Мощные квантово-каскадные лазеры для спектрального диапазона 8 мкм

Владислав Дюделев

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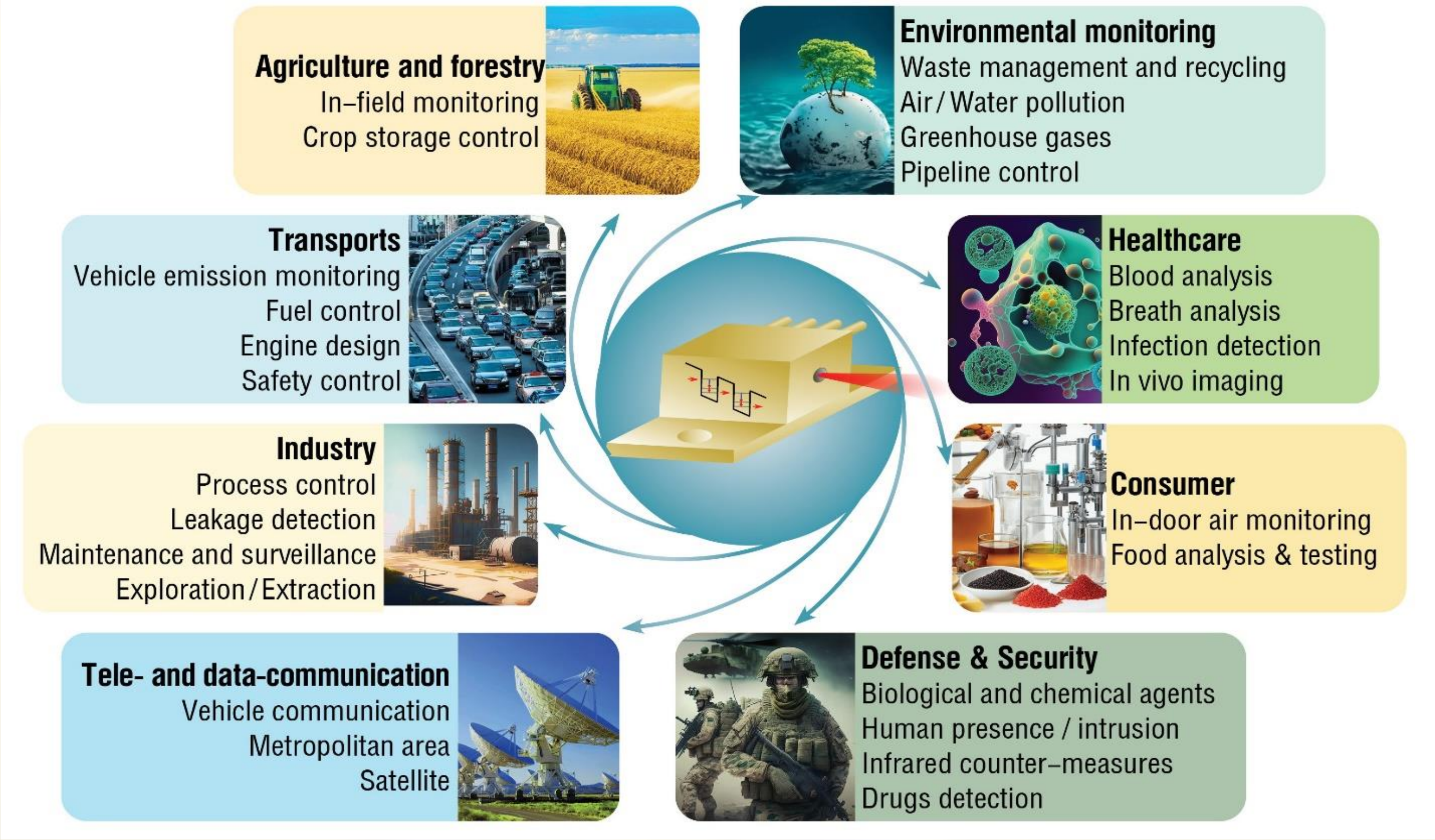
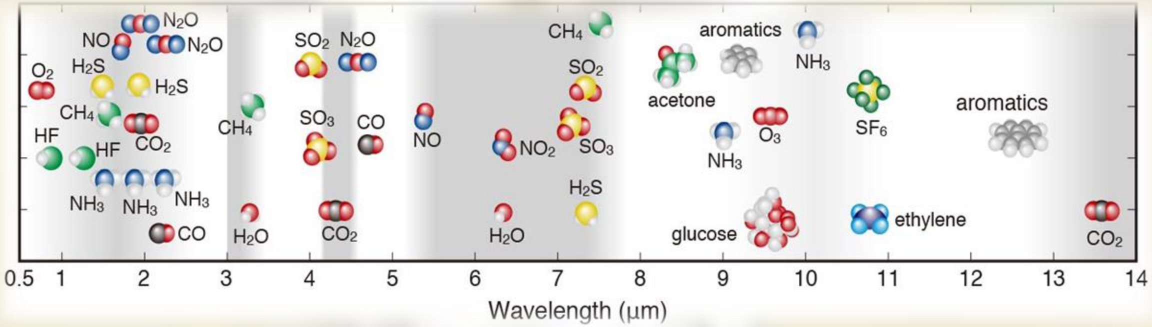
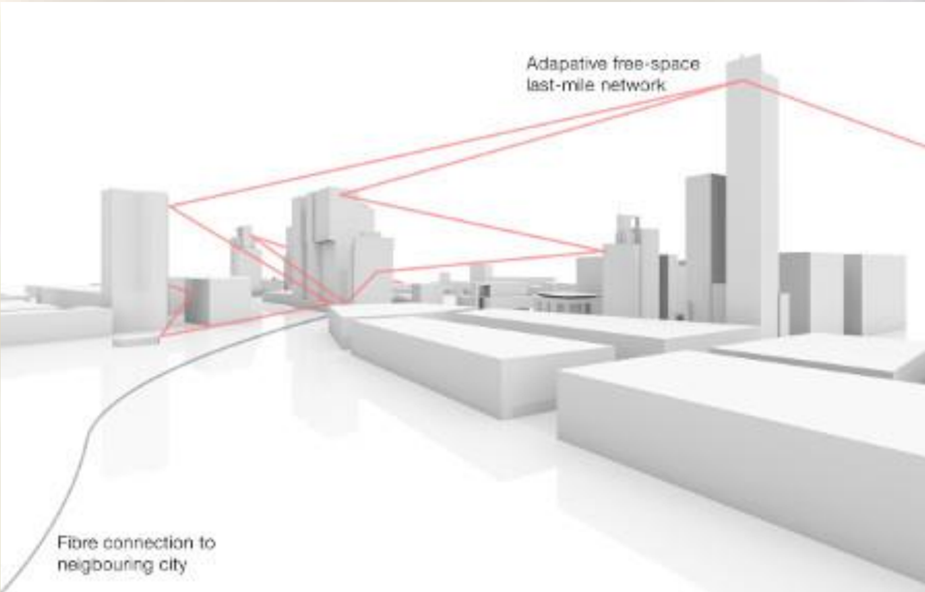
[c]JSC MF Stelmakh Polyus Res Inst, Moscow, Russia
[d]ITMO University, Saint-Petersburg, Russia

