About Omics Group

OMICS Group International through its Open Access Initiative is committed to make genuine and reliable contributions to the scientific community. OMICS Group hosts over 400 leading-edge peer reviewed Open Access Journals and organize over 300 International Conferences annually all over the world. OMICS Publishing Group journals have over 3 million readers and the fame and success of the same can be attributed to the strong editorial board which contains over 30000 eminent personalities that ensure a rapid, quality and quick review process.

About Omics Group conferences

OMICS Group signed an agreement with more than 1000 International Societies to make healthcare information Open Access. OMICS Group Conferences make the perfect platform for global networking as it brings together renowned speakers and scientists across the globe to a most exciting and memorable scientific event filled with much enlightening interactive sessions, world class exhibitions and poster presentations

Omics group has organised 500 conferences, workshops and national symposium across the major cities including SanFrancisco,Omaha,Orlado,Rayleigh,SantaClara,Chicago,Philadelphia,Unitedkingdom,Baltimore,SanAntanio,Dubai,Hyderabad,Bangaluru and Mumbai.

High performance, low dissipation QCL across the Mid-IR range.

08.09.14 / Alfredo Bismuto

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Outline

Introduction

Mid-IR spectral range: applications
Alpes Lasers SA overview

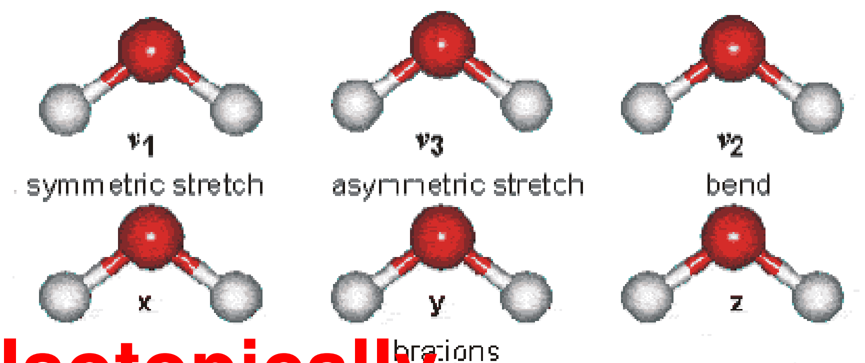
Single mode sources

Fabrication process
QCLs for mass production (device length impact)
Impact of front reflective coating on short devices
DFB sources below 1W between 4.5-9.3 µm
High power DFBs

Conclusion and next steps

Mid-IR range (2-20µm)

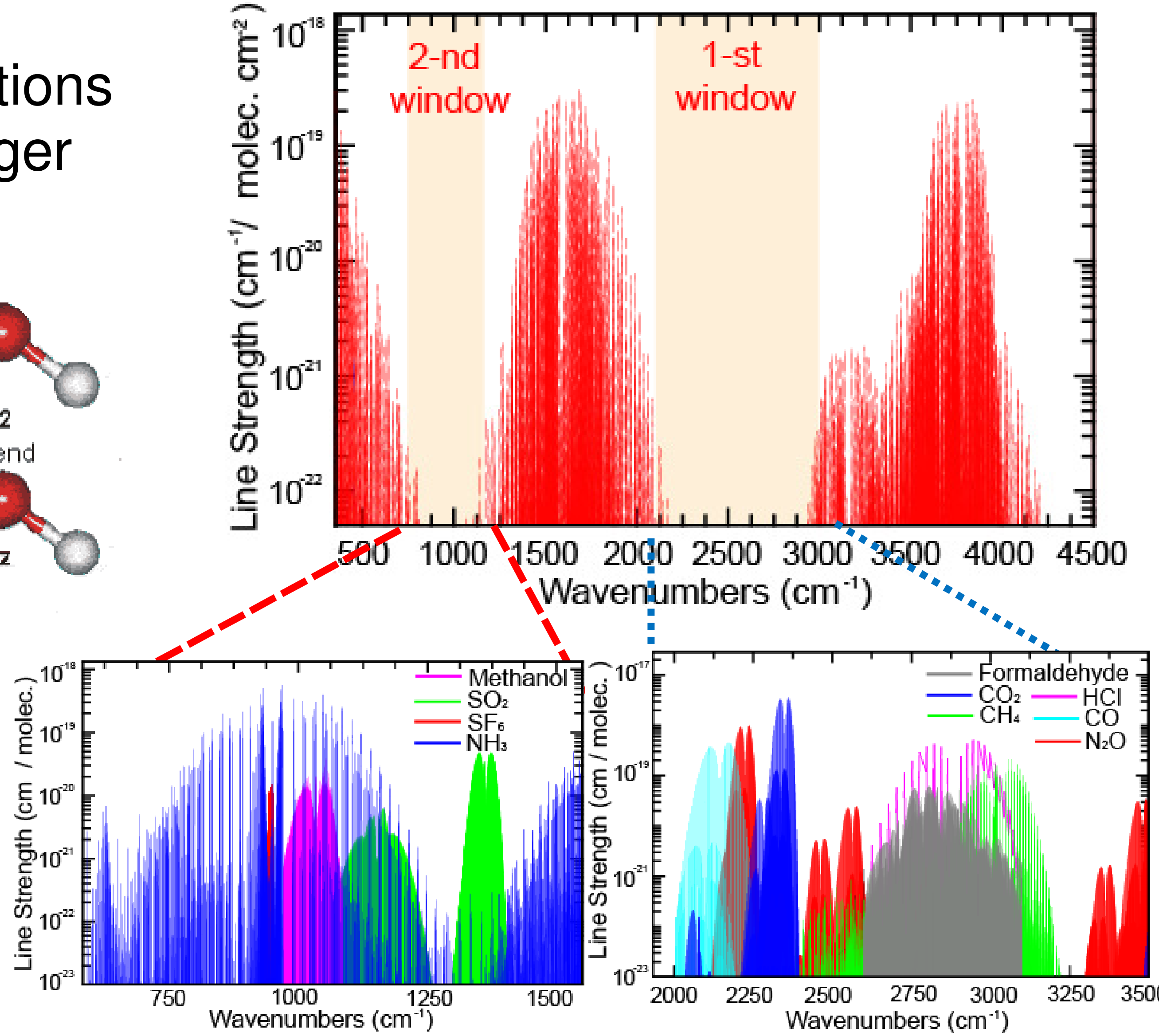
Strong molecular absorptions (orders of magnitude bigger than in the NIR-range)



Isotopically sensitive

NO_2, CO, CO_2, CH_4, NH_3, CH_2CO, O_3, N_2O HF, HCl

H_2O abosorption



ALPES LASERS

Applications

- **Enviromental gas monitoring**
  - **Atmospheric chemistry**
  - **Volcanic emissions**

- **Urban and Industrial emission control**
  - **Industrial plants**
  - **Automobile and Aircraft emissions**
  - **Combustion process control**

- **Rural emission measurements**

- **Biochemical and Clinical diagnostics**
  - **Breath analysis (NO, CO, CH4, S)**
  - **Glucose level control (in-vivo)**

Limitation and challenges

A killer application is still missing...why?

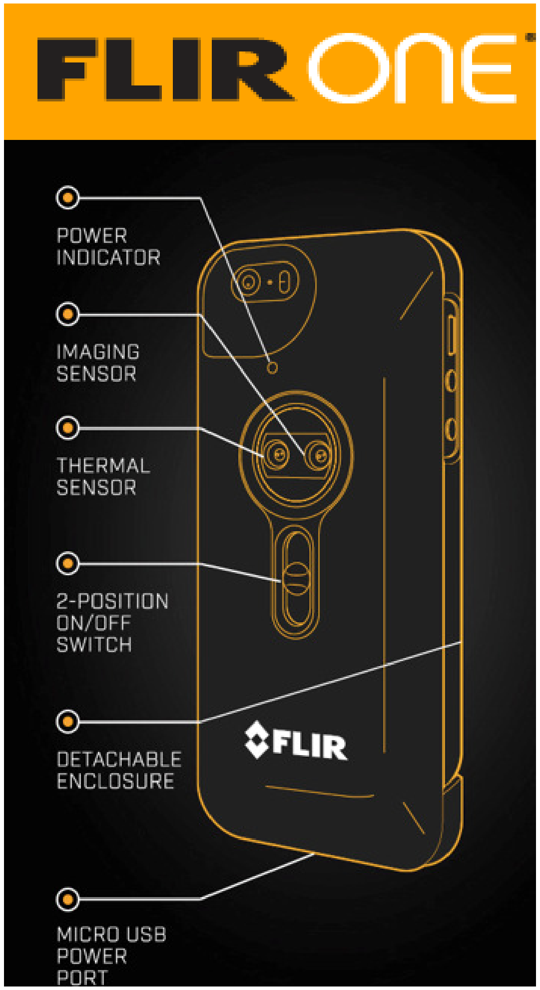
- **Laser sources**
  - Low efficiency (~10%) compared to diode lasers (~50%)
  - High electrical dissipation (W_{el}>1W)
  - Nb of lasers per wafers still low (long lasers & small wafers)
  - Fabrication is still expensive
- **Photonics**
  - Difficult to do photonic integration
  - Optical elements expensive (lenses/windows/fibers)
  - Detectors less sensitive and more expensive

Horizon

Things are changing....

FLIR introduced the FLIRONE project
a IR camera compatible with the Iphone

The cameras should cost less than 350 $



Many big company are trying to develop products in the IR

See also : **http://www.flir.com/flirone/explore/**

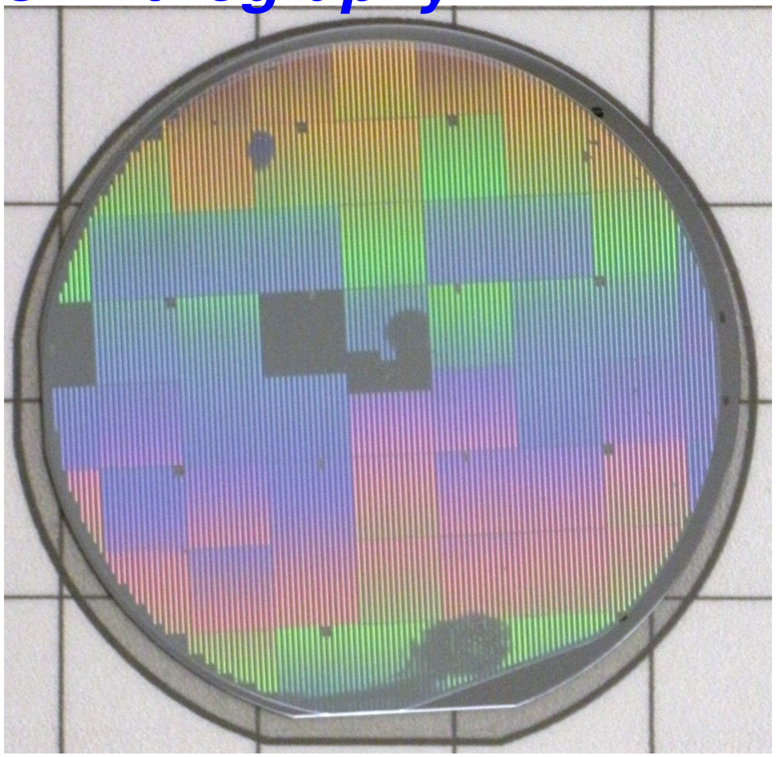
Our company

Alpes Lasers

- founded in 1998
- 21 employees (11PhD, 5 eng.)
- New product design team growing
- Fabless component manufacturer
- Widening products portafolio
- 2400+ sold lasers

DFB technology

UV-lithography



DFB grating during fabrication

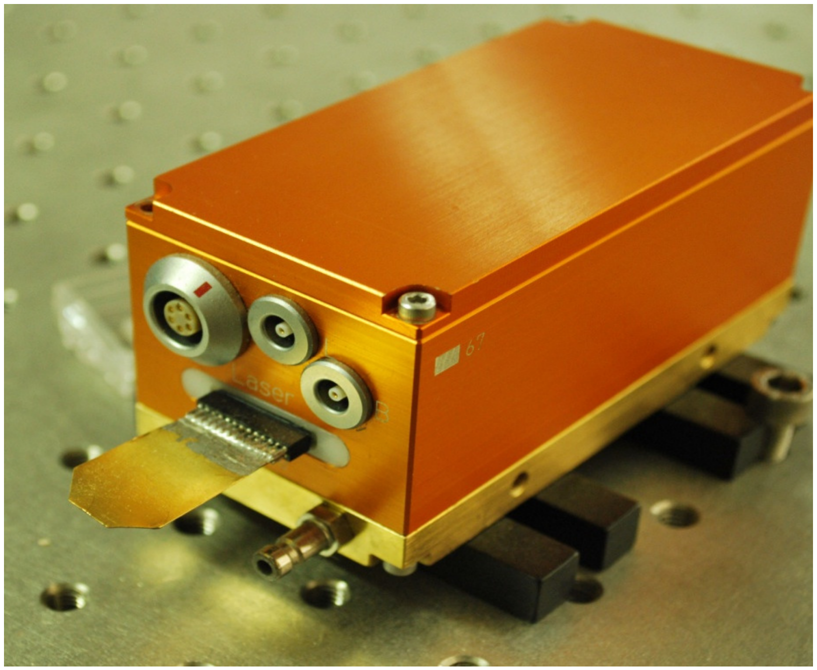
		C7 1.9655 0.8%	D7 1.9145 1.6%	E7 1.8085 2.0%	F7 1.9255 1.6%	G7 1.8765 0.8%		
	B6 1.836 1.2%	C6 1.948 2.0%	D6 1.8645 2.0%	E6 1.8765 2.0%	F6 1.7765 2.0%	G6 1.8695 2.0%	H6 1.933 1.2%	
A5 1.887 0.4%	B5 1.741 2.0%	C5 1.7375 2.0%	D5 1.741 2.0%	E5 1.8835 2.0%	F5 1.734 2.0%	G5 1.746 2.0%	H5 1.887 2.0%	I5 1.7765 0.4%
A4 (LOCK) 00.00000 1.0%	B4 1.8395 2.0%	C4 1.8835 2.0%	D4 (LOCK) 00.00000 2.0%	E4 1.848 1.5%	F4 1.9555 2.0%	G4 1.8765 2.0%	H4 1.873 2.0%	I4 1.7375 1.0%
A3 1.831 1.0%	B3 1.789 2.0%	C3 1.873 2.0%	D3 1.88 2.0%	E3 1.7375 1.5%	F3 1.7565 2.0%	G3 1.887 2.0%	H3 1.799 2.0%	I3 1.843 1.0%
A2 1.746 0.5%	B2 1.9045 2.0%	C2 1.843 2.0%	D2 1.892 2.0%	E2 1.751 2.0%	F2 1.836 2.0%	G2 1.8395 2.0%	H2 1.7615 2.0%	I2 1.9655 0.5%
	B1 1.8695 1.4%	C1 1.9405 2.0%	D1 1.897 2.0%	E1 1.8185 2.0%	F1 1.88 2.0%	G1 1.8595 2.0%	H1 1.826 1.4%	
		C0 1.8545 1.1%	D0 1.724 1.9%	E0 1.729 2.0%	F0 1.7665 1.9%	G0 1.734 1.1%		

Proprietary design tool

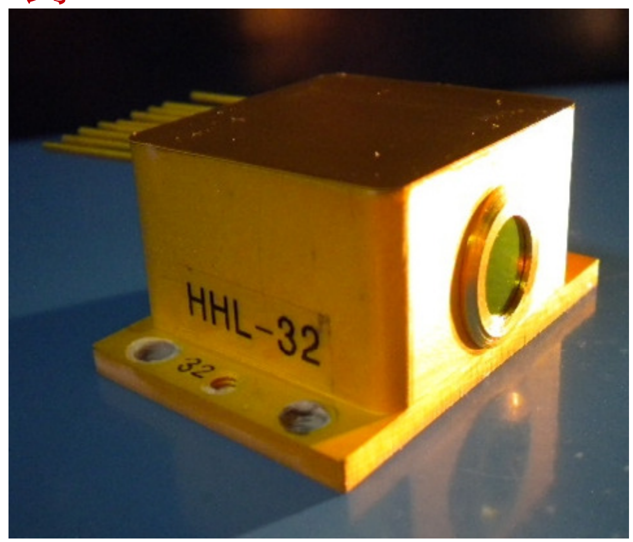
- Gratings written by standard lithography from 4-12 µm
- Many different wavelengths can be fabricated at once
- Efficient device mounting
- Full 2"- wafer process
- Polyvalent production process

QCL subsystems

錞LLH

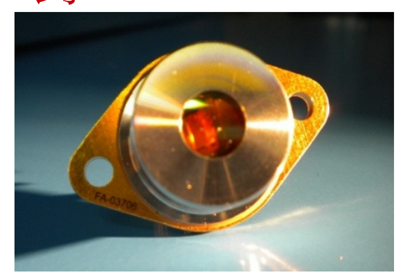


錞HHL-L



錞TO3-L

錞TO3-W



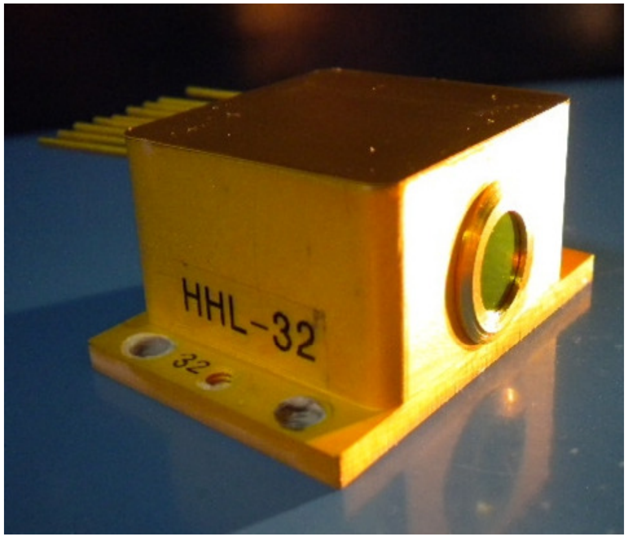
Used only in the initial testing phase

QCL subsystems

- LLH

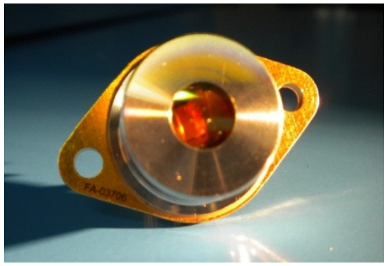
Used only in the initial testing phase

- HHL-L



- TO3-L

- TO3-W



- low consumption packages being
- validated (TO5, etc.)

Outline

Introduction

- Mid-IR spectral range: applications
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Single mode sources

- Fabrication process
- QCLs for mass production (device length impact)
- DFB sources below 1W between 4.5-8 µm
- Impact of front reflective coating on short devices
- High power DFBs

Conclusion and next steps

Thermal budget in QCLs

- Most of QCLs have 5-15 W of electrical dissipation
- Up to 100 W are needed to control the temperature
- Optical power levels of few mW sufficient for many applications

Thermal budget in QCLs

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- Up to 100 W are needed to control the temperature
- Optical power levels of few mW sufficient for many applications

Research goal:

- Low dissipation devices
- Short chips
- Still enough optical power for spectroscopy
-

Advantages of short devices

- Low dissipation (Easy cw bar testing)
- More devices per wafer

Advantages of short devices

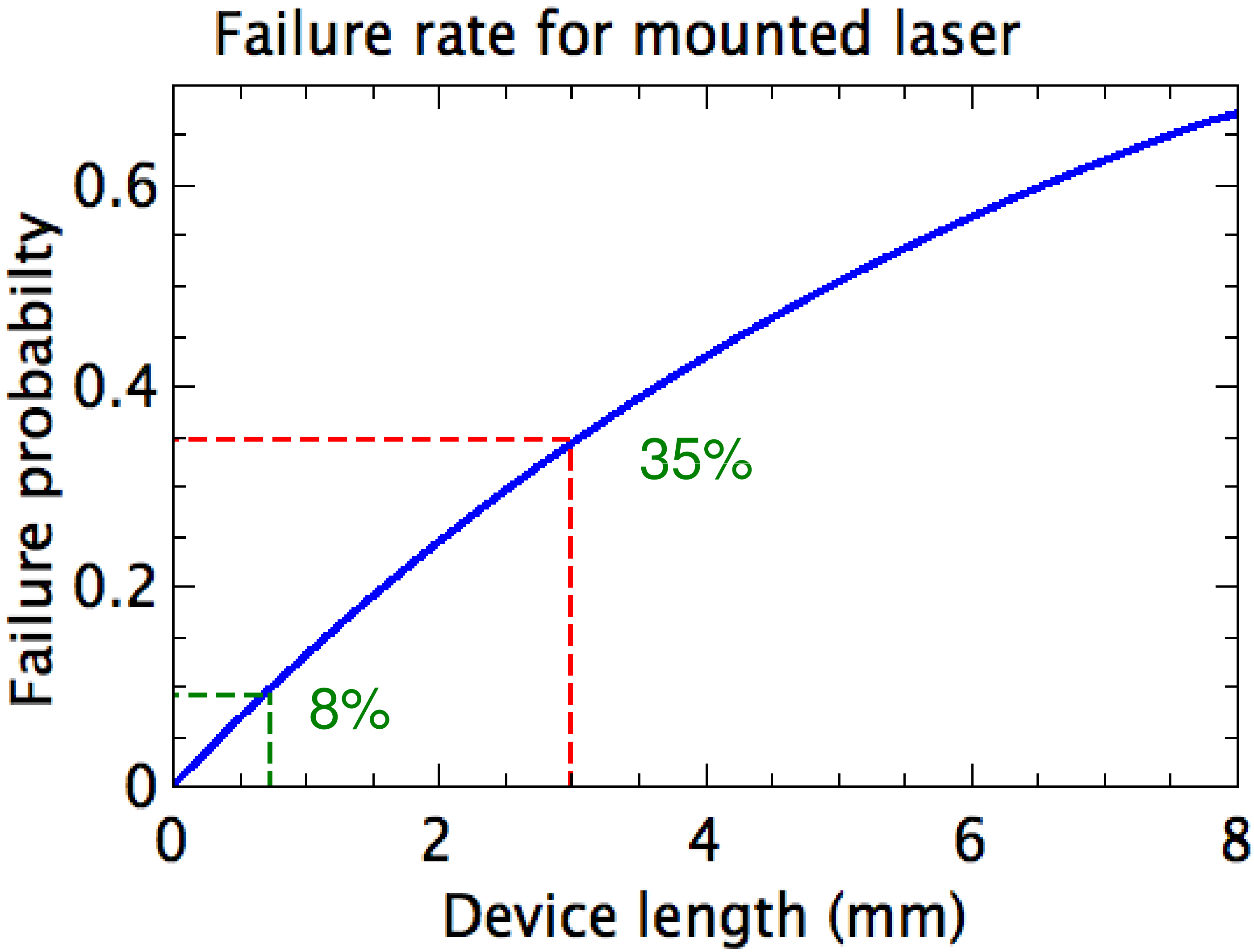
- Low dissipation (Easy cw bar testing)
- More devices per wafer
- Probability of defect (λ) follows a Poissonian law
- Failure rate sensibly reduced with shorter lasers

Number of defects

$$P = \sum_k \lambda^k \frac{e^{-\lambda}}{k!}$$

Probability of major defect in the laser wg

Advantages of short devices



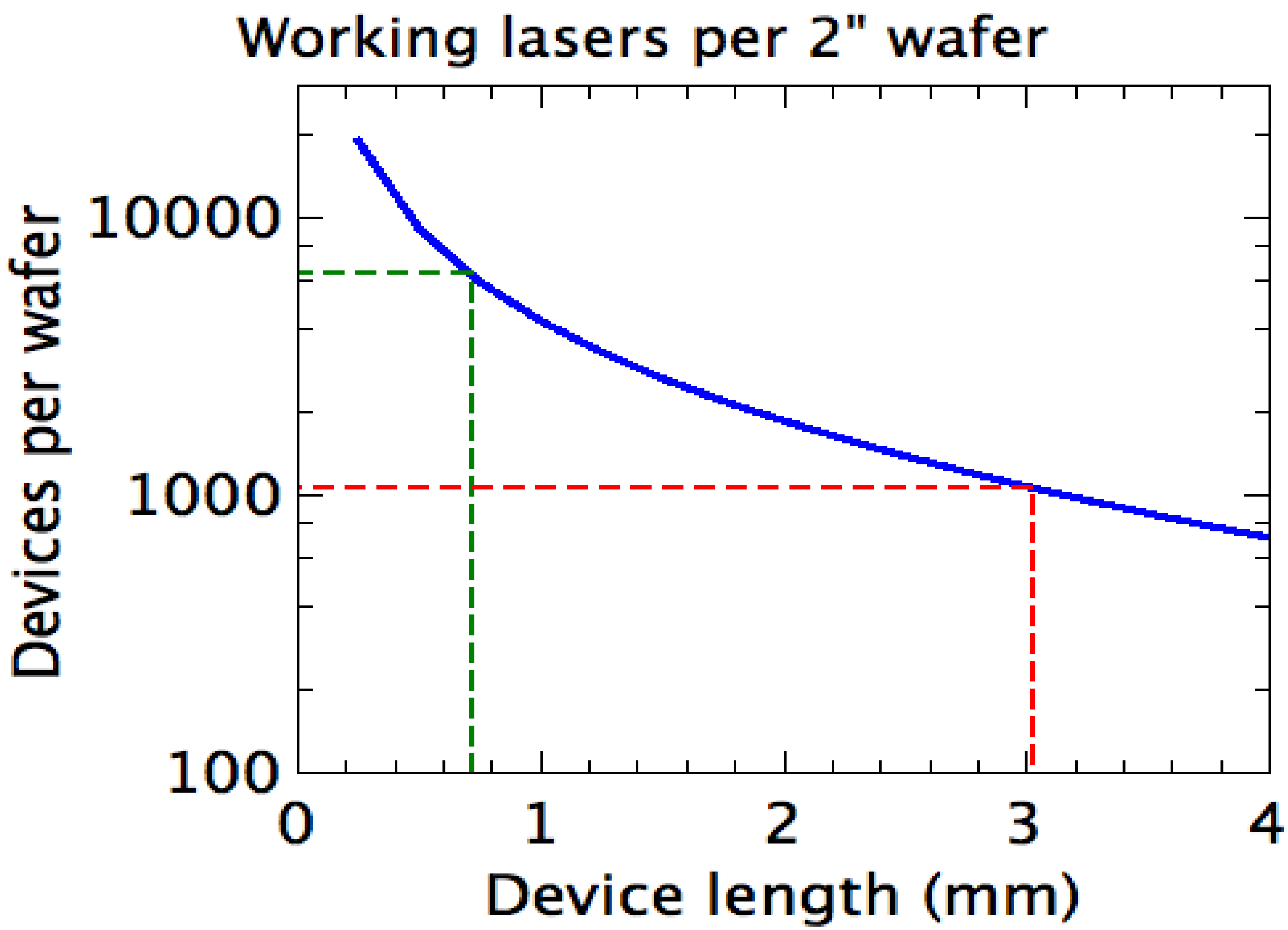
Number of defects

$$P = \sum_k \lambda^k \frac{e^{-\lambda}}{k!}$$

Probability of major defect in the laser wg

- Defect density estimated on the AL-Stock data (preliminary)

