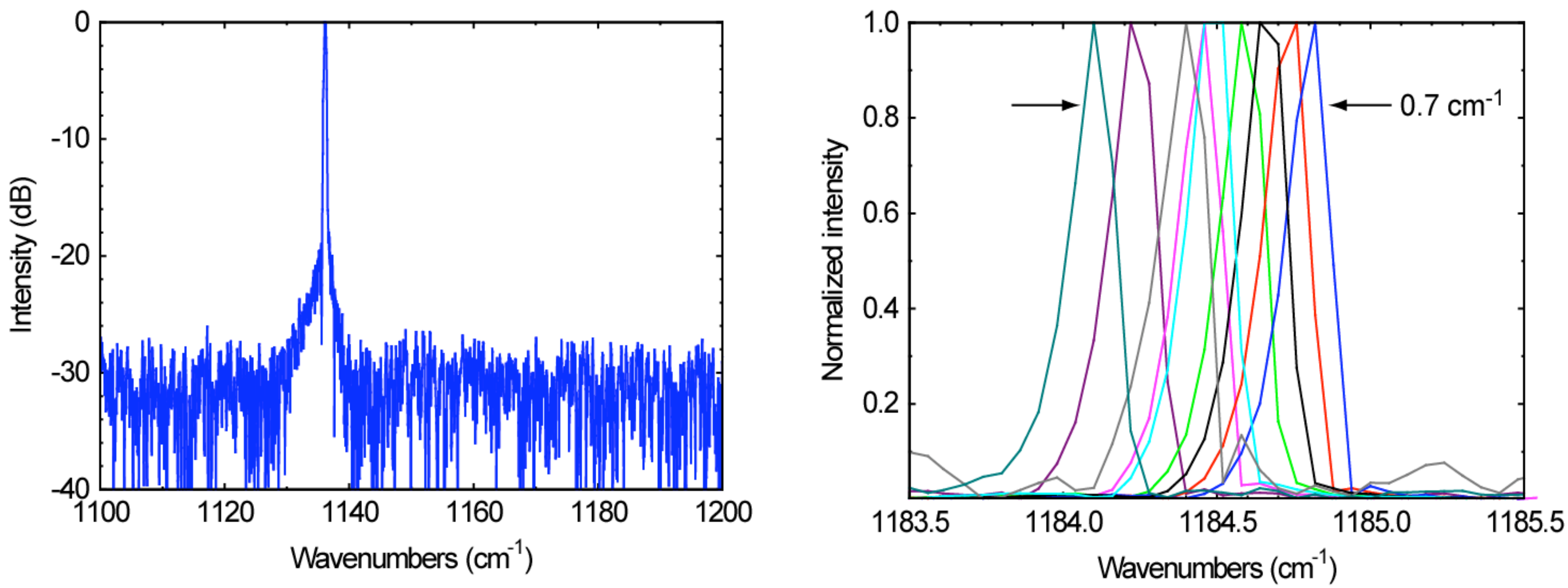


Advantage of BH for EC:

- higher CW operating temperature
- smaller beam divergence
- easier to make an AR coating (deposition on a larger surface)

Room temperature CW EC-QCL at 8.4 μm

Single-mode tuning over 130 cm^{-1} from 7.94 μm to 8.85 μm ($\Delta\lambda/\lambda$ = 11%)



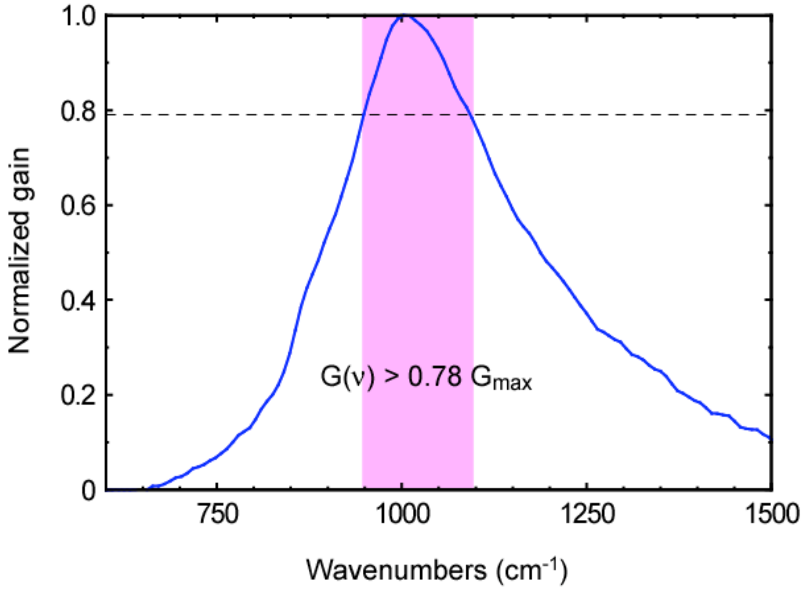
Tuning between the Fabry-Pérot modes of the chip (R < 0.2%)

-> continuous tuning possible at constant I and T by varying grating angle and cavity length

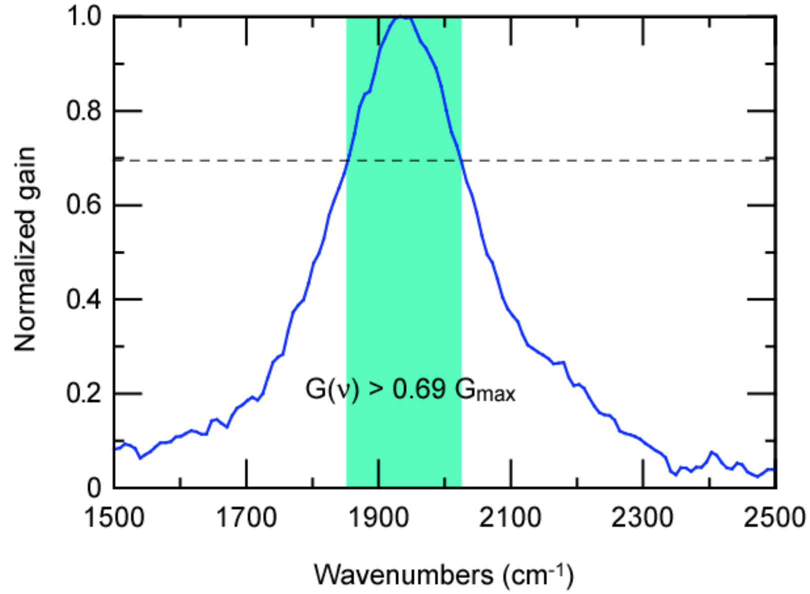
Tuning range limited by gain bandwidth

EC tuning range given by $G(\nu)/G_{max} > \dfrac{\alpha_W + \alpha_{M,b} + \alpha_{M,ext}}{\alpha_W + \alpha_{M,b} + \alpha_{M,AR}}$