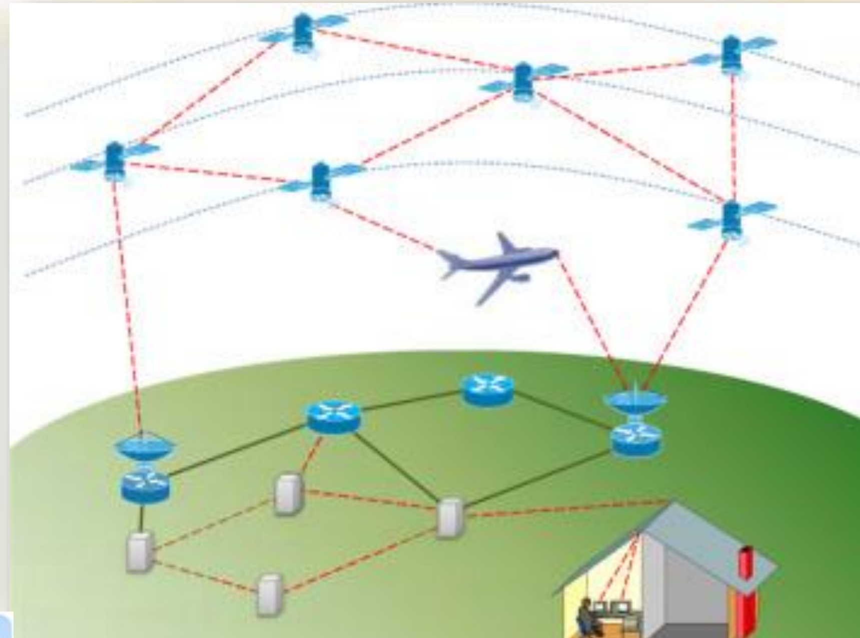
Motivation

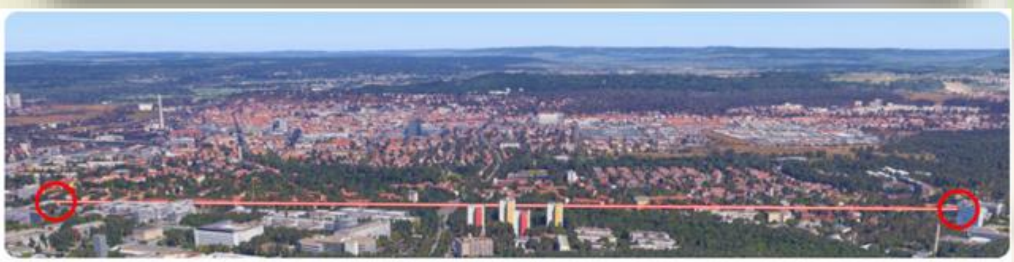

Agriculture and forestry
In–field monitoring
Crop storage control
Environmental monitoring
Waste management and recycling
Air / Water pollution
Greenhouse gases
Pipeline control
Transports
Vehicle emission monitoring
Fuel control
Engine design
Safety control
Healthcare
Blood analysis
Breath analysis
Infection detection
In vivo imaging
Industry
Process control
Leakage detection
Maintenance and surveillance
Exploration / Extraction
Consumer
In–door air monitoring
Food analysis & testing
Tele- and data-communication
Vehicle communication
Metropolitan area
Satellite
Defense & Security
Biological and chemical agents
Human presence / intrusion
Infrared counter–measures
Drugs detection


N_2O NO N_2O O_2 H_2S H_2S CH_4 CO_2 HF HF NH_3 NH_3 NH_3 CO
SO_2 N_2O CH_4 SO_3 CO H_2O CO_2 NO
CH_4 SO_2 NO_2 SO_3 H_2O H_2S
aromatics NH_3 acetone NH_3 O_3 glucose SF_6 aromatics ethylene CO_2
0.5 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Wavelength (µm)

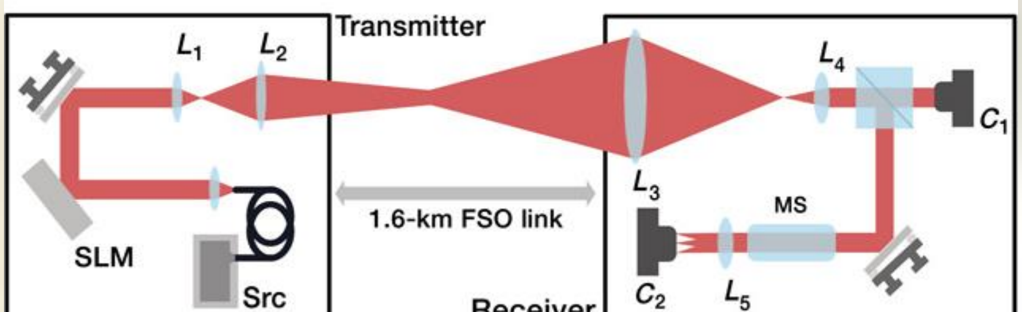
Motivation 2/2: FSO communication







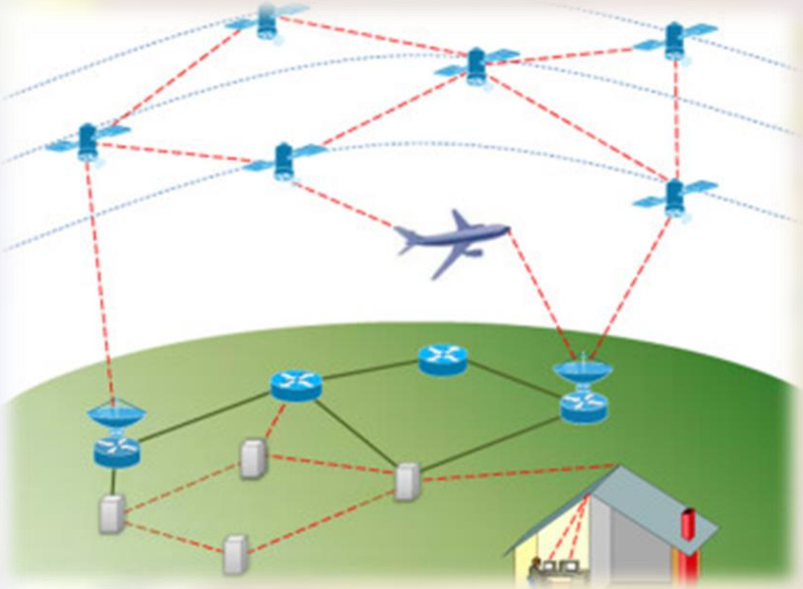
[Lavery et al., Sci. Adv. 3(10) e1700552 (2017)]

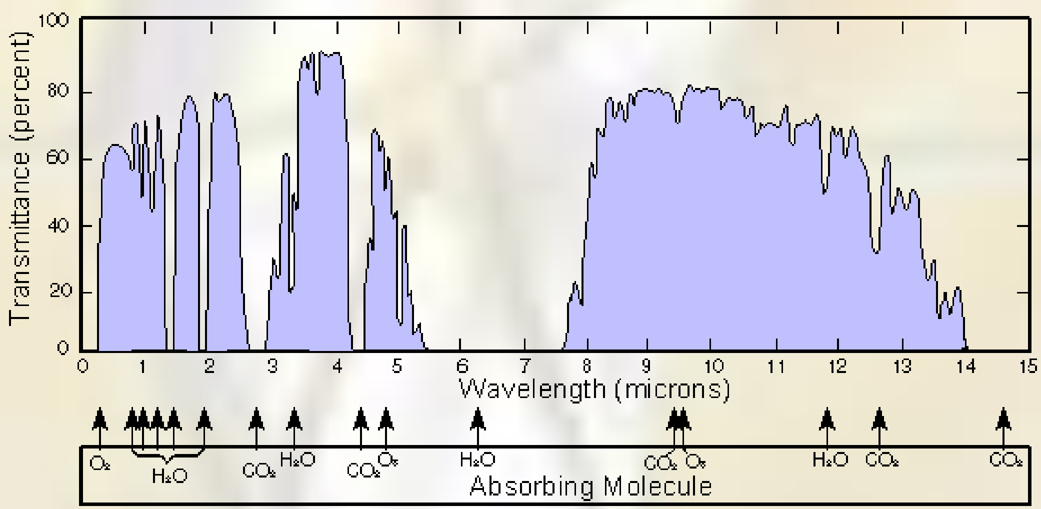


Alpes Lasers SA (Switzerland)
Mirsense (France)
Pranalytica Inc. (USA)
Adtech Optics (USA)
Block Engineering Inc. (USA)
Wavelength Electronics Inc. (USA)
Akela Laser Corporation (USA)
Nanoplus Nanosyst. & Tech. GmbH (Germany)
Hamamatsu Photonics K.K. (Japan)
Thorlabs Inc. (USA)

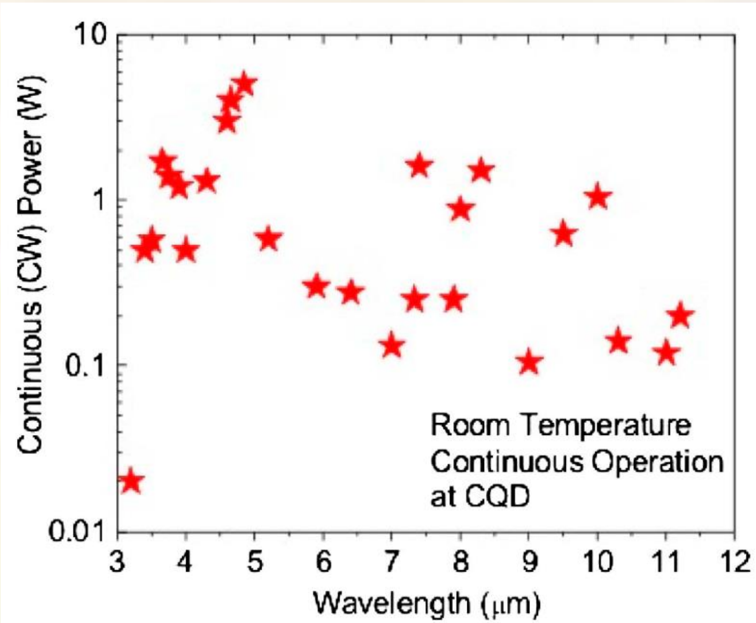
Outline

- Motivation & brief history
- High-power QCLs @ 8 μm
  Upper cladding optimization
- High-power QCLs @ 8 μm
  Strained vs Lattice-matched
- Active region overheating
- Conclusion

