Recent progress on single-mode quantum cascade lasers

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ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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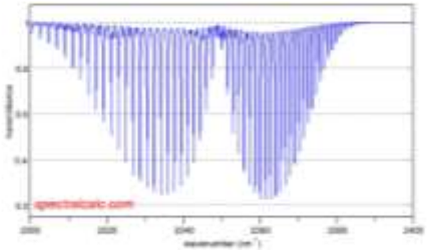
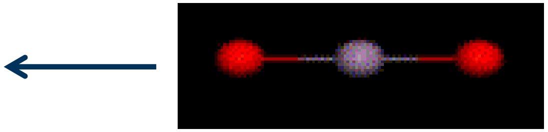
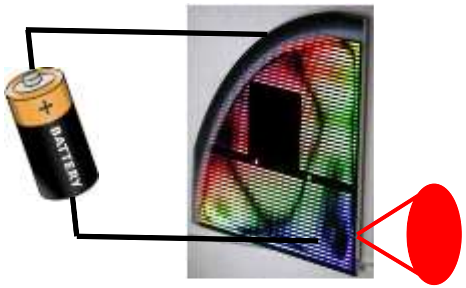
1. Introduction





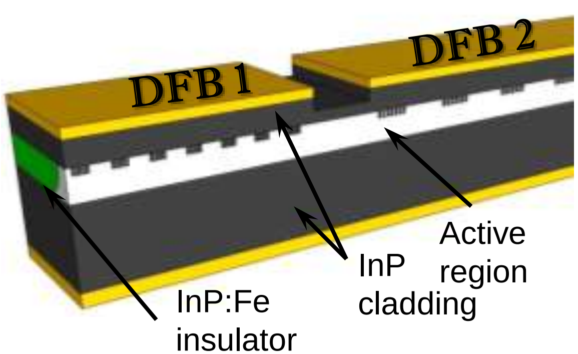
2. Recent developments

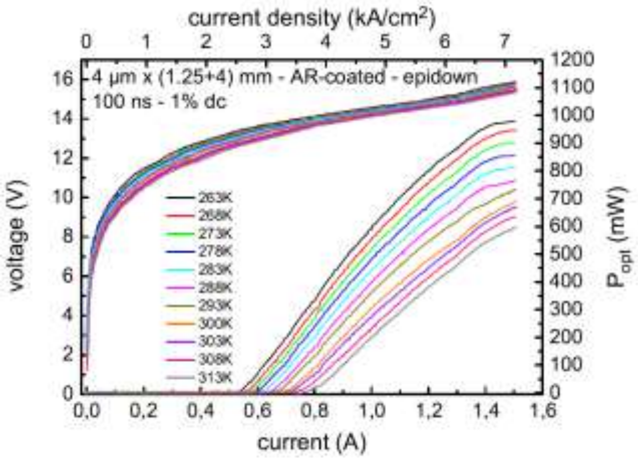


   a. Low electrical dissipation

   b. Master-oscillator power-amplifier (MOPA)

   c. Dual color DFB





3. Conclusion

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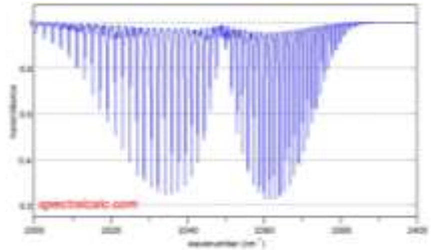

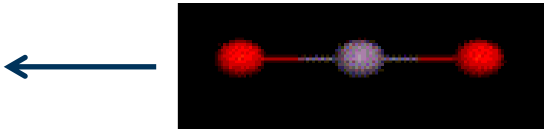

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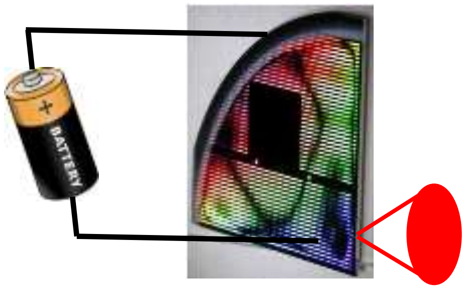

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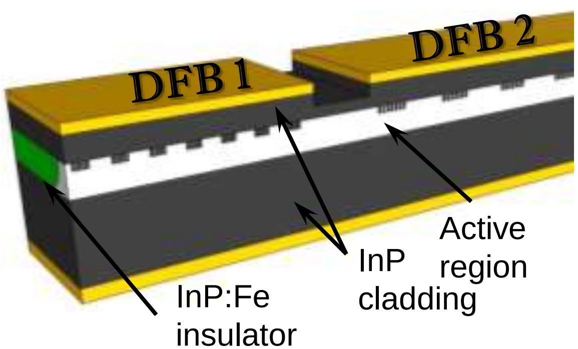
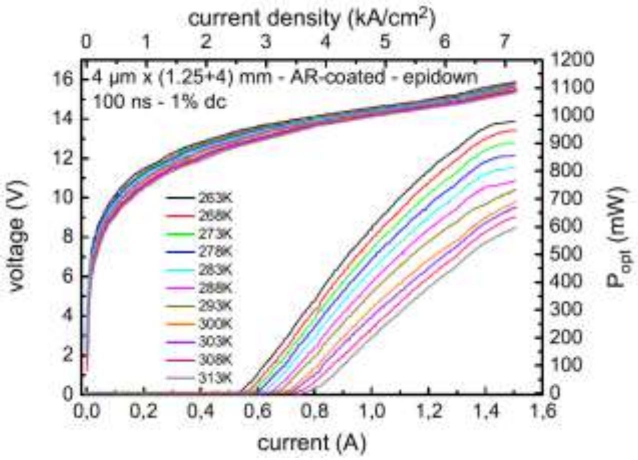
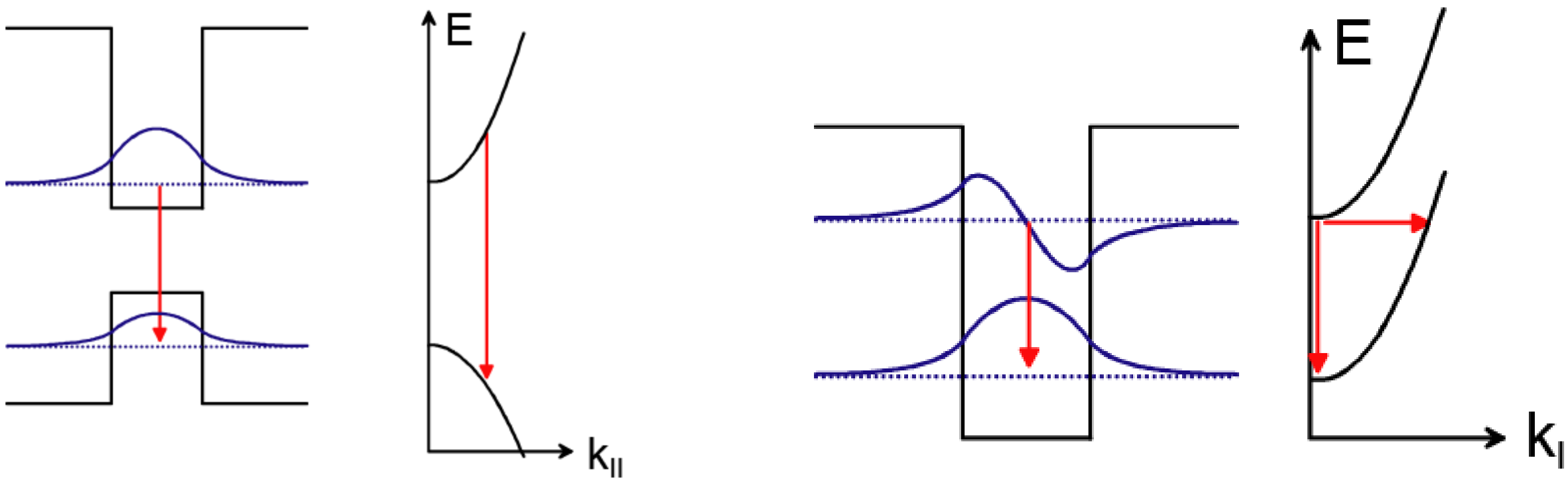




3. Conclusion

1.1 Interband vs. intersubband



- **Interband (IB)**
  - Absorption above E = hν
  - Broad absorption features
  - Long lifetime (>1 ns)
  - Very high radiative efficency
  - Transition energy <->gap
- **Intersubband (ISB)**
  - Absorption at E = hν
  - Narrow absorption features
  - Short lifetime (<1 ps)
  - Very low radiative efficiency
  - Transition energy <->QW thickness

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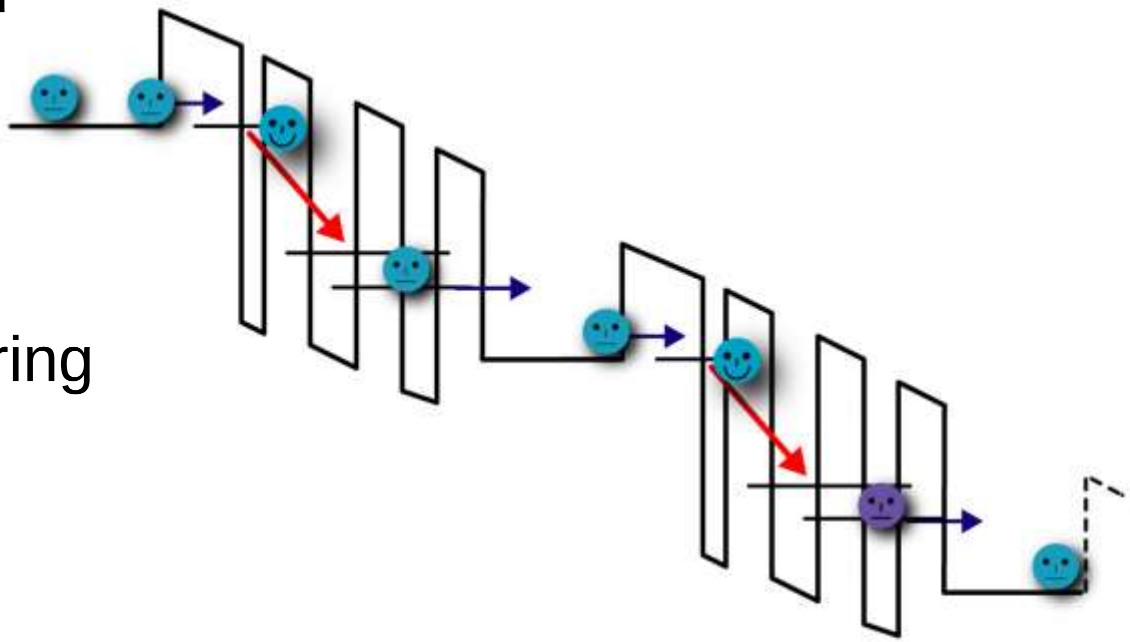
1.1 What is a Quantum Cascade Laser*

- Mid-IR/THz emitting semiconductor laser (3 – 300 µm)
- Based on intersubband transitions
- λ: tailorable by bandstructure engineering
- Cascade of optical transition regions



Faist et al., Science 264, 553 (1994)

1.2 Motivation

- **Spectroscopy of different molecules:**

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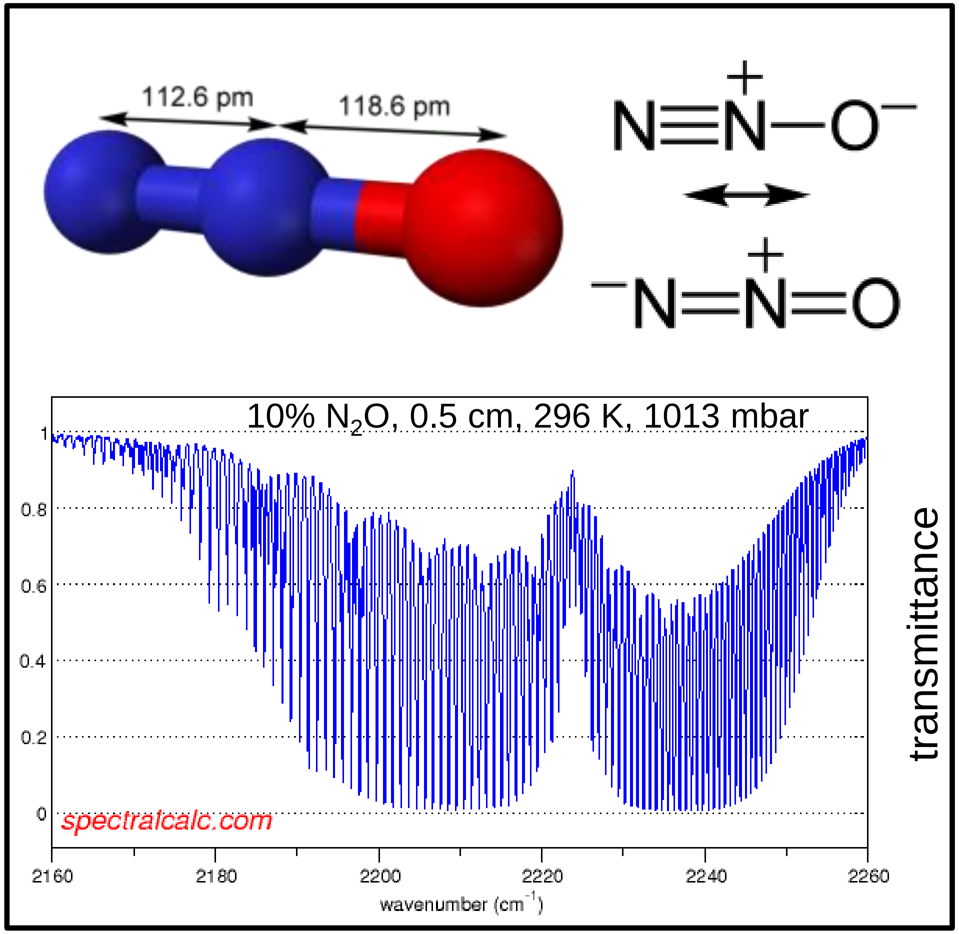

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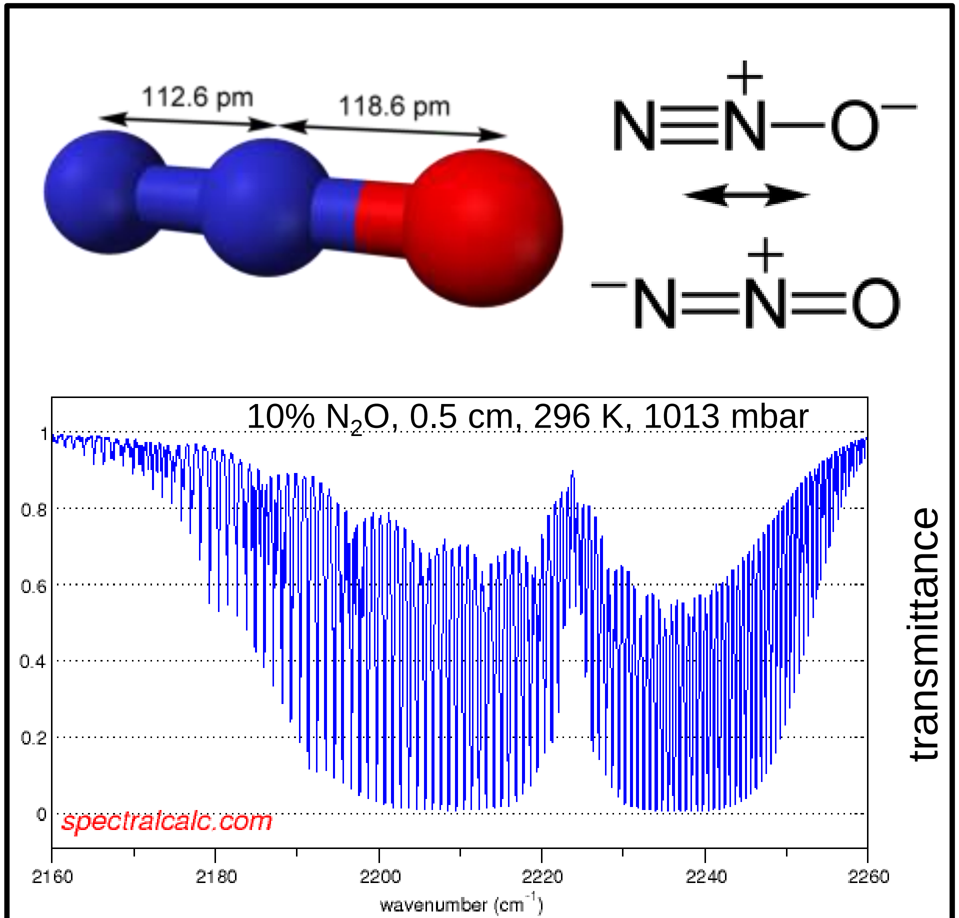
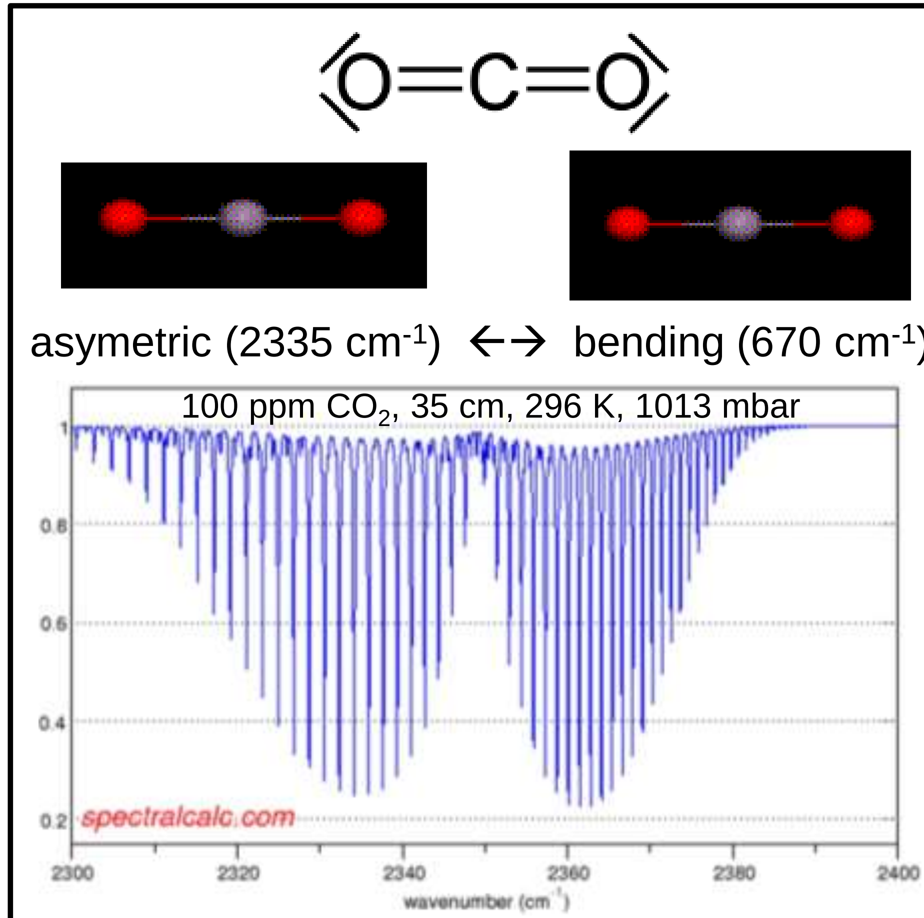
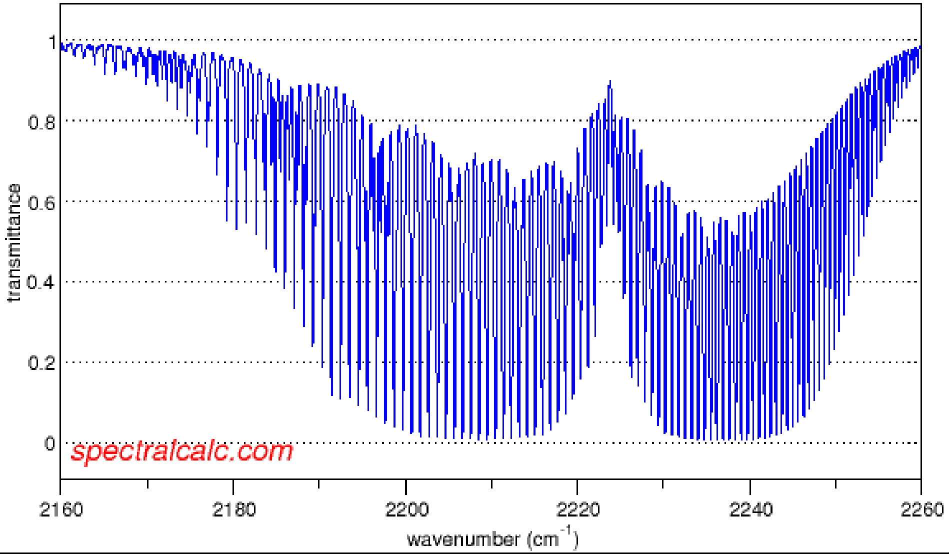




1.3 Properties

- Key properties for detection systems:

i.