10 µm laser



5.2 µm laser



Heterogeneous cascade: active region design

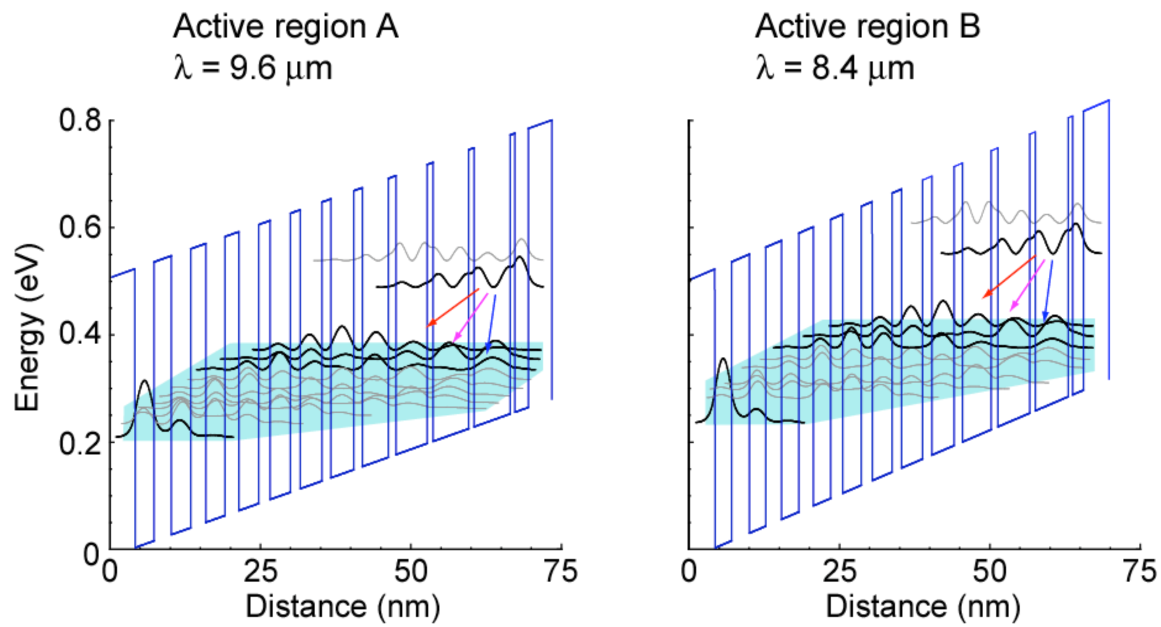
Bound-to-continuum designs:

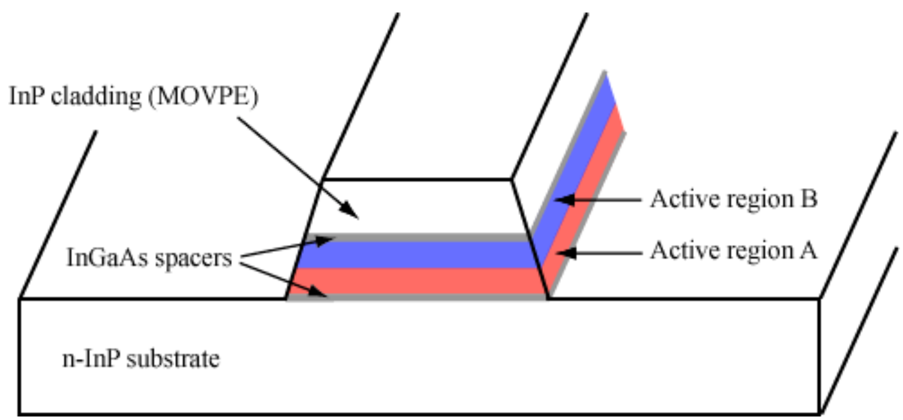
- Several lower states
- homogeneously broadened
- FWHM = 300 cm^{-1} at RT

