Tutorial on short pulse generation with VECSELs and MIXSELs

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SPIE LASE, Vertical External Cavity Surface Emitting Lasers (VECSELs) X
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Acknowledgements

Cesare
Alfieri (2018)

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FIRST
Center for Micro- and Nanoscience

FAST-DOT

intel

erc

nano-tera.ch

Deran
Maas (2008)

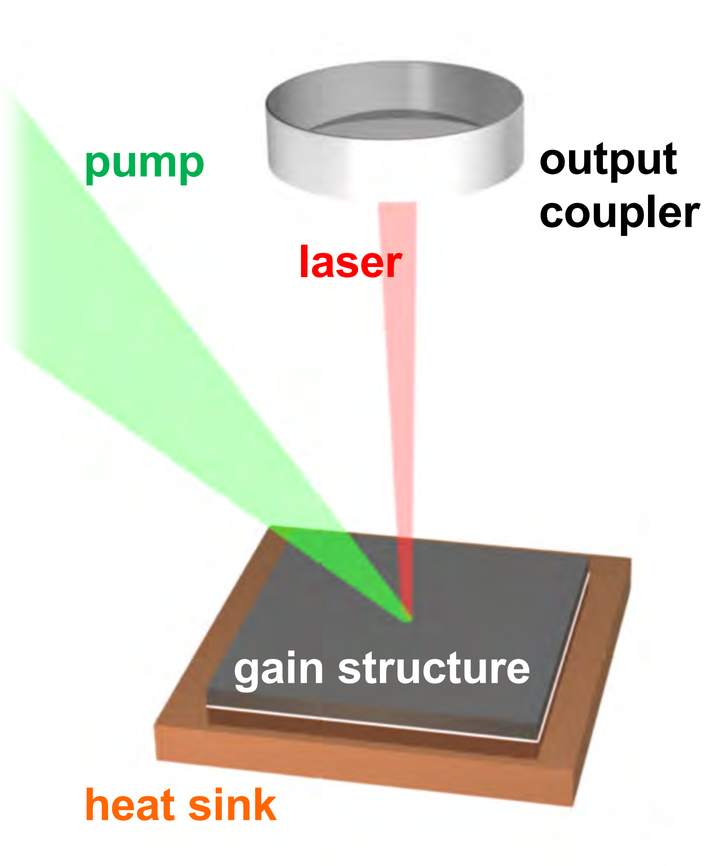
Outline

⇨ 1. **Introduction to ultrafast semiconductor disk lasers**
2. **SESAM-modelocked VECSELs**
3. **MIXSEL**
4. **100-fs VECSEL**
5. **139-fs MIXSEL**
6. **Outlook**

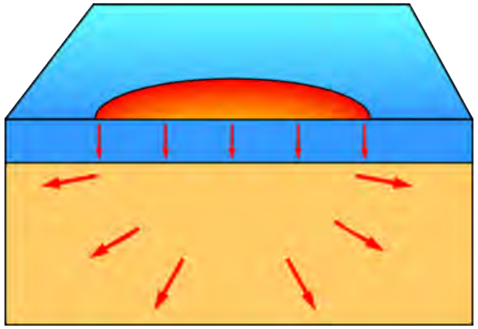
cw optically pumped VECSEL

OP-VECSEL = **O**ptically **P**umped **V**ertical-**E**xternal-**C**avity **S**urface-**E**mitting Semiconductor **L**aser

M. Kuznetsov et al., *IEEE Photon. Technol. Lett.* **9**, 1063 (1997)



- Semiconductor gain structure with reduced thickness (≈ 10 µm)



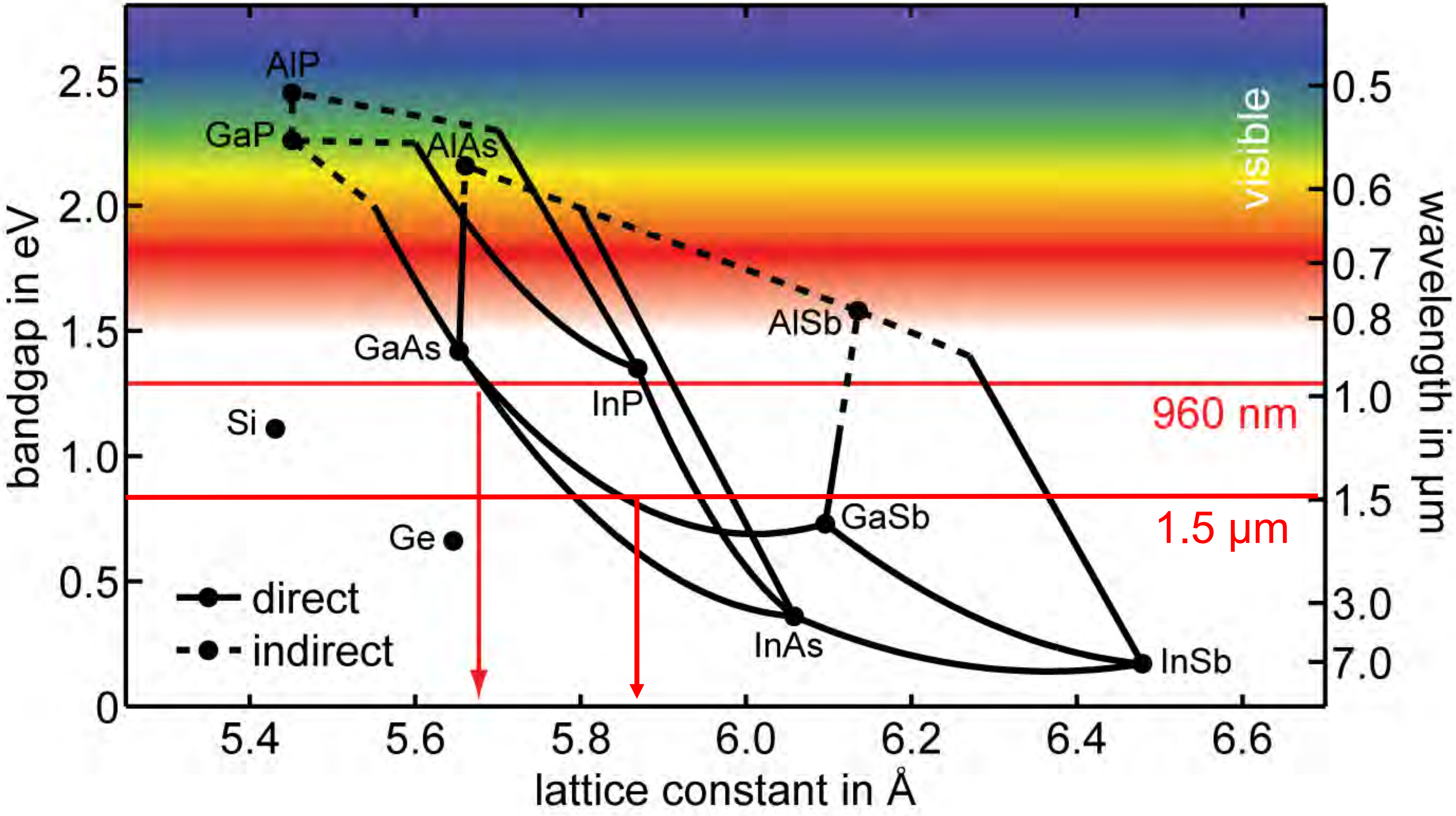
IEEE JQE 38, 1268 (2002)

SDLs = semiconductor disk lasers

Optically pumped semiconductor laser?

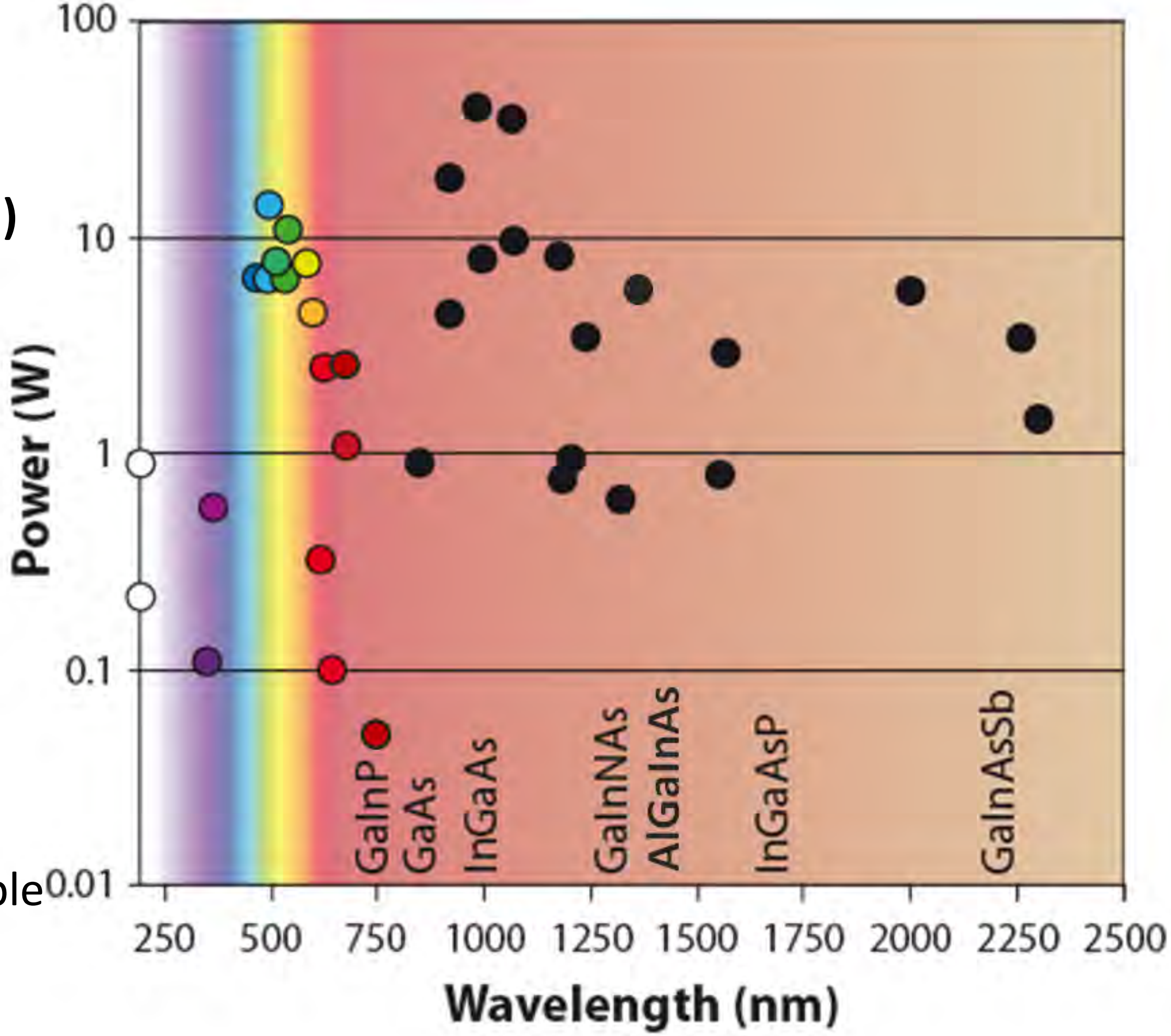
- Maybe a bad idea coming from semiconductor diode lasers?
- But for sure a good idea coming from diode-pumped solid-state lasers:
  - more flexibility in operation wavelengths
  - broad tunability
  - efficient mode conversion from low-beam-quality high-power diode lasers
  - modelocking possible with SESAMs
  - waferscale integration - cheaper ultrafast lasers in the GHz pulse repetition rate regime

Semiconductor materials: bandgap engineering



VECSELs: cw spectral coverage (Jennifer Hastie, 2013)

- 2-2.8 µm – GaInAs**Sb** / AlGaAs**Sb**
- 1.5 µm – InGaAs / InGaAsP
- **1.2-1.5 µm – AlGaInAs / InP (fused)**
- 1.2-1.3 µm – GaIn**N**As / GaAs
- 1-1.3 µm – InAs QDs
- **0.9-1.18 µm – InGaAs / GaAs**
- 850-870 nm – GaAs / AlGaAs
- 700-750 nm – InP QDs
- 640-690 nm – InGaP / AlGaInP
- **Frequency-doubled** VECSELs have been reported throughout the visible and into the UV



Infrared review: N. Schulz et al., *Laser & Photonics Reviews* **2**, 160 (2008)

Visible and UV review: S. Calvez et al., *Laser & Photonics Reviews* **3**, 407 (2009)

2013 *updated by Jennifer Hastie, University of Strathclyde, group of Prof. Martin Dawson*

VECSELs: cw spectral coverage (Mircea Guina, 2017)

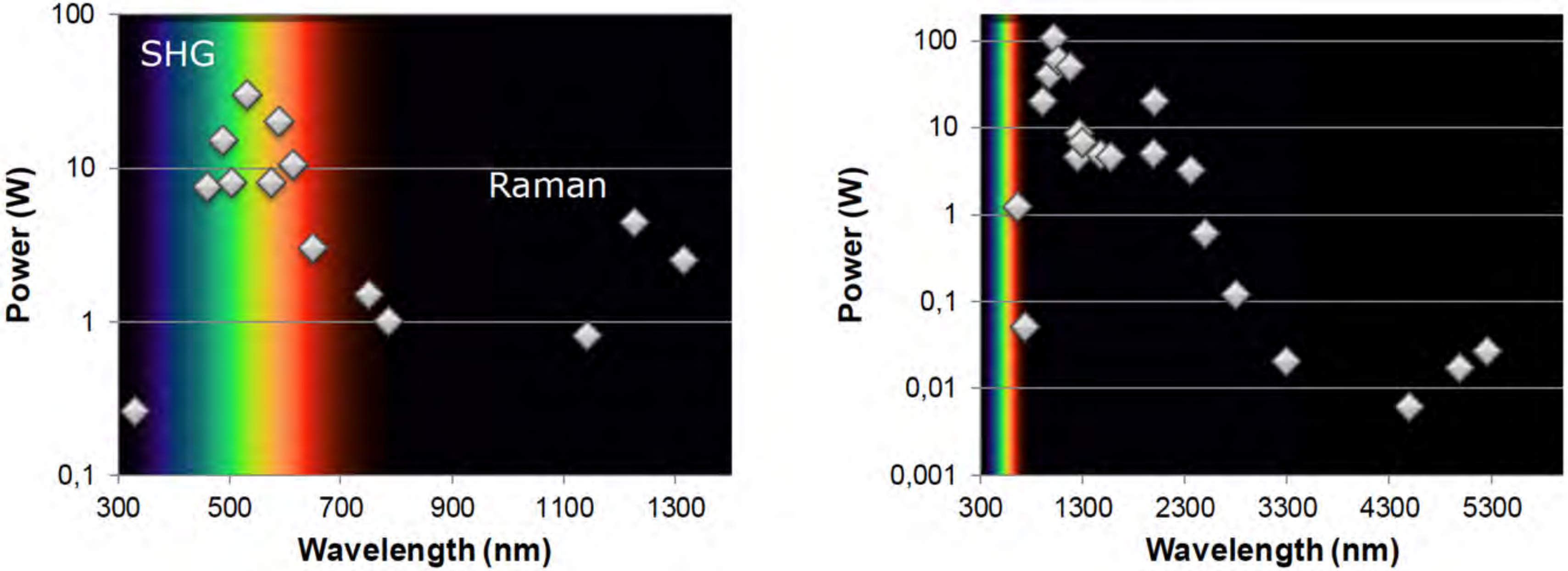


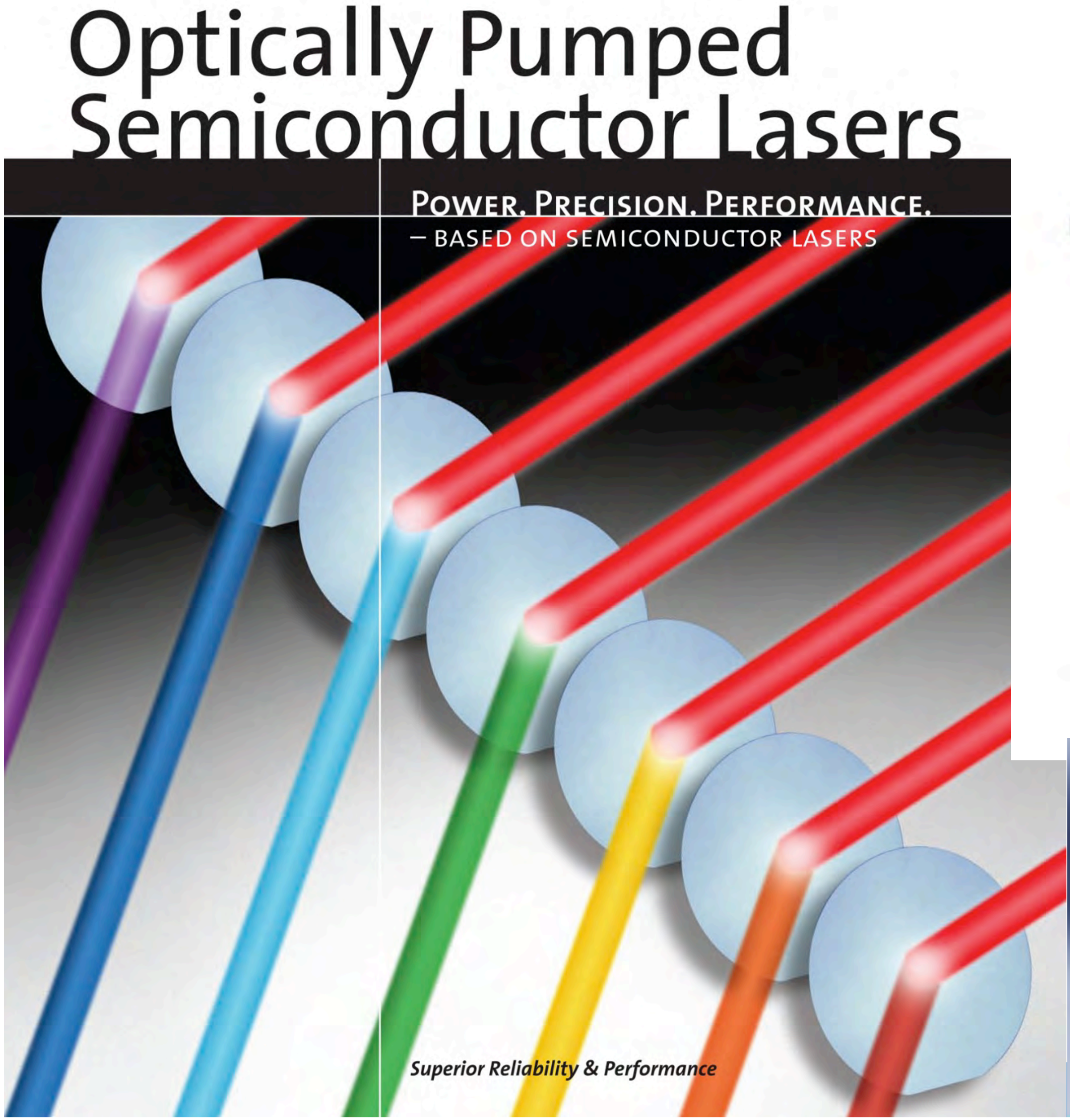
***Figure 1**: Output powers vs. wavelength covered by major types of VECSEL technologies: **left** - frequency converted (second harmonic generation - SHG, and Raman shifting); and **right** - fundamental emission.*

M. Guina et al., “Optically pumped VECSELs: review of technology and progress”
J. Phys. D: Appl. Phys. **50**, 383001 (2017)

SDLs = semiconductor disk lasers

COHERENT

OPSLs = OP-VECSELs



Optically Pumped Semiconductor Lasers

POWER. PRECISION. PERFORMANCE.
– BASED ON SEMICONDUCTOR LASERS

Superior Reliability & Performance

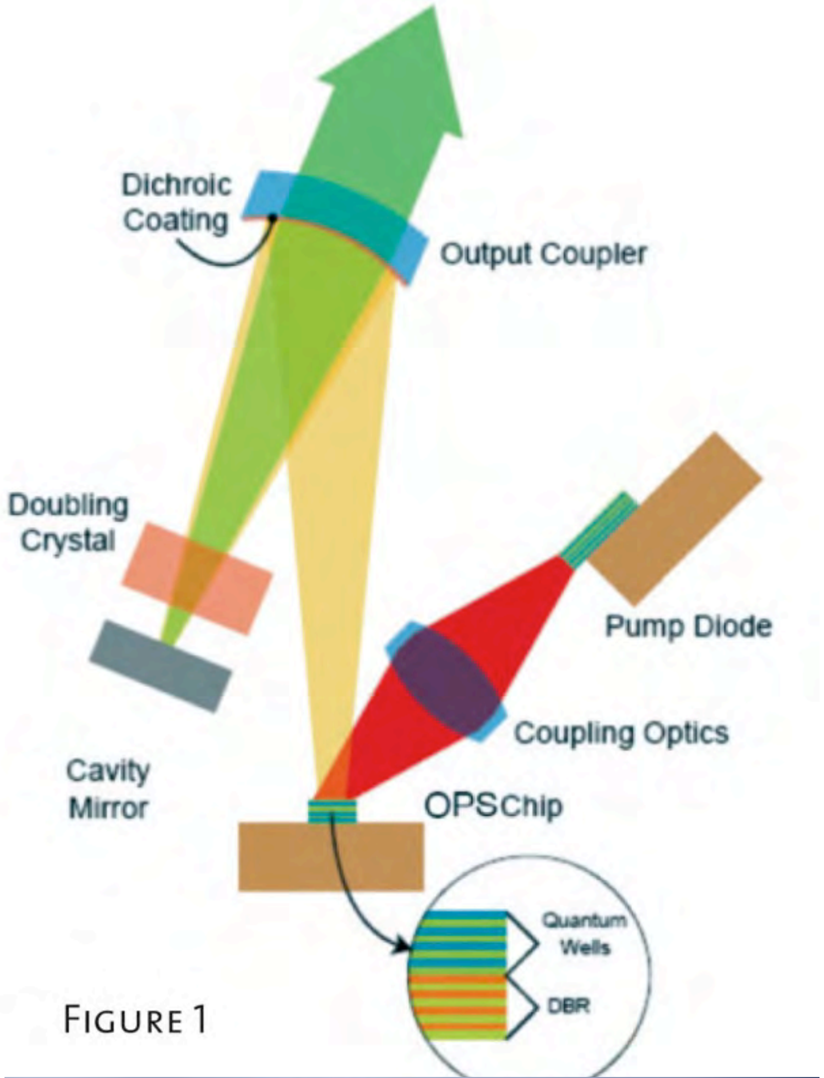
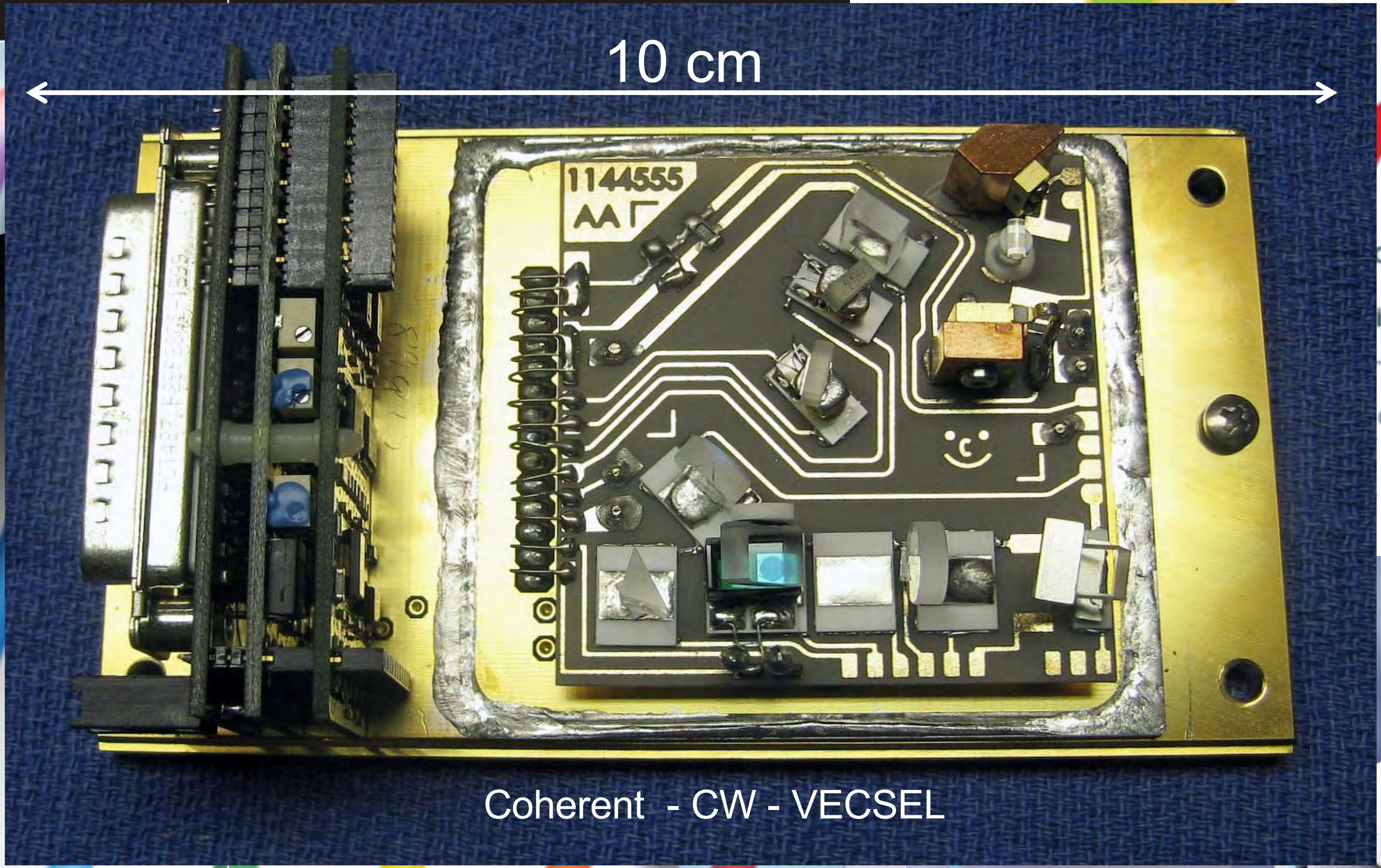


FIGURE 1

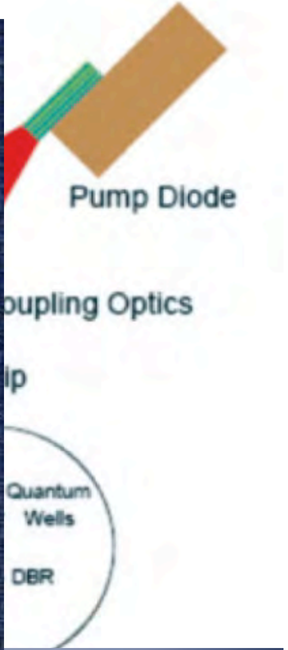
COHERENT

OPSLs = OP-VECSELs

Optically Pumped Semiconductor Lasers

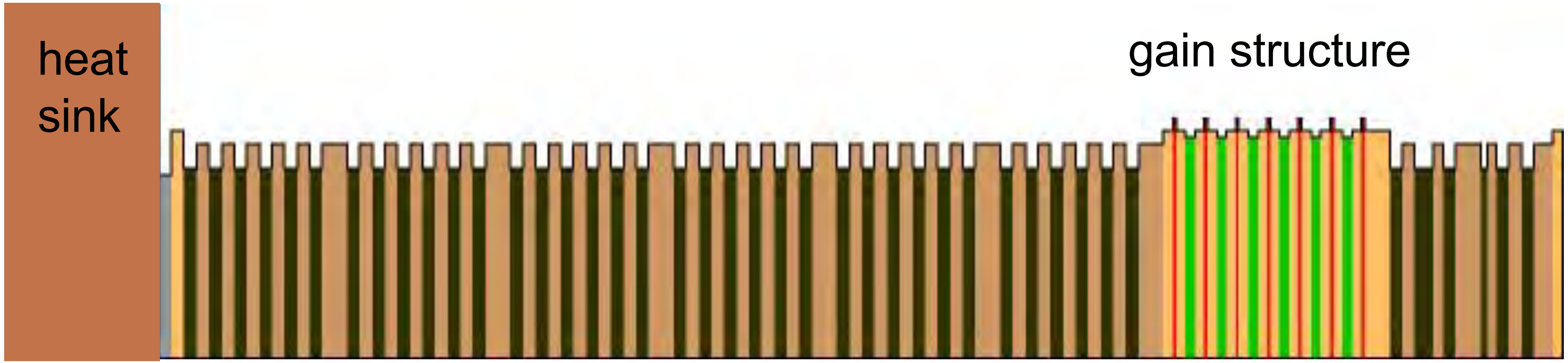


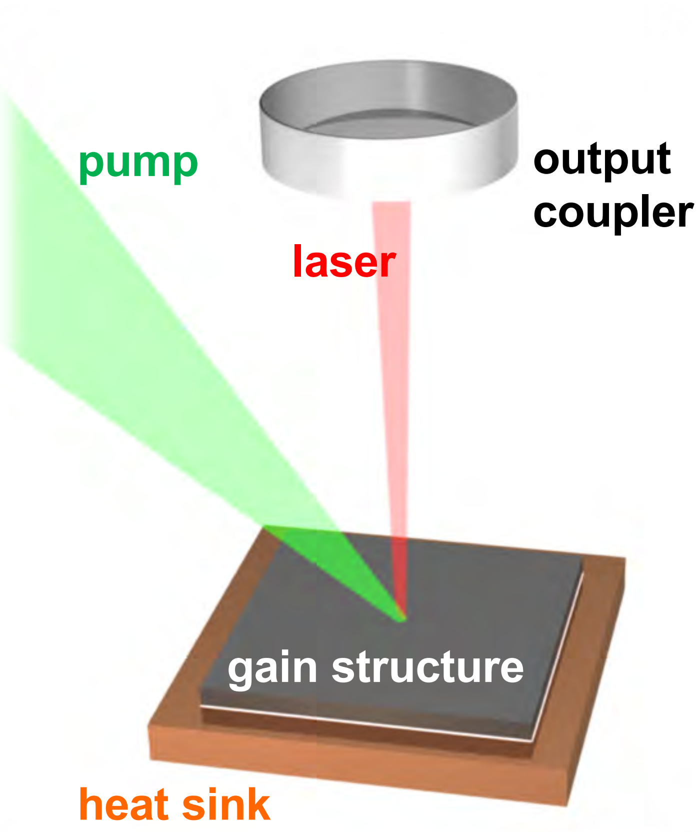
Coherent - CW - VECSEL

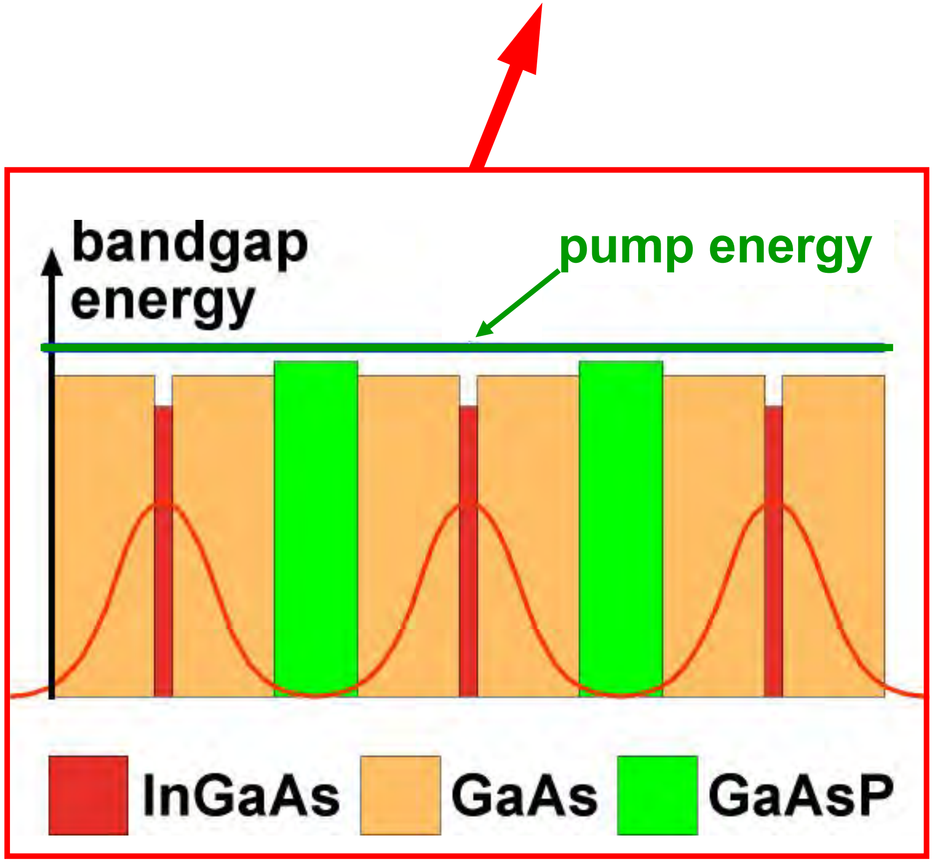


Superior Reliability & Performance

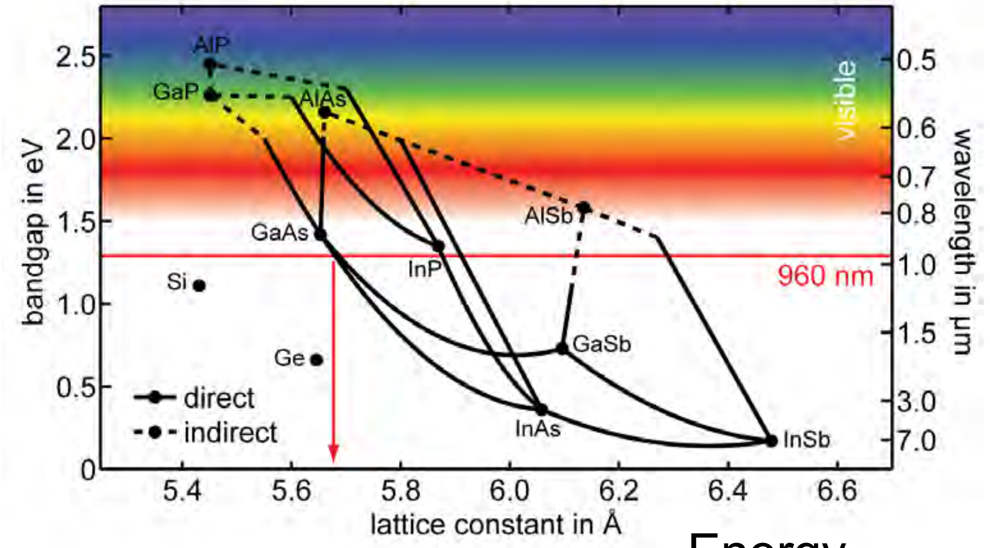
VECSEL gain structure (basic principle)