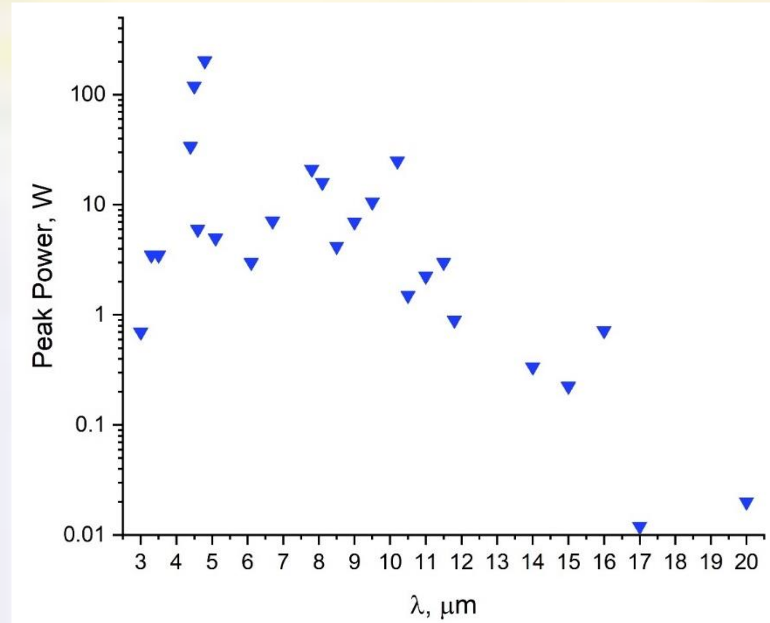




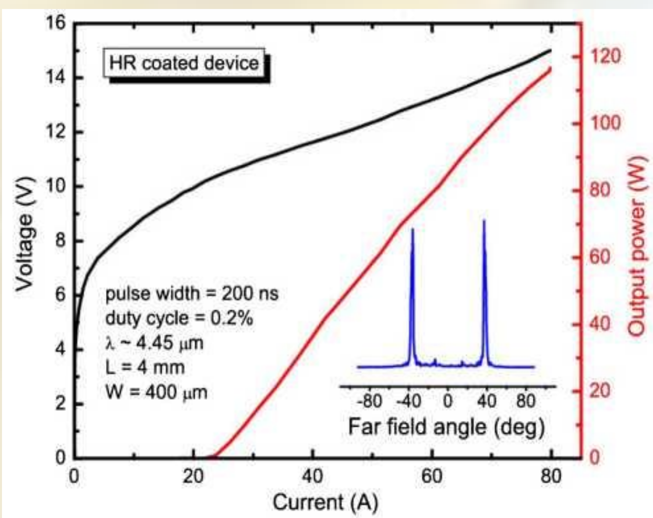
Mid-IR QCLs: 3 Decades



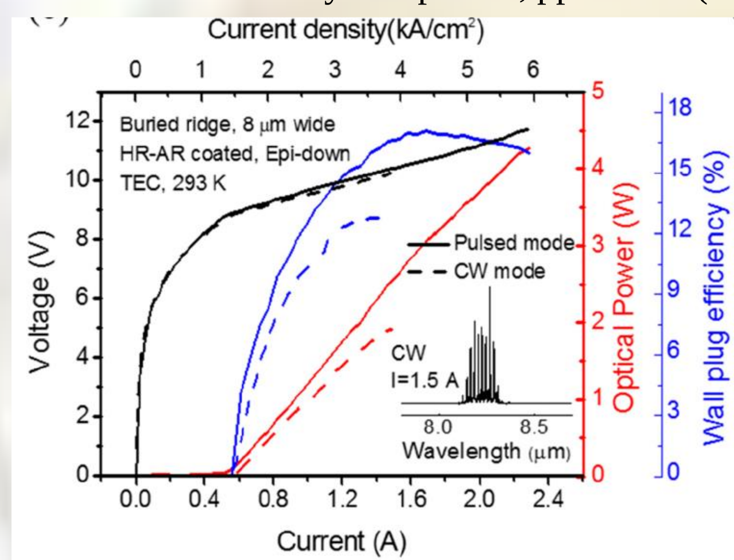
M. Razeghi et al., Appl. Opt. ,**56**, H30,2017



V.V. Dudelev et al. Phys. Usp. v.67, pp. 92–98 (2024).

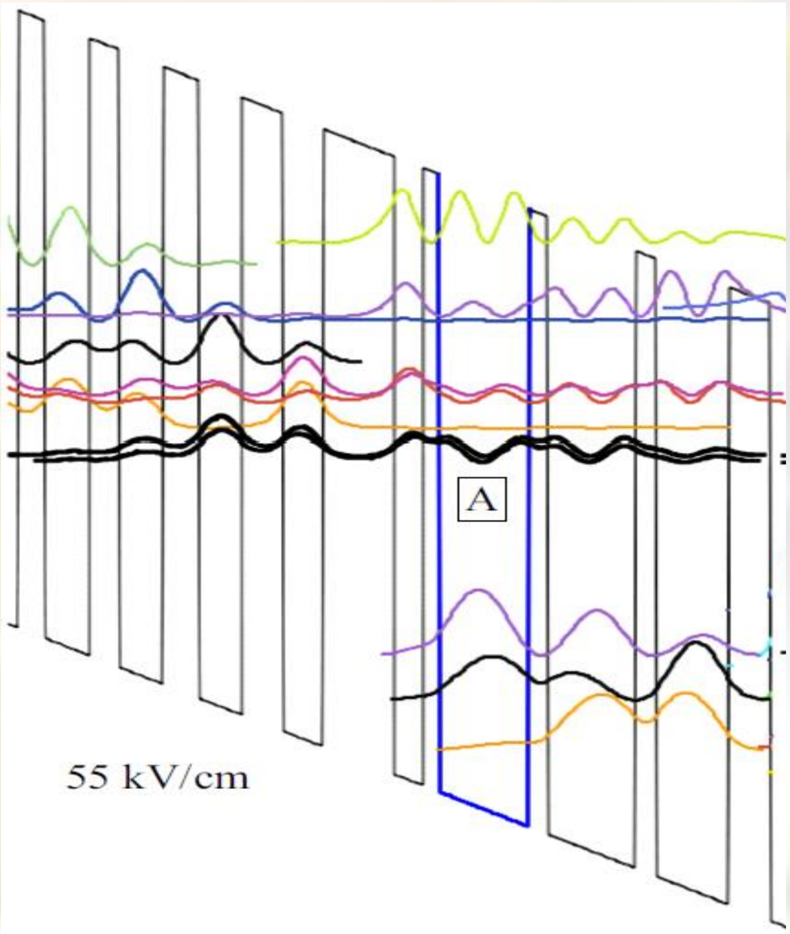


Y. Bai et al Appl. Phys. Lett., **95,** 221104, 2009



W. Zhou et al., Opt. Exp., 27, 15776, 2019

QCL structure λ = 8 μm



Structure:

- Two-phonon resonance scattering
- Lattice-matched heterostructure $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$

Upper level lifetime: τ_{upp} = 2.32 ps
Radiating transition time: $\tau_{up\text{-}low}$ = 5.8 ps
Lower level lifetime: τ_{low} = 0.30 ps
Matrix element: $|M|^2_{up\text{-}low}$= 6.45 nm^2

Figure of merit (FOM):

$|M|^2_{up\ low} \cdot \tau_{up} \cdot (1 - \tau_{low}/\ \tau_{up\text{-}low})$

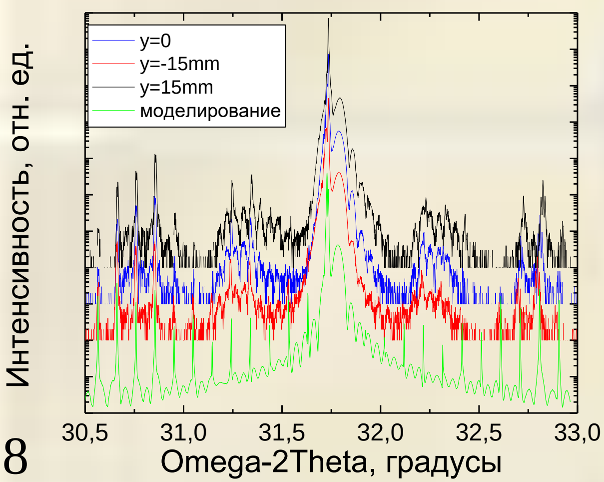
FOM = 14 ps nm^2

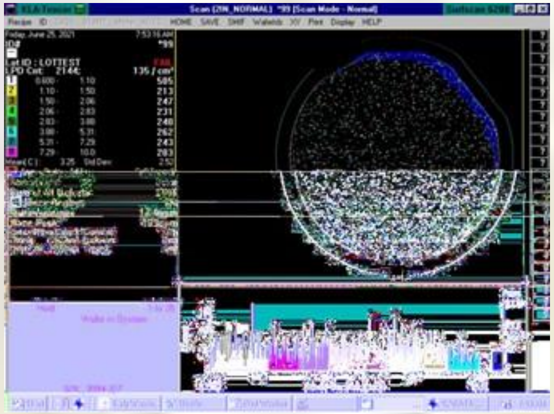
Active region:
$In_{0.53}Ga_{0.47}As$ / $Al_{0.48}In_{0.52}As$ 50x: **2.4**/2.4/**2.6**/2.1/**2.6**/1.8/**2.7**/1.6/**2.9**/1.7/ /**3.1**//2.5/**4.4**/1.2/**5.2**/1.2/**5.3**/1.0/**1.7**/4.3