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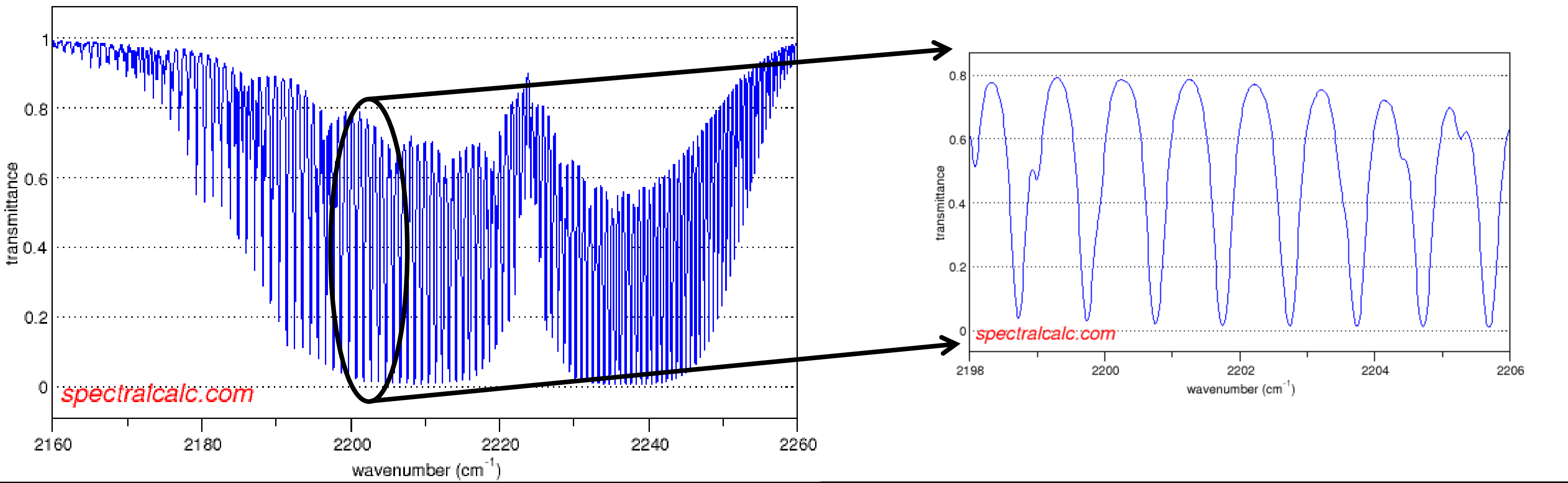

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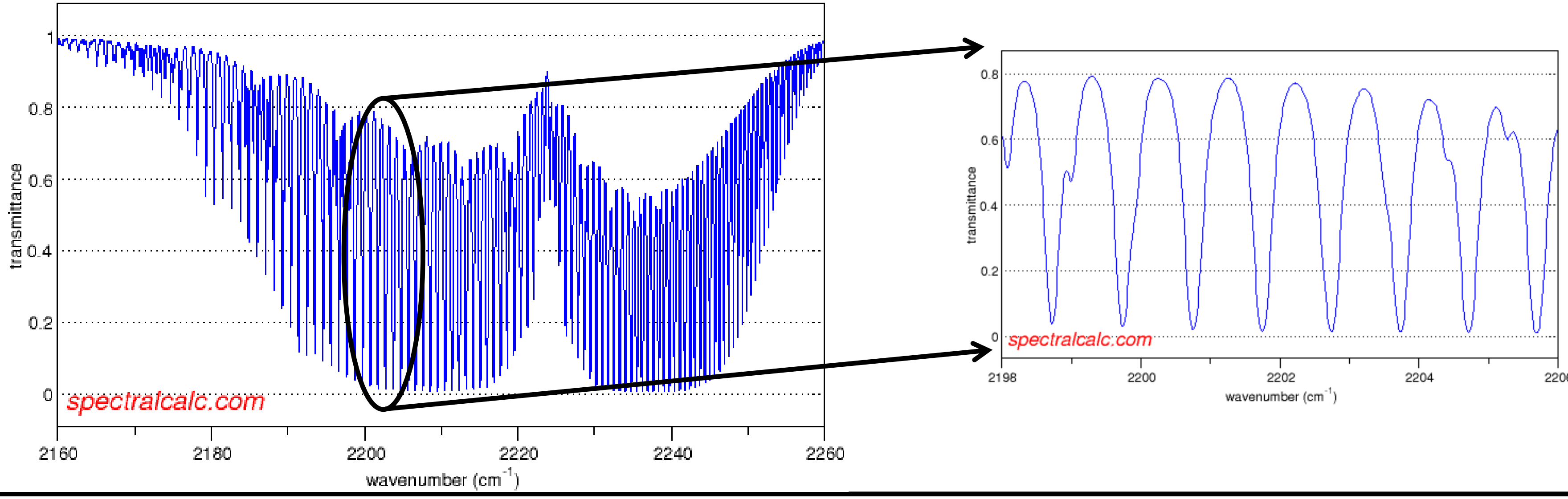
  i. single-mode device ➔ mode-selection



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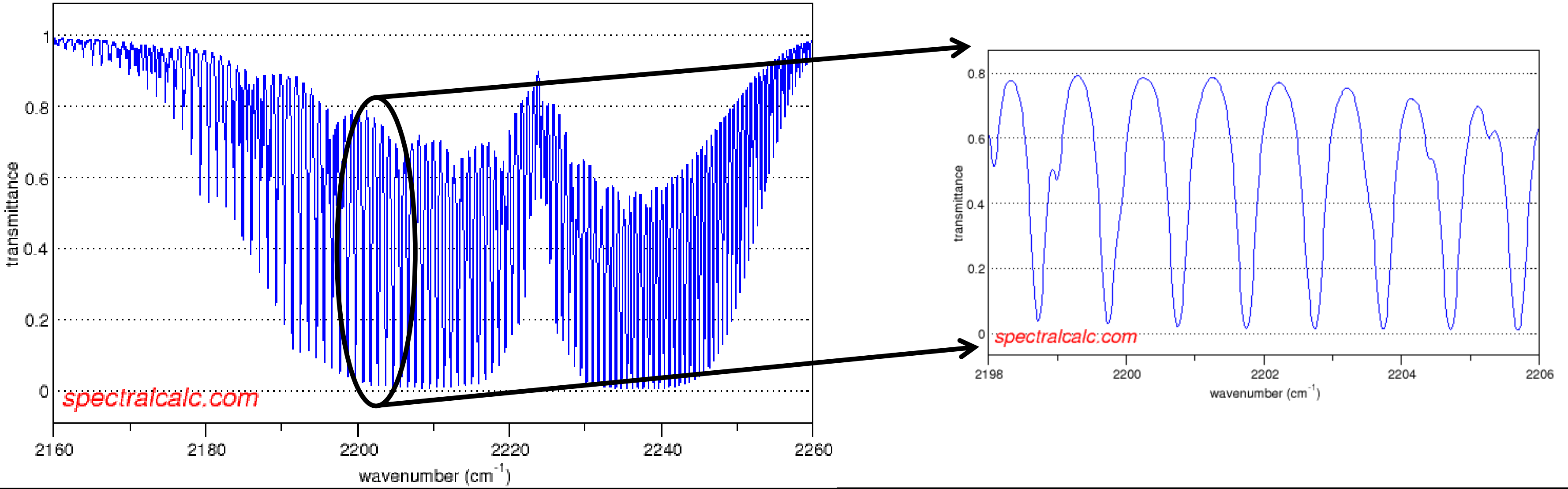

ii.a tunability

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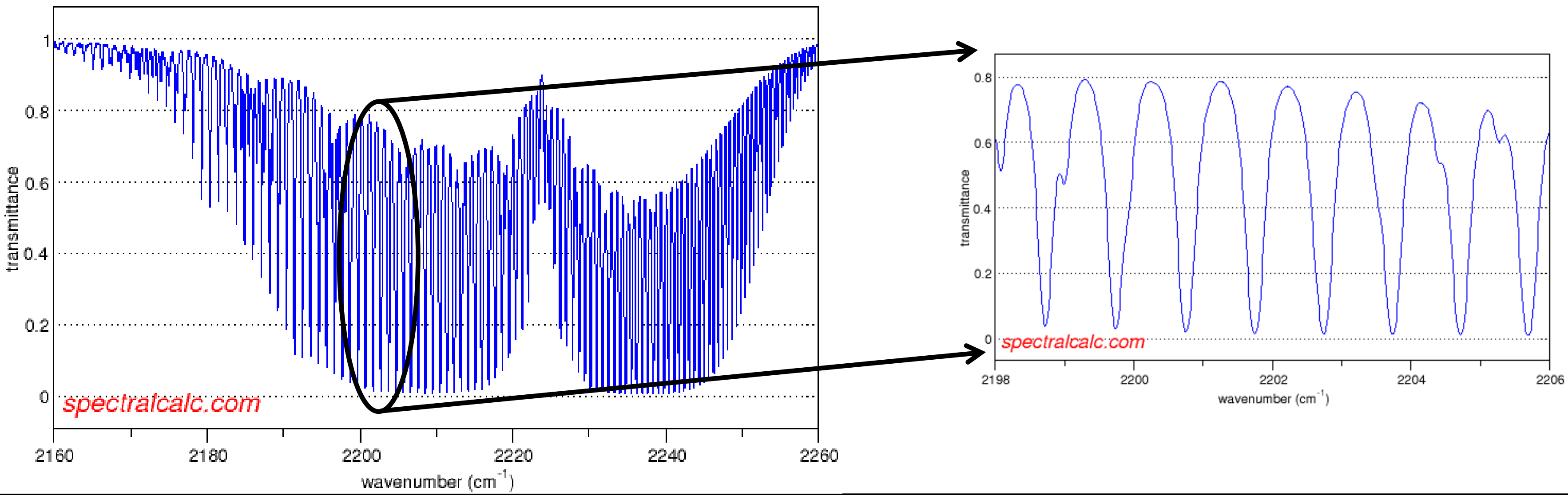

ii.a tunability	ii.b low el. dissipation

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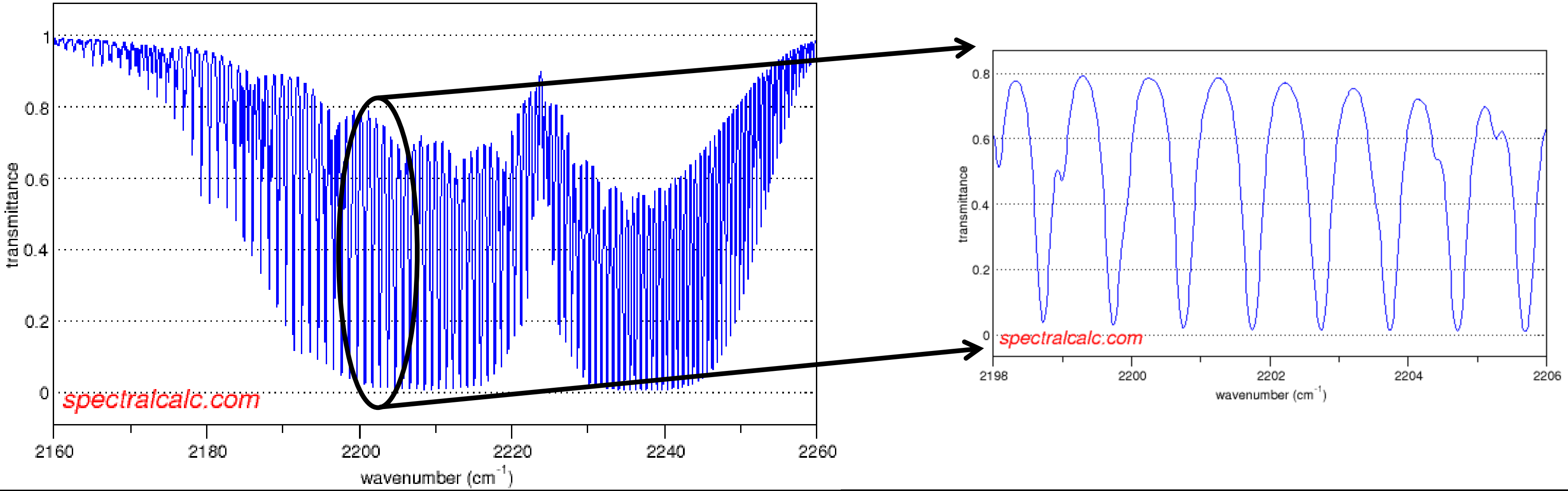

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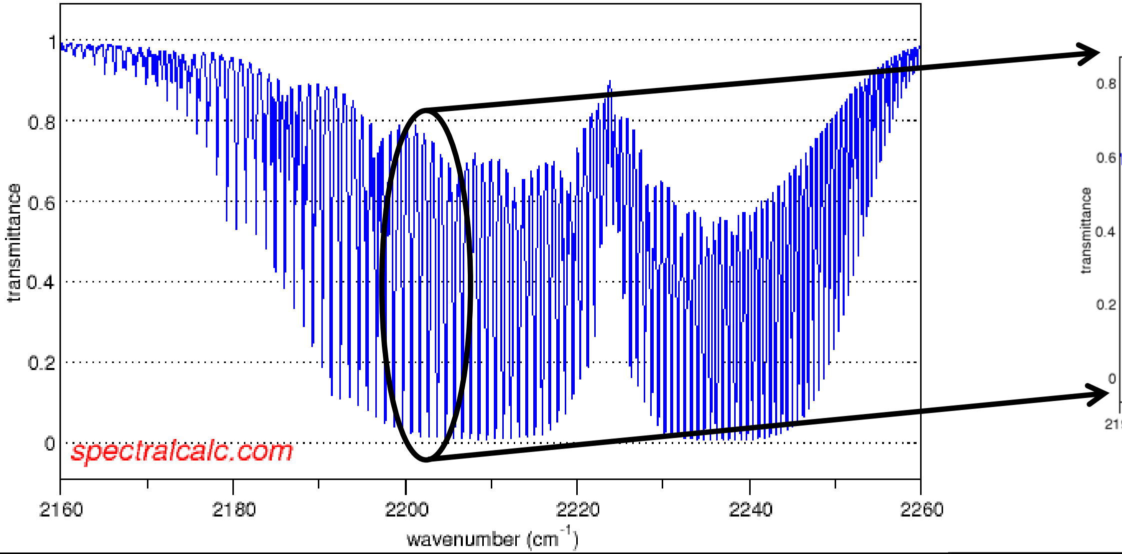

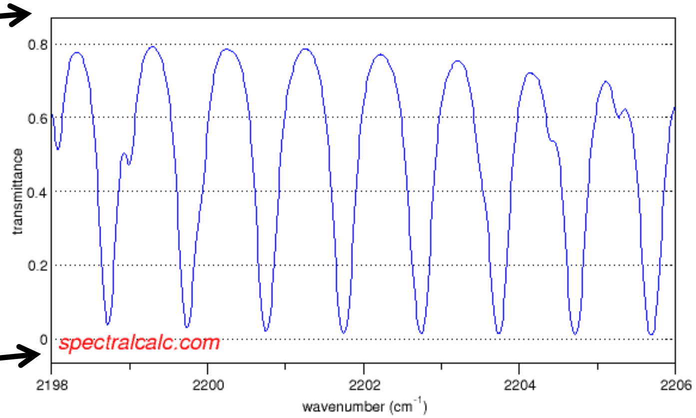

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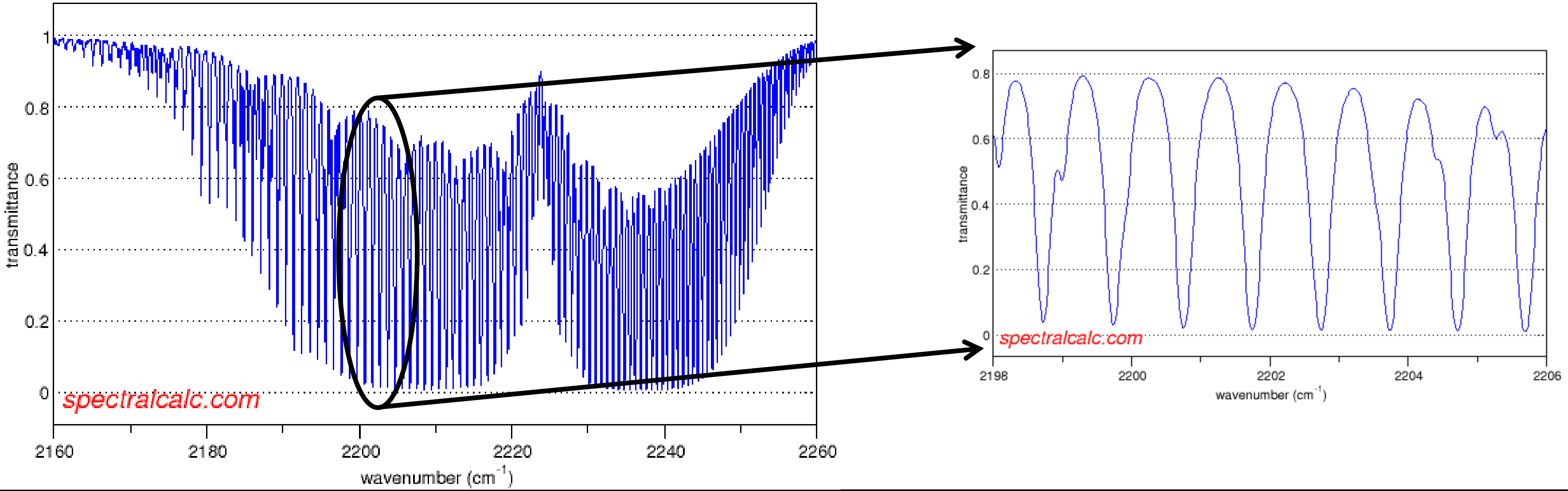
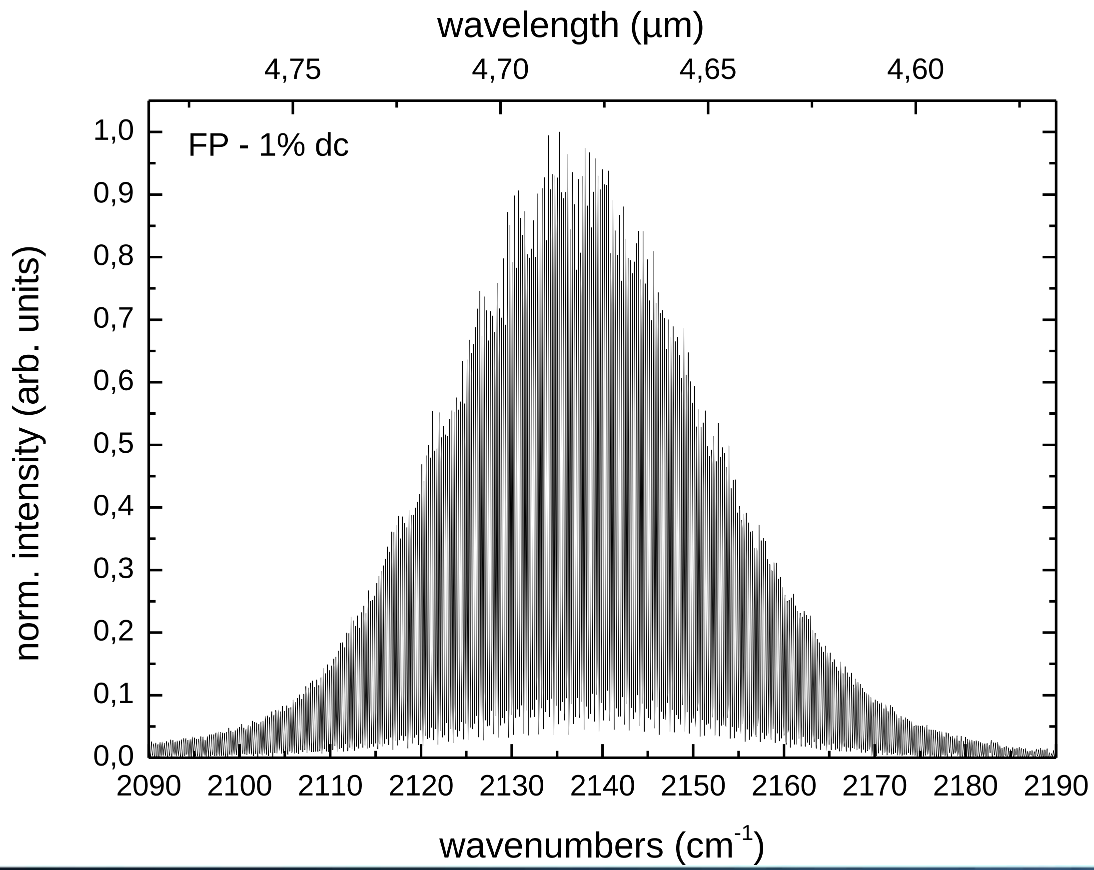


1.4 Mode control in semiconductor-based lasers

Fabry-Pérot devices

→ **broad spectral emission**



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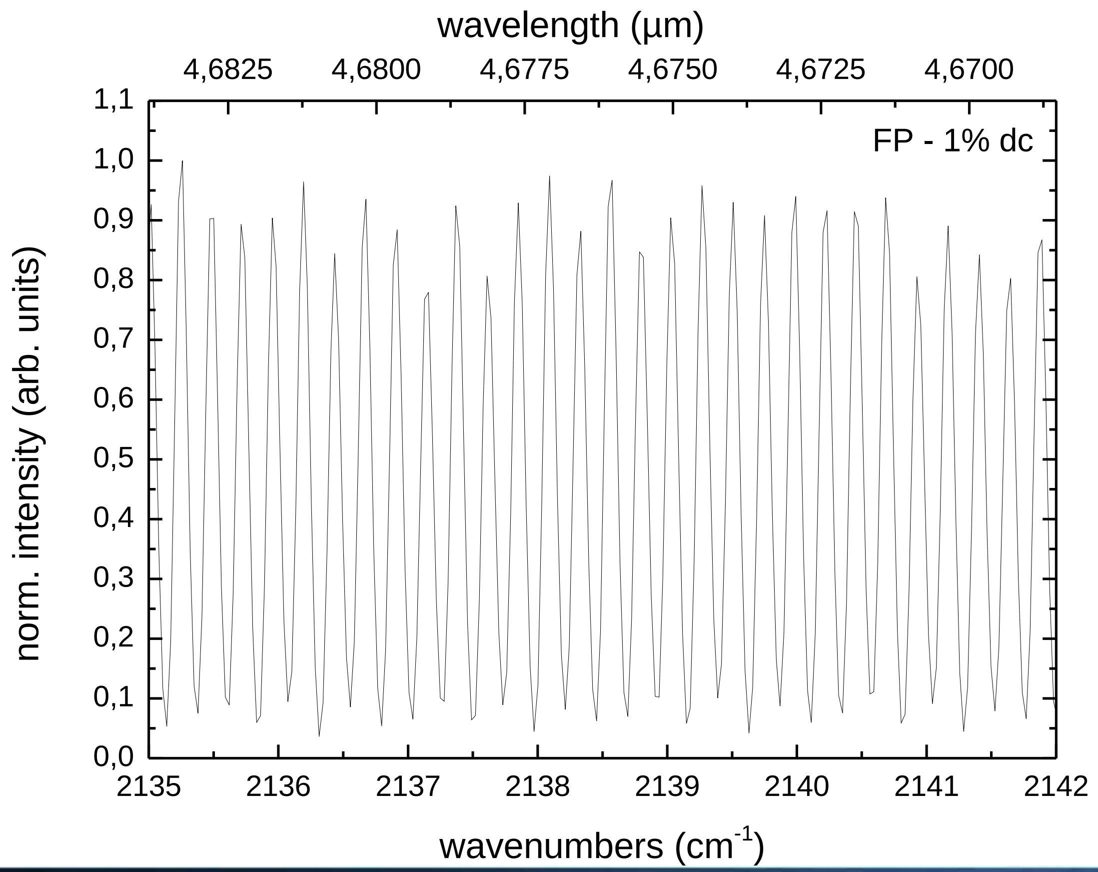