Advantages of short devices



Number of defects

for many applications

$$P = \sum_k \lambda^k \frac{e^{-\lambda}}{k!}$$

an law

Probability of major defect in the laser wg

Doublefold impact on the number of chips/wafer

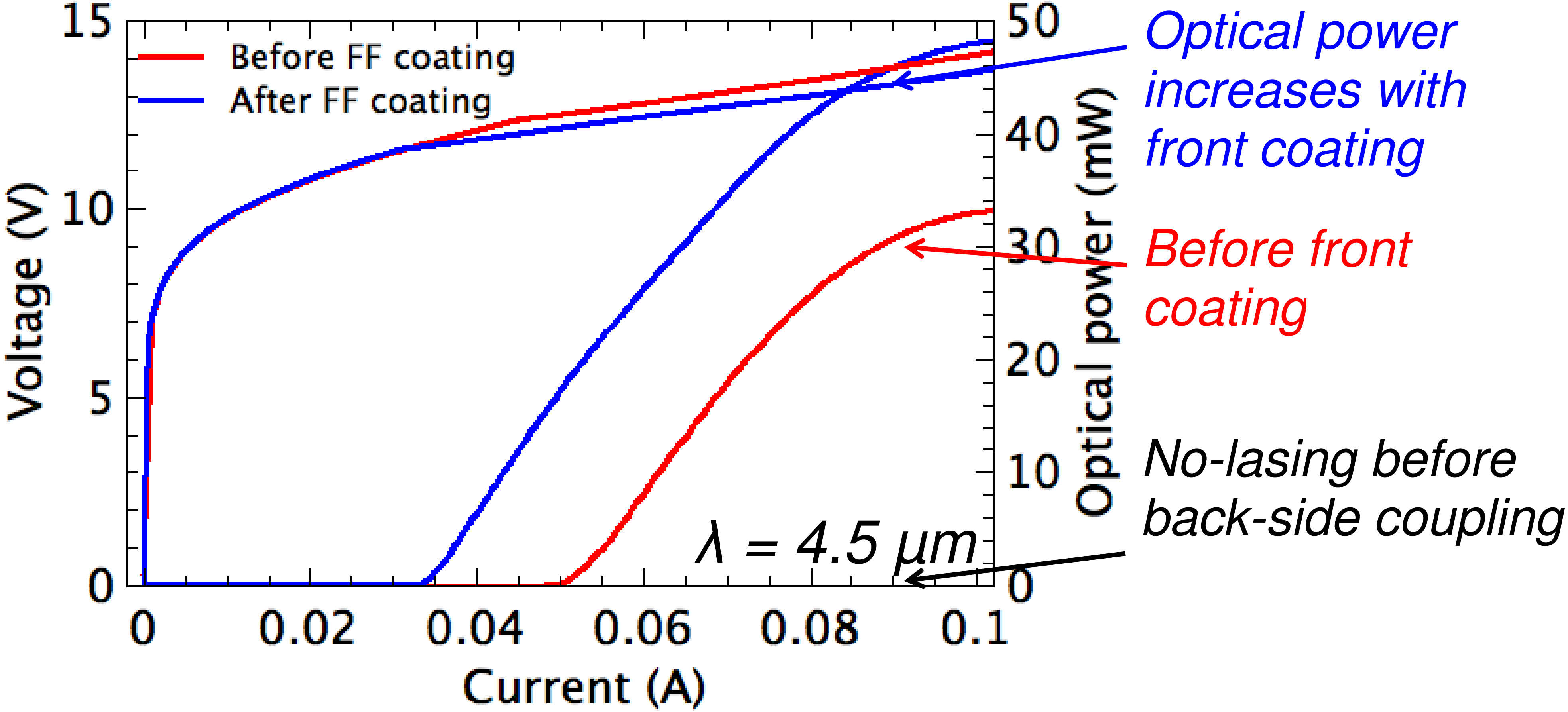
Optimizing reflectivity for short devices

- Starting range 4.5 µm and 5.5 µm
- Optimize the grating coupling to obtain both

low consumption DFBs and **high power DFBs** on the **same wafer**

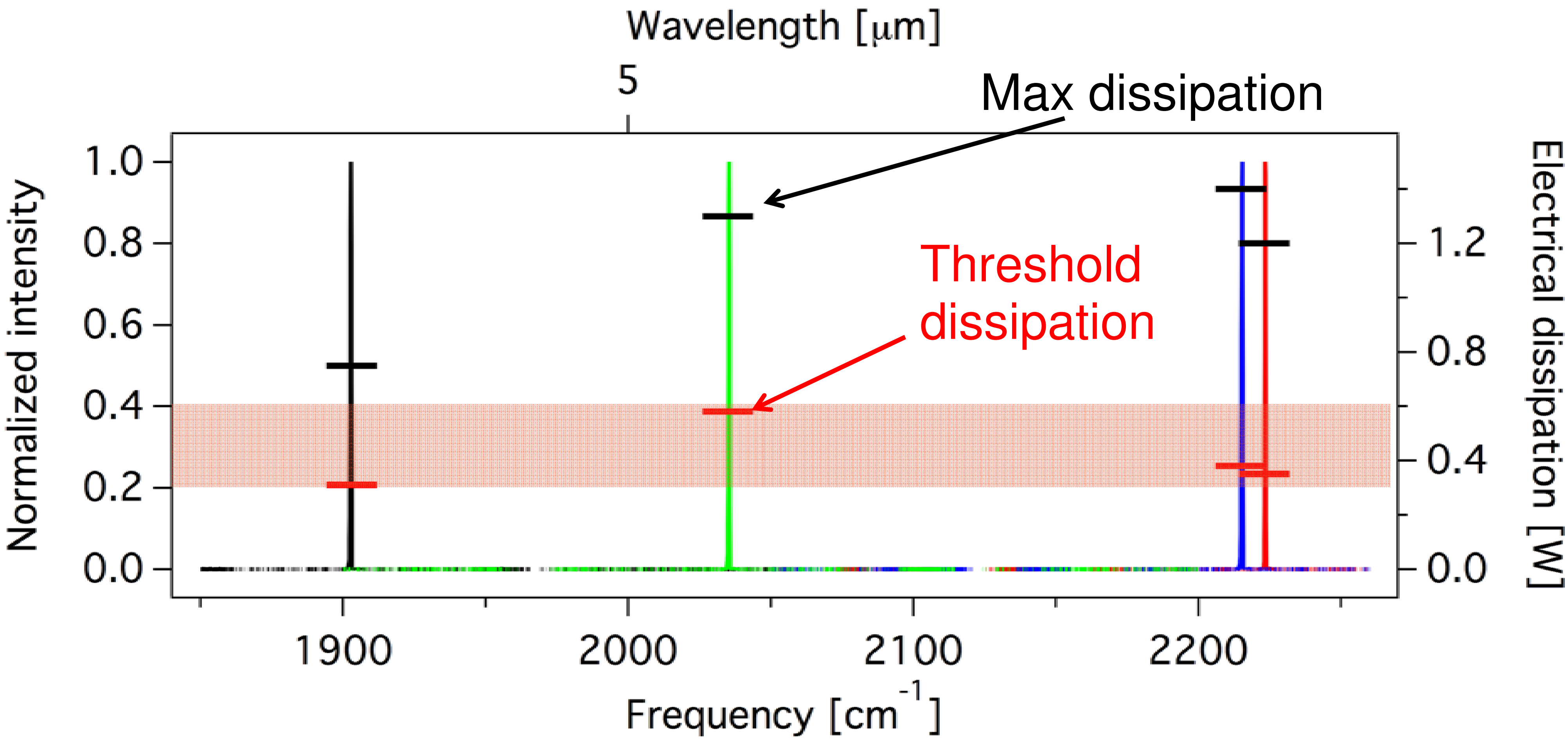
- *750 µm long devices, 3-4 µm wide*
- Back-facet HR coating
- Partial front HR coating

Front HR coating (dielectric)



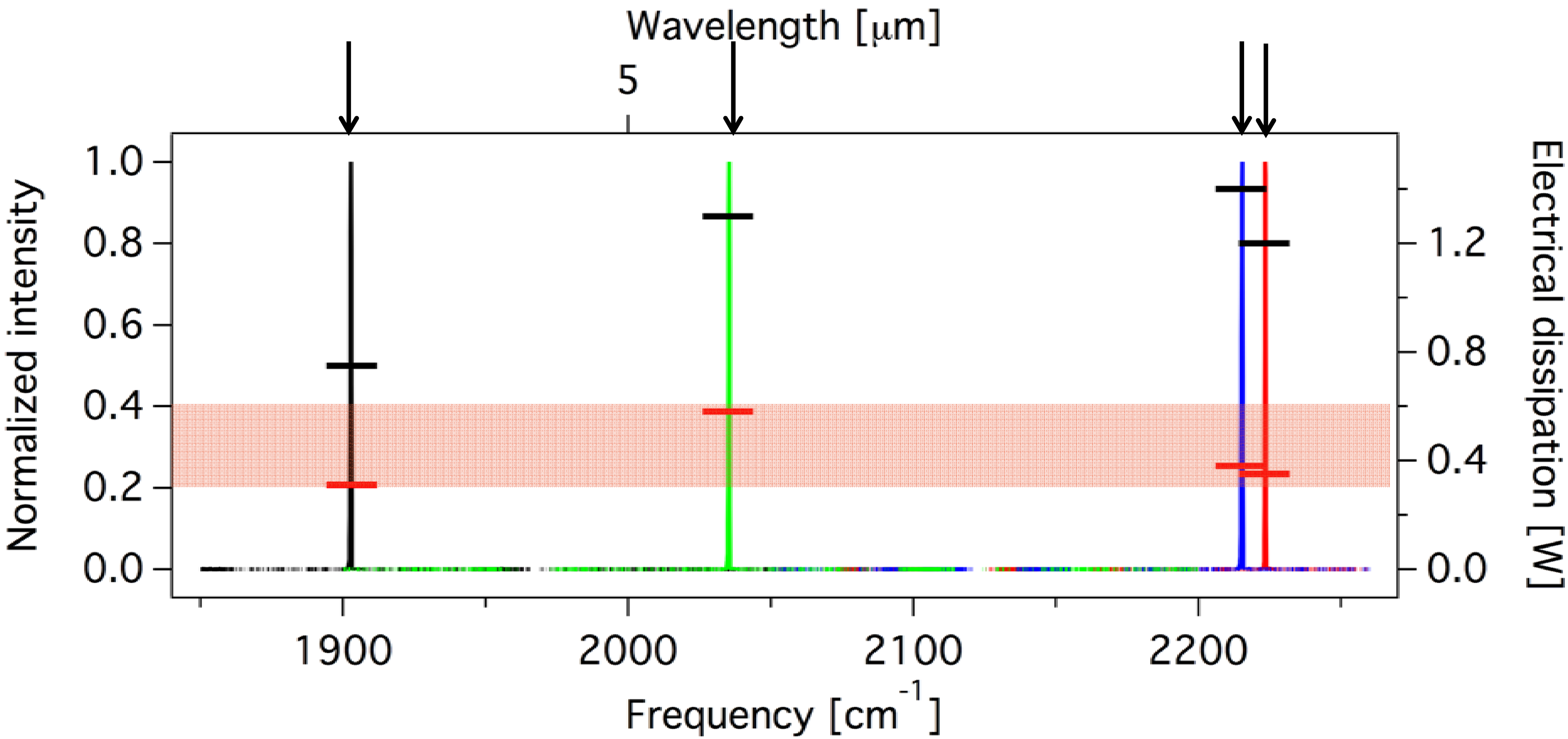
750 µm long devices
3 µm wide ridge

Low consumption devices



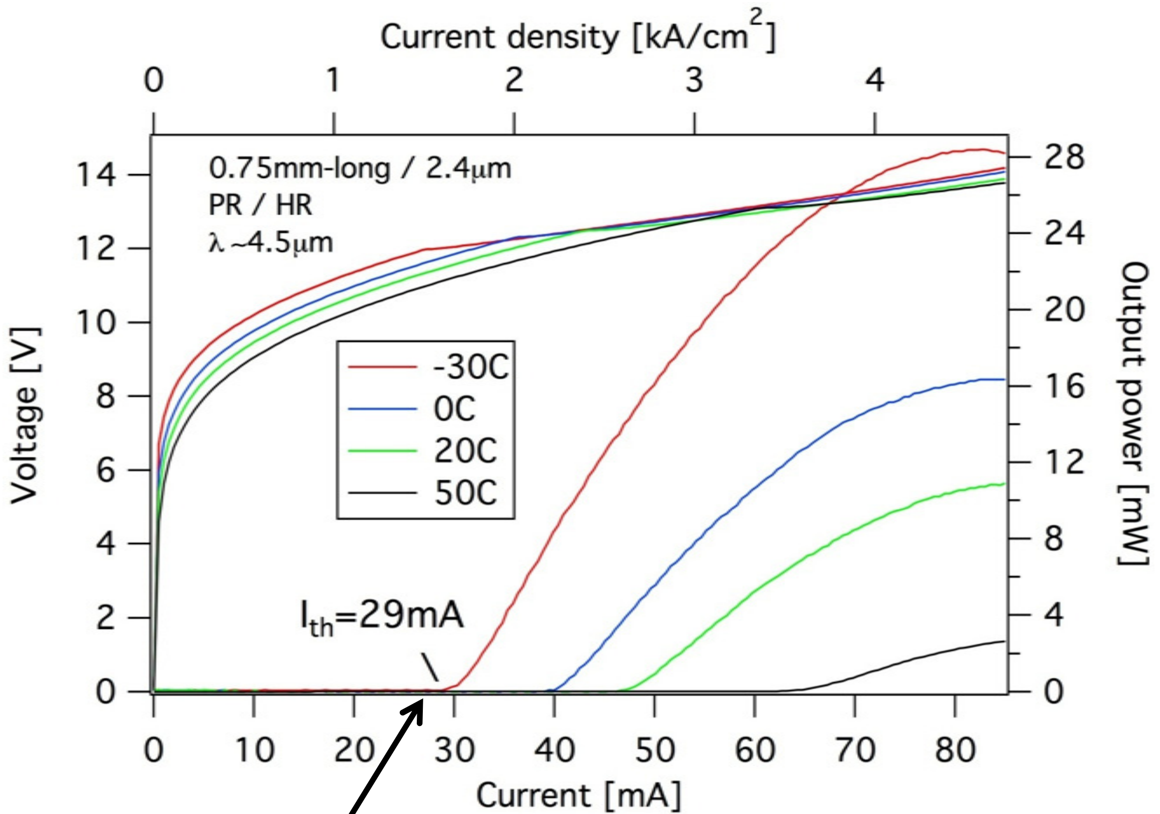
- Dissipation at threshold as low as 0.3W
- Max consumption < 1.4W between 4.5m and 5.3m

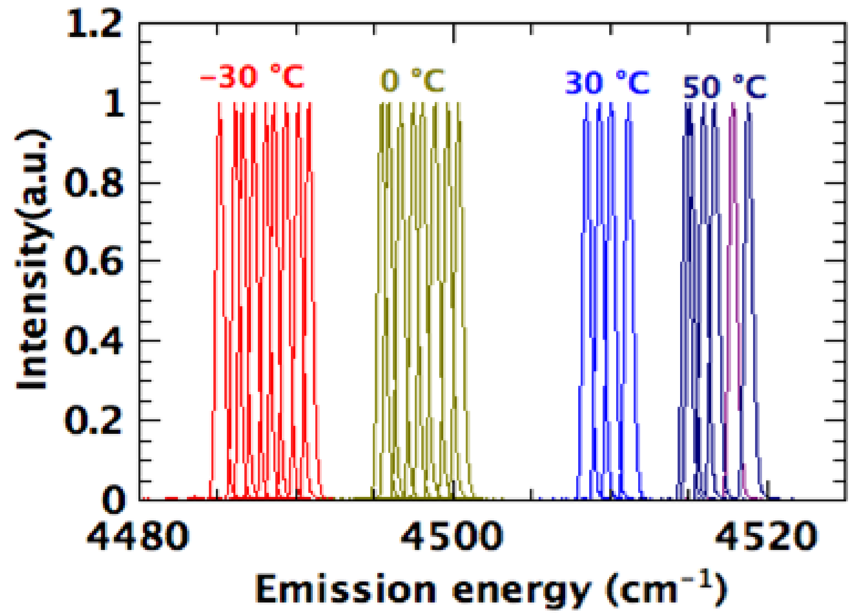
Low consumption devices

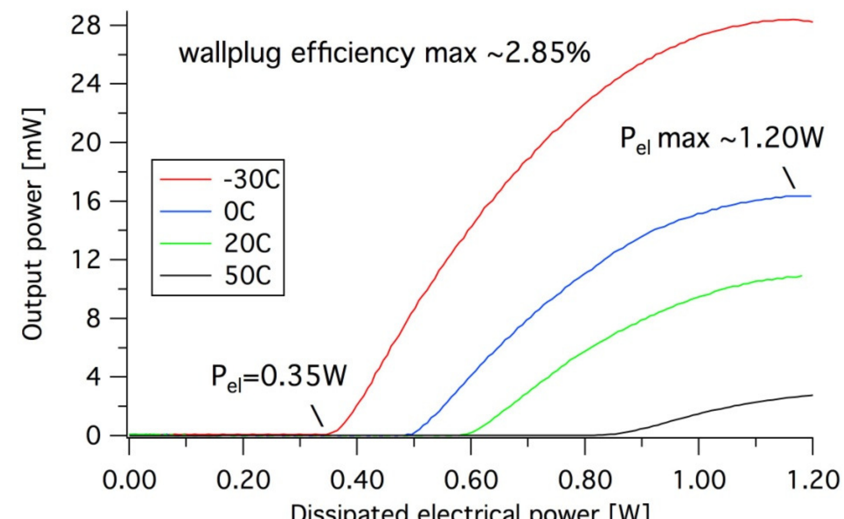


- Dissipation at threshold as low as 0.3W
- Max consumption < 1.4W between 4.5□m and 5.3□m