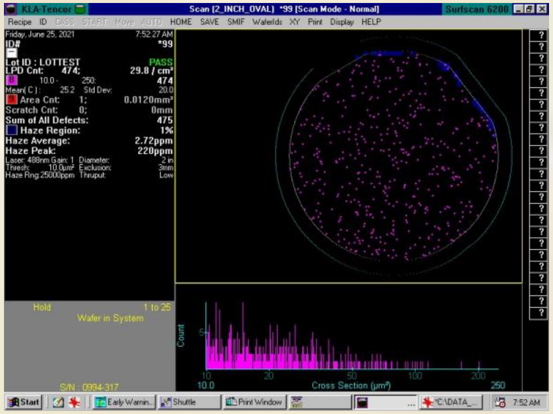
[A.V. Babichev et al. / Tech. Phys. Lett. 43(7) 666 (2017)]

QCL efficiency vs cladding doping

Structure a	Composition	Thickness, nm	Doping, cm^{-3}
Contact layer	InP	200	$1x10^{18}$
Upper cladding	InP	4000	$1x10^{17}$
Structure b			
Contact layer	$In_{0.53}Ga_{0.47}As$	200	$1x10^{19}$
Upper cladding	InP	2000	Gradient $1x10^{16} \div 1x10^{18}$
Upper cladding	InP	2000	$1x10^{16}$
Structure c			
Contact layer	$In_{0.53}Ga_{0.47}As$	200	$1x10^{19}$
Upper cladding	InP	4000	$1x10^{17}$

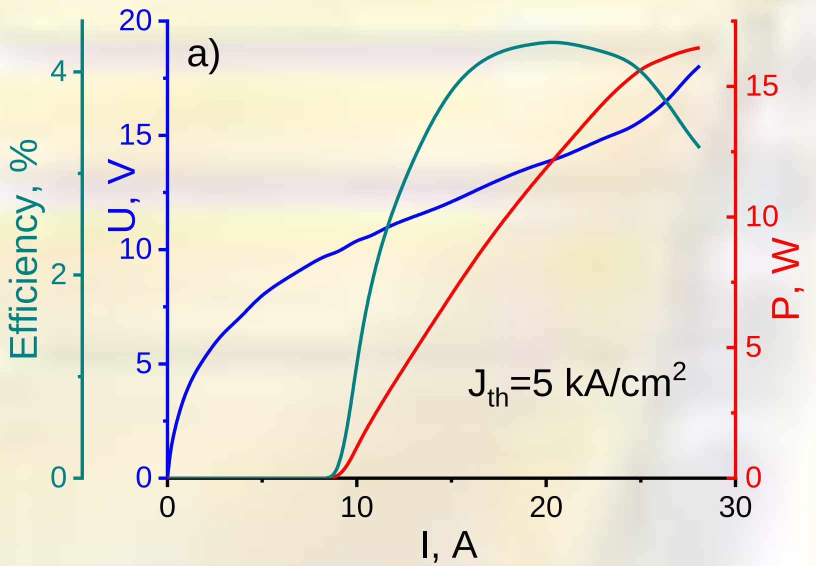


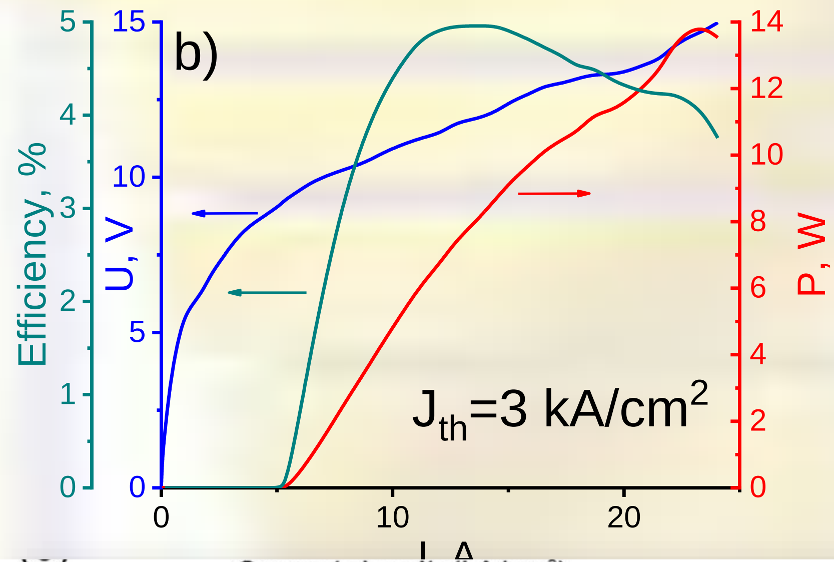


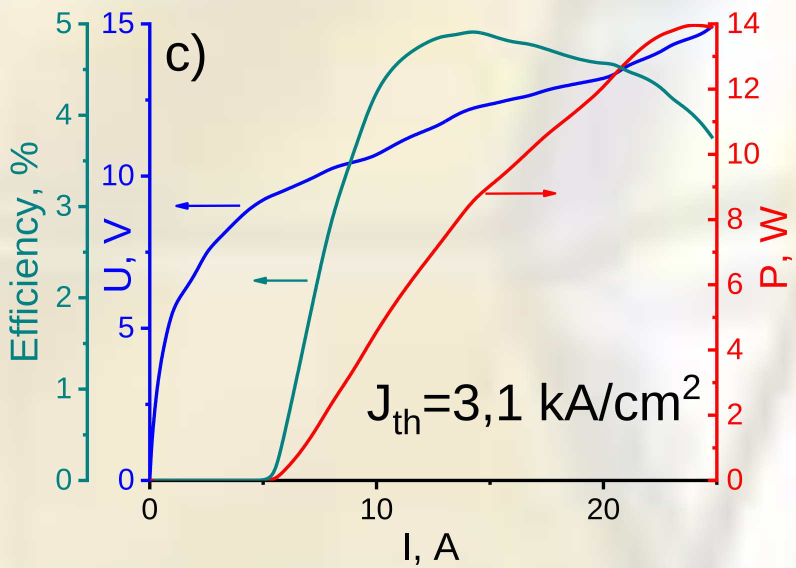


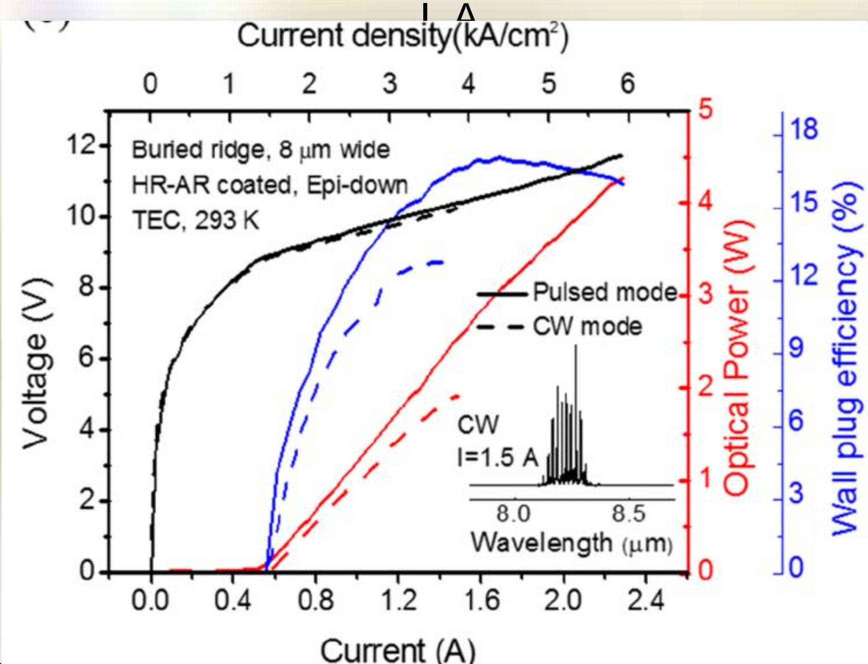
Growth: MOCVD, JSC Polyus (Moscow, Russia)