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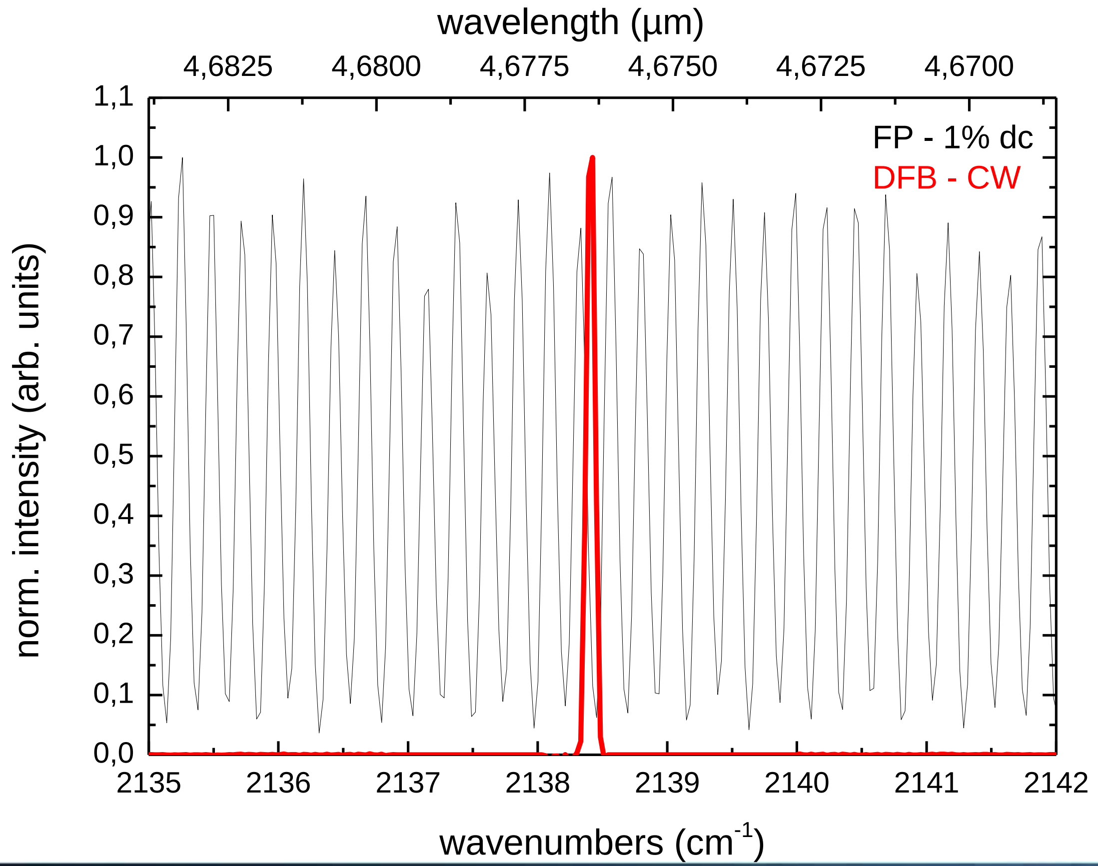

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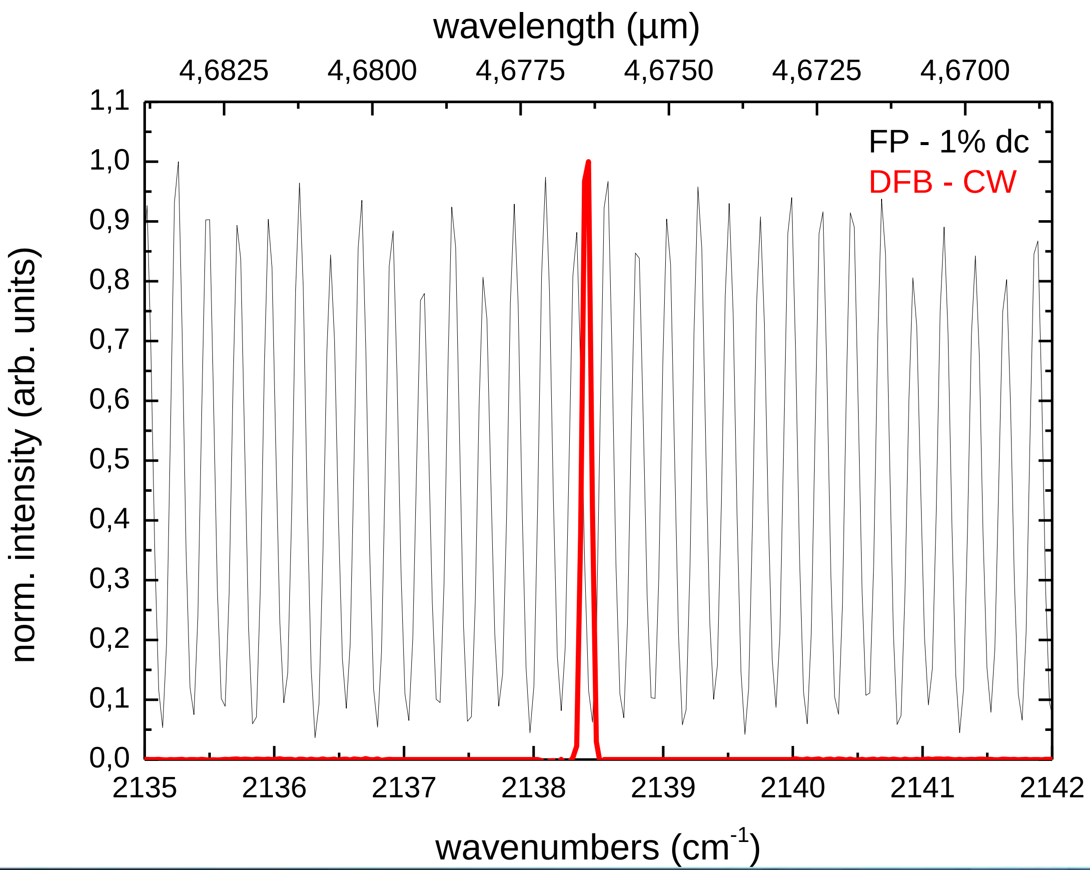
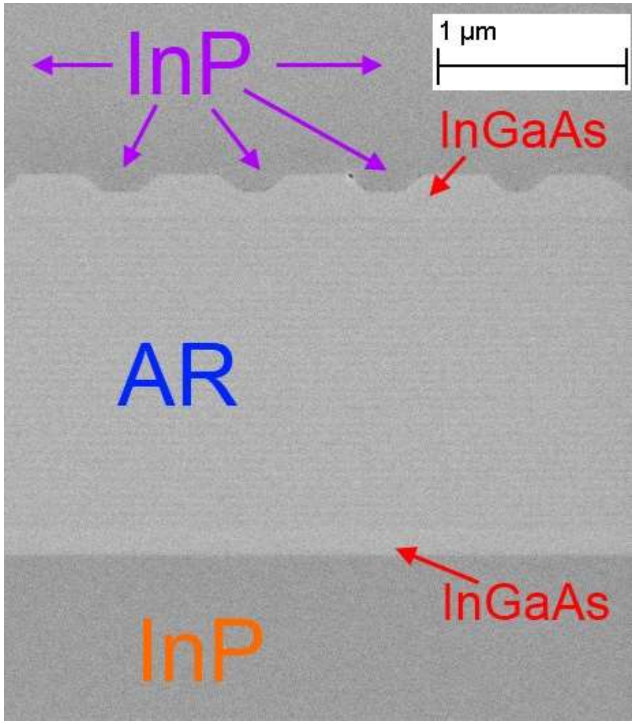
DFB devices

→ **single-mode emission**



Sideview (SEM)



1.4 Mode control in semiconductor-based lasers

Fabry-Pérot devices

→ **broad spectral emission**

DFB devices

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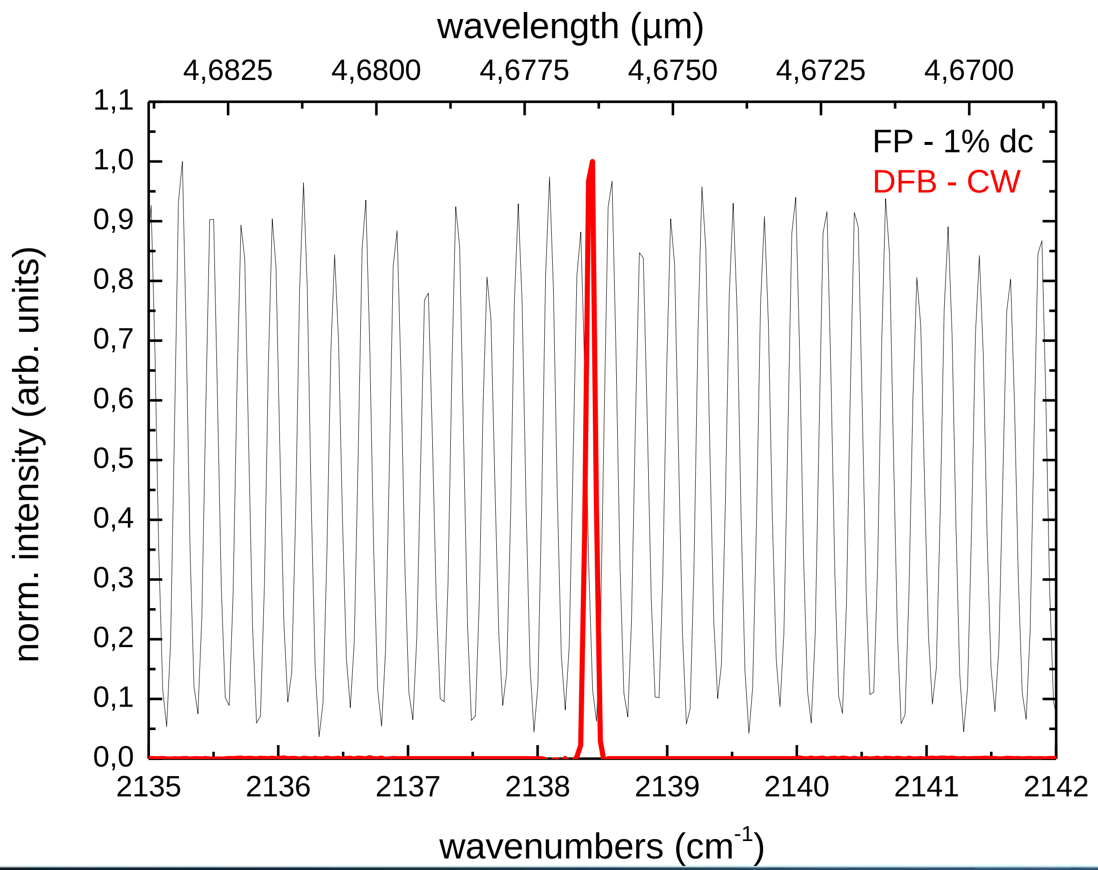

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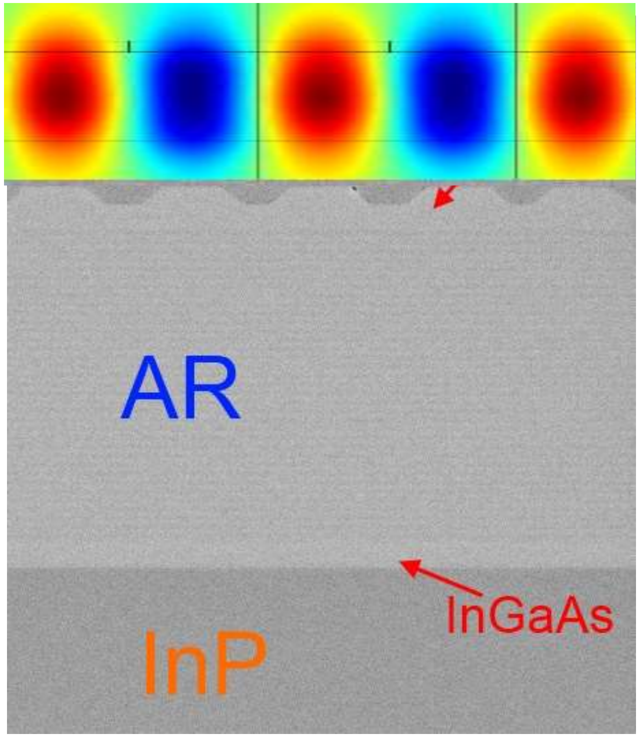
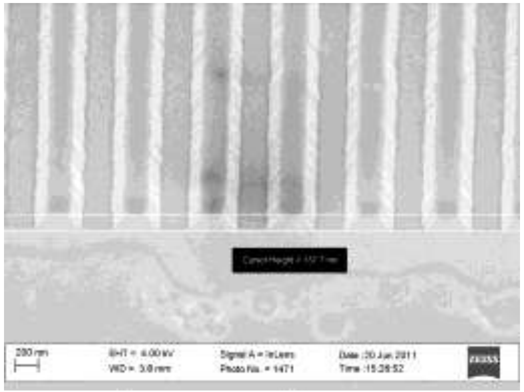


1.5 Distributed feedback gratings

<u>DFB-QCL</u>: different orders N, $$N \cdot \frac{\lambda}{2} = n_{eff} \cdot \Lambda$$

<u>1st order</u>



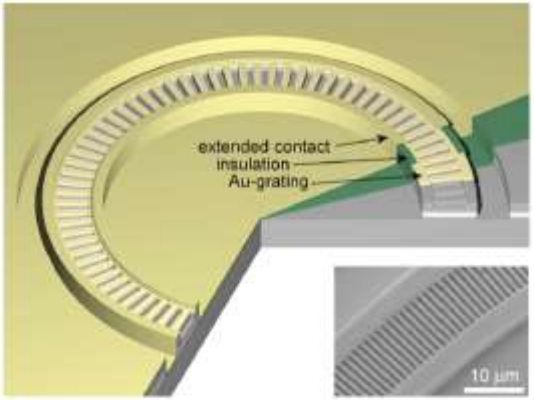
J. Faist et al., APL 70 (1997)

D. Hofstetter et al., PTL 12 (2000)

Q. Lu et al., APL 98 (2011)

B. Hinkov et al., El. Lett. 48 (2012)

<u>2nd order</u>



D. Hofstetter et al., APL 75 (1999)

S. Kumar et al., Opt. Express (2007)

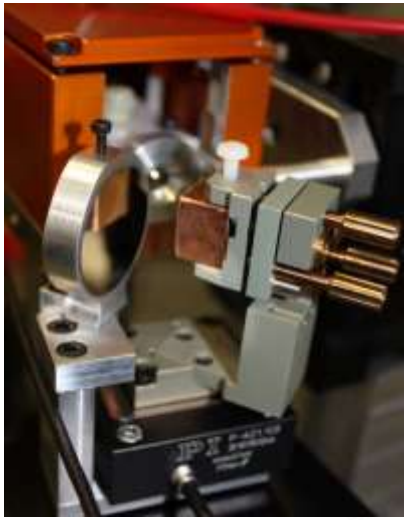
E. Mujagic et al., APL 93 (2008)

<u>3rd order</u>

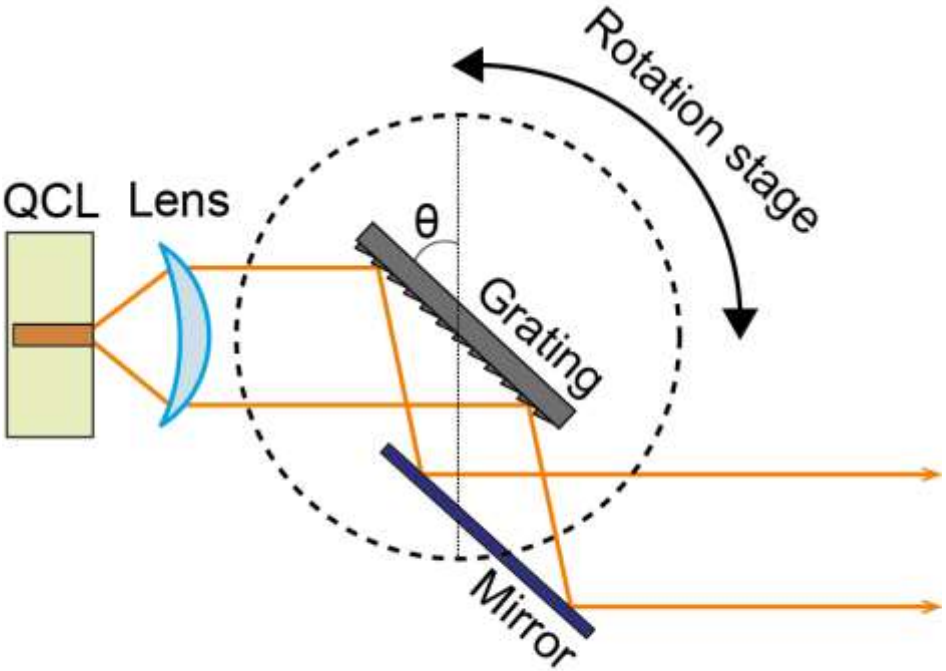
M. I. Amanti et al., Nature Photon. 3 (2009)

J. P. Commin et al., APL 97 (2010)

1.6 External cavity systems



- Main components
  - QCL
  - Collimating lens
  - Diffraction grating



- Littrow configuration
- Bragg condition → tuning
- Front/back extraction

1.7 Singlemode emission

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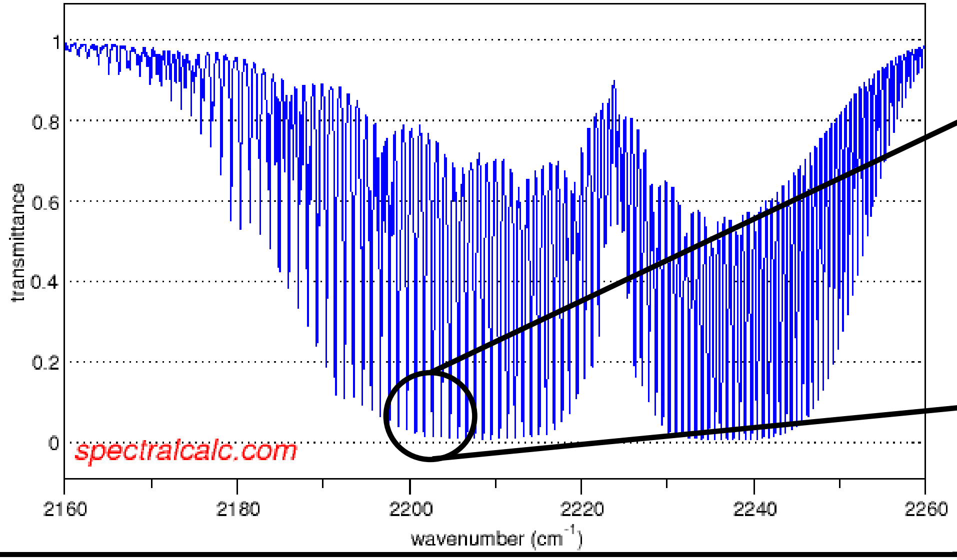

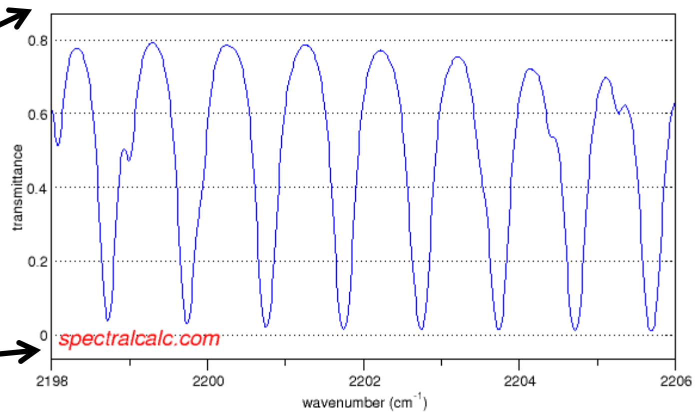

1.3 Properties

- Key properties for detection systems:

ii.a tunability	ii.b low el. dissipation	ii.c high power	ii.d multicolor

1.4 Performance-discussion of QC lasers

- Threshold current from rate-equation approach:

$$I_{th} = \frac{A}{\tau_{eff}}\left[\frac{\varepsilon_0 n L_p \lambda(2\gamma_{32})}{4\pi q_0 \Gamma z_{32}^2}\alpha_{tot} + q_0 n_2^{therm}\right]$$

- Optical output power:

$$P_{in} = N_p \cdot W_{photon} \cdot S \cdot w_{act} \qquad S \sim (J - Jth)$$

- Wallplug efficiency: $\eta_{wp} = \frac{P_{opt}}{U \cdot I}$

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- Threshold current from rate-equation approach:

wavelength

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dipole matrix el.

