Semiconductor disk lasers and SESAMs: material and design optimization

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Plenary Talk, 10. May 2021, 3 pm

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Jacob Nürnberg (2020)


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Dr. Matthias Golling

FIRST Center for Micro- and Nanoscience

FAST-DOT

intel

nano-tera.ch


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Acknowledgements, long-wavelength effort (> 2 µm)

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Dr. Matthias Golling

Dr. Özgür Alaydin

FIRST

Center for Micro- and Nanoscience

erc

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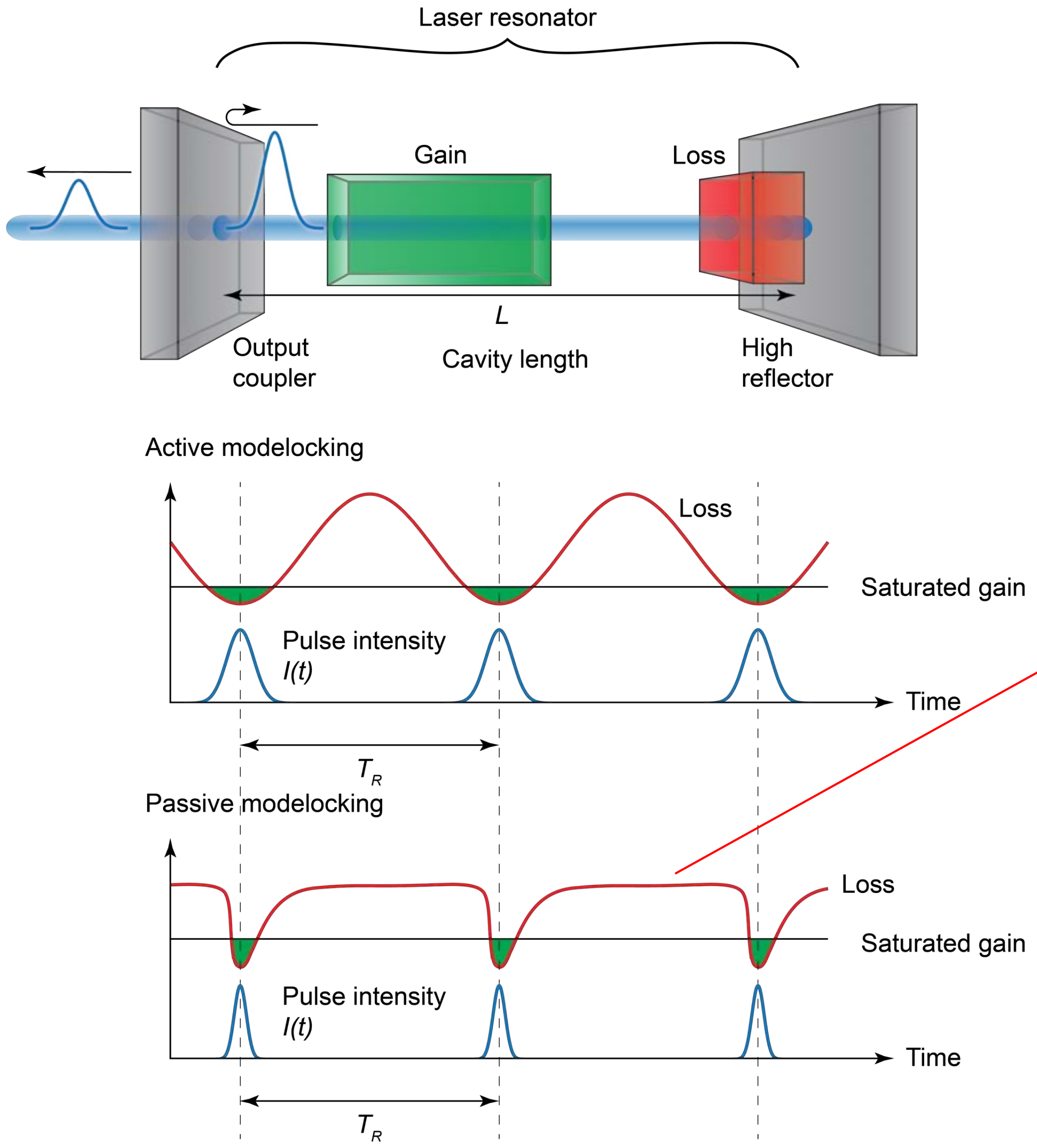
Outline

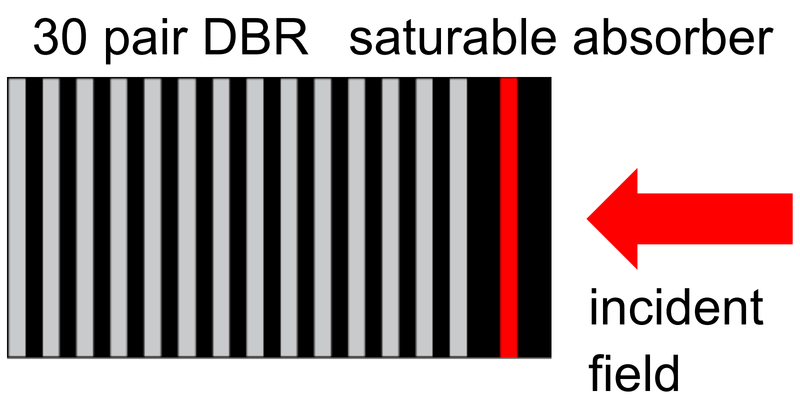
1. SESAM, VECSEL and MIXSEL basic device structure
2. Dual-comb modelocking and application demonstration
3. III-V semiconductor material
4. MIXSEL and SESAM modelocked VECSEL
5. Long wavelength SESAMs (> 2µm)
6. Outlook