QCL efficiency vs cladding doping





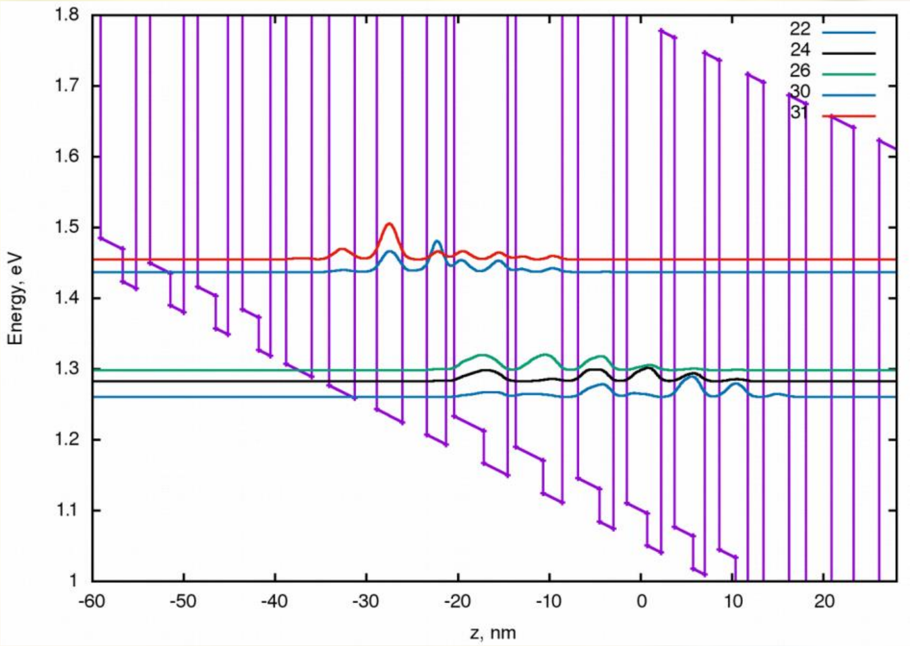




[E.Cherotchenko et al., Nanomaterials 12(22), 3971 (2022)]

[W. Zhou et al., Opt. Exp., 27, 15776 (2019)]

Strain-balanced QCL structure λ = 8 μm



Structure:
- Two-phonon resonance scattering
- Strained heterostructure $Al_{0.63}In_{0.37}As/Ga_{0.35}In_{0.65}As/In_{0.53}Ga_{0.47}As$
- 40 quantum cascades

$Al_{0.63}In_{0.37}As/Ga_{0.35}In_{0.65}As/In_{0.53}Ga_{0.47}As$
vs **$In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As/InP$**
ΔE_c = 740 meV => lower escape rate

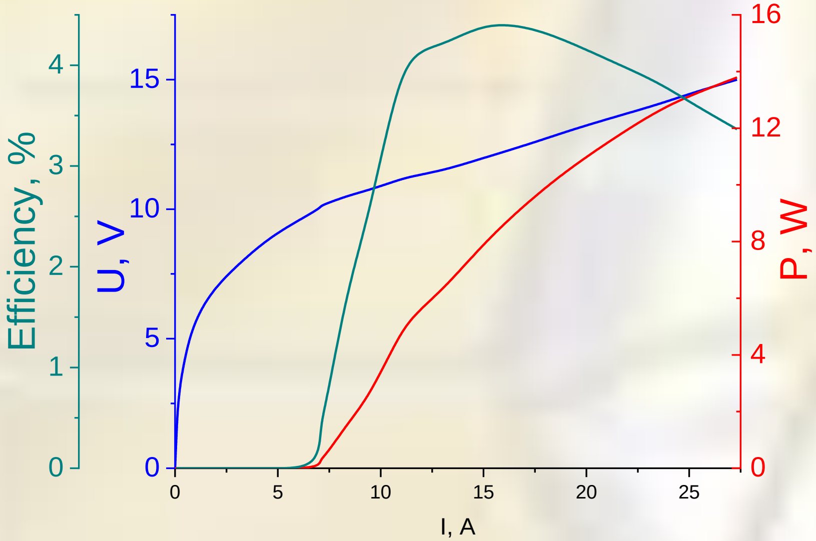
Growth:
MBE: Riber 49 Connector Optics Ltd (St Petersburg, Russia)
MOCVD: JSC Polyus (Moscow, Russia)

[A.V.Babichev et al., Bulletin of RAS Physics 87, 839 (2023)]
[V.V.Dudelev et al, Physics: Uspekhi 67(1), 92 (2024)]

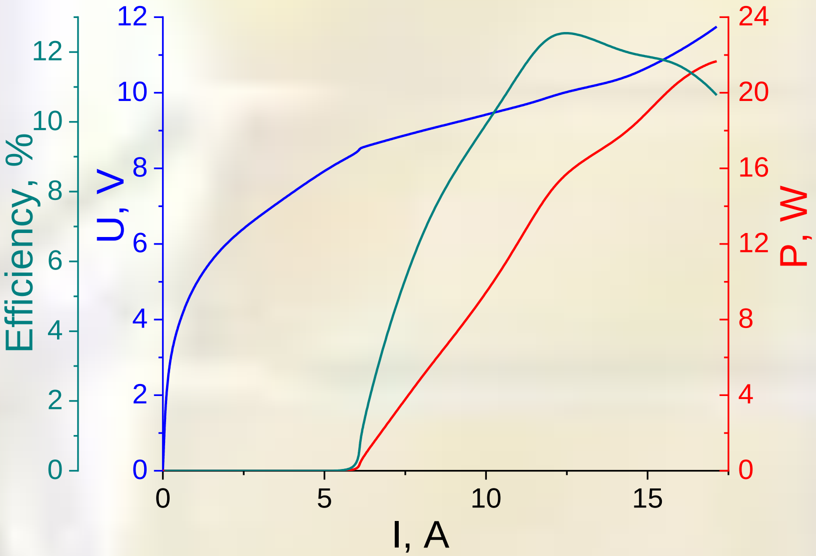
Strain-balanced vs lattice-matched

Ridge width - 50 μm;
Cavity length: 5 mm;
Uncoated facets
Pulsed pumping: ~ 100 ns, 11 kHz