Low-dissipation DFB devices at 4.5 μm

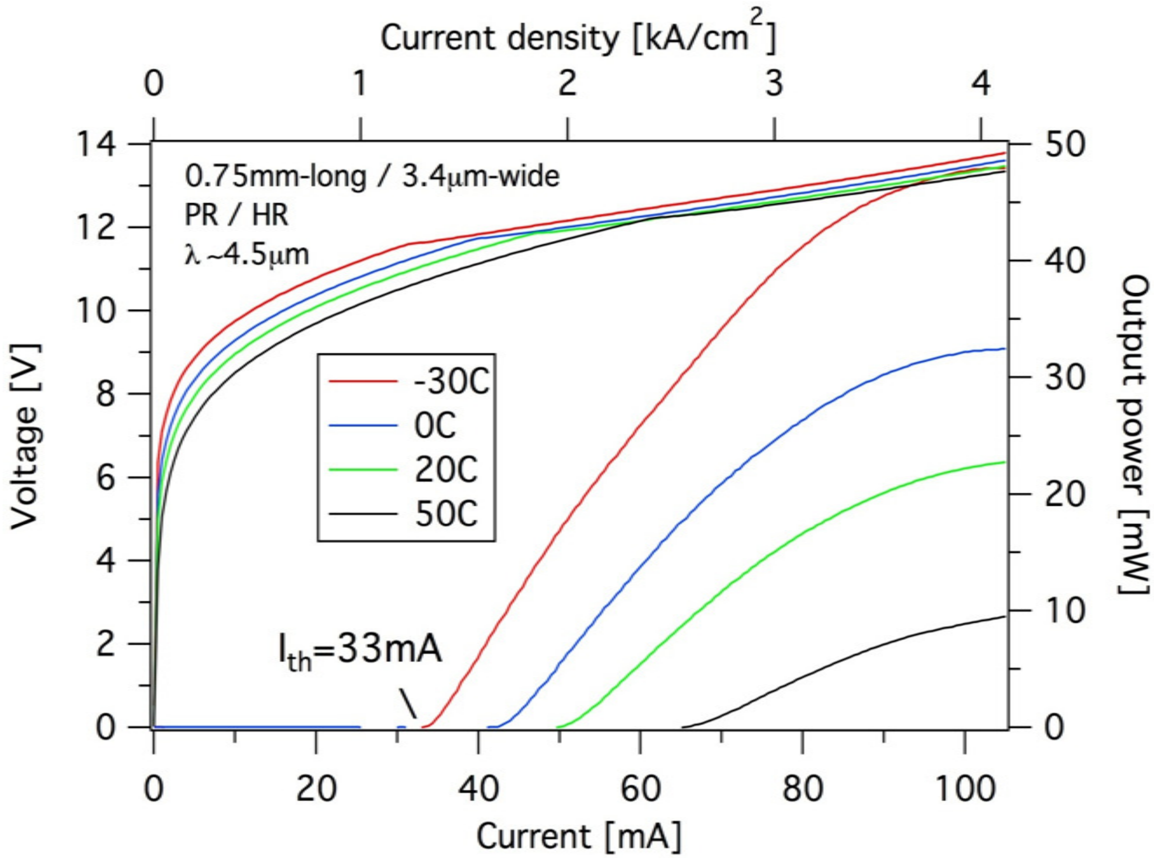


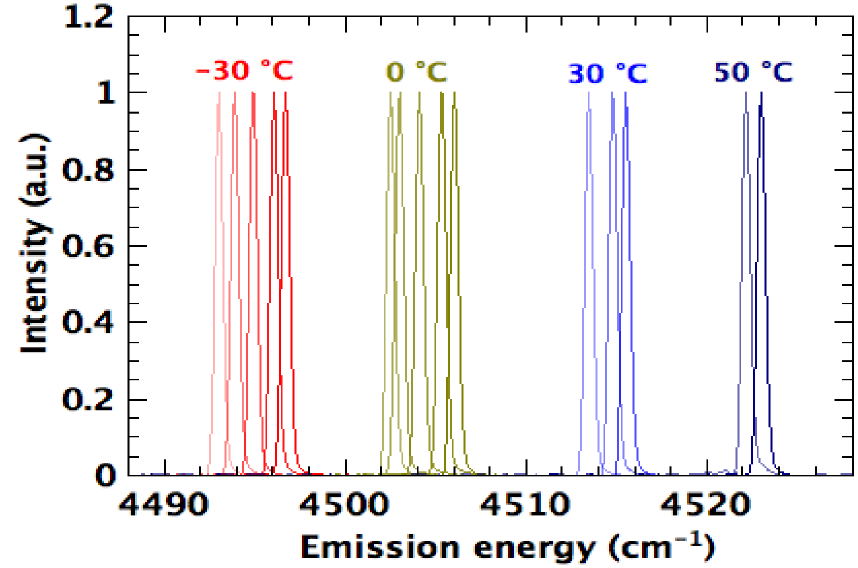


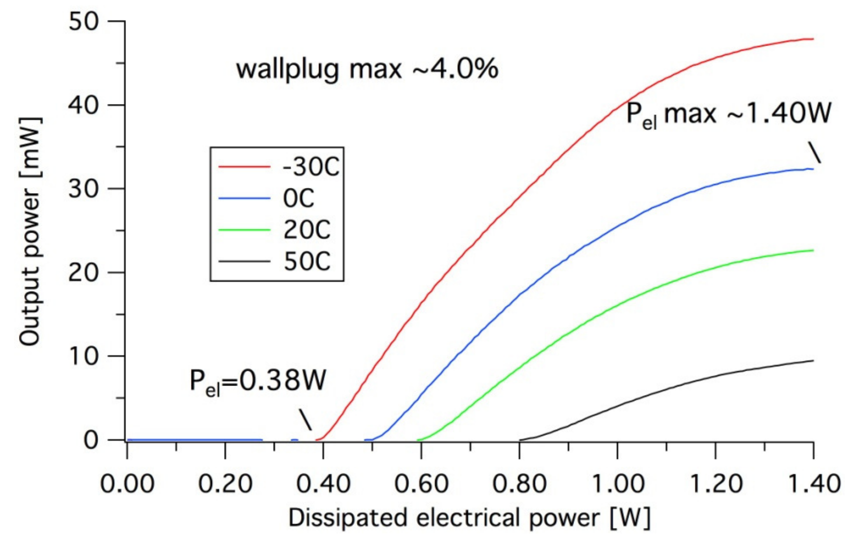


- very low threshold current : 29mA
- P_{el} max ~1.2W
- Single mode

Low-dissipation DFB devices at 4.5 □m

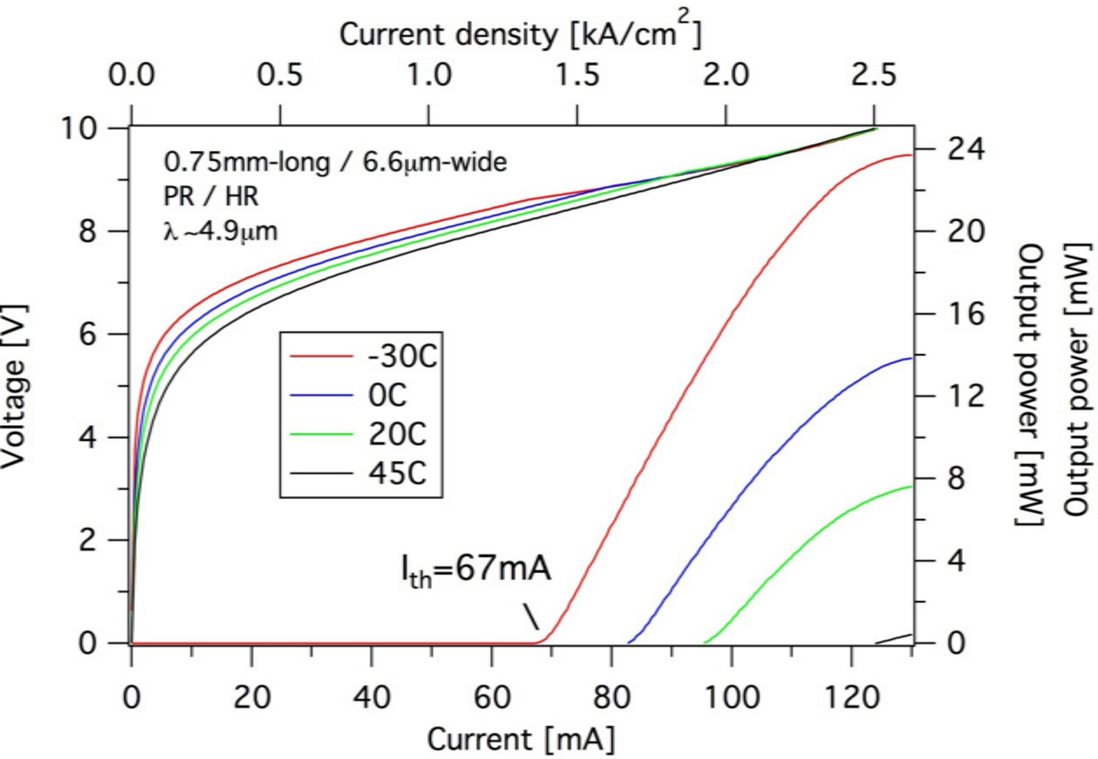


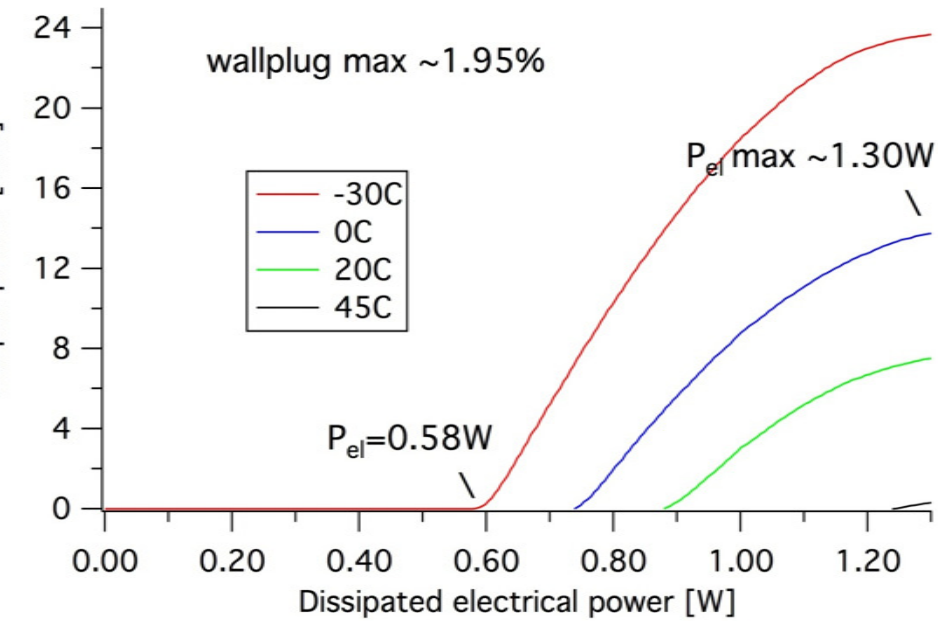




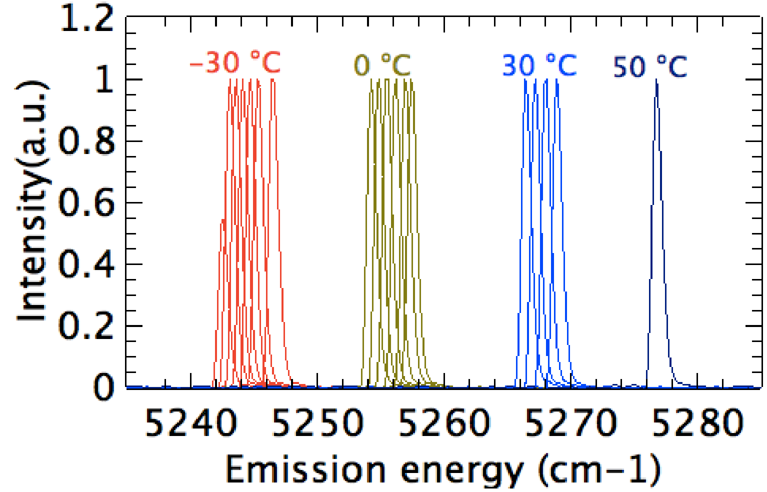
- opt power up to 48mW
- P_{el} max ~1.4W
- Single mode

Low-dissipation DFB devices at 4.90□m

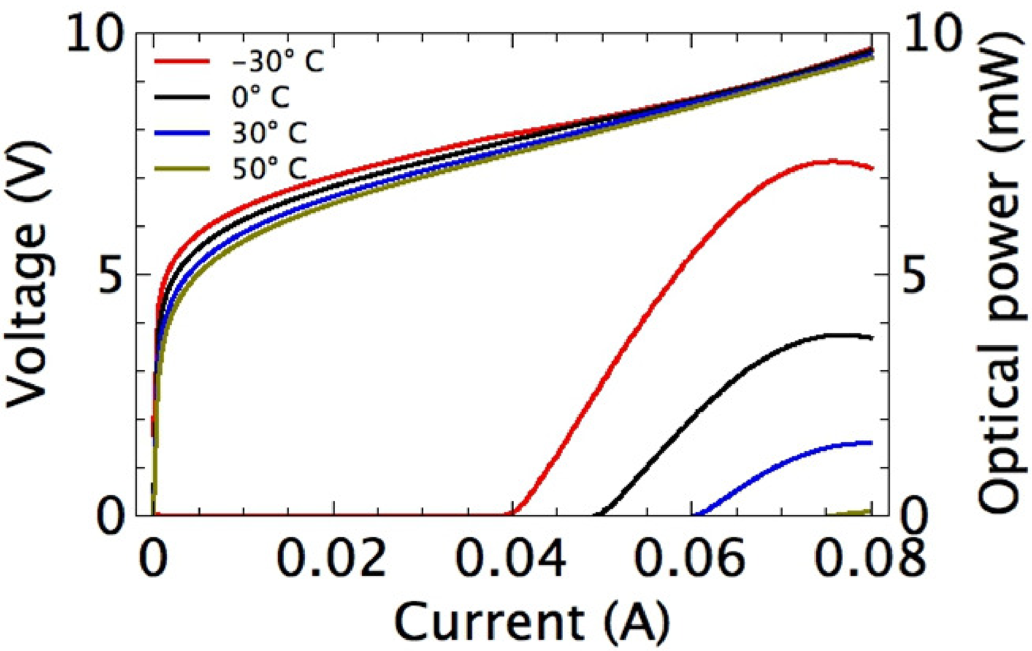


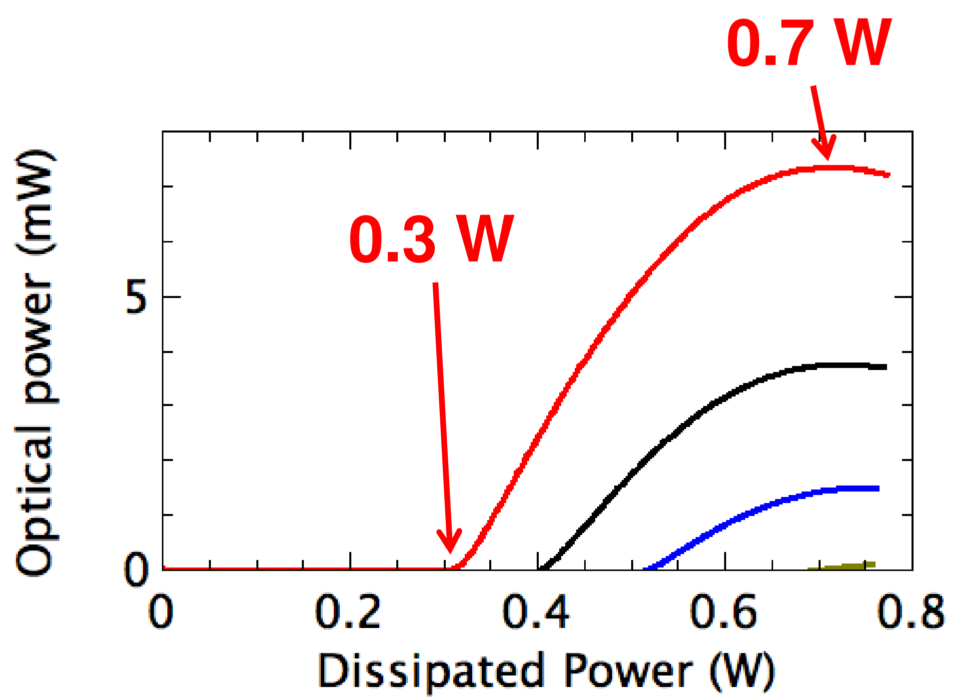


Low dissipation devices



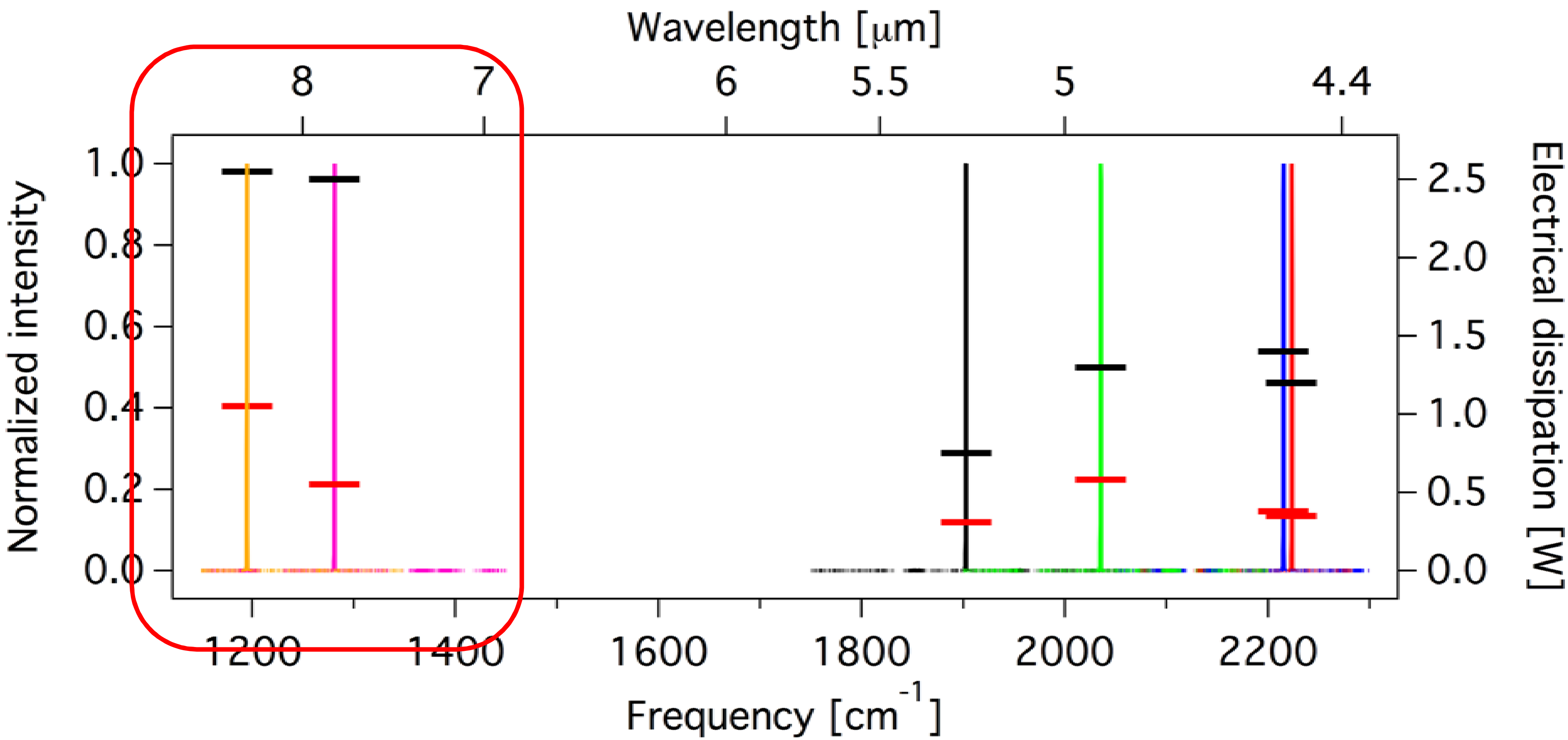
- Gain starving (too low doped structure)
- Elctrical dissipation as low as 0.3 W
- No cooling needed
- Max dissipation 0.7 W





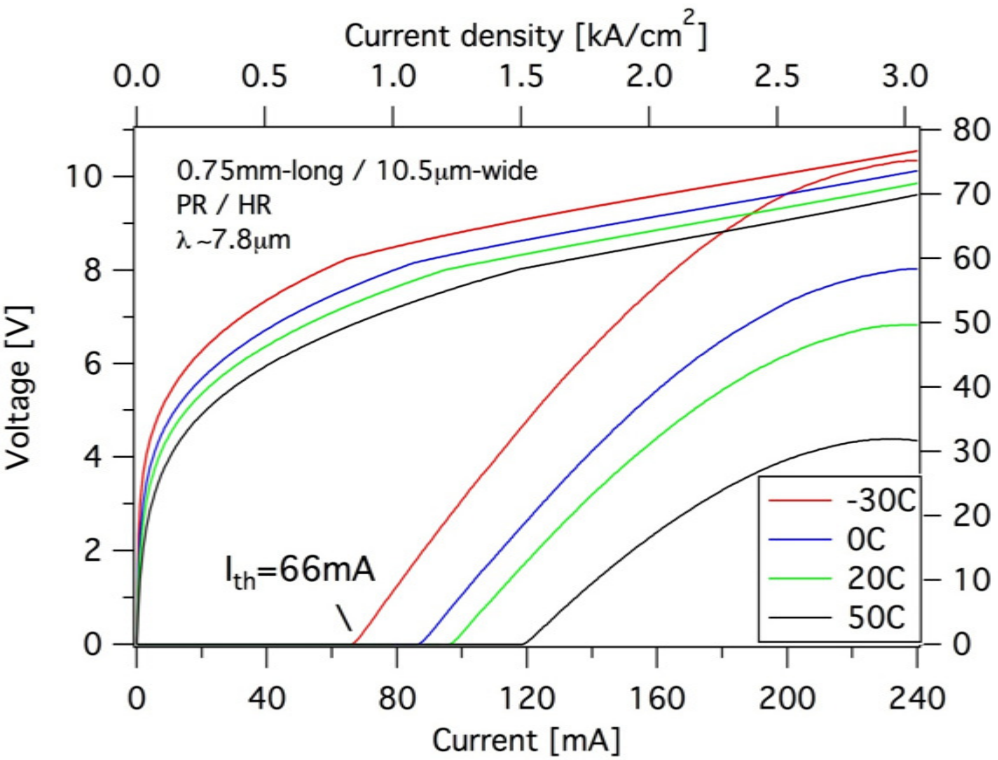
Low consumption devices

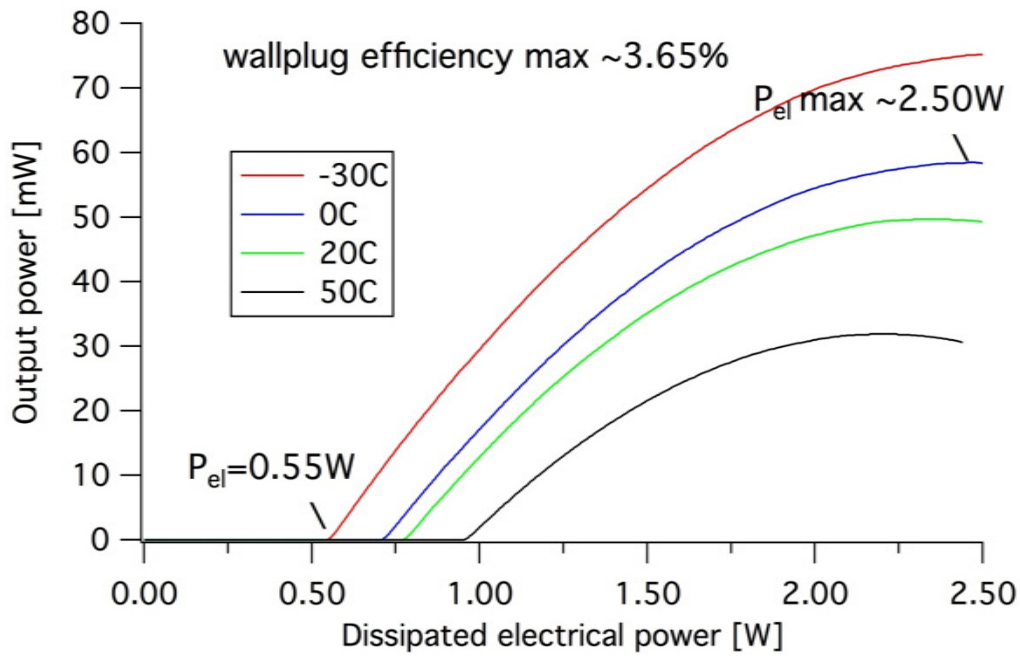
2-nd atmopheric window



- Max consumption < 2.6W between 4.5µm and 8.4µm

Low-dissipation DFB devices at 7.8□m





- Very low threshold current : 66 mA
- Very low threshold power : 0.55 W
- Pmax > 70 mW / huge dynamical range

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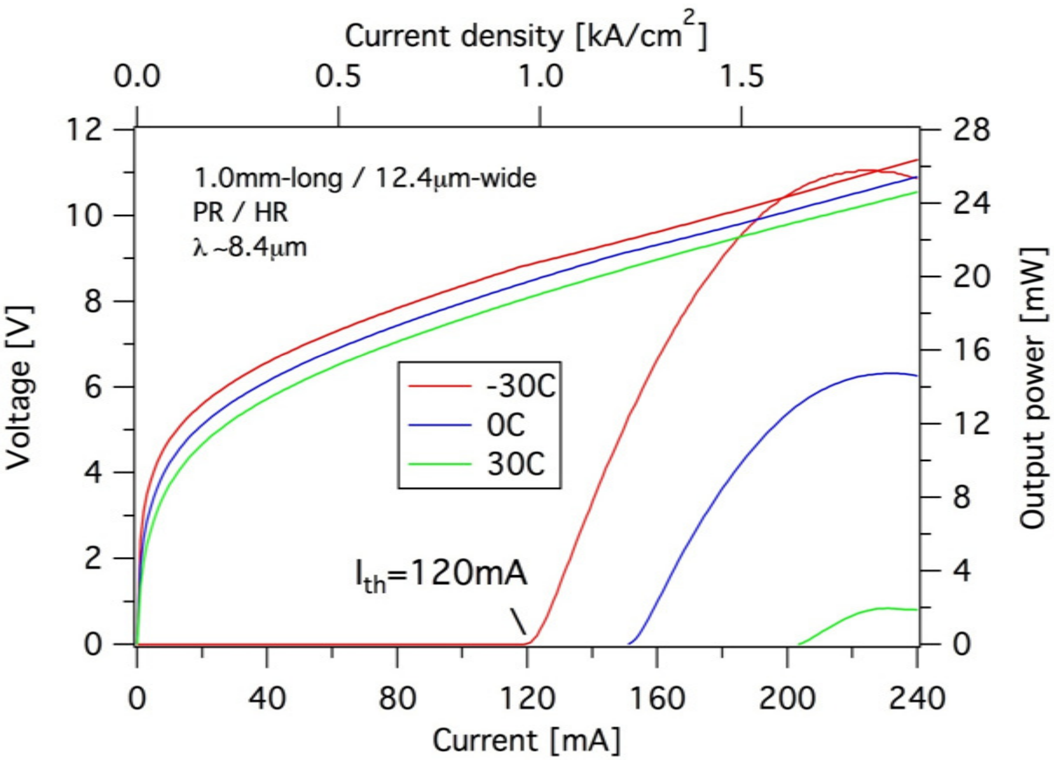
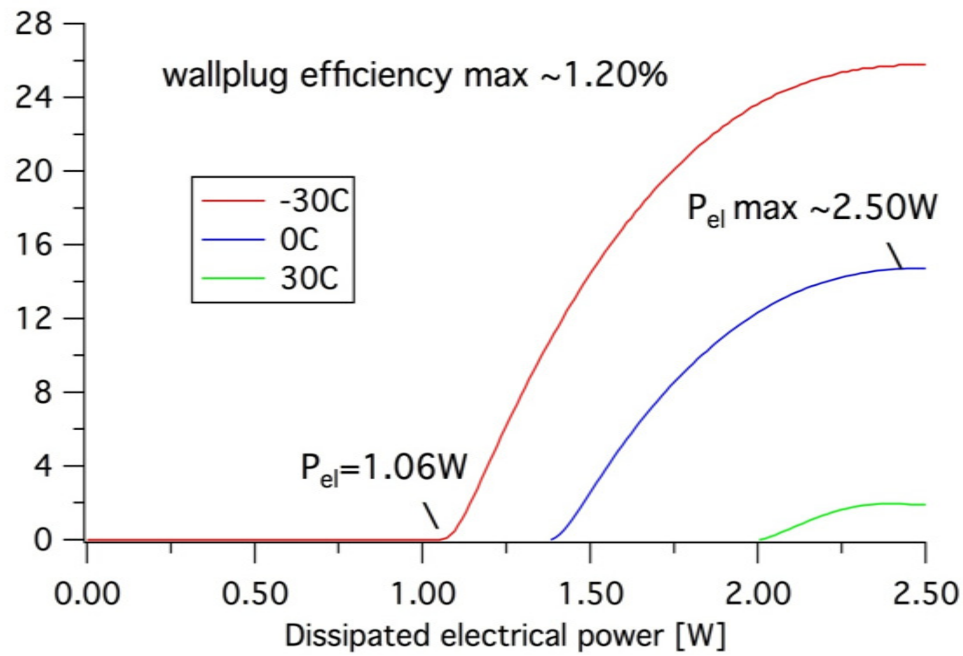
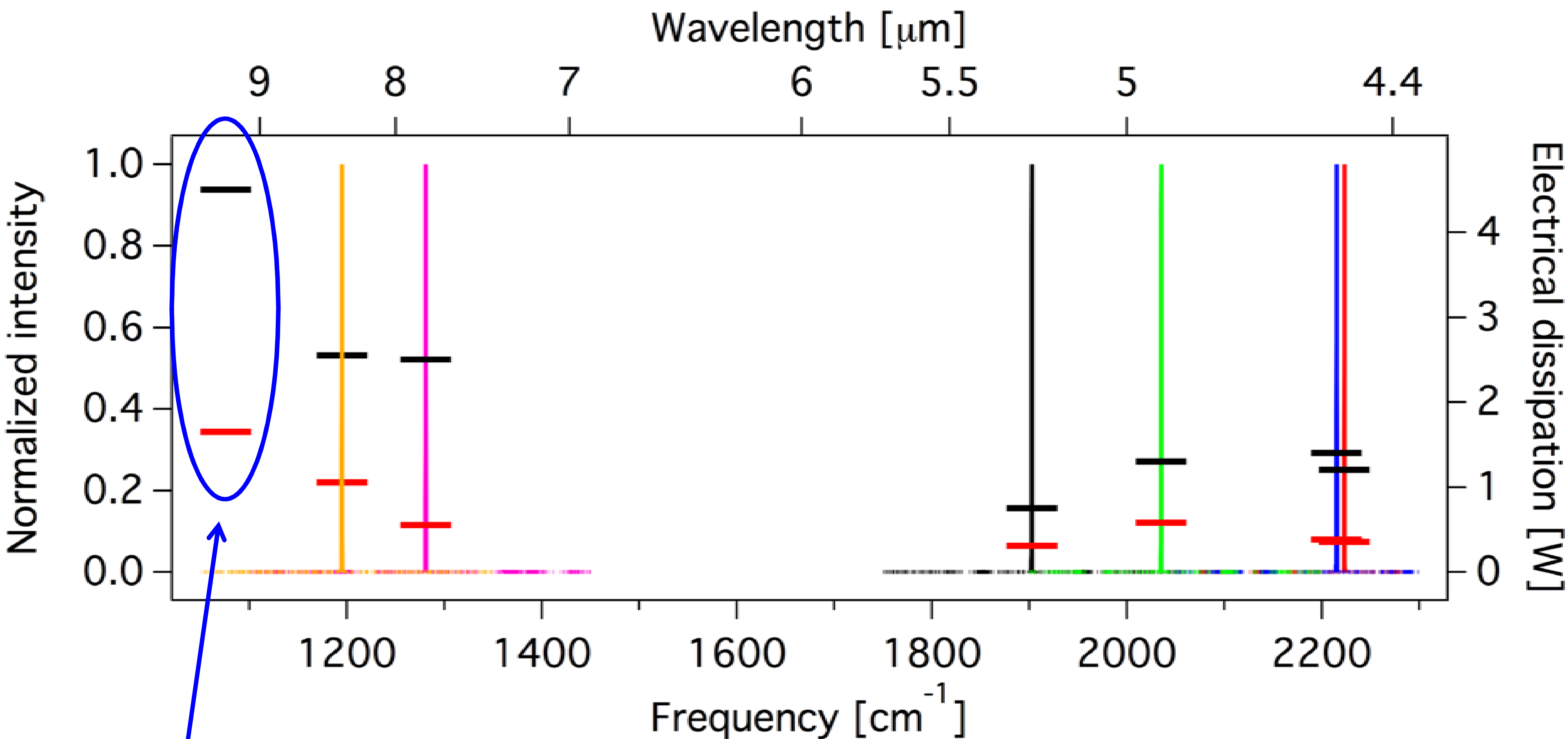
Low-dissipation DFB devices at 8.4□m