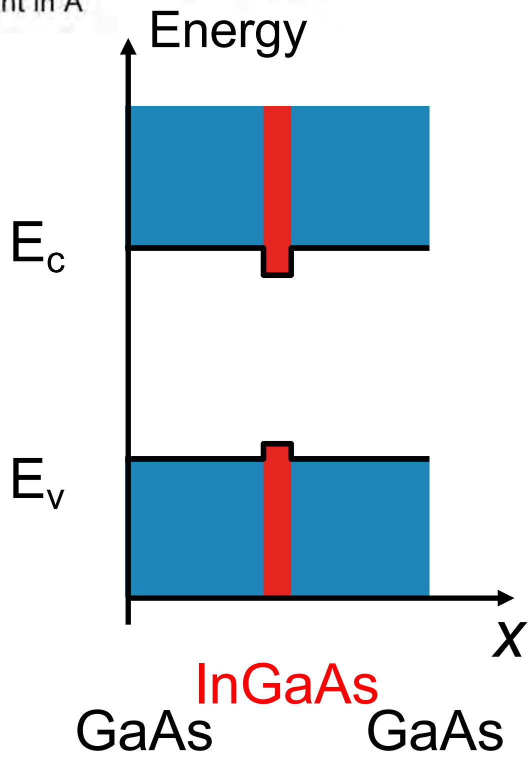
VECSEL structure



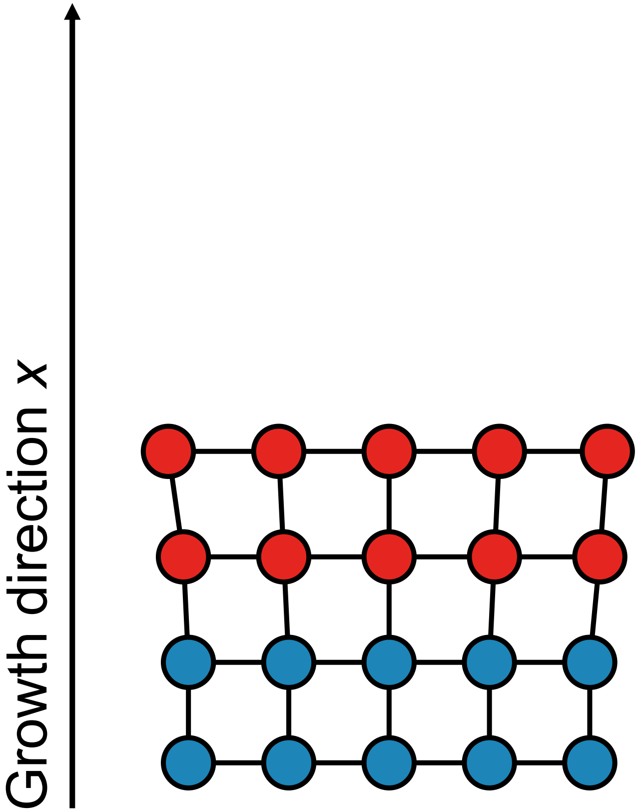
InGaAsQuantum well

Conduction band

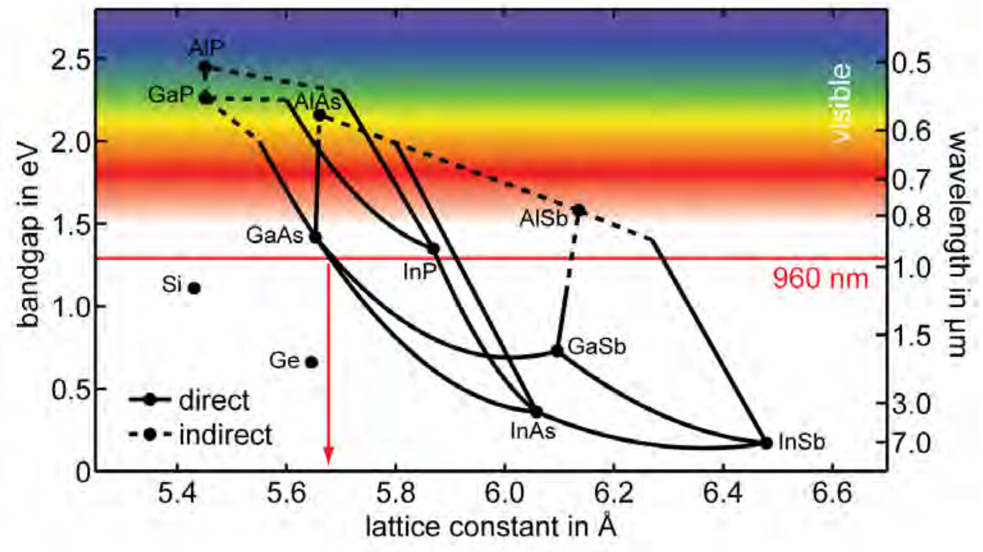
Valence band



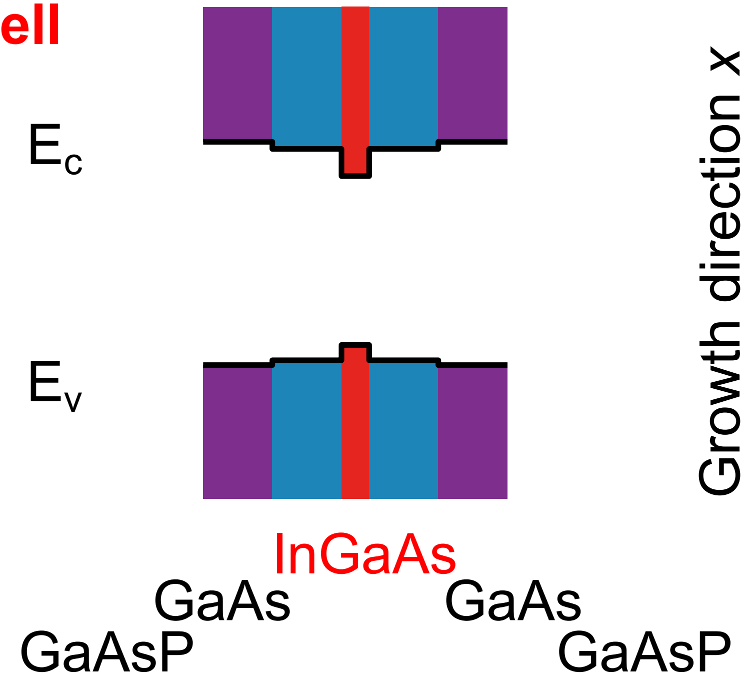
Strain



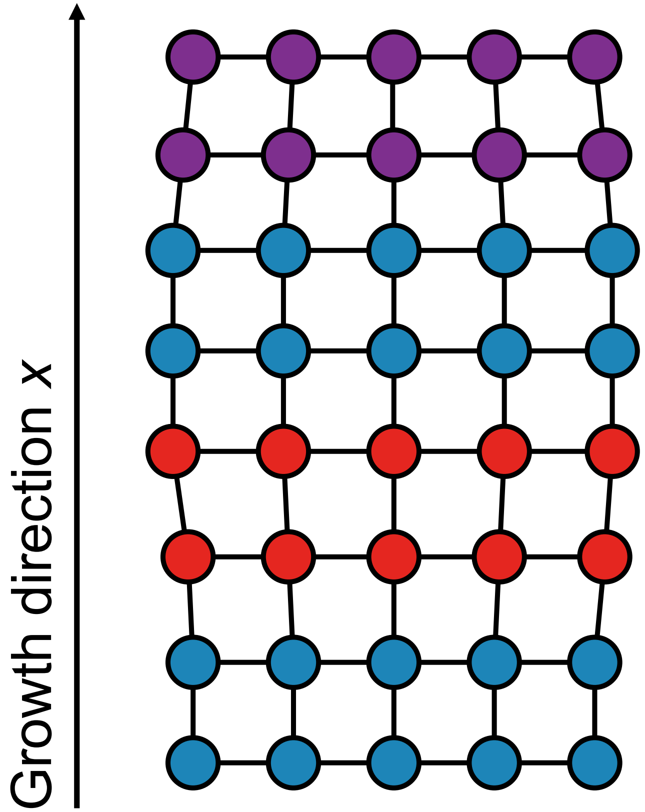
VECSEL structure



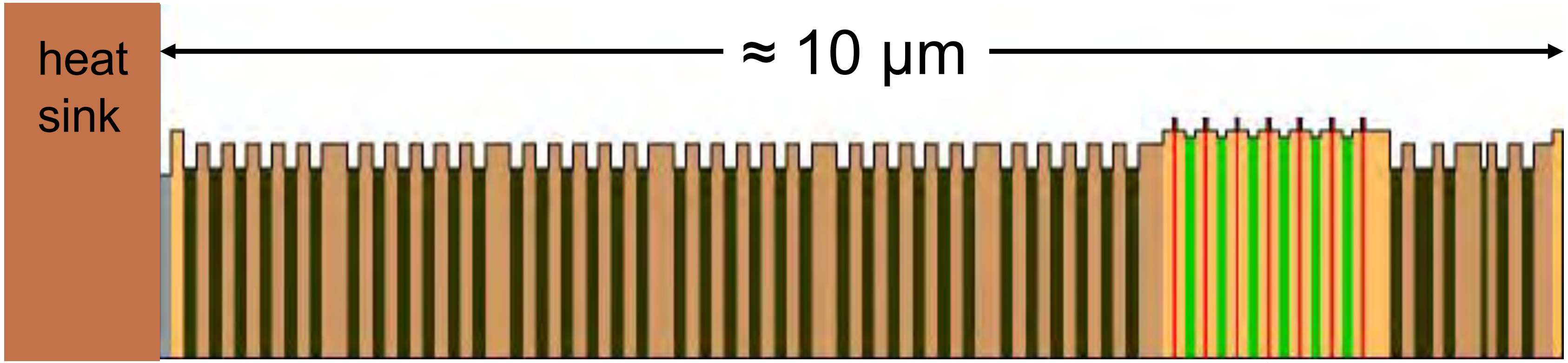
InGaAsQuantum well



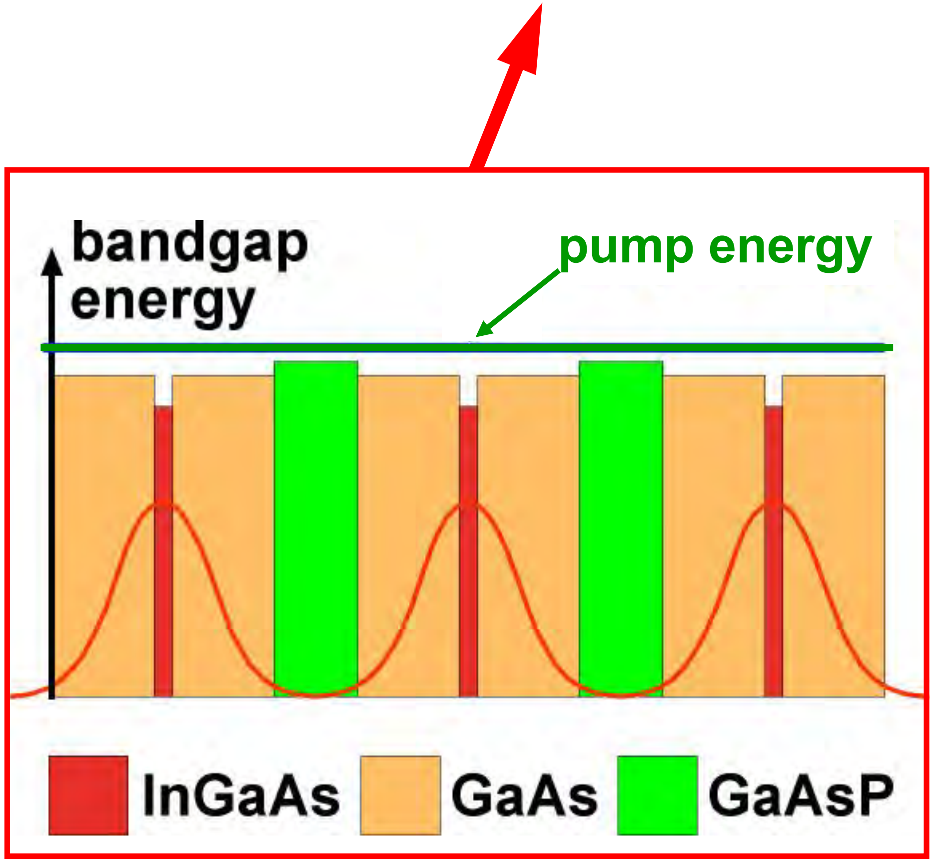
Strain-compensation



VECSEL gain structure (basic principle)



- 7 **$In_{0.13}Ga_{0.87}As$** QWs (8 nm) in anti-nodes of standing-wave pattern, designed for gain at ≈ 960 nm
- **GaAs** spacer layers
- Strain-compensating **$GaAs_{0.94}P_{0.06}$** layers
- Pump at 808 nm



cw optically pumped VECSEL

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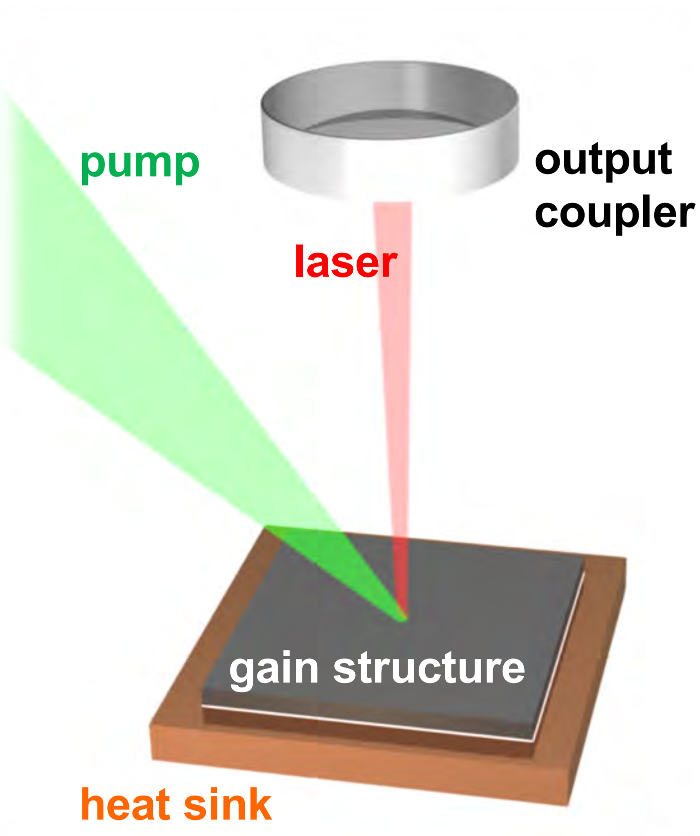
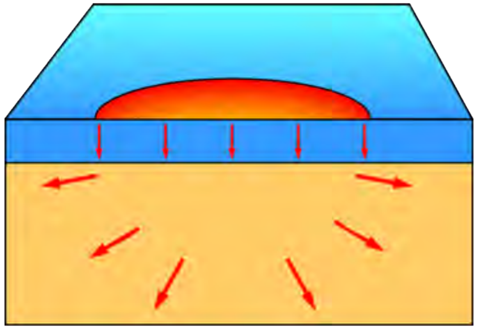


- Semiconductor gain structure with reduced thickness (≈ 10 µm)

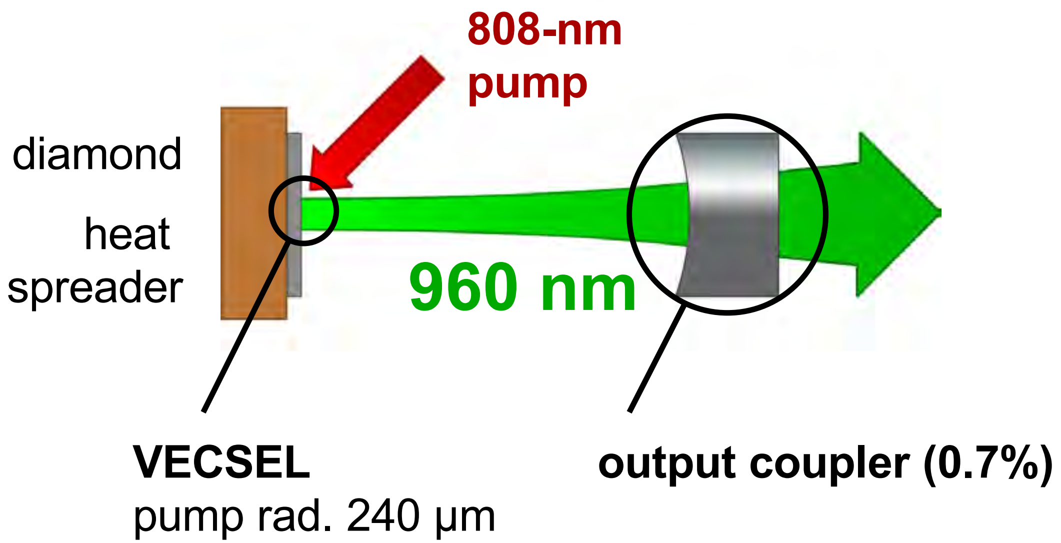


IEEE JQE 38, 1268 (2002)

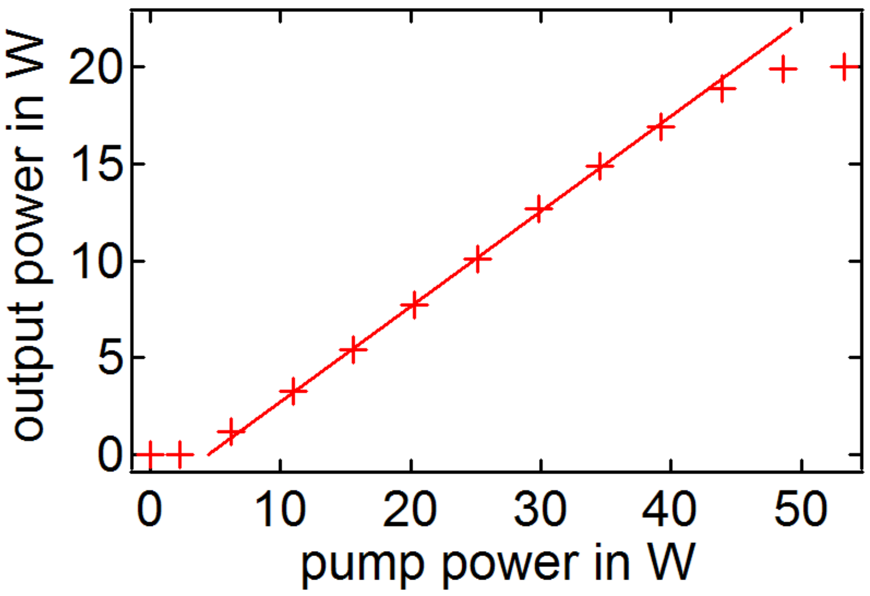
- Pump: high power diode bar
- External cavity for diffraction-limited output

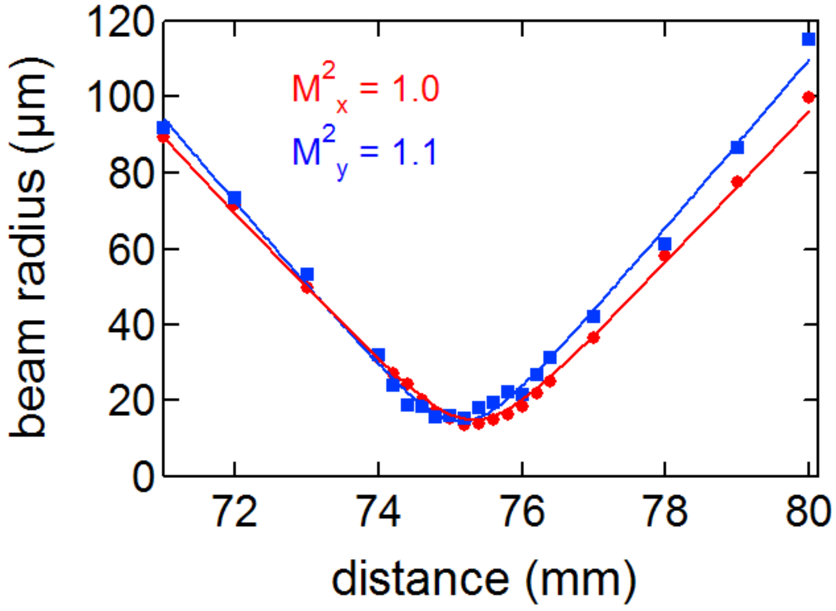
SDLs = semiconductor disk lasers

High power TEM$_{00}$ cw-operation



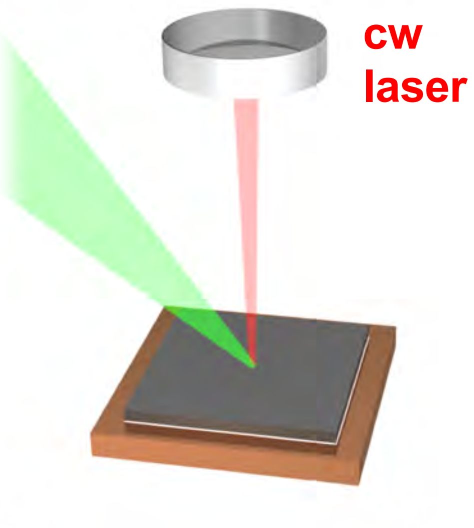
- Maximum power ***P* = 20.2 W**
- opt.-to-opt. efficiency **up to 43%**
- **$M^2 < 1.1$**



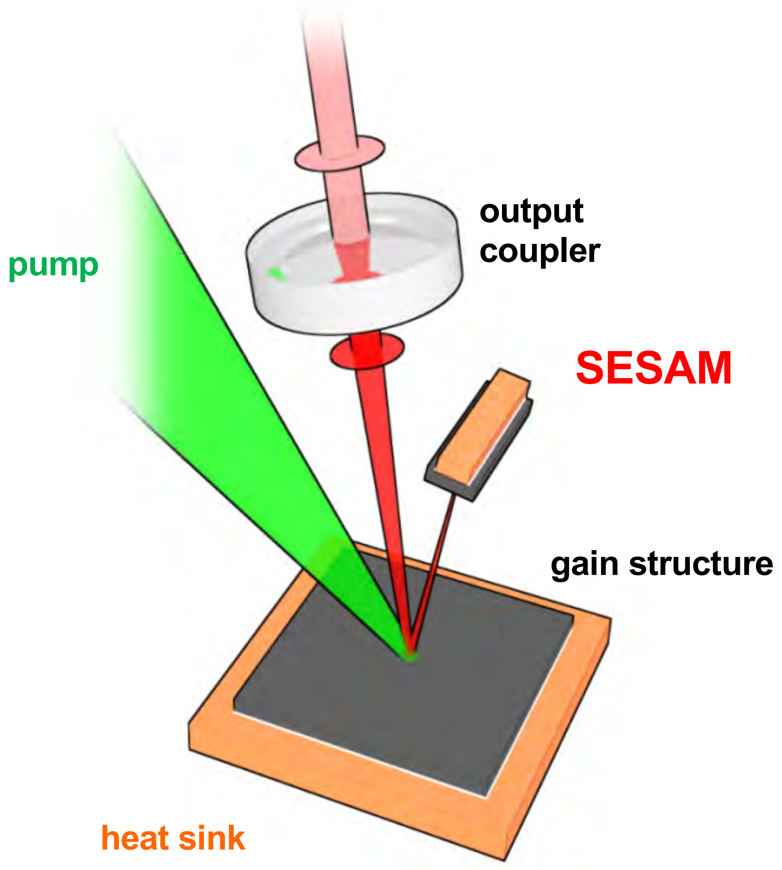


B. Rudin, A. Rutz, M. Hoffmann, D. J. H. C. Maas, A. R. Bellancourt, E. Gini, T. Südmeyer, U. Keller
Opt. Lett. **33**, 2719 (2008)

Ultrafast VECSELs: Modelocking with SESAMs



SESAM
Semiconductor
Saturable
Absorber Mirror



First SESAM-modelocking demonstration in 2000:

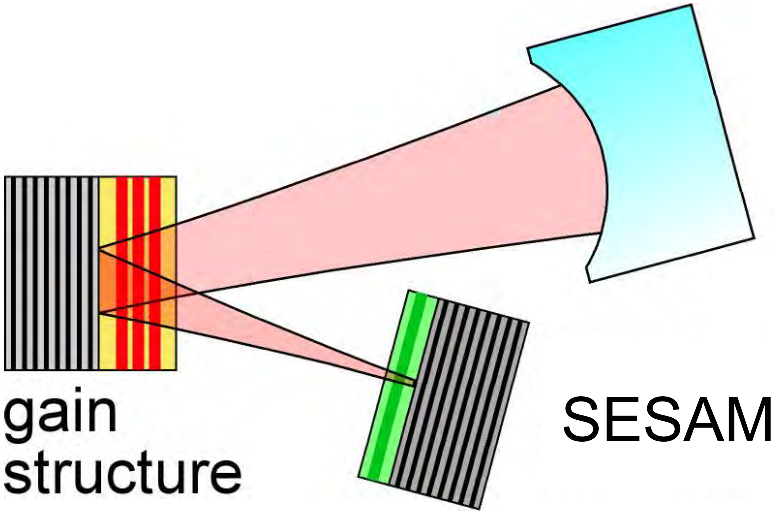
S. Hoogland et al.,
IEEE Photonics Technology Letters **12** (9), 1135, 2000

Milestone results:
https://ulp.ethz.ch/research/vecsel-mixsel/milestones.html

Review article for VECSELs: U. Keller and A. C. Tropper, *Physics Reports* **429**, Nr. 2, pp. 67-120, 2006

Motivation for semiconductor lasers: Wafer scale integration

2015 Review: B. W. Tilma *et al.*, “Recent advances in ultrafast semiconductor disk lasers”, *Light Sci Appl* **4**, e310 (2015)

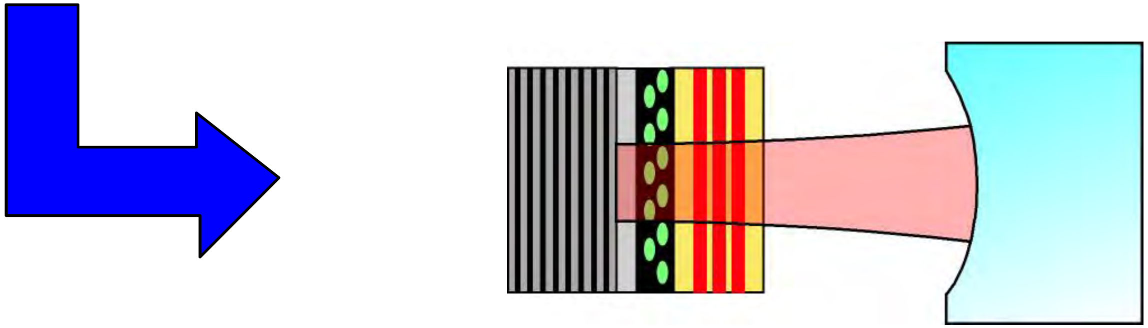


Passively modelocked VECSEL

vertical **e**xternal **c**avity **s**urface **e**mitting **l**aser

D. Lorenser et al., *Appl. Phys. B* **79**, 927, 2004

Review: *Physics Reports* 429, 67-120, 2006

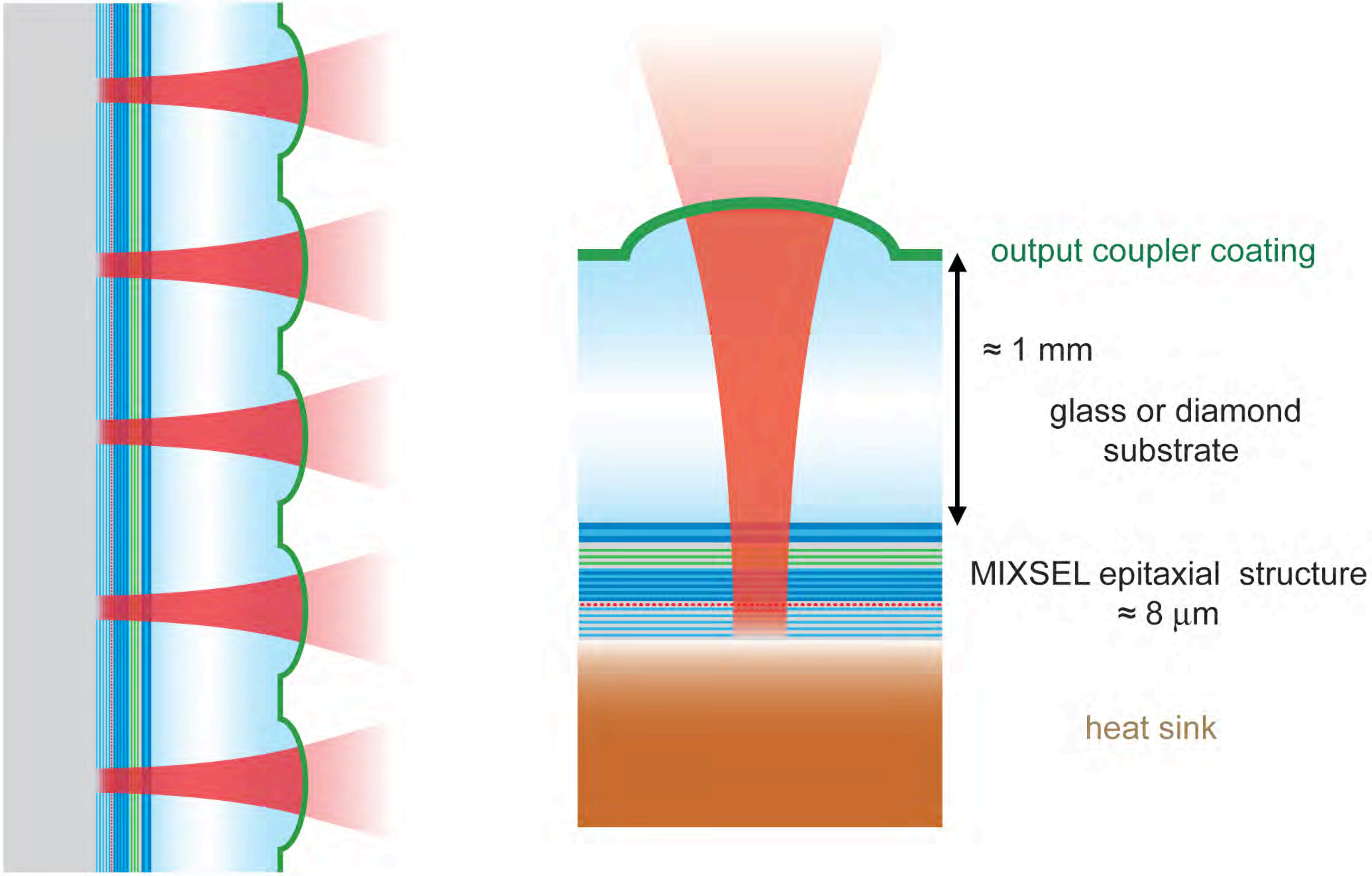


MIXSEL

modelocked **i**ntegrated e**x**ternal-cavity **s**urface **e**mitting **l**aser

D. J. H. C. Maas et al., *Appl. Phys. B* **88**, 493, 2007

MIXSEL wafer scale integration



output coupler coating

≈ 1 mm

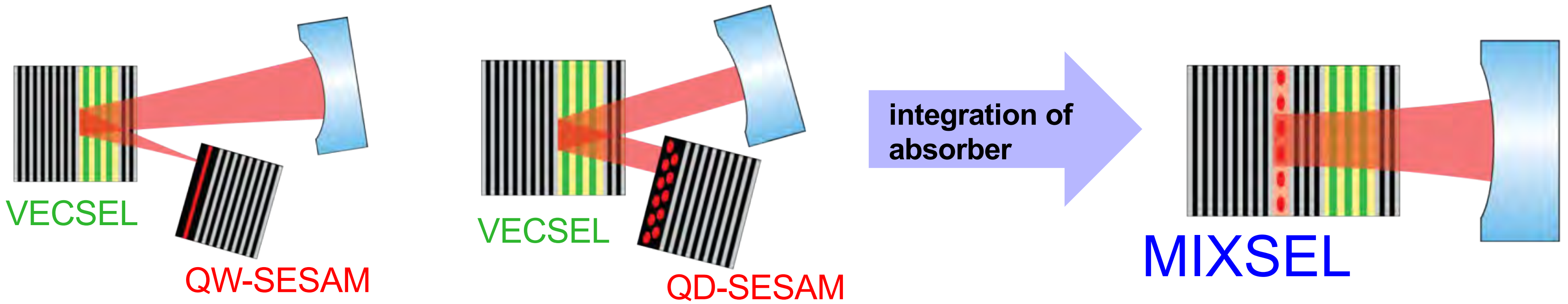
glass or diamond
substrate

MIXSEL epitaxial structure
≈ 8 µm

heat sink

A. R. Bellancourt et al., “Modelocked integrated external-cavity surface emitting laser”
IET Optoelectronics, vol. 3, Iss. 2, pp. 61-72, 2009 (invited paper)

Development to the MIXSEL

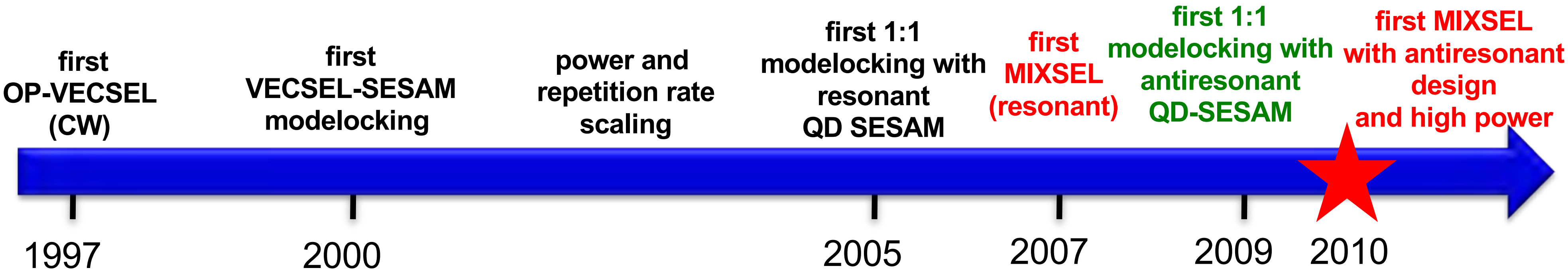


MIXSEL

Modelocked Integrated External-Cavity
Surface Emitting Laser

focusing on
SESAM

no focusing required
stronger saturation
1:1 modelocking



- 1997 – **first OP-VECSEL (CW)**
- 2000 – **first VECSEL-SESAM modelocking**
- **power and repetition rate scaling**
- 2005 – **first 1:1 modelocking with resonant QD SESAM**
- 2007 – **first MIXSEL (resonant)**
- 2009 – **first 1:1 modelocking with antiresonant QD-SESAM**
- 2010 – **first MIXSEL with antiresonant design and high power**

VECSEL CW
>0.5 W
M. Kuznetsov et al., *IEEE PTL* 9, 1063 (1997)
not ETH Zurich

Quantum-Well SESAM
4 GHz, **2.1 W,** 4.7 ps
A. Aschwanden et al., *Opt. Lett.* 30, 272 (2005)

Quantum-Dot SESAM
50 GHz, 102 mW, 3.3 ps
D. Lorenser et al., *IEEE JQE,* 42, 838 (2006)

(Antiresonant) MIXSEL
2.5 GHz, **6.4 W,** 28 ps
March 2010
B. Rudin et al., *Opt. Express* in prep.

Gigahertz frequency comb sources

Ti:sapphire

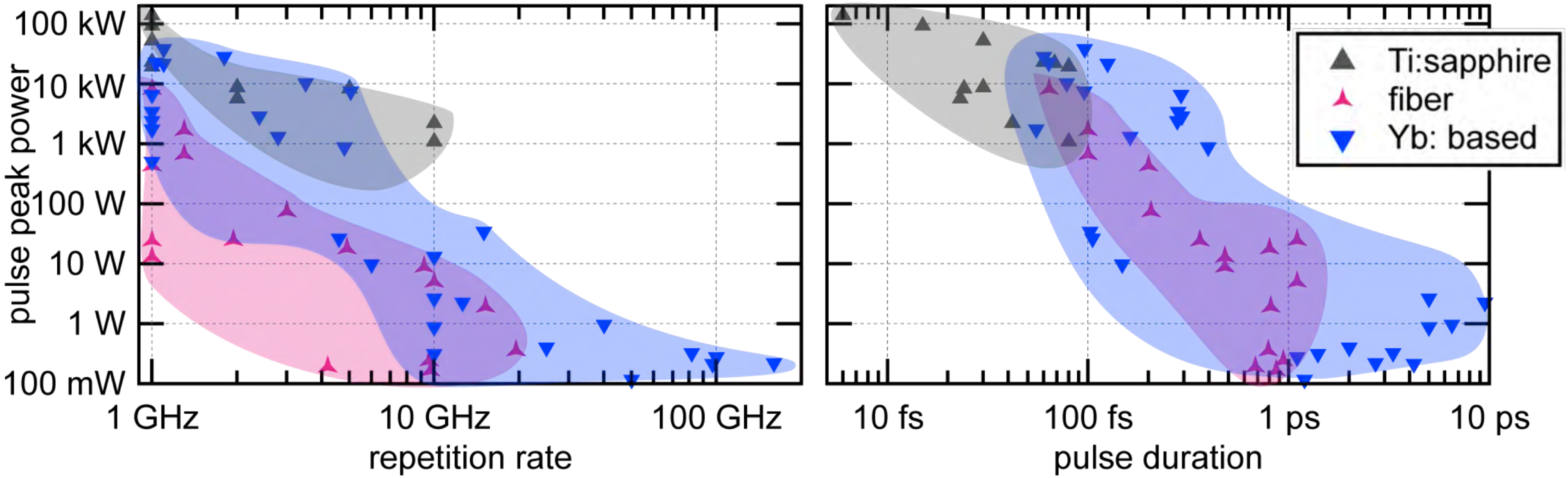
✓ performance

fiber lasers

- performance

Yb-based lasers

✓ performance



Gigahertz frequency comb sources

Ti:sapphire

- ✓ performance
- ✗ complexity
- ✗ cost
- • spectral flexibility

fiber lasers

- • performance
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Yb-based lasers

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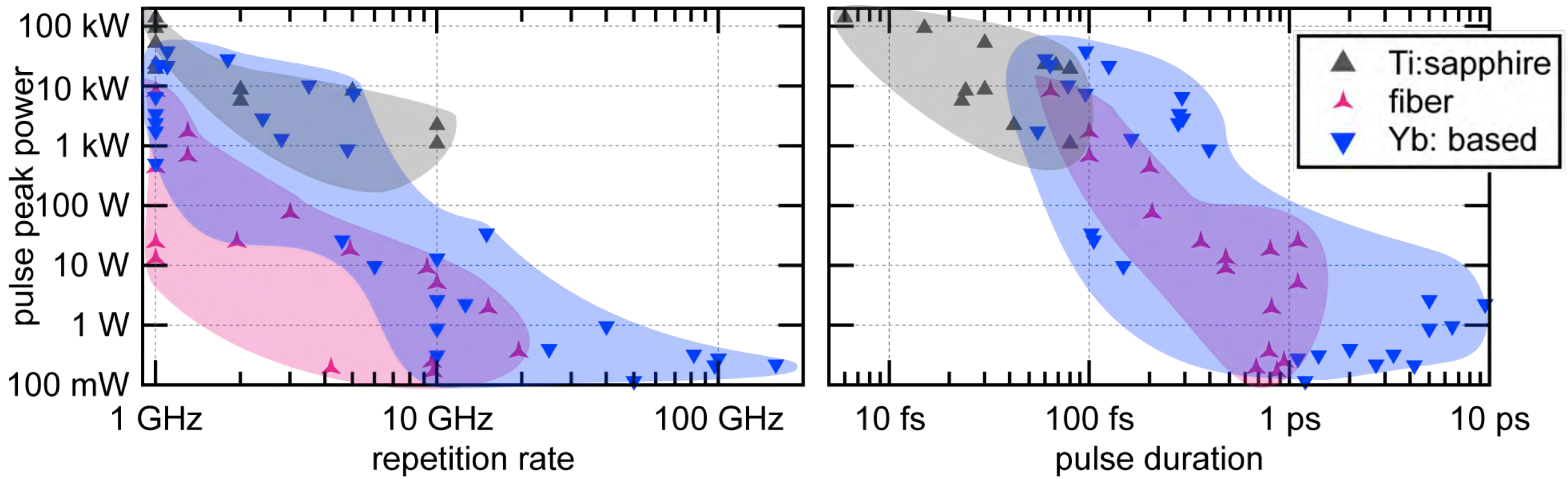