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wavelength (λ), broadening ($2\gamma_{32}$), therm. backfilling (n_2^{therm}), dipole matrix el. (z_{32}^2)

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area — wavelength — broadening — therm. backfilling

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area (A), wavelength (λ), broadening ($2\gamma_{32}$), therm. backfilling (n_2^{therm}), overlapp factor (Γ), dipole matrix el. (z_{32}^2)

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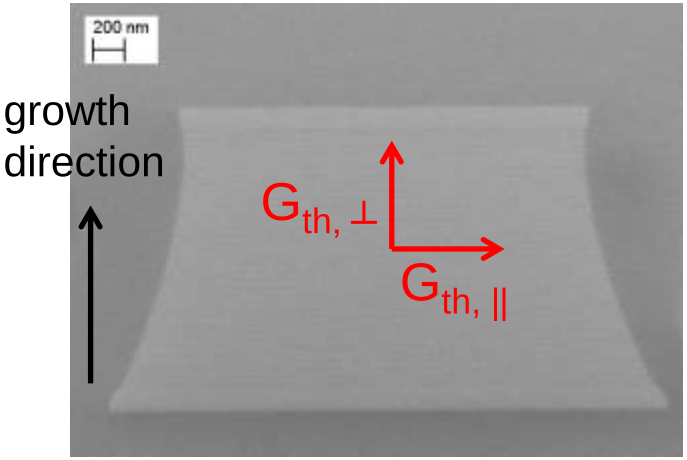
1.8 Performance-discussion of QC lasers

- As expected for a layered semiconductor media:

$G_{th,\,||} > G_{th,\,\perp}$,



- Typically $G_{th,\,||} / G_{th,\,\perp} = 3.3$*

***A. Lops et al.,**
J. Appl. Phys. 100 (2006)

1.8 Performance-discussion of QC lasers

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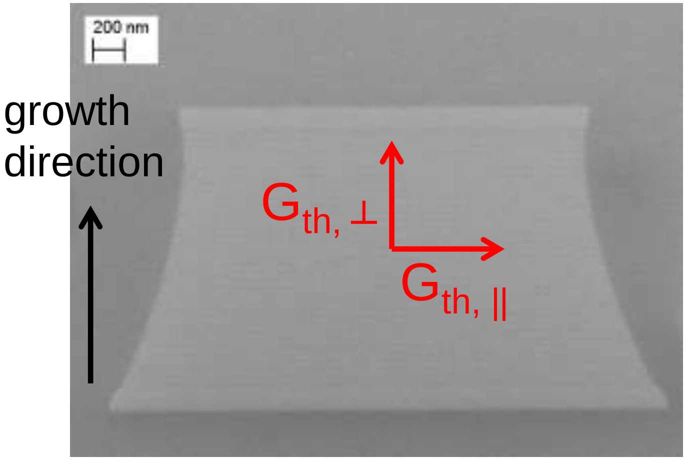

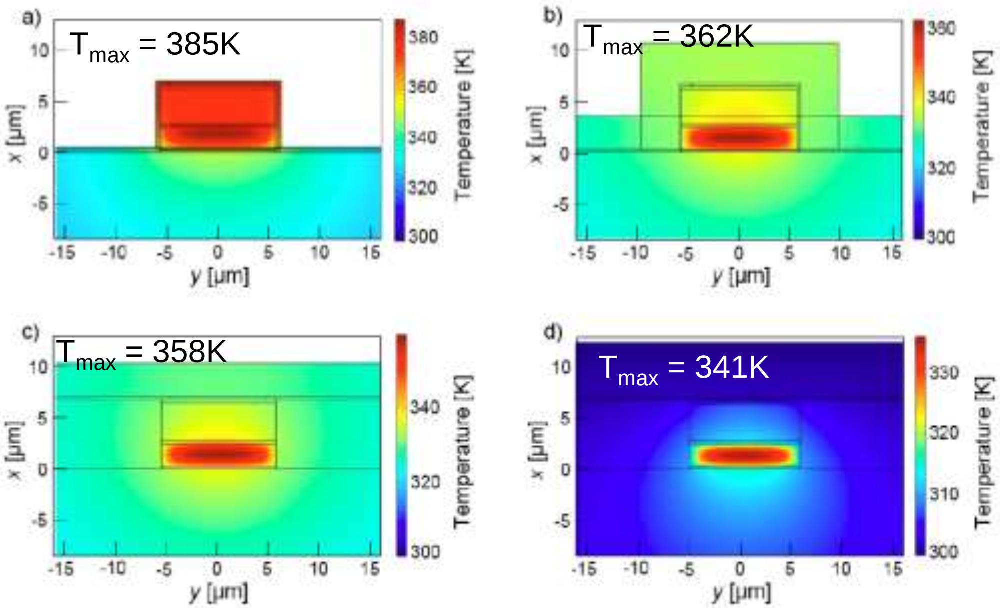

Fig. 2.14: Temperature mappings of the front facet of identical QC laser structures (with 12 µm-wide and 3 mm-long waveguides) and an input electrical power of 8.8 W (24.4 kW/cm³). Conventional ridge waveguide with 0.3 µm Si_3N_4 passivation and 0.2 µm (a) and 4.0 µm (b) top gold. Buried waveguide heterostructure (BH) waveguide design for epi-up (c) and epi-down (d) mounting.

- Typically $G_{th,\parallel} / G_{th,\perp} = 3.3$*

A. Lops et al., J. Appl. Phys. 100 (2006)

A. Wittman , PhD thesis 18363, ETHZ (2009)

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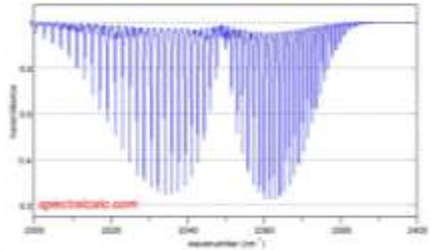
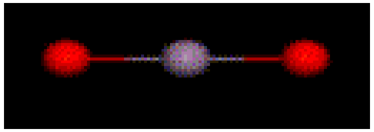
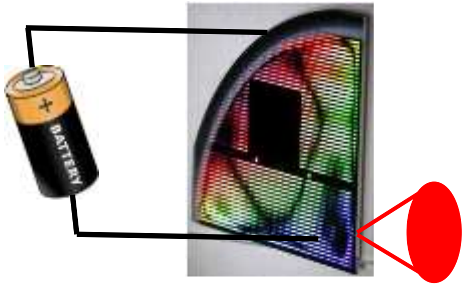




2. **Recent developments**



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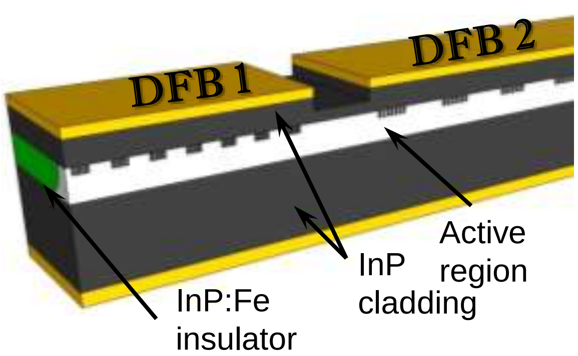
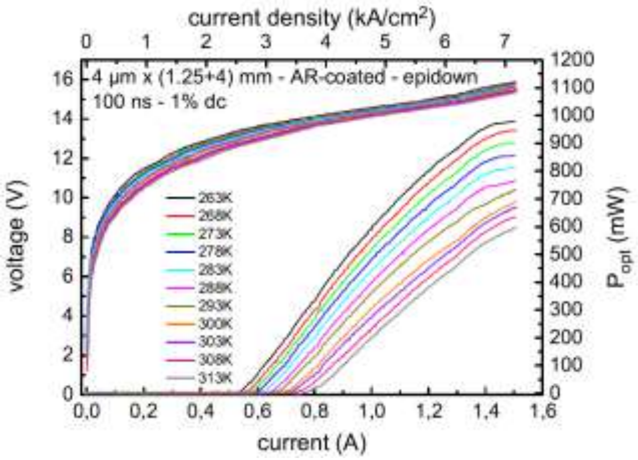
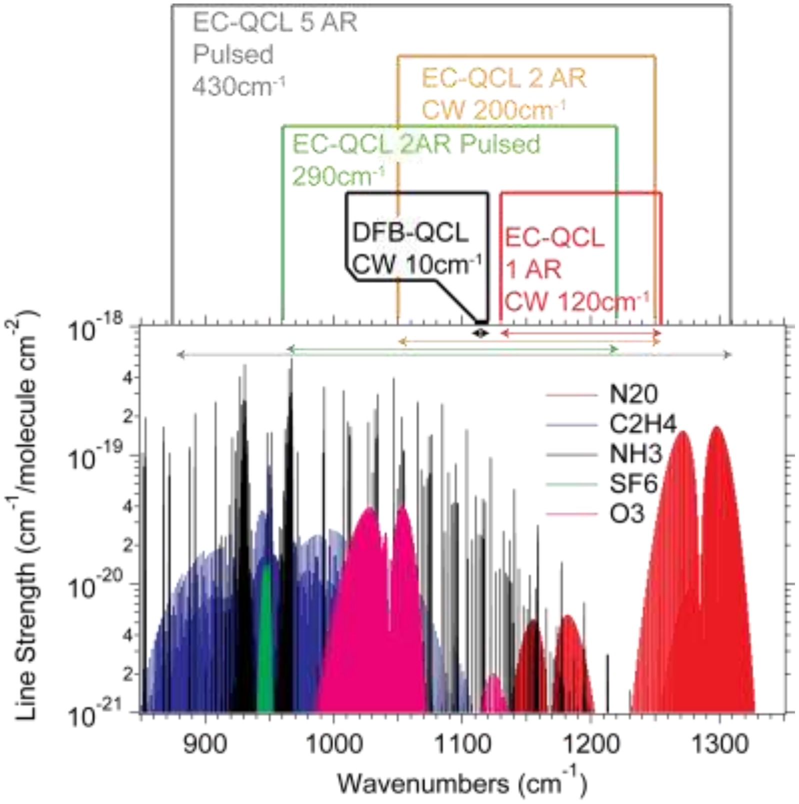




3. Conclusion

2. Recent developments:

- <u>Widely tunable devices (ext. cavity):</u>



A. Hugi et al., Semicond. Sci. Technol. 25, 083001 (2010)

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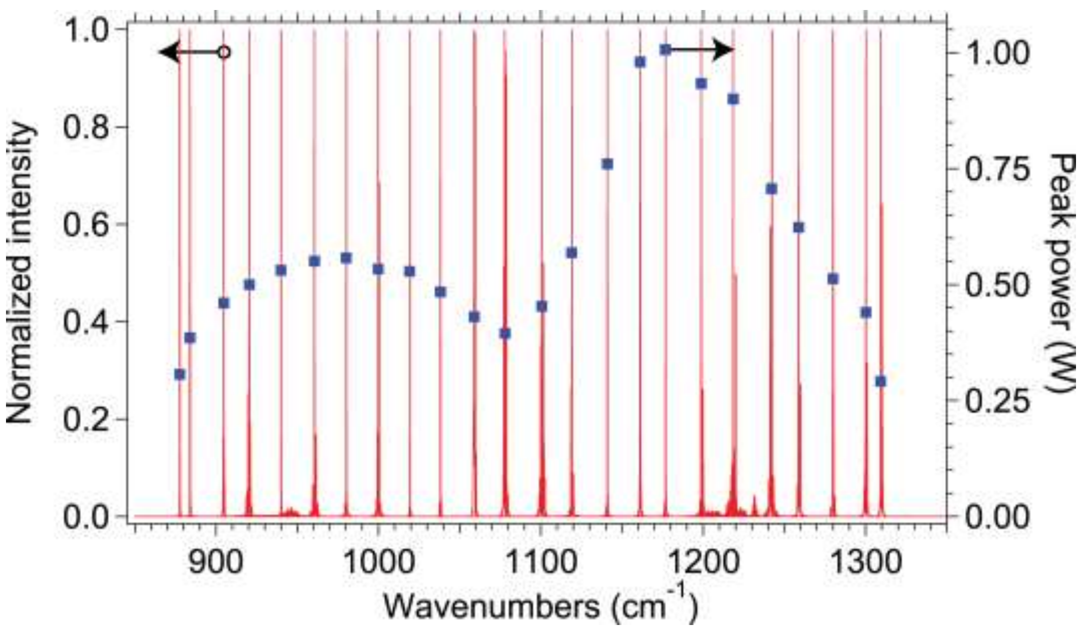
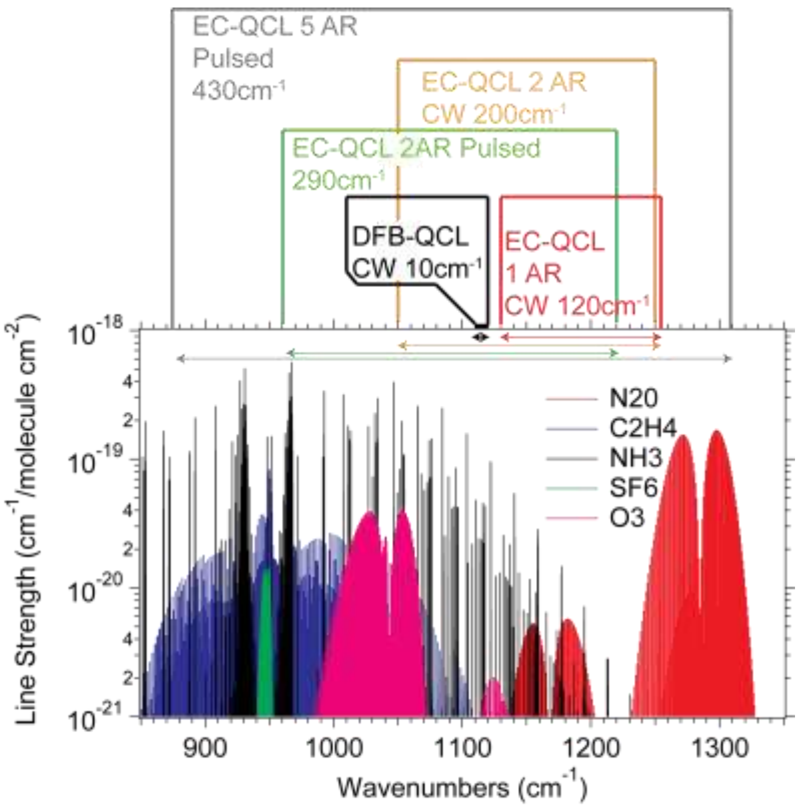




Pulsed operation:

432 cm^{-1} tuning (7.5μm – 11.4μm)

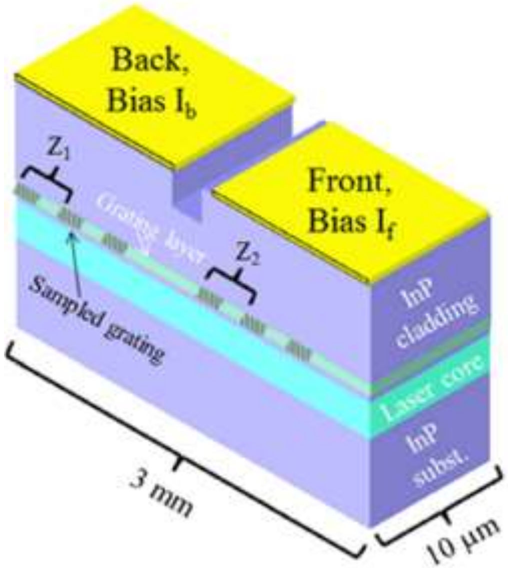
1 W peak power

A. Hugi et al., Appl. Phys. Lett. 95, 061103 (2009)

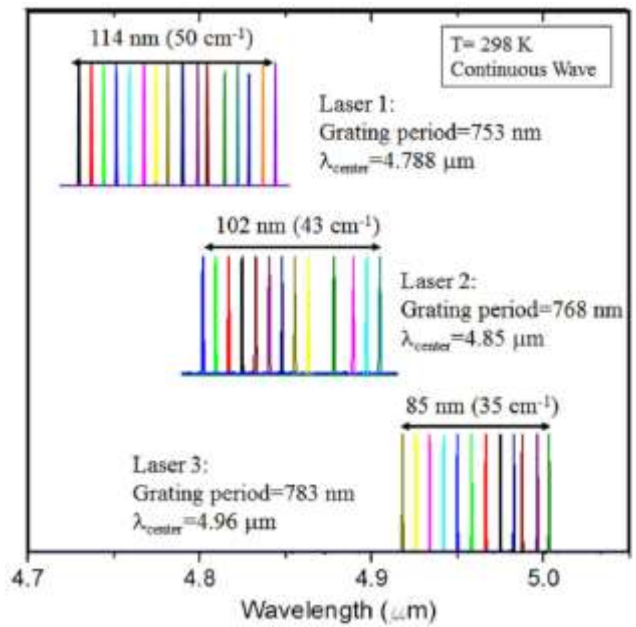
A. Hugi et al., Semicond. Sci. Technol. 25, 083001 (2010)

2. Recent developments:

- Widely tunable DFBs



- Sampled DFB gratings
- Two different grating periods



- λ ~ 4.8 µm
- 50 cm^{-1} gap-free tuning
- 100 mW CW power

S. Slivken et al., Appl. Phys. Lett. 100 (2012)

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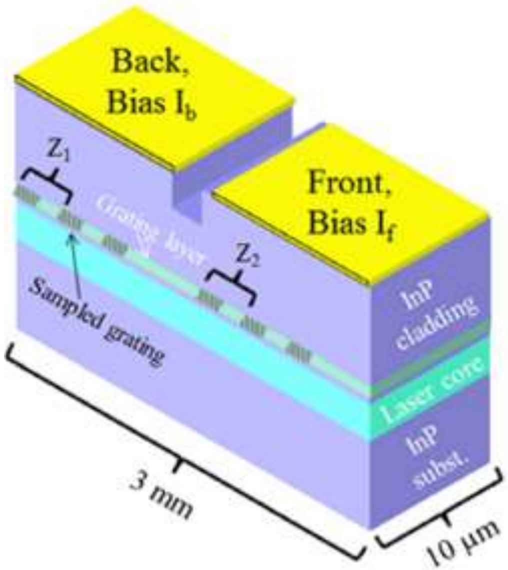

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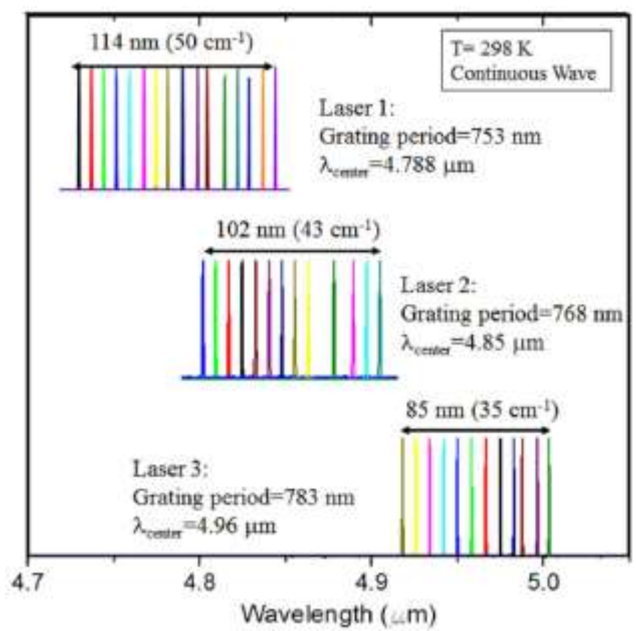

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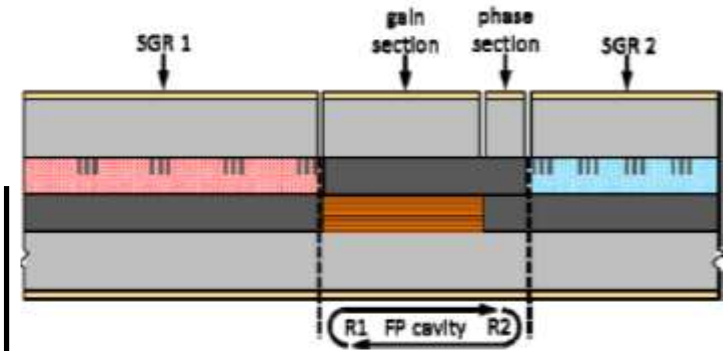
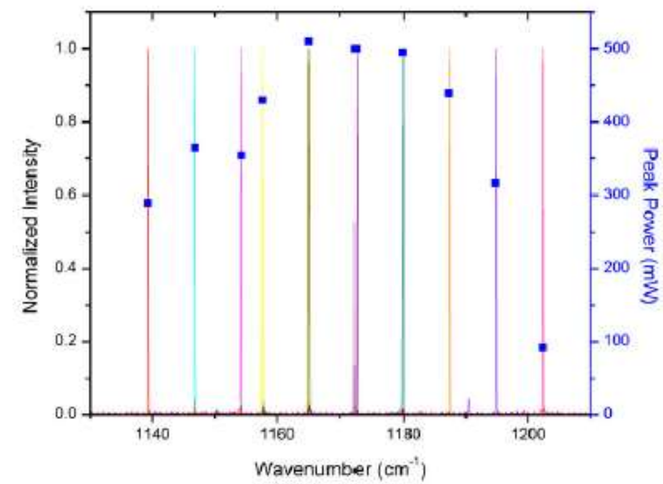
S. Slivken et al., Appl. Phys. Lett. 100 (2012)

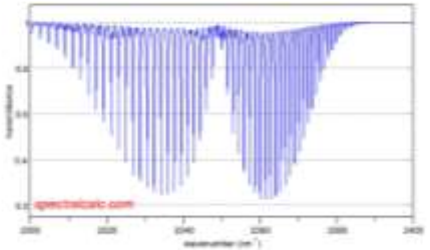


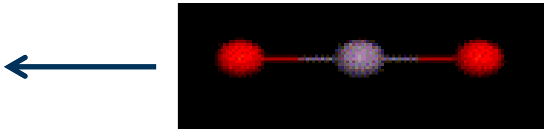


- λ ~ 8.5 μm
- 63 cm^{-1} tuning
- 100-500 mW peak power

T. Mansuripur et al., Opt. Express 20 (2012)

1. Introduction





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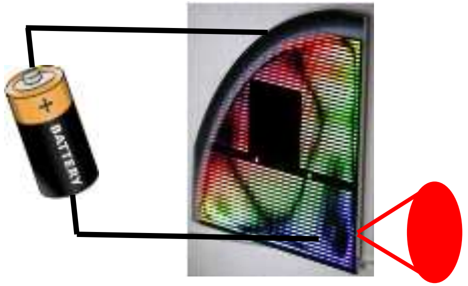
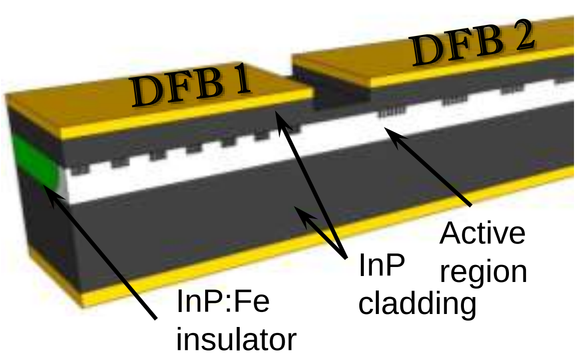
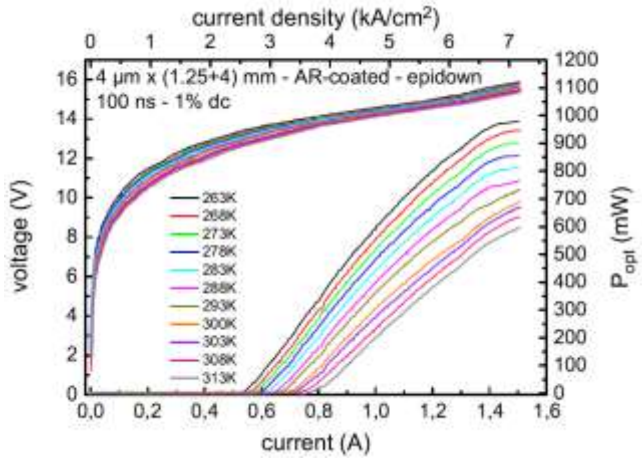


a. **Low electrical dissipation**

b. Master-oscillator power-amplifier (MOPA)

c. Dual color DFB





3. Conclusion

2. Recent developments:

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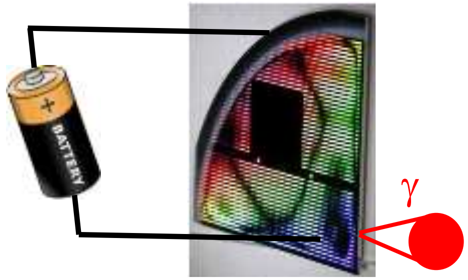