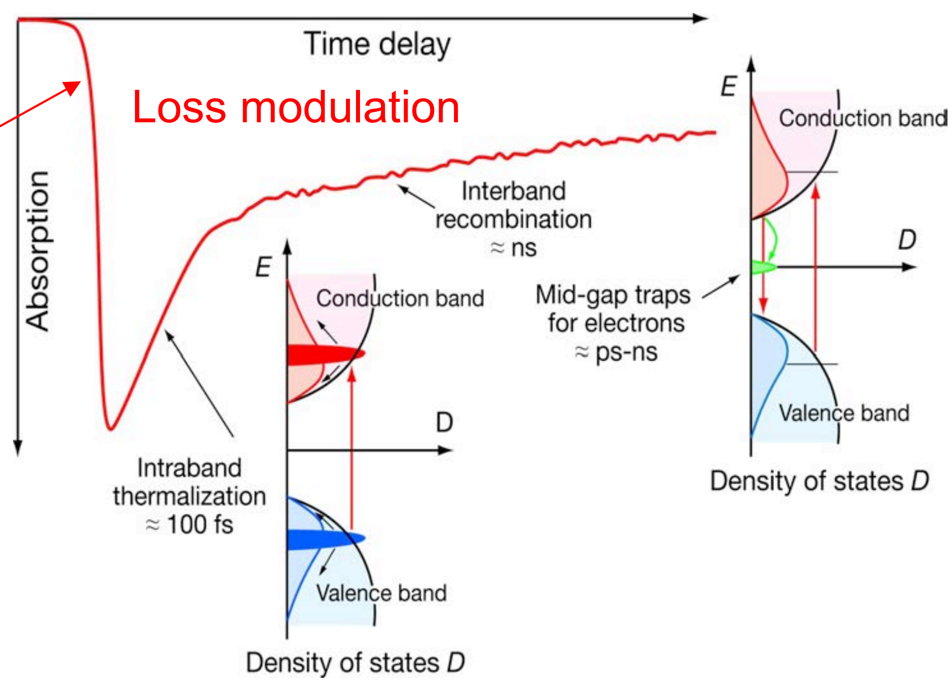
Passively modelocked lasers



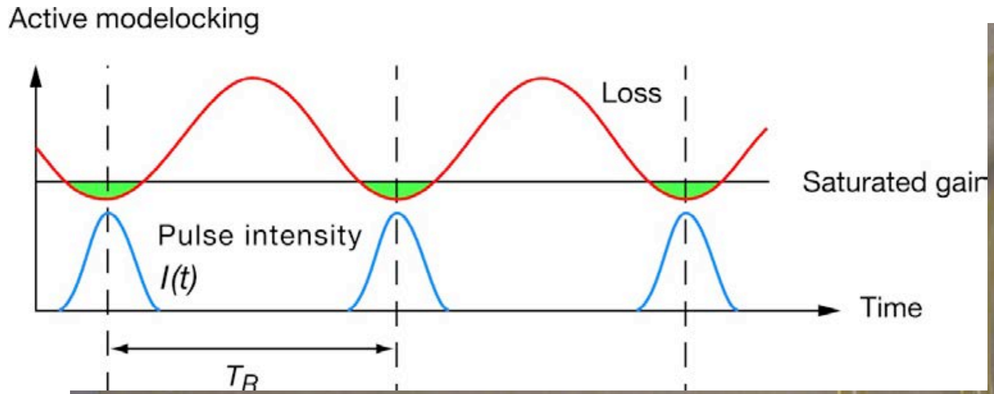
Semiconductor Saturable Absorber Mirror

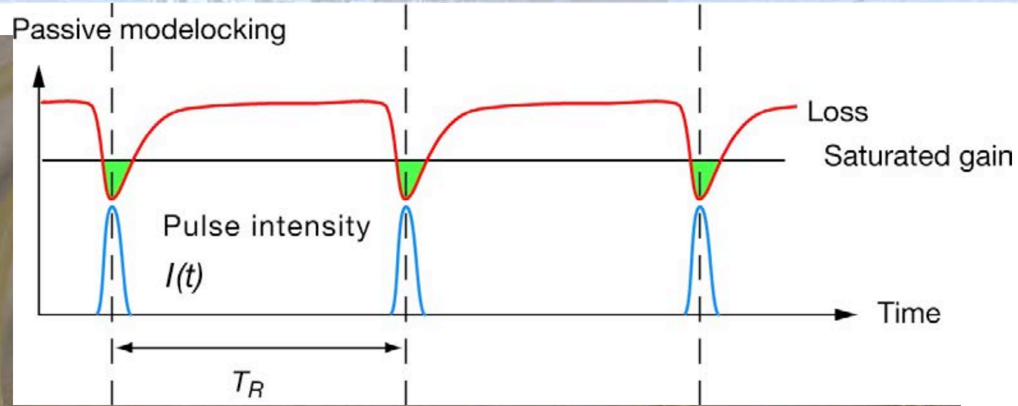
SESAM