Gigahertz frequency comb sources

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fiber lasers

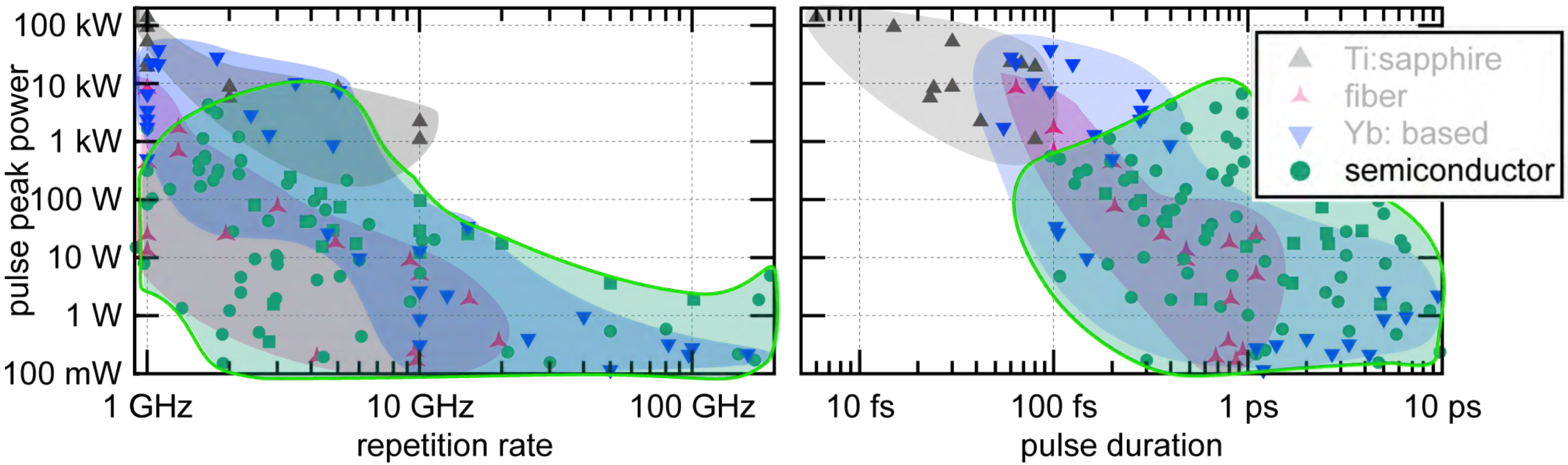
- performance
- complexity
- cost
- spectral flexibility

Yb-based lasers

- ✓ performance
- ✓ complexity
- cost
- spectral flexibility

Optically pumped ultrafast semiconductor disk lasers

- performance
- ✓ complexity
- ✓ cost
- ✓ spectral flexibility



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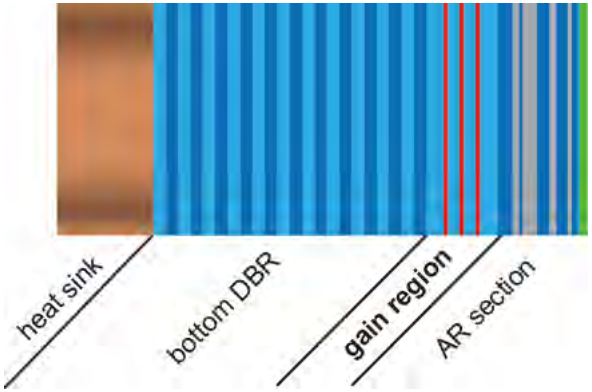
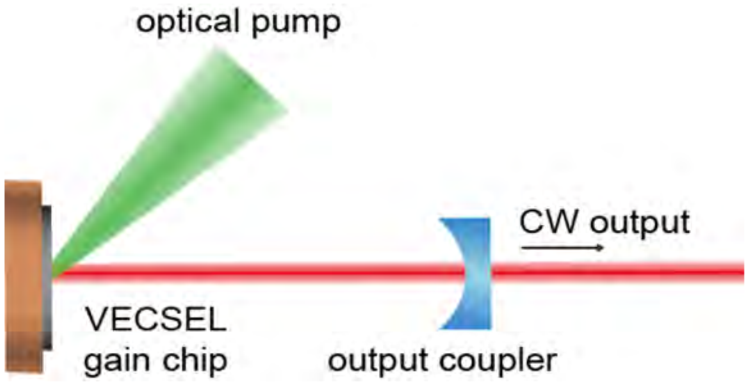
Semiconductor disk lasers

VECSEL

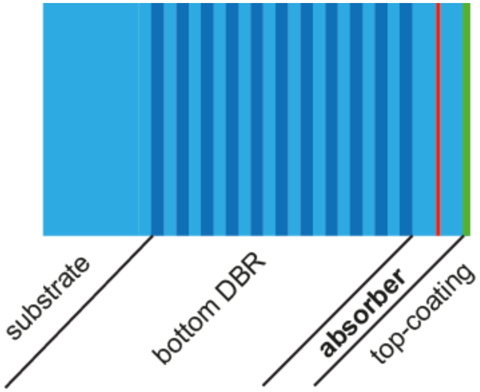
vertical external-cavity surface-emitting laser





SESAM

semiconductor saturable absorber mirror

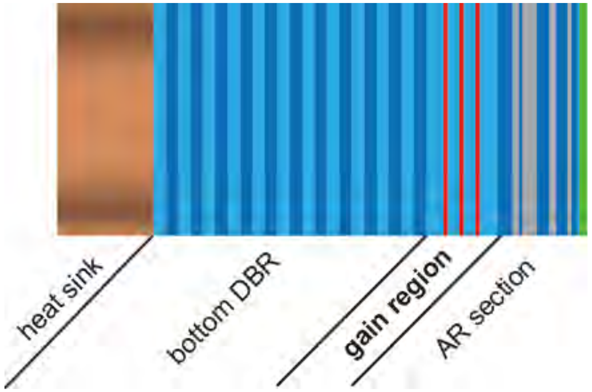


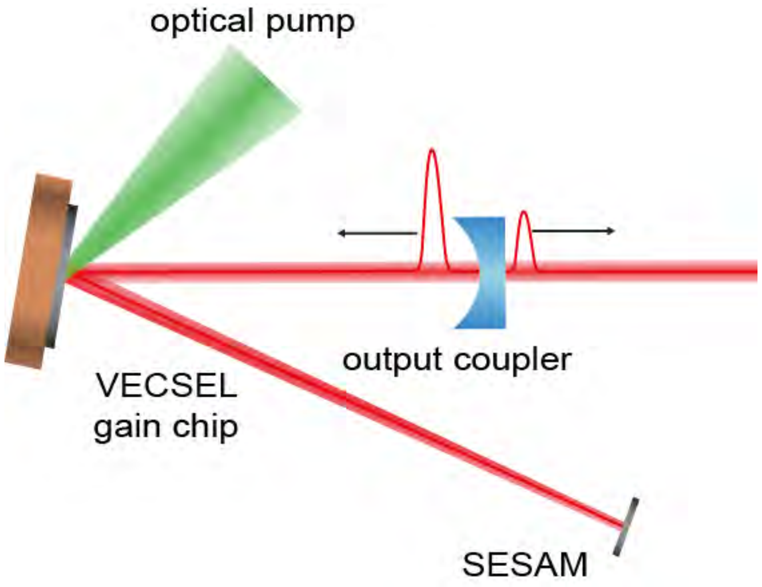
Semiconductor disk lasers

3-GHz pulse repetition rate: cavity length of ≈ 5 cm

VECSEL

vertical external-cavity surface-emitting laser





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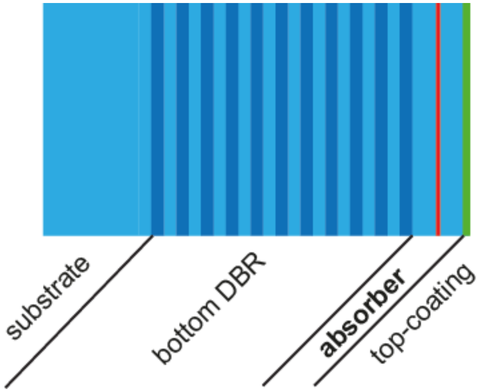
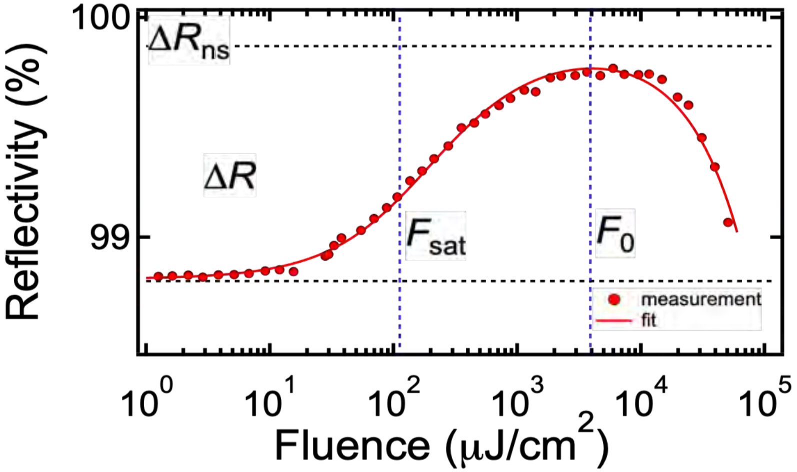


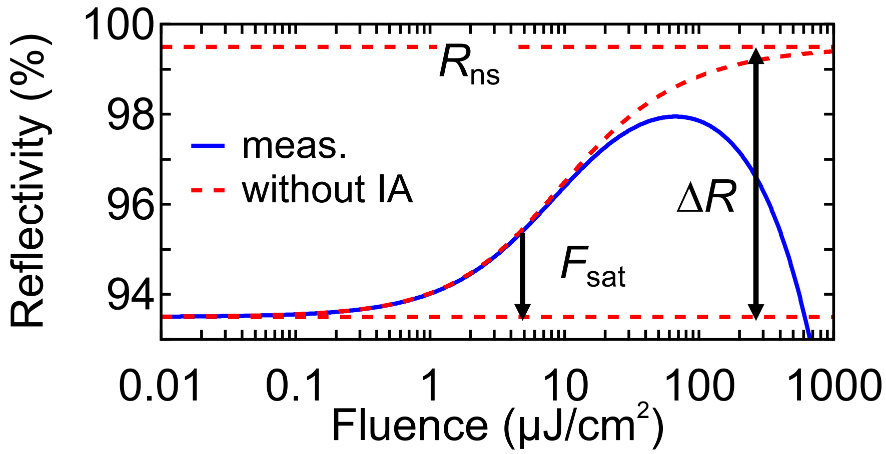


SESAM properties

SESAM Semiconductor saturable absorber mirror

U. Keller et al., *Optics Lett.* **17**, 505 (1992)
U. Keller et al., *IEEE J. Sel. Top. Quant.* **2**, 435 (1996)

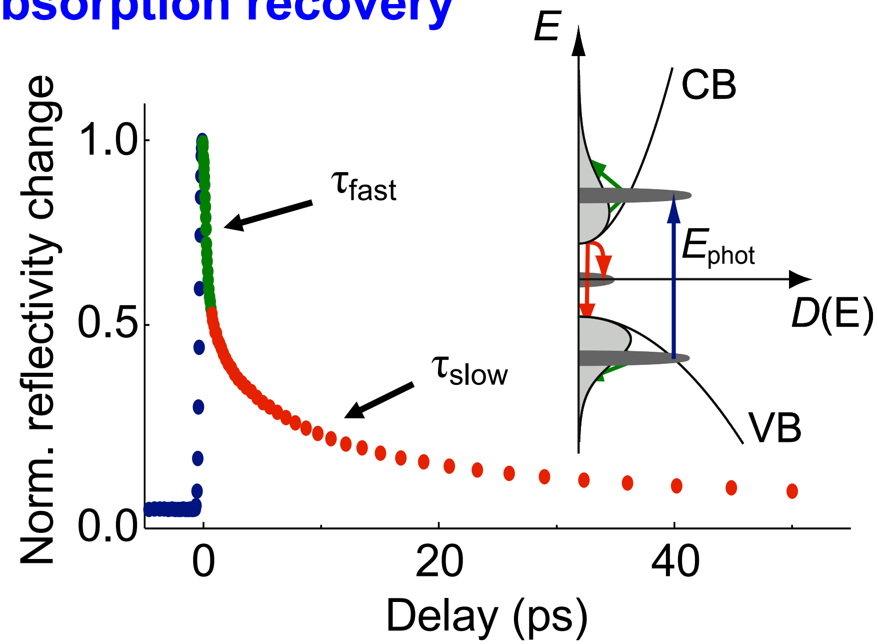
Nonlinear reflectivity



- F_{sat}: **Saturation fluence** (fluence at which reflectivity increases by 37 %)
- ΔR: **Modulation depth**
- ΔR_{ns}: Non-saturable losses

- **Induced absorption** (IA) effects lead to roll-over at high fluences

Absorption recovery



Excitation

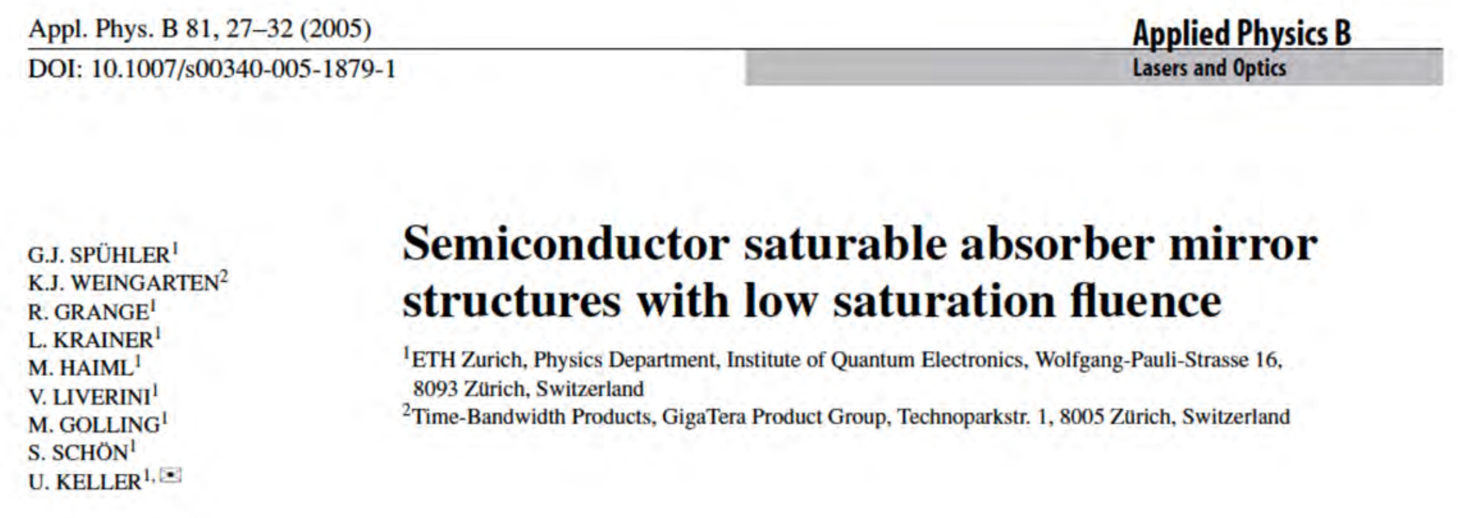
Intraband thermalization
τ_{fast} < 500 fs

Interband & mid-gap defect state recombination
τ_{slow} > 5 ps

SESAM design

2005

1) SESAMs with low saturation fluence:



Appl. Phys. B 81, 27–32 (2005)
DOI: 10.1007/s00340-005-1879-1

Applied Physics B
Lasers and Optics

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M. GOLLING[1]
S. SCHÖN[1]
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Semiconductor saturable absorber mirror structures with low saturation fluence

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[2] Time-Bandwidth Products, GigaTera Product Group, Technoparkstr. 1, 8005 Zürich, Switzerland

SESAM design

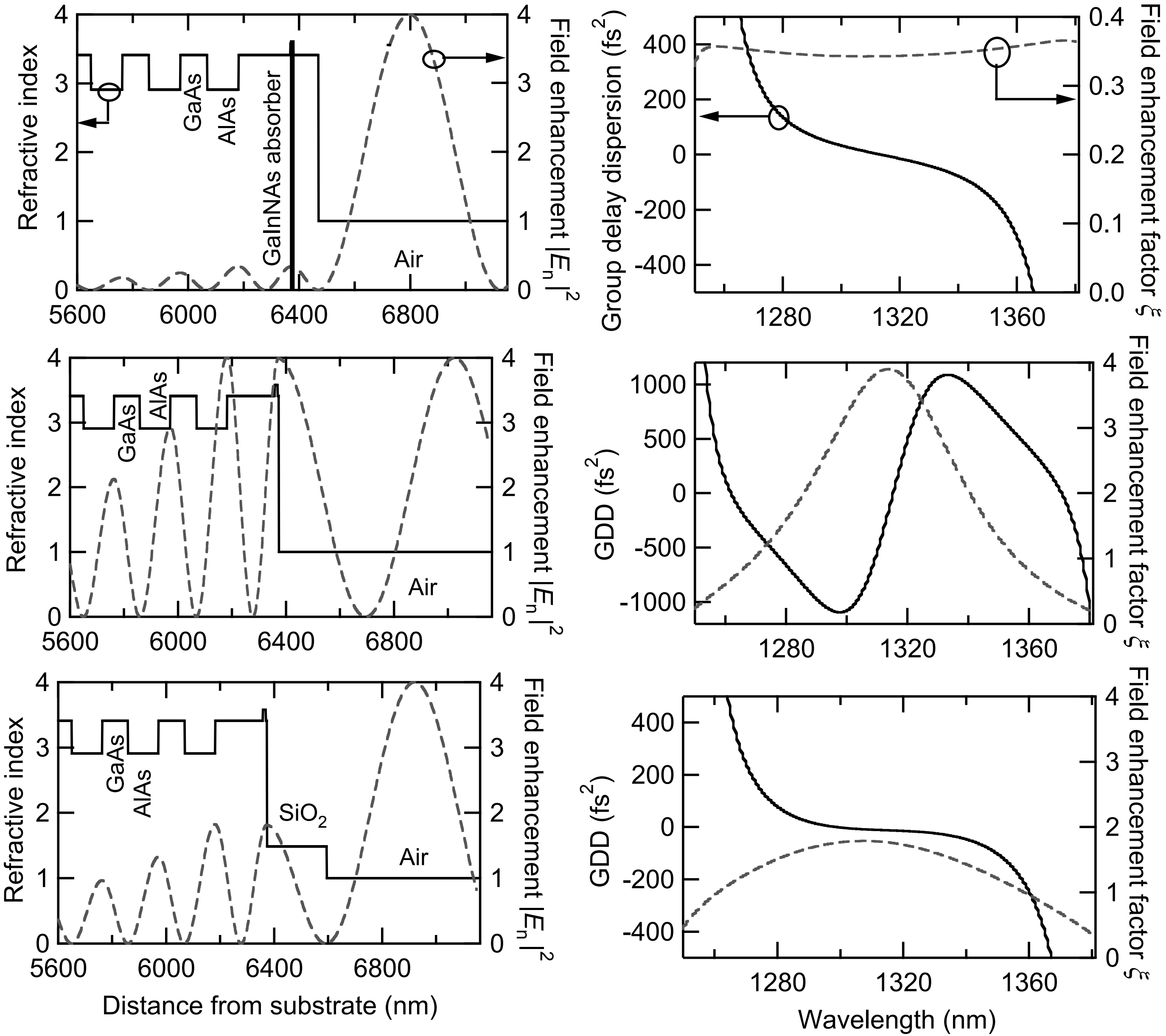
Standing wave pattern

GDD and field enhanc. factor

antiresonant

resonant

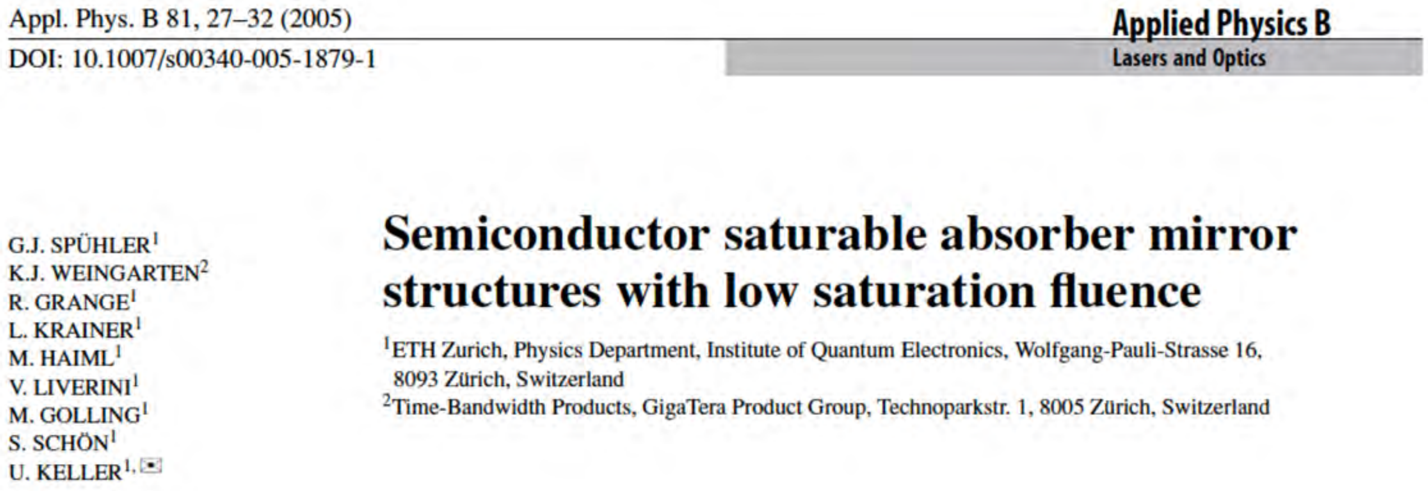
E-SESAM



SESAM design

2005

1) SESAMs with low saturation fluence:



Appl. Phys. B 81, 27–32 (2005)
DOI: 10.1007/s00340-005-1879-1
Applied Physics B
Lasers and Optics

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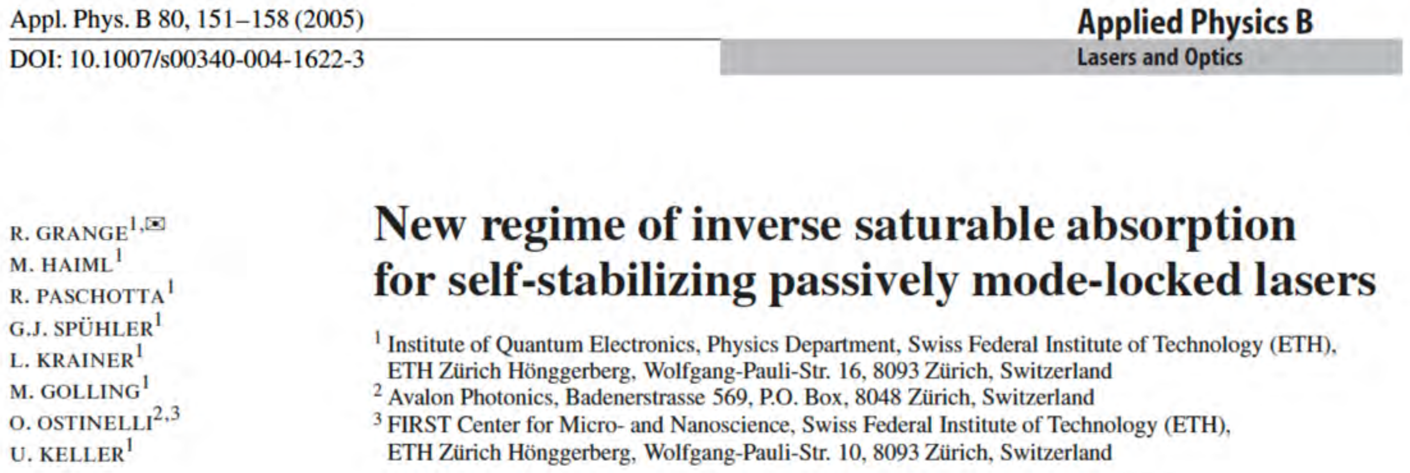
Semiconductor saturable absorber mirror structures with low saturation fluence

[1] ETH Zurich, Physics Department, Institute of Quantum Electronics, Wolfgang-Pauli-Strasse 16, 8093 Zürich, Switzerland
[2] Time-Bandwidth Products, GigaTera Product Group, Technoparkstr. 1, 8005 Zürich, Switzerland

2) SESAMs with inverse saturable absorption:



Appl. Phys. B 80, 151–158 (2005)
DOI: 10.1007/s00340-004-1622-3
Applied Physics B
Lasers and Optics

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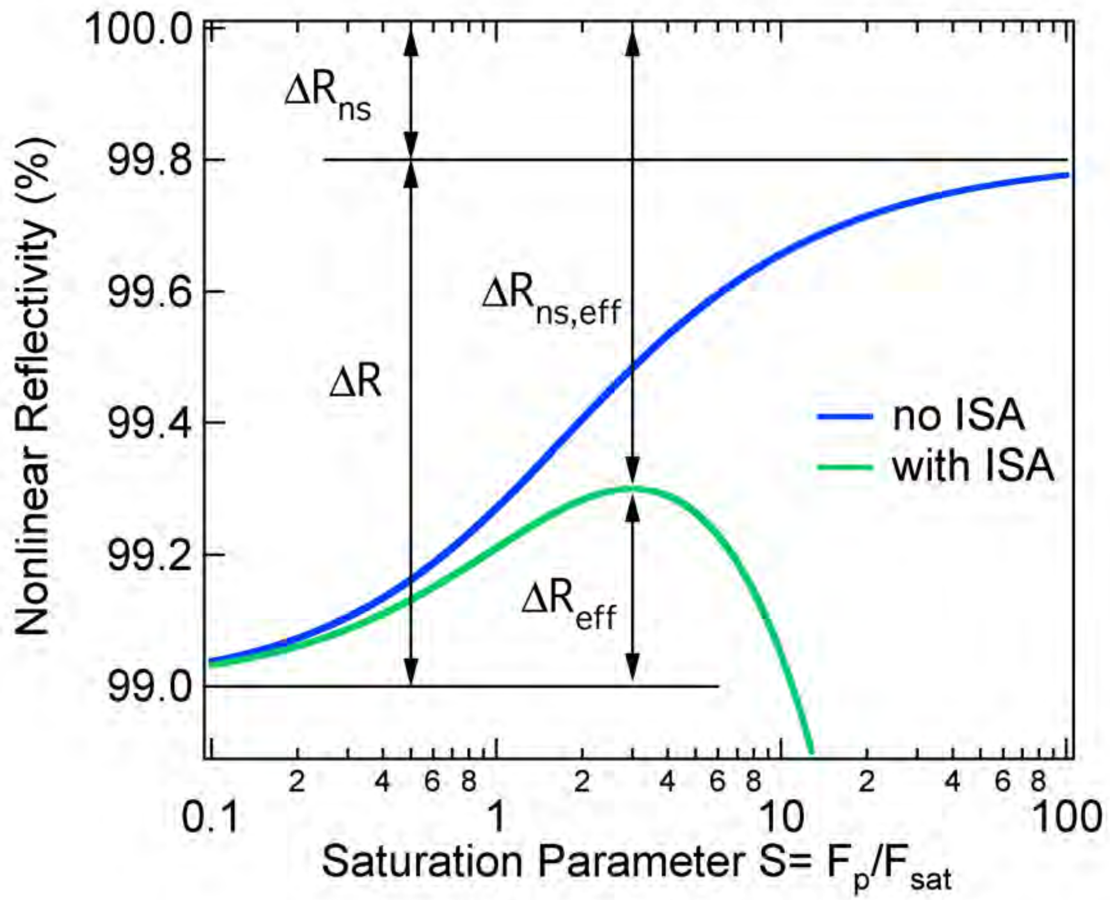
New regime of inverse saturable absorption for self-stabilizing passively mode-locked lasers

[1] Institute of Quantum Electronics, Physics Department, Swiss Federal Institute of Technology (ETH), ETH Zürich Hönggerberg, Wolfgang-Pauli-Str. 16, 8093 Zürich, Switzerland
[2] Avalon Photonics, Badenerstrasse 569, P.O. Box, 8048 Zürich, Switzerland
[3] FIRST Center for Micro- and Nanoscience, Swiss Federal Institute of Technology (ETH), ETH Zürich Hönggerberg, Wolfgang-Pauli-Str. 10, 8093 Zürich, Switzerland

Inverse saturable absorption (ISA)

SESAM reflectivity for a pulse fluence F_p



the reflectivity decreases
at higher pulse energies

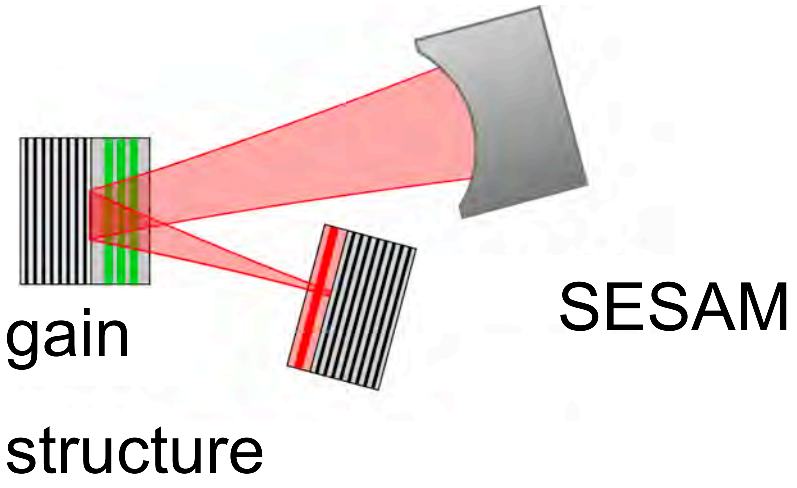
⬇

the roll-over = inverse saturable absorption

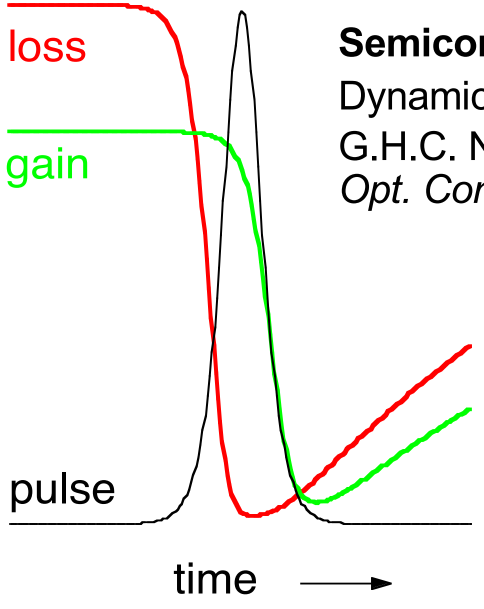
$$R_{ISA}(F_p) = R_P(F_p) - \frac{F_p}{F_2}$$

- F_2 is the inverse slope of the roll over
- The smaller F_2, the stronger is the roll-over

Dynamic gain saturation in semiconductor lasers



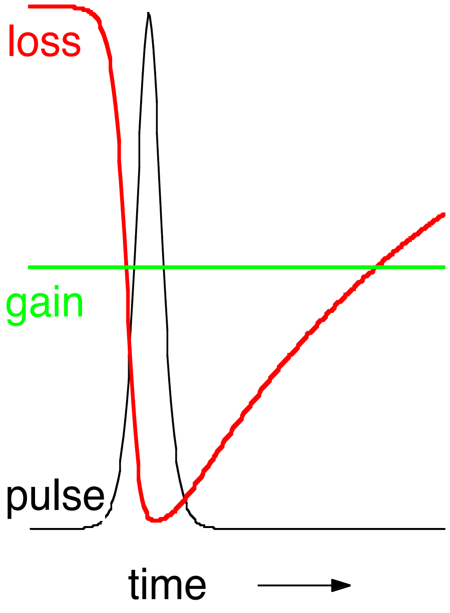
Important difference between semiconductor lasers and diode-pumped solid-state lasers



Semiconductor and dye lasers

Dynamic gain saturation

G.H.C. New,
Opt. Com. 6, 188, 1974



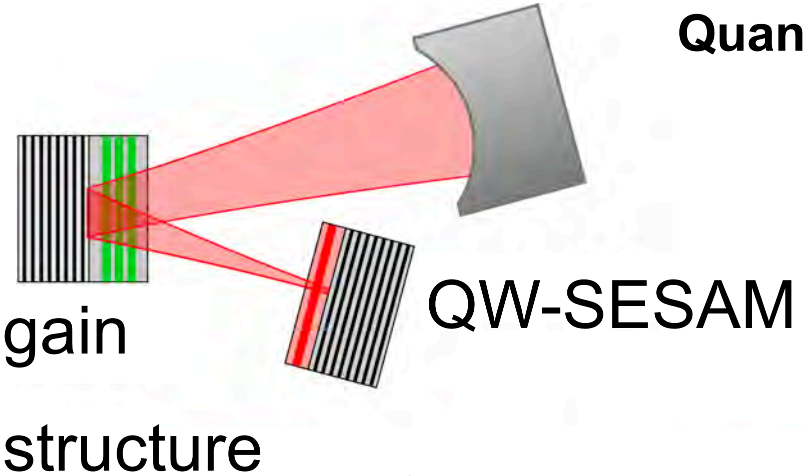
Solid-state lasers

No dynamic gain saturation

Soliton modelocking

F. X. Kärtner, U. Keller,
Opt. Lett. 20, 16, 1995

SESAM-VECSEL modelocking



Quantum-well (QW) SESAM-modelocked VECSEL

1.5 GHz	**2.2 W**	6 ps	[1]
4 GHz	2.1 W	4.7 ps	[1]
10 GHz	**1.4 W**	6.1 ps	[2]

[1] A. Aschwanden et al., *Optics Lett.* **30**, 272, 2005

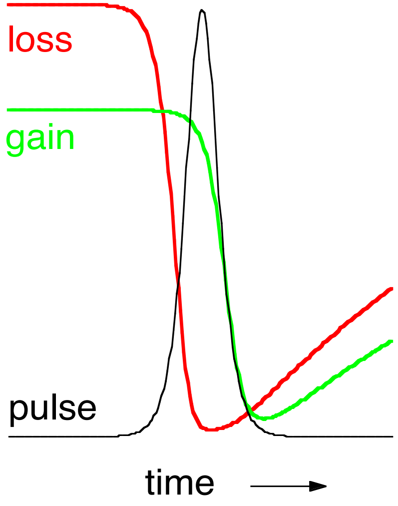
[2] A. Aschwanden et al., *Appl. Phys. Lett.* **86**, 131102, 2005

$$\frac{E_{sat,a}}{E_{sat,g}} = \frac{F_{sat,a}}{F_{sat,g}} \boxed{\frac{A_a}{A_g}} < 1$$

typically 1/4 – 1/20 for QW-SESAMs

example: 2.2 W, 6 ps QW-VECSEL

$$\frac{A_a}{A_g} = \frac{\pi \cdot (40\mu\text{m})^2}{\pi \cdot (175\mu\text{m})^2} = 0.052$$



OP-VECSEL milestones 2006

- **First room temperature VECSEL:**

  20 µW average power:

  J.V. Sandusky et al., IEEE Photon. Technol. Lett. **8**, 313 (1996)

- **High-power cw operation:**

  0.5 W in TEM_{00} beam: M. Kuznetsov et al., *IEEE Photon. Technol. Lett.* **9**, 1063 (1997)
  1.5 W: *W. J. Alford et al., J. Opt. Soc. Am. B* **19**, *663 (2002)*
  30 W: J. Chilla et al., *Proc. SPIE* **5332**, 143 (2004) - Coherent
  20 W in TEM_{00} beam: B. Rudin et al., *Optics Lett.* **33**, 2719, 2008

- **Passive mode locking with SESAM:**

  20 mW: S. Hoogland et al., *IEEE Photon. Technol. Lett.* **12**, 1135 (2000)
  200 mW: R. Häring et al., *Electron. Lett.* **37**, 766 (2001)
  950 mW: R. Häring et al., *IEEE JQE* **38**, 1268 (2002)
  2.1 W, 4.7 ps, 4 GHz, 957 nm
  2.2 W, 6 ps, 1.5 GHz, 957 nm
  A. Aschwanden et al., *Opt. Lett.* **30**, 272 (2005)

Modelocked VECSEL review: *Physics Reports* **429**, 67, 2006

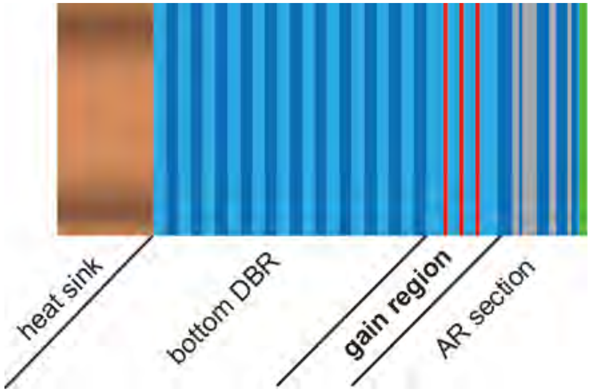
Outline

1. Introduction to ultrafast semiconductor disk lasers
2. SESAM-modelocked VECSELs
3. MIXSEL
4. 100-fs VECSEL
5. 139-fs MIXSEL
6. Outlook

Semiconductor disk lasers

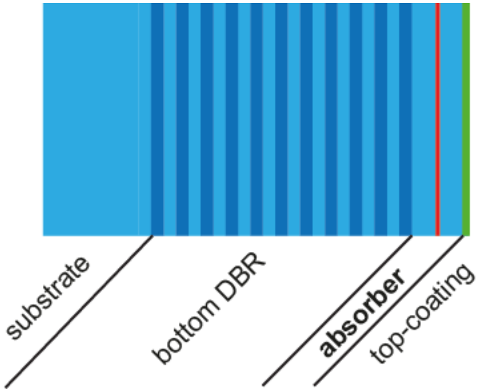
3-GHz pulse repetition rate: cavity length of ≈ 5 cm