- did not lase while uncoated/HR !
- As for the 4.9 µm case the design is too little doped
- low threshold power : 1.06W

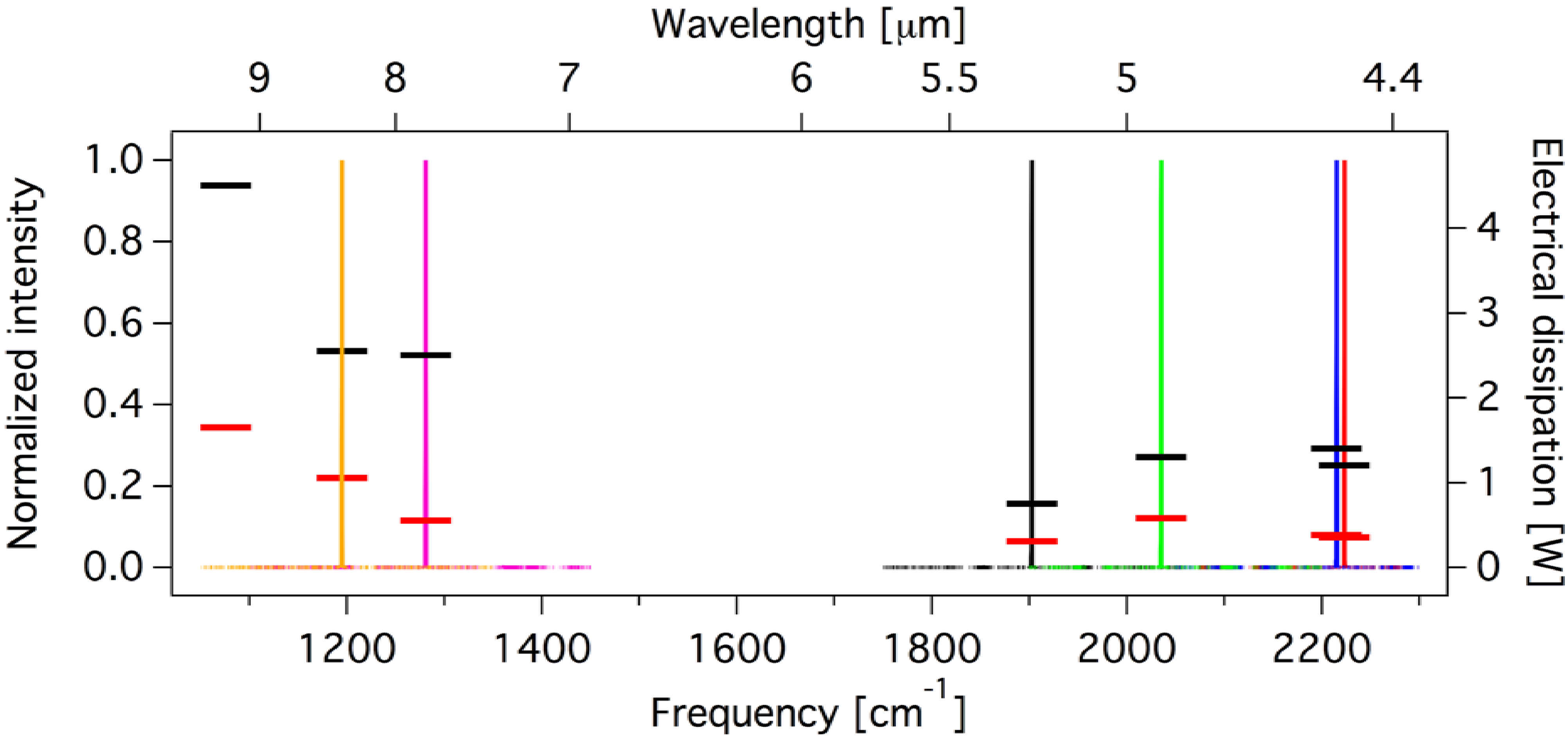
Low consumption devices (9.3 µm)



preliminary results at 9.3μm (only HR on back facet)

FF coating being developed

Low consumption devices



Can we package this devices in low-dissipation packages?

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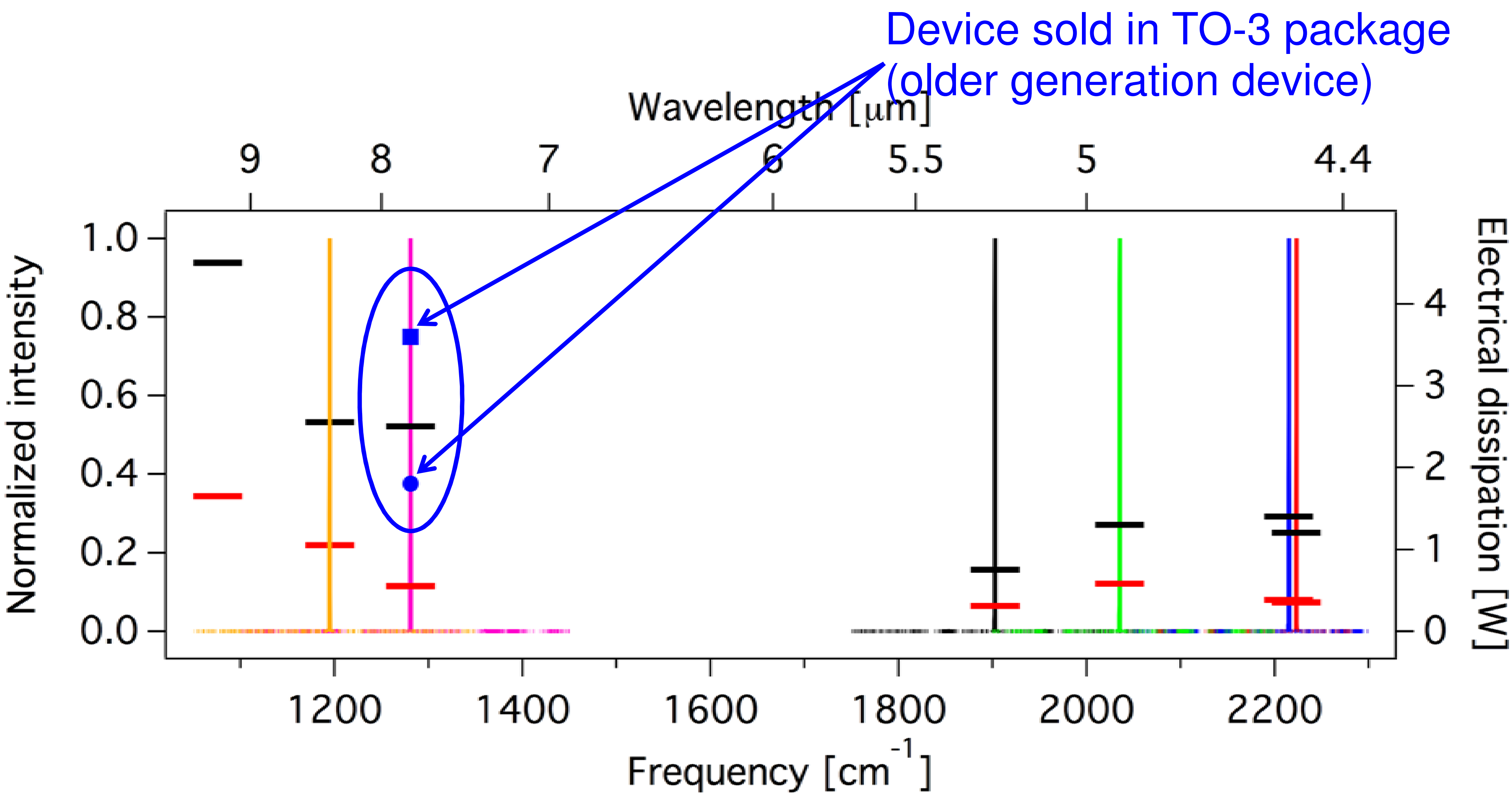
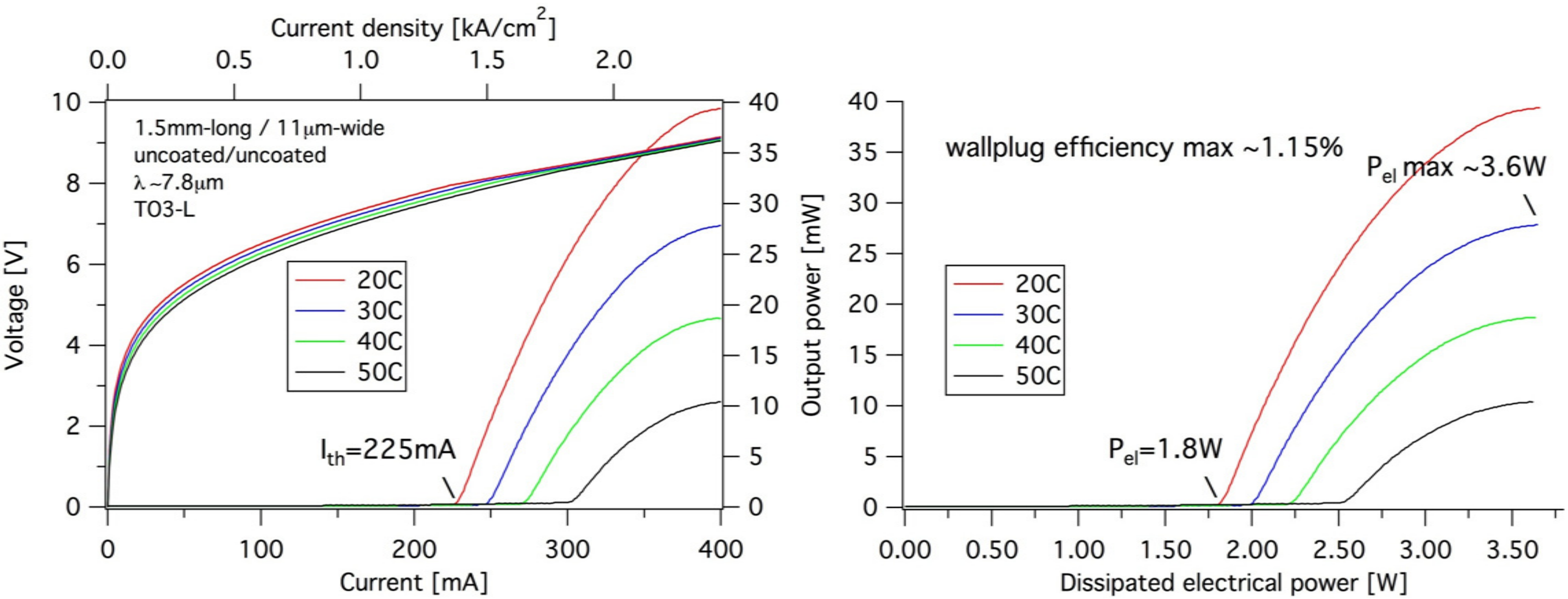
DFB devices at 7.8□m in TO3-L (dissipation level)



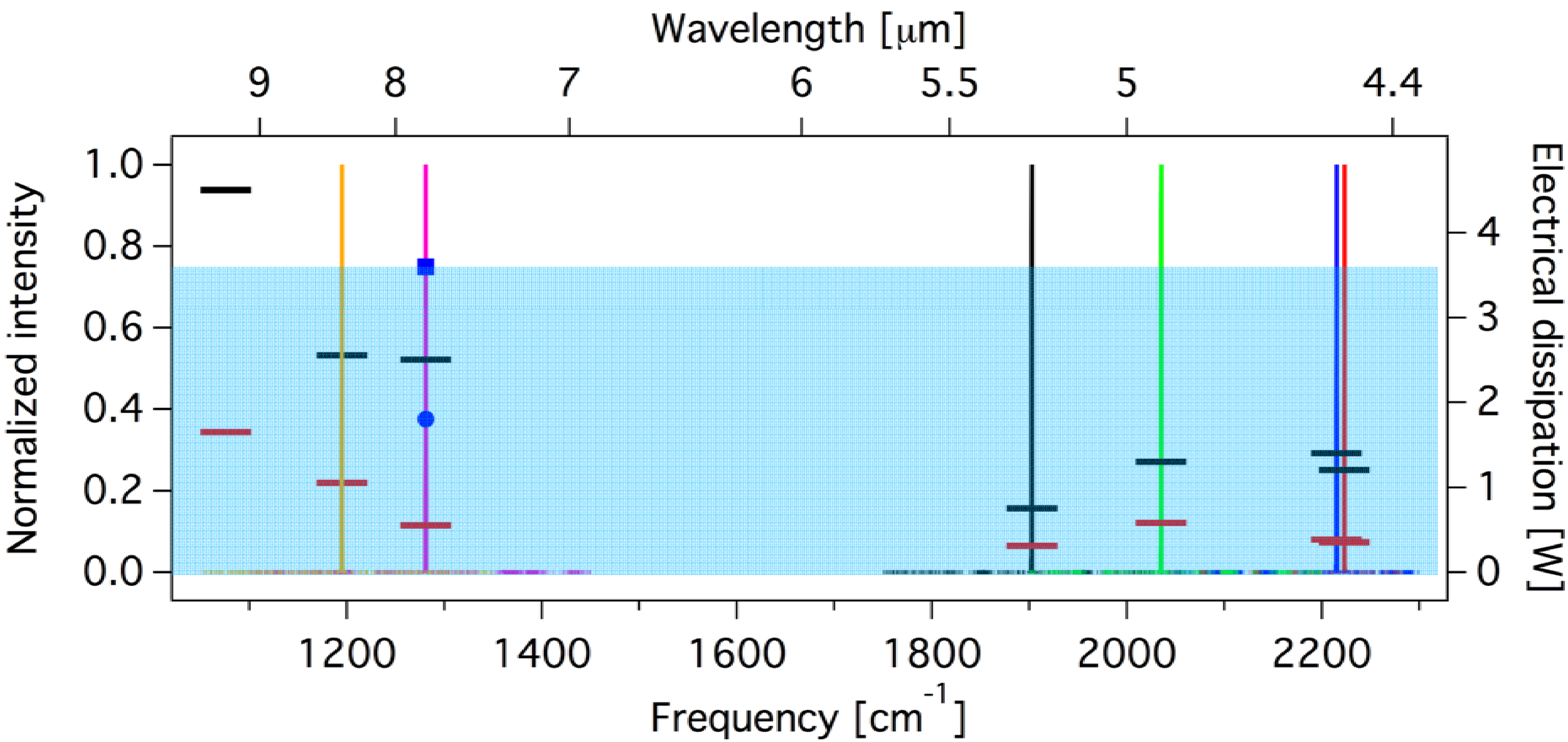
• blue : uncoated device in a TO3-L

DFB devices at 7.8m in TO3-L



- higher currents but CW operation in TO3-L
- max electrical power : up to 3.6W

DFB devices at 7.8□m in TO3-L (dissipation level)



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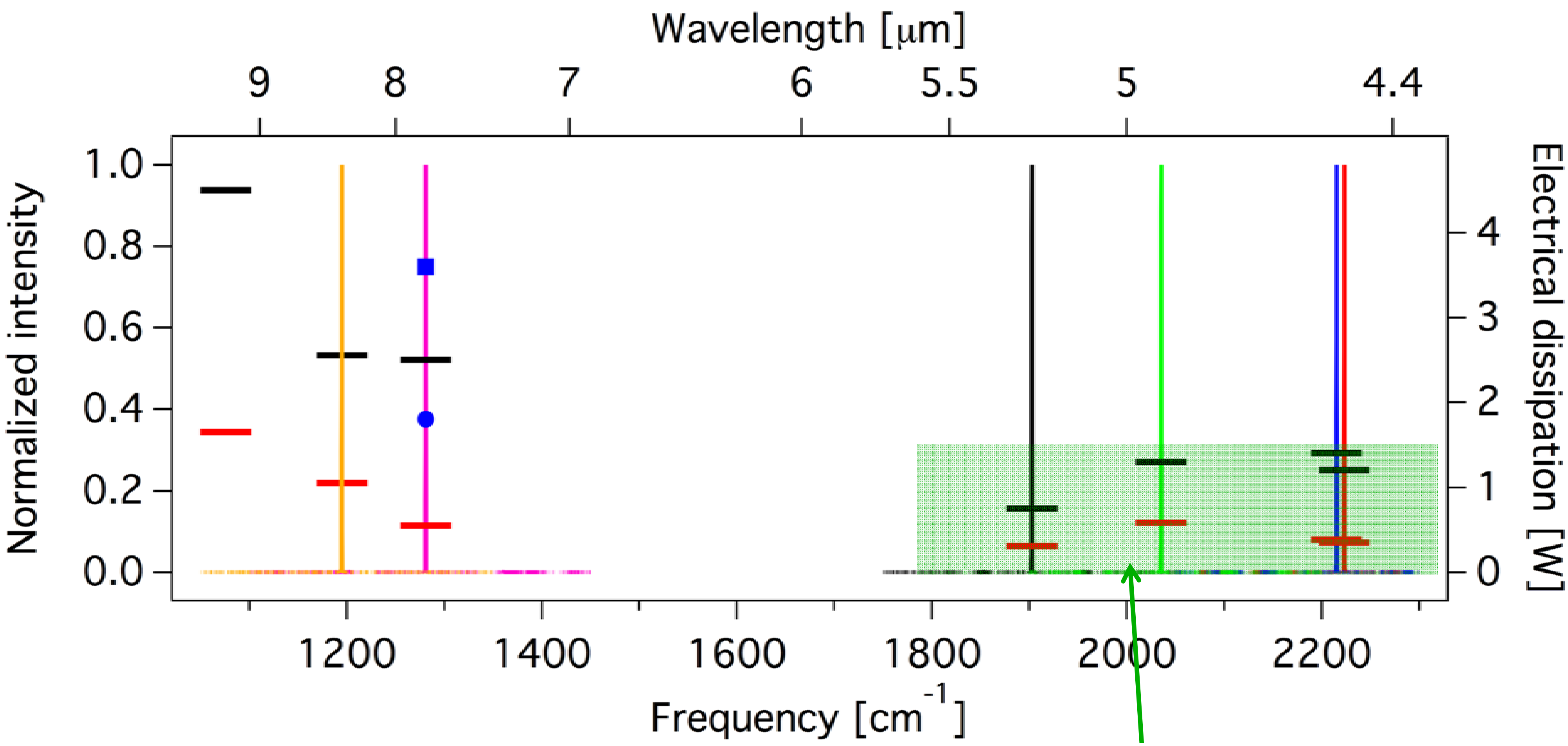
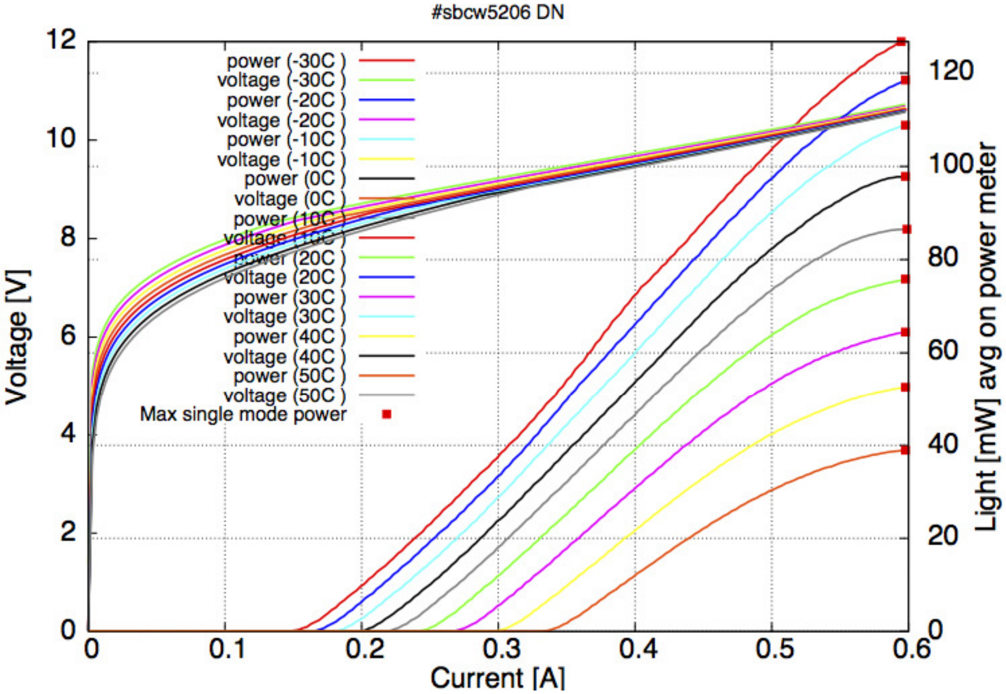
DFB devices at 7.8□m in TO3-L (dissipation level)

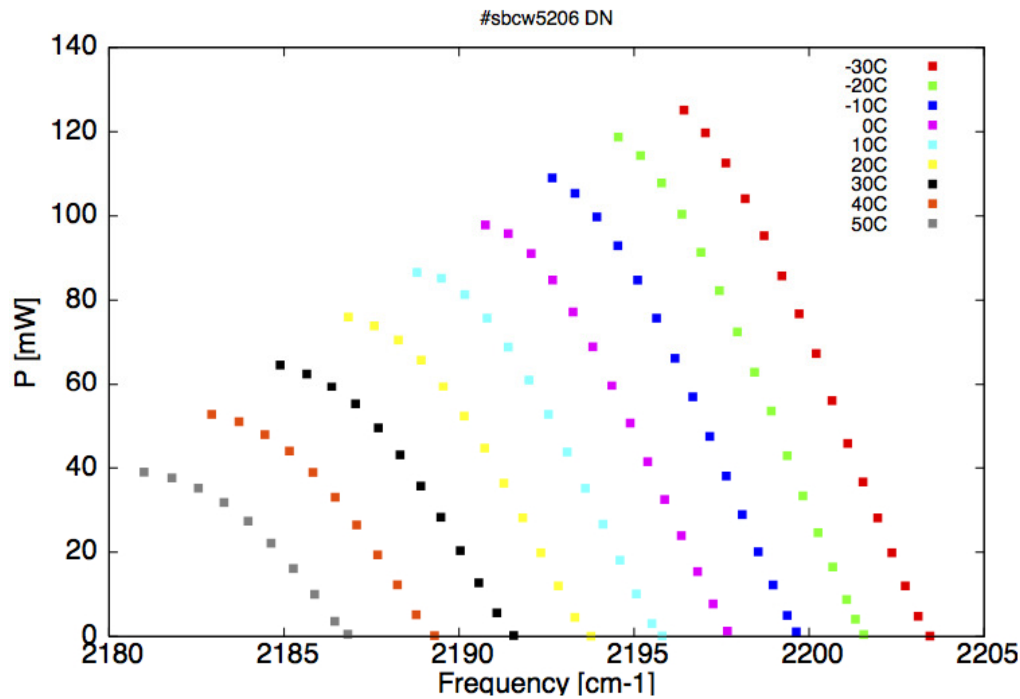


Smaller packages are being investigated

High power DFB devices

High-power device at 4.56 µm





- ~ 80mW/facet at RT / still > 40mW/facet at 50C
- P_{el} max < 6.4W
- Single mode across the full range