$\Delta\nu$ = 150 cm^{-1} between the 2 peaks

-> strong spectral overlap

2 stacks of 20 periods

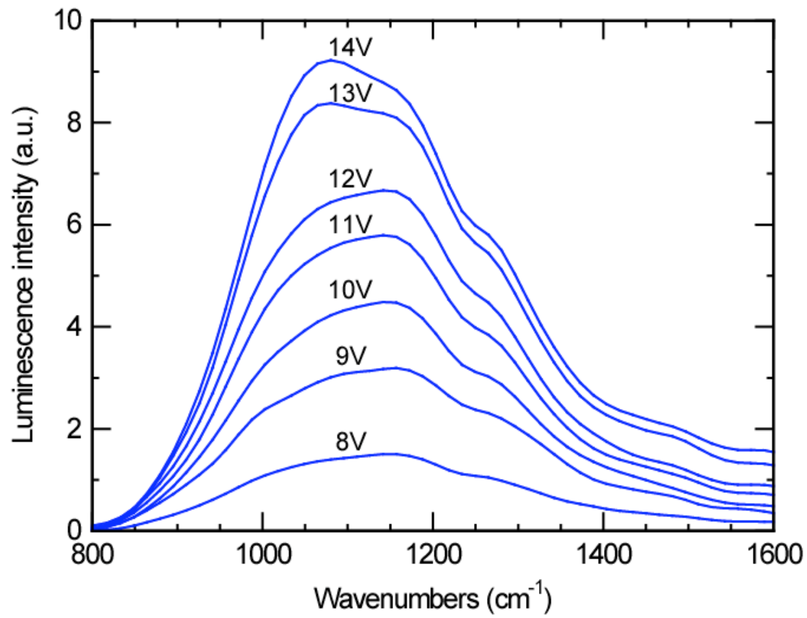


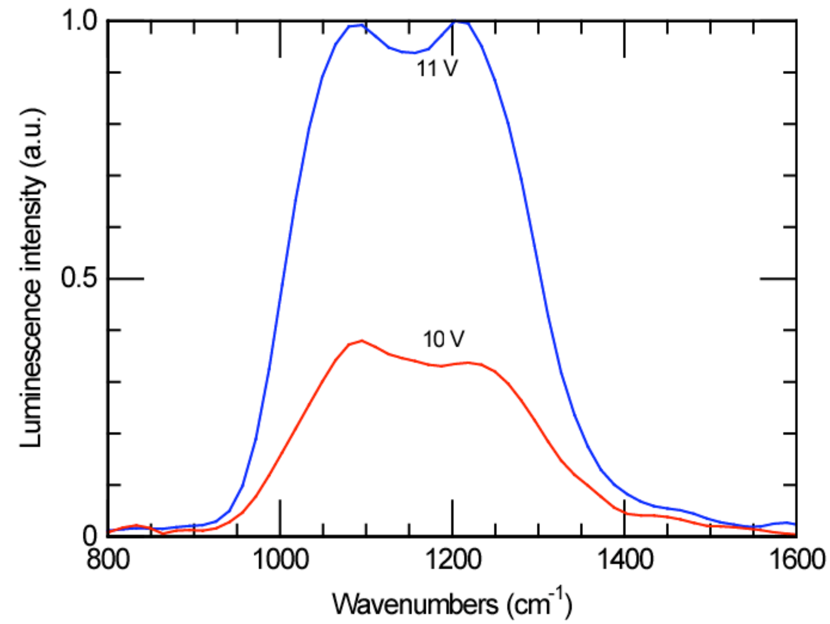


Spontaneous emission spectra

100 µm square mesa
Room temperature (300 K)

Cryogenic temperature (80 K)





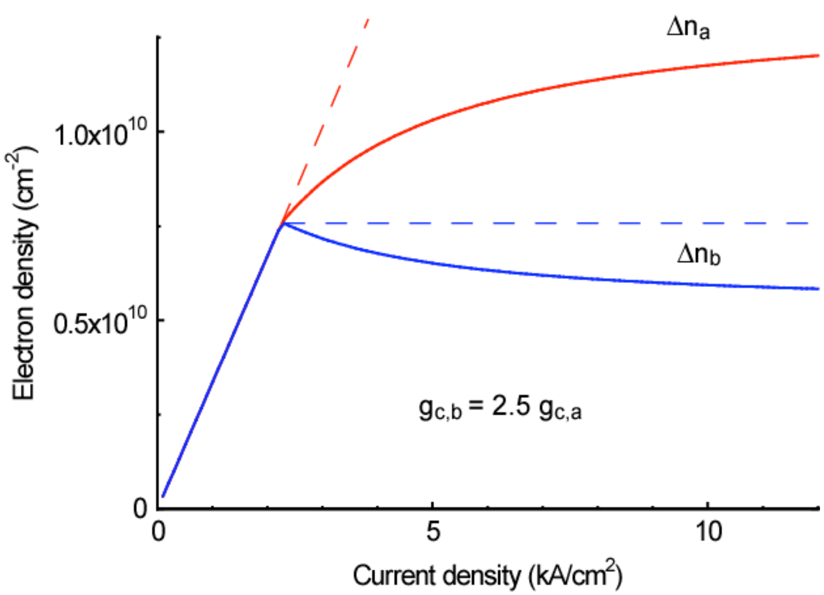
FWHM = 350 cm^{-1}
$I(\nu)/I_{max} > 0.8$ over 205 cm^{-1}

Rate equation model

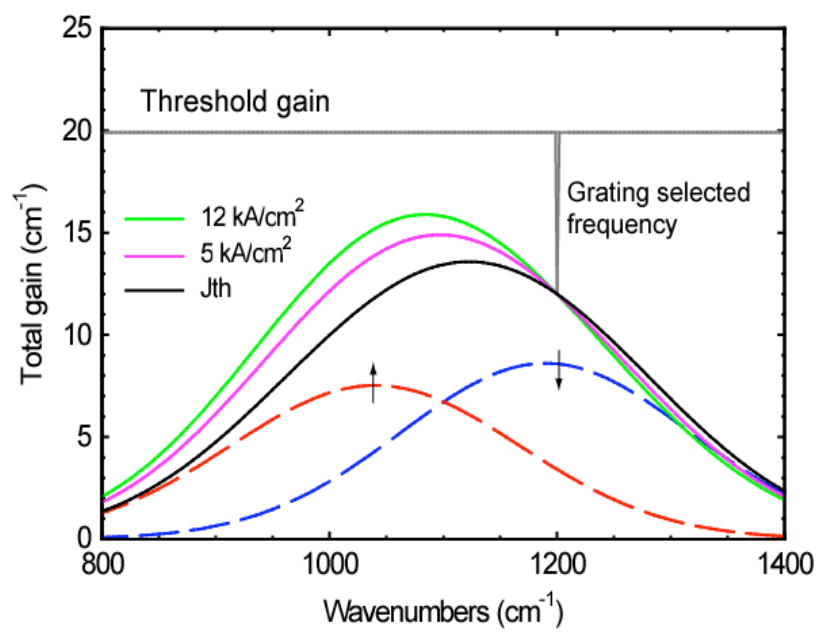
$$\frac{dn_{3,i}}{dt} = \frac{J}{q} - \frac{n_{3,i}}{\tau_{3,i}} - Sg_{c,i}(n_{3,i} - n_{2,i}) = 0$$

$$\frac{dn_{2,i}}{dt} = \frac{n_{3,i}}{\tau_{32,i}} - \frac{n_{2,i}}{\tau_{2,i}} - Sg_{c,i}(n_{3,i} - n_{2,i}) = 0, \qquad i = a, b$$

$$\frac{dS}{dt} = \frac{c}{n} S\Big[g_{c,a}(n_{3,a} - n_{2,a}) + g_{c,b}(n_{3,b} - n_{2,b}) - \alpha\Big] = 0$$