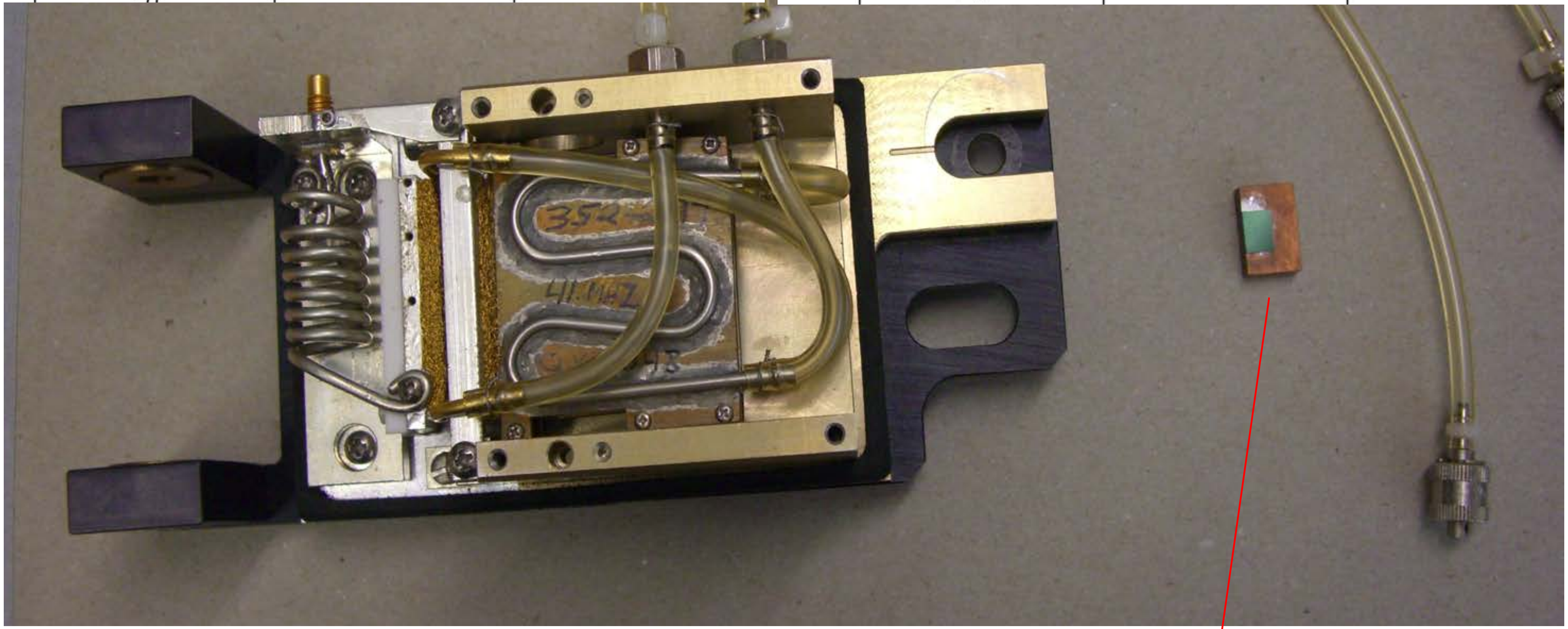




Innovation: before and after



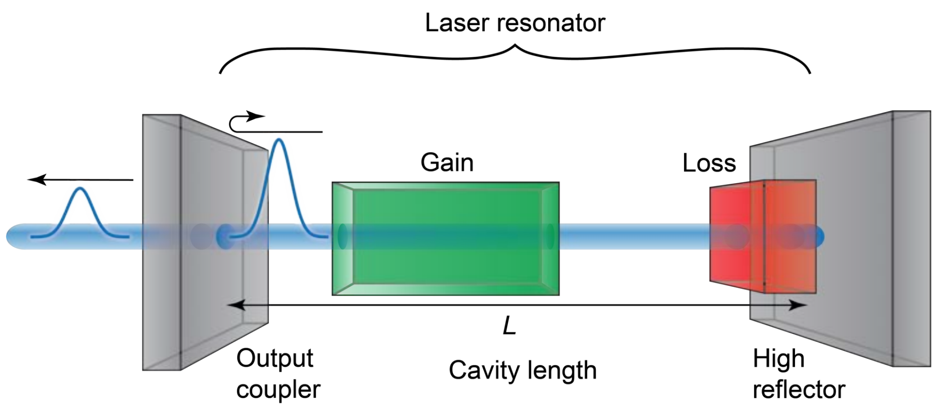




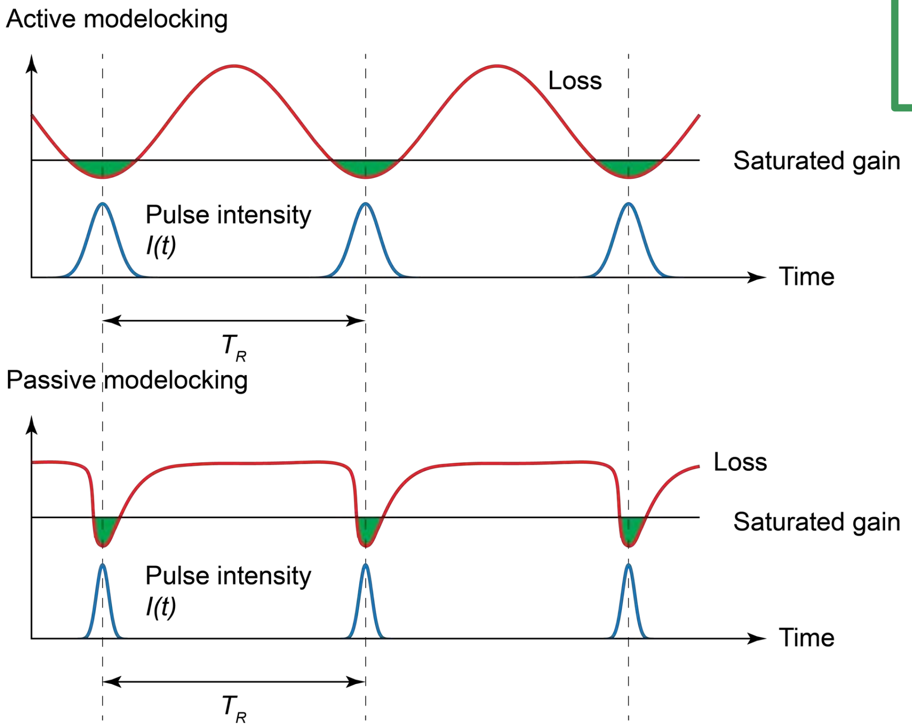
acousto-optic modelocker
needs RF power and water cooling