Lattice – matched

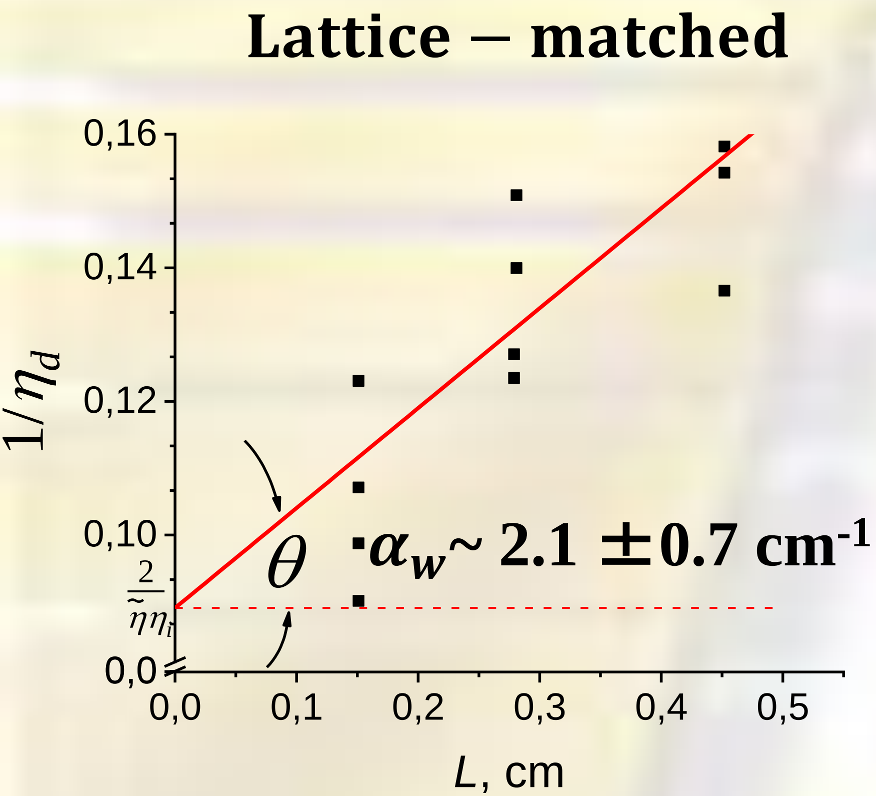


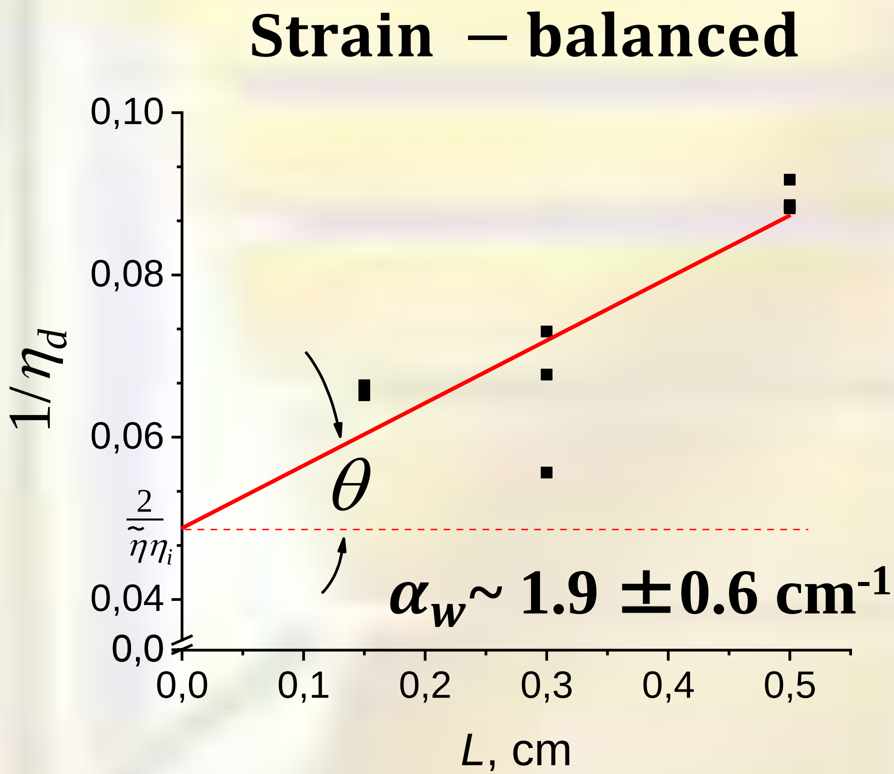
Strain – balanceded



High Output Power > 21 W for QCL with strained design

QCL waveguide losses





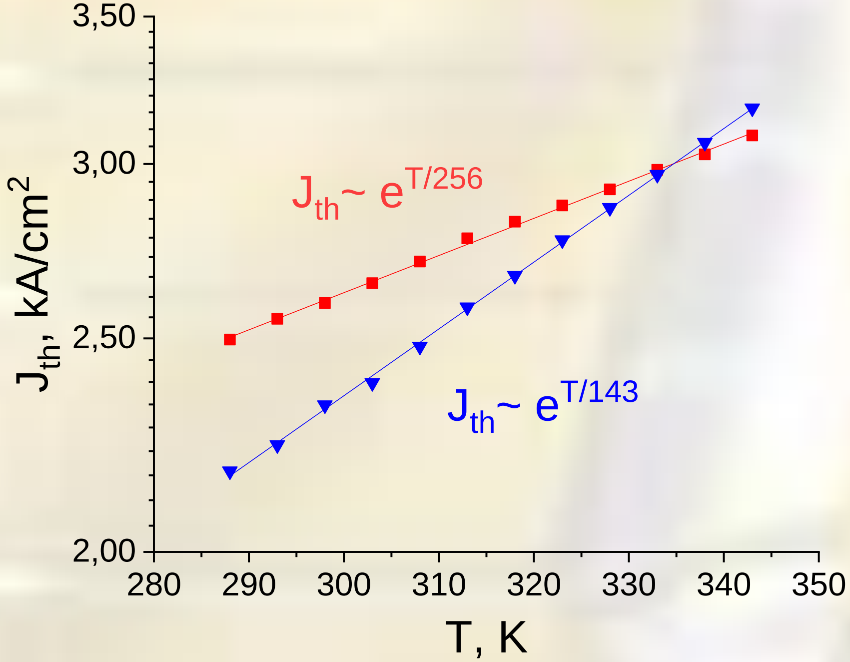
$$\frac{1}{\eta_d} = \frac{2}{\tilde{\eta}\eta_i}\left(1 + \frac{\alpha_w L}{\ln\frac{1}{R}}\right)$$

$$\theta = \frac{2}{\tilde{\eta}\eta_i} \cdot \frac{\alpha_w}{\ln\frac{1}{R}}$$

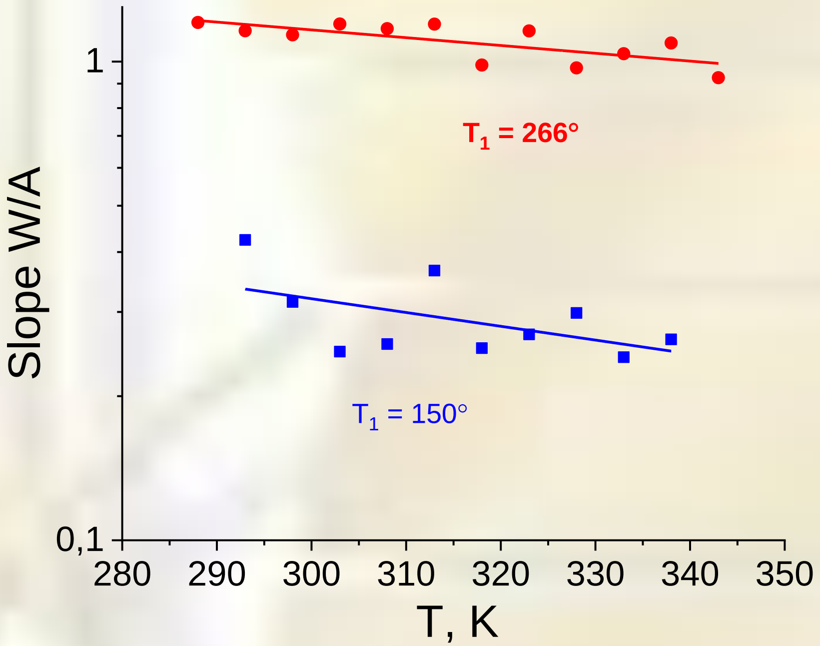
Ridge width - 50 μm; Cavity length: 1.5-5 mm, Uncoated facets
Pulsed pumping: ~ 100 ns, 11 kHz

Strained vs lattice-matched

Threshold current thermal stability

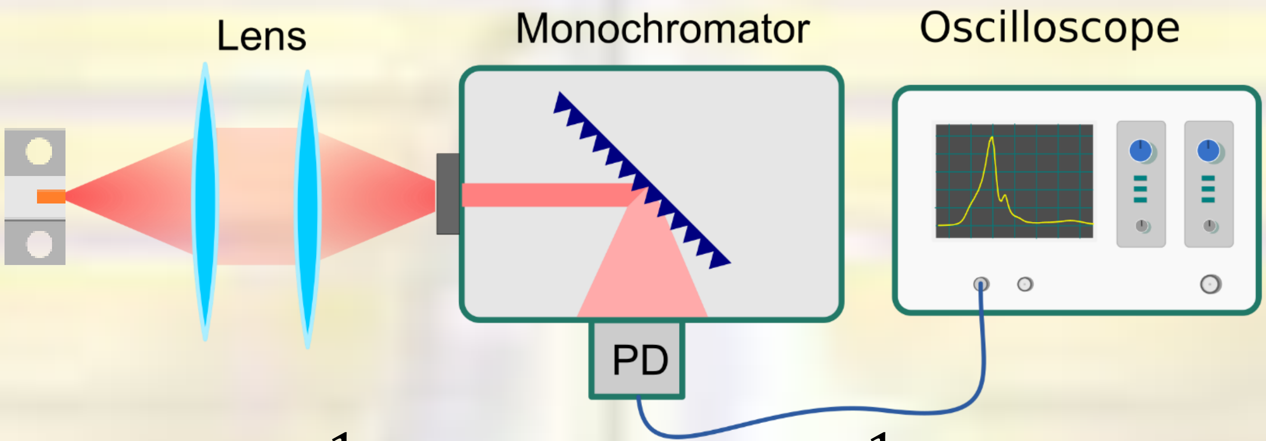


Differential efficiency thermal stability



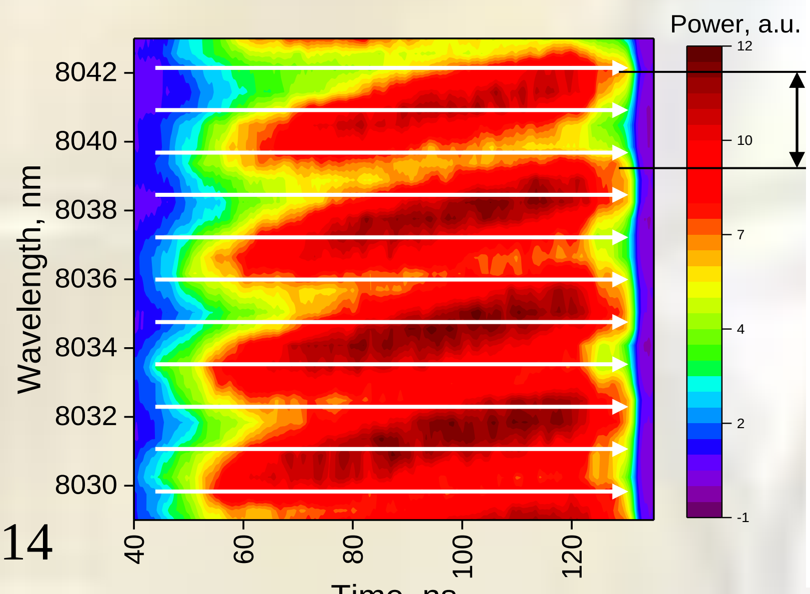
Blue - lattice-matched design,
Red - strain-balanced design