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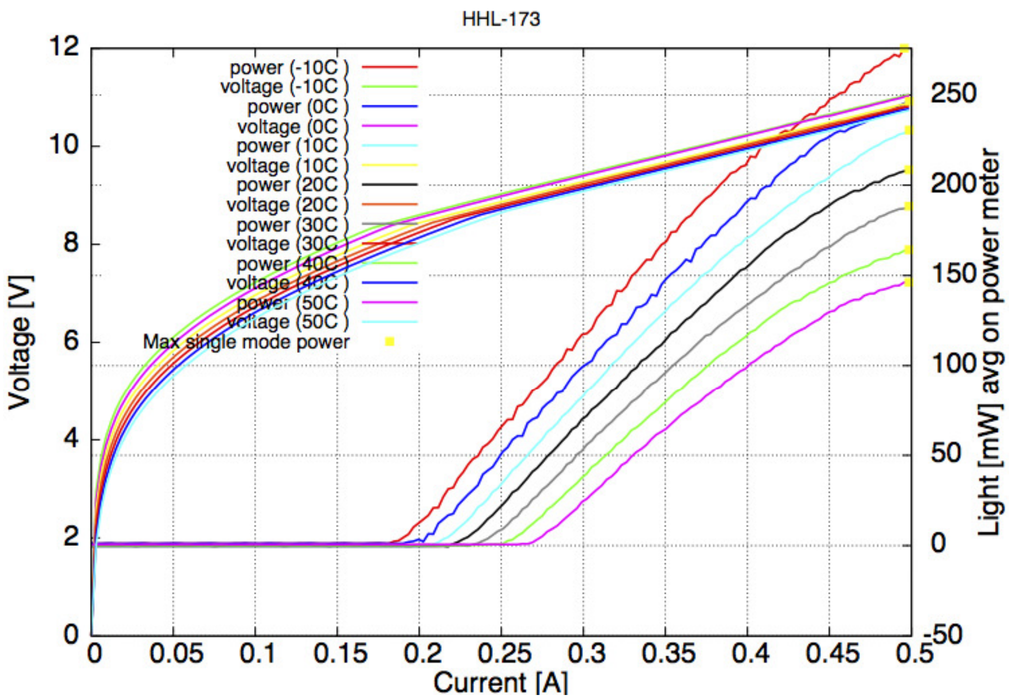
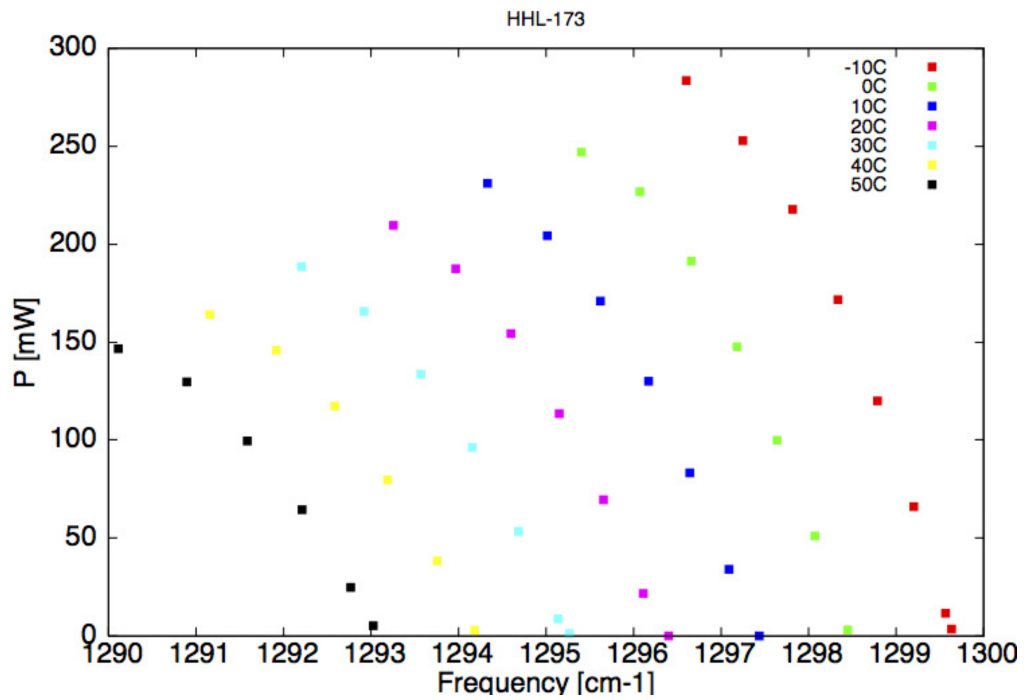
High power DFB devices

High-power device at 7.72 µm





- ~ 200mW at RT / still >140mW at 50C
- P_{el} max < 5.5W
- Single mode across the full range

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Conclusion and next steps

- Low-dissipation DFB lasers between 4.5 and 9.3 µm with $T_{op\ up\ to\ >50C}$
- High-power DFB using the same fabrication process (140mW at 50C episide-up)
- Soon to be expanded from 3.3 µm to 14 µm
- Genetic optimisation of the active region design to increase the efficiency
- Broad gain optimisation for cw operation
- Cloud simulation capability

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Thank you for your attention

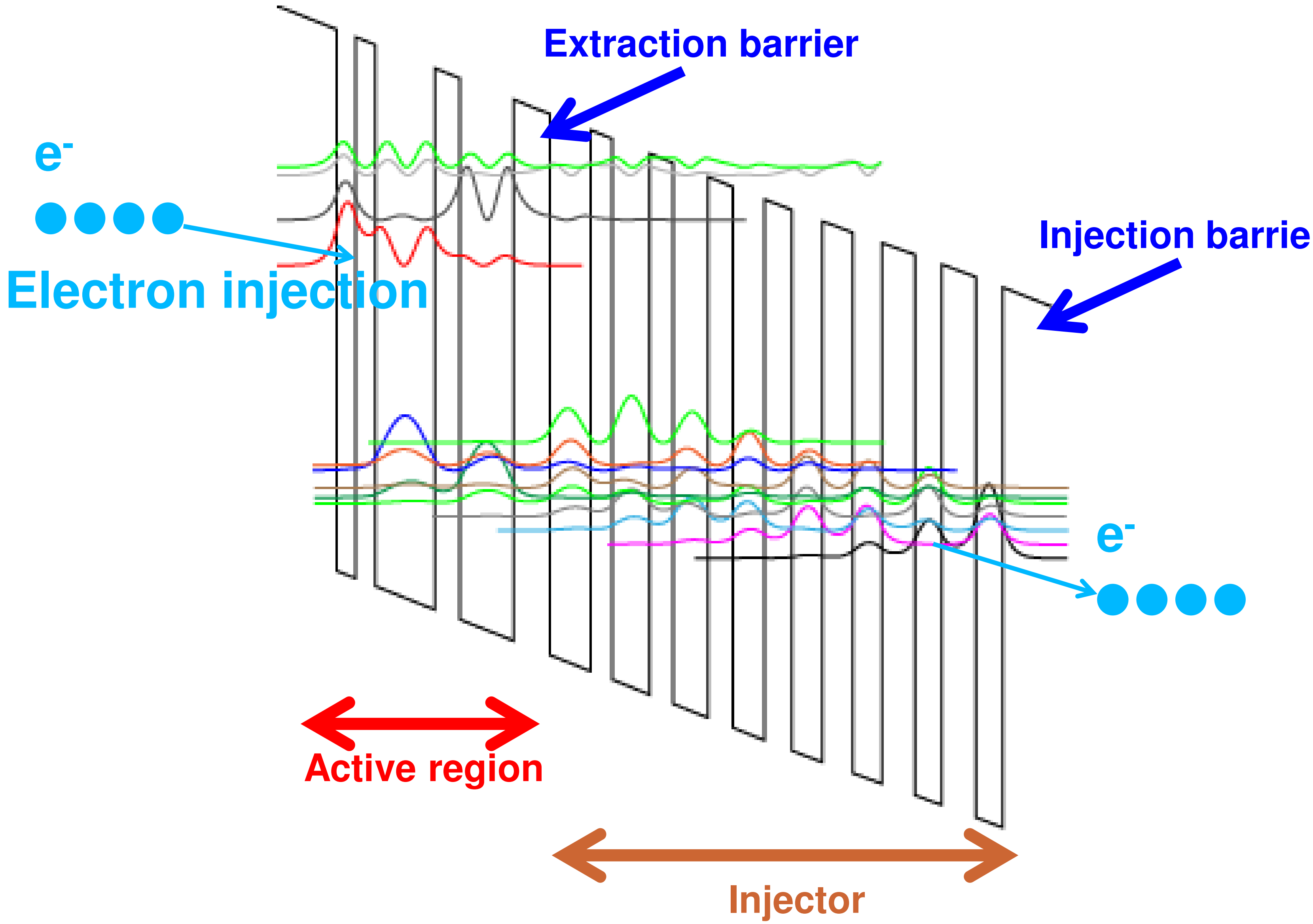
How to improve QCLs?

Better wallplug efficiency, higher powers, broader gain

- Technology
  - Growth and processing
- Design
  - Local optimization yields contradictory results
  - Try and error very expensive

Reliable simulation tool

QCL design

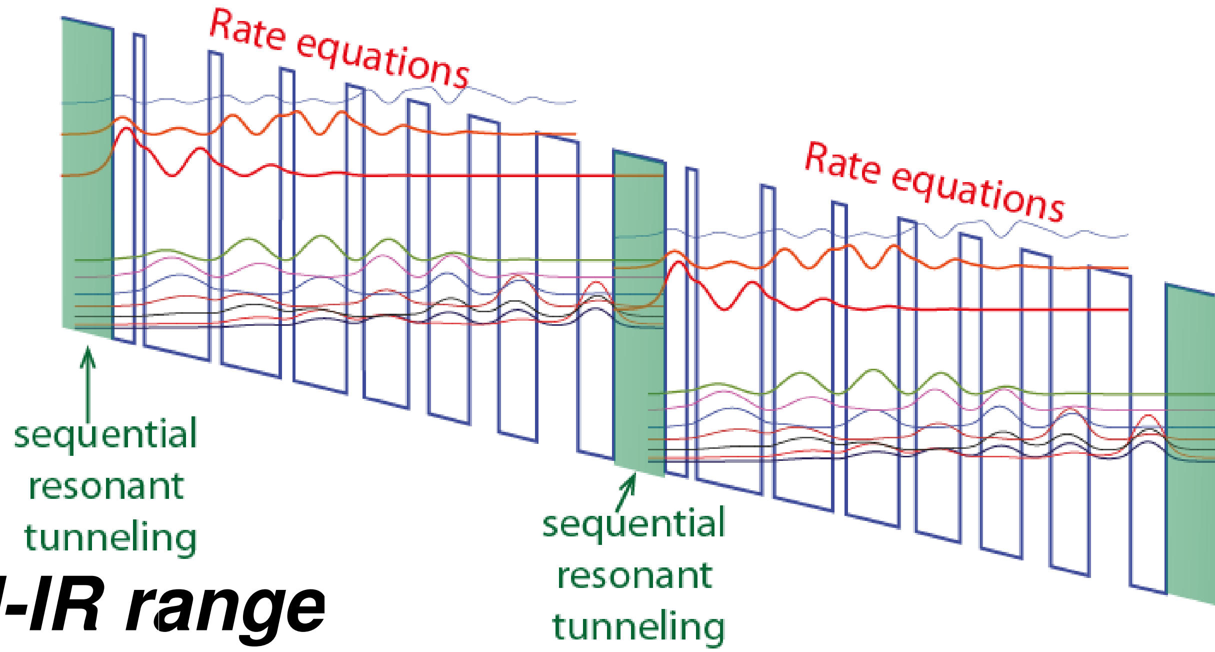


Extraction barrier
e-
Electron injection
Injection barrier
e-
Active region
Injector

ALPES LASERS

Design tool

Density matrix formalism



Reliable in the whole Mid-IR range

Able to predict optical power-current-voltage curves

[1] H. Willenberg et al., Phys. Rev. B. 67, 085315 (2003)
[2] R. Terazzi et al., New J. Phys. 12, 033045 (2010)

Quantum cascade laser

The scattering mechanisms implemented in the computation

- LO-Phonons
- Interface roughness
- Alloy disorder
- Ionized impurities (Dopants)

Missing interactions:

- Electron-electron
- LA-Phonon

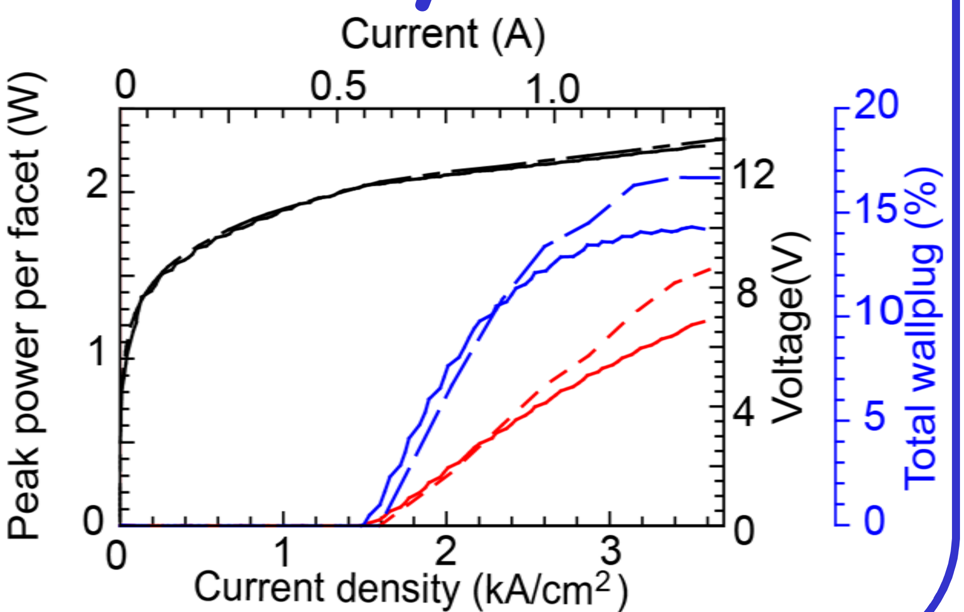
Program input parameters

waveguide losses *laser length* *laser width*

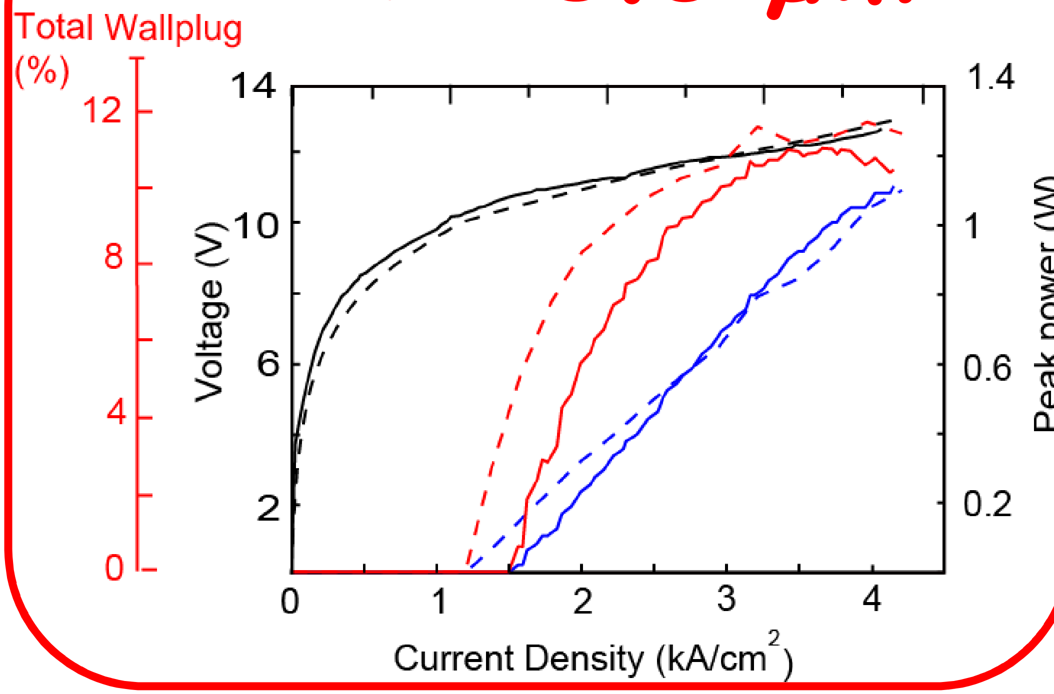
[1] Unuma et al., J. Appl. Phys. 93, 1586 (2003)

Examples

λ= 4.5 μm*



λ= 8.5 μm**



Reliable across the whole Mid-IR range (4-10 μm)

In the 3-4 μm range intervalley scattering missing

*** A. Bismuto et al., Appl. Phys. Lett. 98, 091105 (2011)**

**** A. Bismuto et al., Appl. Phys. Lett. 96, 141105 (2010)**

Toward genetic optimization

Simulation tool able to predict actual laser performance

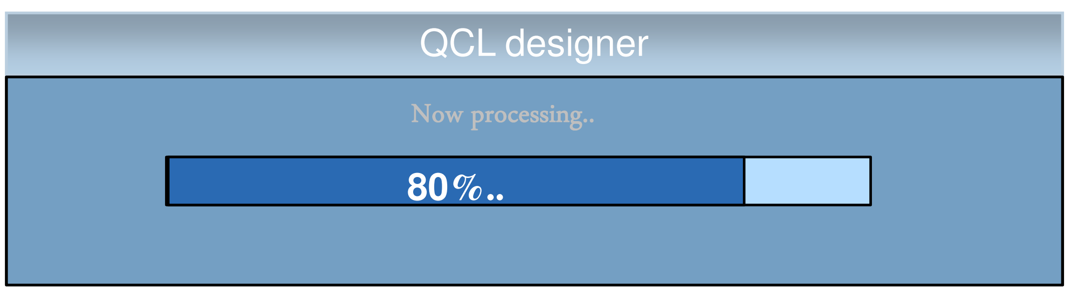
Too many parameters to control manually (~20 layers)

Use of genetic algorithms (fully automized)

Merit function selection **Wallplug efficiency**

Use of ETH Cluster (BRUTUS, 10000 cores)

Currently using Amazon cloud service



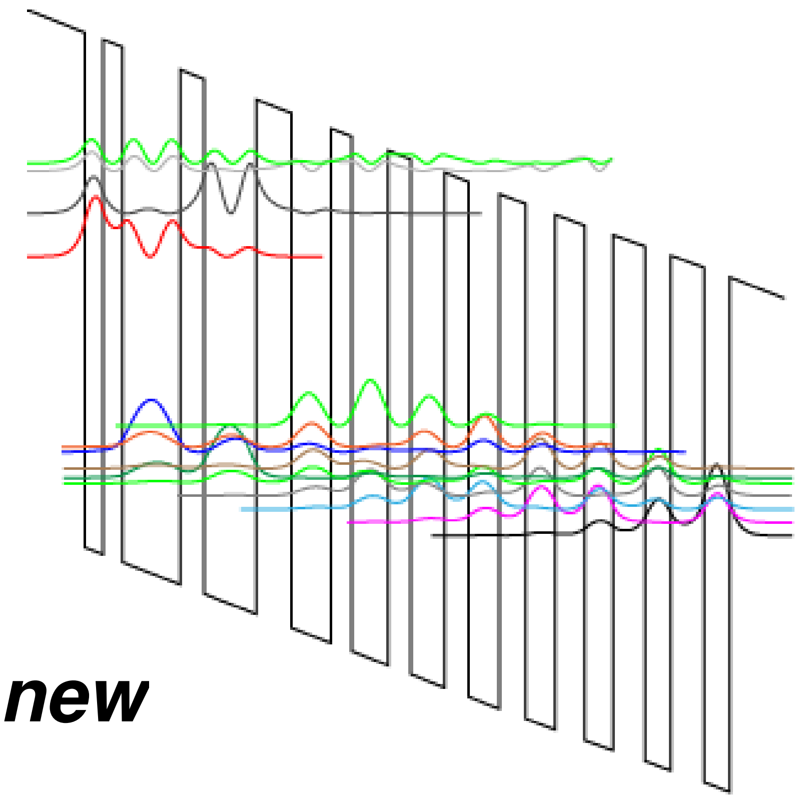
Toward genetic optimization

Starting point: Bound to continuum design at 4.6 µm

Q. Yang et Al., Appl. Phys. Lett. 93, 251110 (2008)

Random variation of the reference design (less than 20%)

Best designs used to create the new population (*Darwin's law*)



33000 individuals per population

32 designs selected to create the new generation

A. Bismuto et al., APL 101, 021103 (2012)

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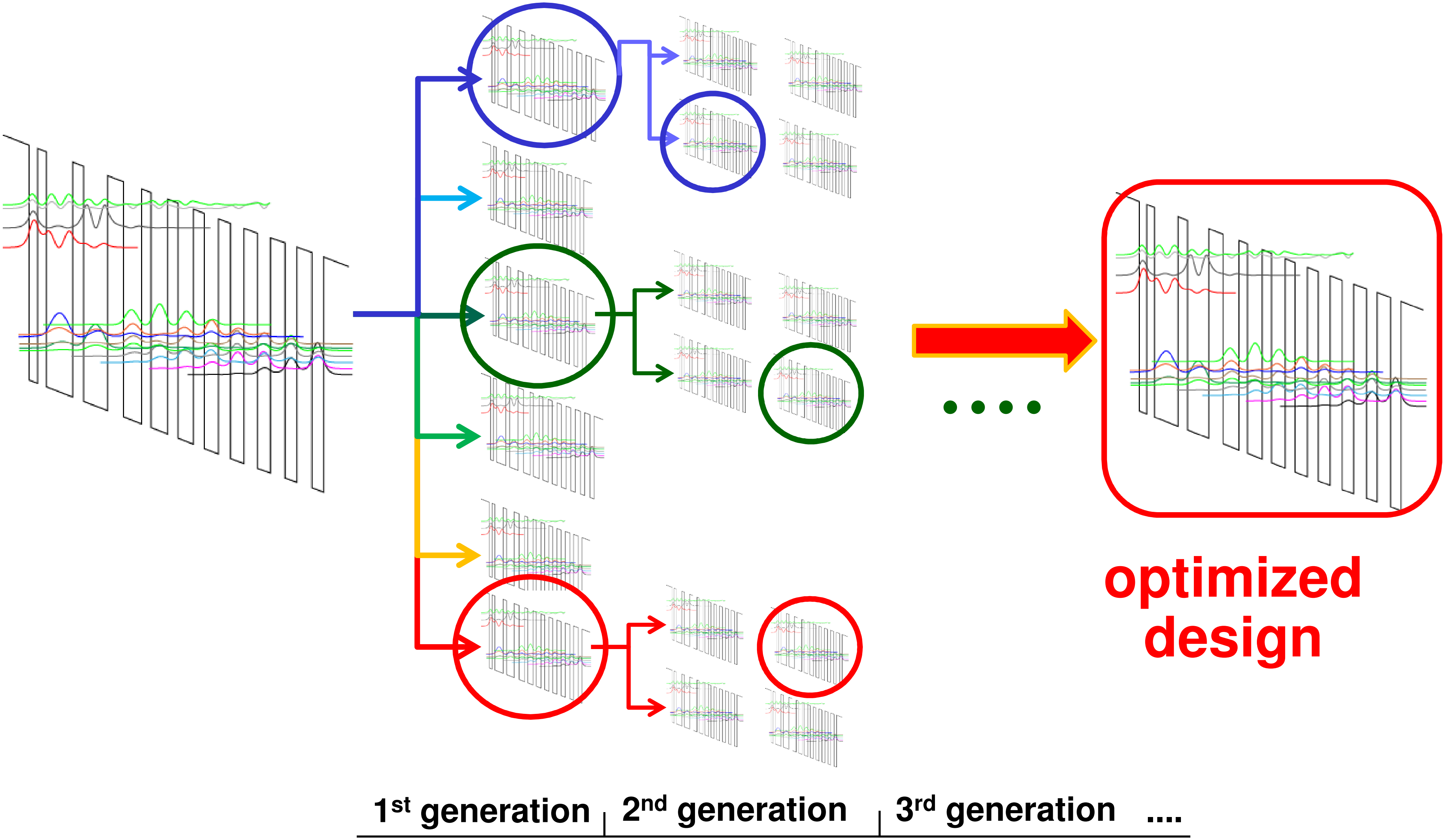
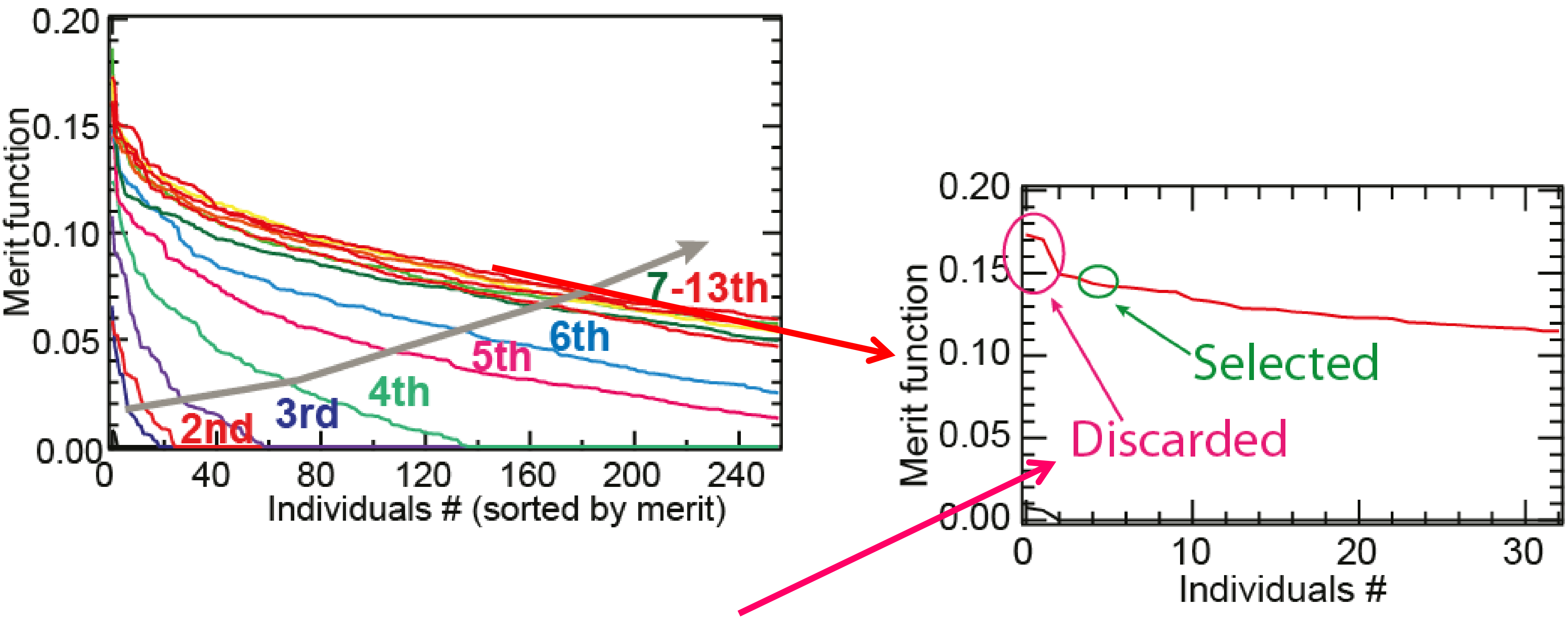
Toward genetic optimization