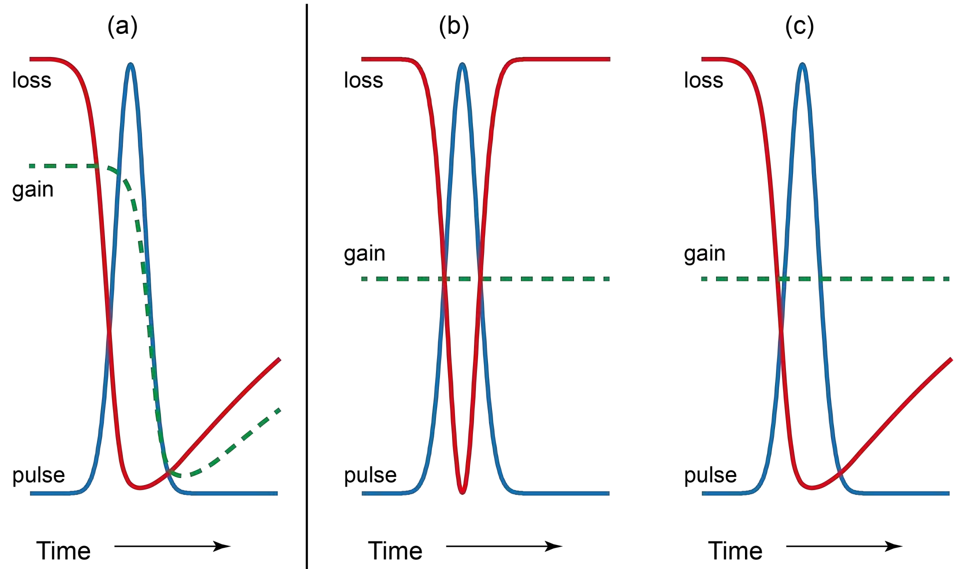
SESAM modelocker

Passively modelocked lasers



Laser material	σ [cm^2]	τ_L
Semiconductor laser	$\approx 10^{-14}$	≈ 1 ns
Dye laser:rhodamine 6G	$\approx 10^{-16}$	≈ 5 ns
Ti:sapphire @ 780 nm	3.8×10^{-19}	2.5 μs
Cr:LiSAF @ 830 nm	4×10^{-20}	67 μs
Nd:YAG @ 1.064 μm	6.5×10^{-19}	250 μs
Yb:YAG @ 1.03 μm	2×10^{-20}	950 μs
Nd:glass @ 1.054 μm	4×10^{-20}	350 μs





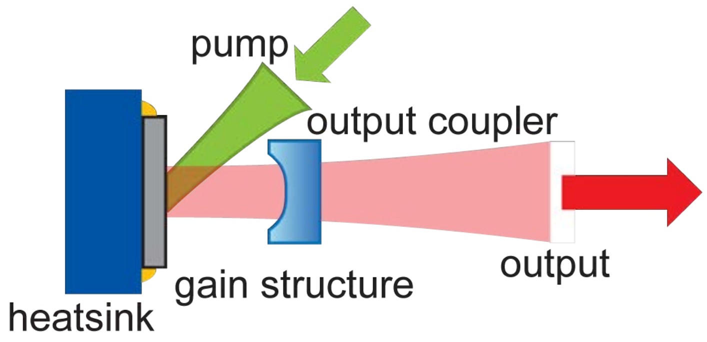
semiconductor and dye lasers

ion-doped solid-state lasers

Optically pumped VECSEL

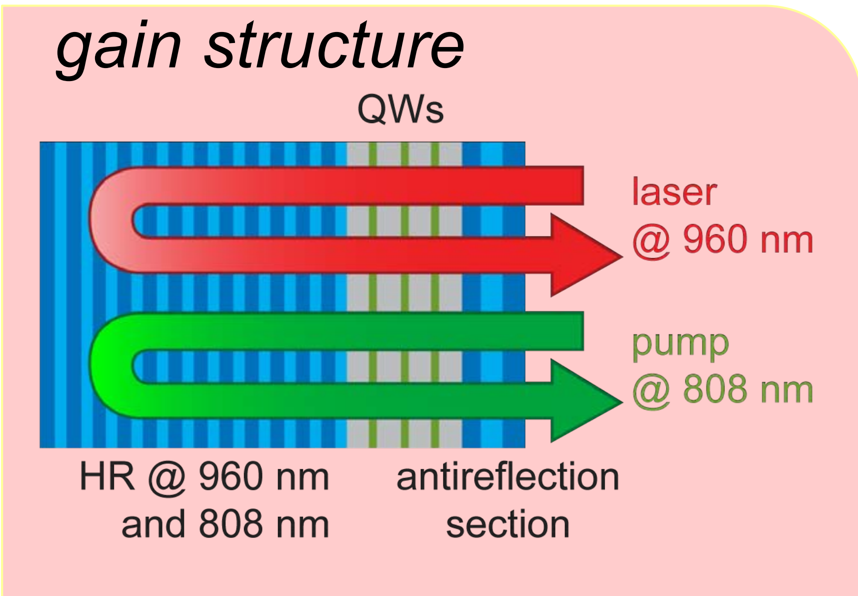
VECSEL (Vertical External-Cavity Surface-Emitting Laser) #1

- gain structure (low gain)
- output coupler (a few percent)
- high-Q cavity
- low noise



External cavity:

- intracavity frequency doubling
- **modelocking**
- **single mode operation (TEM_{00})**



Diode-pumped semiconductor laser:

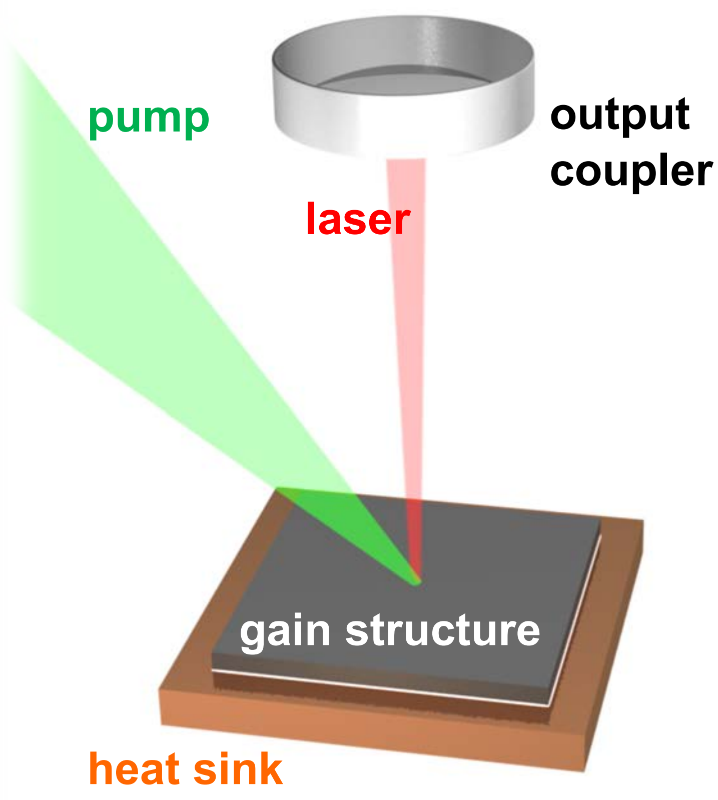
- bandgap engineering
- **high level of integration**
- wafer scale technology
- power scaling