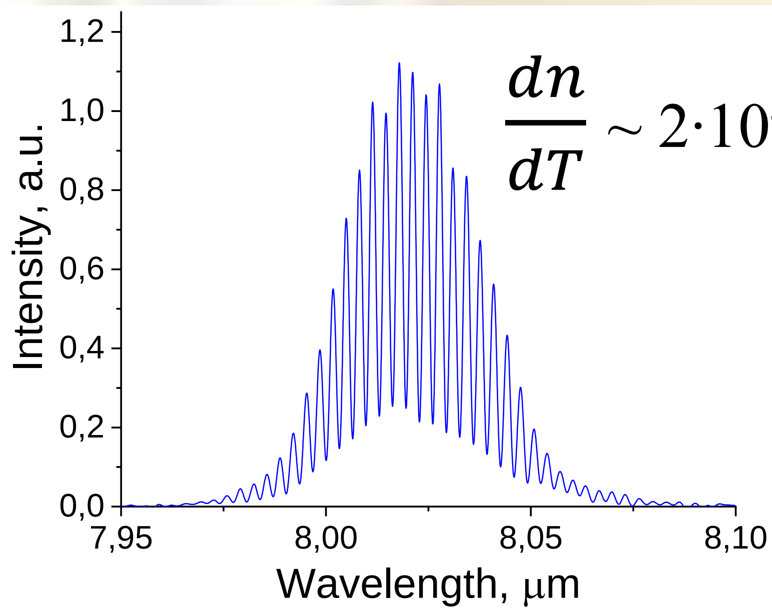
Measurement of QCL heating dynamics



1 GHz b/w

$$T' = \frac{\partial n}{\partial t}\left(\frac{\partial n}{\partial T}\right)^{-1} = \frac{n}{\lambda_j}\frac{\partial \lambda_j}{\partial t}\left(\frac{\partial n}{\partial T}\right)^{-1}$$