Merit function: Wallplug efficiency

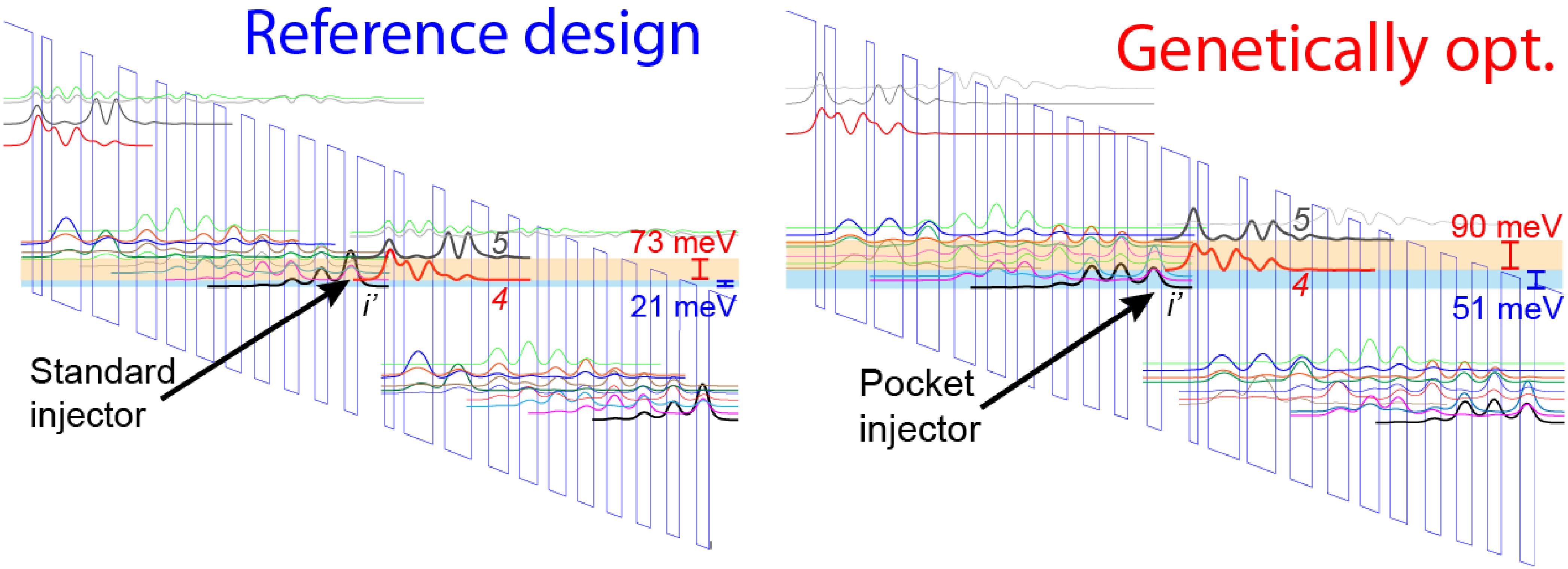


Unstable pathological structures were excluded (e.g. coherent transport of electrons over unphysical lengths)

Structure in the average position of the best generation selected

A. Bismuto et al., APL 101, 021103 (2012)

Designs comparison

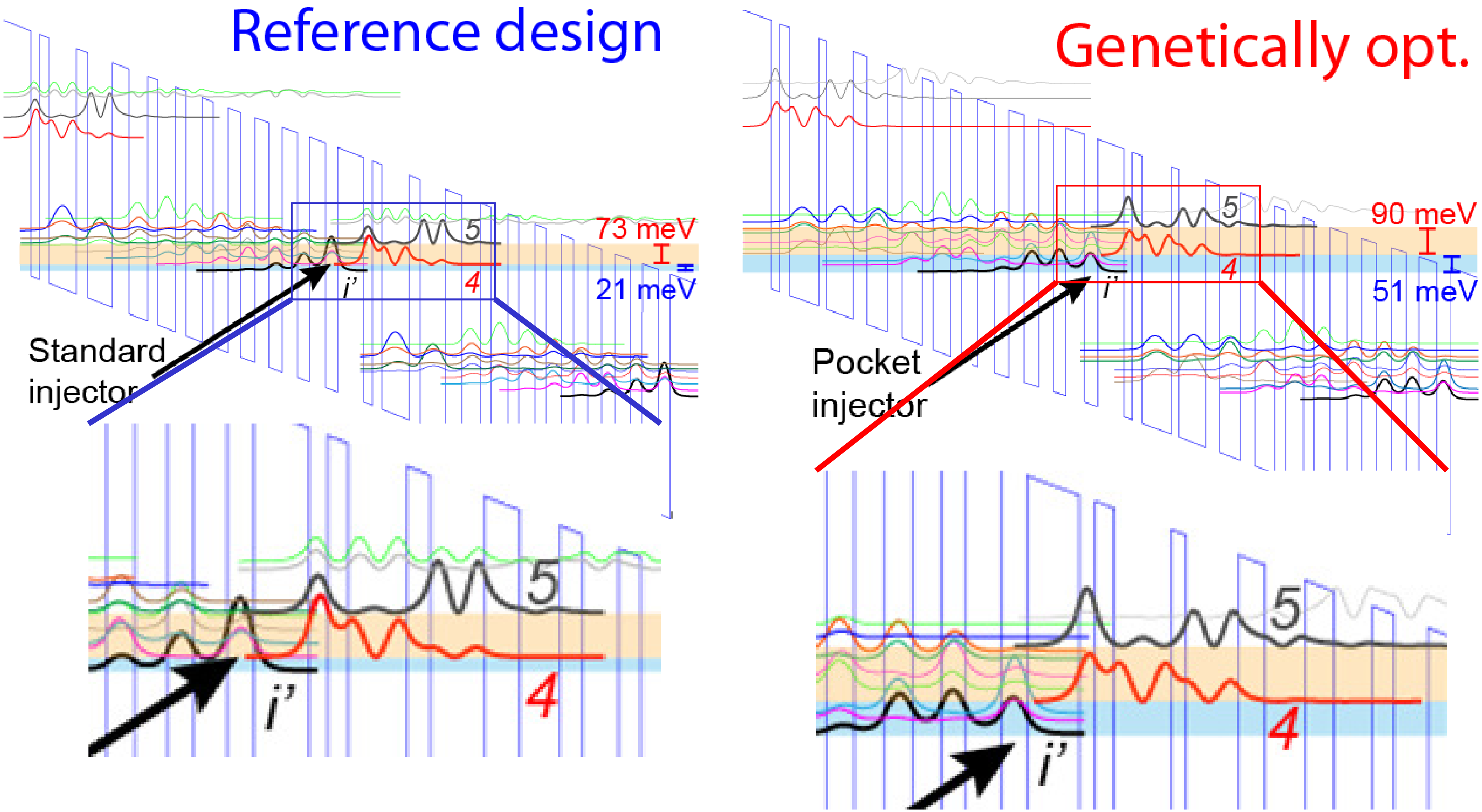


Emission wavelength kept constant

Lower alignement voltage, higher gain

A. Bismuto et al., APL 101, 021103 (2012)

Designs comparison



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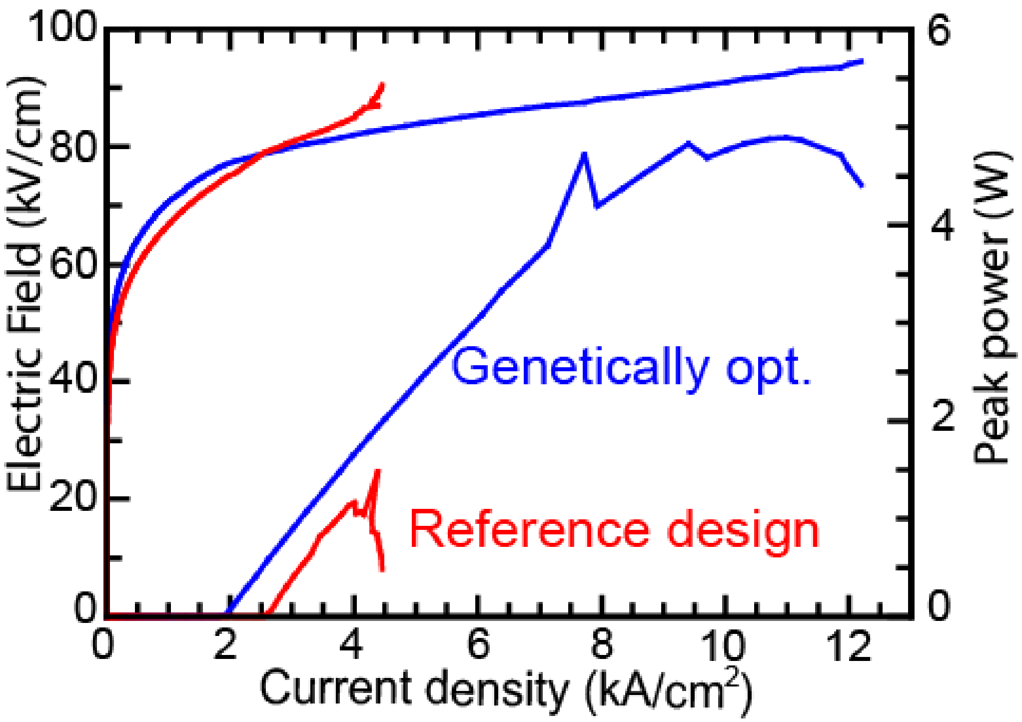
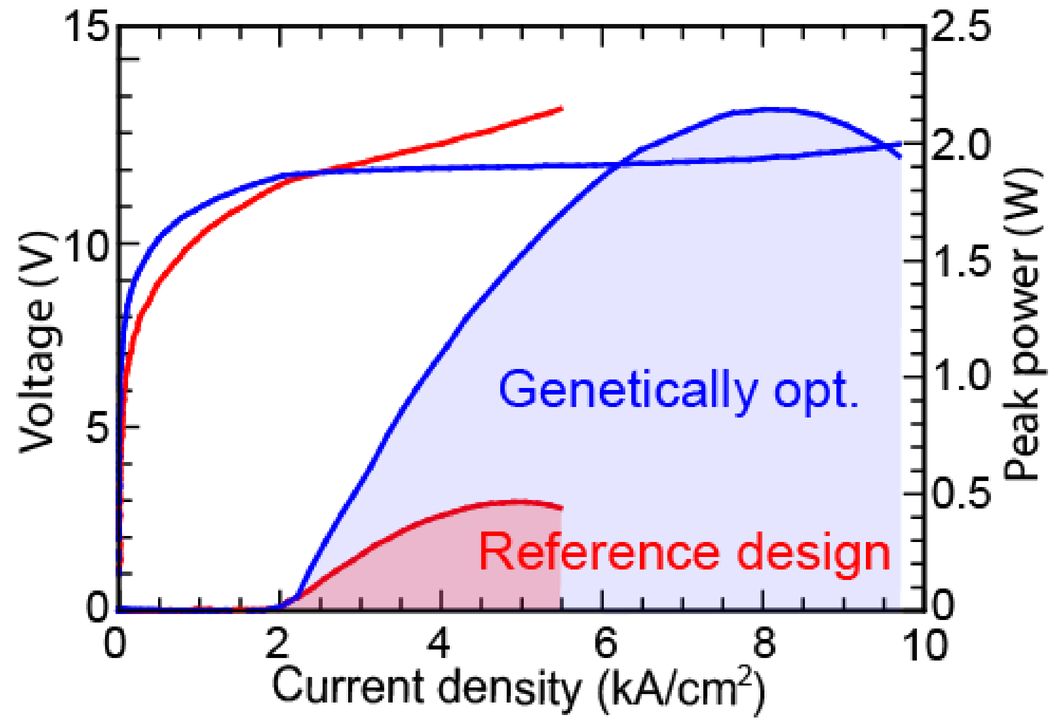
Light-current-voltage

Simulations



Measurements



8.5 µm wide, 4.9 mm long laser

Lower alignment voltage

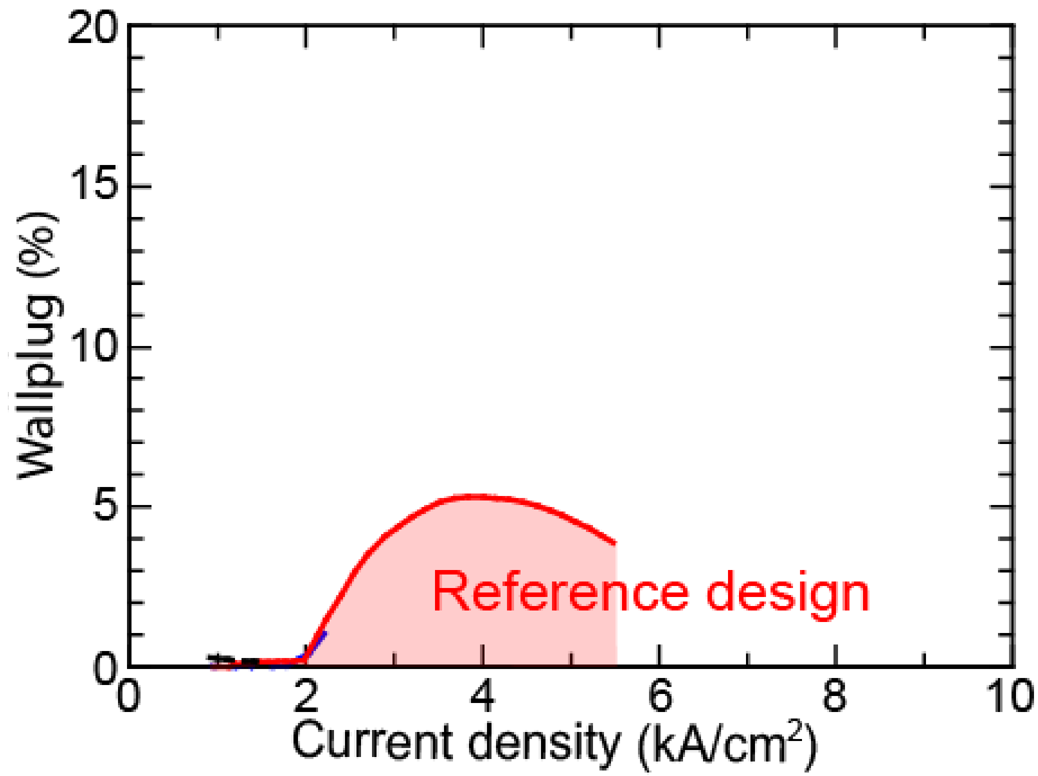
Higher power

Smaller threshold

A. Bismuto et al., APL 101, 021103 (2012)

Wallplug improvement

The optimized design shows higher efficiency

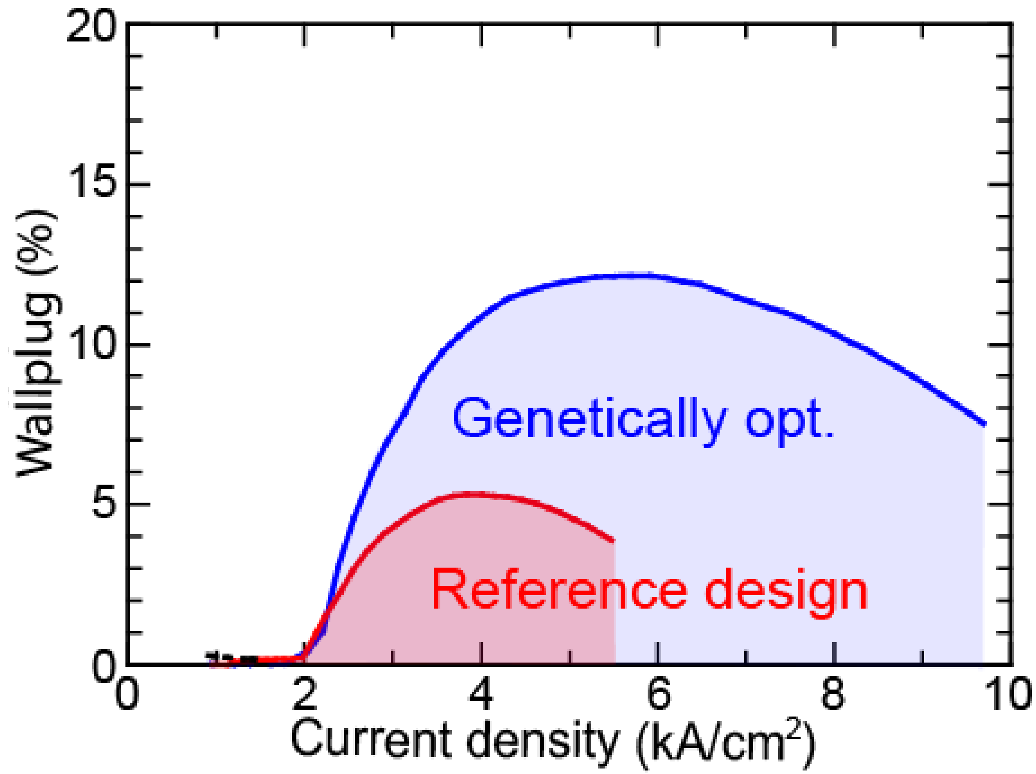


growth optimization has to be performed also on the optimized design

A. Bismuto et al., APL 101, 021103 (2012)

Wallplug improvement

The optimized design shows higher efficiency



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A. Bismuto et al., APL 101, 021103 (2012)

Wallplug improvement

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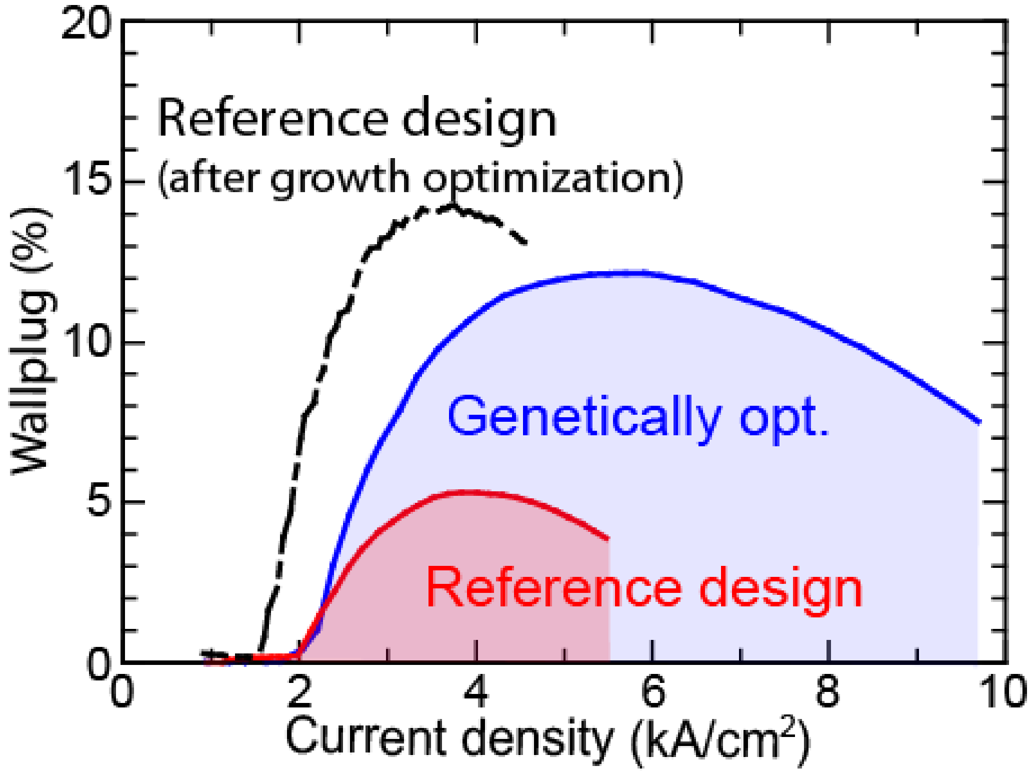


growth optimization as to be performed also on the optimized design

A. Bismuto et al., APL 101, 021103 (2012)

Quantum cascade laser

The scattering mechanisms implemented in the computation

- LO-Phonons
- Interface roughness
- Alloy disorder
- Ionized impurities (Dopants)

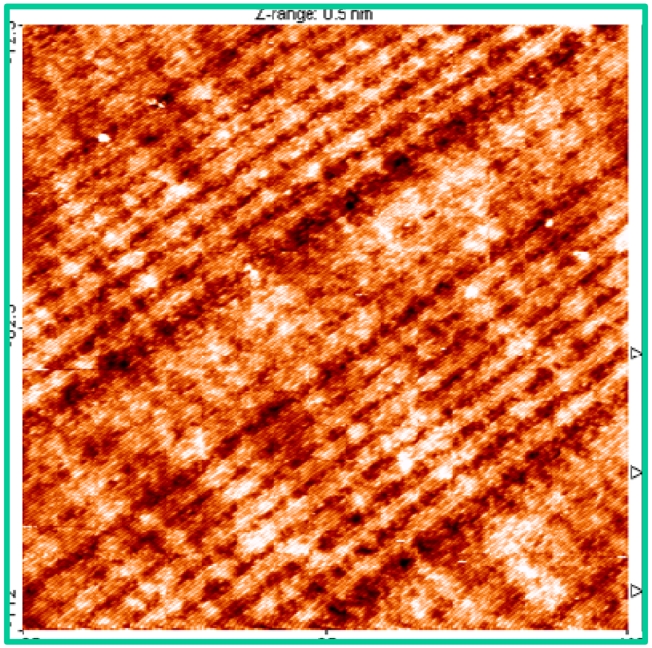
Interface roughness has a major impact on laser performance

How to improve the quality of the interfaces...

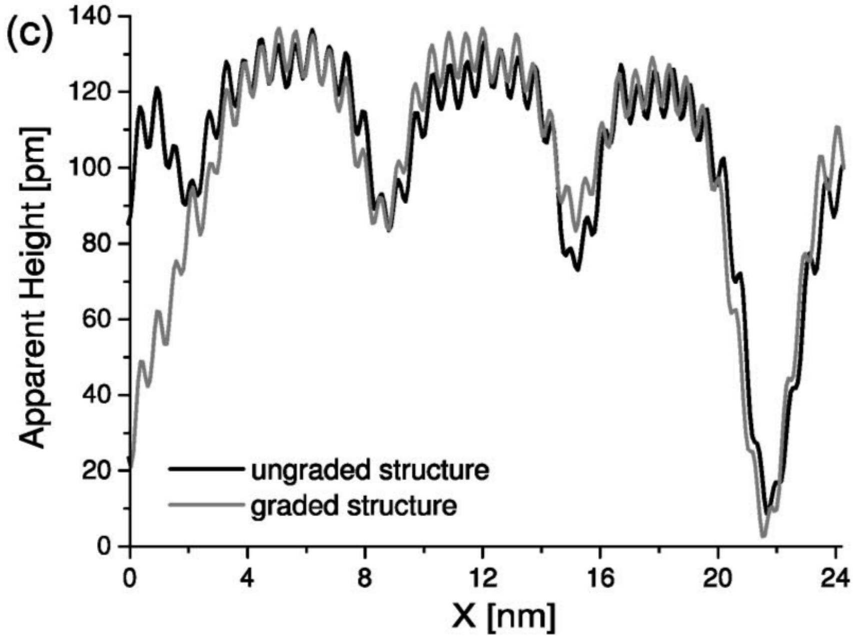
[1] Unuma et al., J. Appl. Phys. 93, 1586 (2003)

Epitaxy: Interfaces

STM cross-section



Cut across interfaces



Interfaces are
- graded (over 3-4ML)
- rough

P. Offerman et al., Appl. Phys. Lett. 83, 4131 (2003)

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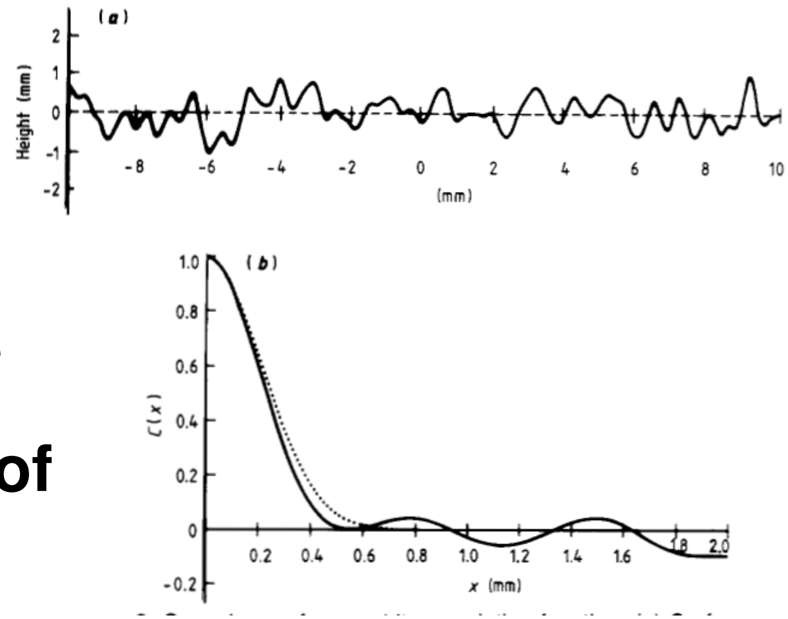
Interface roughness

Most relevant scattering mechanism in mid-IR quantum cascade lasers

$$\langle \Delta(r)\Delta(r') \rangle = \Delta^2 exp\left(-\frac{| r - r' |^2}{\Lambda^2}\right)$$

average step height (Δ) — correlation length (Λ)



- **Historically, focused on the minimization of**
- **the emission broadening**
- ***Recently high performance broad gain***
- ***lasers were presented [1,2]***

..Is emission broadening the right parameter?