VECSEL



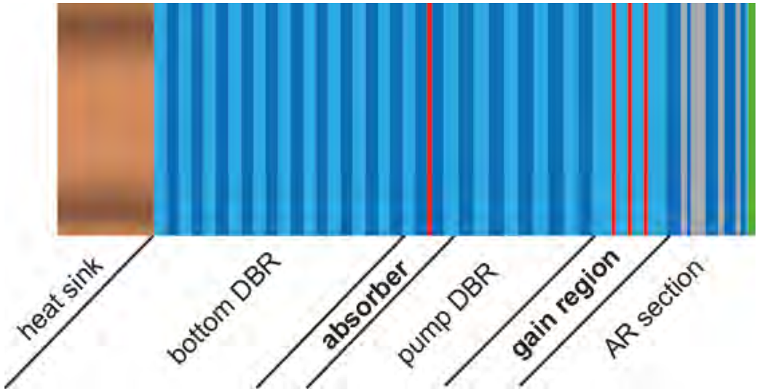
&

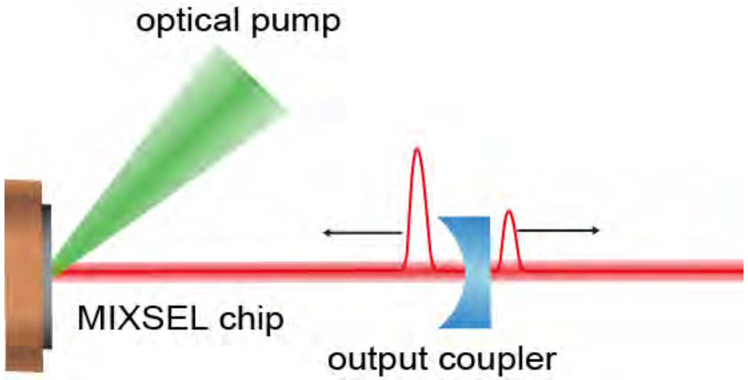
SESAM



MIXSEL

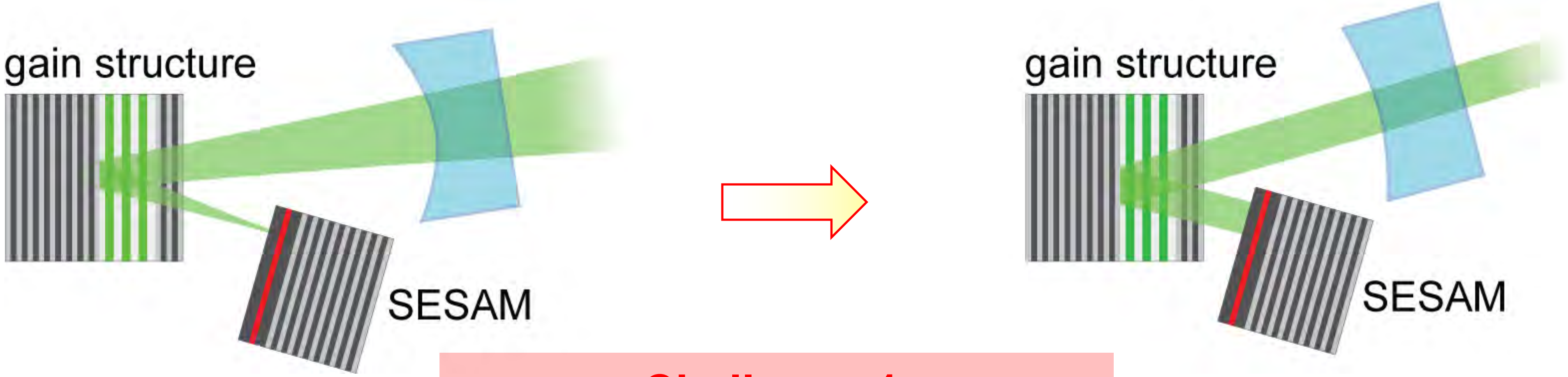
modelocked integrated external-cavity surface-emitting laser





D. J. H. C. Maas et al., *Appl. Phys. B* **88**, 493, 2007

Towards Absorber Integration



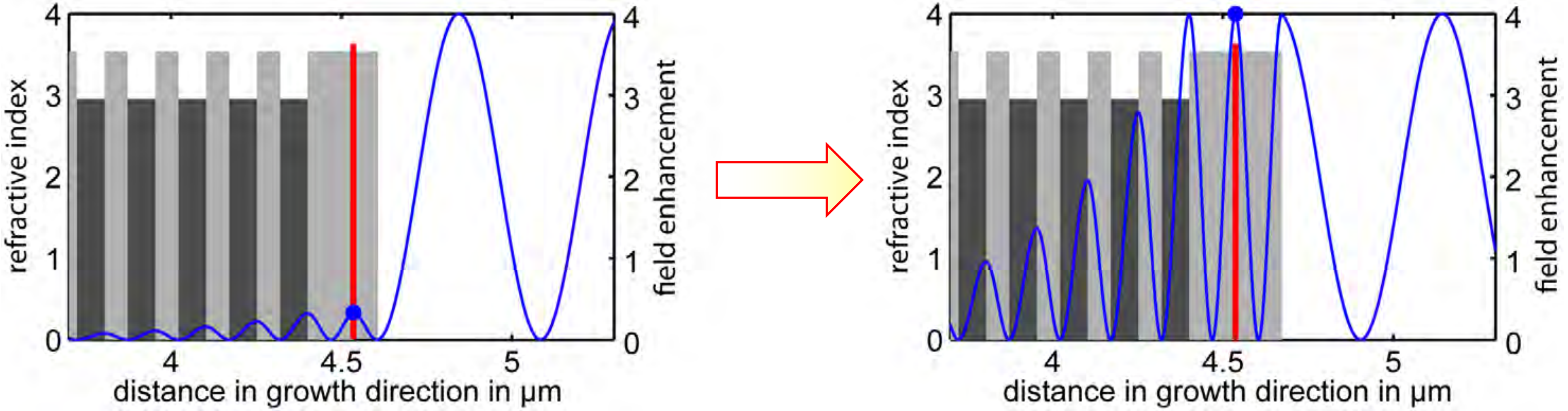
$$\frac{E_{sat,a}}{E_{sat,g}} = \frac{F_{sat,a} A_a}{F_{sat,g} A_g} < 0.1$$

Challenge 1

Reduction of saturation fluence

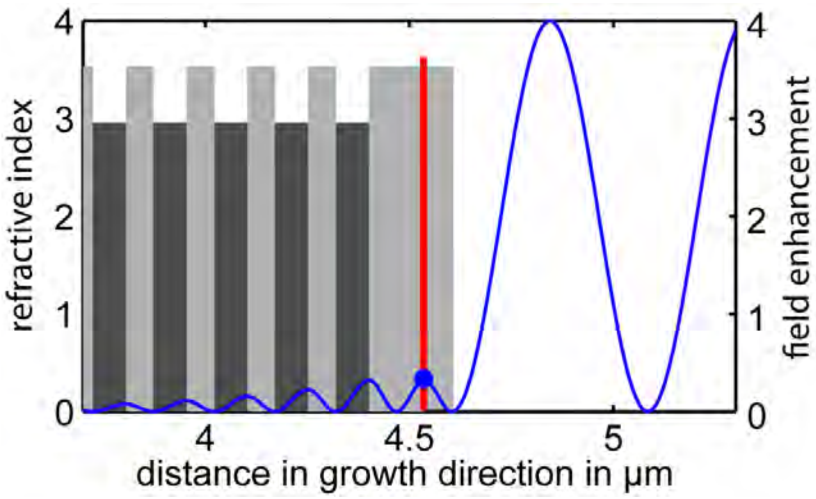
⇨ Increase field in absorber

$$\frac{E_{sat,a}}{E_{sat,g}} = \frac{F_{sat,a} A_a}{F_{sat,g} A_g} < 0.1$$

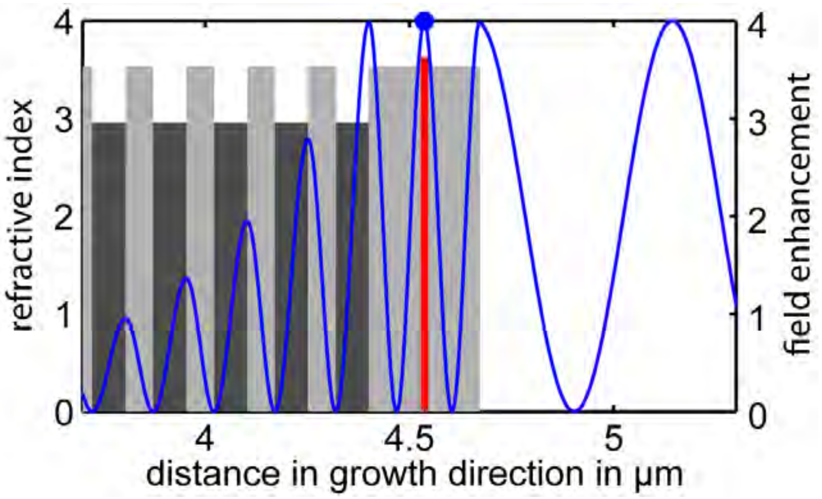


Towards Absorber Integration

antiresonant SESAM



resonant SESAM



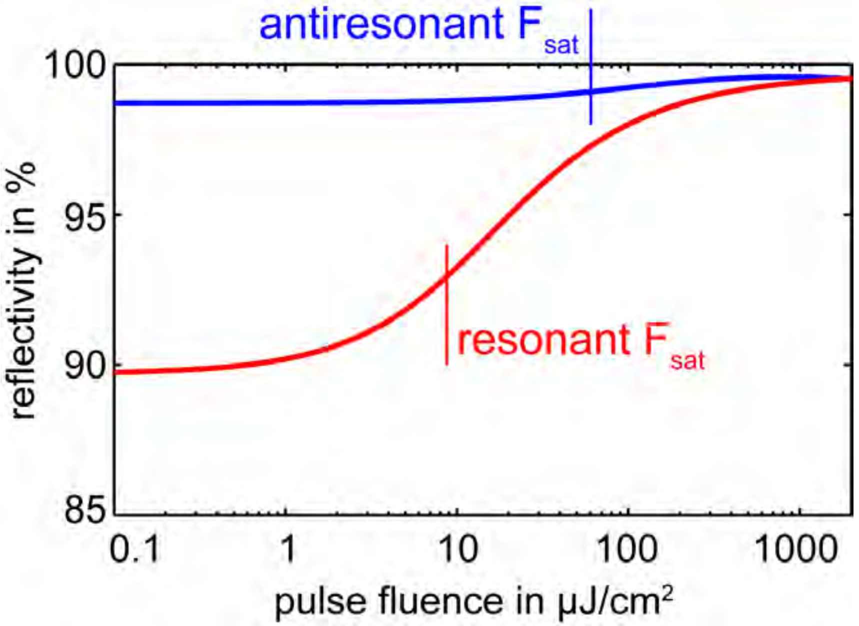
Challenge 2

Problem: increase of modulation depth

$$F_{\text{sat}} \cdot \Delta R = \text{const.}$$

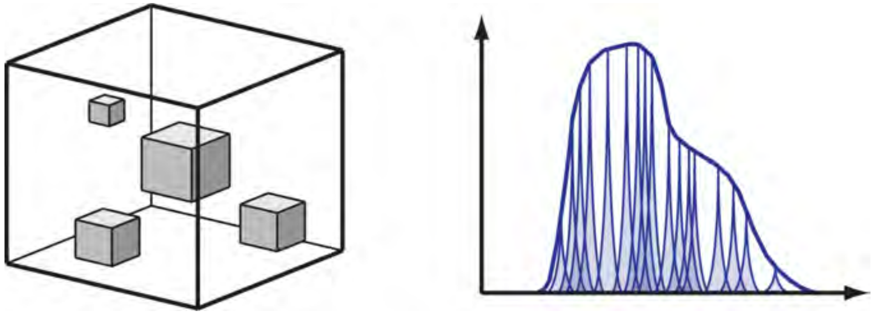
No possibility for uncoupled F_{sat} and ΔR for QW SESAMs

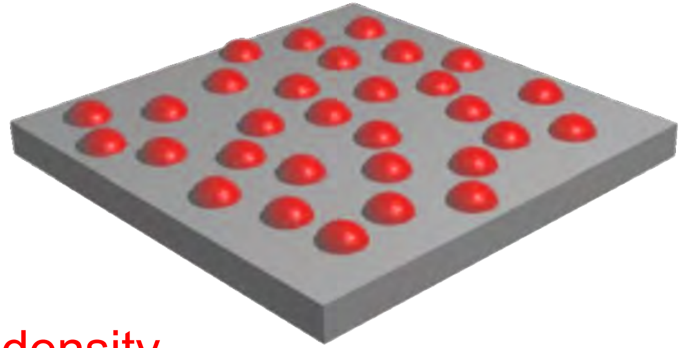
What can we do?



Towards Absorber Integration: Quantum Dots (QDs)

QDs absorbers offer more growth parameters than QWs absorbers





QD size and size distribution

⇨ determine absorption spectrum

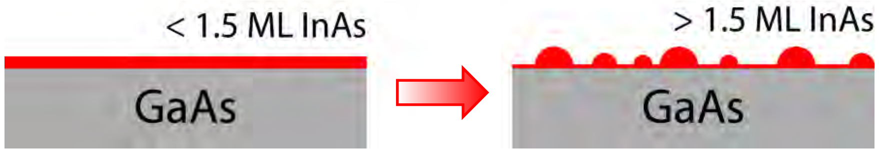
QD density

⇨ determines modulation depth

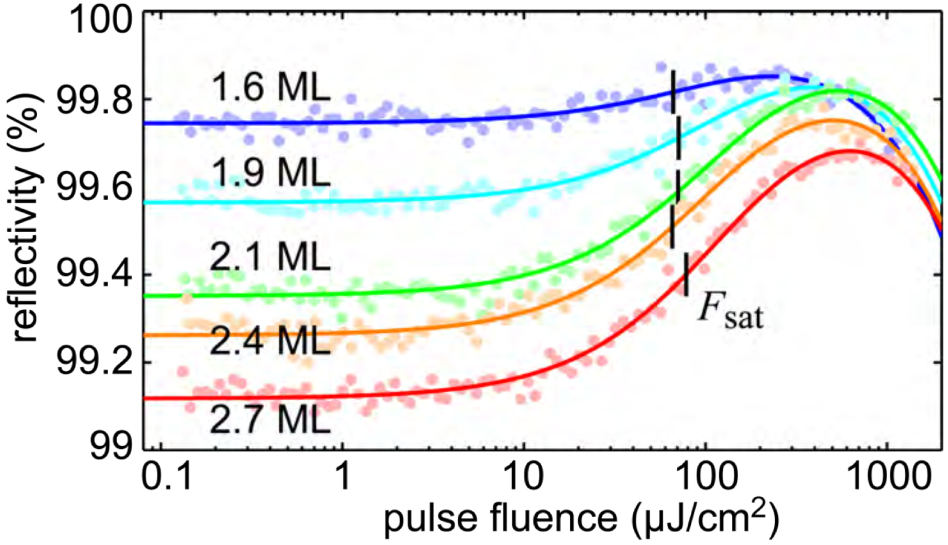
QD growth

- Stranski-Krastanov growth on MBE
- InAs on GaAs substrate
- In ML coverage determines density

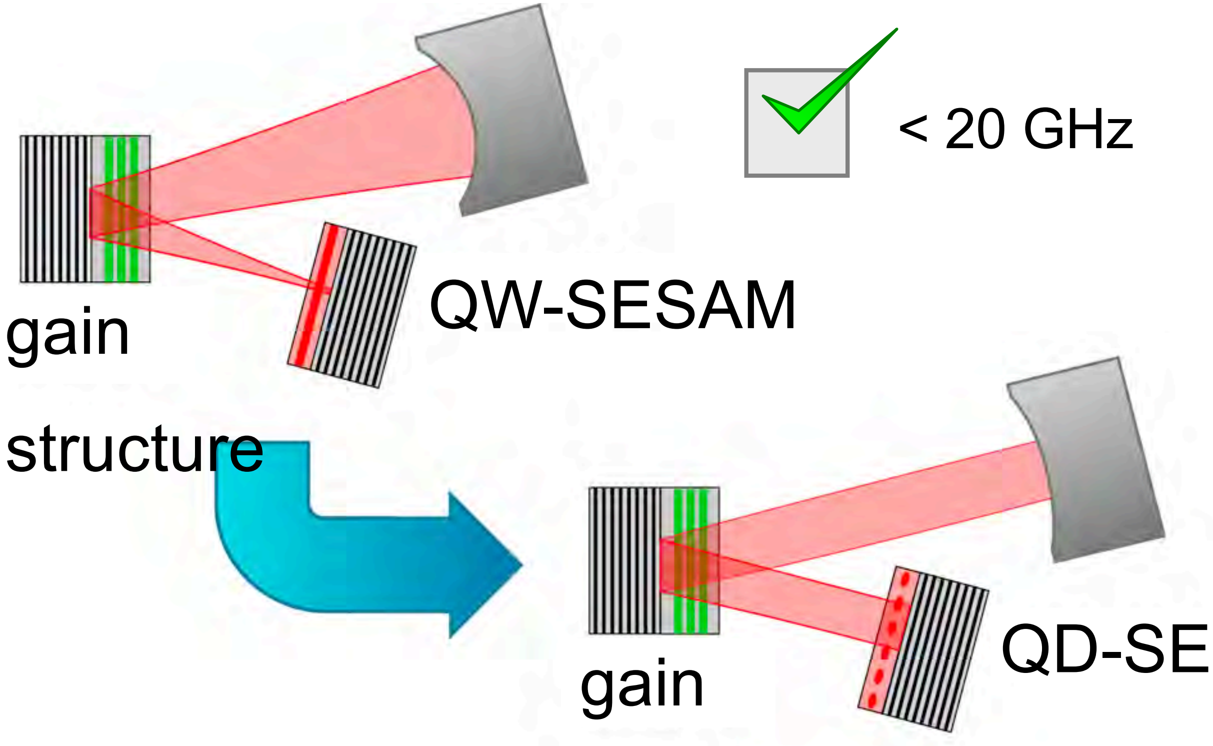
Self-assembled QD formation:



ΔR can be tuned with dot density, while F_{sat} stays constant!

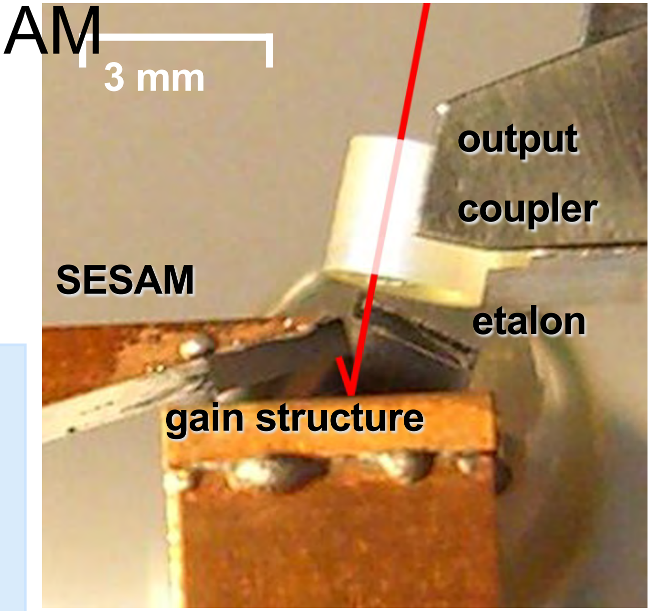


SESAM-VECSEL modelocking



☑ < 20 GHz

☑ up to 50 GHz demonstrated



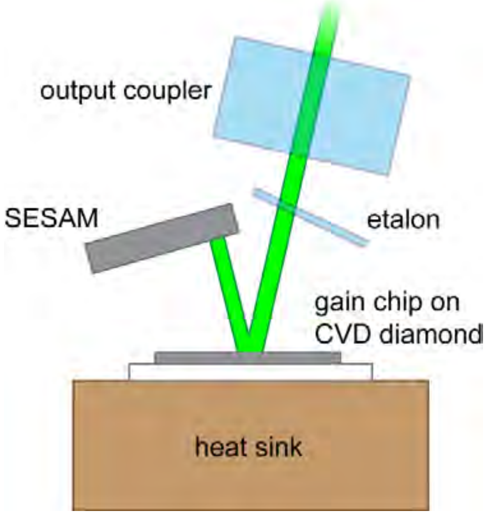
QD-SESAM modelocking: up to 50 GHz repetition rate

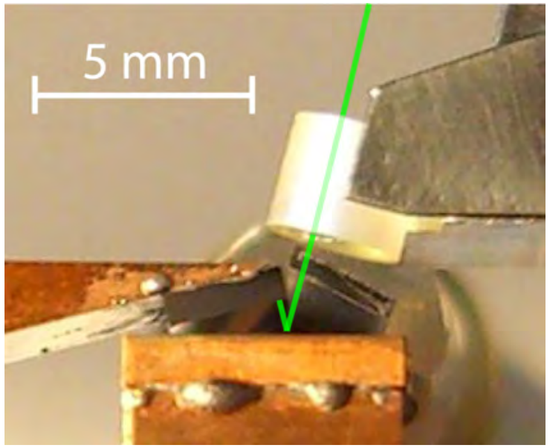
D. Lorenser et al., IEEE J. Quantum Electron. **42**, 838-847, 2006

- **102 mW** average power, center wavelength 958.5 nm
- **3.3 ps** pulse duration

Towards Absorber Integration: “1:1 modelocking”

Modelocking with identical mode sizes on gain and absorber:



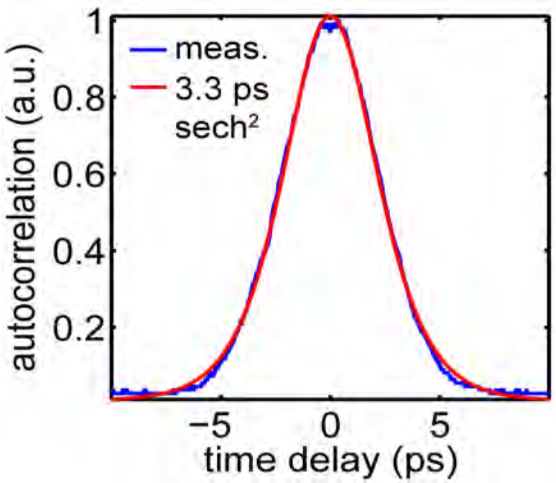


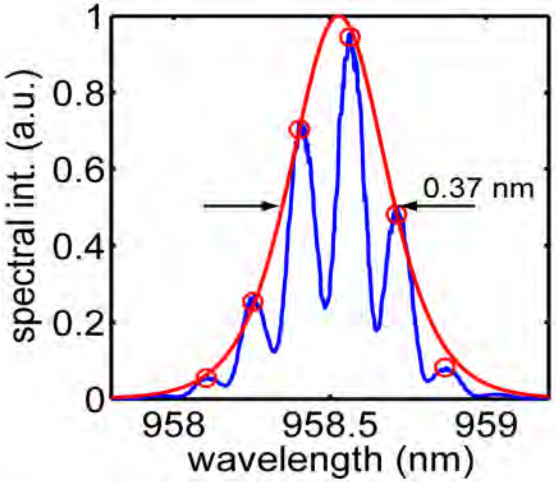
Resonant QD SESAM:

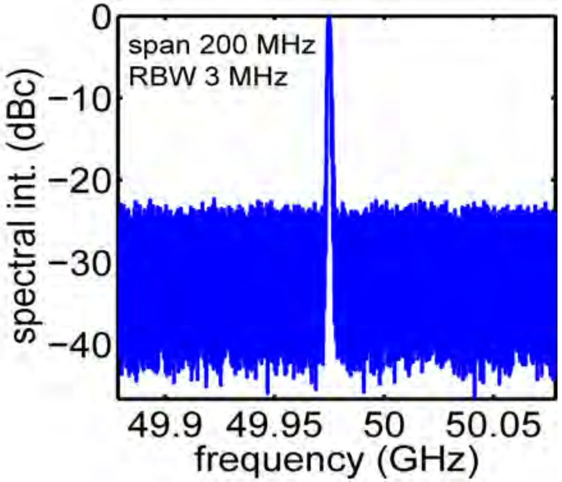
- ΔR = 1%
- F_{sat} = 2 µJ/cm^2

Laser output:

- P_{out} = 102 mW
- τ_p = 3.3 ps
- f_{rep} = 50 GHz



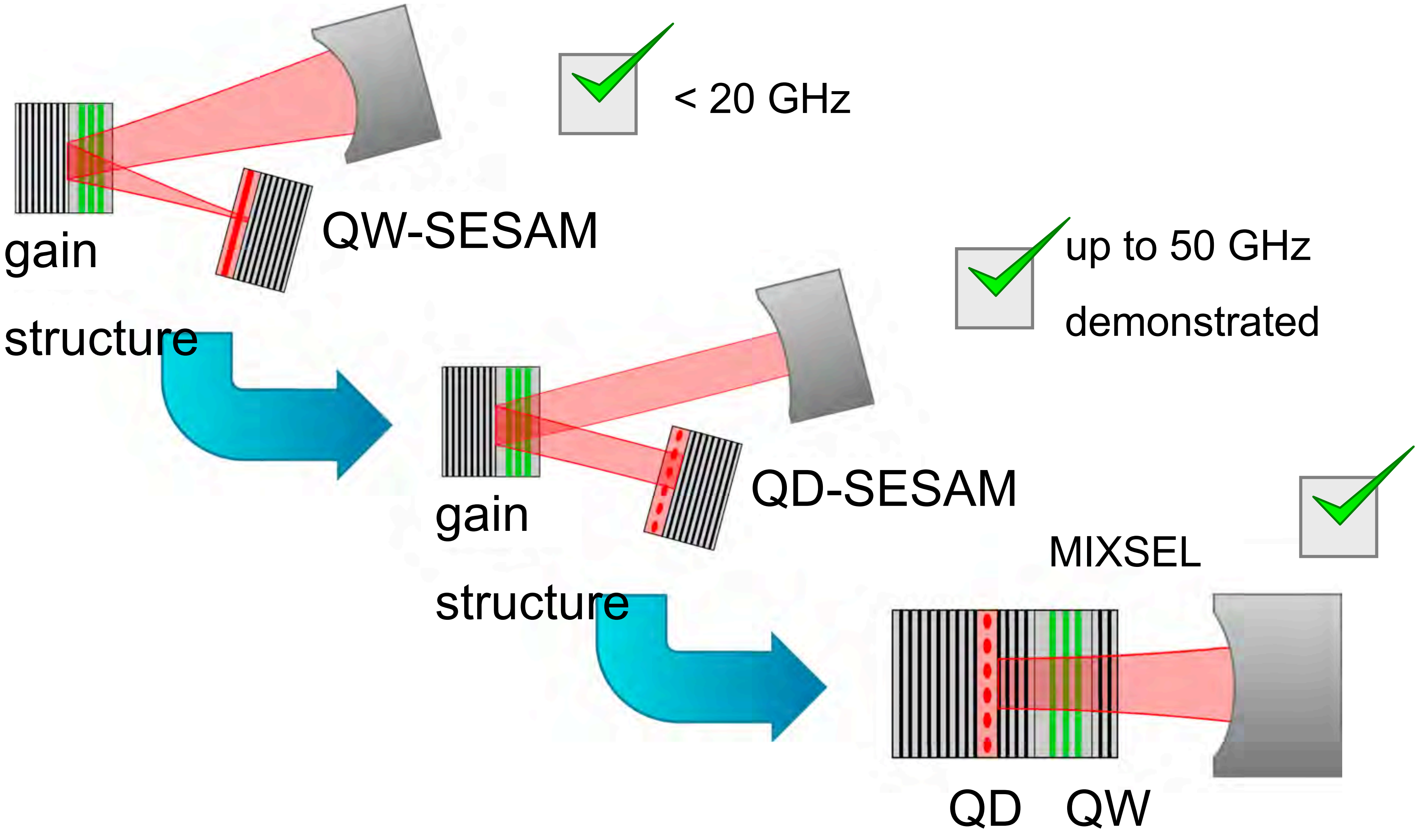




➡ Integration of absorber is now conceptually possible!

D. Lorenser et al., IEEE J. Quantum Electron. **42**, 838-847 (2006)

SESAM-VECSEL modelocking and MIXSEL



gain structure

QW-SESAM

☑ < 20 GHz

gain structure

QD-SESAM

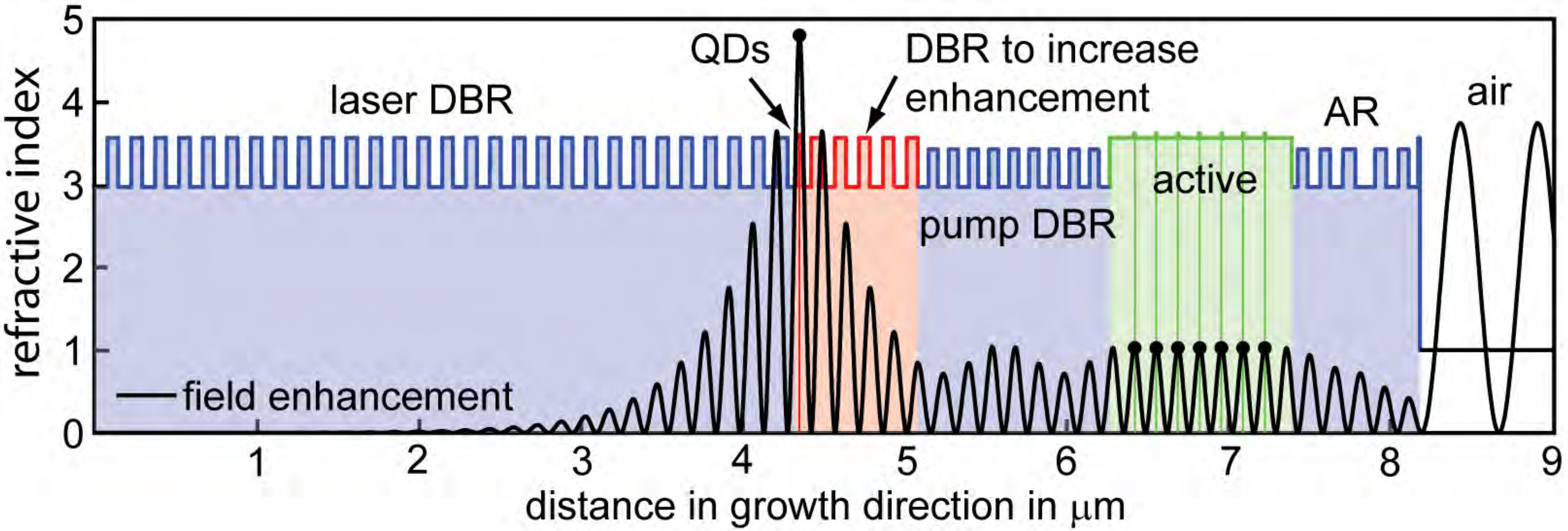
☑ up to 50 GHz demonstrated

MIXSEL ☑

QD QW

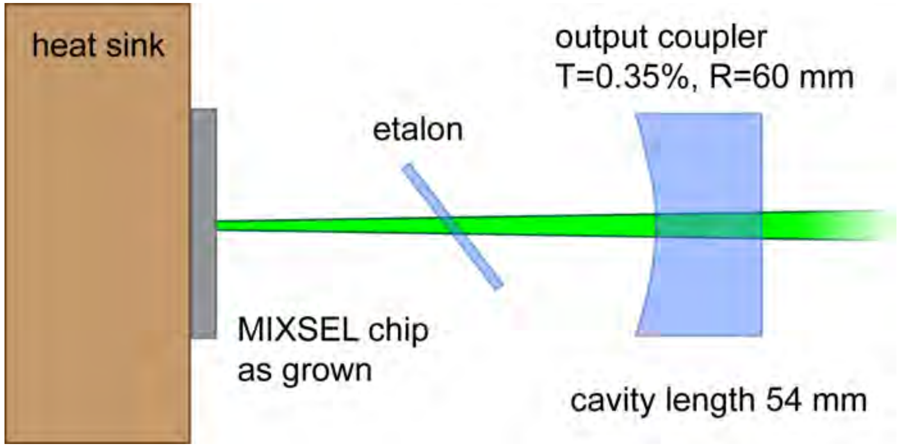
First MIXSEL demonstration: 35 ps, 40 mW, 2.8 GHz

Resonant design



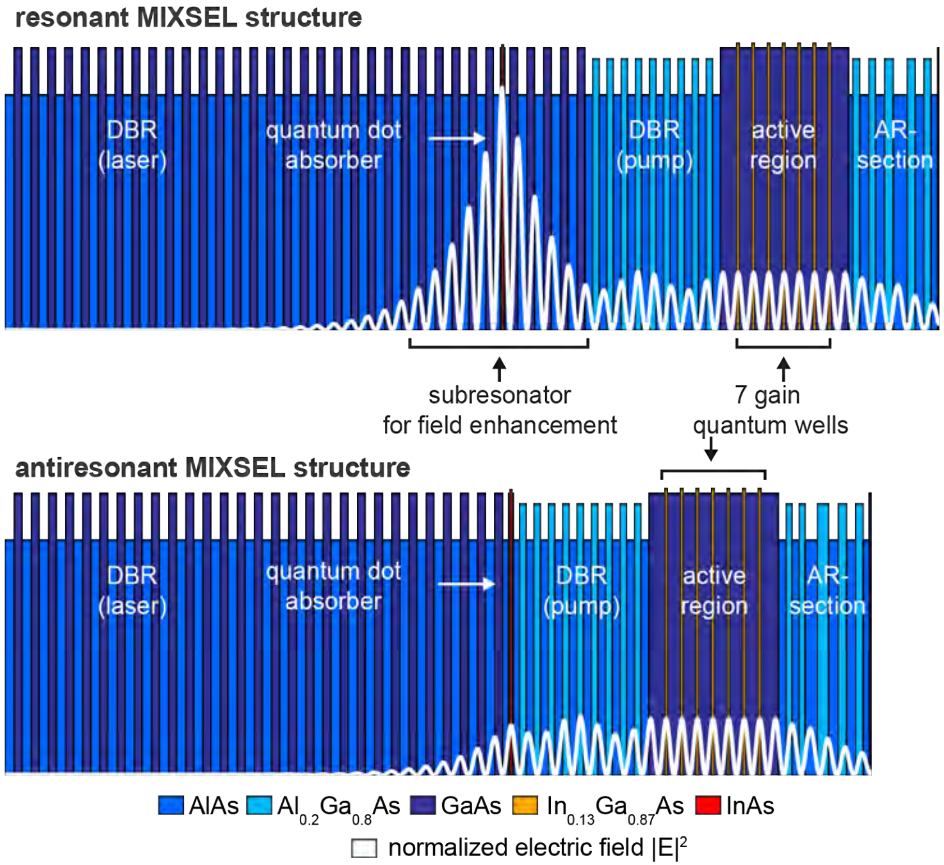
Sections:

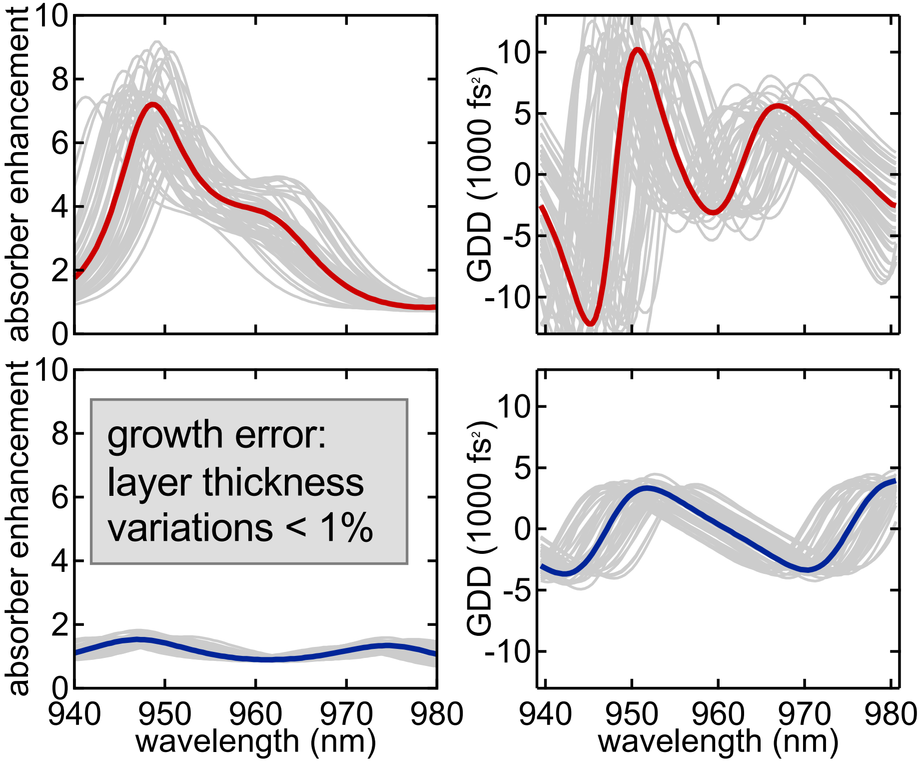
- 30 pair bottom mirror for the laser
- 1 layer of self-assembled InAs QD
- DBR to increase field in absorber
- 9 pair mirror for the pump
- active region with 7 InGaAs QWs
- AR coating



D. J. H. C. Maas et al., Applied Physics B **88**, 493-497 (2007)

Antiresonant MIXSEL Design





Advantages

- less variations in absorber enhancement
- reduced GDD for shorter pulses
- less sensitive to growth errors

Requirement

- QDs with strong saturation
- study on QD-growth parameters optimization of growth temperature and post-growth annealing

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A.-R. Bellancourt, Y. Barbarin, D. J. H. C. Maas, M. Shafiei, M. Hoffmann, M. Golling, T. Südmeyer, U. Keller, OE, 17, 12, (2009)

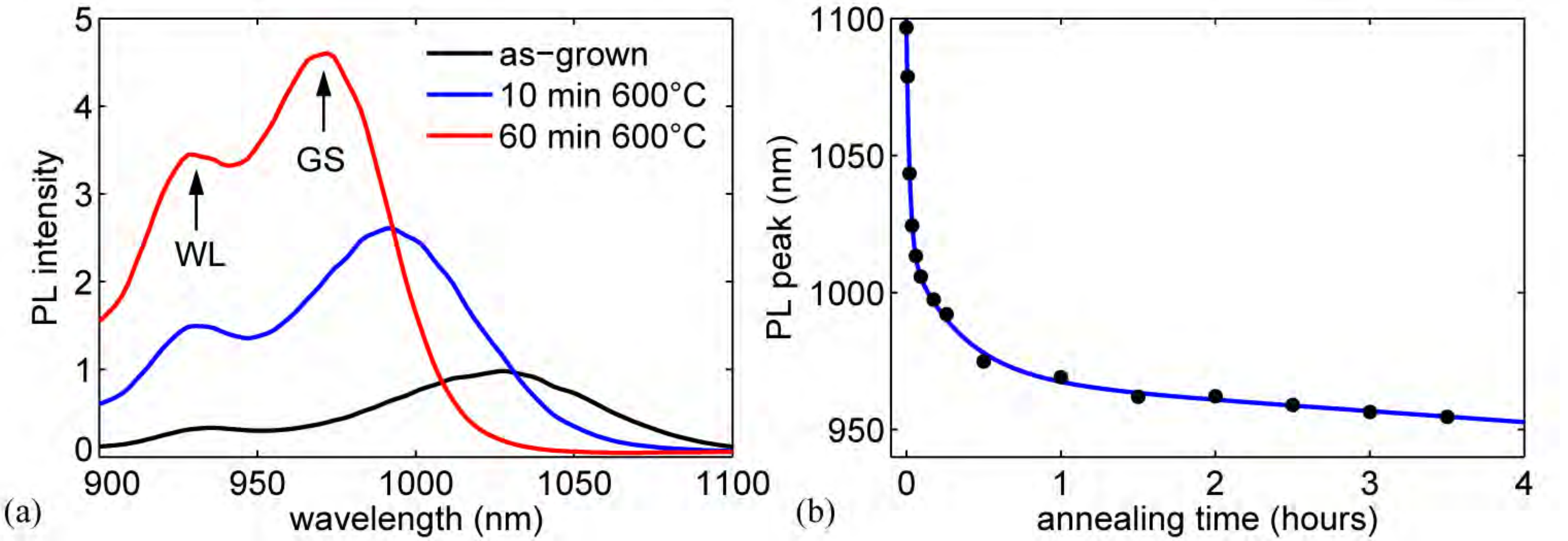
D. J. H. C. Maas, A. R. Bellancourt, M. Hoffmann, B. Rudin, Y. Barbarin, M. Golling, T. Südmeyer, U. Keller, OE, 16, 23, (2008)