#1 Kuznetsov et al., IEEE Photonics Technology Letters **9**, 1063 (1997)

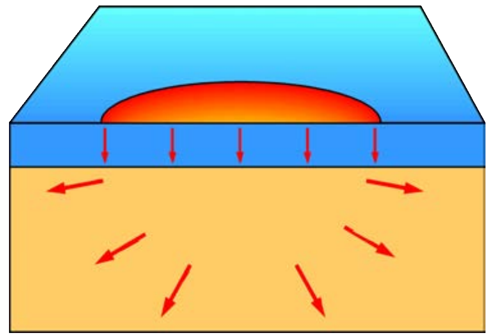
cw optically pumped VECSEL

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)

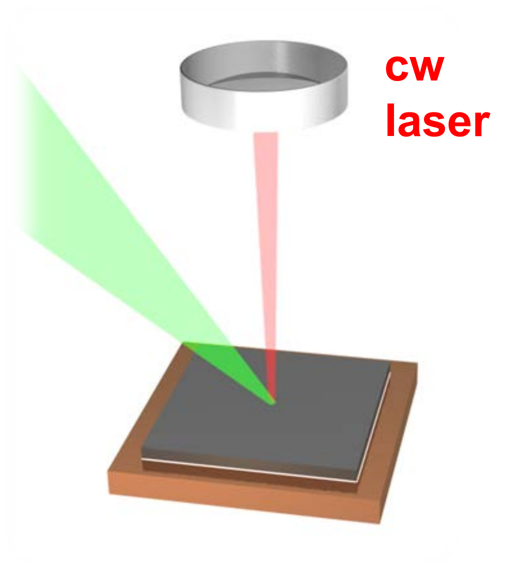


IEEE JQE 38, 1268 (2002)

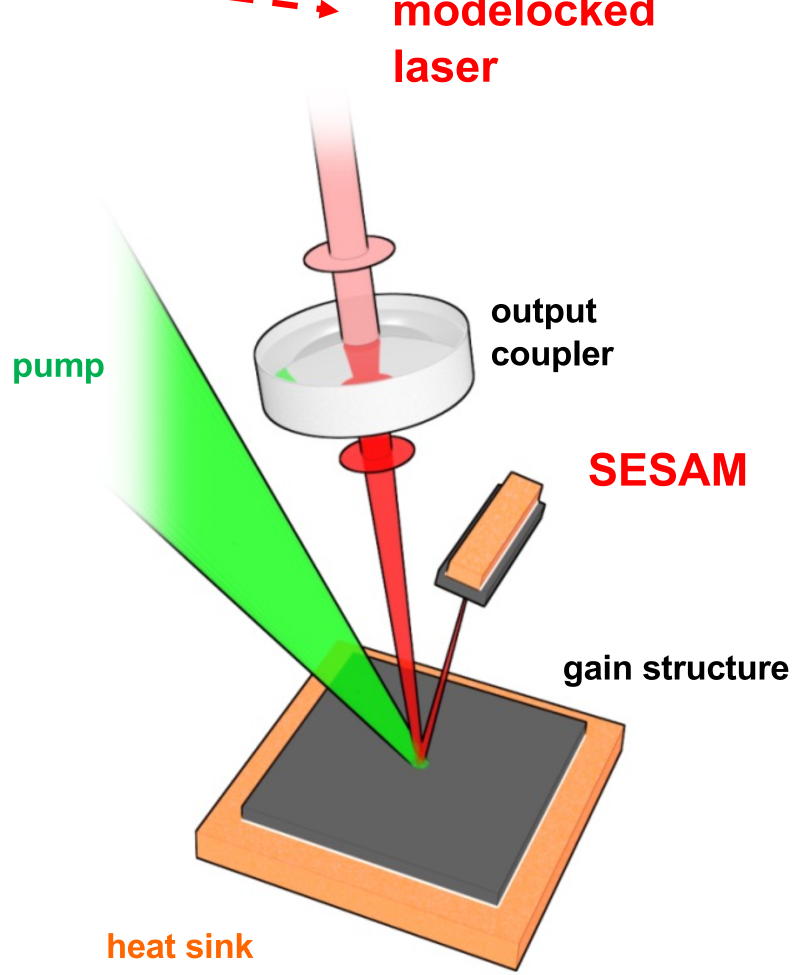
- Pump: high power diode bar
- External cavity for diffraction-limited output

SDLs = semiconductor disk lasers

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

Optically pumped MIXSEL

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

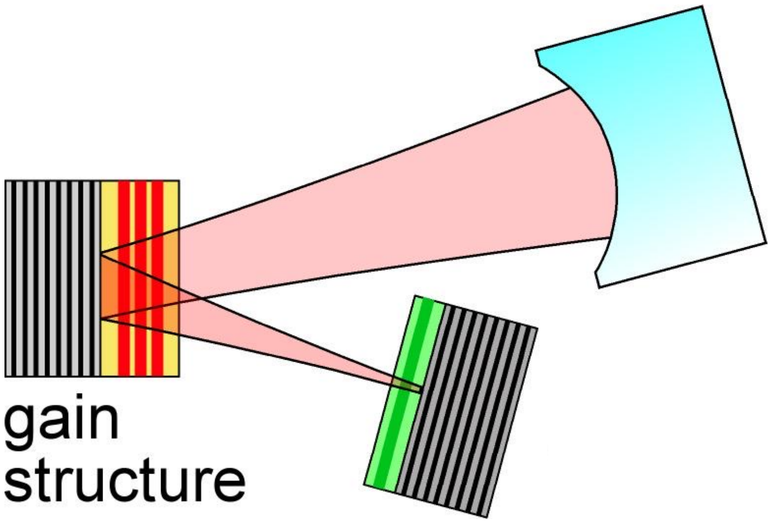
3-GHz pulse repetition rate: cavity length of ≈ 5 cm