[1] A.Bismuto et al., Appl. Phys. Lett. 96, 141105 (2010)
[2] Y. Yao et al., New J. Phys. 97, 081115 (2010)
[3] Unuma et al., J. Appl. Phys. 93, 1586 (2003)

How to modify the correlation length?

Growth temperature ⟷ Correlation length (Λ)

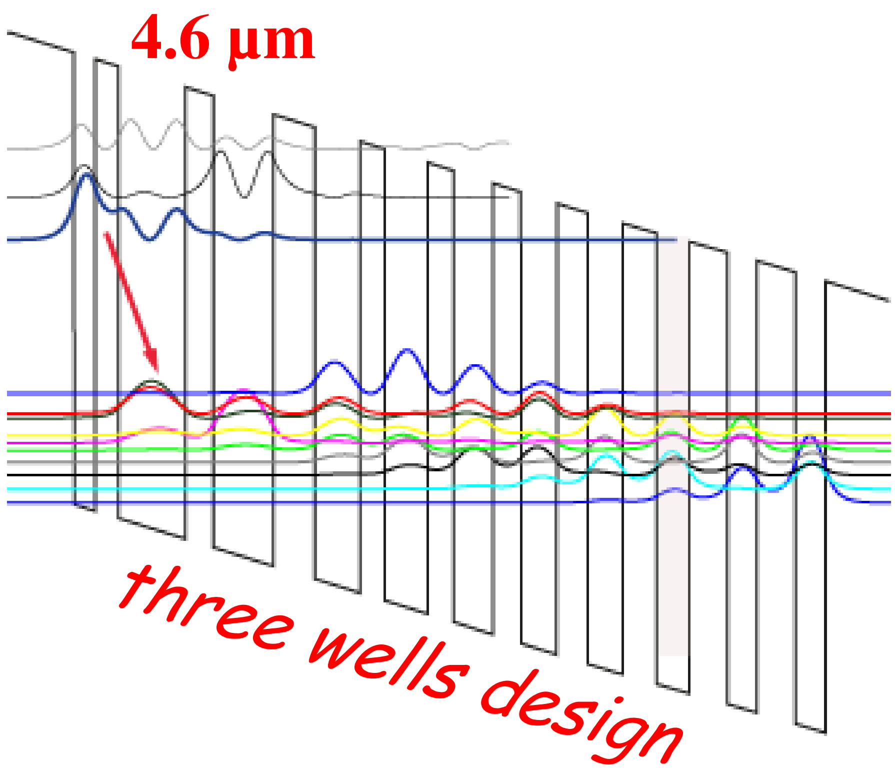
Smaller effect temperature dependence of step height (Δ)

Same processing

T=475 °C

T=515 °C

T=525 °C



Diagonal design more sensitive to the interface roughness

How to modify the correlation length?

Growth temperature ⟷ Correlation length (Λ)

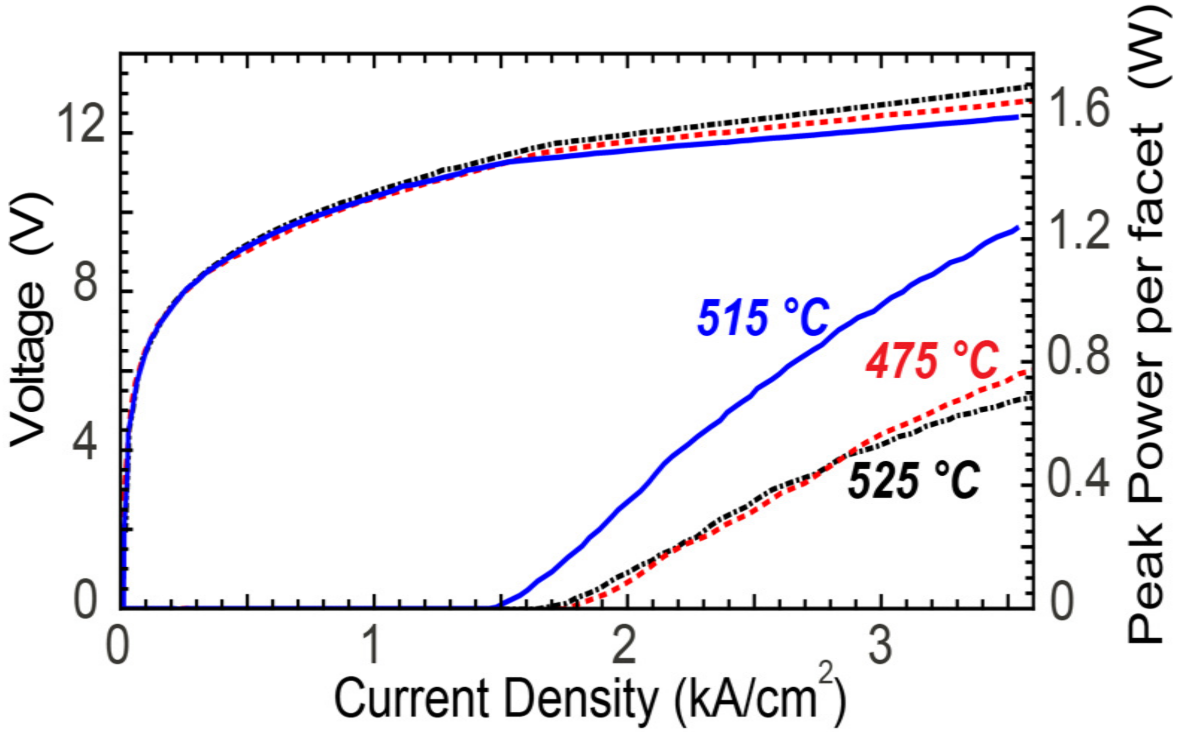
Smaller effect temperature dependence of step height (Δ)

Same processing

T=475 °C

T=515 °C

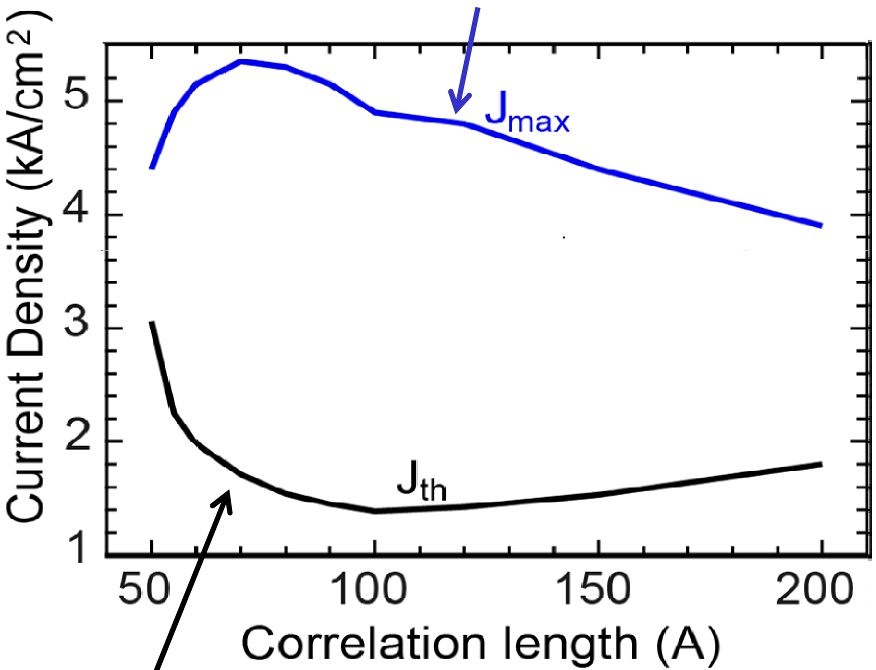
T=525 °C



Growth conditions are modified to systematically vary interface roughness

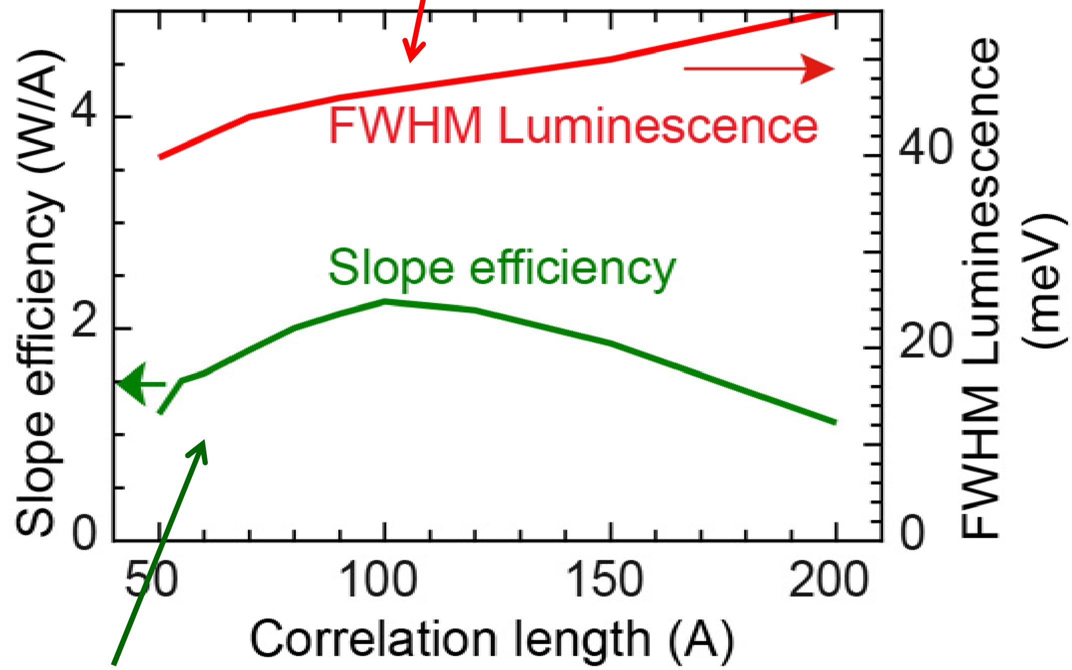
Simulated performance

Current at roll-over



Threshold current density

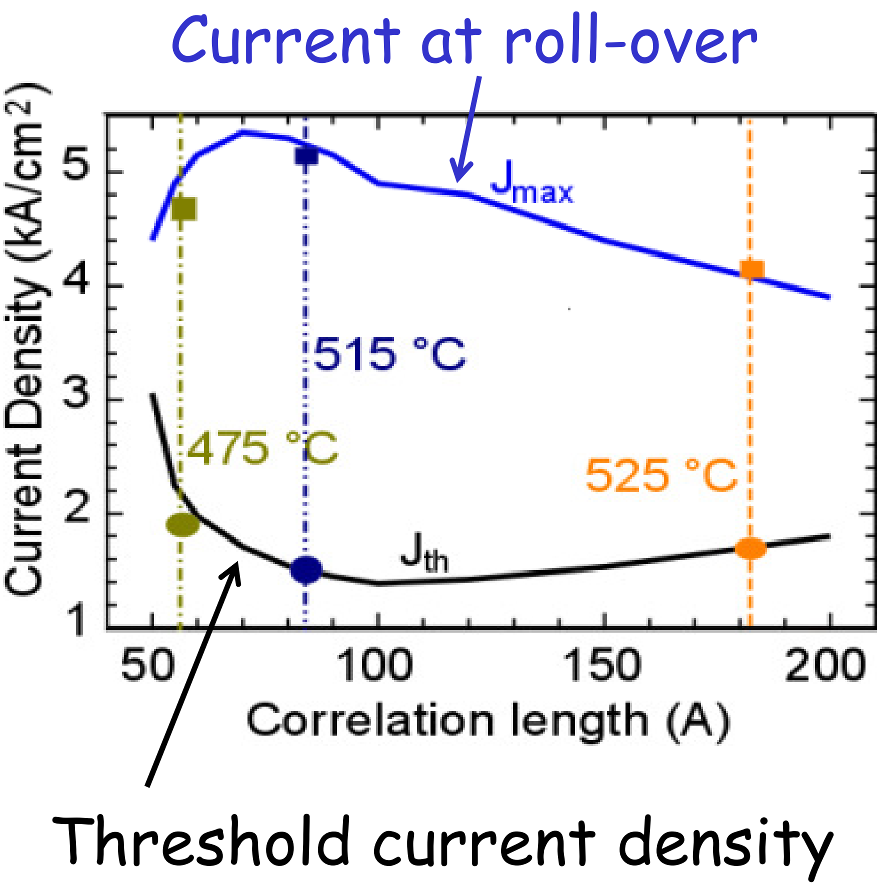
FWHM luminescence

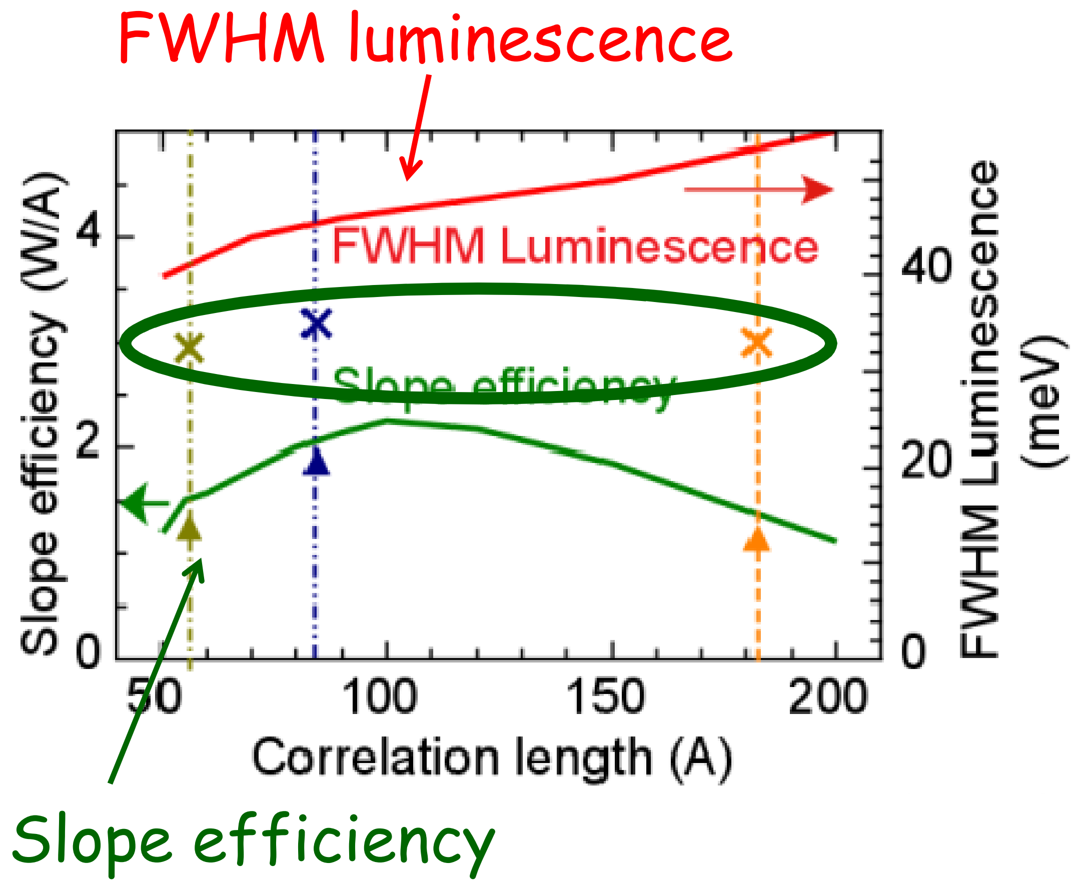


Slope efficiency

[1] A.Bismuto et al., Appl. Phys. Lett. 98, 091105 (2011)

Simulated performance





Model fails to predict emission linewidths

[1] A.Bismuto et al., Appl. Phys. Lett. 98, 091105 (2011)

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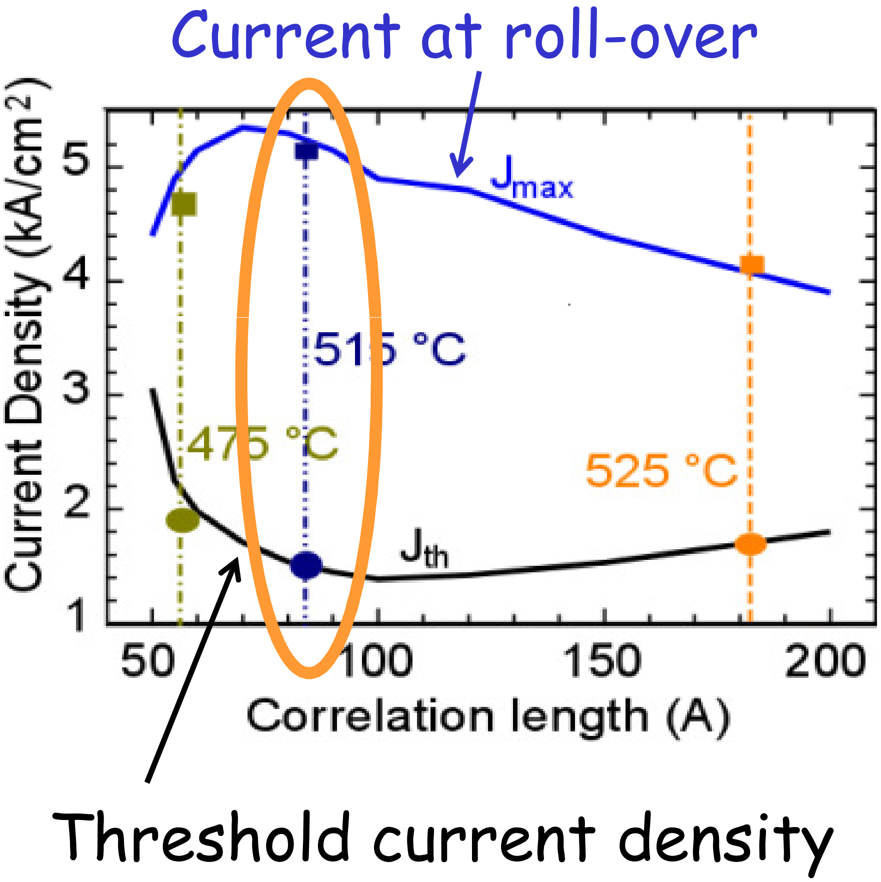
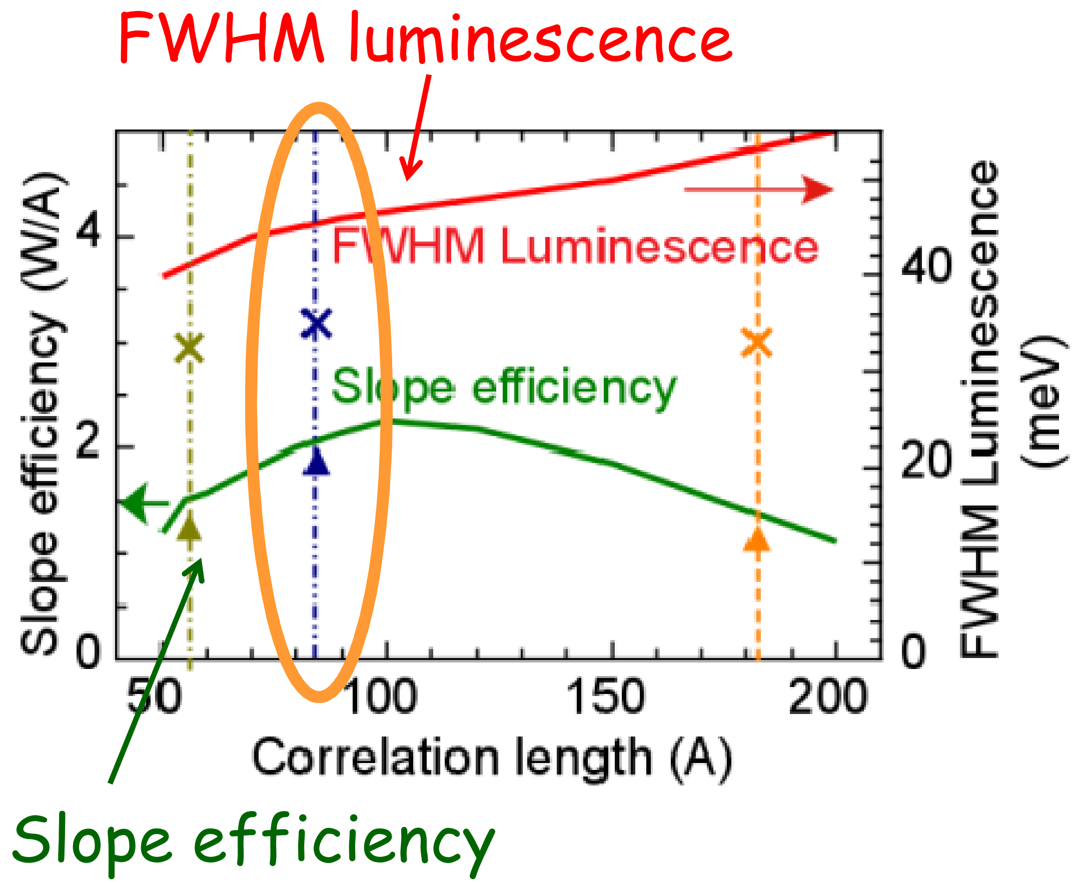
Simulated performance

Model fails to predict emission linewidths



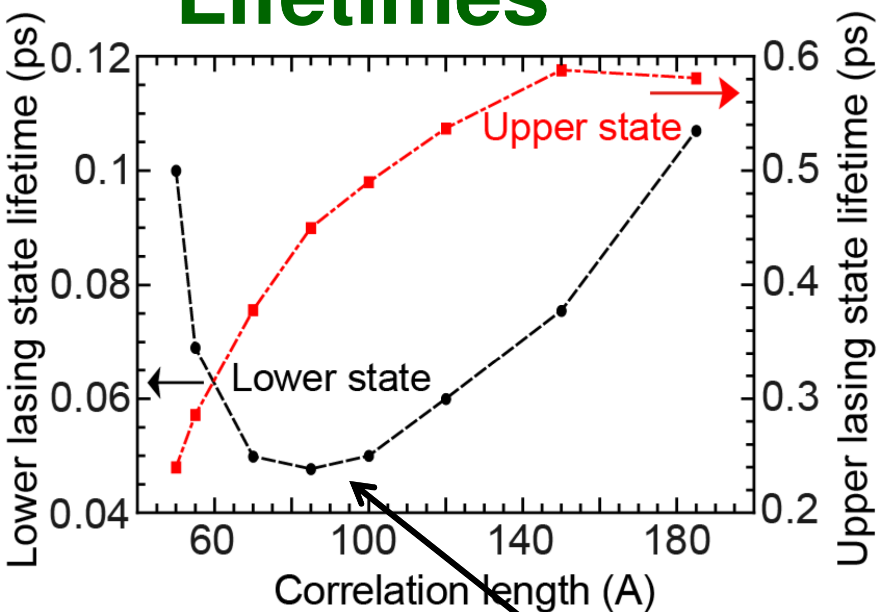


Best laser performance for Λ ~ 90 A

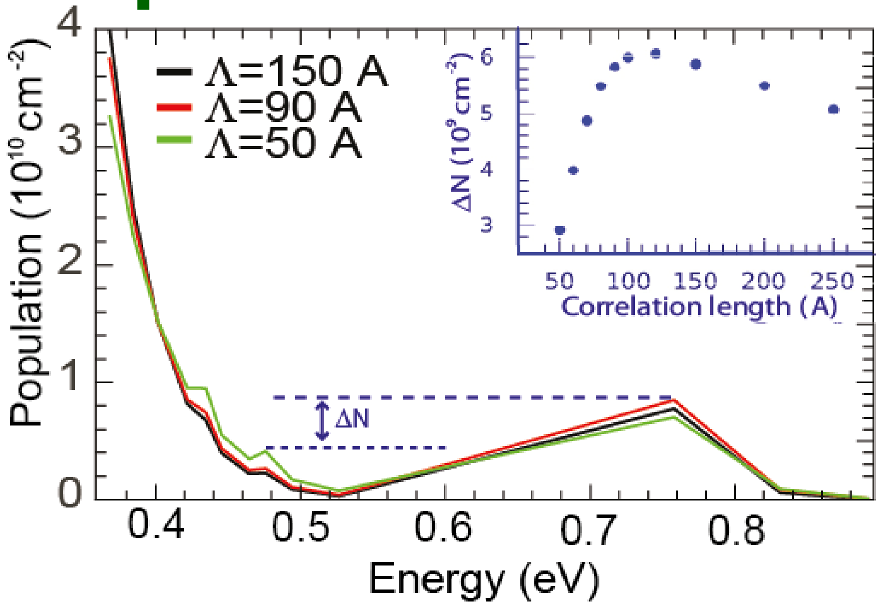
[1] A.Bismuto et al., Appl. Phys. Lett. 98, 091105 (2011)

How to justify laser behavior ?