Photoluminescence (PL) shift during annealing

The QDs are annealed in the growth of a MIXSEL:

Strong blueshift of the PL peak

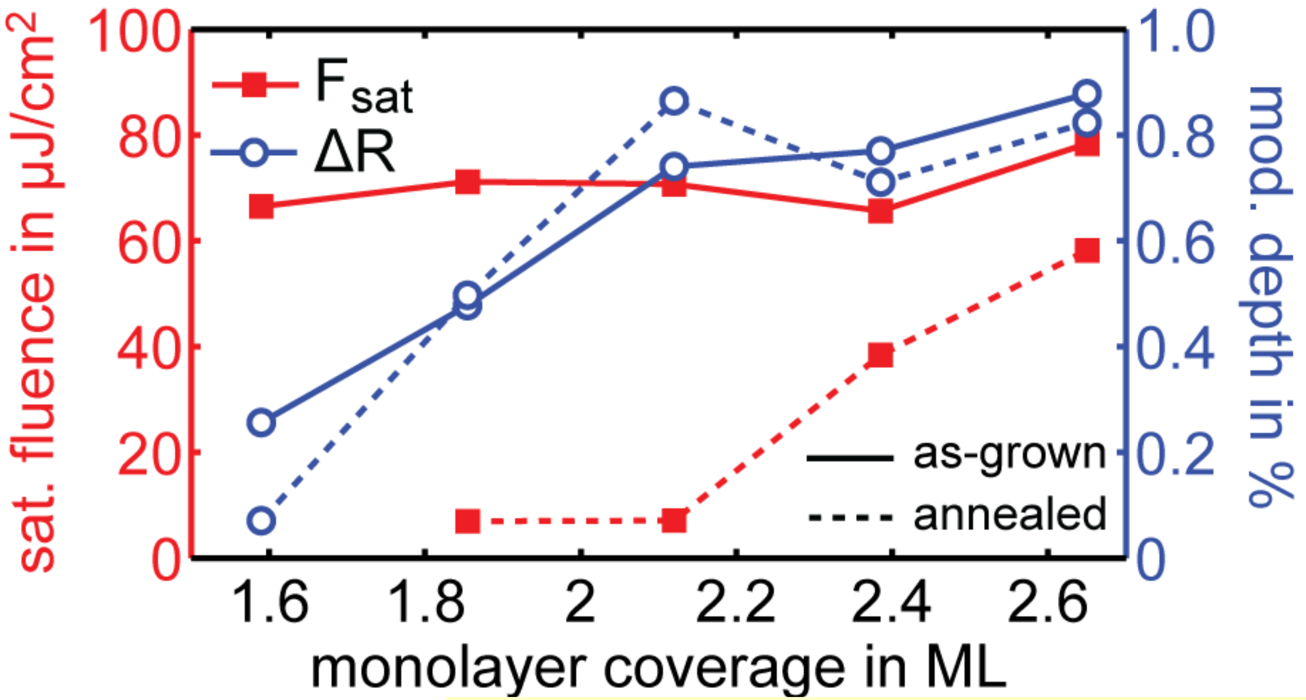
Case with 1.6 ML InAs coverage



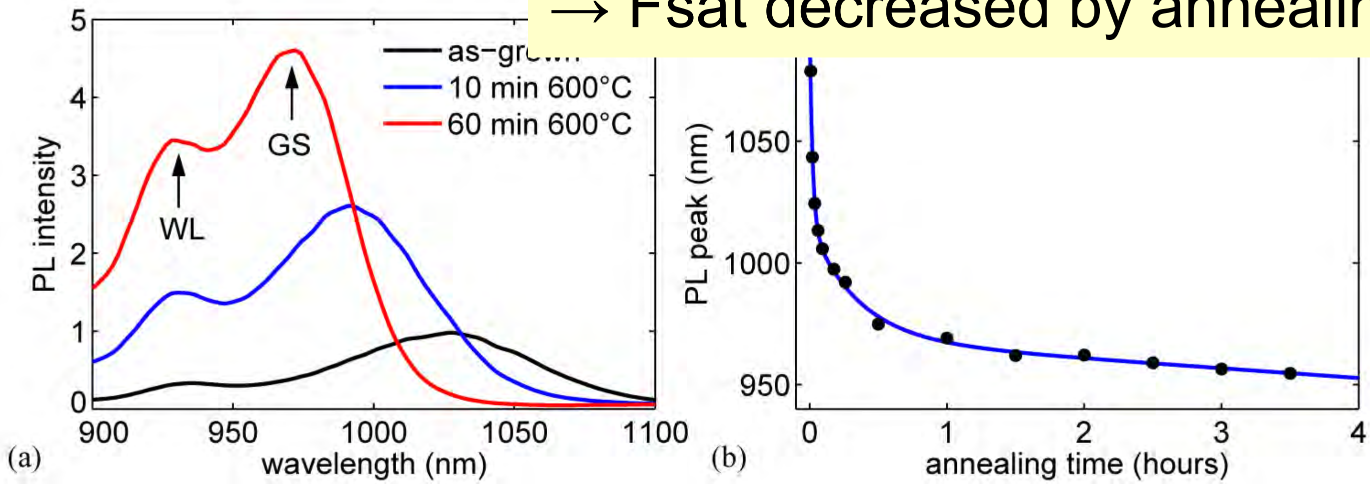
D.J.H.C. Maas, A.-R. Bellancourt, M. Hoffmann, B. Rudin, Y. Barbarin, M. Golling, T. Südmeyer, and U. Keller, *Optics Express* **16**, 18646 (2008)

QD-SESAM annealing benefits: lower F_{sat}

Optics Express **16**, 18646 (2008)



→ Fsat decreased by annealing and $\Delta R \approx$ constant



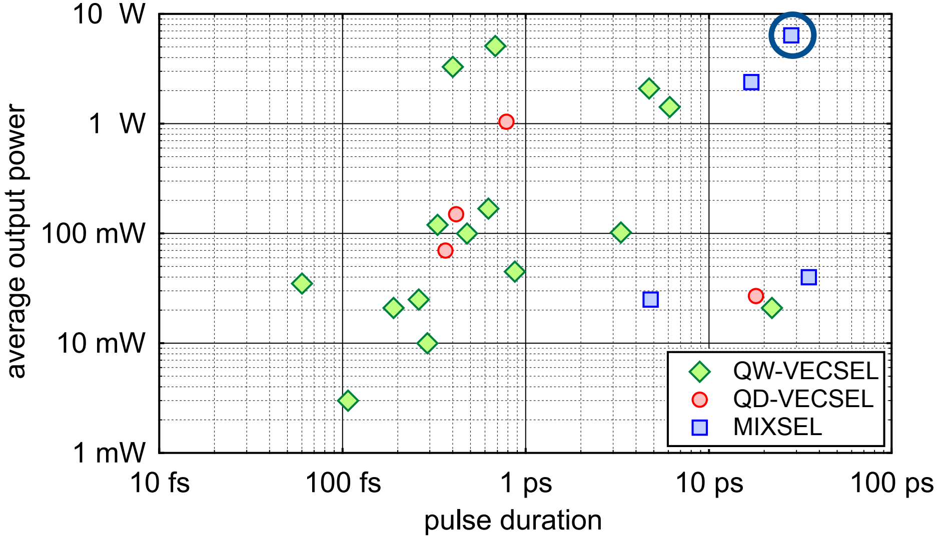
High Power MIXSEL

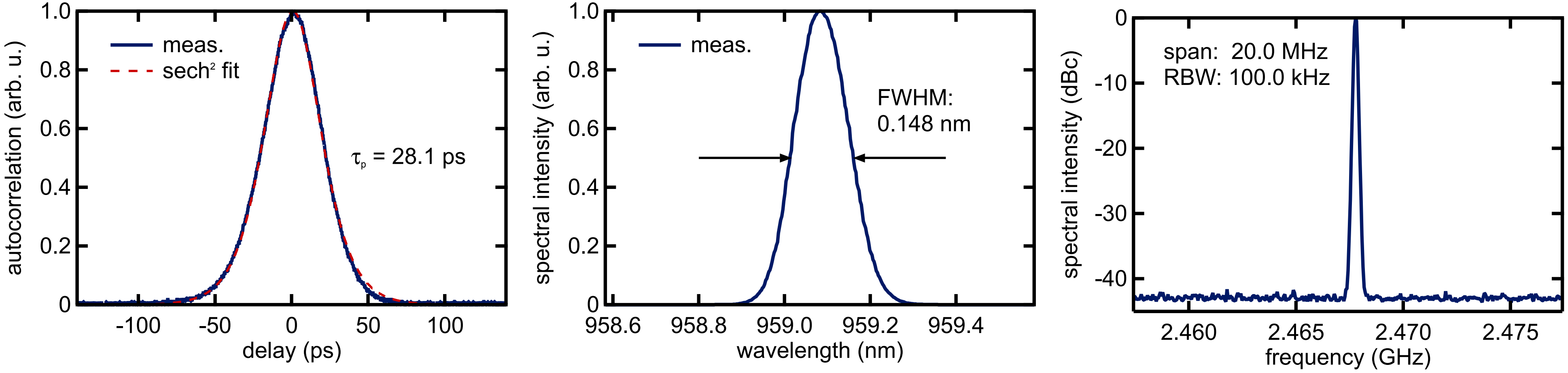
Average power	**6.4 W**
Center wavelength	959.1 nm
Pulse duration	28.1 ps
FWHM spectral width	0.15 nm

- optical pumping **36.7 W** at **808 nm**
- pump / laser spot radius: **≈215 µm**
- cavity length: **60.8 mm ⇨ 2.47 GHz**
- fluence on the MIXSEL : **252 µJ/cm^2**

highest average power from an ultrafast semiconductor laser

Optics Express **18**, 27582 (2010)

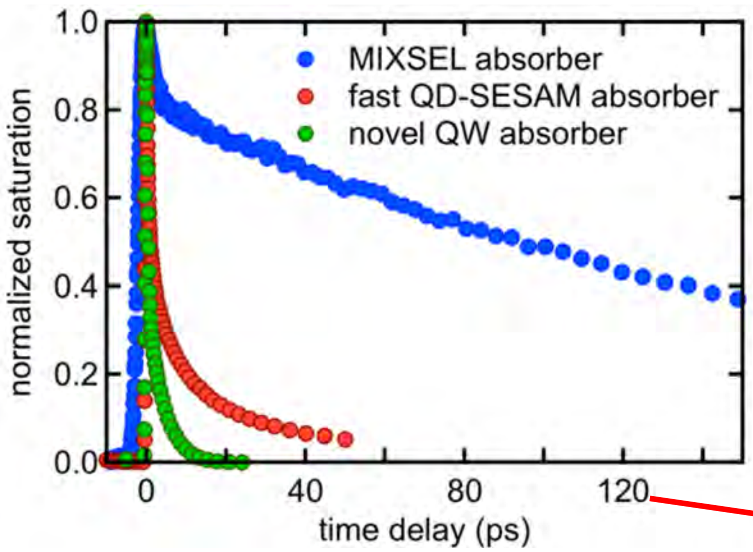




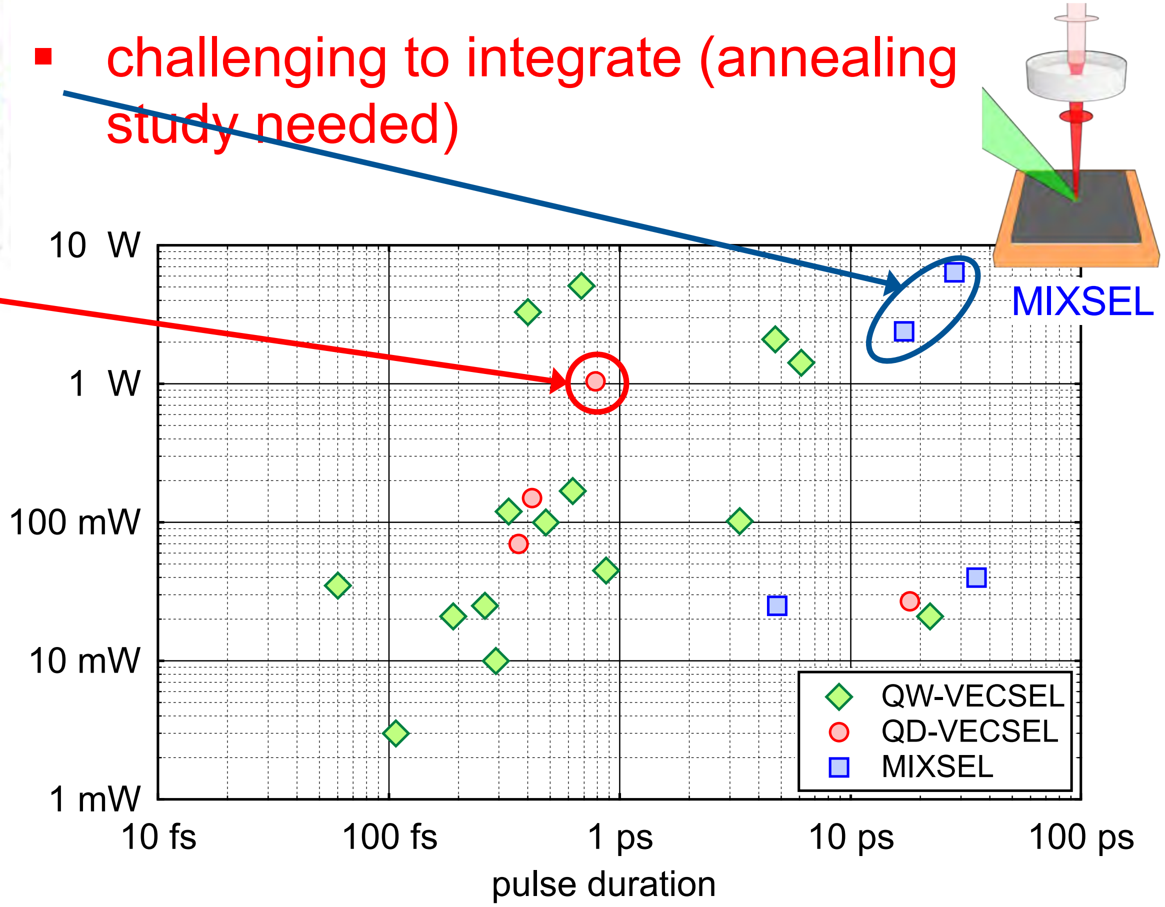
B. Rudin, V.J. Wittwer, D.J.H.C. Maas, M. Hoffmann, O.D. Sieber, Y. Barbarin, M. Golling, T. Südmeyer, U. Keller, OE **18**, 27582 (2010)

Pulse Shortening

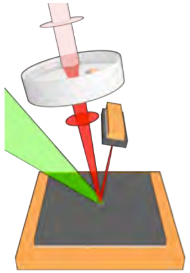
absorber recombination



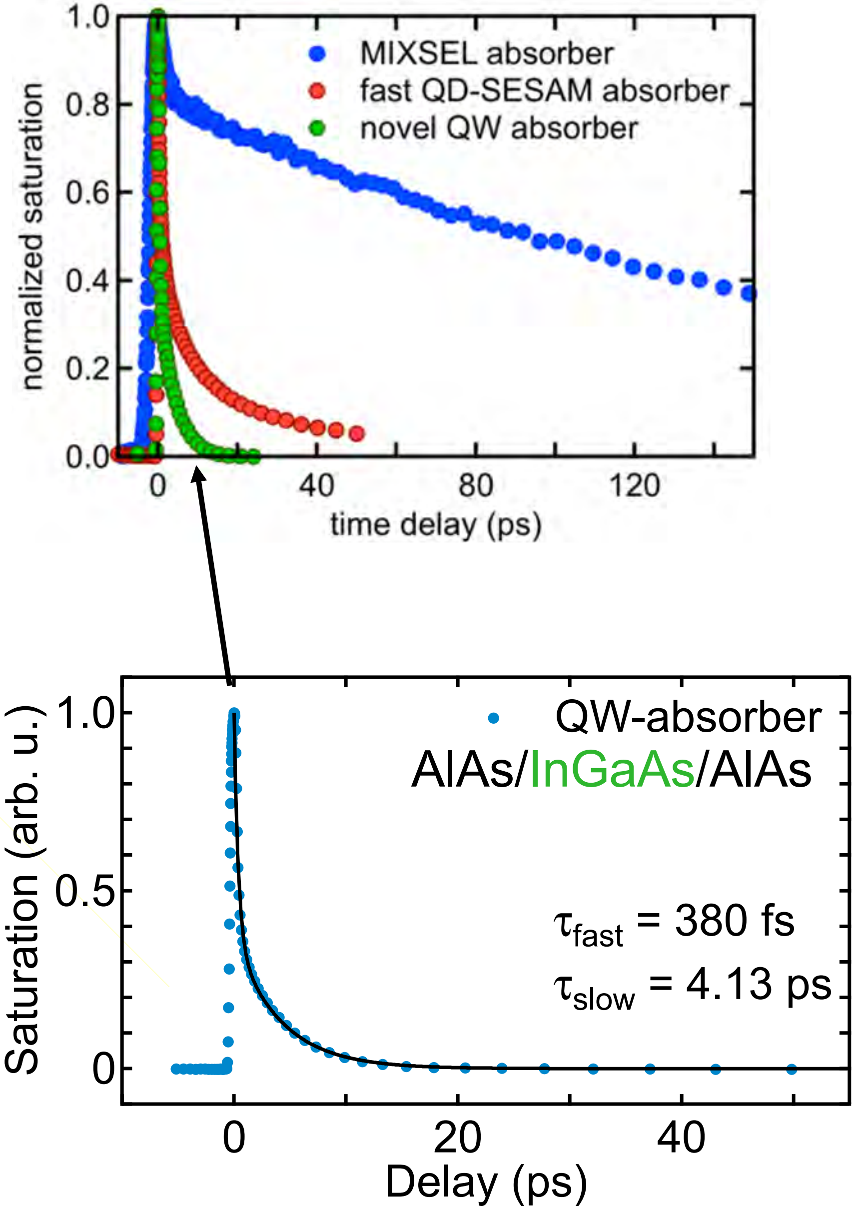
- slow recombination of the QD absorber in the MIXSEL *Optics Express* **18**, 27582 (2010)
- compared to the absorber in the QD SESAM for femtosecond pulses
- challenging to integrate (annealing study needed)



SESAM-modelocked QD-VECSEL:
M. Hoffmann et al.,
Opt. Express **19**, 8108 (2011)



Novel quantum well saturable absorber



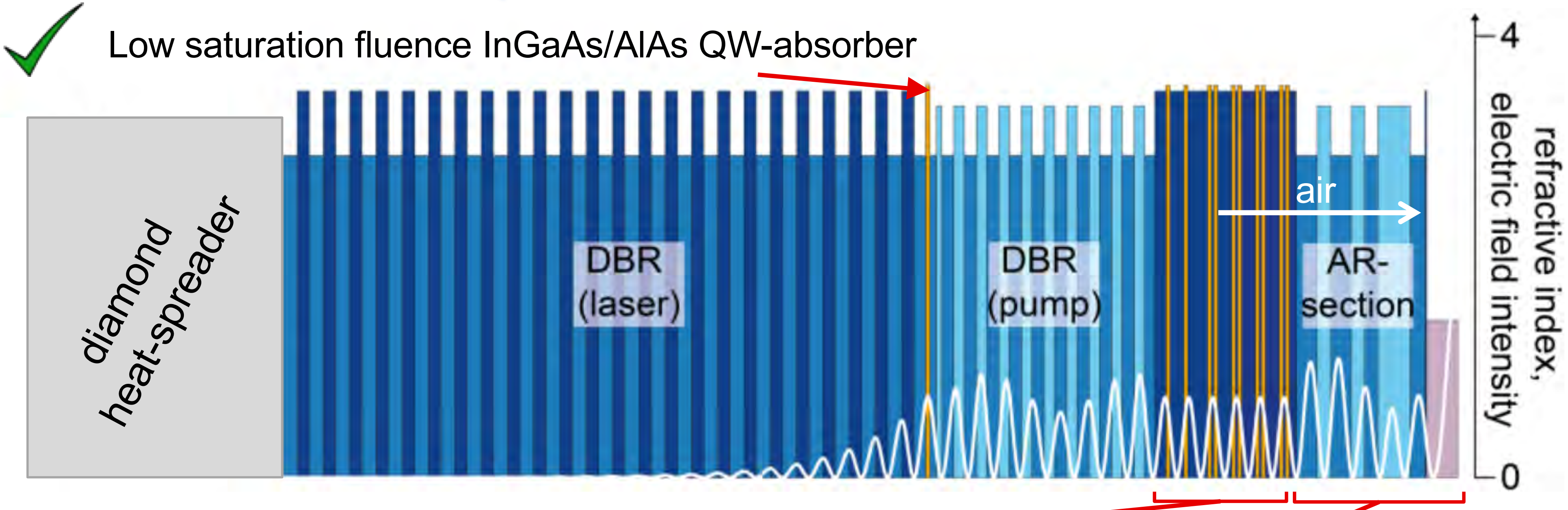
Saturable absorber

- Single **InGaAs quantum well**
- Embedded in **AlAs**
- Grown by molecular beam epitaxy (MBE)
- Low-temperature grown (< 300° C)
- Operated close to the **bandedge**

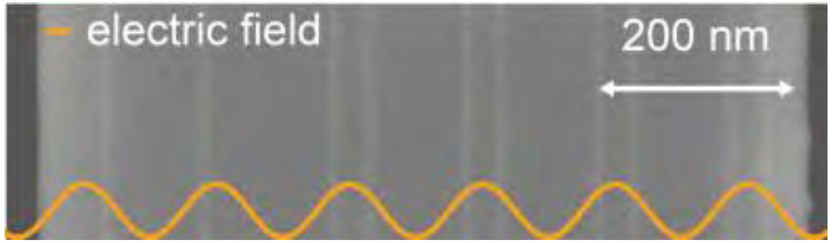
Absorbers for integration	InGaAs QWs	InAs QDs
Low saturation fluence	+	+
Fast recovery dynamics	+	–
Simple fabrication	+	–
Non-saturable losses	+	+
Temperature sensitivity	–	+
Design freedom	–	+

2013 NIR MIXSEL structure

✓ Low saturation fluence InGaAs/AlAs QW-absorber

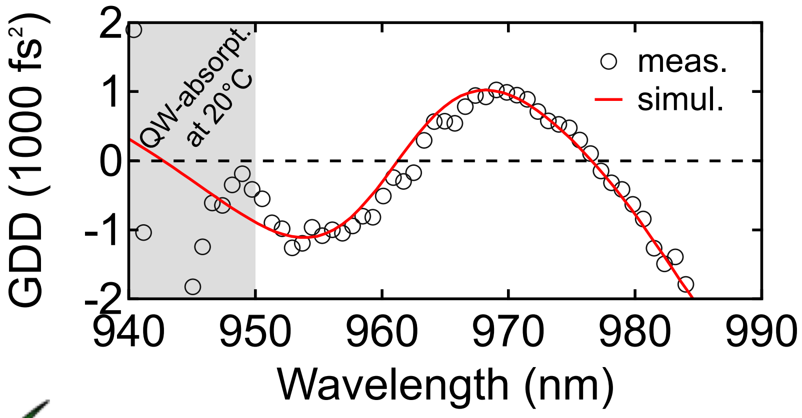


10 quantum well active region



✓ Higher gain saturation fluence and more broadband gain

Anti-reflection section

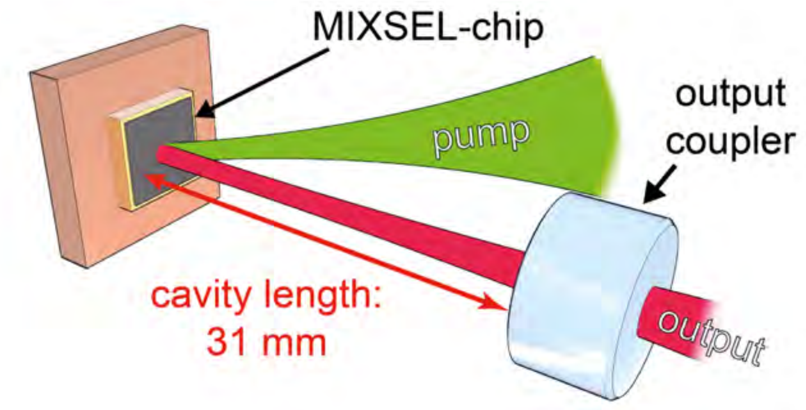


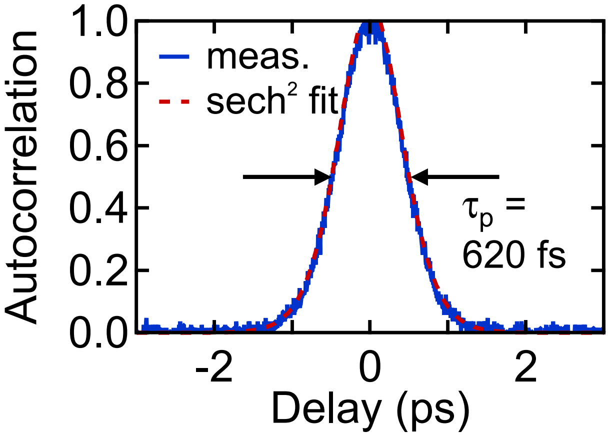
✓ Low and flat group-delay dispersion

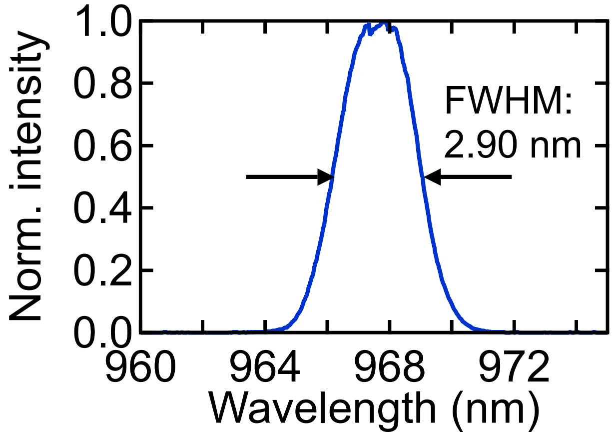
M. Mangold et al., *Opt. Express* **21**, 24904 (2013)

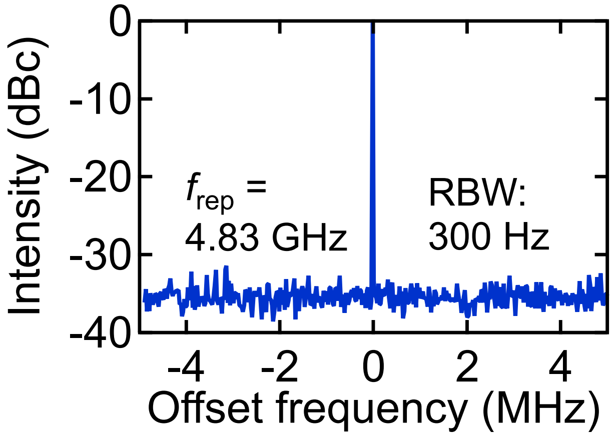
2013 First femtosecond MIXSEL

Pulse duration:	**620 fs**
Average output power:	101 mW
Repetition rate:	4.83 GHz
Center wavelength:	967.7 nm







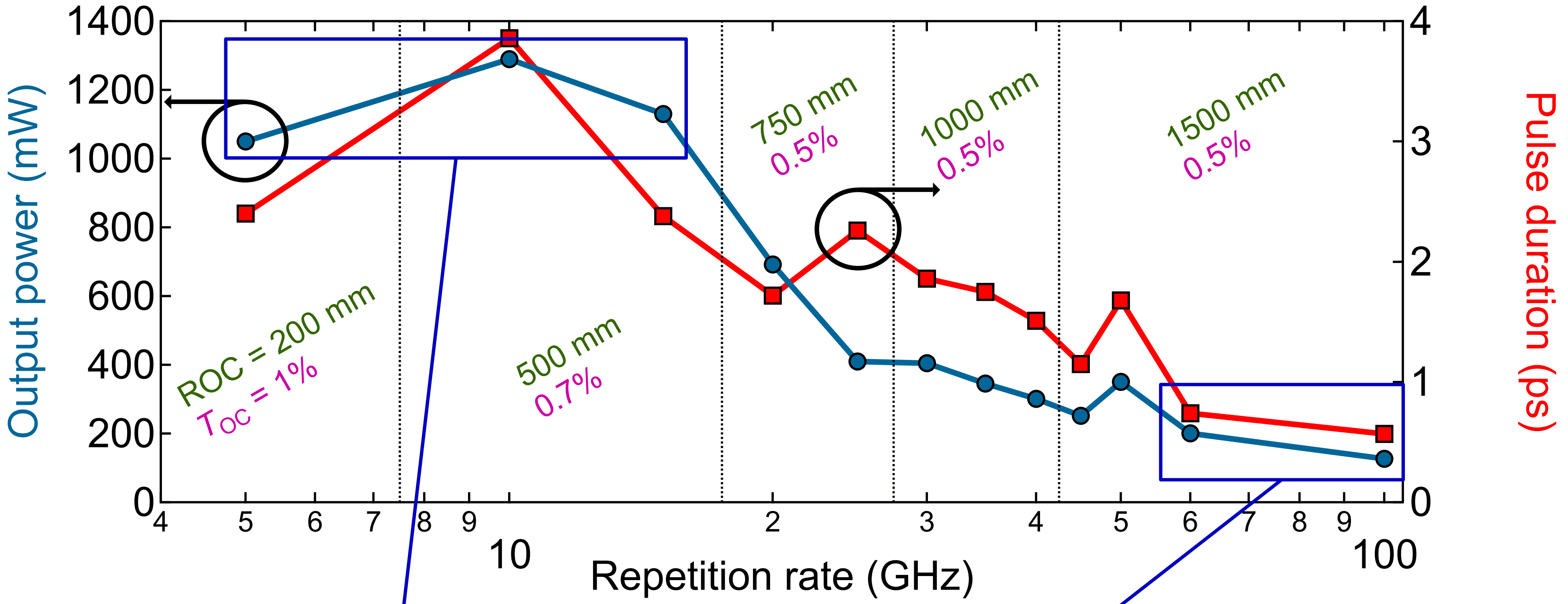


- Optical pumping **24.9 W** at **808 nm**
- Heat sink temperature: **+ 11 ° C**
- Output coupling: **0.35 % (ROC 200 mm)**
- Beam quality: **$M^2 < 1.05$**

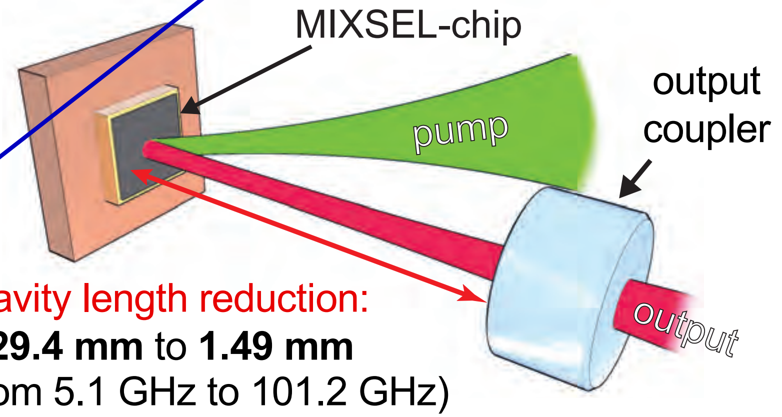
Shorter pulse duration enable scaling to higher repetition rates

M. Mangold et al., *Opt. Express* **21**, 24904 (2013)

Repetition-rate scaling of MIXSEL



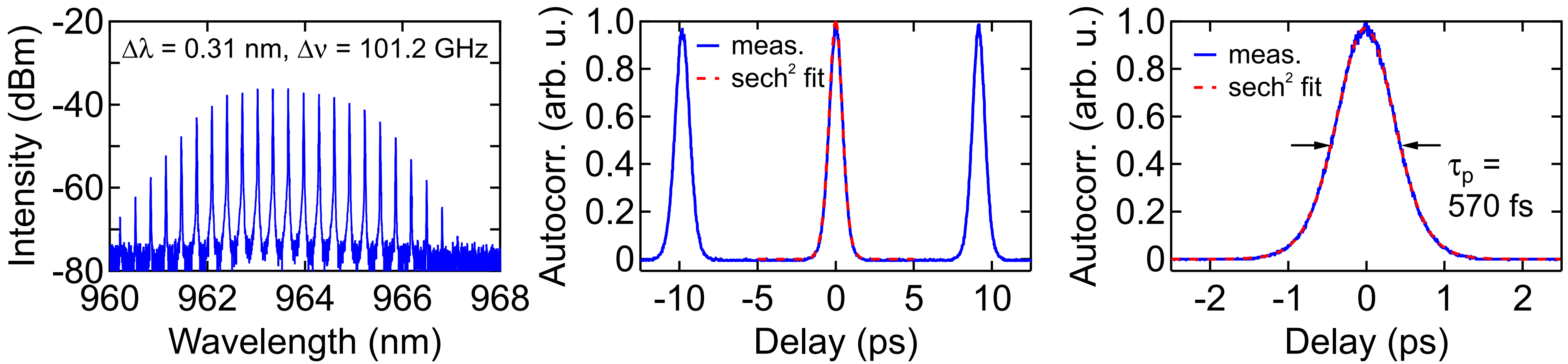
- Repetition rate-tuning from 5 GHz to 101 GHz with single MIXSEL structure
- Watt-level operation up to 15 GHz
- Femtosecond operation at 60 GHz and 101 GHz
- $M^2 < 1.1$ for all measurements



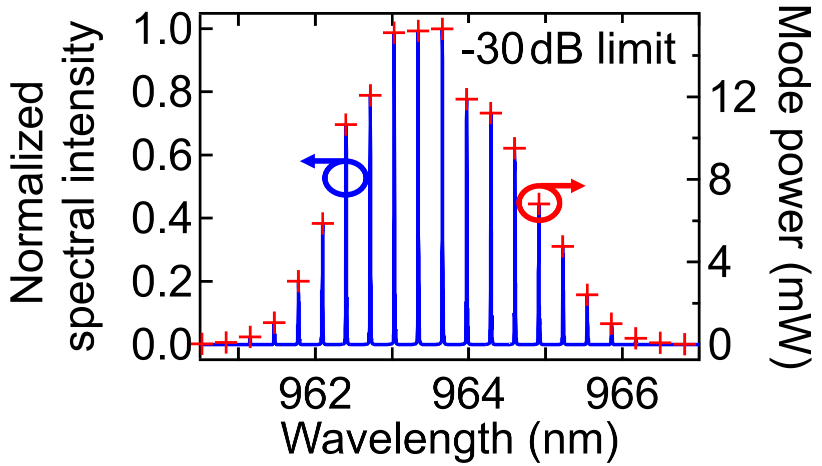
cavity length reduction:
29.4 mm to **1.49 mm**
(f_{rep} from 5.1 GHz to 101.2 GHz)

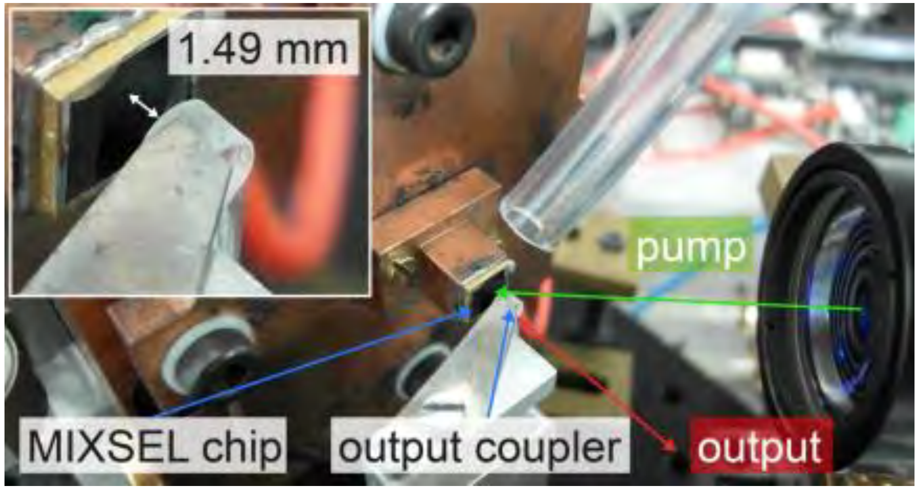
M. Mangold et al., *Opt. Express* **22**, pp. 6099 (2014)