The maximum gain is not clamped at threshold value



Single-mode operation up to roll-over expected over 225 cm^{-1}

Heterogeneous external cavity QCL

Tuning range: 265 cm^{-1} (2.25 μm)

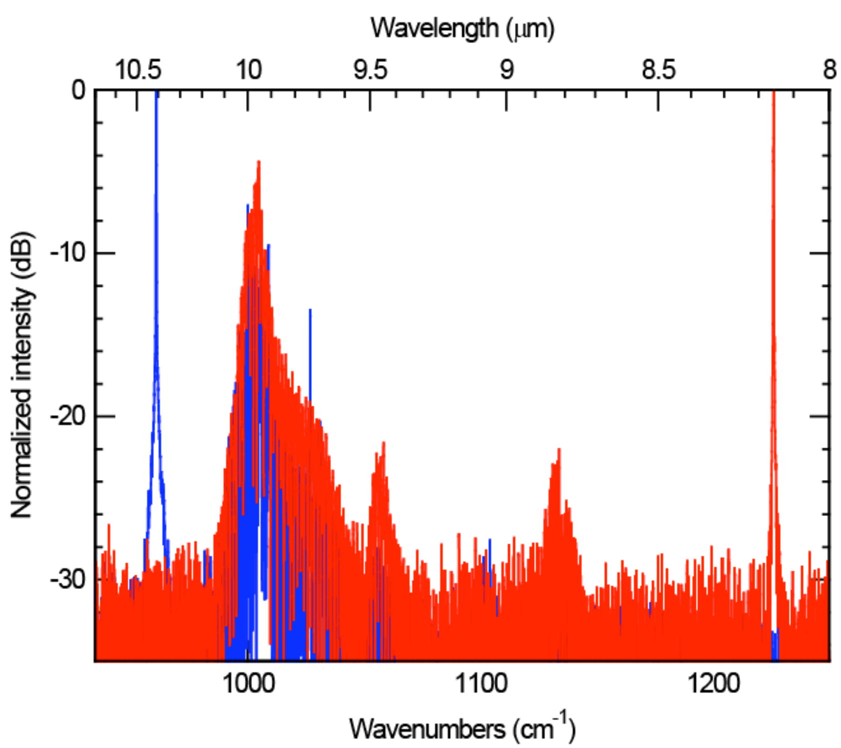
Without AR coating: 212 cm^{-1}

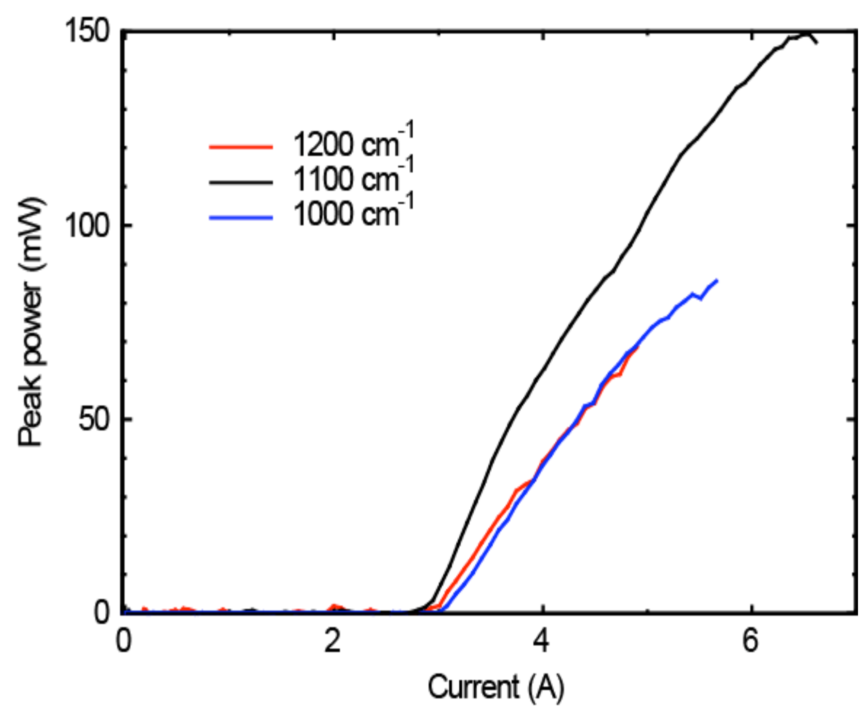
$\Delta\lambda/\lambda = 24\%$

Duty cycle = 2%, T = 293K

Peak power > 65 mW

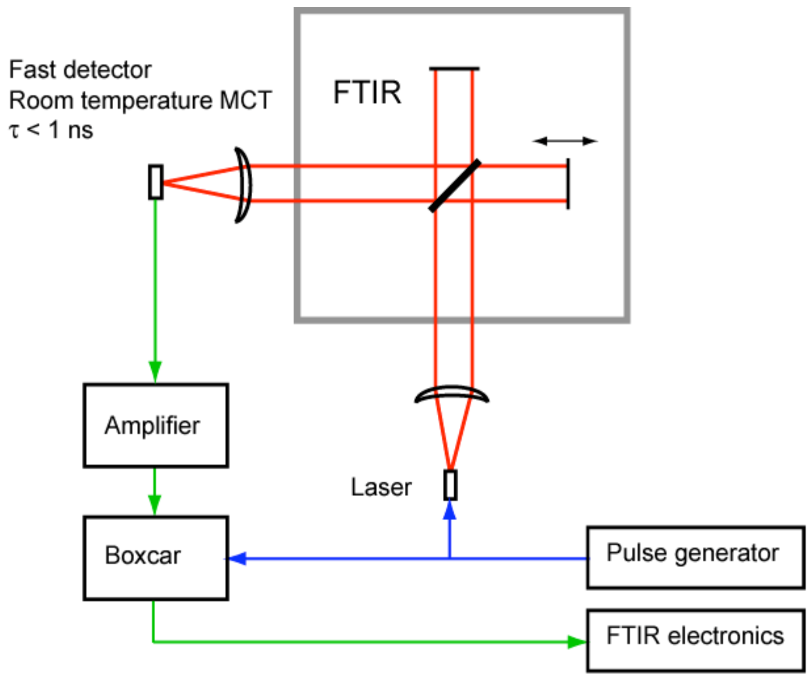