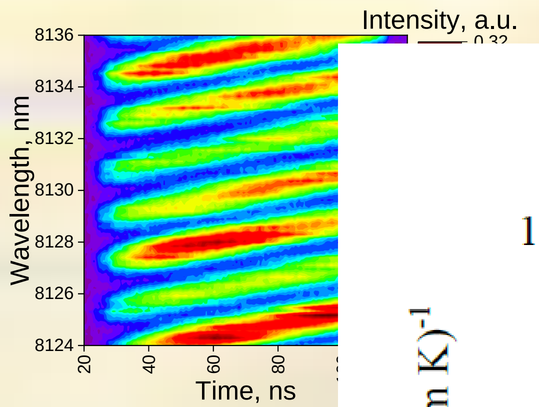


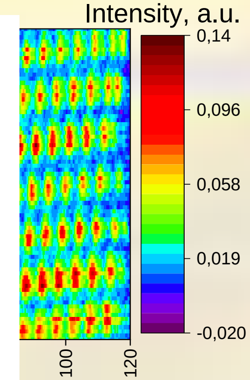
$$\frac{dn}{dT} \sim 2 \cdot 10^{-4}$$

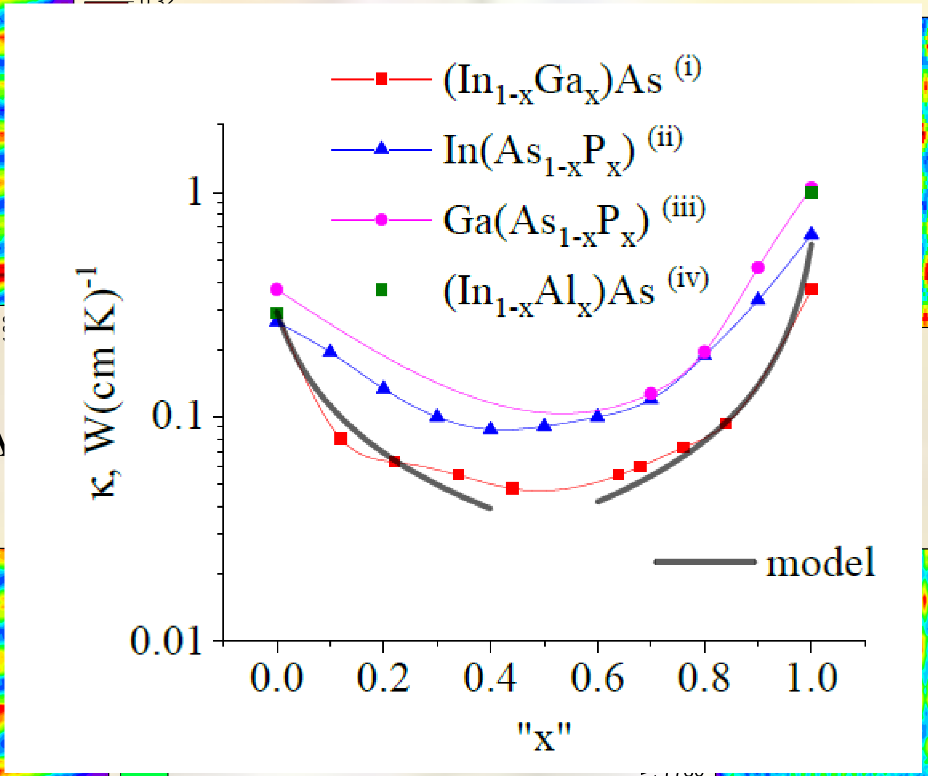
Strained vs lattice-matched

Lattice-matched design

Strain-balanced design

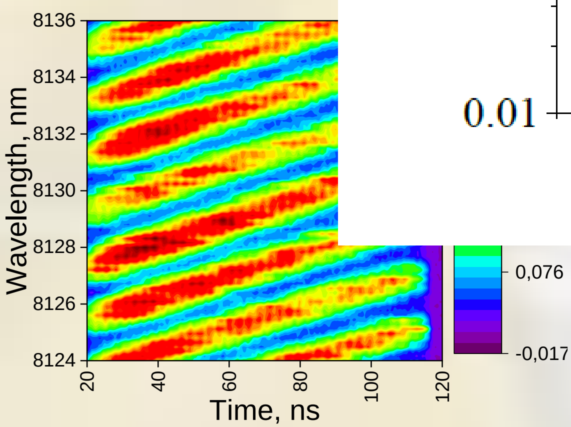


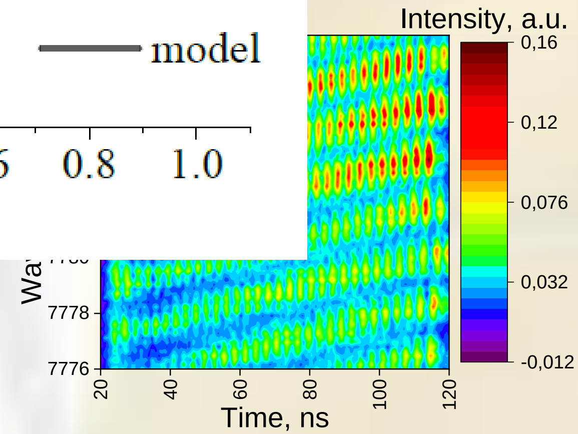




$$\frac{\partial\lambda}{\partial t} = 0.24\ \text{Å}$$

Å/ns

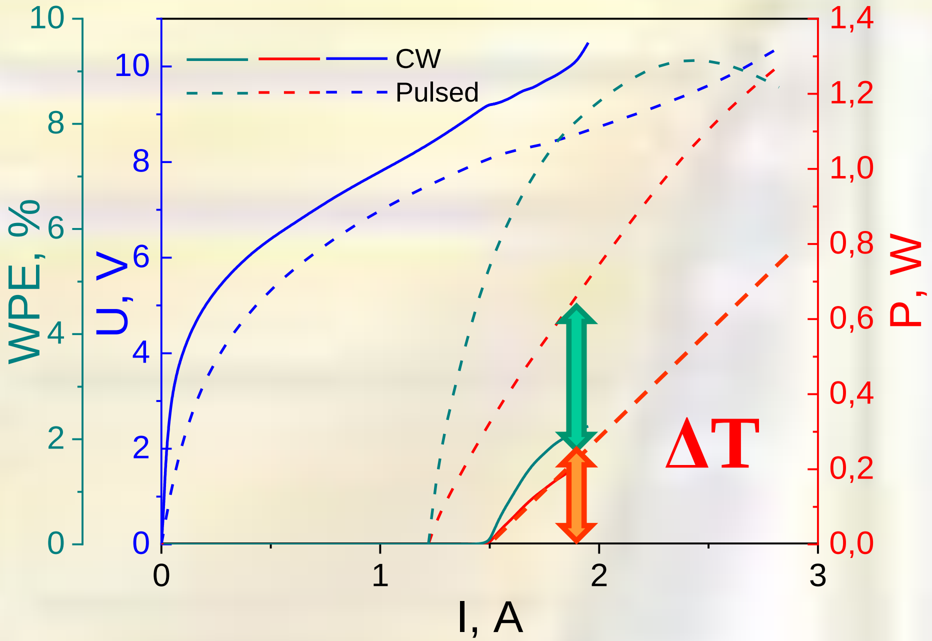


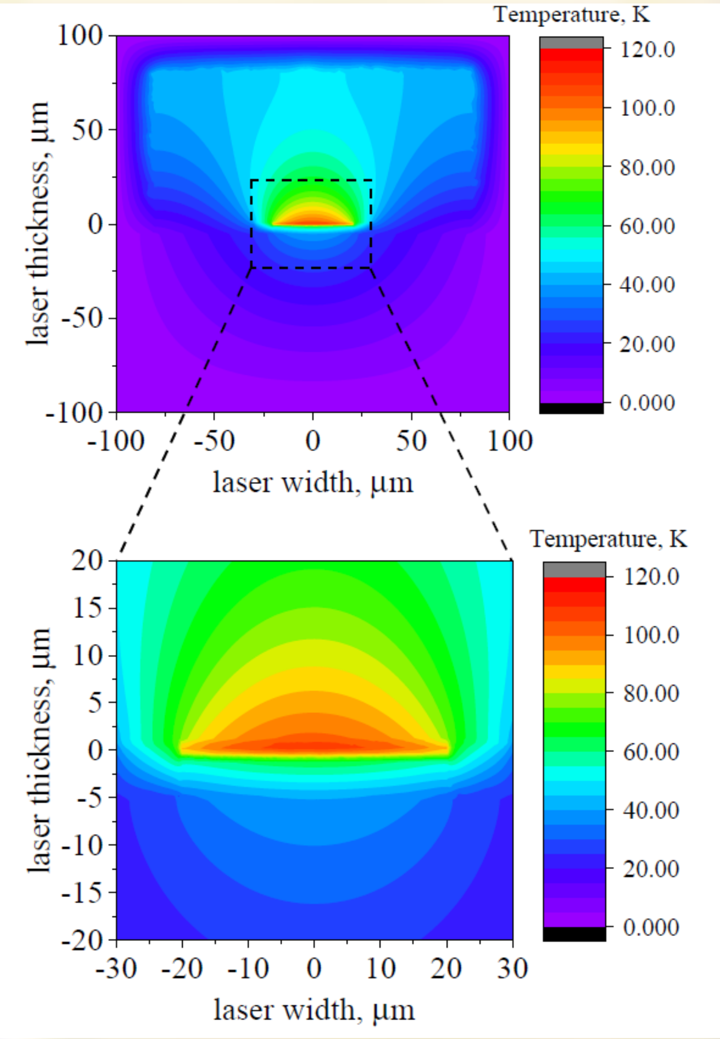


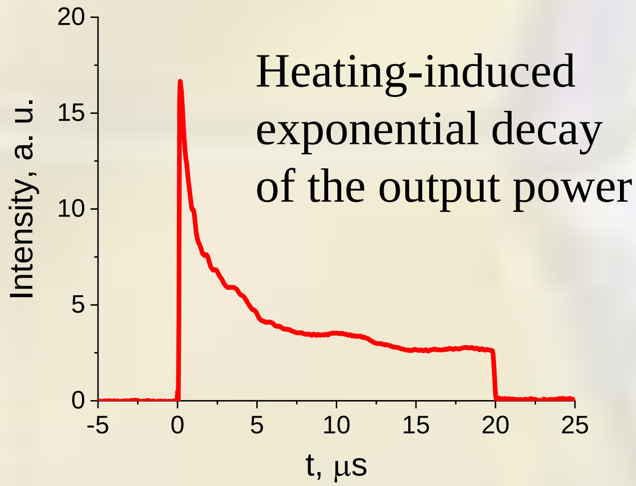
$$\frac{\partial\lambda}{\partial t} = 0.41\ \text{Å/ns}$$

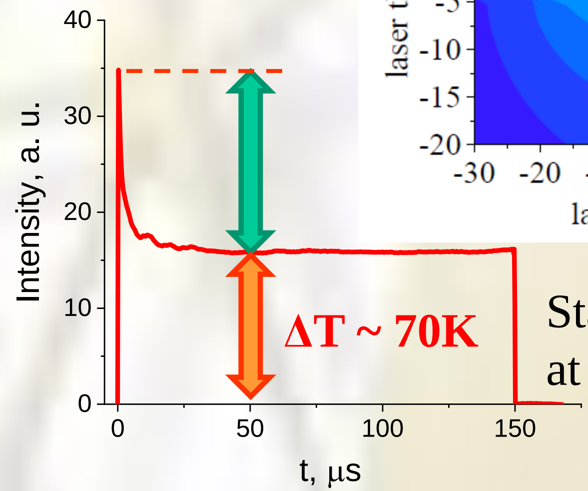
$$\frac{\partial\lambda}{\partial t} = 0.31\ \text{Å/ns}$$

Active region overheating: CW vs pulsed









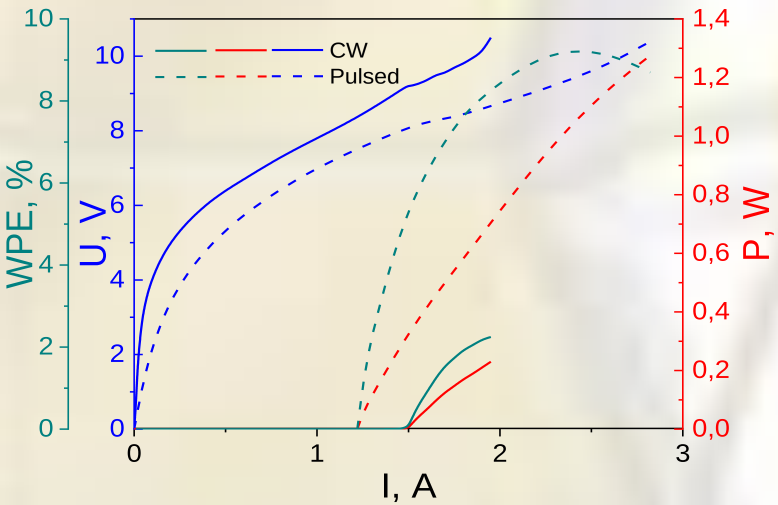
Stabilization at quasi-CW

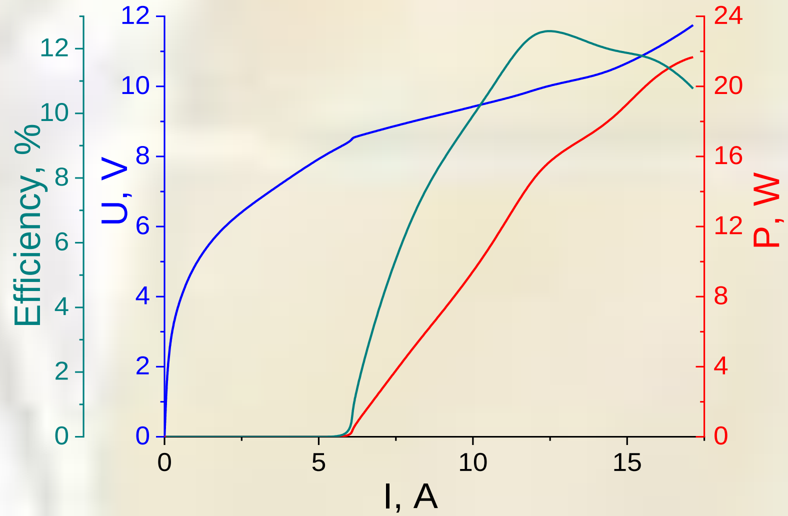
Conclusion & Outlook

- ✓ Record-high peak power >21 W (>10 W / facet) @ 8 µm
- ✓ QCL efficiency depends on cladding composition and doping
- ✓ Estimated waveguide losses are ~ 2 cm^{-1} for lattice- matched and strain QCL design
- ✓ Active region overheating may reach 100 K

- ❑ Optimization of waveguide claddings to reduce optical losses
- ❑ Optimization of chip design to improve heat spreading
- ❑ Optimization of injector doping to reduce transparency current

… and all other measures to improve efficiency





Thank you!
Questions?
vlad@kuch.ioffe.ru

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