Femtosecond 100-GHz MIXSEL



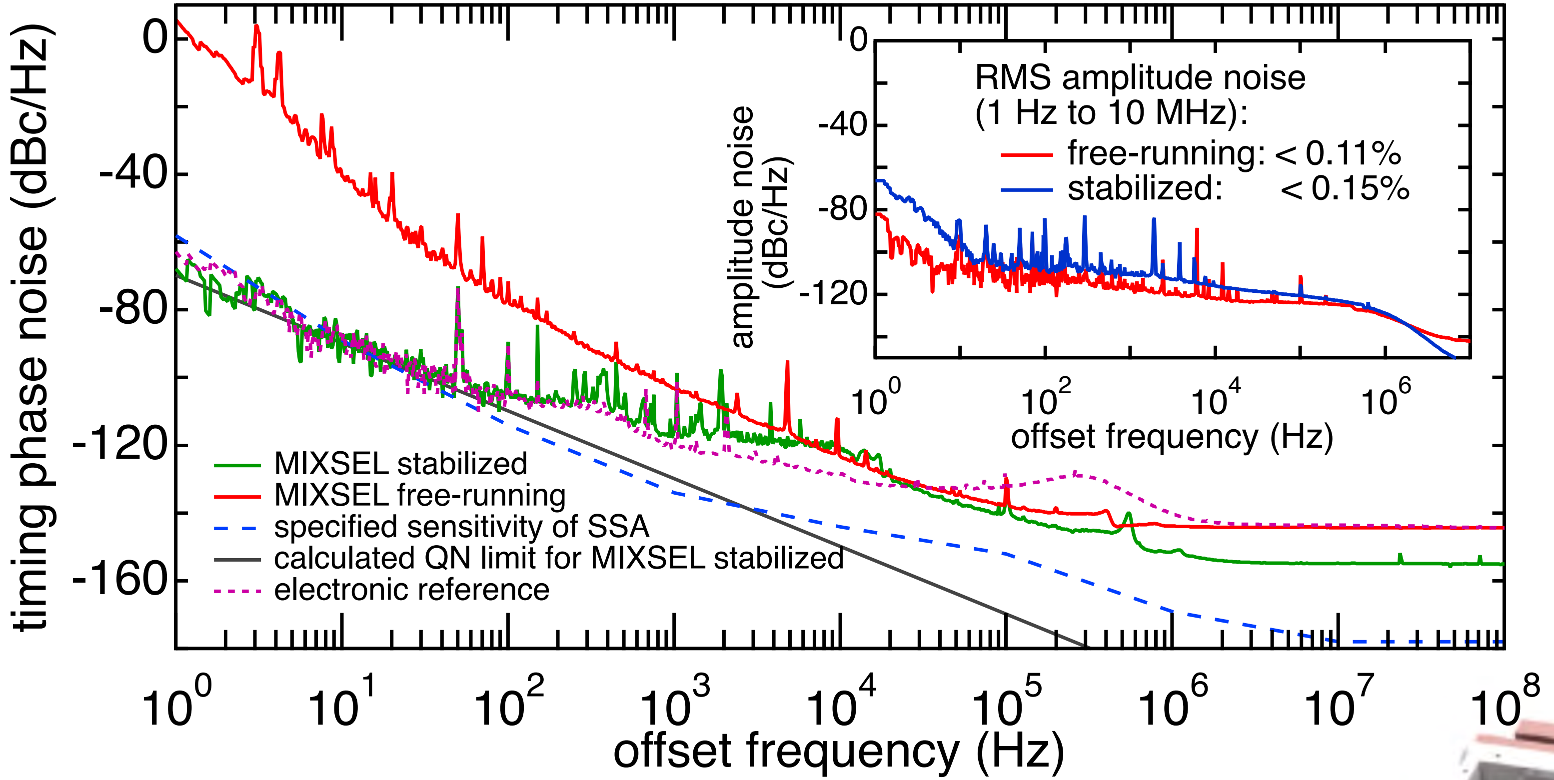
Pulse duration:	**570 fs**
Average output power:	**127 mW**
Repetition rate:	**101.2 GHz**
Av. mode power (-30 dB):	**7.5 mW**





M. Mangold et al., *Opt. Express* **22**, pp. 6099 (2014)

Picosecond MIXSEL noise characterization

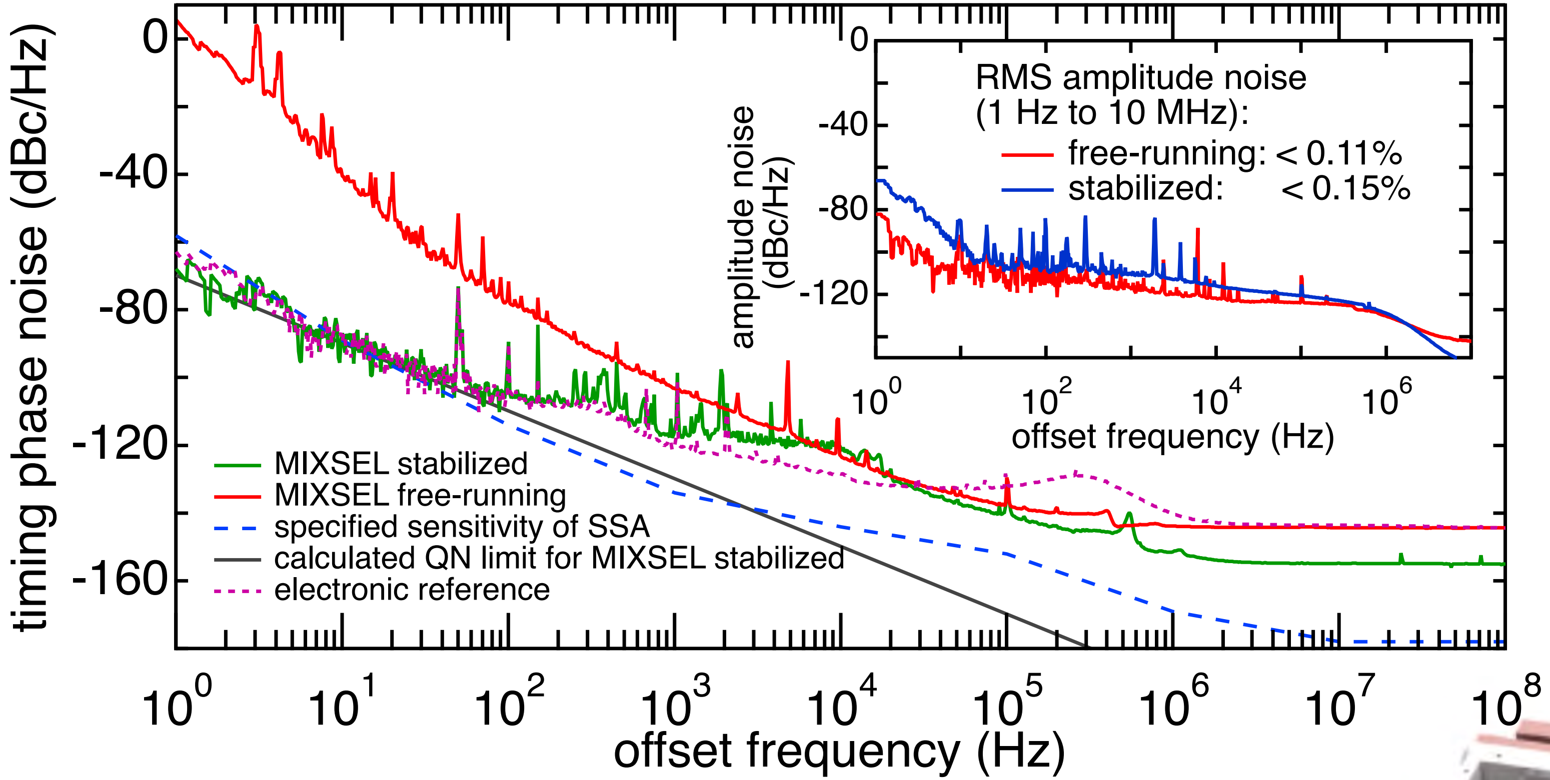


MIXSEL: >645 mW output power, 14.3 ps pulses, 2 GHz pulse reprate

- **127 fs** timing jitter – free-running [100 Hz, 100 MHz]
- **31 fs** timing jitter – stabilized [100 Hz, 100 MHz]
- **< 0.15%** amplitude noise [1 Hz, 10 MHz]

M. Mangold, S. M. Link, A. Klenner, C. A. Zaugg, M. Golling, B. W. Tilma, U. Keller, *IEEE Photonics Journal* **6**, 1500309 (2014)

Picosecond MIXSEL noise characterization

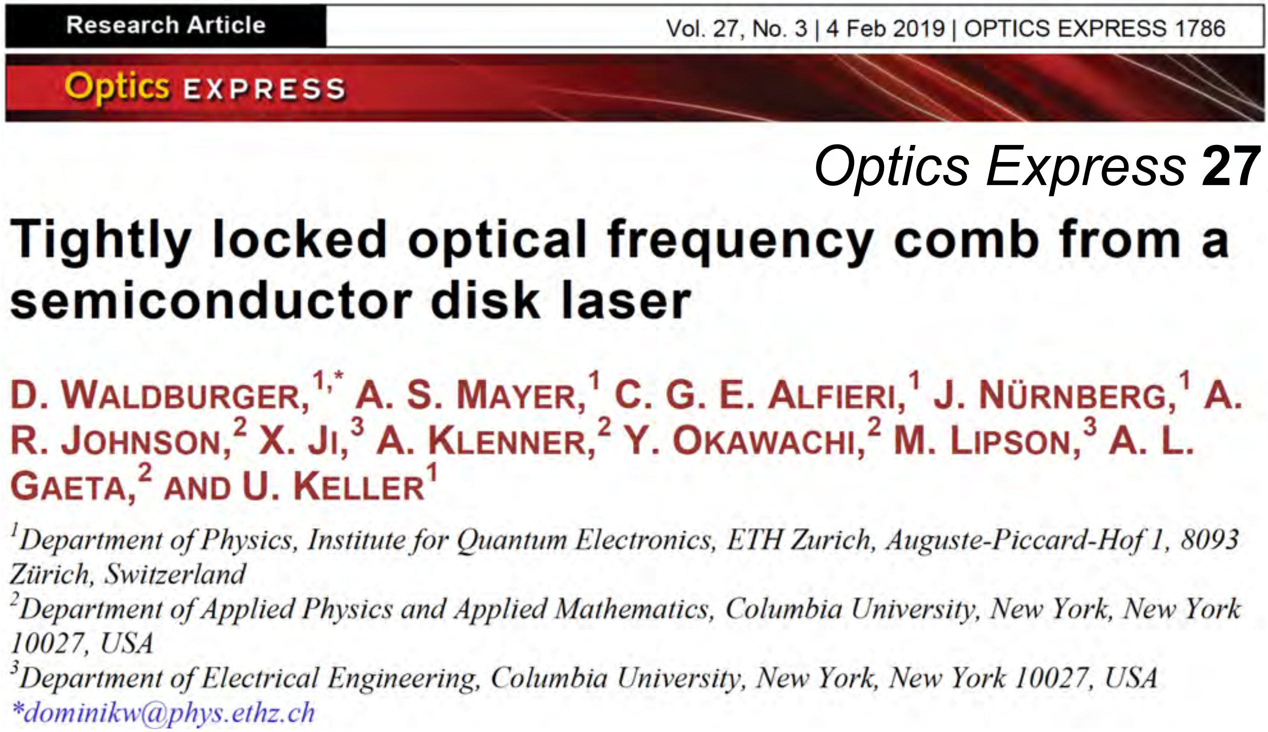


MIXSEL: >645 mW output power, 14.3 ps pulses, 2 GHz pulse reprate

- **127 fs** timing jitter – **free-running integrated over [100 Hz, 100 MHz]**
- Pulse repetition rate 2 GHz -> 0.5 ns between the pulses = 1/ (2 GHz)
- 127 fs / 0.5 ns **≈ 2.5 10^{-4} comb line spacing variations, integrated over 1/ (100 Hz) = 10 ms!**

M. Mangold, S. M. Link, A. Klenner, C. A. Zaugg, M. Golling, B. W. Tilma, U. Keller,
IEEE Photonics Journal **6**, 1500309 (2014)

Motivation for further pulse shortening



Research Article Vol. 27, No. 3 | 4 Feb 2019 | OPTICS EXPRESS 1786

Optics EXPRESS

Optics Express **27**, 1786 (2019)

Tightly locked optical frequency comb from a semiconductor disk laser

D. Waldburger,[1,*] A. S. Mayer,[1] C. G. E. Alfieri,[1] J. Nürnberg,[1] A. R. Johnson,[2] X. Ji,[3] A. Klenner,[2] Y. Okawachi,[2] M. Lipson,[3] A. L. Gaeta,[2] and U. Keller[1]

[1] *Department of Physics, Institute for Quantum Electronics, ETH Zurich, Auguste-Piccard-Hof 1, 8093 Zürich, Switzerland*

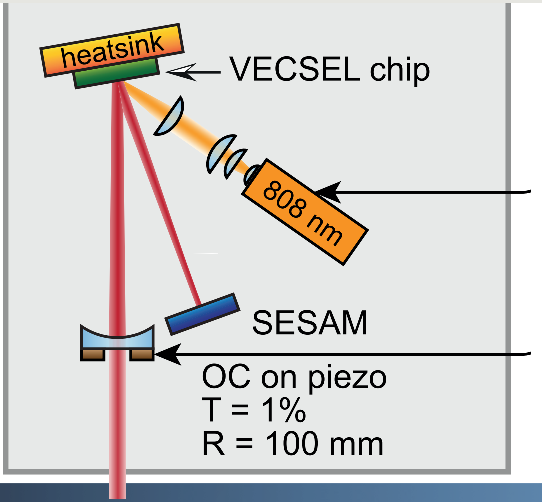
[2] *Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York 10027, USA*

[3] *Department of Electrical Engineering, Columbia University, New York, New York 10027, USA*

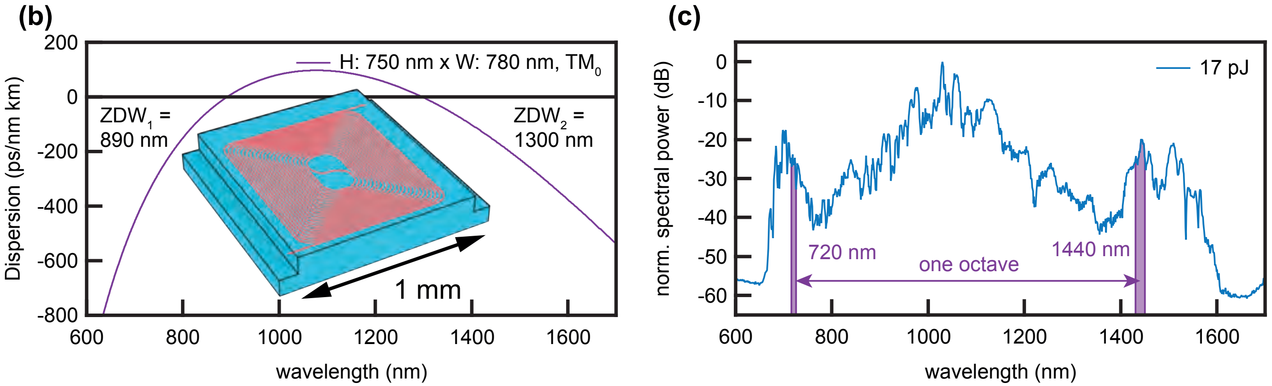
**dominikw@phys.ethz.ch*

Dominik Waldburger

122-fs pulses &160-mW



No additional amplification and pulse compression with Silicon nitride waveguide



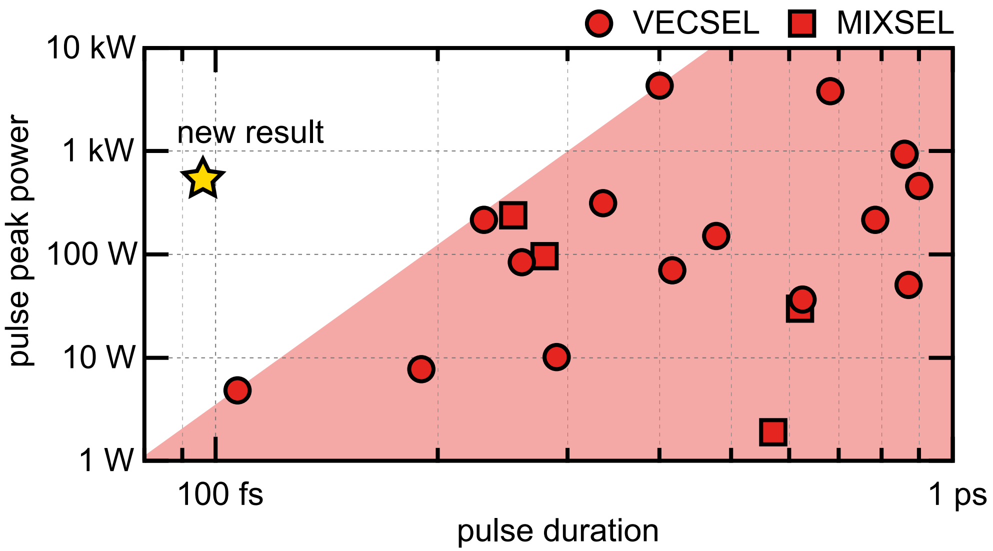
Outline

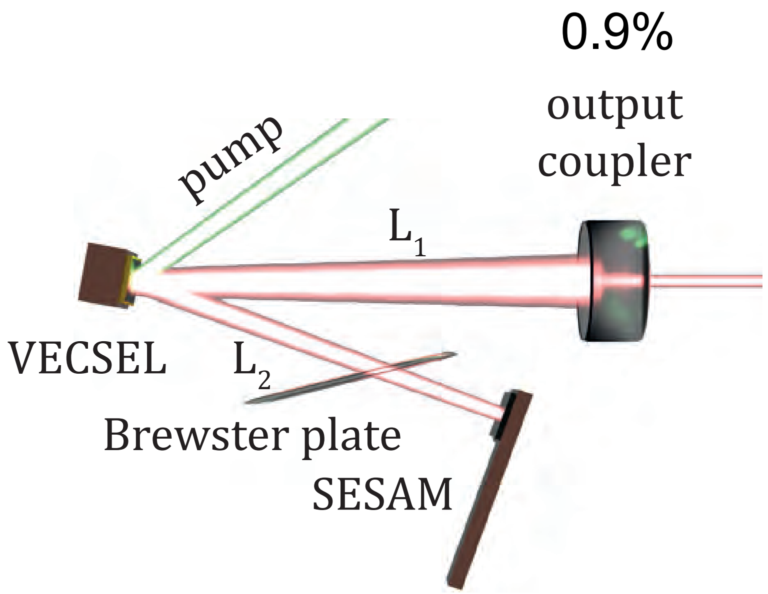
1. **Introduction to ultrafast semiconductor disk lasers**
2. **SESAM-modelocked VECSELs**
3. **MIXSEL**
4. **100-fs VECSEL**
5. **139-fs MIXSEL**
6. **Outlook**

World-record 100-fs 100-mW 1.63-GHz VECSEL

FIRST
Center for Micro- and Nanoscience

Pulse duration vs Power in near infrared (NIR)






Dominik
Waldburger


Dr. Matthias
Golling

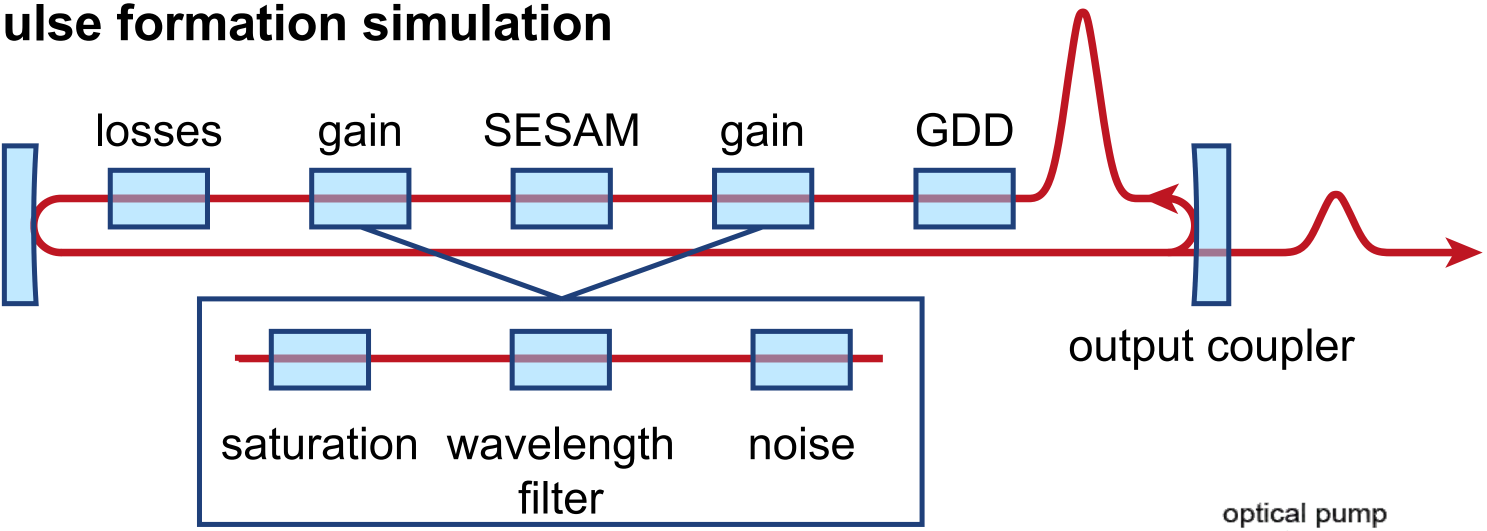
QW-SESAM (single InGaAs)
LT (260 degrees) MBE grown in AlAs barriers
recovery times 560 fs/5.5 ps
SiN_x top coating for field enhancement 2
4.3 μJ/cm^2, $\Delta R = 2\%$

D. Waldburger, S. M. Link, M. Mangold, C. G. E. Alfieri, E. Gini, **M. Golling**, B. W. Tilma, U. Keller, Optica **3**, 844–852 (2016)

Pulse shortening strategies

Oliver
Sieber

Pulse formation simulation



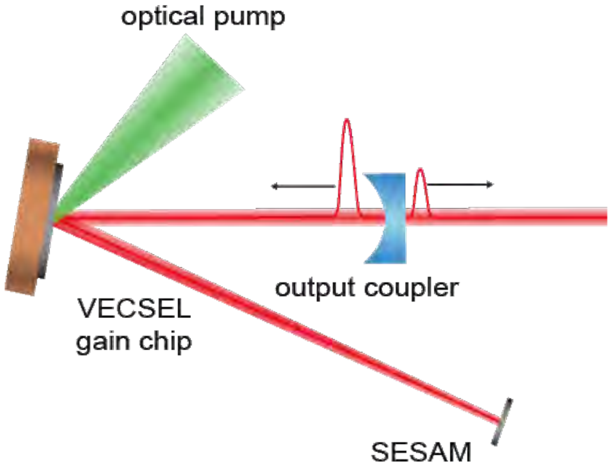
losses gain SESAM gain GDD

output coupler

saturation wavelength filter noise

Guidelines

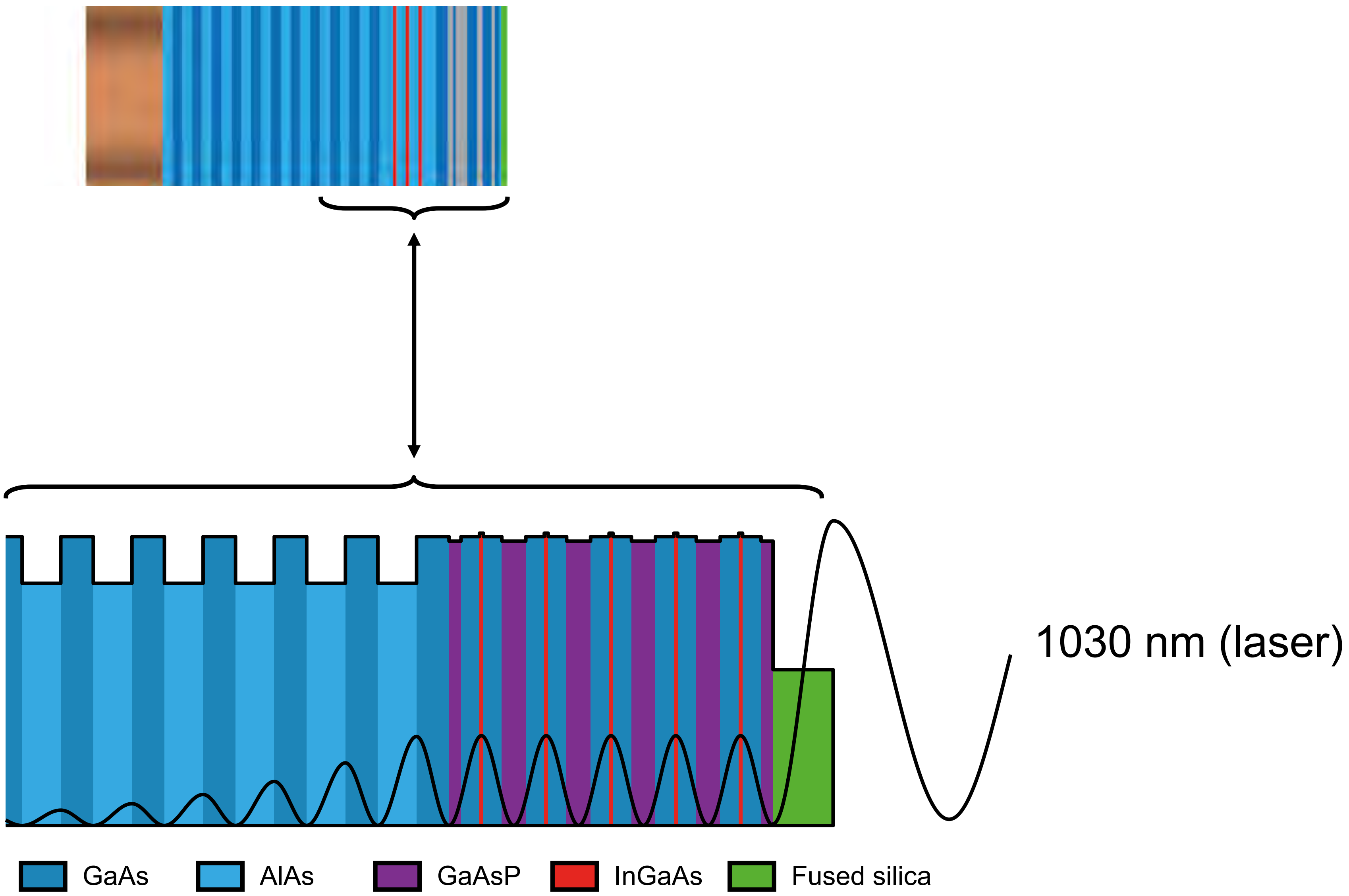
- Broad gain bandwidth
- High gain saturation fluence
- Flat & zero group delay dispersion (GDD)



O. D. Sieber, M. Hoffmann, V. J. Wittwer, M. Mangold, M. Golling, B. W. Tilma, T. Südmeyer, U. Keller, *Appl. Phys.* B **113**, 133-145 (2013)

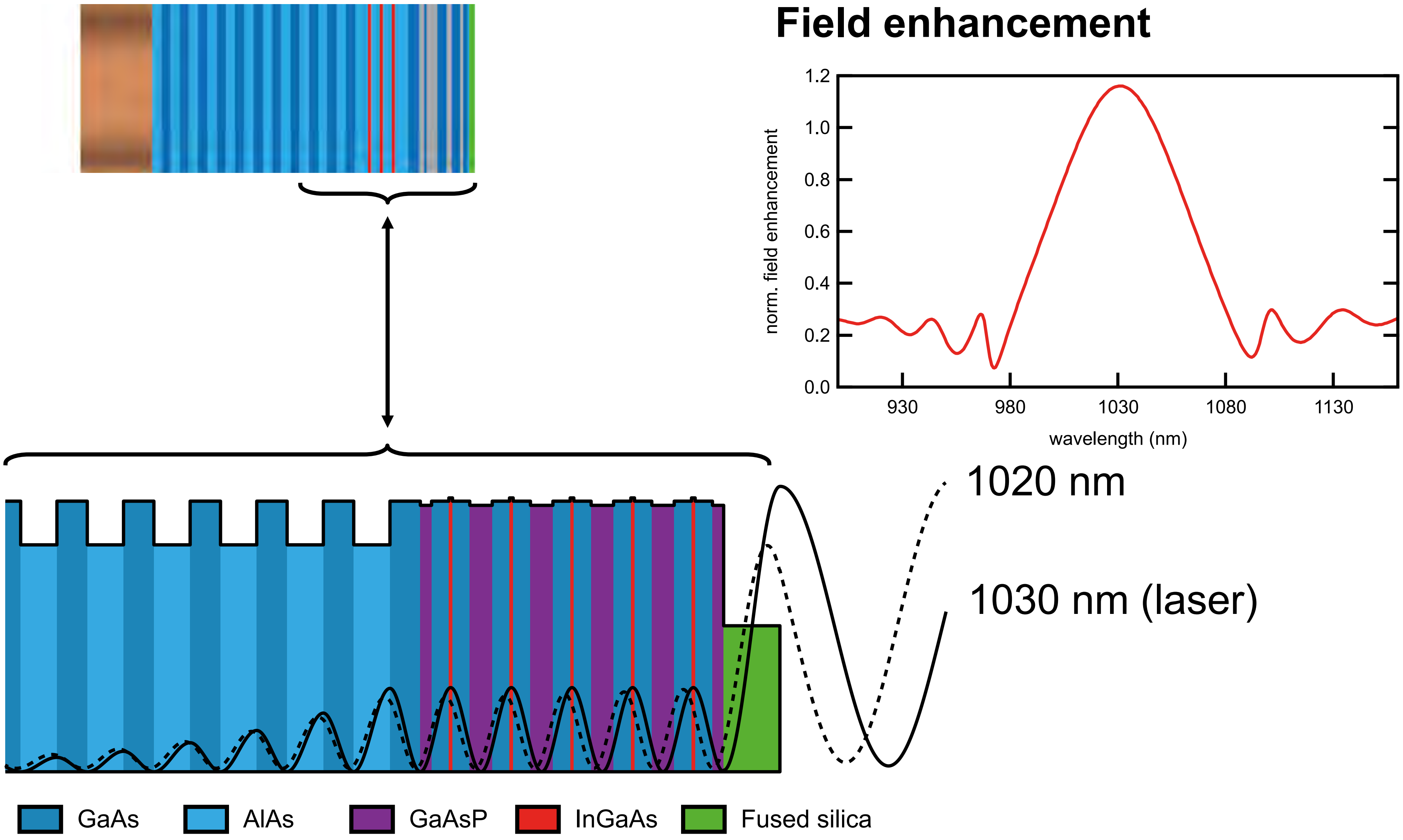
InGaAs quantum well position in VECSEL chip

D. Waldburger et al., *Optica* **3**, 844–852 (2016)



InGaAs quantum well position in VECSEL chip

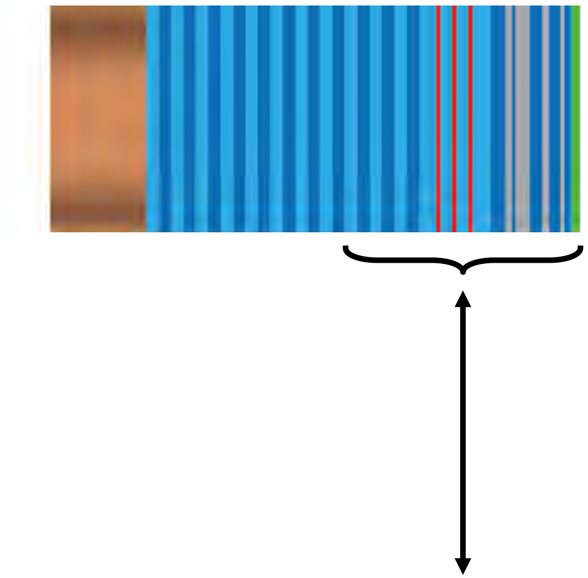
D. Waldburger et al., *Optica* **3**, 844–852 (2016)

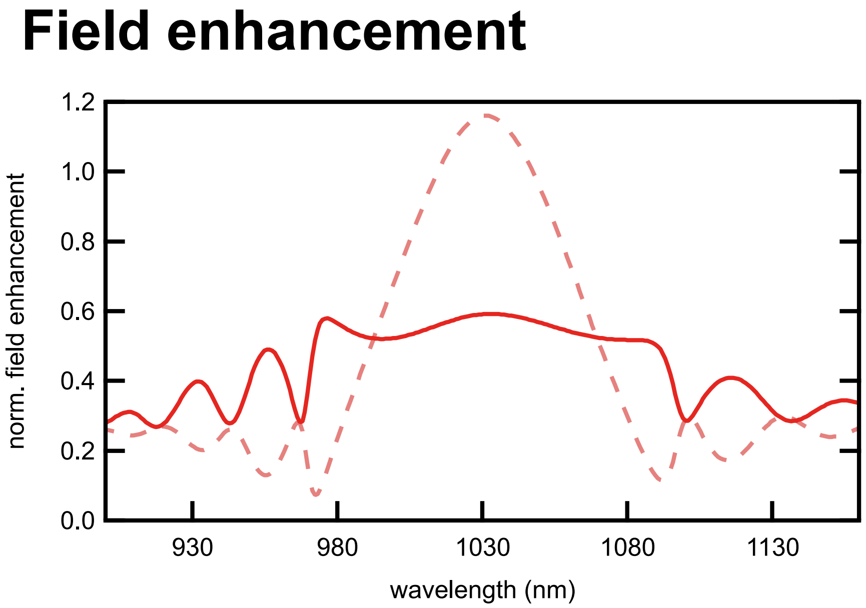


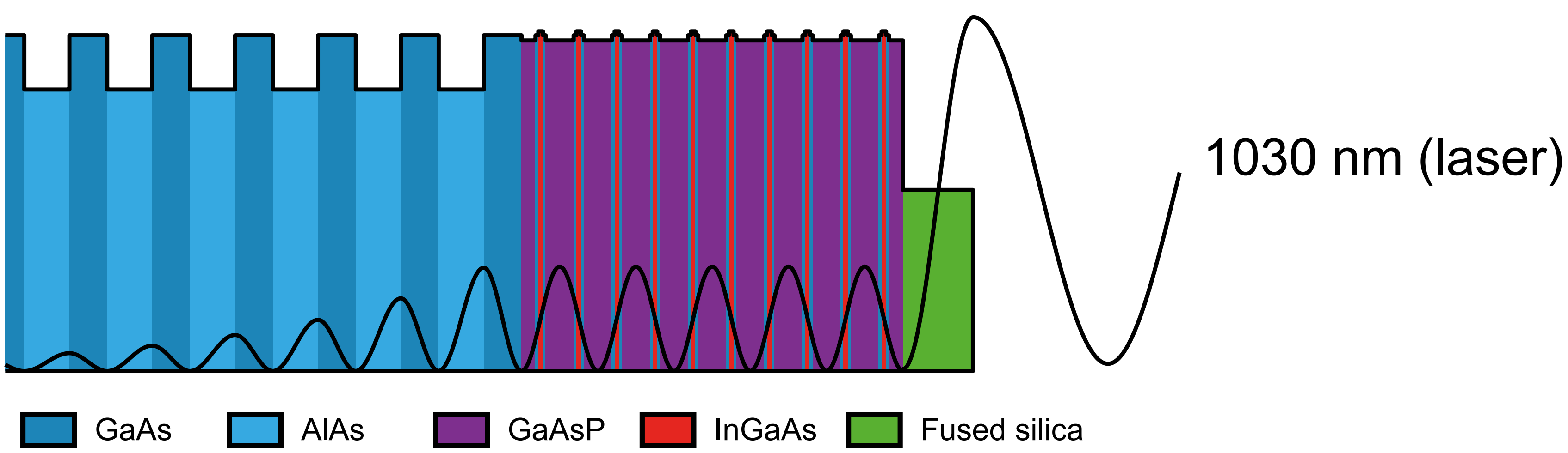
Field enhancement

InGaAs quantum well position in VECSEL chip

D. Waldburger et al., *Optica* **3**, 844–852 (2016)




Field enhancement



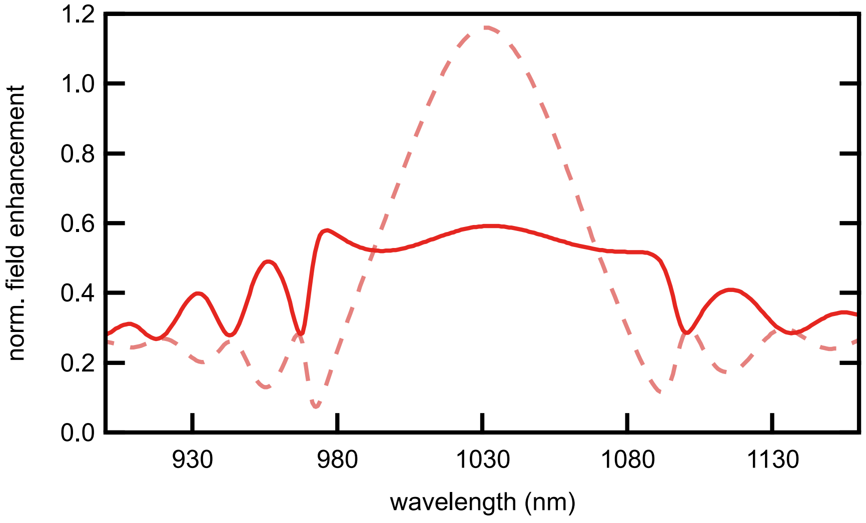
InGaAs quantum well position in VECSEL chip

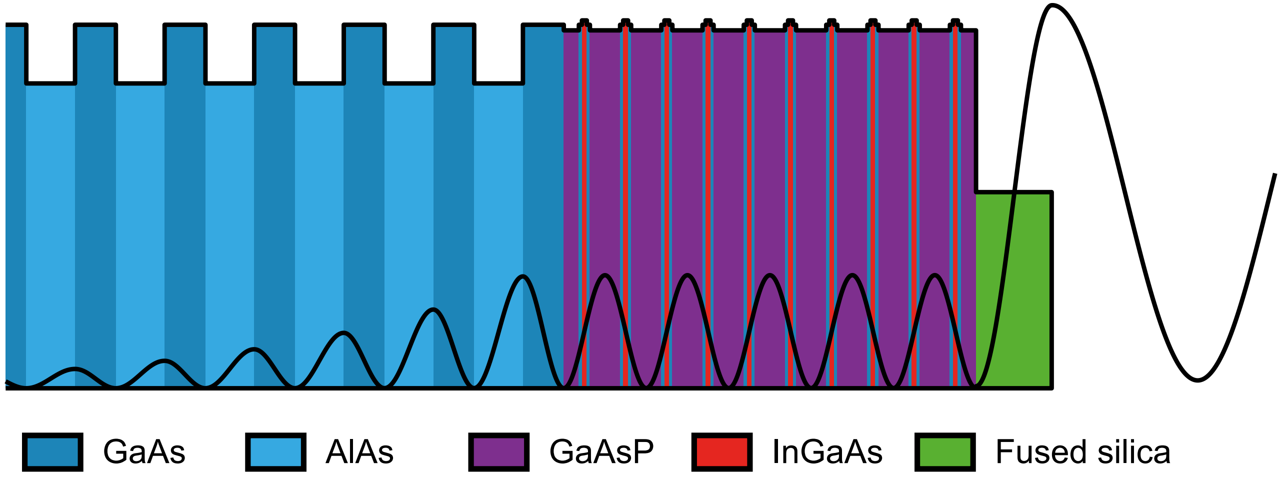
D. Waldburger et al., *Optica* **3**, 844–852 (2016)