Maximum peak power: 150 mW

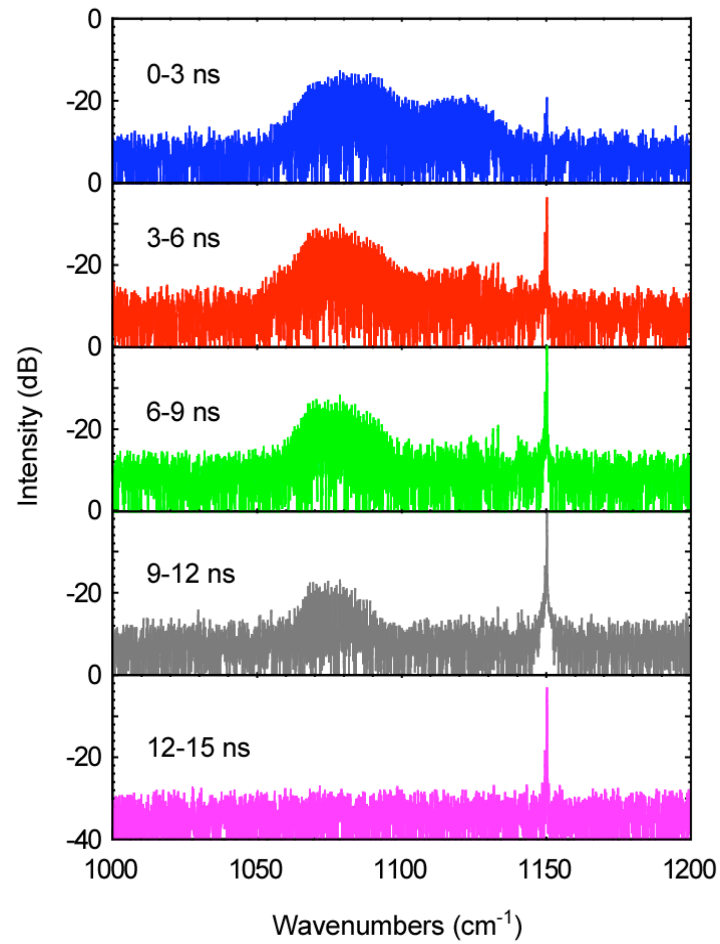




EC-QCL: time-resolved spectra

SMSR = 30 dB after 12 ns
-> single-mode behavior expected in CW

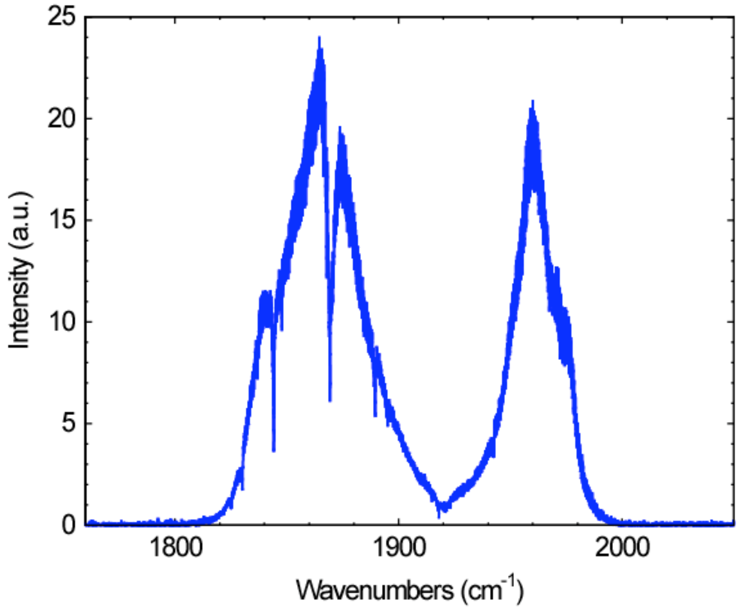


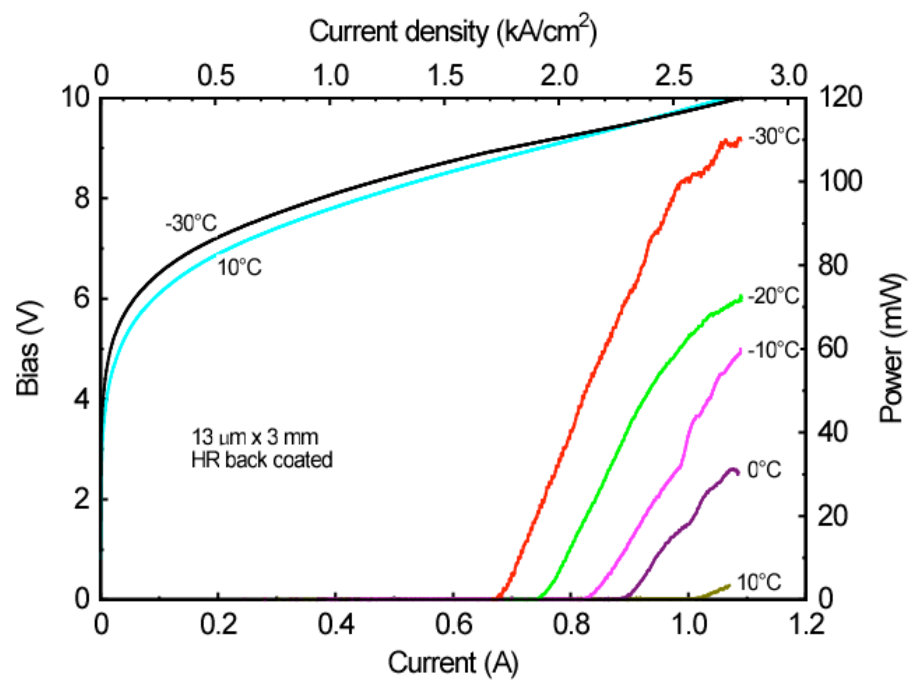


CW heterogeneous QCL near 5 μm

2 strained bound-to-continuum designs
- 15 periods centered at 5.2 μm
- 15 periods centered at 5.5 μm
- $\Delta\nu = 100\ cm^{-1}$