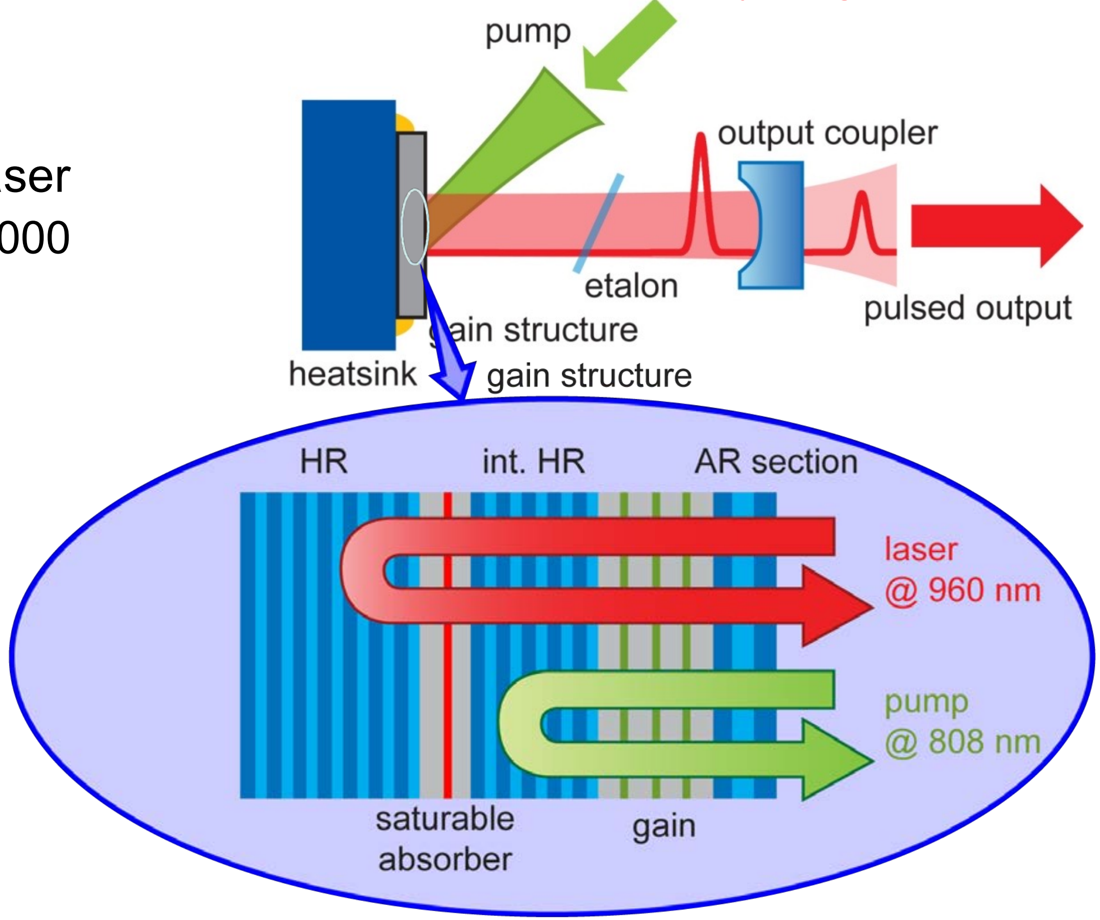
Passively modelocked VECSEL

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

S. Hoogland et al., *IEEE PTL* **12** (9), 1135, 2000

Review with Anne Tropper:
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