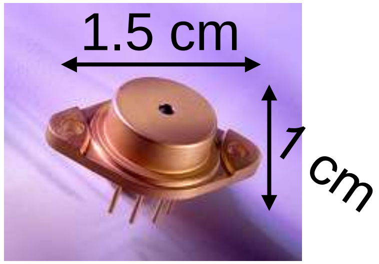

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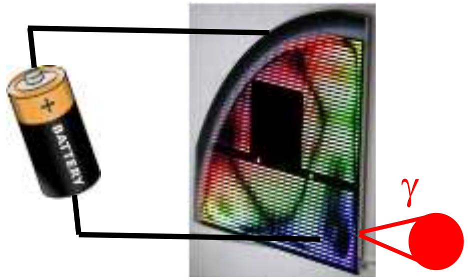

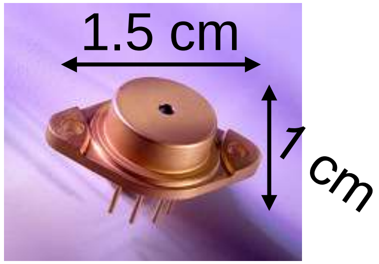

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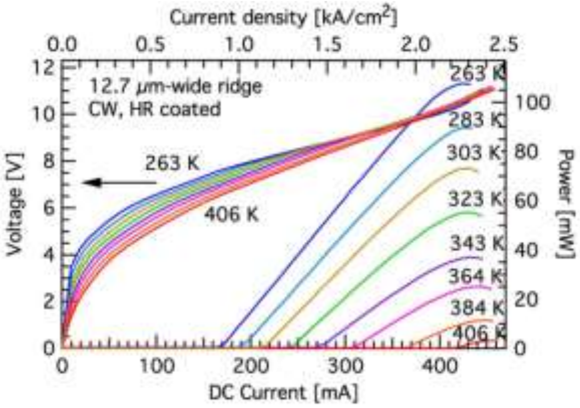

Wittmann et al., Photon. Technol. Lett. 21 (2009)

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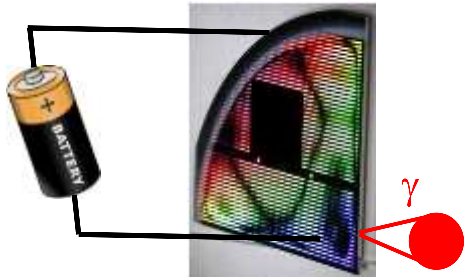

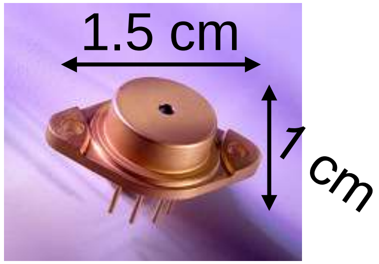

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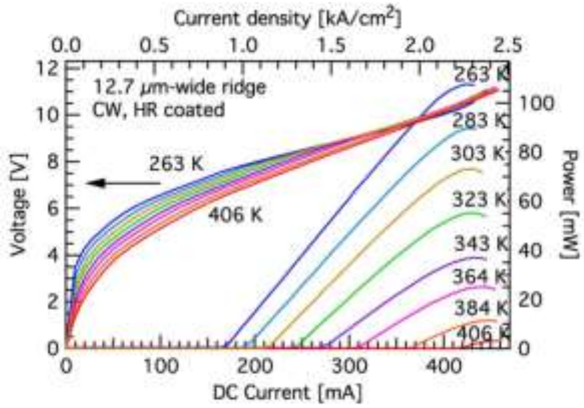

Wittmann et al., Photon. Technol. Lett. 21 (2009)

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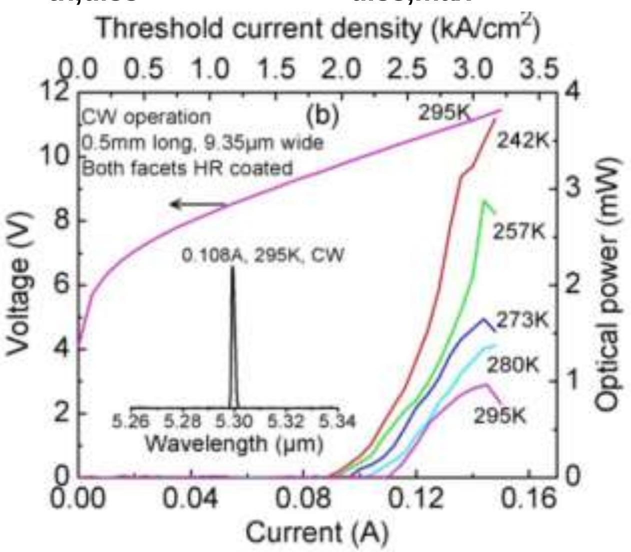

R. Cendejas et al., Photon. J. 3 (2011)

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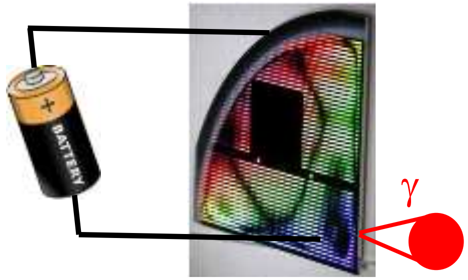

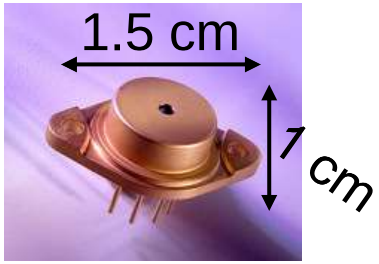

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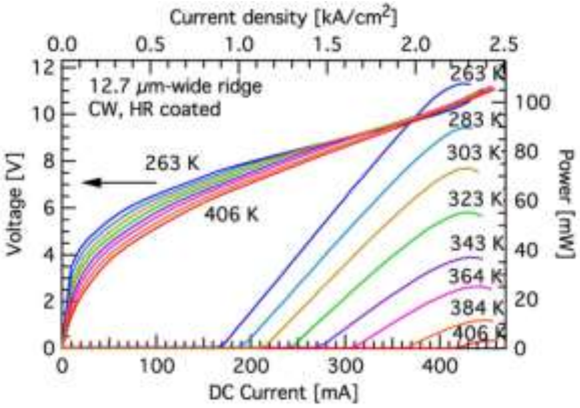

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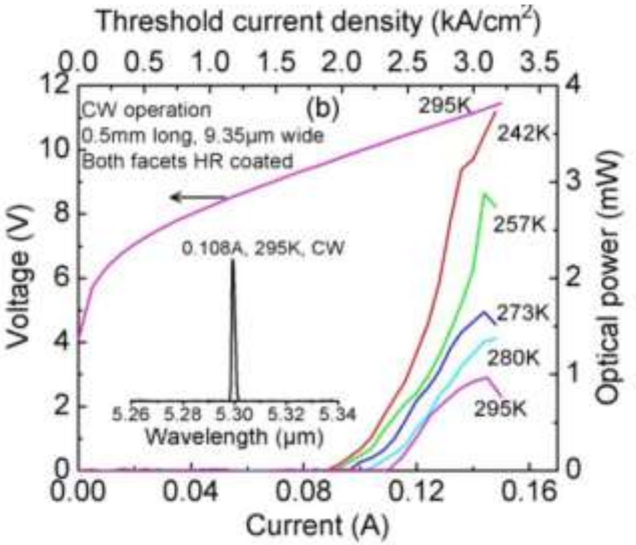
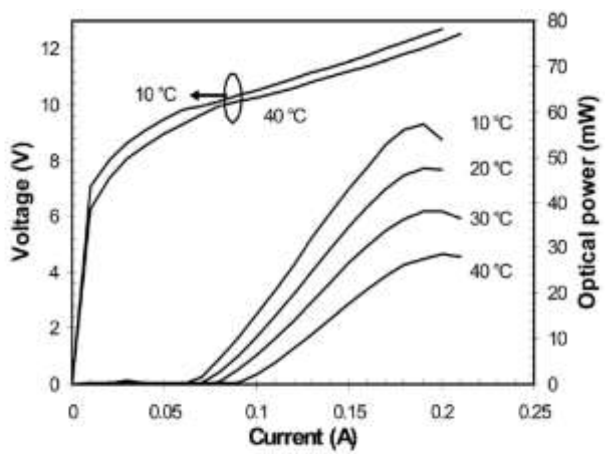


R. Cendejas et al., Photon. J. 3 (2011)

$P_{th,diss}$ ~ 0.7 W, $P_{diss,max}$ ~ 2.4 W



F. Xie et al.,
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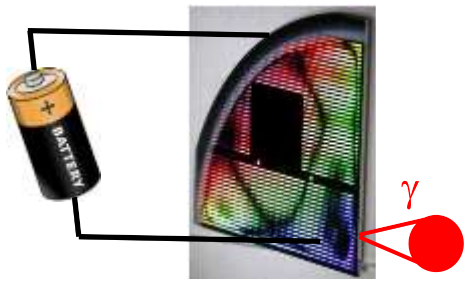

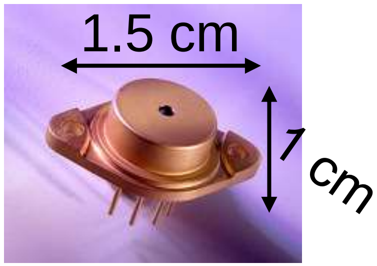

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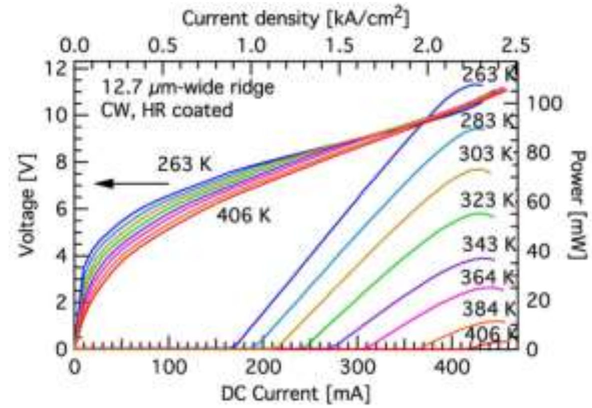

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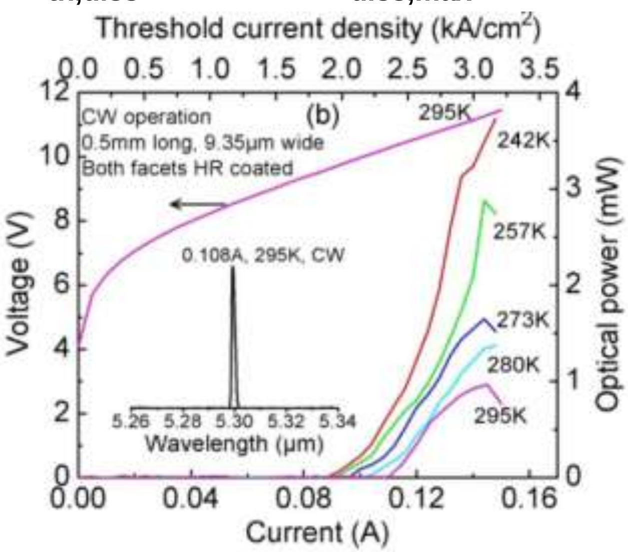

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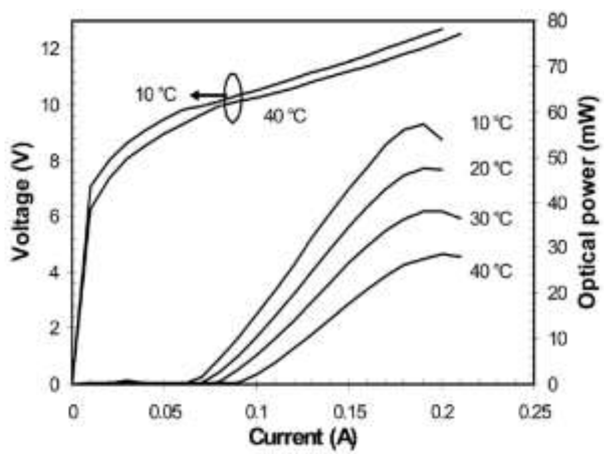

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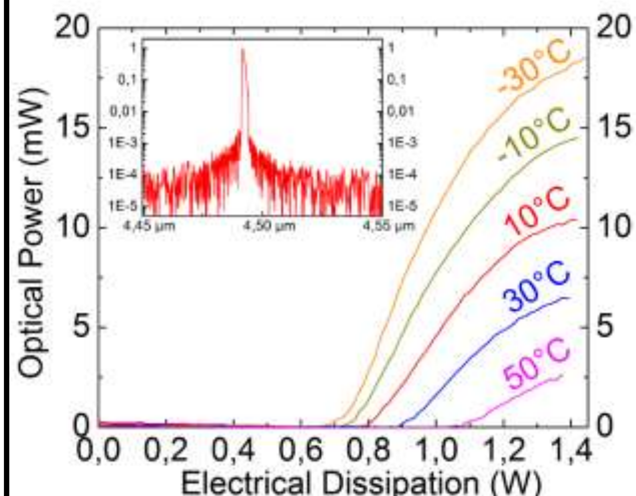

B. Hinkov et al., El. Lett. 48 (2012)

2a. Low dissipation – AR design

- MBE: 35 x $In_{0.635}Ga_{0.365}As$ / $Al_{0.665}In_{0.335}As$ on InP substrate

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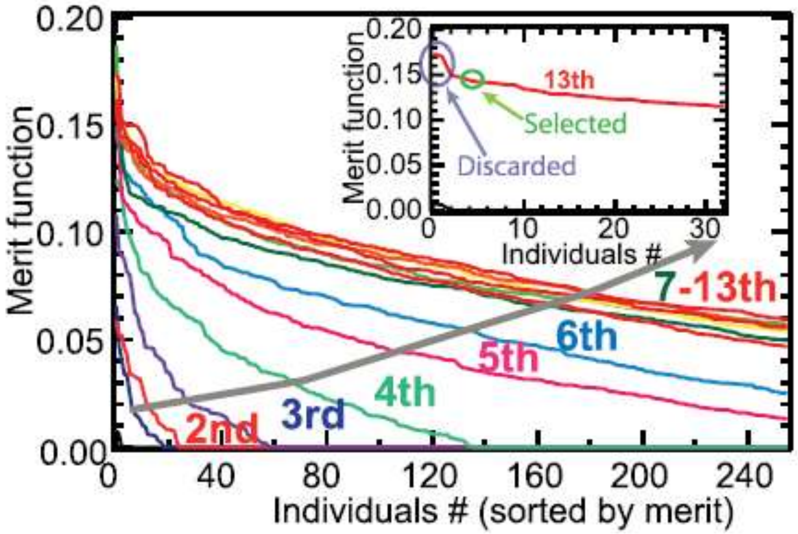

A. Bismuto et al., Appl. Phys. Lett. 101 (2012)

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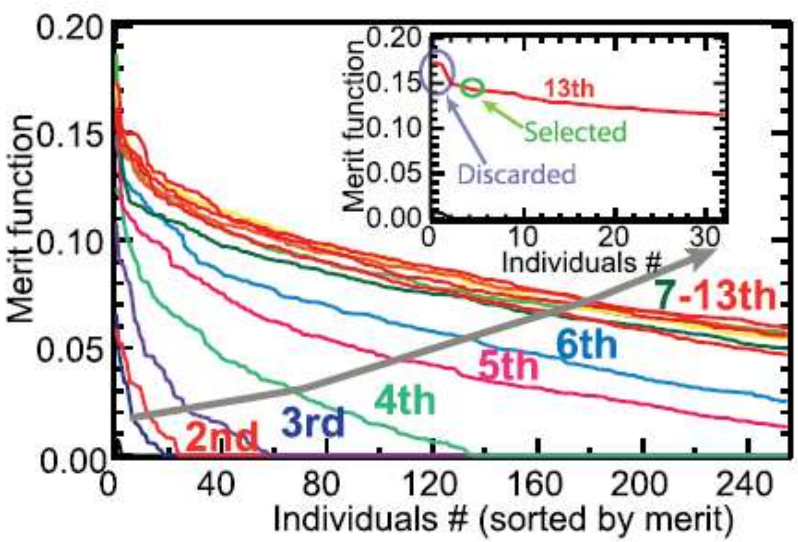

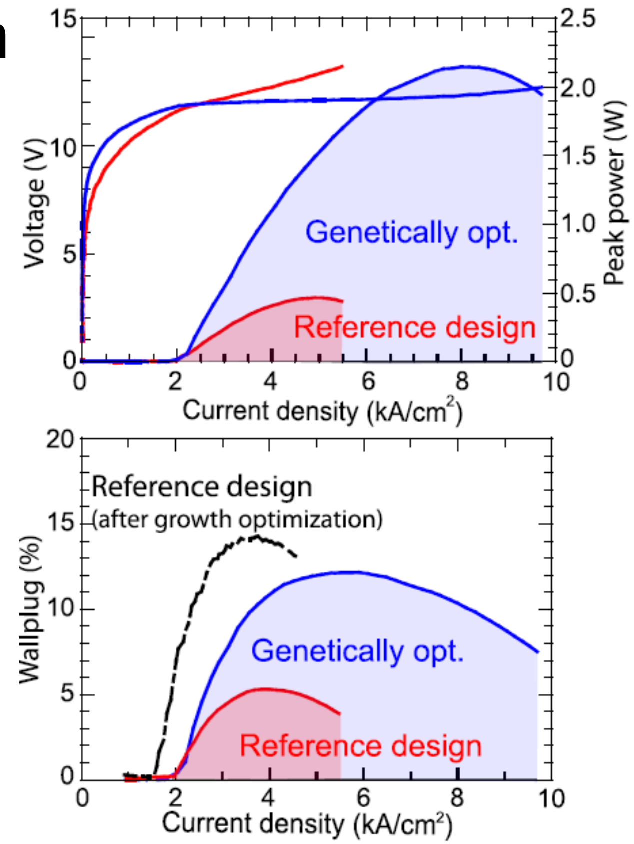

A. Bismuto et al., Appl. Phys. Lett. 101 (2012)

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- **Buried heterostructure**:
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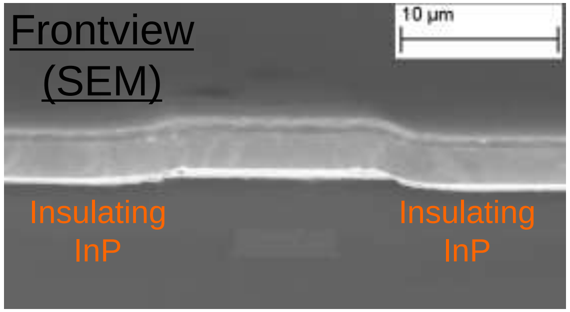

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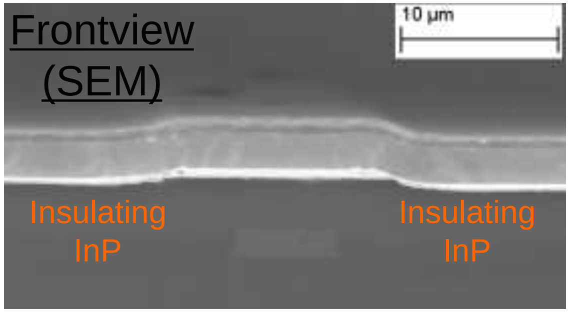

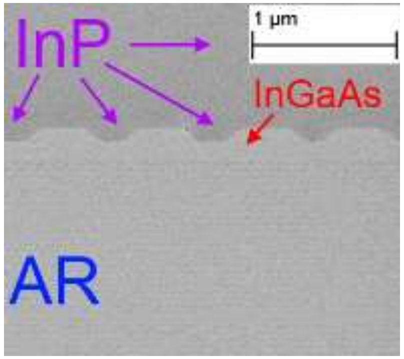

$$I_{th} = \frac{A}{\tau_{eff}} \left[\frac{\varepsilon_0 n L_p \lambda (2\gamma_{32})}{4\pi q_0 \Gamma z_{32}^2} \alpha_{tot} + q_0 n_2^{therm} \right]$$

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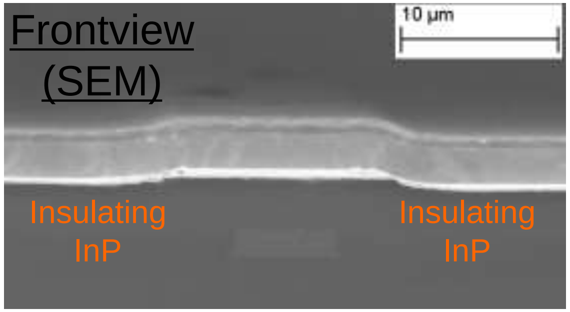

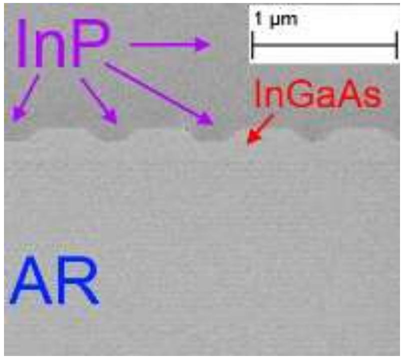

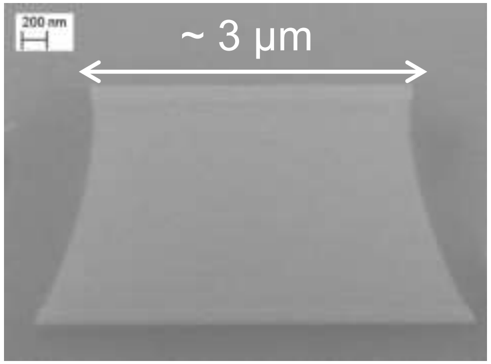

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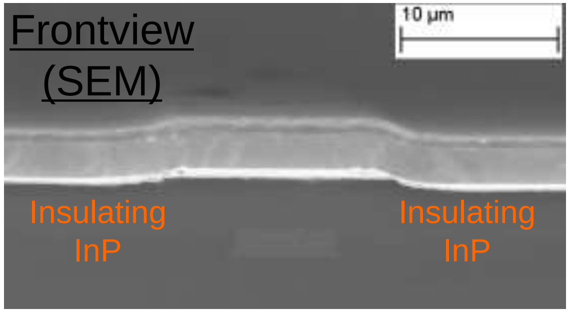