Pulse formation simulation

- ✓ Broad gain bandwidth
- ✓ High gain saturation fluence
- ✗ Reduced overall gain

Field enhancement





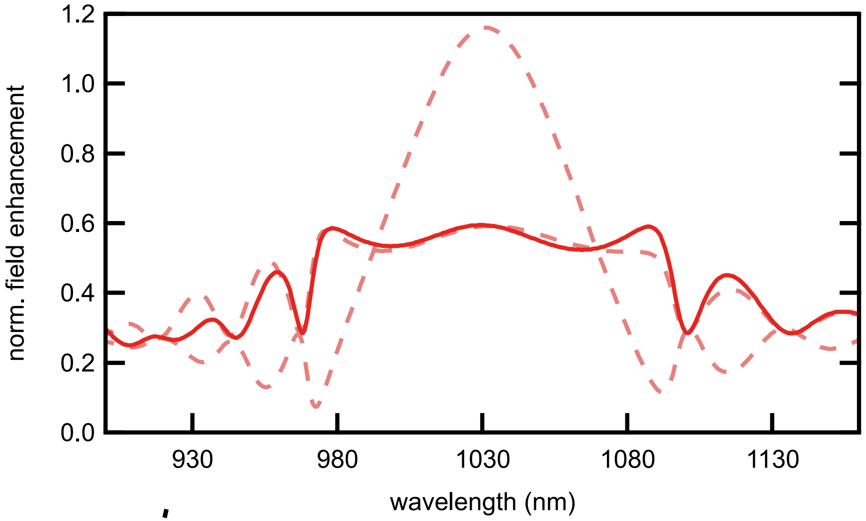
InGaAs quantum well position in VECSEL chip

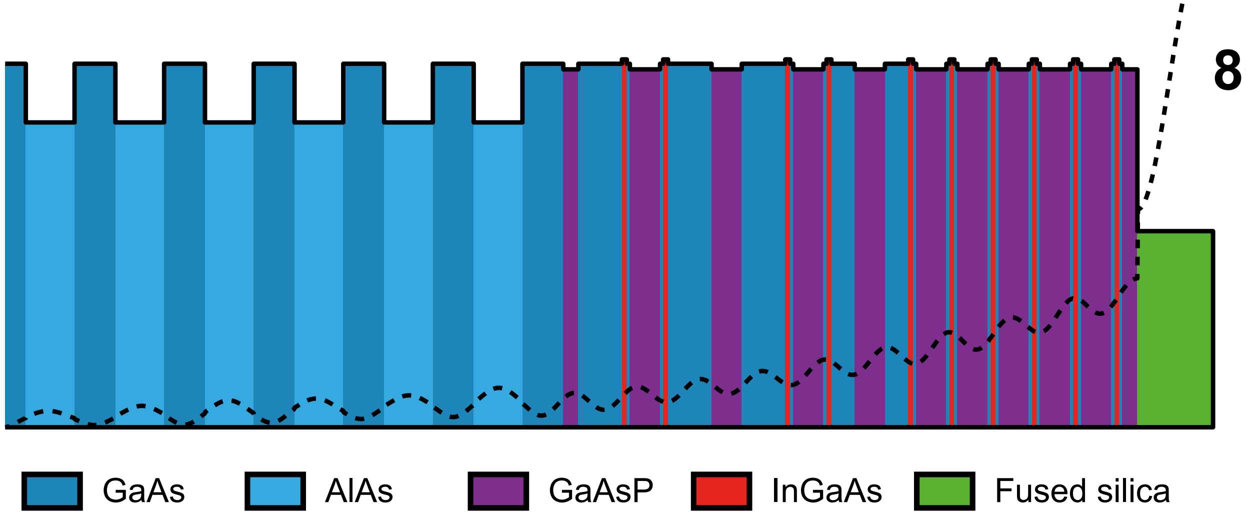
D. Waldburger et al., *Optica* **3**, 844–852 (2016)

Pulse formation simulation

- ✓ Broad gain bandwidth
- ✓ High gain saturation fluence
- ✗ Reduced overall gain
- ➢ **Optimize pump absorption**

Field enhancement

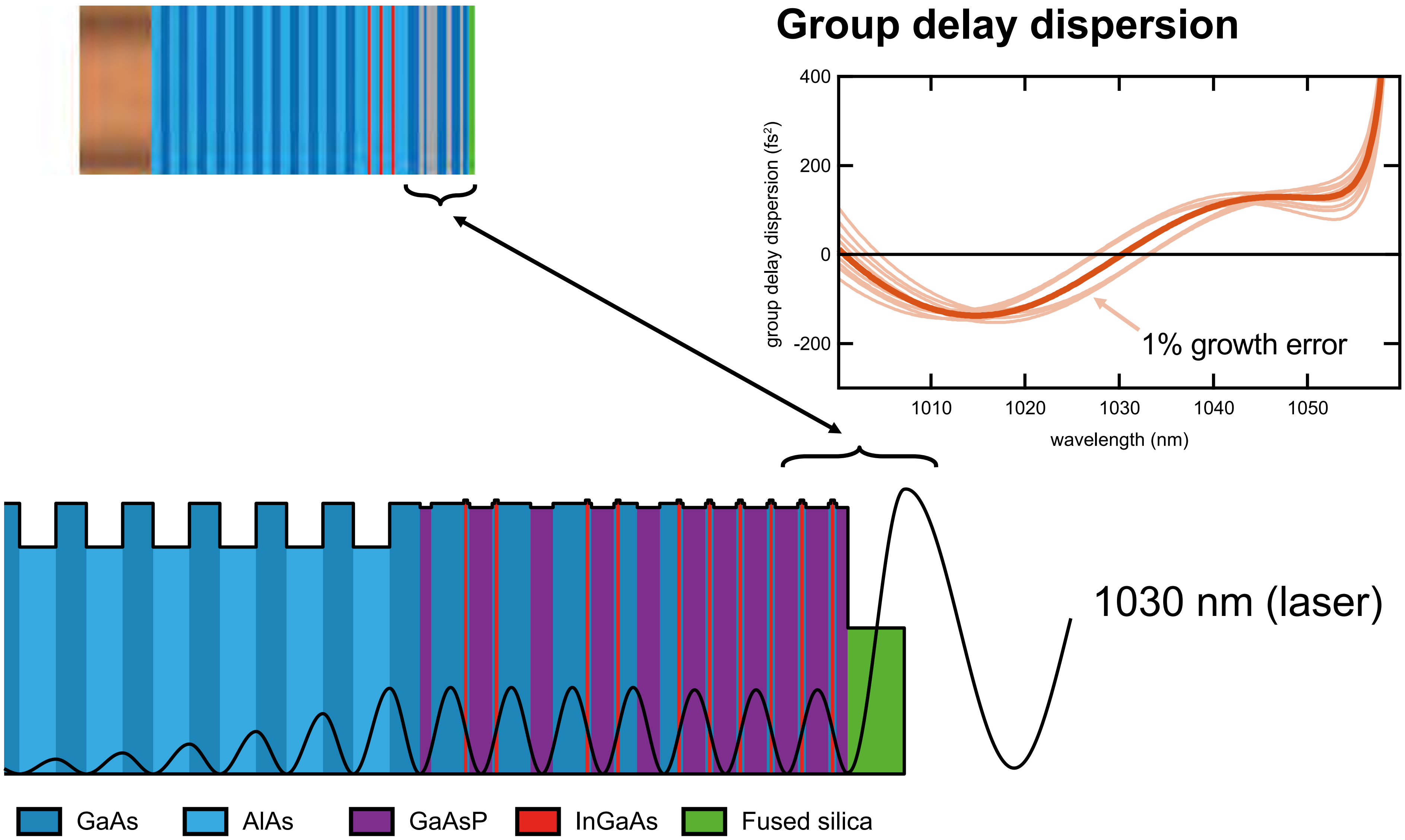




808 nm (pump)

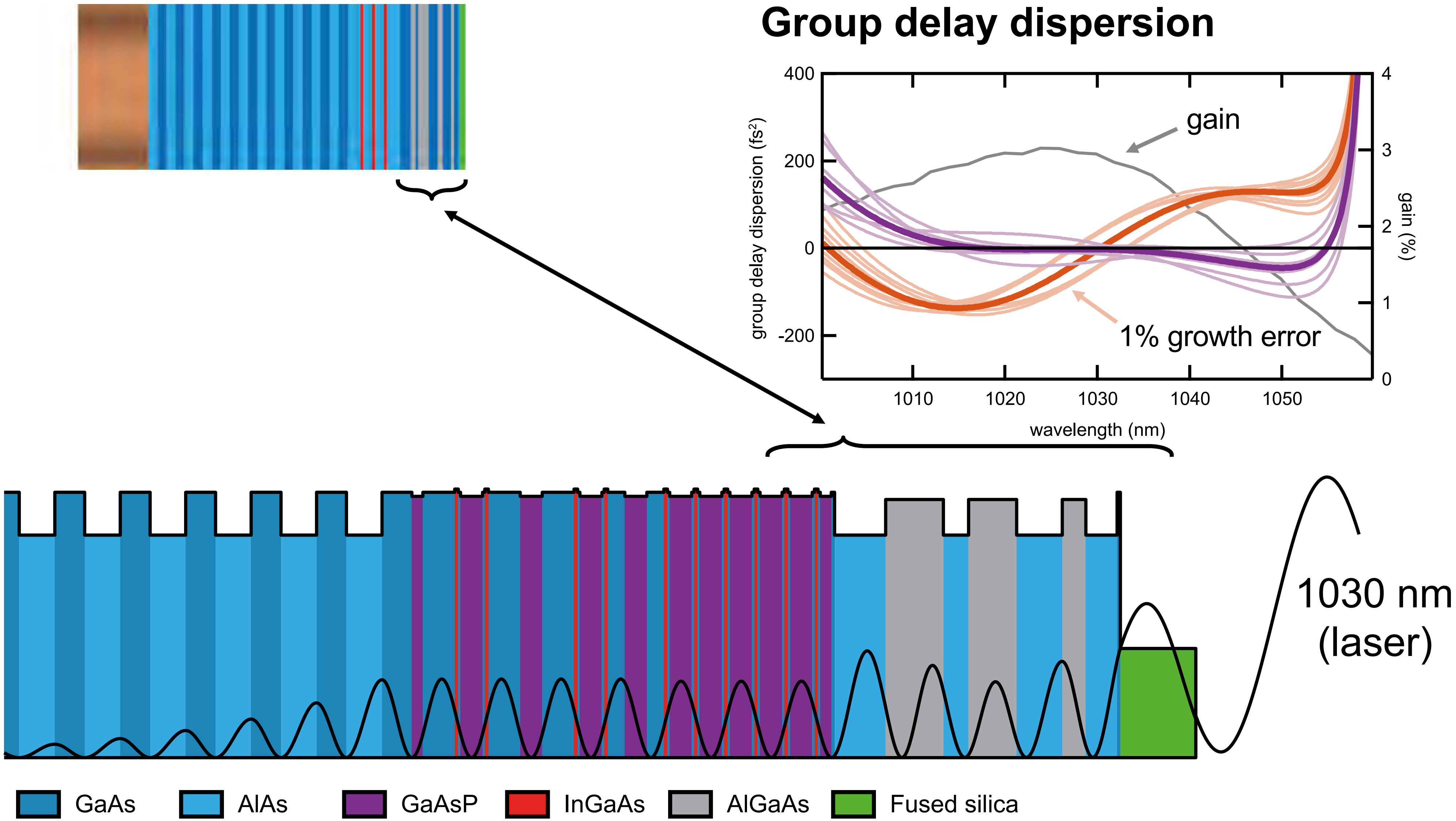
Anti-reflection coating

D. Waldburger et al., *Optica* **3**, 844–852 (2016)



Anti-reflection coating

D. Waldburger et al., *Optica* **3**, 844–852 (2016)



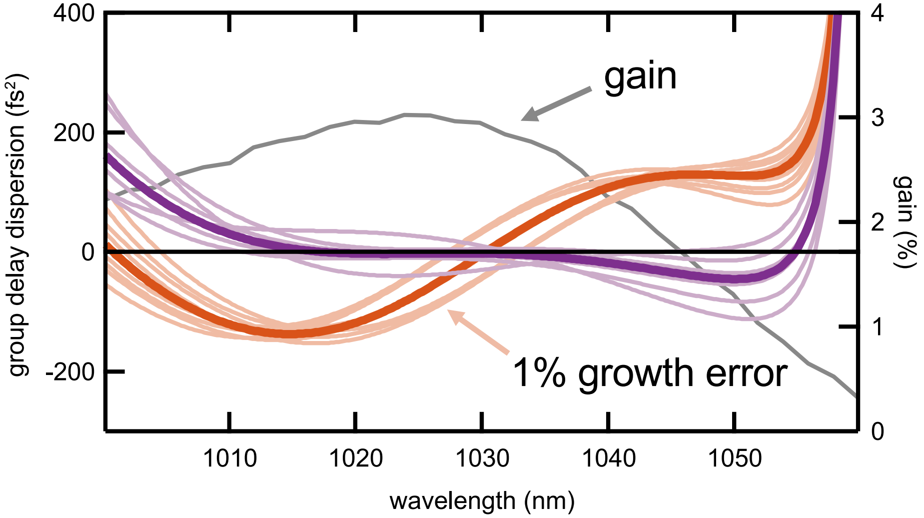
Anti-reflection coating

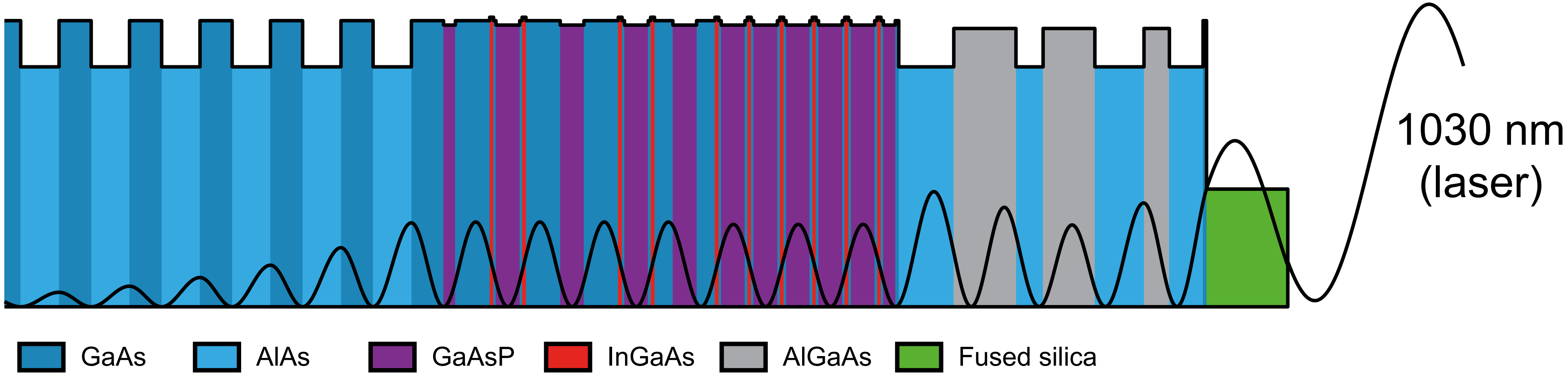
D. Waldburger et al., *Optica* **3**, 844–852 (2016)

Pulse formation simulation

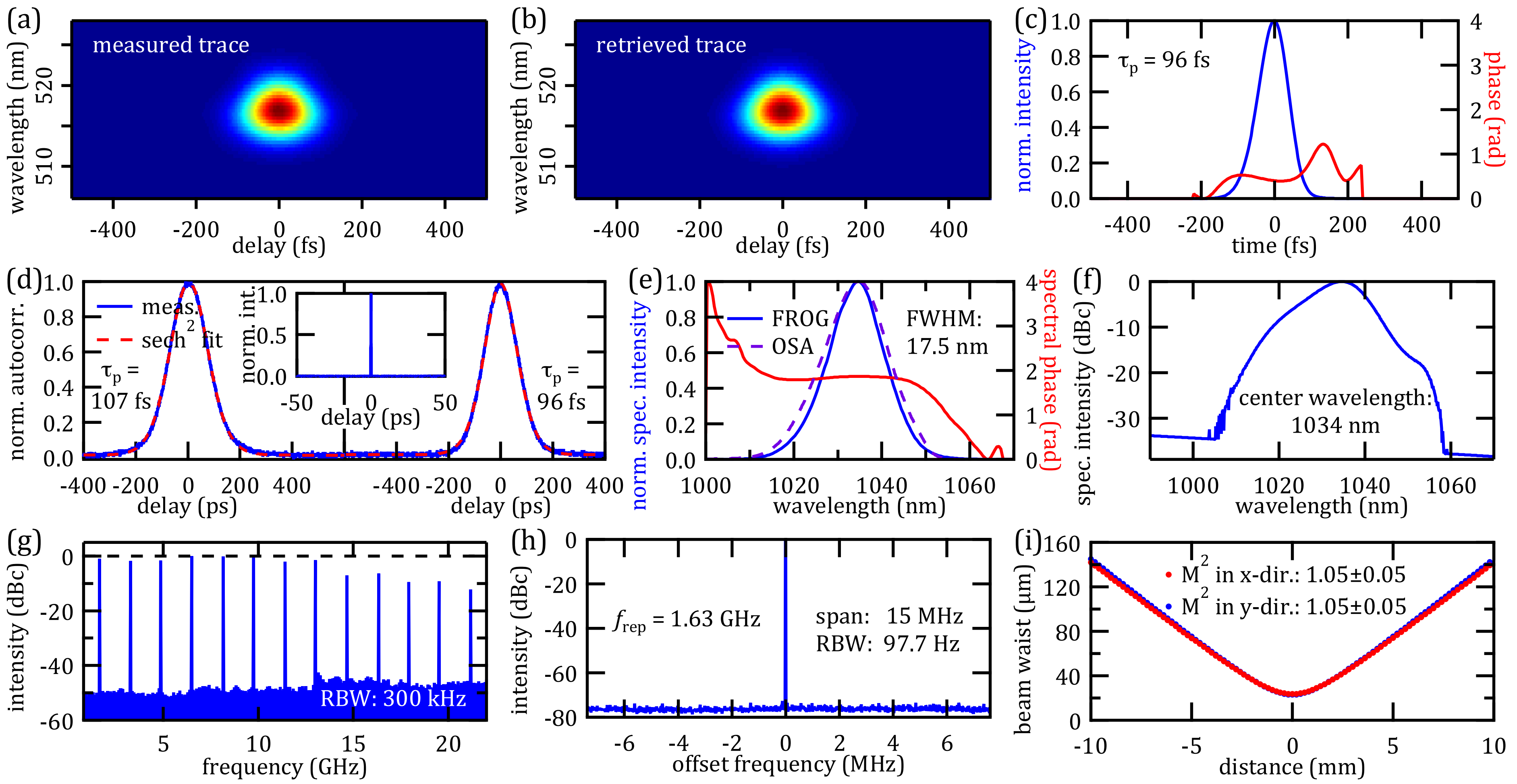
- ✓ Broad gain bandwidth
- ✓ High gain saturation fluence
- ✓ Flat & zero group delay dispersion
- ✗ Reduced overall gain

Group delay dispersion

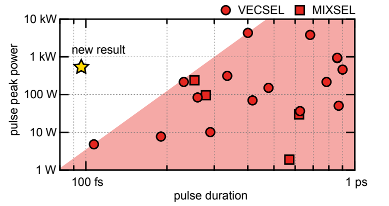




World-record 100-fs 100-mW 1.63-GHz VECSEL



Pulse duration	96 fs
Pulse repetition rate	1.63 GHz
Average power	100 mW
Pulse peak power	560 W



D. Waldburger et al., *Optica* **3**, 844–852 (2016)

Outline

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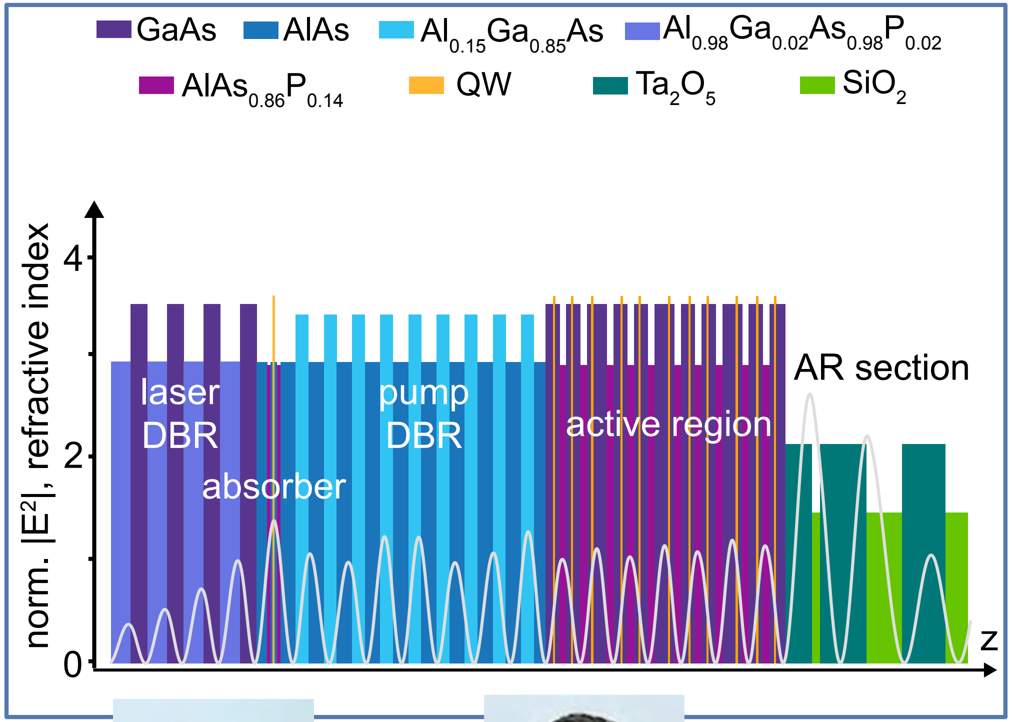
139-fs NIR MIXSEL at 1.034 µm center wavelength



Cesare
Alfieri

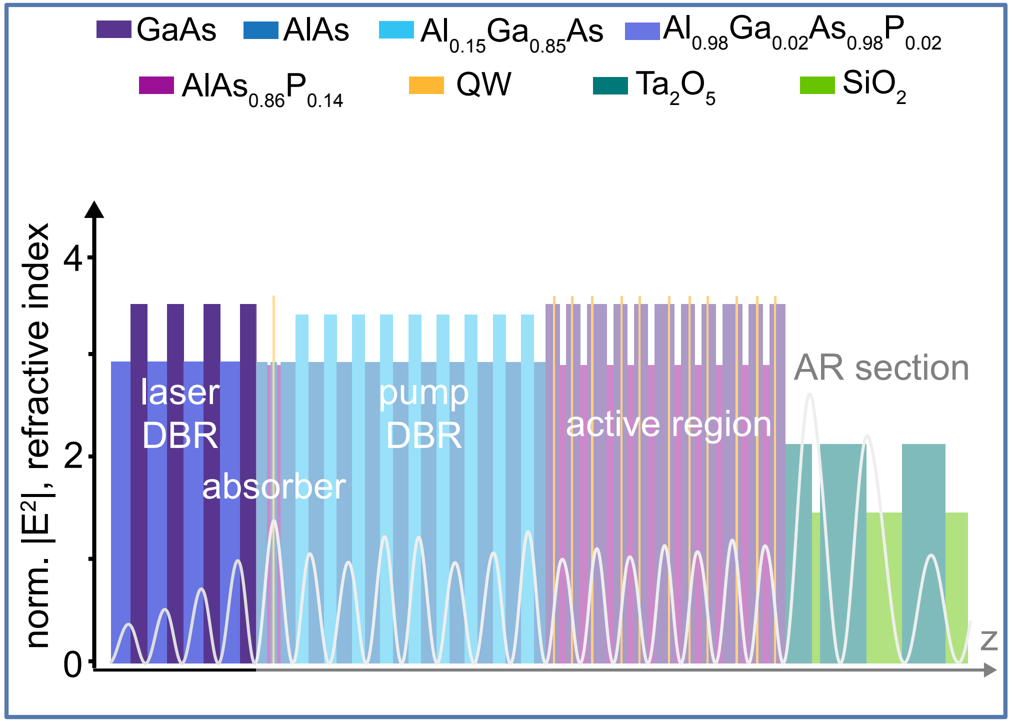
Dominik
Waldburger

C. G. E. Alfieri*, D. Waldburger*, J. Nürnberg, M. Golling, U. Keller,

“Sub-150-fs from a broadband MIXSEL”, *Opt. Letters* **44**, 25 (2019)

139-fs NIR MIXSEL

Opt. Letters **44**, 25 (2019)



Design novelties

⤇ **Quaternary GaAs/AlGaAsP DBR**

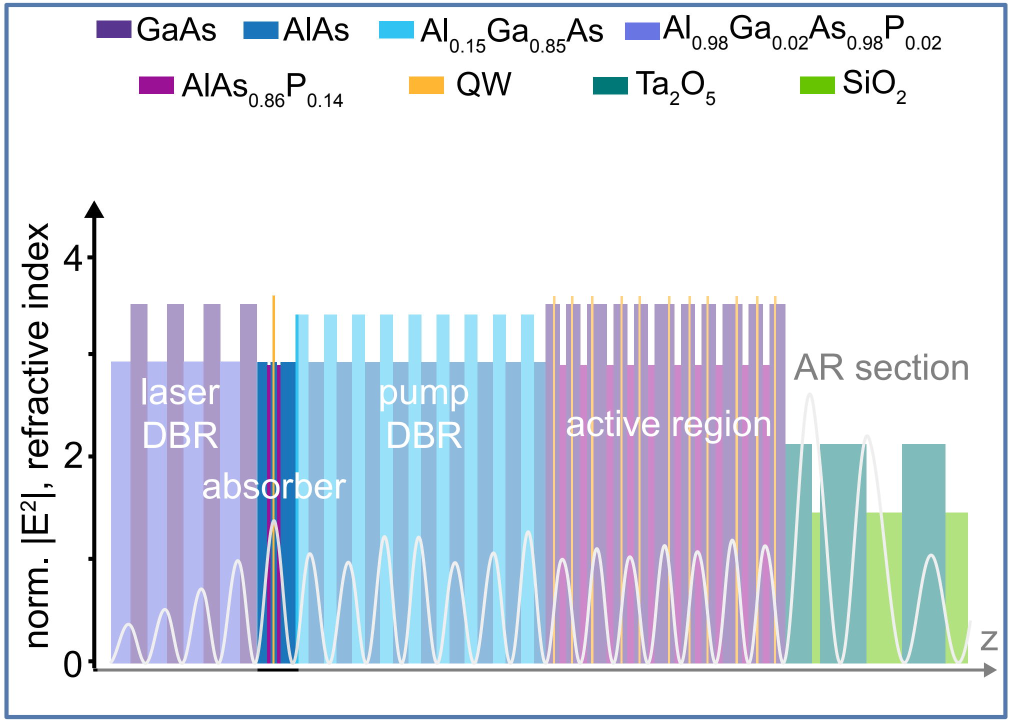
- ⤇ Ga to decrease oxidation
- ⤇ P for strain compensation

C. G. E. Alfieri*, D. Waldburger*, J. Nürnberg, M. Golling, U. Keller,

"Sub-150-fs from a broadband MIXSEL", *Opt. Letters* **44**, 25 (2019)

139-fs NIR MIXSEL

Opt. Letters **44**, 25 (2019)



Design novelties

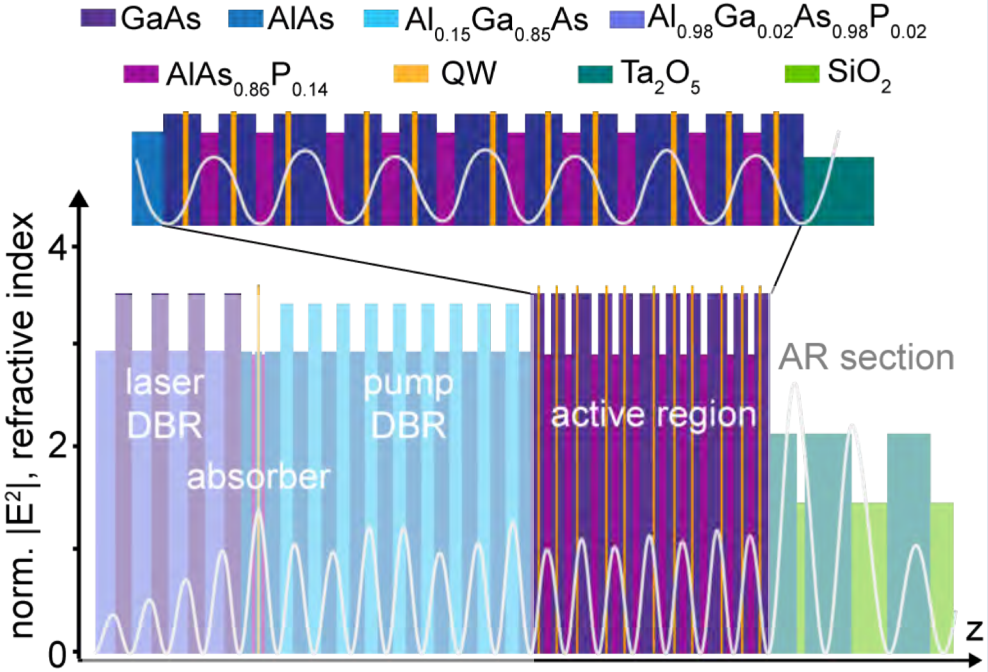
- ⤇ Quaternary GaAs/AlGaAsP DBR
  - ⤇ Ga to decrease oxidation
  - ⤇ P for strain compensation
- ⤇ **Strain-compensated absorber InGaAs QW in AlAsP/AlAs barriers**

C. G. E. Alfieri[*], D. Waldburger*, J. Nürnberg, M. Golling, U. Keller,

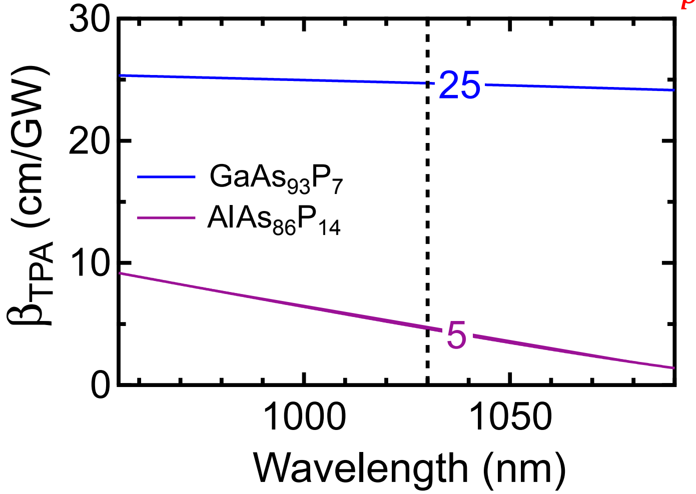
“Sub-150-fs from a broadband MIXSEL”, *Opt. Letters* **44**, 25 (2019)

139-fs NIR MIXSEL

Opt. Letters **44**, 25 (2019)



Two-photon absorption (TPA) losses $\propto \frac{\beta_{TPA}}{\tau_{pulse}}$ [1]



Design novelties

⤇ Quaternary GaAs/AlGaAsP DBR

  ⤇ Ga to decrease oxidation

  ⤇ P for strain compensation

⤇ Strain-compensated QW absorber

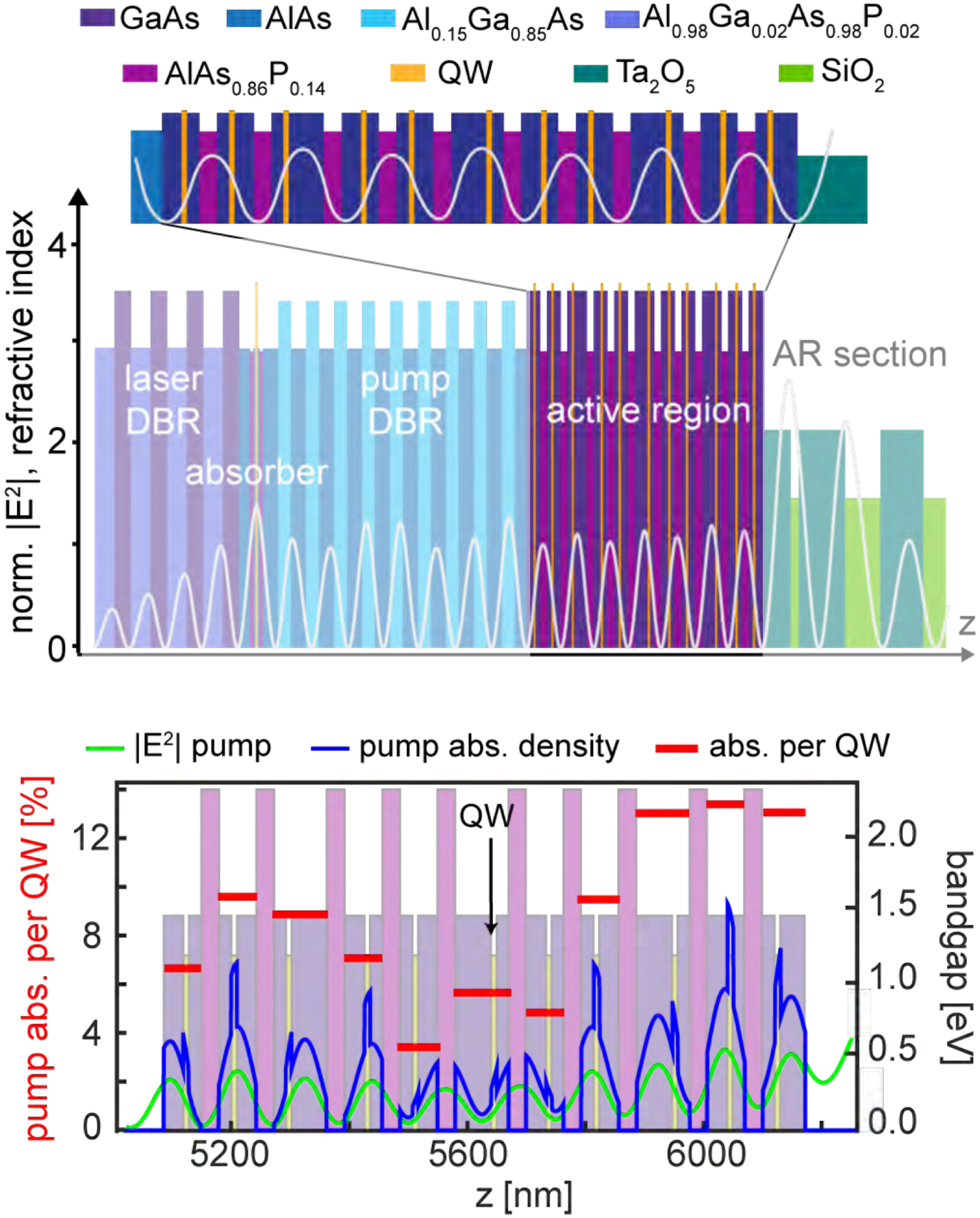
⤇ **Large-bandgap AlAsP strain-compensation for the active region:**

  ⤇ **Reduced TPA losses**

C. G. E. Alfieri, A. Diebold, F. Emaury, E. Gini, C. J. Saraceno, U. Keller.
Opt. Express **24**, 27587-27599 (2016)

Femtosecond MIXSEL

Opt. Letters **44**, 25 (2019)



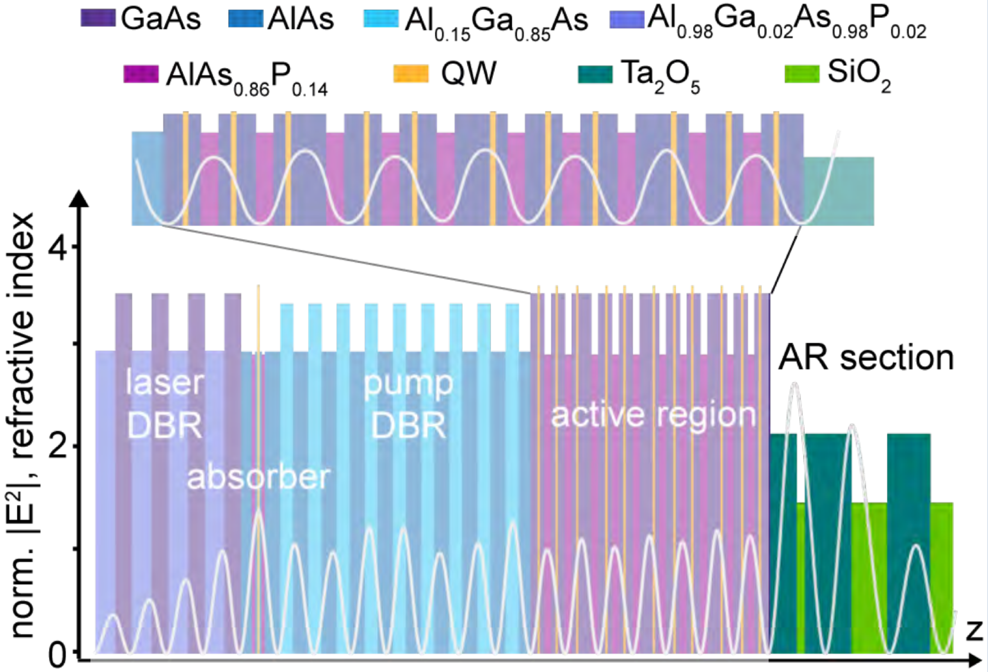
93% of pump absorption

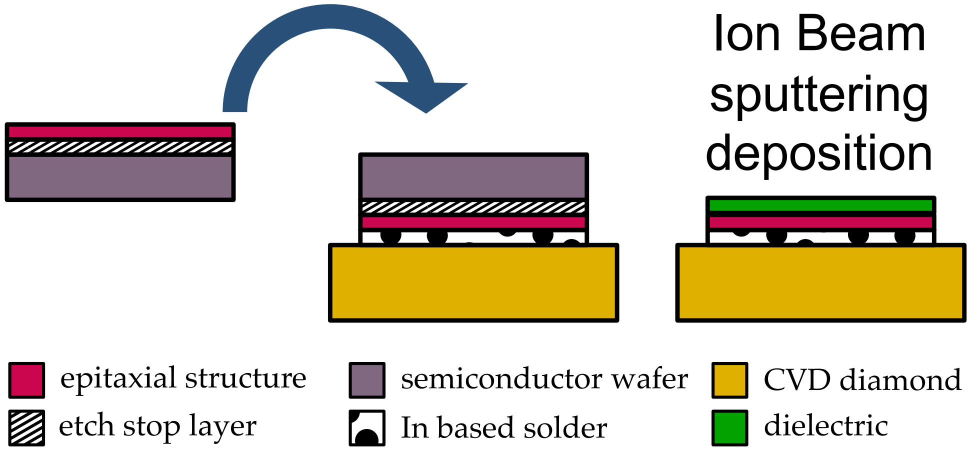
Design novelties

- ⤇ Quaternary GaAs/AlGaAsP DBR
  - ⤇ Ga to decrease oxidation
  - ⤇ P for strain compensation
- ⤇ Strain-compensated absorber
- ⤇ Large-bandgap AlAsP strain-compensation for the active region:
  - ⤇ Reduced TPA losses
  - ⤇ **Optimized pump absorption**
  - ⤇ **Better carrier confinement**
  - ⤇ **No spectral filtering**