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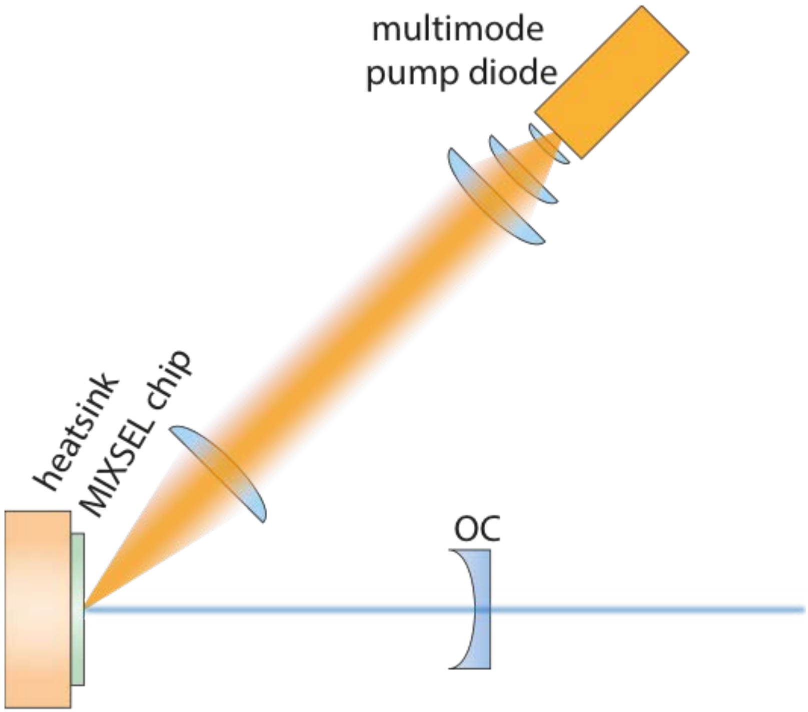
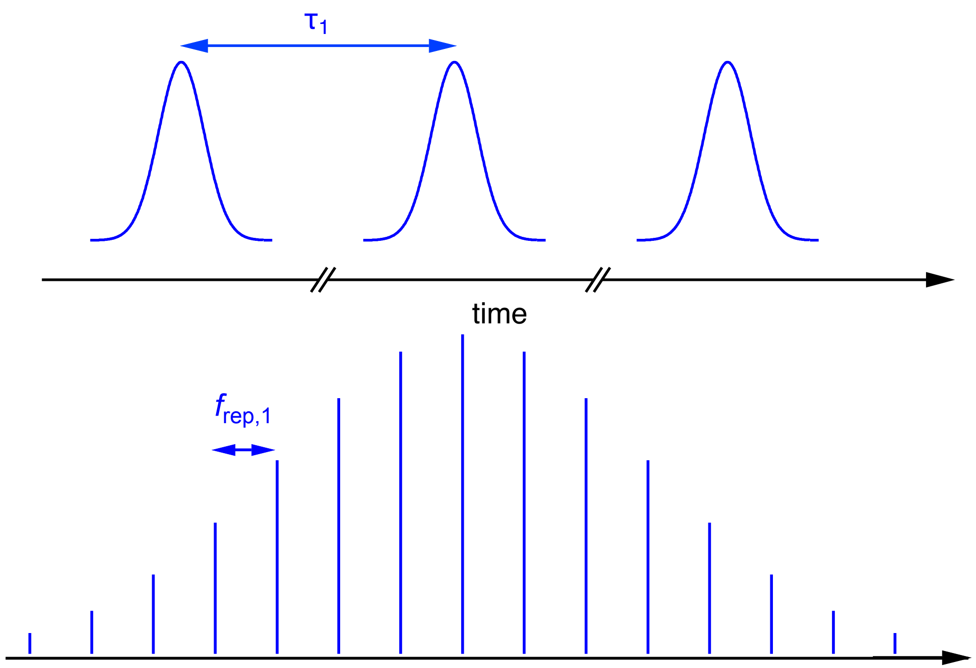
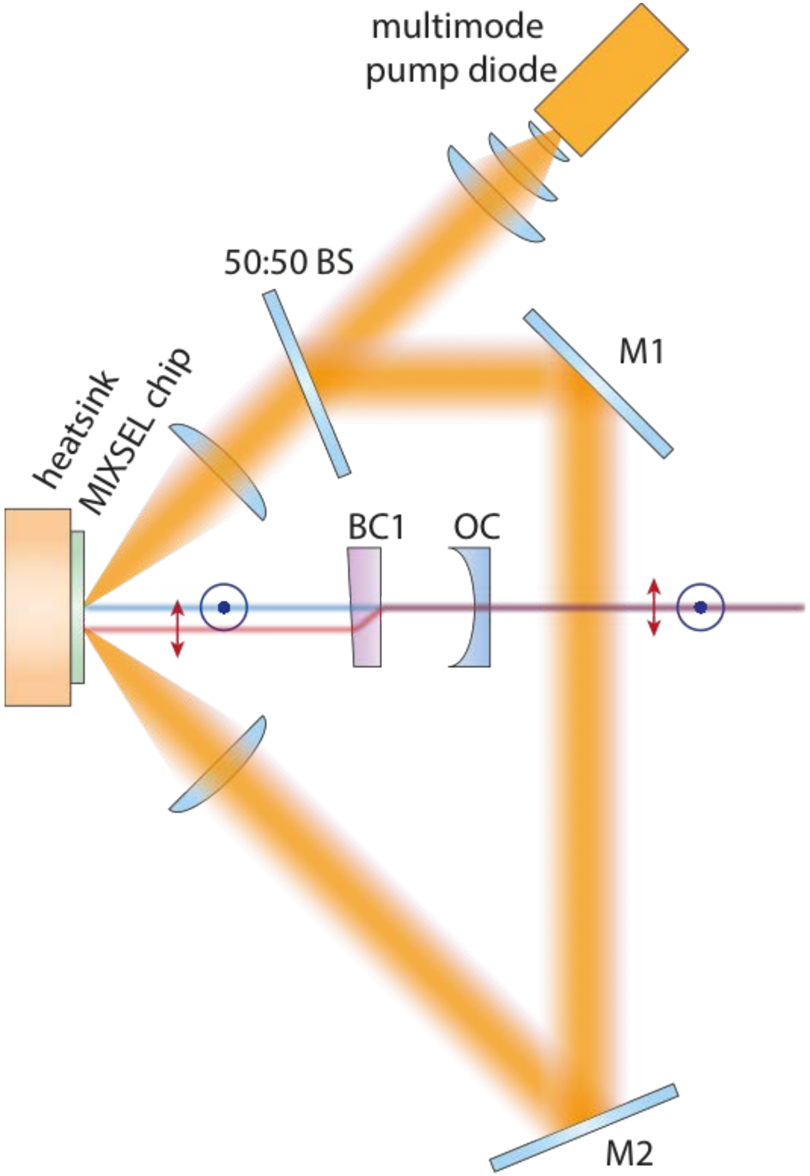
Dual-Comb MIXSEL

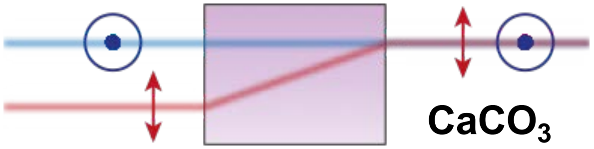


Sandro
Link (2017)