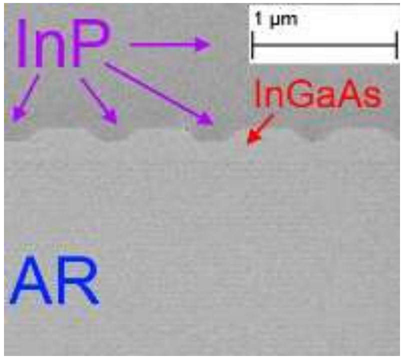

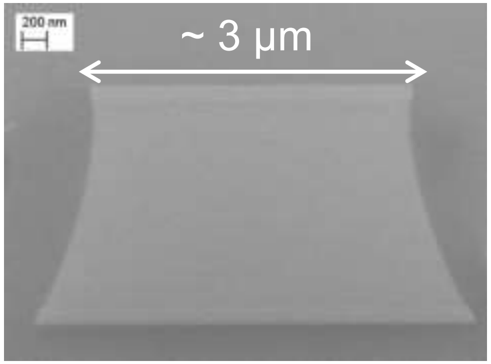

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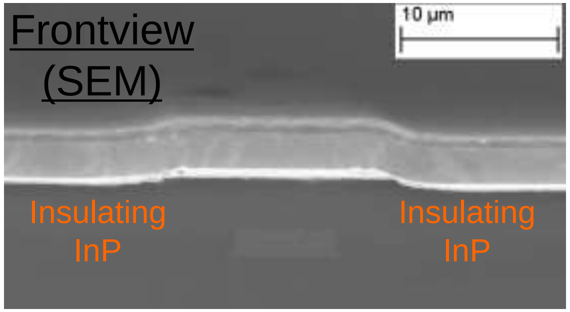

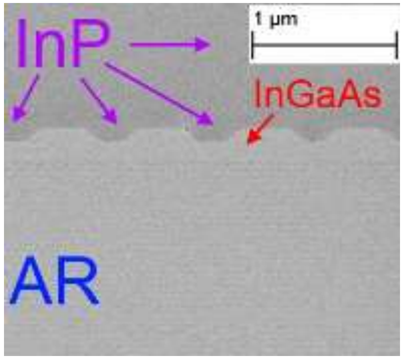

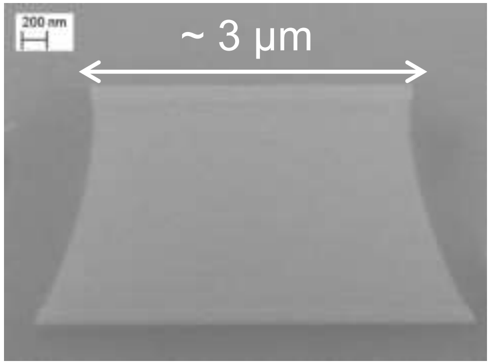

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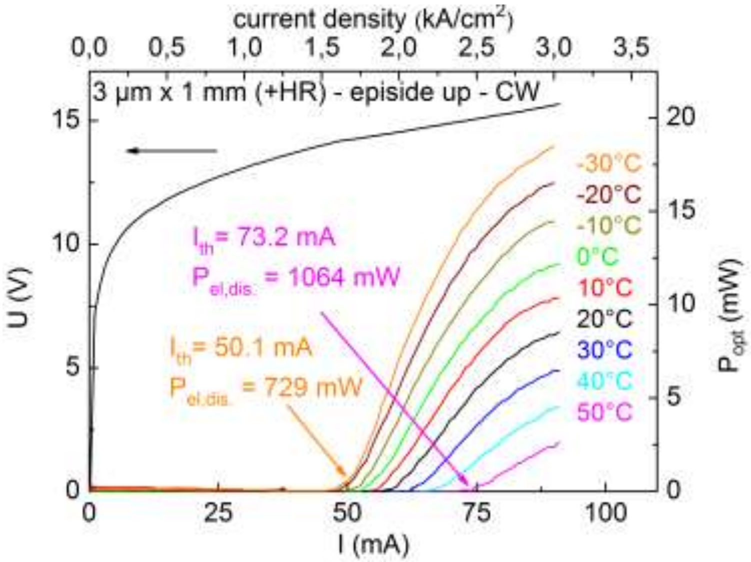

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B. Hinkov et al., El. Lett. 48 (2012)

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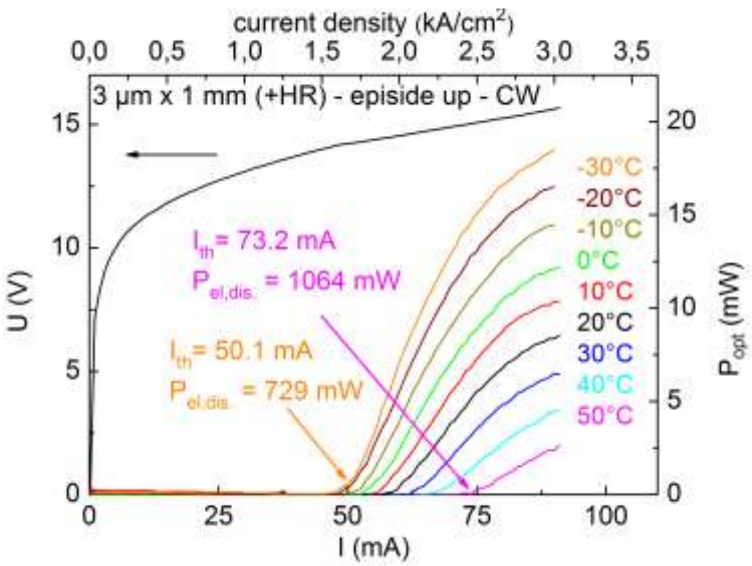

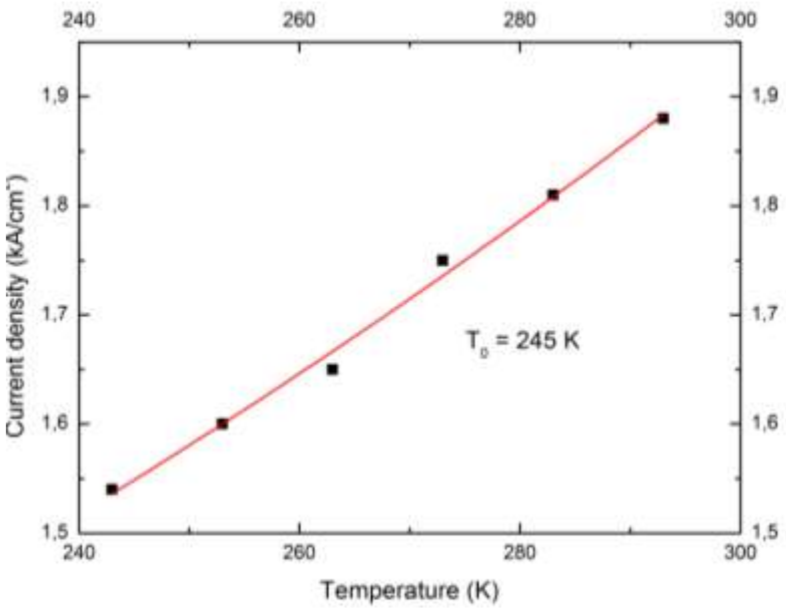

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- High T_0 = 245 K
(interband lasers typically ~ 55K*)

B. Hinkov et al., El. Lett. 48 (2012)

****W. W. Bewley et al., Opt. Express 20 (2012)***

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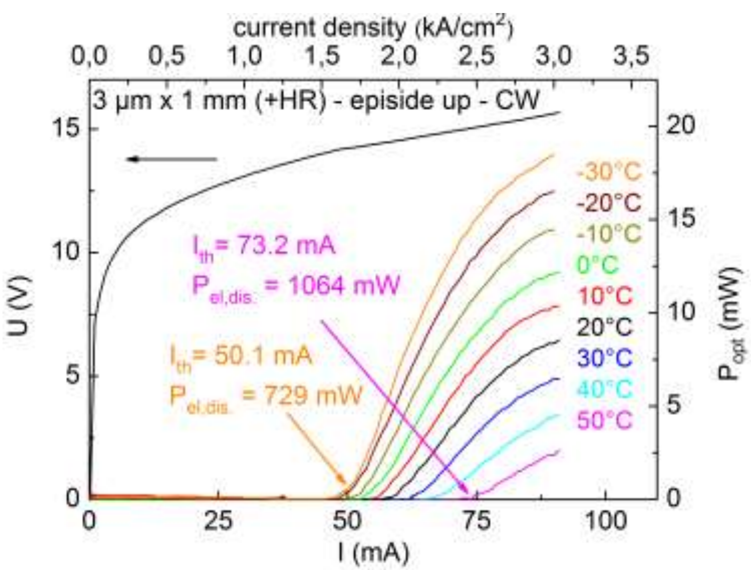

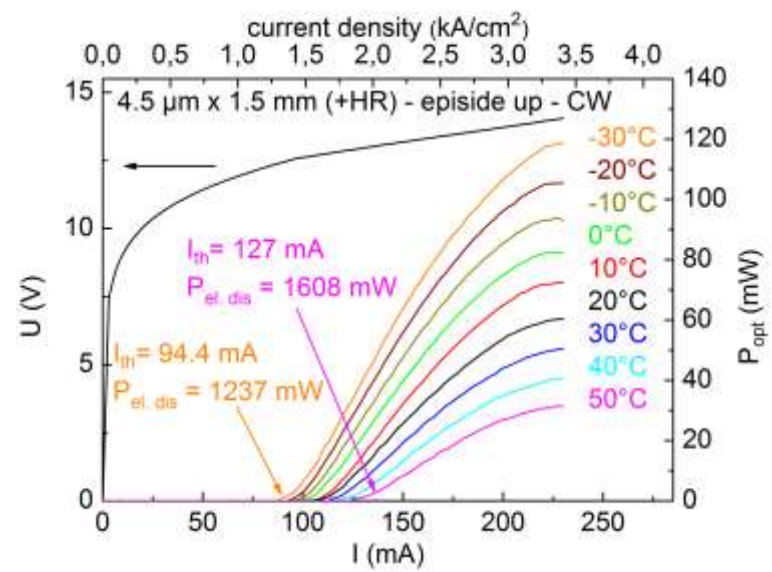

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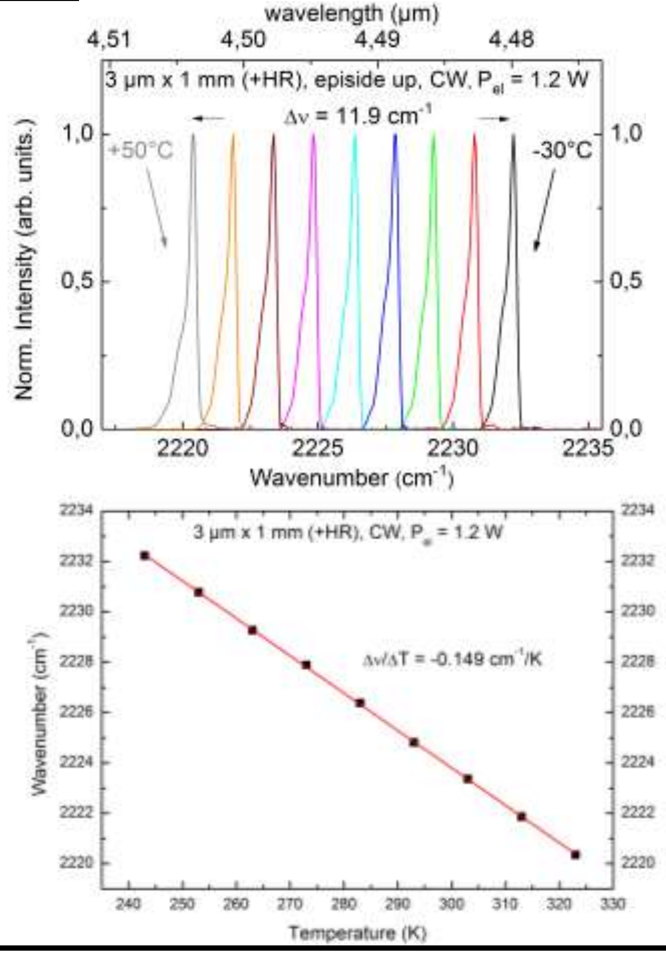
- **P_{opt} > 25 mW (323 K)**
- $\eta_{wallplug}$ ~ 4%

B. Hinkov et al., El. Lett. 48 (2012)

2a. Results II: spectra and tunability

Temp.:

FIXED POWER



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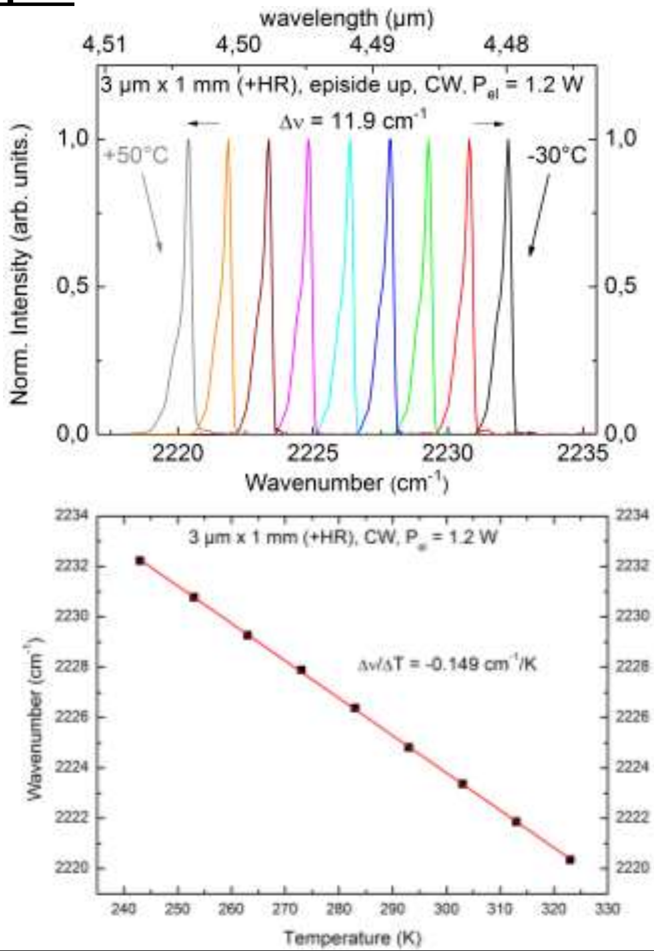
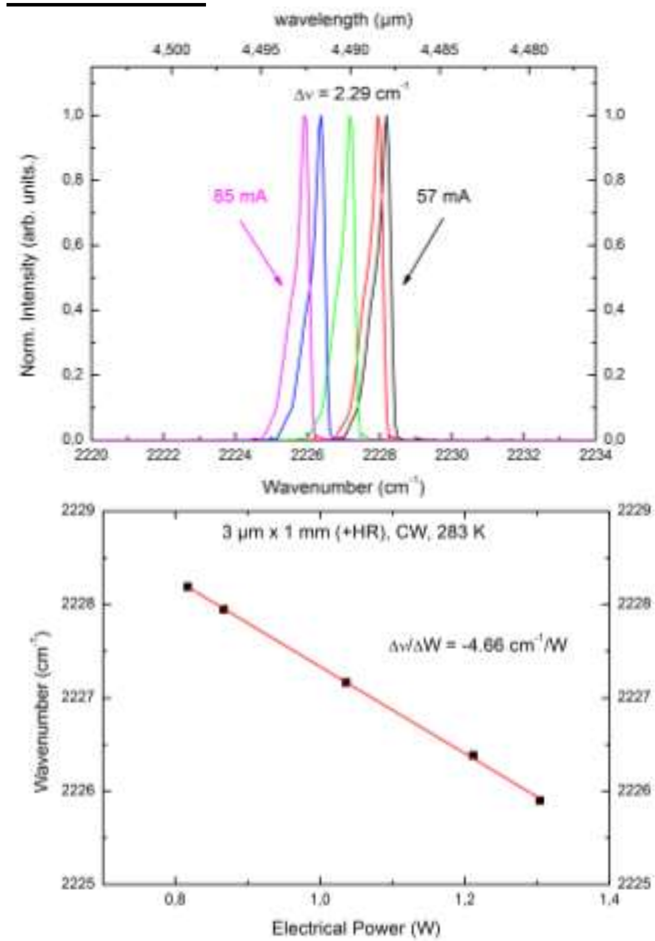
Temp.:

F I X E D P O W E R



Power:

F I X E D T E M P E R A T U R E



B. Hinkov et al., El. Lett. 48 (2012)

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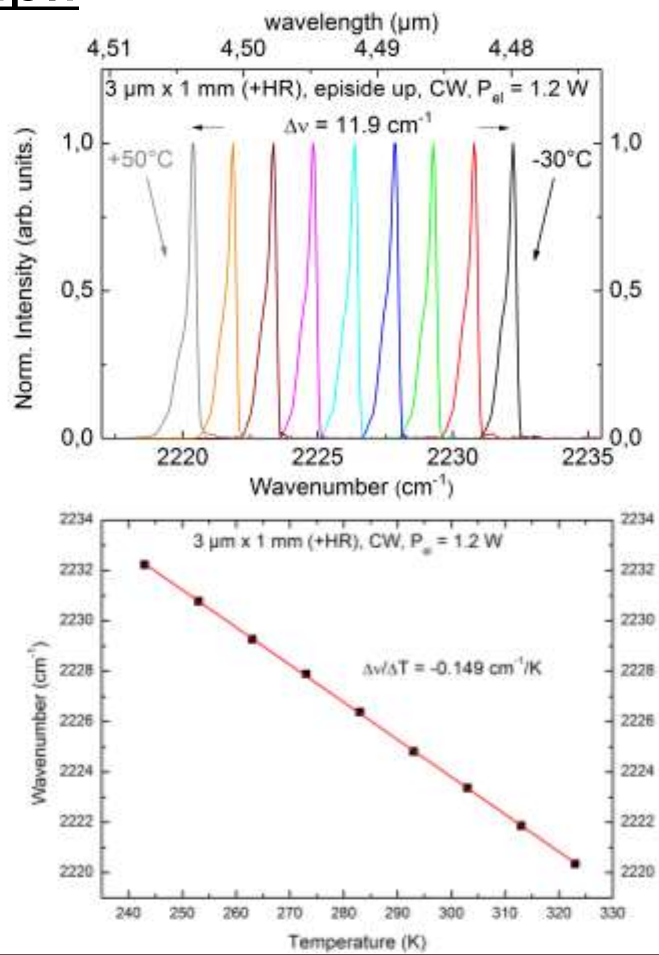
2a. Results II: spectra and tunability

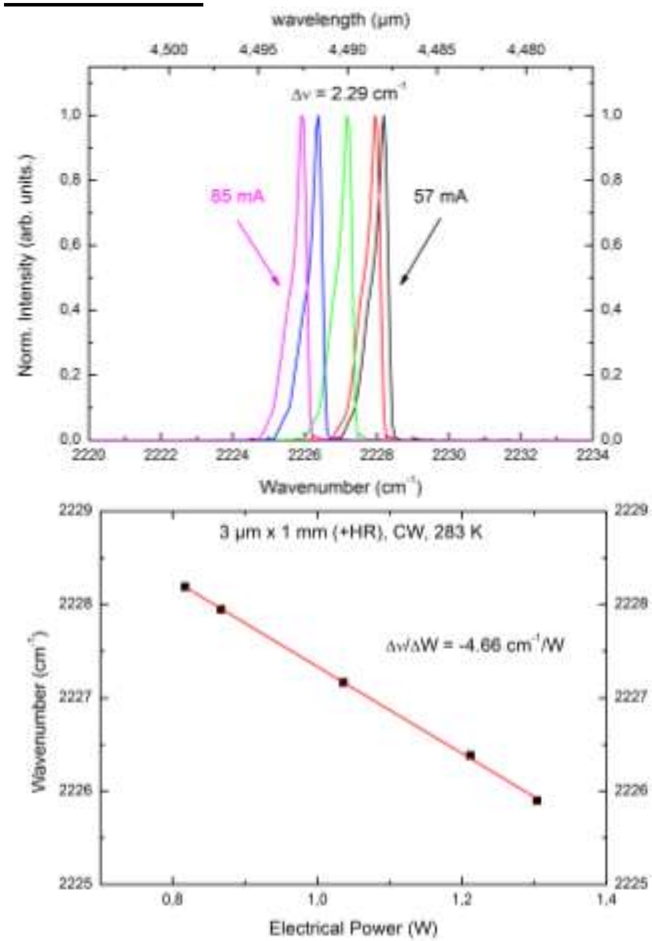
Temp.:

FIXED POWER



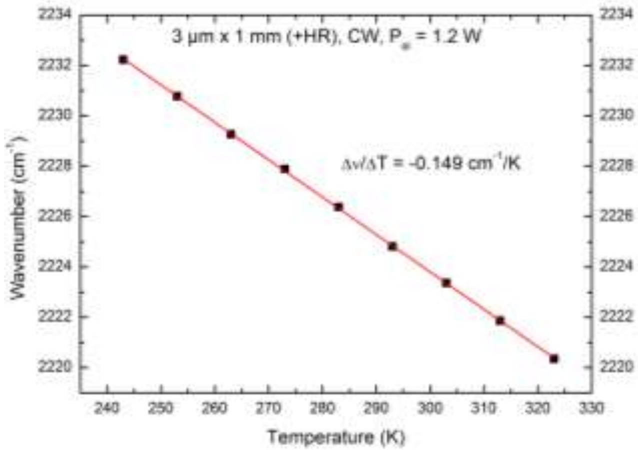
Power:

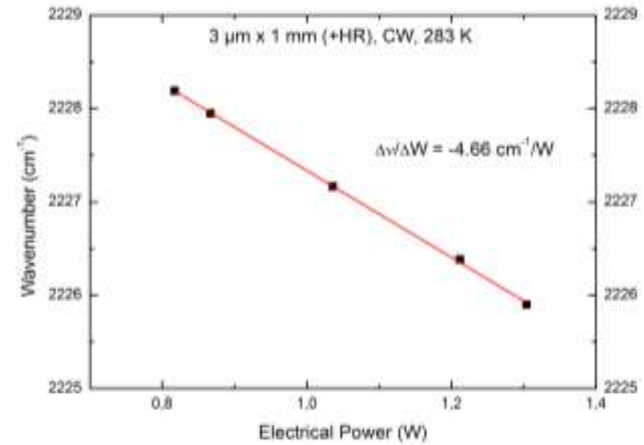
FIXED TEMPERATURE



- ***Single-mode + mode hop free tuning*** **(SMSR >27 dB)**

2a. Results III: Thermal conductivity





$$^{*}G_{th} = \frac{\Delta W}{\Delta T} \cdot \frac{1}{A} = \frac{1}{A} \cdot \underbrace{\left(\frac{\Delta \nu}{\Delta T}\right)_P}_{\beta_{Temp}} \cdot \underbrace{\left(\frac{\Delta \nu}{\Delta W}\right)_T^{-1}}_{\beta_{Power}^{-1}}$$

➔ G_{th} ~ 1200 W/K cm^2

Beck et al., Science 295, 301 (2002)

- ➔ therm. conduction: ratio of direct heating & current-heating
- ➔ *very high* G_{th} (junction-up!)
- ➔ *junction-down* (G_{th} ~ 50% higher) → *lower power-tuning*!