Lifetimes



Population inversion



Lower lasing state shows a minimum corrisponding to best laser performance

Population inversion shows a maximum

resonance corresponding to qΛ~1
(q exchanged wavevector during intersubband transition)
(transition energy of 34 meV)

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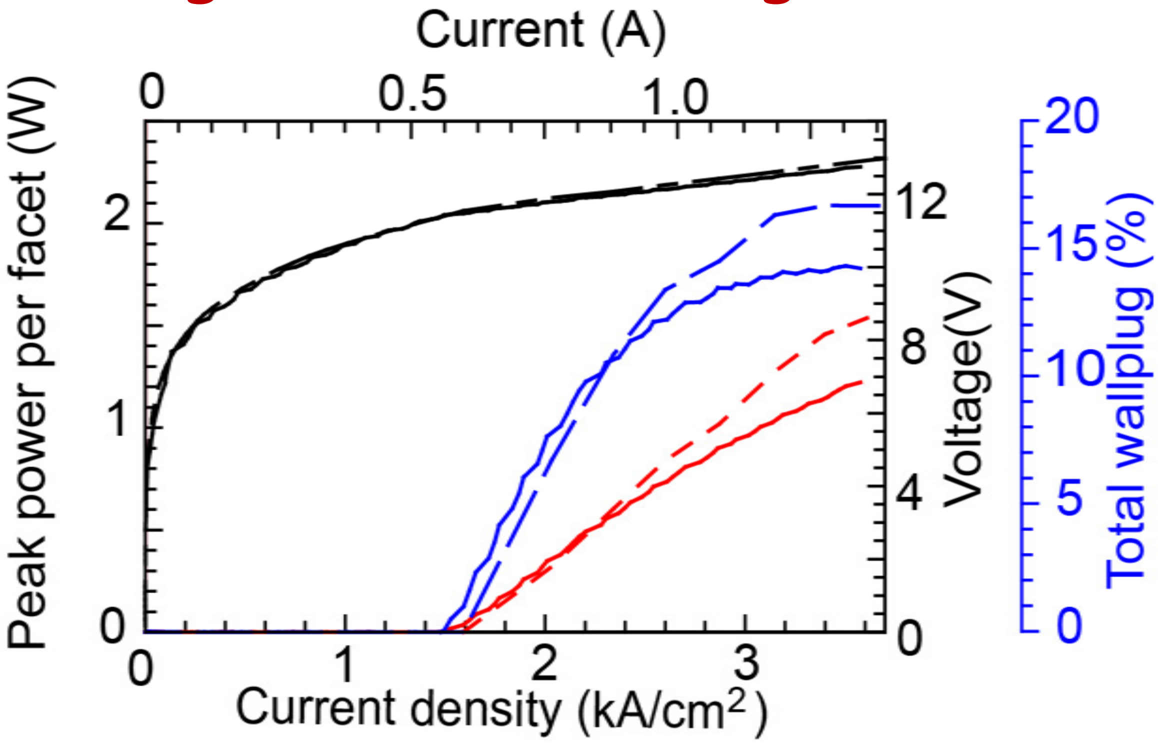
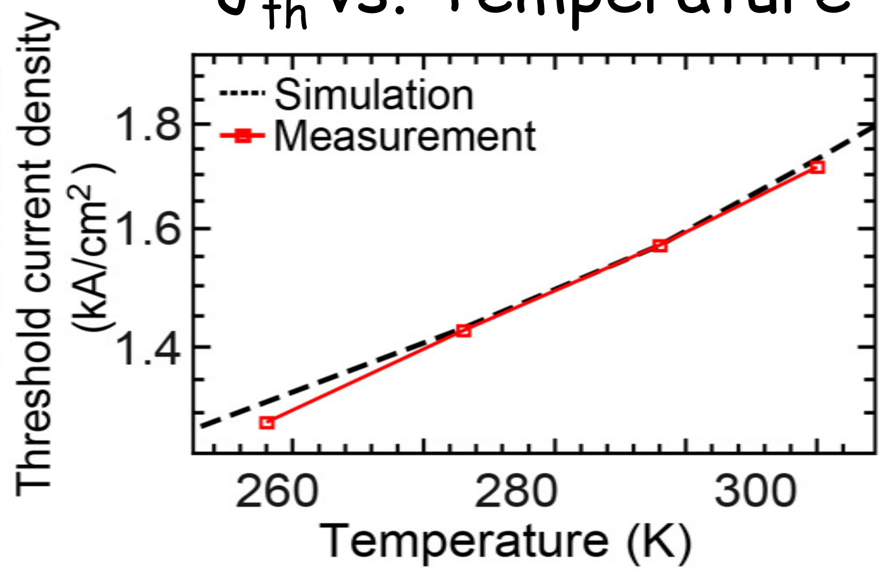
Best sample

Light-current-voltage



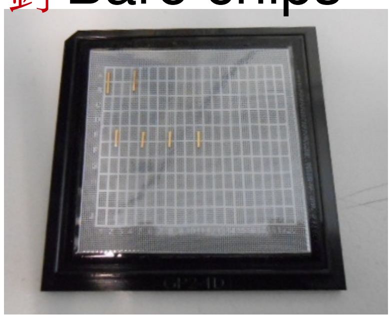
J_{th} vs. Temperature



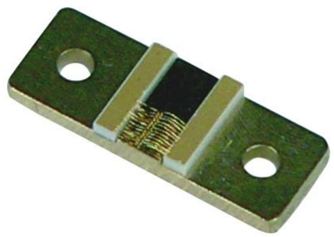
Simulated curves (dashed)
Measured curves

QC lasers and electronics

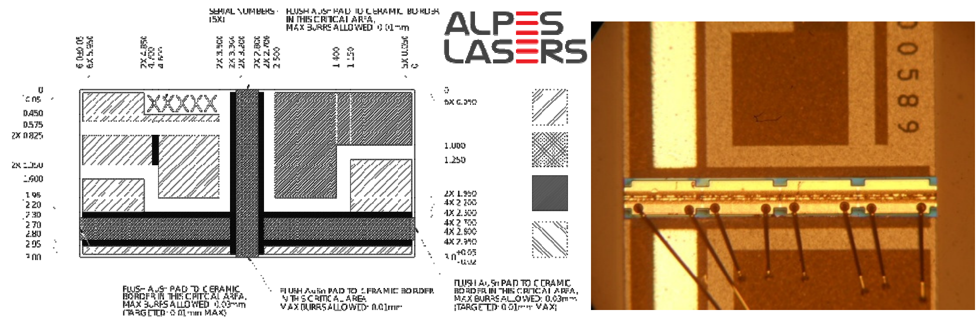
- Bare chips



- NS



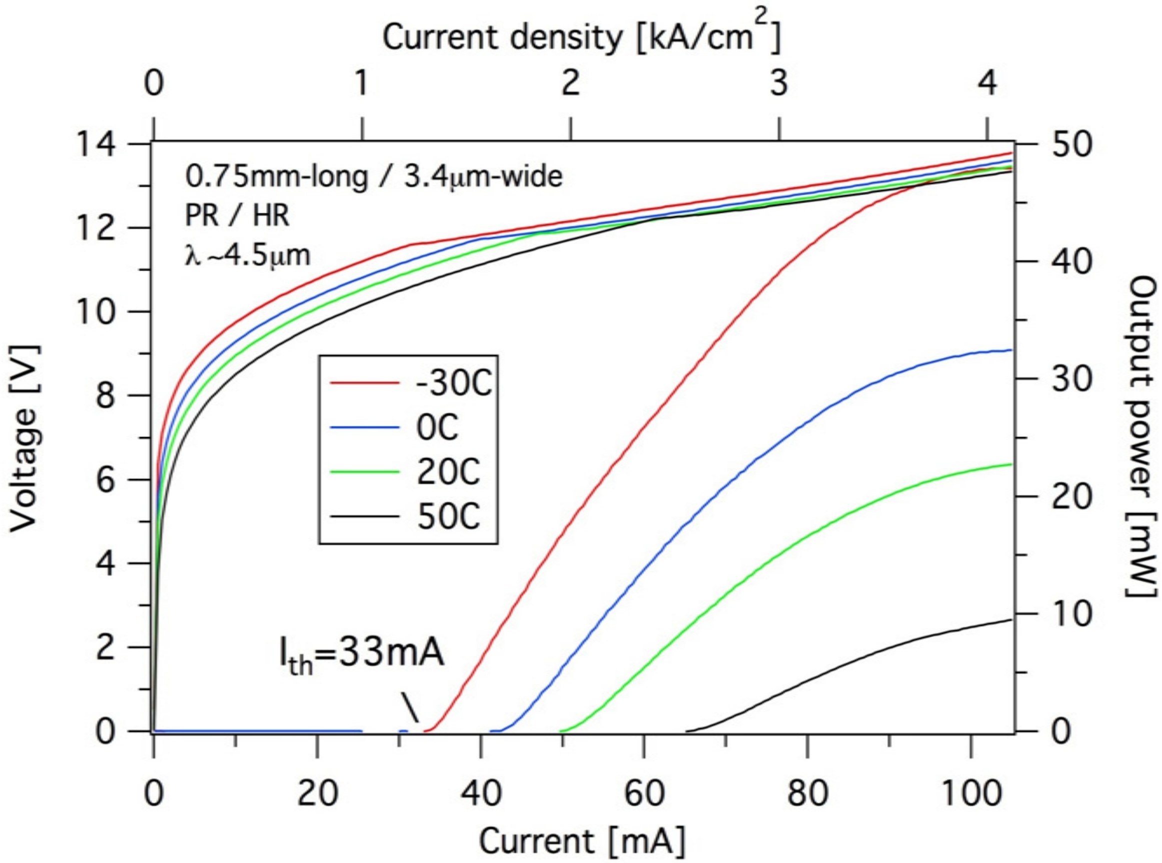
- AlN submount (3x6mm)

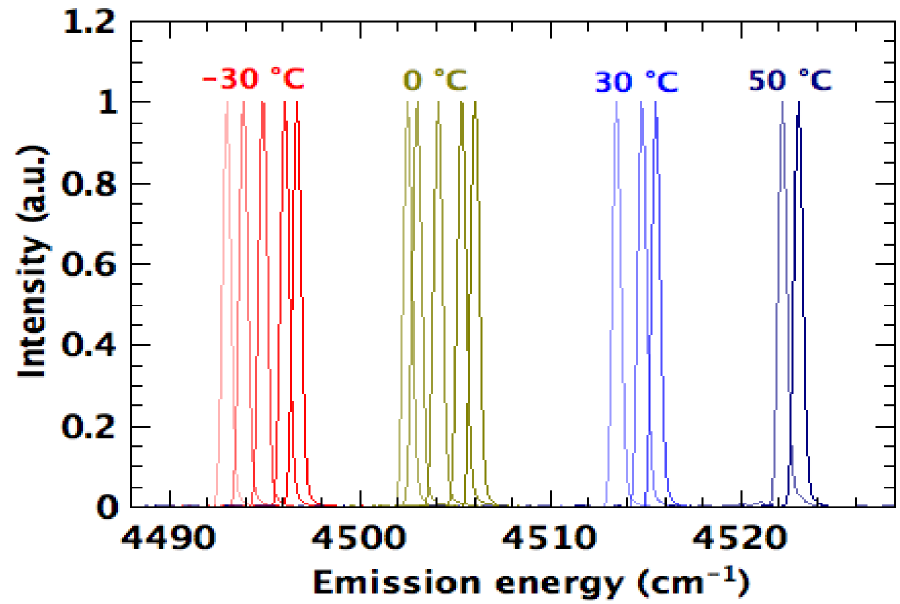


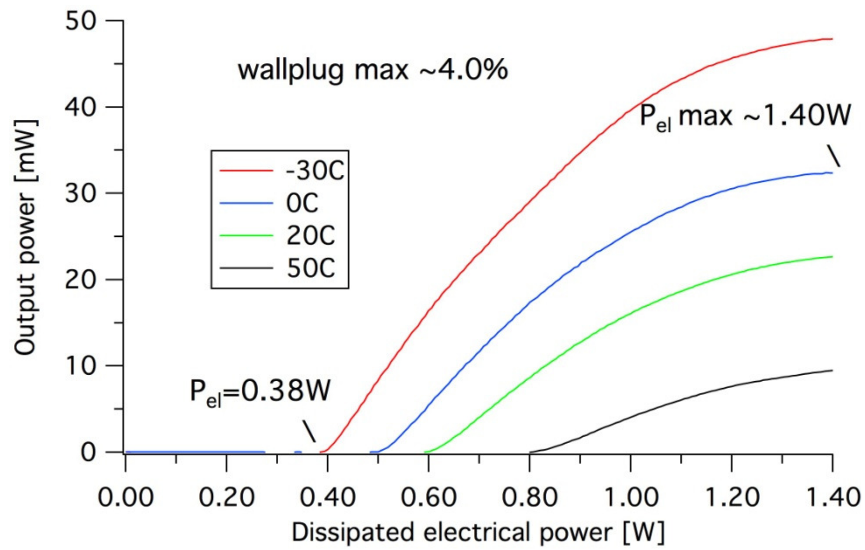
- TC3

- Driver kits

Low-dissipation DFB devices at 4.5 □m

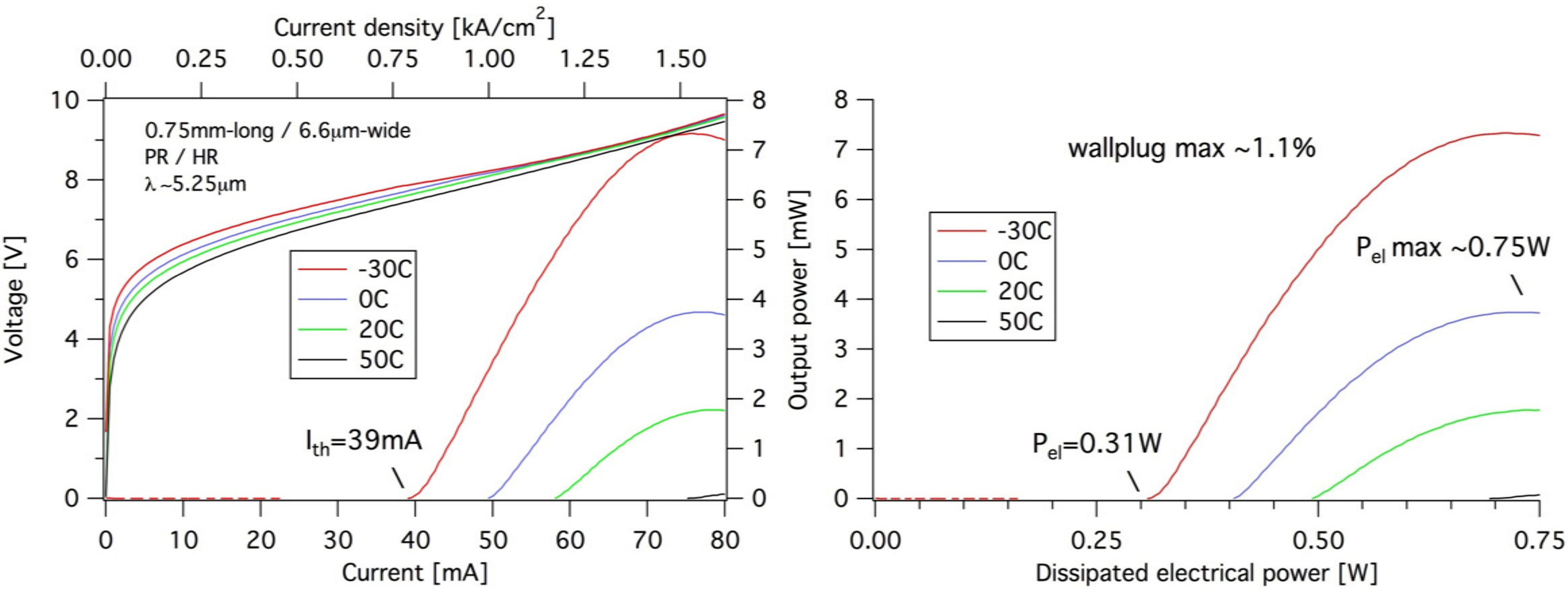






- opt power up to 48mW
- P_{el} max ~1.4W

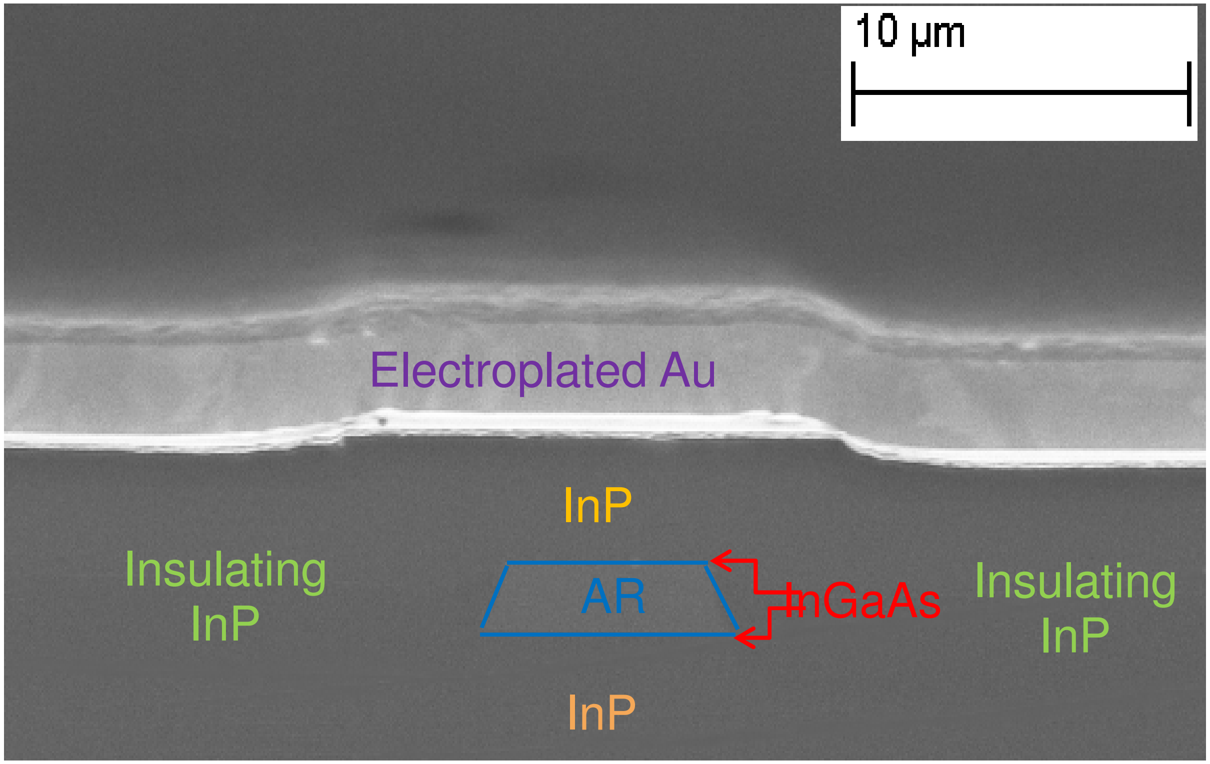
Low-dissipation DFB devices at 5.25□m



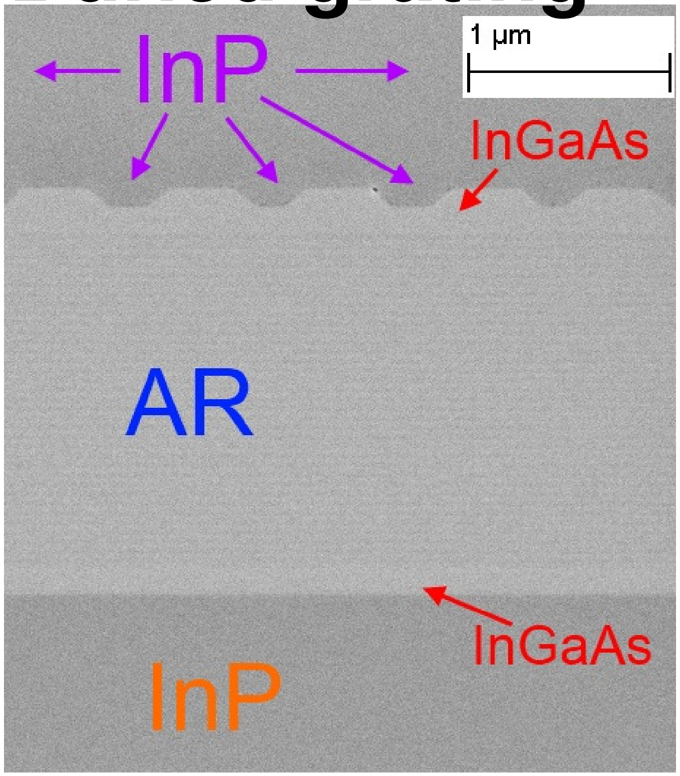
very low threshold power : 0.31W

Fabrication process

Front facet



Buried grating



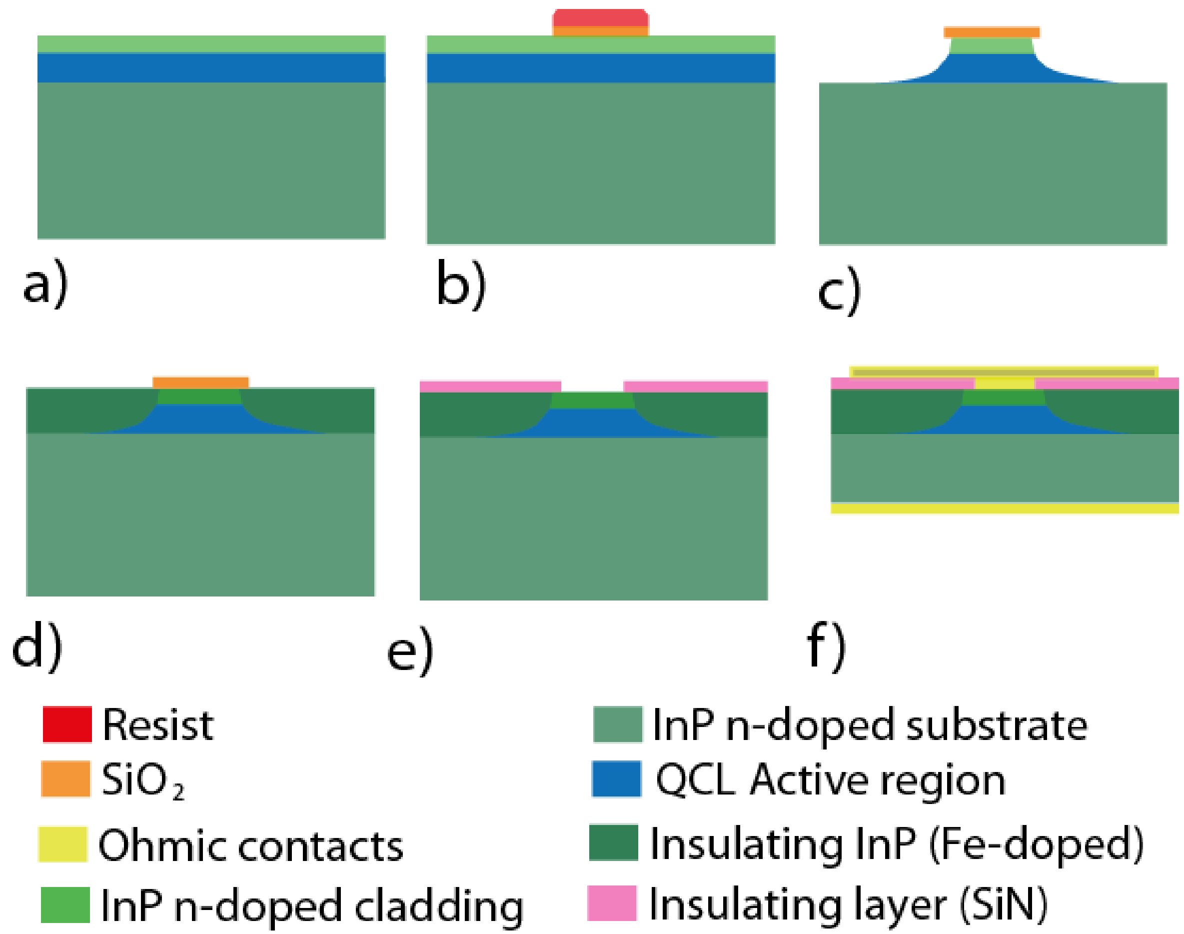
- Most of QCLs have 5-15 W of electrical dissipation
- Up to 100 W are needed to control the temperature

*Courtesy of B. Hinkov, ETHZ

BH Fabrication process

Importance of the fabrication process:

- Optical losses
- Thermal conductance
- Device yield
- Spectral purity (DFBs)



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