Femtosecond MIXSEL

Opt. Letters **44**, 25 (2019)





Flip-chip bonding / substrate removal

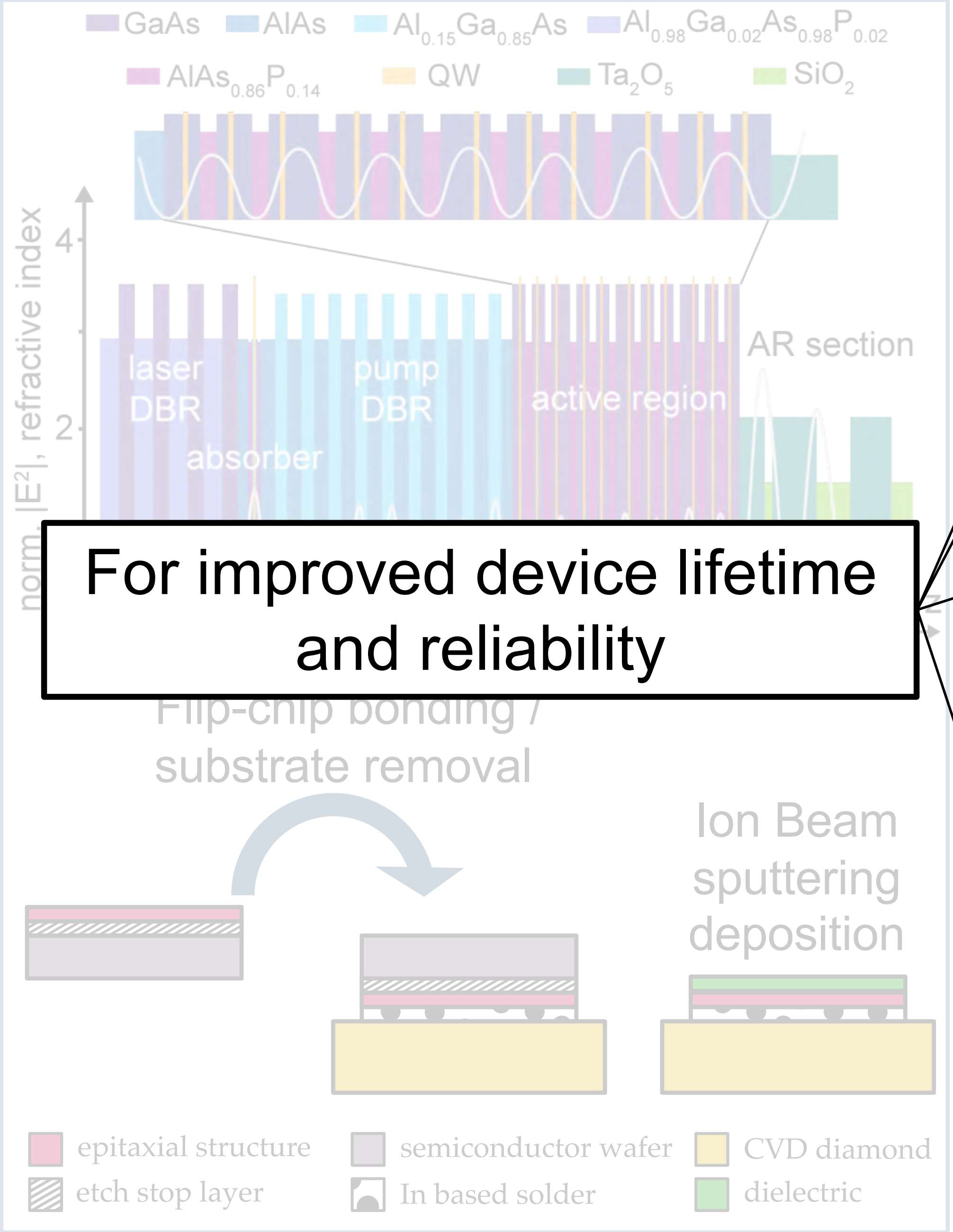
Ion Beam sputtering deposition

Design novelties

- ⤇ Quaternary GaAs/AlGaAsP DBR
  - ⤇ Ga to decrease oxidation
  - ⤇ P for strain compensation
- ⤇ Strain-compensated absorber
- ⤇ Large-bandgap AlAsP strain-compensation for the active region:
  - ⤇ Reduced TPA losses
  - ⤇ Optimized pump absorption
  - ⤇ Better carrier confinement
  - ⤇ No spectral filtering
- ⤇ **Dielectric IBS top coating:**
  - ⤇ Precise layer thickness
  - ⤇ Protection against oxidation
  - ⤇ Reduced TPA losses

Femtosecond MIXSEL

Opt. Letters **44**, 25 (2019)

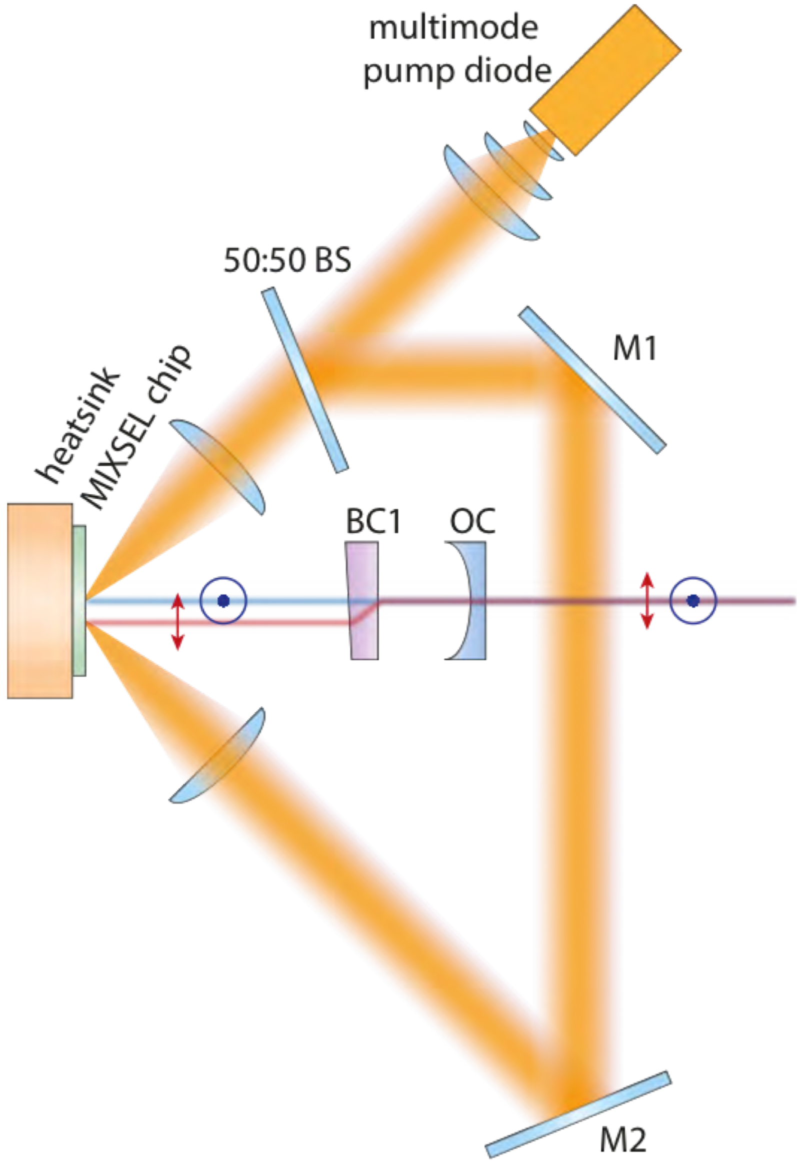


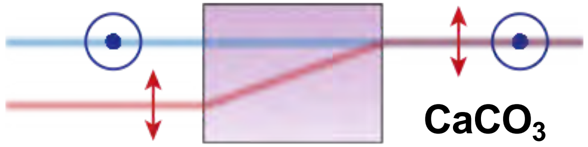
For improved device lifetime and reliability

Design novelties

- ⤇ Quaternary GaAs/AlGaAsP DBR
  - ⤇ Ga to decrease oxidation
  - ⤇ P for strain compensation
- ⤇ Strain-compensated absorber
- ⤇ Large-bandgap AlAsP strain-compensation for the active region:
  - ⤇ Reduced TPA losses
  - ⤇ Optimized pump absorption
  - ⤇ Better carrier confinement
  - ⤇ No spectral filtering
- ⤇ **Dielectric IBS top coating:**
  - ⤇ Precise layer thickness
  - ⤇ Protection against oxidation
  - ⤇ Reduced TPA losses

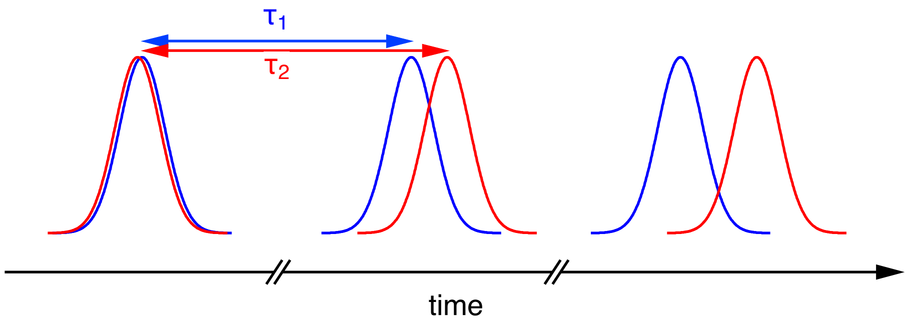
Motivation: Dual-Comb MIXSEL

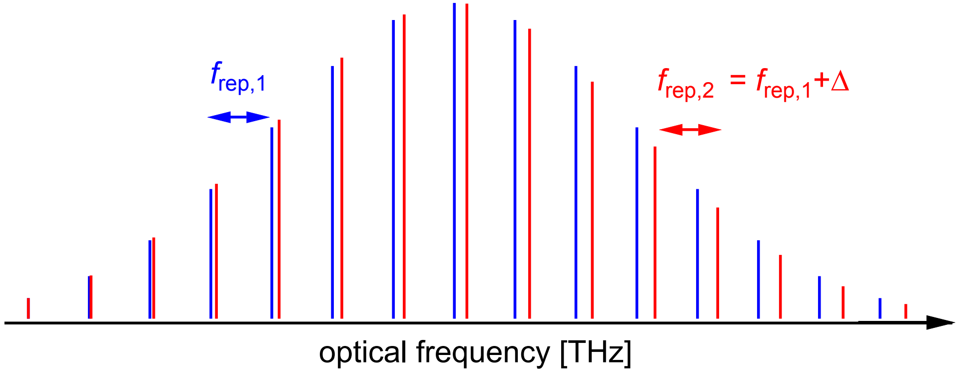




Intracavity birefringent crystal (BC)

- Two spatially separated beams
- Orthogonal polarizations
- Different optical path length

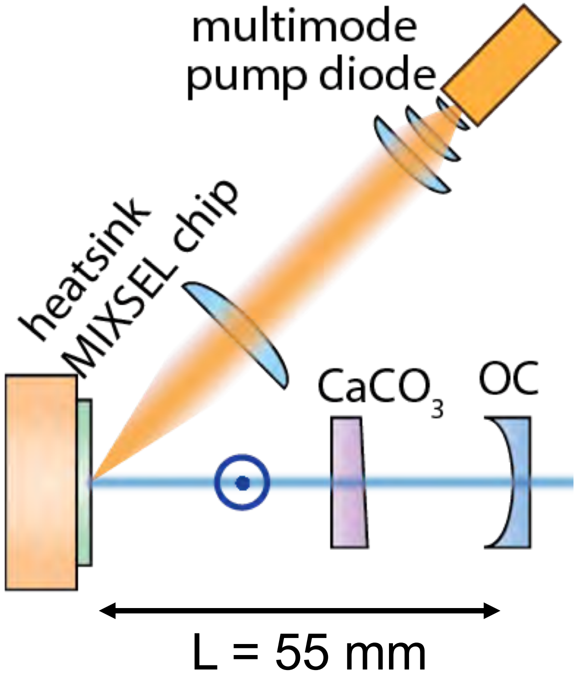


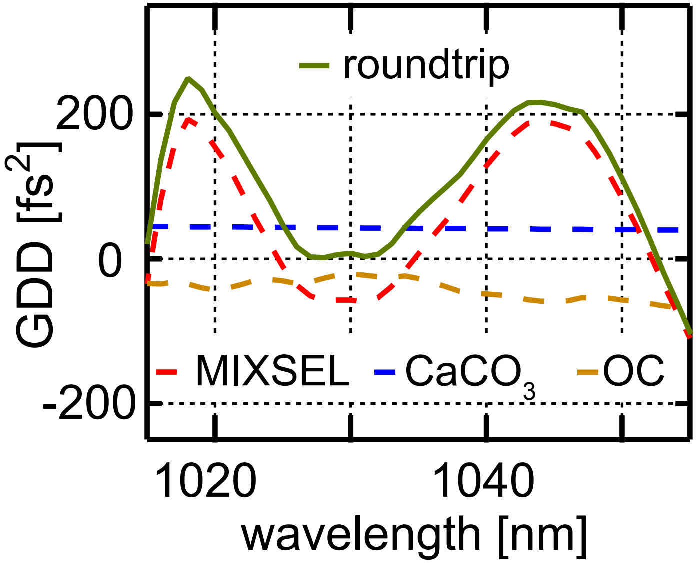


S. M. Link, A. Klenner, M. Mangold, C. A. Zaugg, M. Golling, B. W. Tilma, and U. Keller, *Opt. Express* **23**, 5521 (2015).
S. M. Link, D. J. H. C. Maas, D. Waldburger, U. Keller, *Science* **356**, 1164 (2017).

Group delay dispersion (GDD) optimization

To reach short sub-200-fs pulses, small but positive cavity dispersion **($0\ fs^2$ <GDD< $50\ fs^2$)** is required over a large spectral range



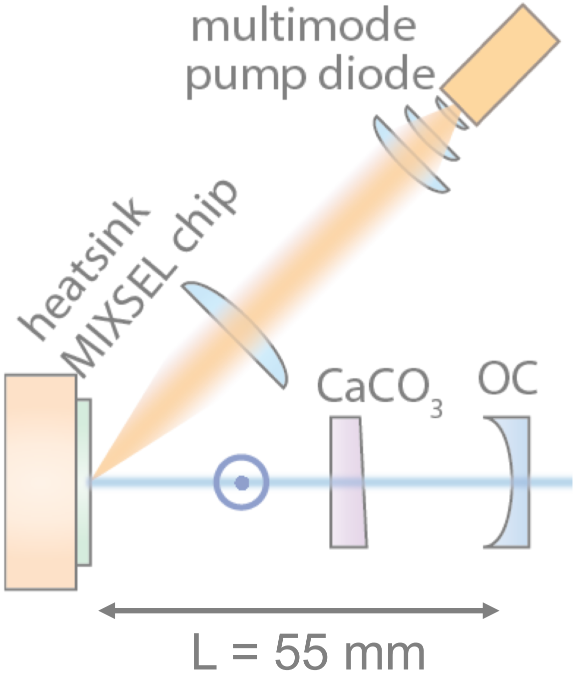


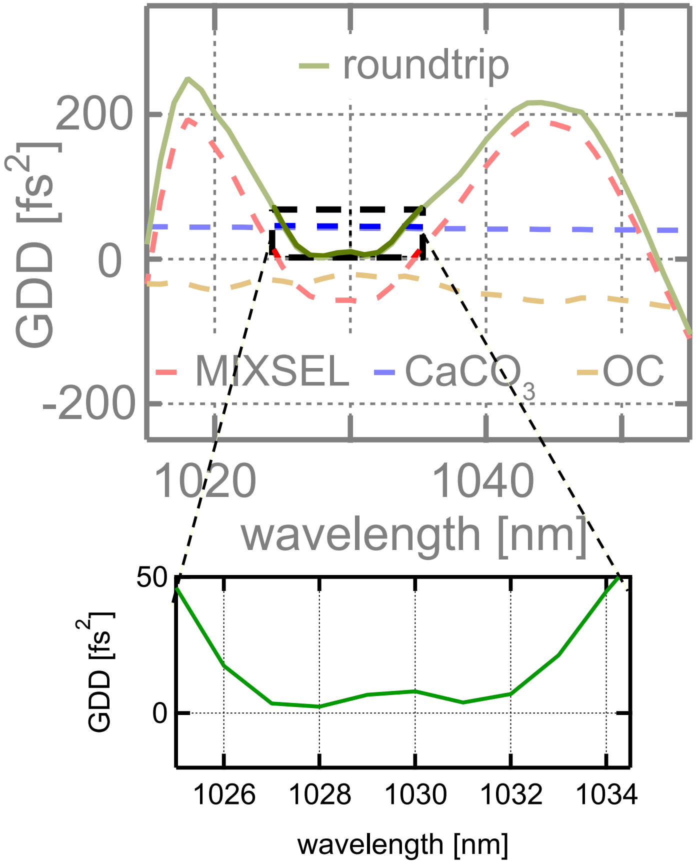
- \+ GDD from the MIXSEL (**IBS top-coating)**
- \+ GDD from the output coupler
- \+ 2 × GDD from a **1-mm thick Calcite crystal**

O. Sieber, M. Hoffmann, V. J. Wittwer, M. Mangold. M. Golling, B. W. Tilma, T. Südmeyer, U. Keller, *Appl. Phys. B* **113**, 133 (2013)

Group delay dispersion (GDD) optimization

To reach short sub-200-fs pulses, small but positive cavity dispersion **($0\ \mathrm{fs}^2 <$ GDD $< 50\ \mathrm{fs}^2$)** is required over a large spectral range [1]





- \+ GDD from the MIXSEL (**IBS top-coating)**
- \+ GDD from the output coupler
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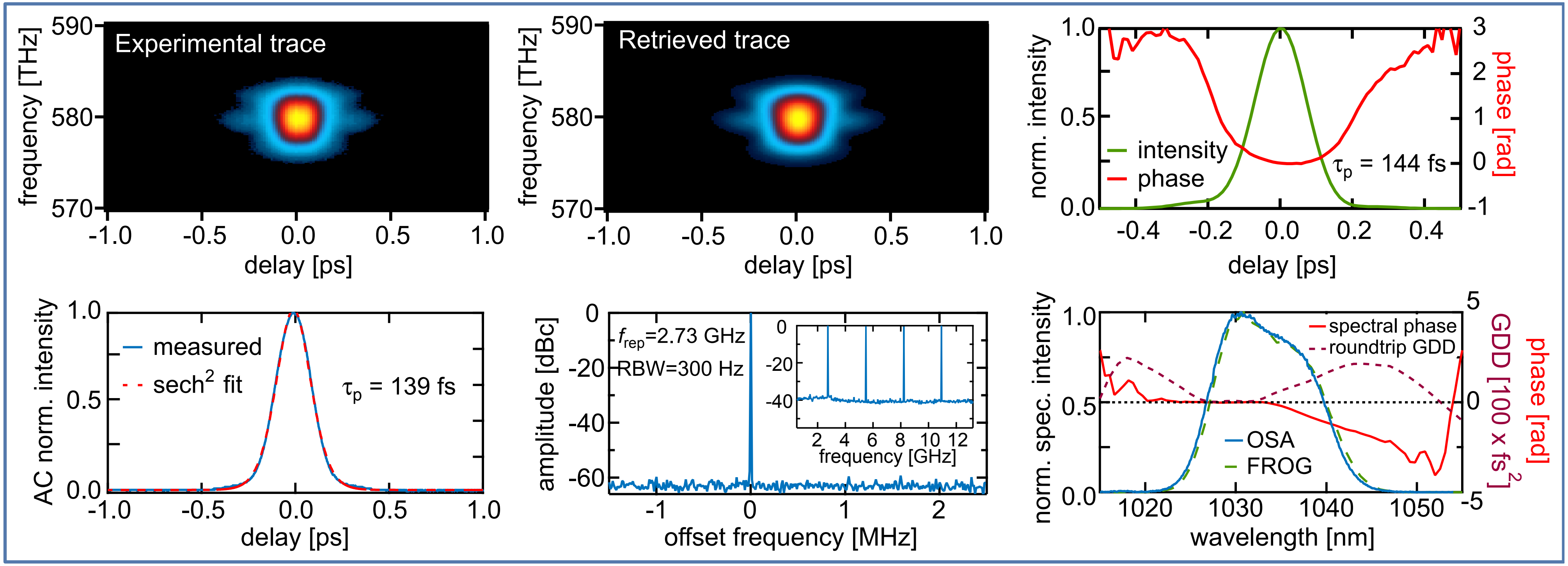
= **Cavity GDD balanced in the 1025-1035 nm region**

Modelocking performance

Opt. Letters **44**, 25 (2019)



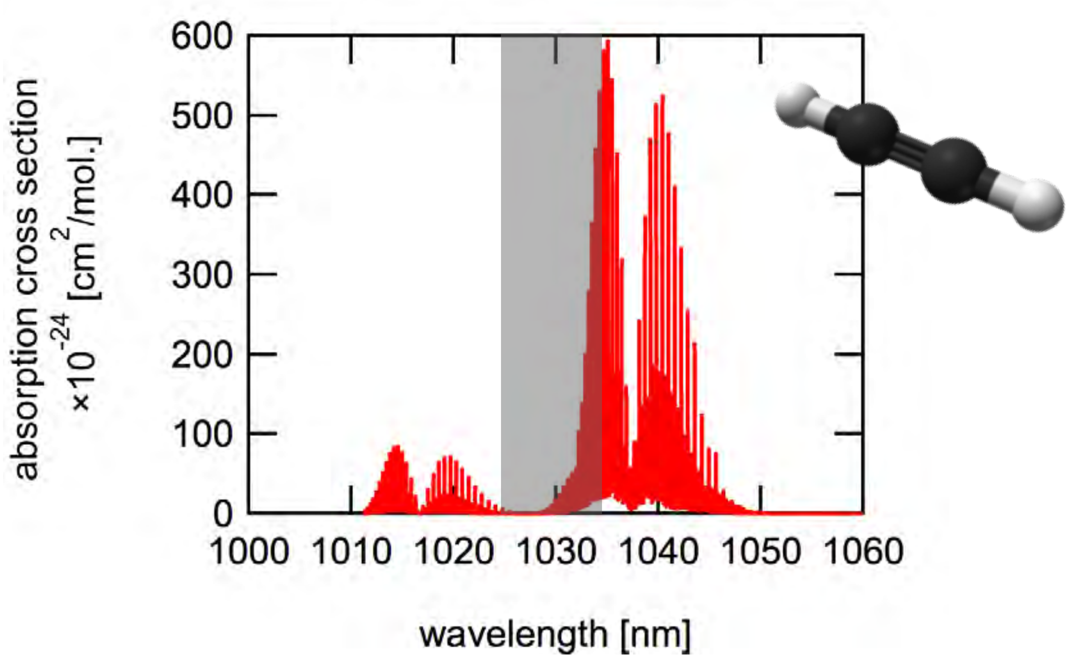
center wavelength [nm]	1033
bandwidth [nm]	13
pulse duration [fs]	139
average output power [mW]	30
pulse repetition rate [GHz]	2.73
Dual-comb operation	✓

- ✓ 13 nm of FWHM bandwidth (prev. 7.4 nm)
- ✓ Central wavelength tuned to C_2H_2
- ✓ First sub-150-fs MIXSEL
- ✓ Sufficient output power for spectroscopy
- ✓ Sufficient resolution for spectroscopy
- ✓ Turn-key for hundreds of hours

C. G. E. Alfieri***,** D. Waldburger*, J. Nürnberg, M. Golling, U. Keller, “Sub-150-fs from a broadband MIXSEL”, *Opt. Letters* **44**, 25 (2019)

Spectroscopy of acetylene

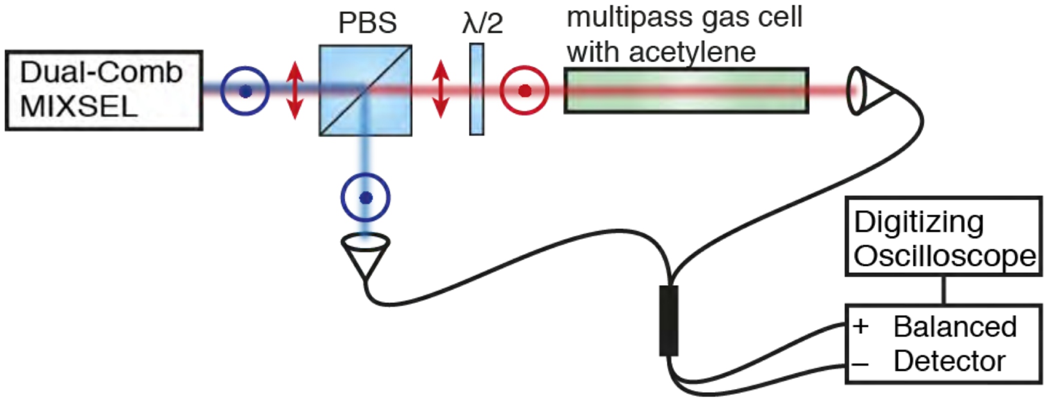
I. E. Gordon et. Al., J. Quant. Spectrosc. Radiat. Transf. **203**, 3 (2017).



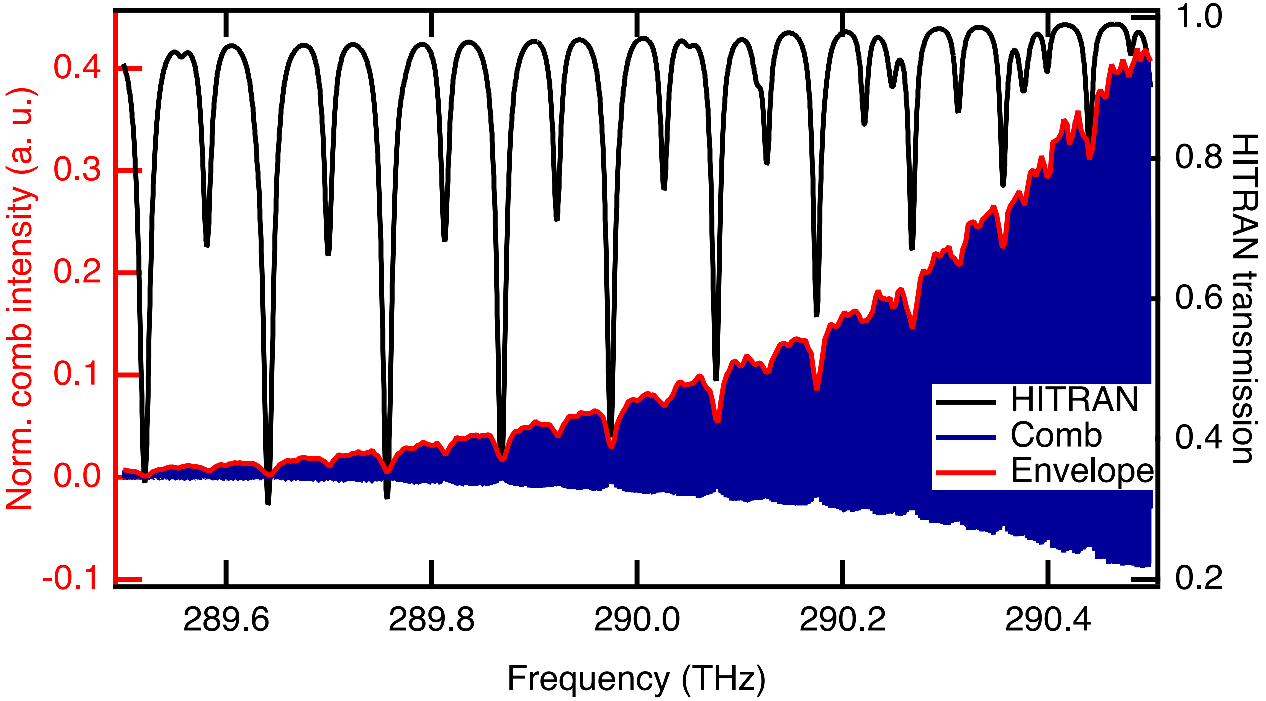
- Acetylene absorption lines (HITRAN 2016)
- Weak absorption in the near IR
- MIXSEL spectrum not perfectly matched

J. Nürnberg[*], C. G. E. Alfieri[*], Z. Chen, D. Waldburger, N. Picqué, U. Keller, *Optics Express* **27**, 3190 (2019)

Spectroscopy of acetylene



- Absorption in commercial fiber coupled multipass gas cell*
  *Manufacturer: Wavelength References
- 740 Torr pressure of acetylene (C_2H_2)
- 80 cm absorption path length
- *A posteriori* calibration to optical domain

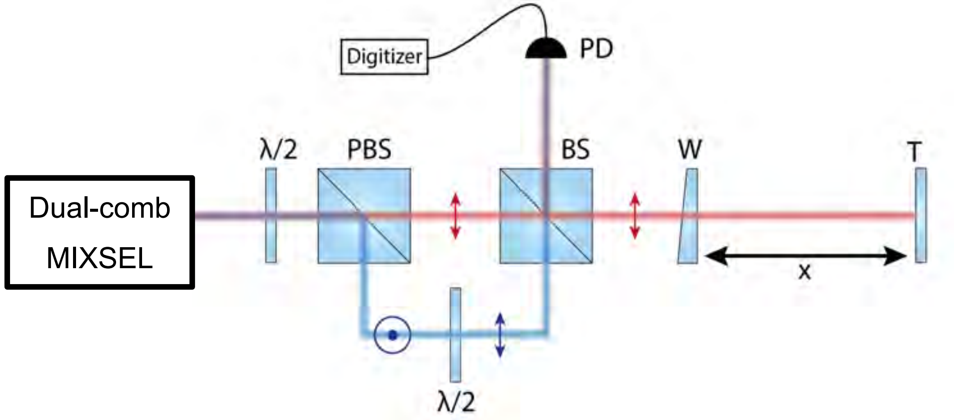


J. Nürnberg*, C. G. E. Alfieri*, Z. Chen, D. Waldburger, N. Picqué, U. Keller, *Optics Express* **27**, 3190 (2019)

Outline

1. Introduction to ultrafast semiconductor disk lasers
2. SESAM-modelocked VECSELs
3. MIXSEL
4. 100-fs VECSEL
5. 139-fs MIXSEL
6. Outlook

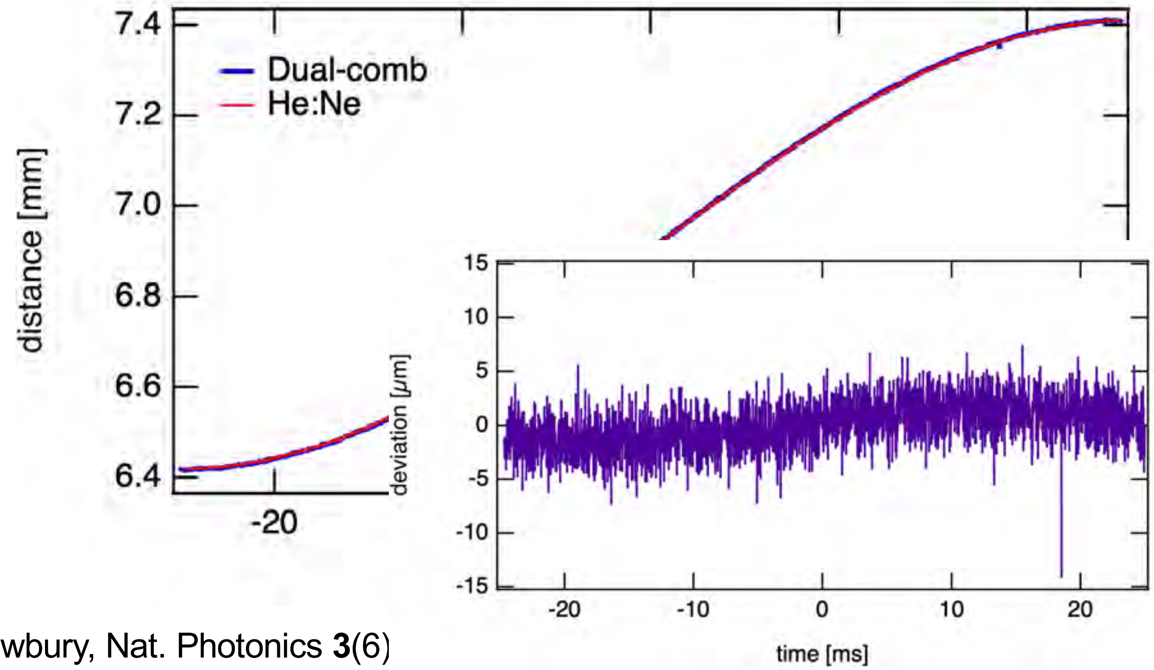
Outlook: Dual-Comb LIDAR



- Signal reflects of reference and target
- Beatnote contains two interferograms
- Time delay encodes distance

Motion tracking

- Measure displacement of a 10 Hz shaker
- Reference to He-Ne-interferometer
- RMS deviation < 5 µm



I. Coddington, W. C. Swann, L. Nenadovic, N. R. Newbury, Nat. Photonics **3**(6)

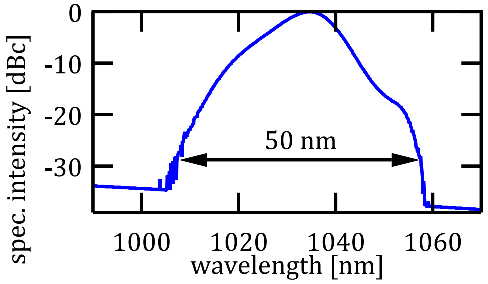
Outlook

Near infrared InGaAs SDLs

Pulse shortening of VECSELs and MIXSELs [1.2]

- ps dual-comb MIXSEL *Science* **356**, 1164 (2017)
- small optical bandwidth

100 fs pulses



- fs dual-comb MIXSEL with broader spectrum
- nonlinear broadening in Si_3N_4 waveguides [3, 4]

[1] D. Waldburger et al., *Optica* **3**, 844 (2016); [2] C. G. E. Alfieri*, D. Waldburger* et al., *Opt. Letters* **44**, 25 (2019)

[3] A. S. Mayer et. al., *Opt. Express* **23**, 15440 (2015); [4] D. Waldburger et al., *Opt. Express* **27**, 1786 (2019)

Outlook

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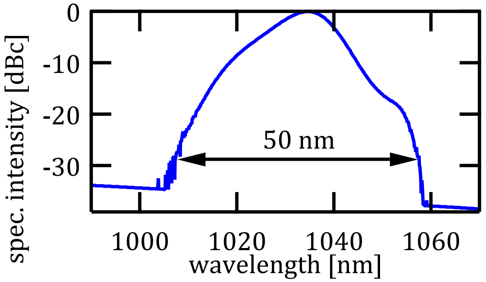

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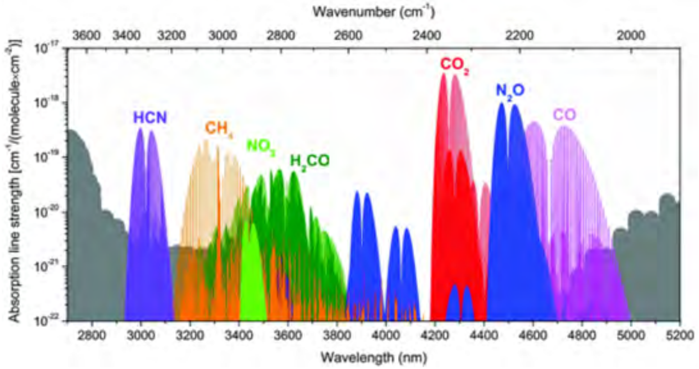
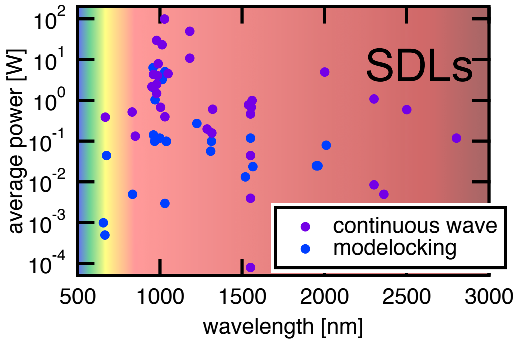
Bandgap engineering

- 960 nm
  → water
- 1030 nm
  → acetylene

- UV-Visible
  → electronic transitions
- Mid-IR fingerprint region
  →ro-vibrational transition





- second harmonic generation
  → UV-Visible
- bandgap engineering
  →Mid-IR
  ERC adv. grant