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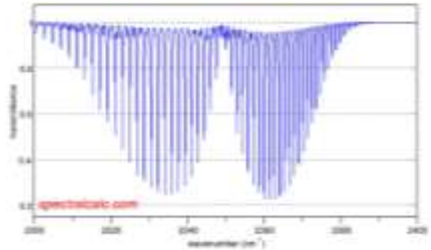
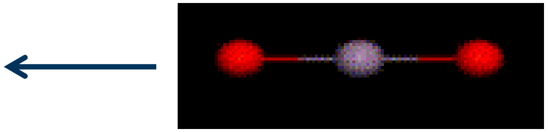
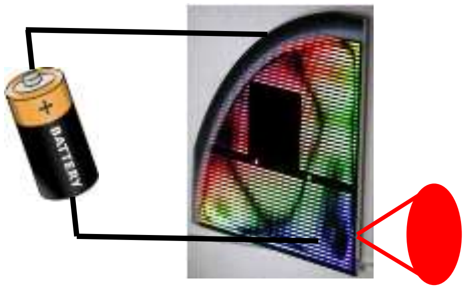
1. Introduction



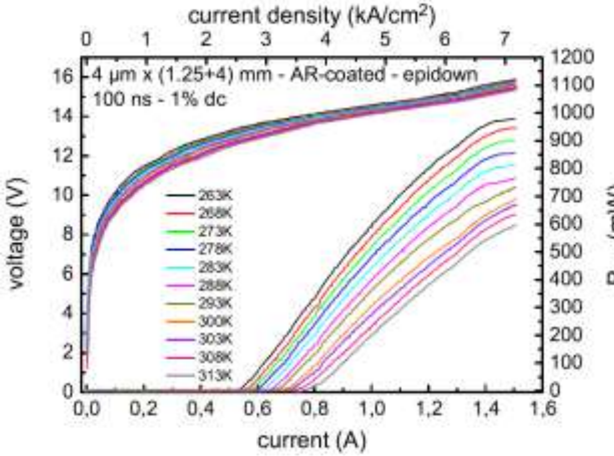


2. Recent developments

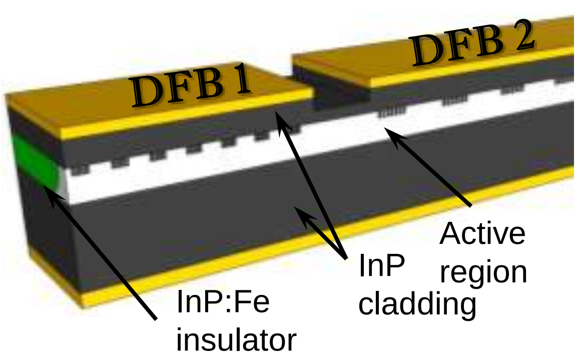


   a. Low electrical dissipation

   b. **Master-oscillator power-amplifier (MOPA)**



   c. Dual color DFB



3. Conclusion

2. Recent developments:

- **b.** High optical output power

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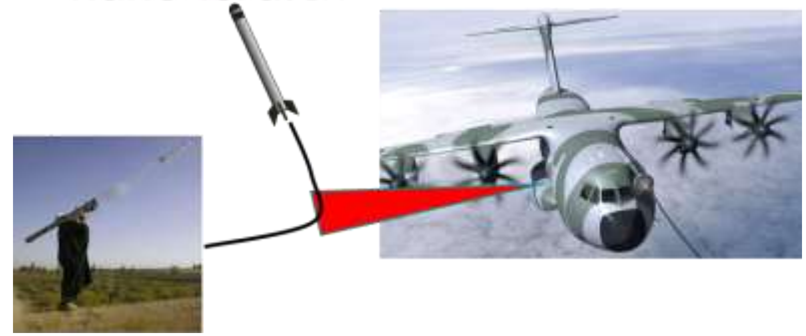
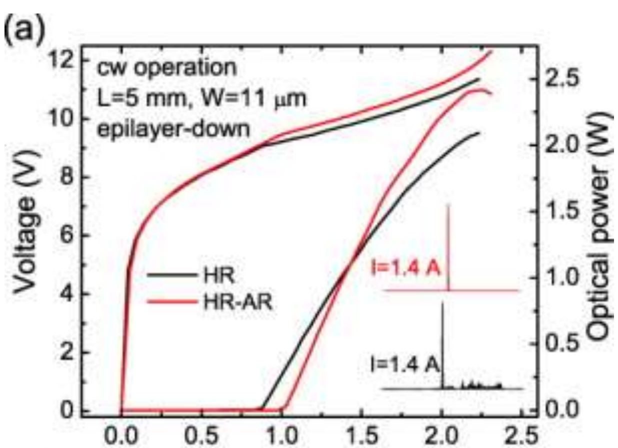


CW:

P_{opt} = 2.4 W

η_{max} = 10%

P_{diss} = 20 W



Q. Y. Lu et al., Appl. Phys. Lett. 98 (2011)

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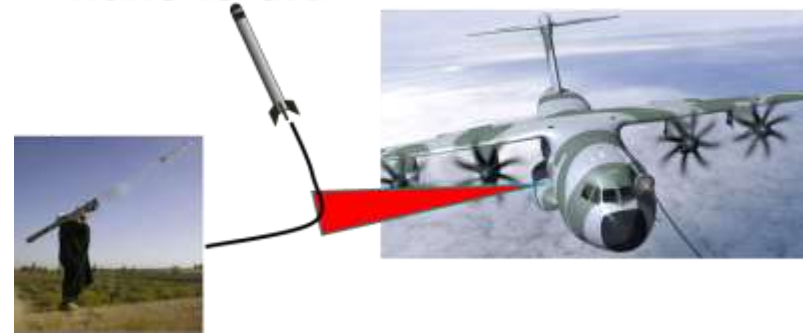
2. Recent developments:

- **b.** <u>High optical output power</u>



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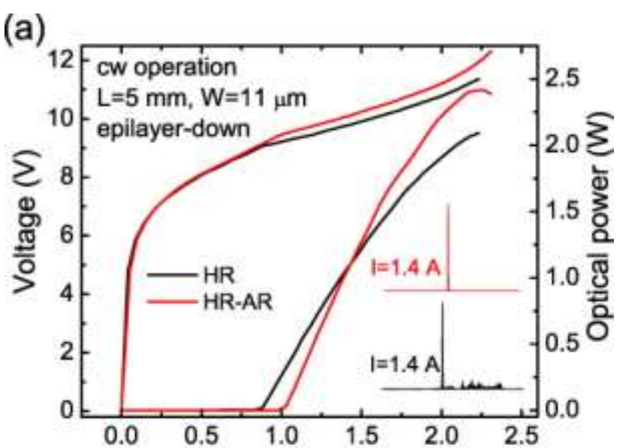


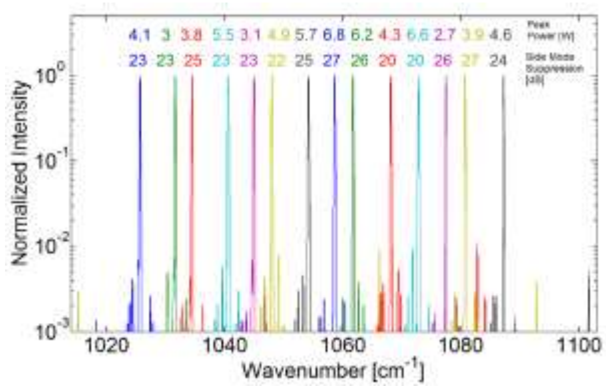
Q. Y. Lu et al., Appl. Phys. Lett. 98 (2011)

Pulsed:

P_{opt} = 2.7 W – 10 W

array of tapered DFBs

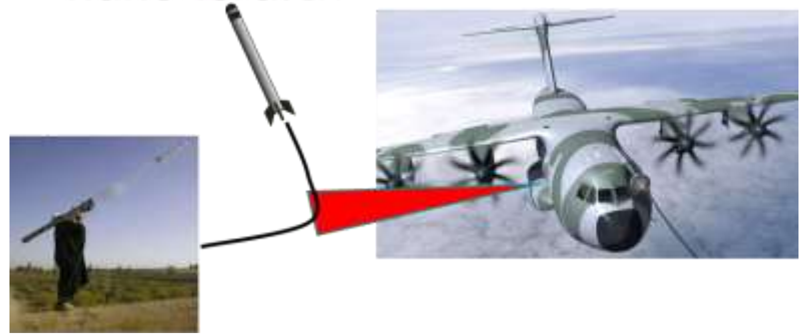
duty cycle: 0.025%



P. Rauter et al., Opt. Express 21 (2013)

2. Recent developments:

- **b.** High optical output power



CW:

P_{opt} = 2.4 W

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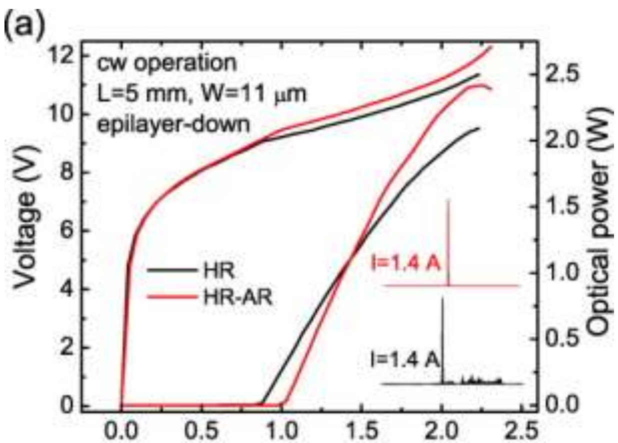

Q. Y. Lu et al., Appl. Phys. Lett. 98 (2011)

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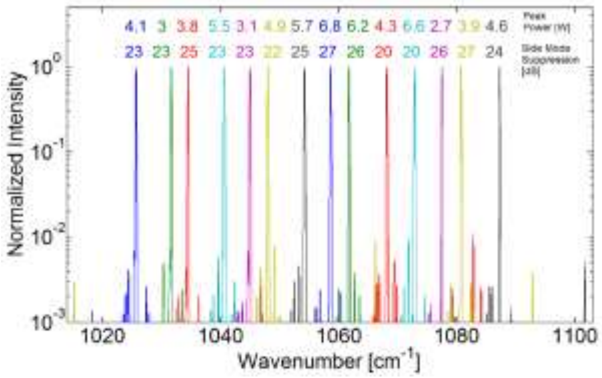
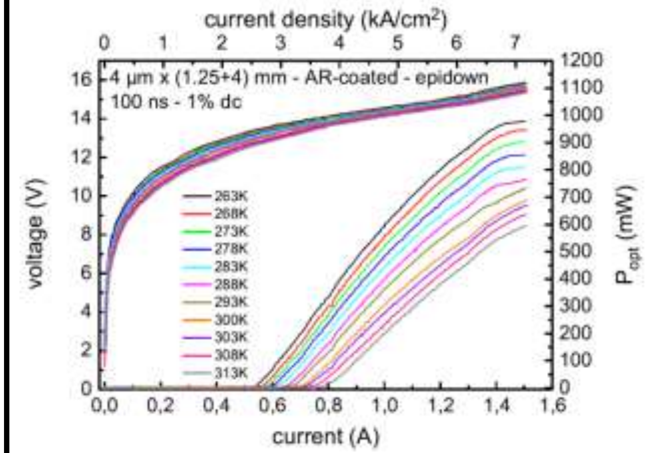


P. Rauter et al., Opt. Express 21 (2013)

P_{opt} = 1 W

Narrow (~4 µm) single-emitters

duty cycle: 1%

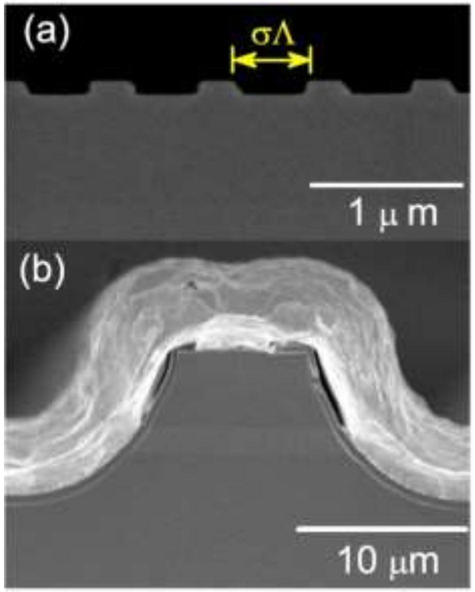


B. Hinkov et al., unpublished

2b. How to increase the DFB output power

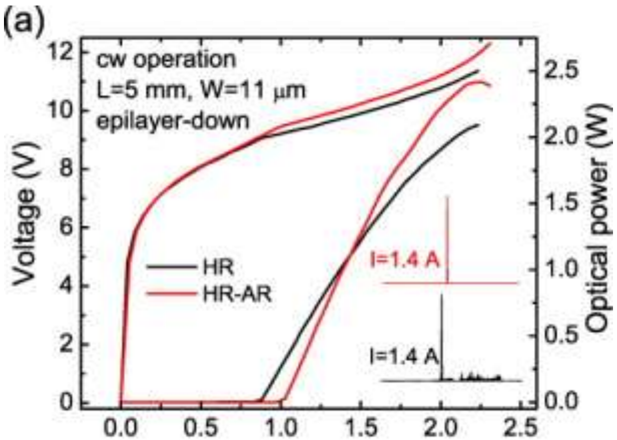
- 1st approach:
  scale up the length of a DFB device

- Surface DFB grating (*complex coupling*)
  → lifts degeneracy (0.4 cm^{-1} discrimination)



- $\kappa = \frac{1}{\Lambda} \cdot \frac{\Delta n}{n_{eff}}$ → κ ~ 1.37 cm^{-1}

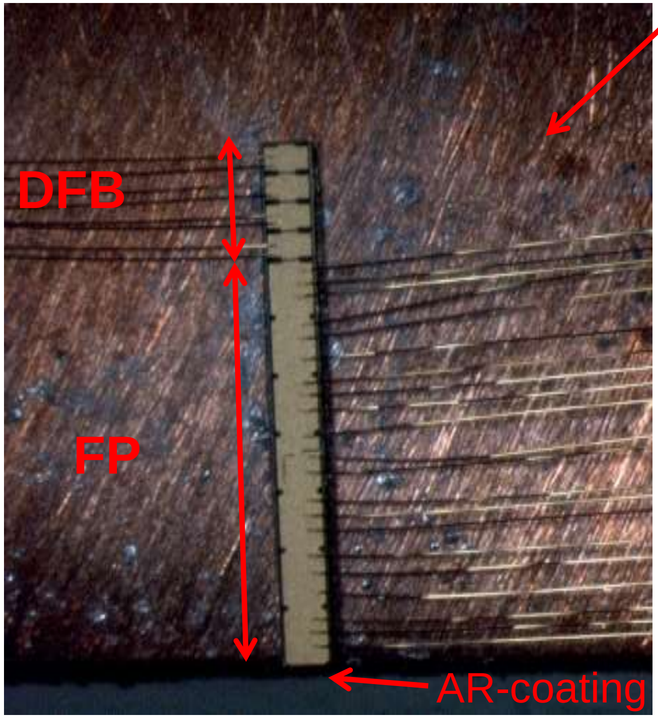
- But weak coupling κ needed,
  very susceptible to defects



Q. Y. Lu et al., Appl. Phys. Lett. 98 (2011)

2b. MOPA*

**M. Troccoli et al., APL 80 (2002)*



- *Alternative*: two sectional device
- *DFB*: singlemode seed

  FP: amplifier section
- *AR-coating*:

  a. suppress FP-selflasing & additional FP-modes within stopband

  b. suppress spatial hole burning in the FP-section

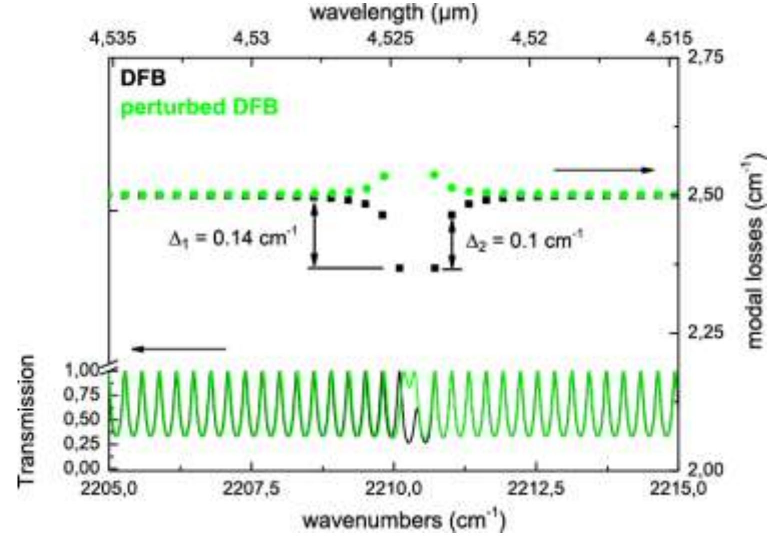
B. Hinkov et al., under review

2b. MOPA vs. DFB

- A. **DFB**: 5.25 mm, $\kappa \sim 1.4\ cm^{-1}$
- Mode-discrimination: bi-mode

  $0.14\ cm^{-1}$ (FP-level)

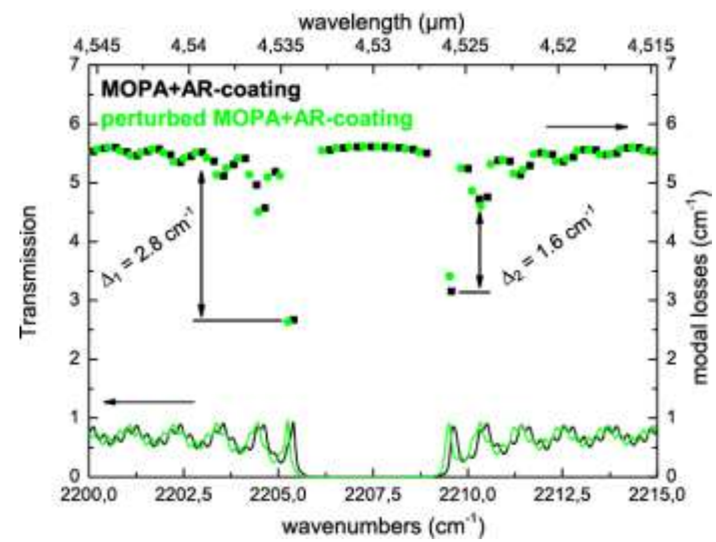
  $0.1\ cm^{-1}$ (non-stopband mode)



- B. **MOPA**: 5.25 mm (1.25 mm DFB), $\kappa \sim 35\ cm^{-1}$
- Mode-discrimination:

  $2.8\ cm^{-1}$ (FP-level)

  $1.6\ cm^{-1}$ (non-stopband mode)



→ > 1 order of magnitude higher

B. Hinkov et al., under review

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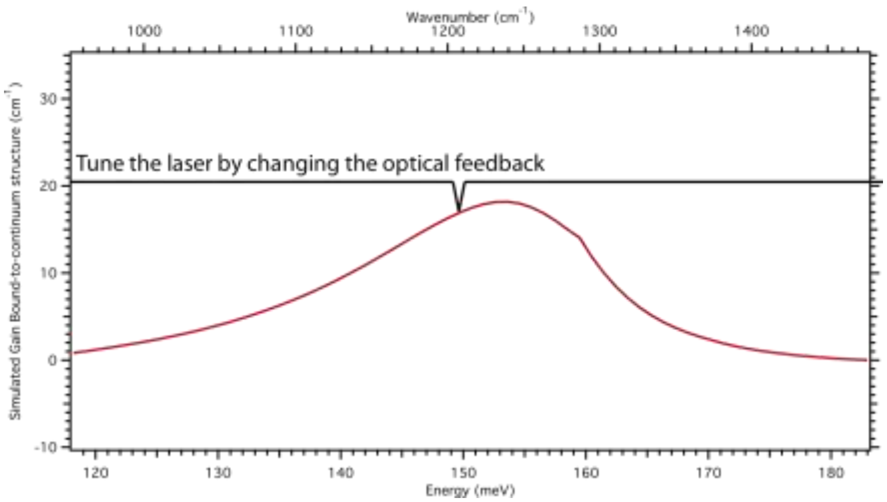
2b. MOPA vs. DFB