CW operation up to 283 K
- 110 mW CW at 243 K
- Jth = 1.75 kA/cm^2 CW at 243 K





Conclusions

Broadly- (> 250 cm^{-1}), continuously-tunable room temperature CW sources are feasible in the 4-10 μm range with heterogeneous cascade active regions and buried het processing

Powerful tool for

High resolution MIR spectroscopy

- enables the spectroscopy of entire absorption bands

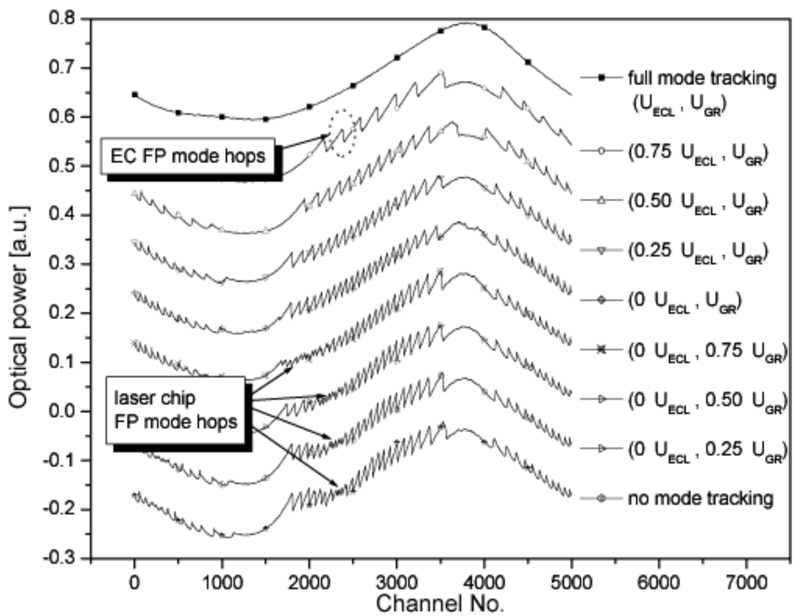
Trace gas analysis

- detection of several trace gases with one source
- analysis of complicated gas mixtures

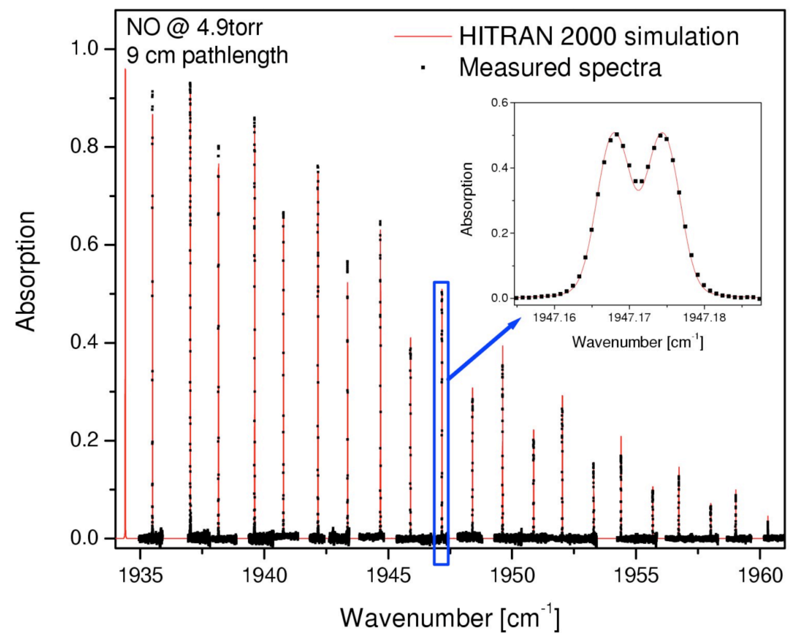
Combines the advantages of laser spectroscopy, i.e. high resolution and high sensitivity, with a broad wavelength range

Spectroscopy of NO at Rice University

Mode hop free tuning

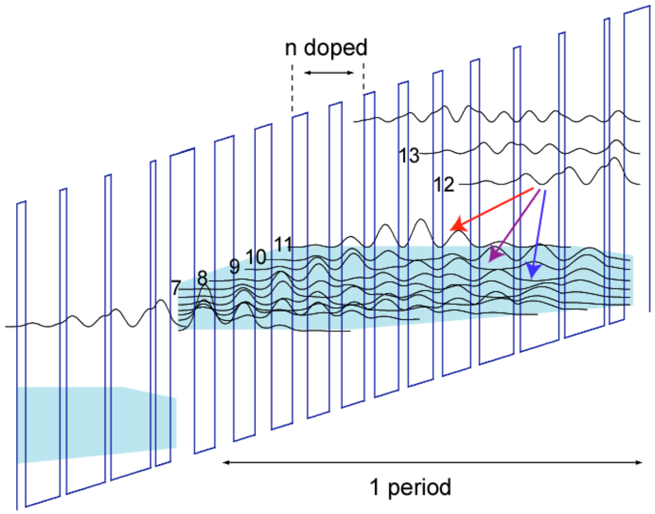


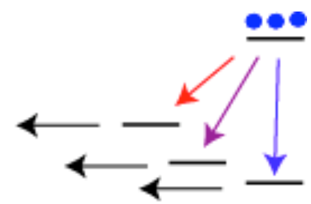
Two lines separated by 0.006 cm^{-1} (180 MHz) are resolved