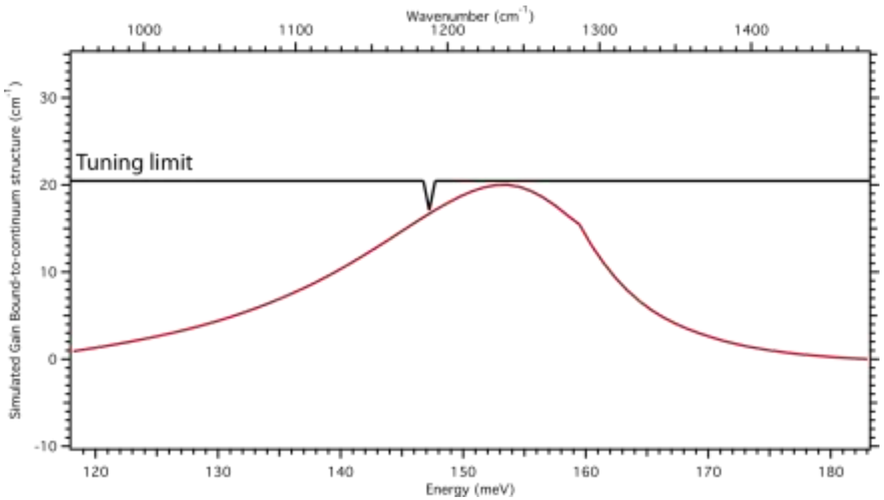
- Spectral coverage depends on:

$$\frac{g_{DFB}(\lambda)}{\alpha_{DFB}} > \frac{g(\lambda_{max})}{\alpha_{FP}}$$

- DFB: $\frac{g_{DFB}(\lambda)}{g(\lambda_{max})} > 0.94$

- MOPA: $\frac{g_{DFB}(\lambda)}{g(\lambda_{max})} > 0.49$





B. Hinkov et al., under review

Courtesy of S. Riedi

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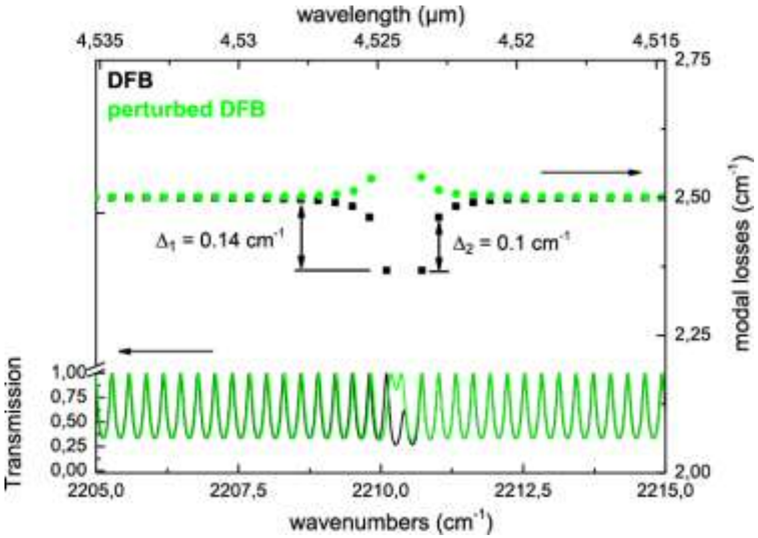


$$\frac{g_{DFB}(\lambda)}{\alpha_{DFB}} > \frac{g(\lambda_{max})}{\alpha_{FP}}$$

B. Hinkov et al., under review

Courtesy of S. Riedi

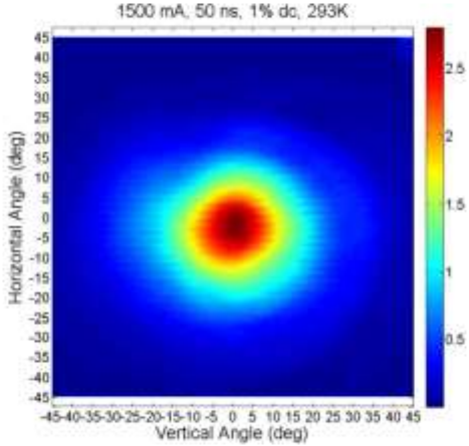
2b. MOPA

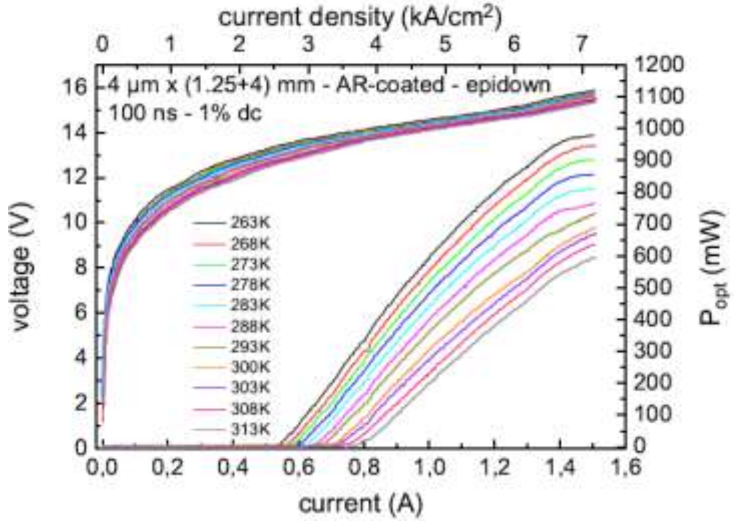
- *Non-tapered device*, 4 µm x (1.25+4) mm + AR-coating

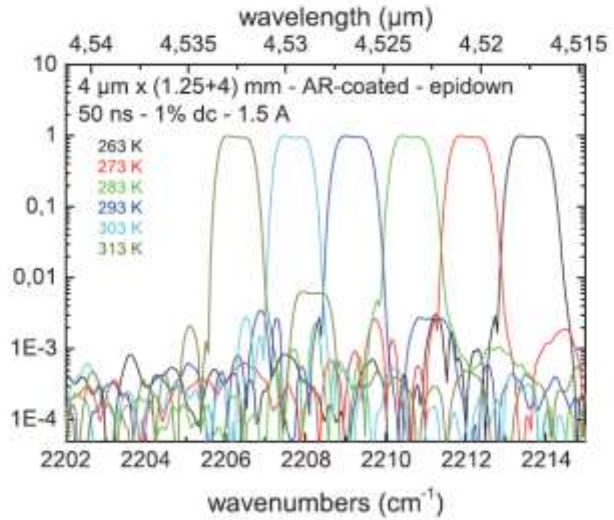
  $P_{opt,peak}$ = 1 W (1% duty cycle)

- Continuous tuning (263K - 313K)

- symm. farfield TM_{00}: FWHM (25° / 27°)

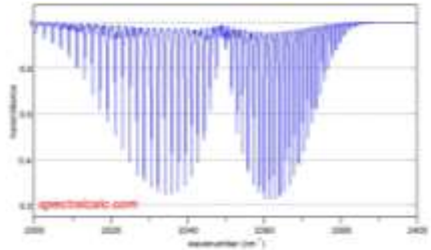


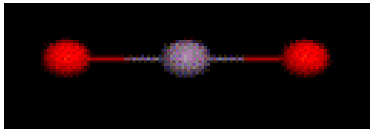




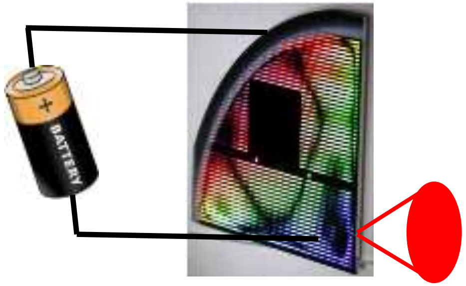
B. Hinkov et al., under review

1. Introduction





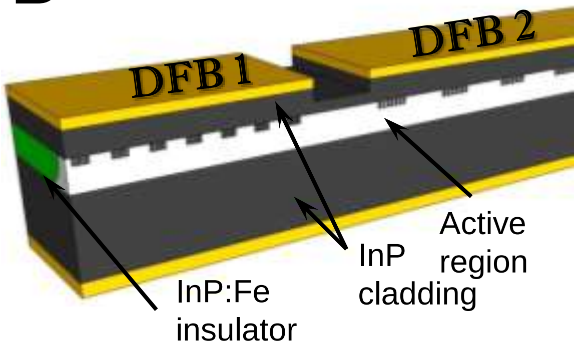
2. Recent developments

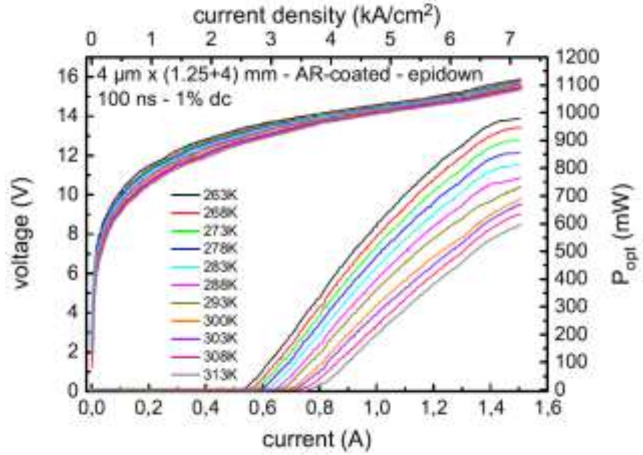


   a. Low electrical dissipation

   b. Master-oscillator power-amplifier (MOPA)

   c. **Dual color DFB**

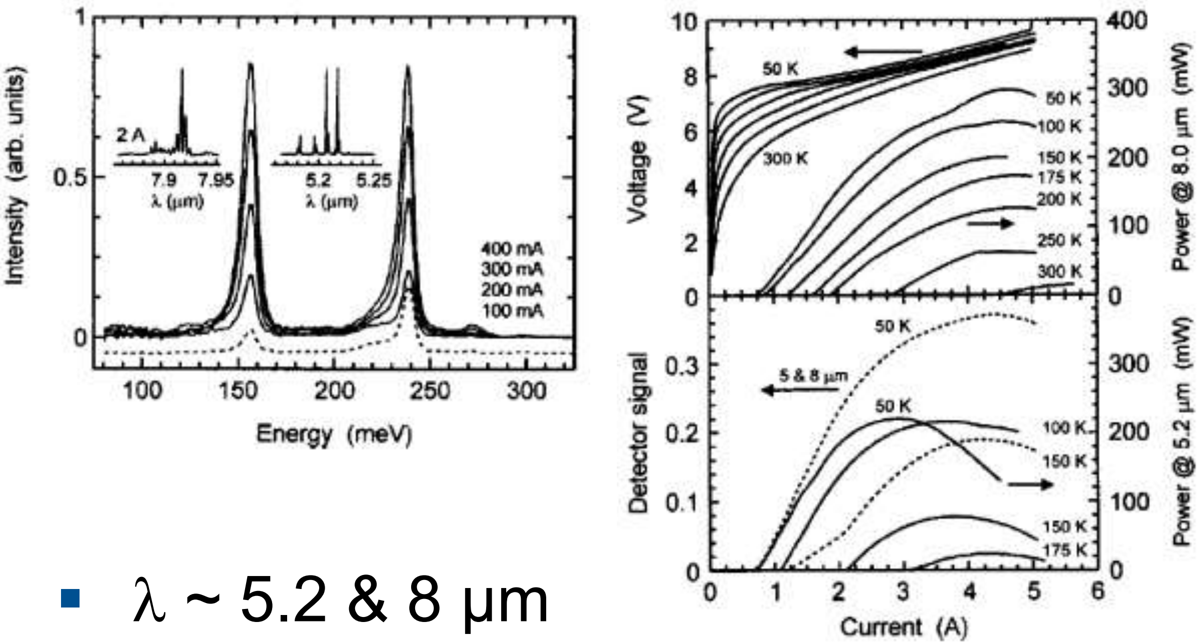




3. Conclusion

2. Recent developments:

- **c.** Dual color



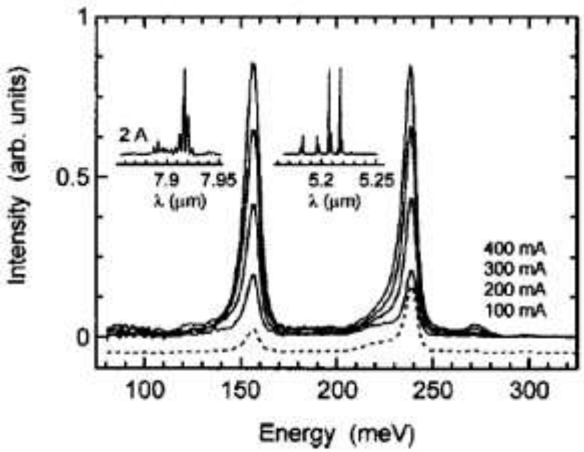
- λ ~ 5.2 & 8 μm

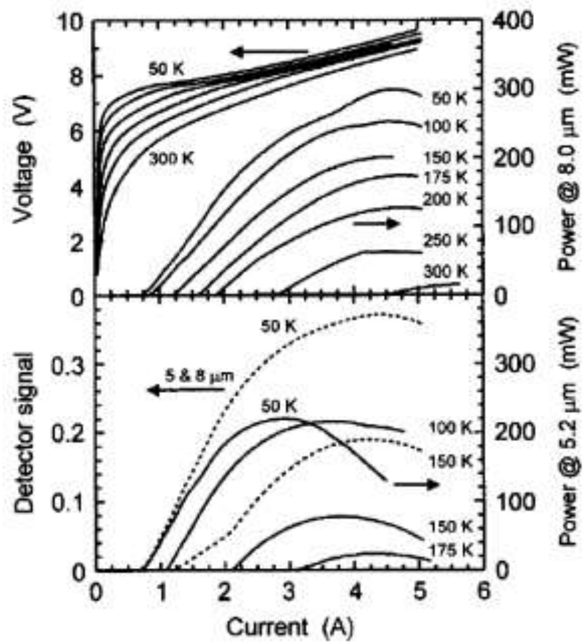
- Simultaneous emission

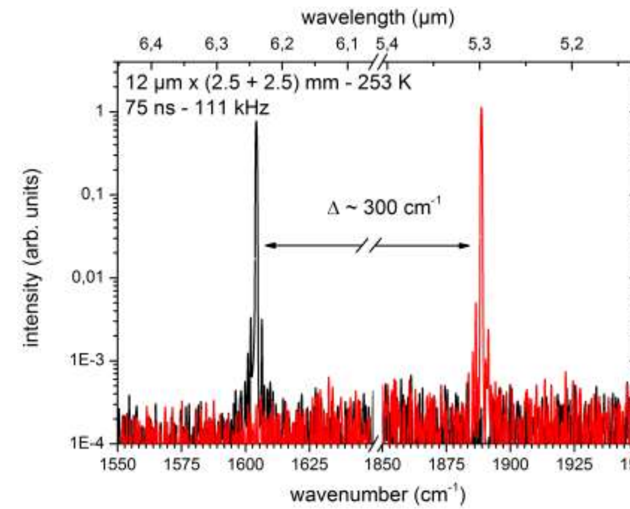
C. Gmachl et al., APL 79 (2001)

2. Recent developments:

- **c.** Dual color







- λ ~ 5.2 & 8 μm
- Simultaneous emission

2 electrically separated DFBs

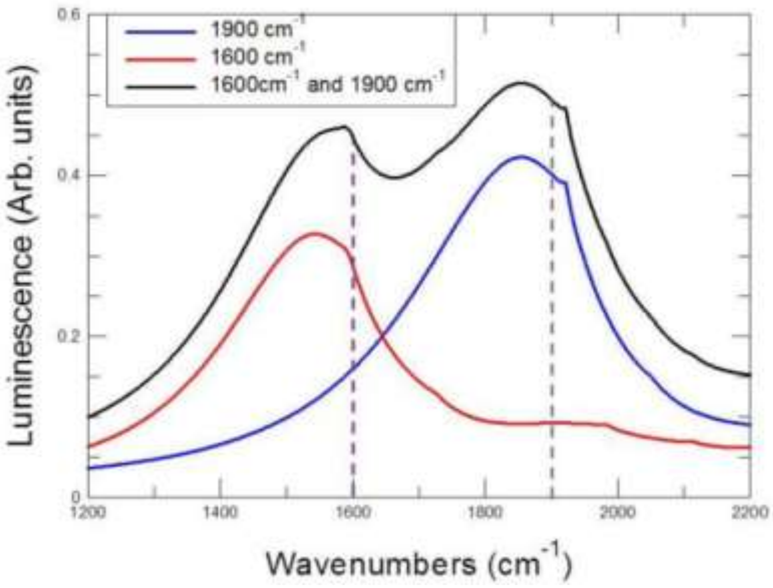
λ can be adressed individually or in parallel

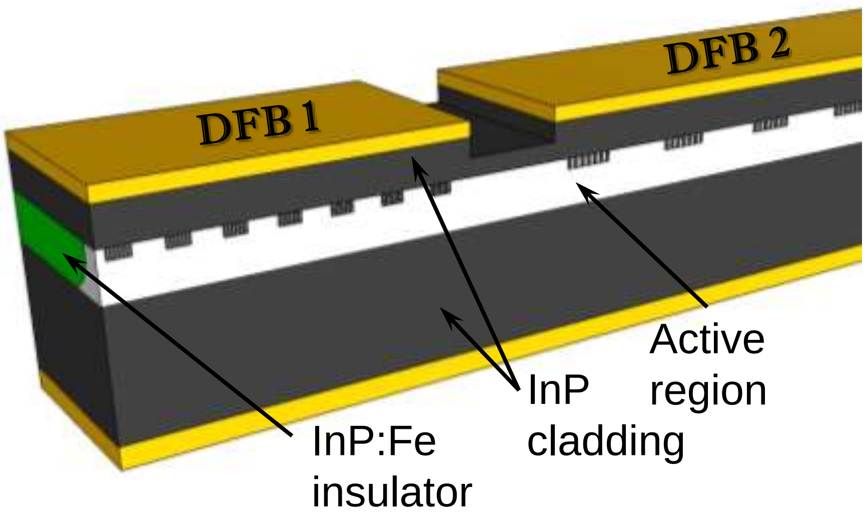
C. Gmachl et al., APL 79 (2001)

P. Jouy et al., unpublished

5.1 Dual color DFBs - concept

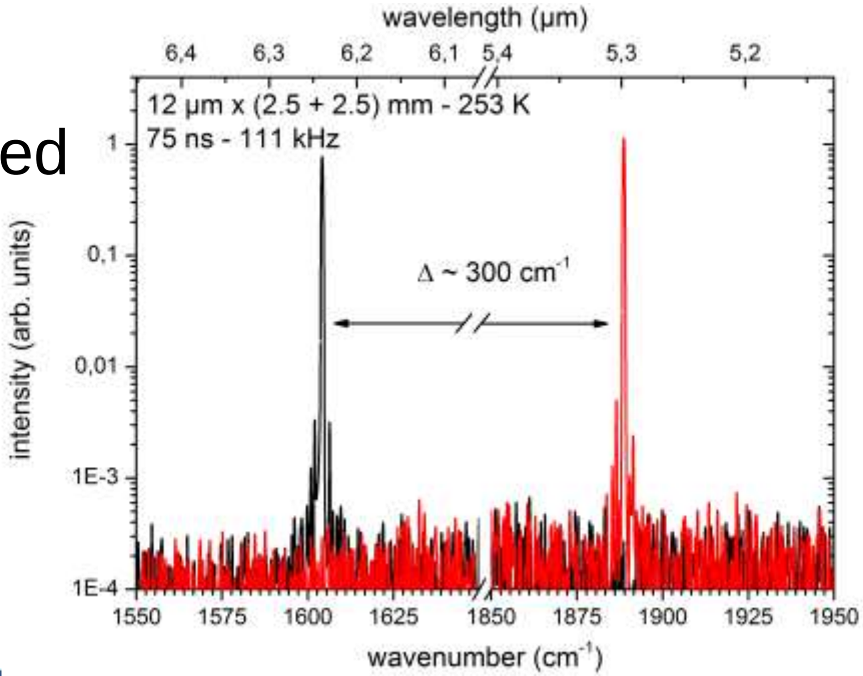
- *Dual* single-wavelength emitting devices (λ/4-shifted)
- Detection of two different species from one optical waveguide
- Species can be separated by very different wavelengths



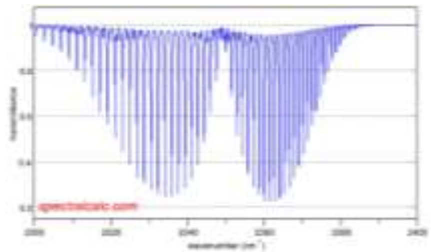


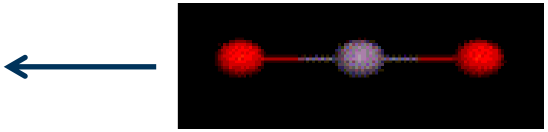
5.2 Dual color DFBs - results

- Two color active region: 1600 cm^{-1} (NO_2) & 1900 cm^{-1} (NO)
- 2 electrically separated sections
- Both wavelengths can be addressed individually or in parallel
- 300 cm^{-1} separation



1. Introduction





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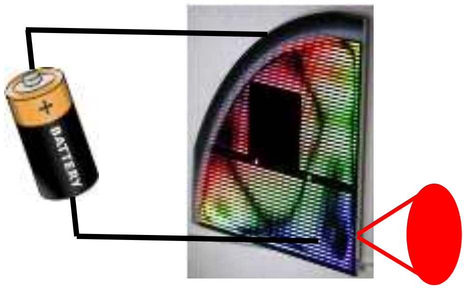

a. Low electrical dissipation

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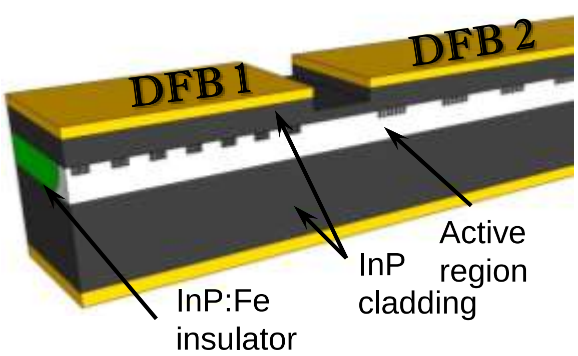
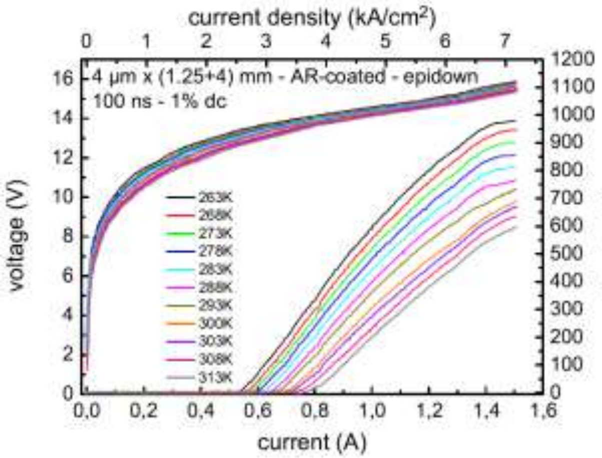
3. Conclusion





6. Conclusion:

- Overview of recent developments in DFB QC lasers (tunability, el. dissipation, high output power, dual-wavelength)

- *3 examples in more detail:*

1. *low dissipation* DFB QCL (< 1W, $P_{opt,CW}$ >> 10 mW)

2. *MOPA* QCL (new design, $P_{opt,peak}$ ~ 1W untapered)

3. *Dual-color* DFB QCL (selective dual-λ, 300 cm^{-1} separation)