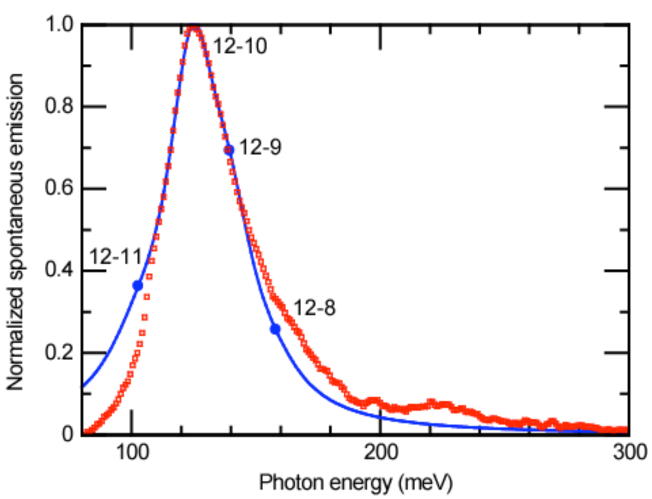
Wysocki et al., Appl. Phys. B **81**, 769 (2005)

Bound-to-continuum design (λ = 10 μm)





Transition from a bound state to a miniband
- several lower states
- spread oscillator strength
- homogeneous broadening of the gain



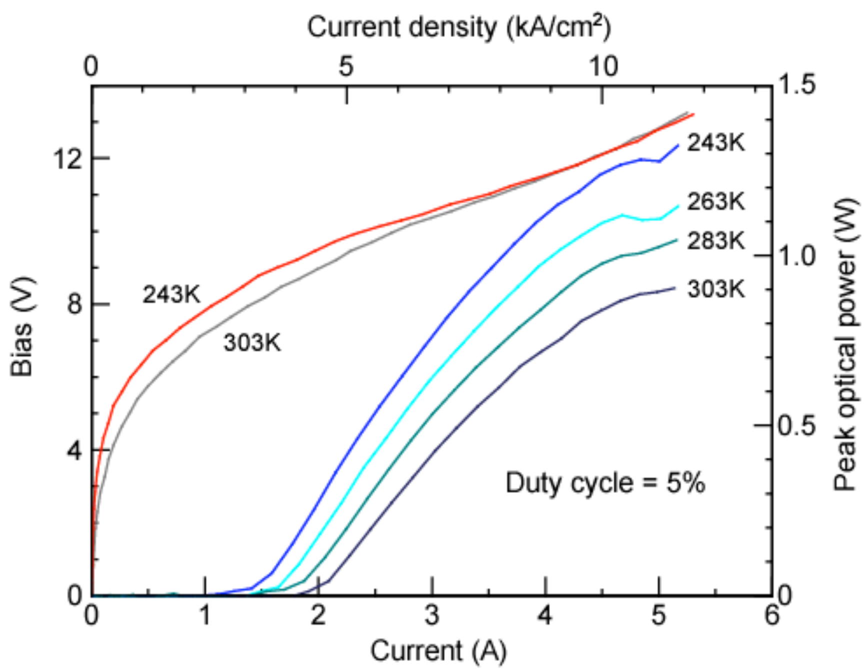
FWHM of spontaneous emission
@ 300K = 297 cm^{-1}

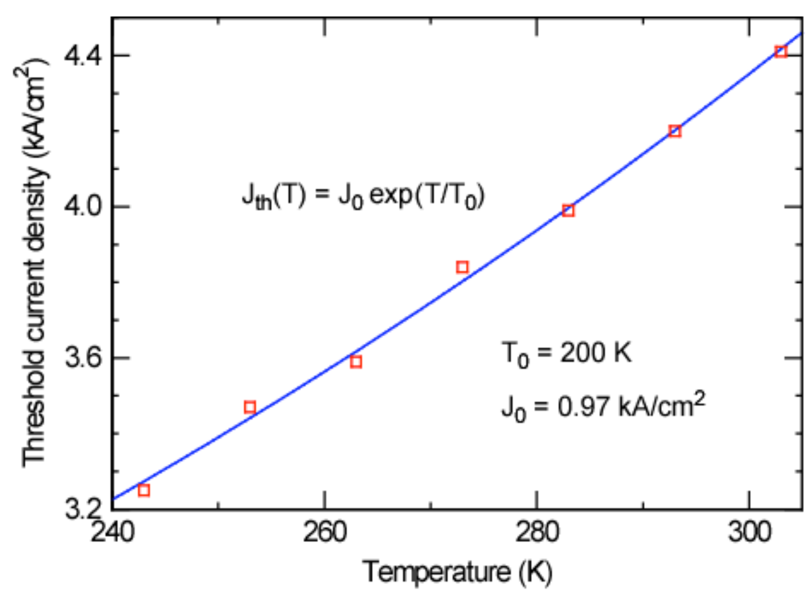
Maulini et al., APL **84**, 1659 (2004)

Heterogeneous QCL: FP device performances

18 µm wide, 2.5 mm long chip

High reflection back coated





Performances on TEC:

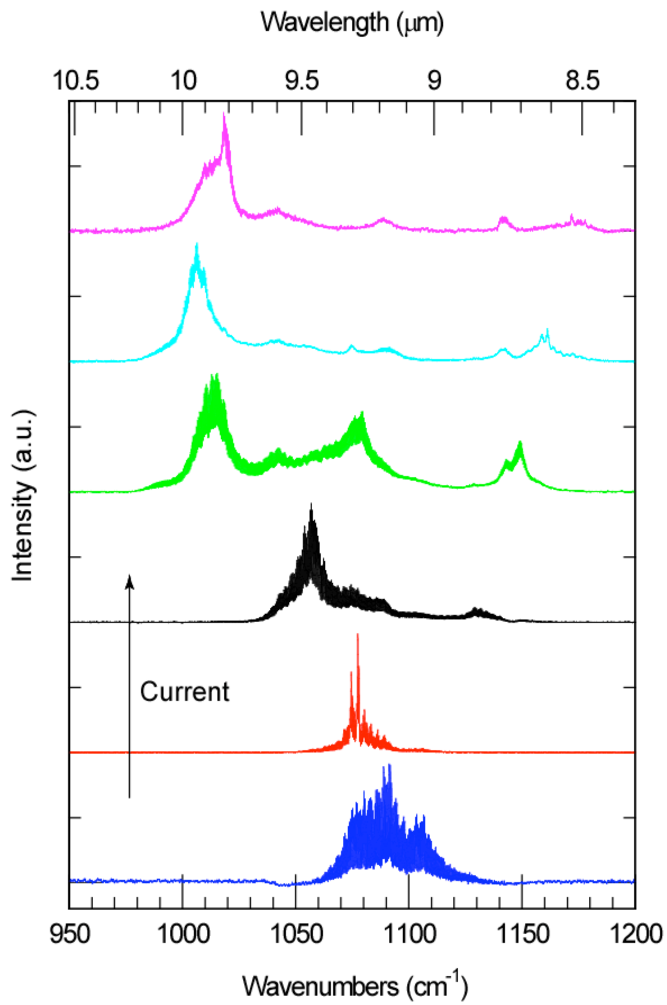
High peak power: > 1 W

Lasing for duty cycles up to 50%

Threshold current density:

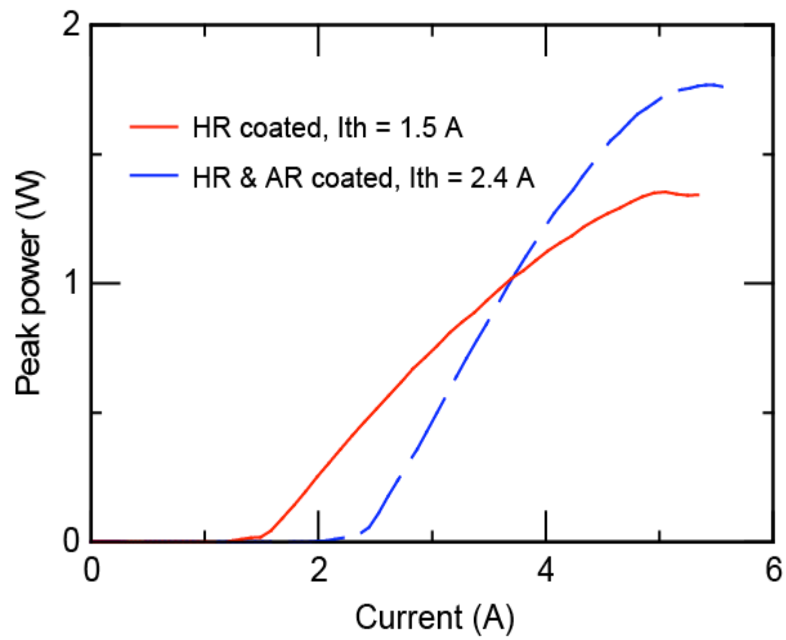
- 3.25 kA/cm² @ 243 K
- 4.4 kA/cm² @ 303 K

Heterogeneous QCL: device performances II



Broadband emission: > 200 cm^{-1}

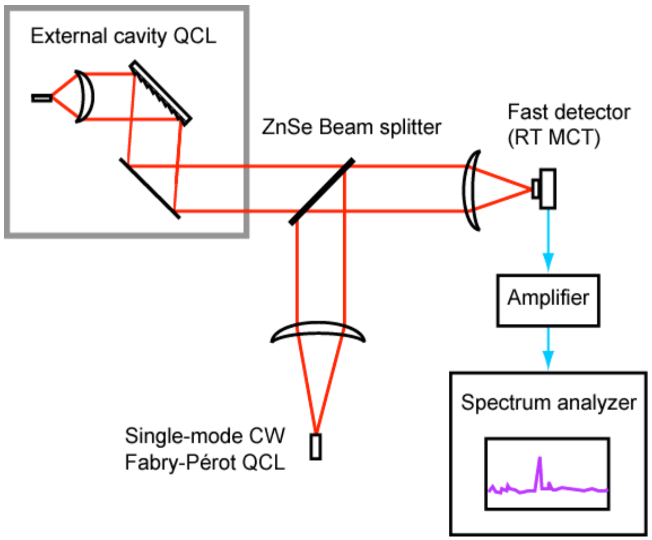
8.4 to 10.2 μm ($\Delta\lambda/\lambda$ = 20%)

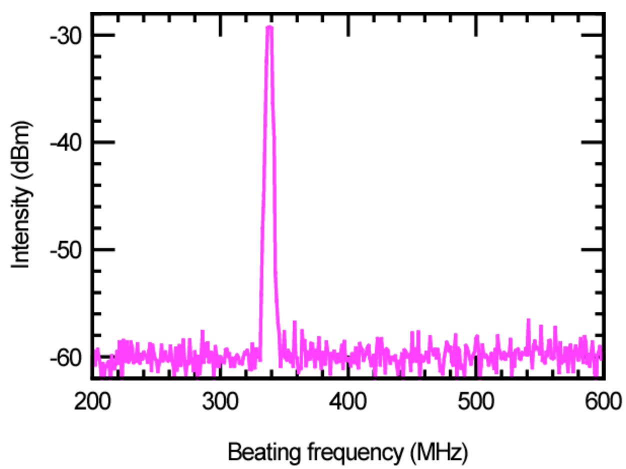


Anti-reflection coating:

R_{AR} = 0.7%

EC Laser linewidth





Heterodyne measurement:

- convolution of the lineshapes of the 2 lasers
- gives an upper limit to linewidth
- FWHM of beat note = 5 MHz

Theory:

- Fabry-Pérot device: $\Delta\nu$ = 88 Hz (P = 50 mW)
  Henry, JQE **18**, 259 (1982)
- External cavity:
  reduction by a factor F^2 with $F = 1 + l/nL = 10$
  Kazarinov and Henry, JQE **23**, 1401 (1987)
  linewidth enhancement factor dependent
  on detuning $\alpha < 0.7$
  -> $\Delta\nu < 2$ Hz