Dual-Comb MIXSEL

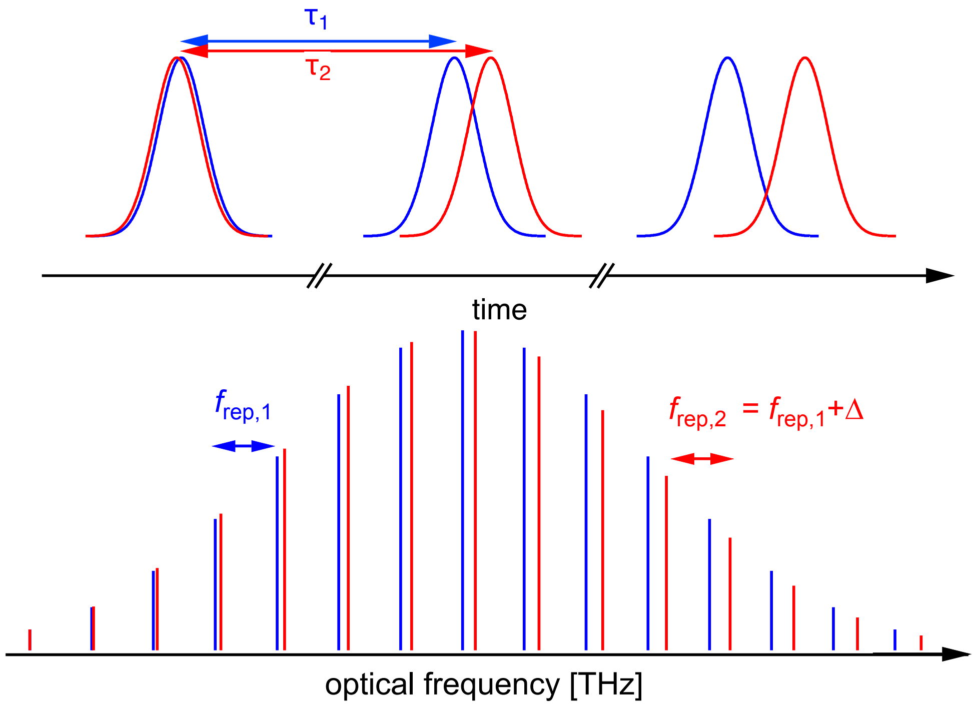




Intracavity birefringent crystal (BC)

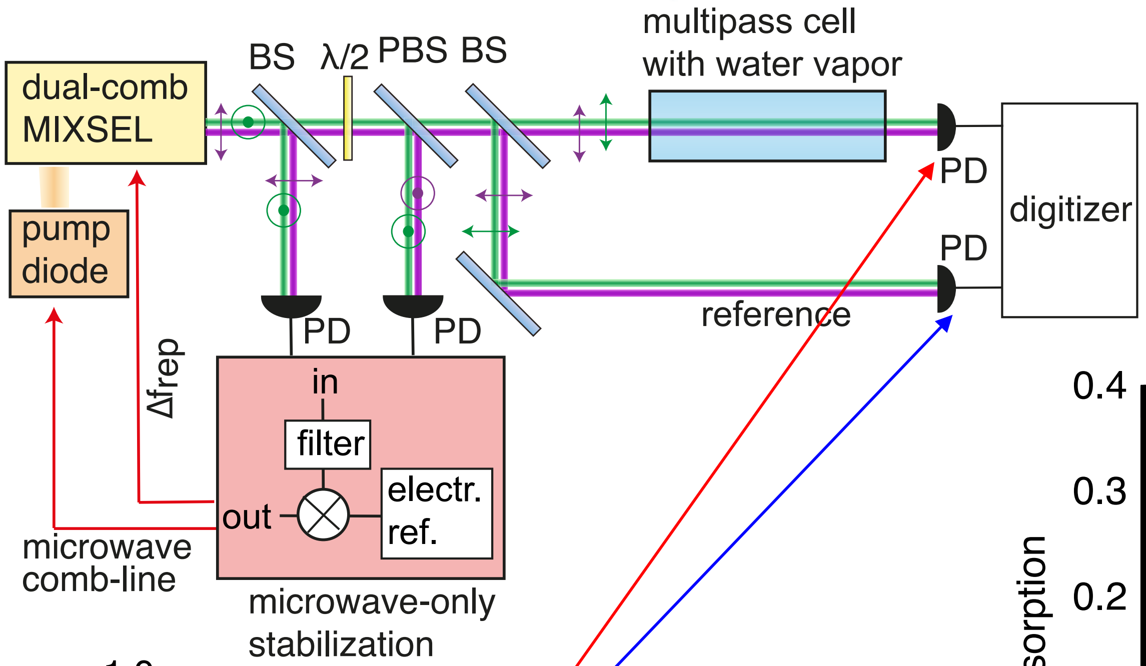
- Two spatially separated beams
- Orthogonal polarizations
- Different optical path length

Sandro Link (2017)



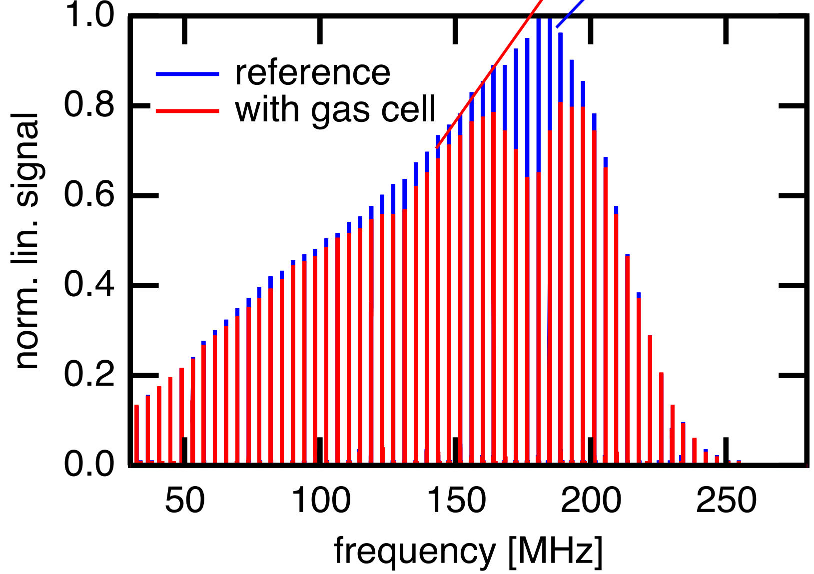
S. M. Link, A. Klenner, M. Mangold, C. A. Zaugg, M. Golling, B. W. Tilma, U. Keller, *Opt. Express* **23**, 5521 (2015).
S. M. Link, A. Klenner, U. Keller , *Opt. Express* **24**, 1889 (2016): SESAM decouples noise stabilization

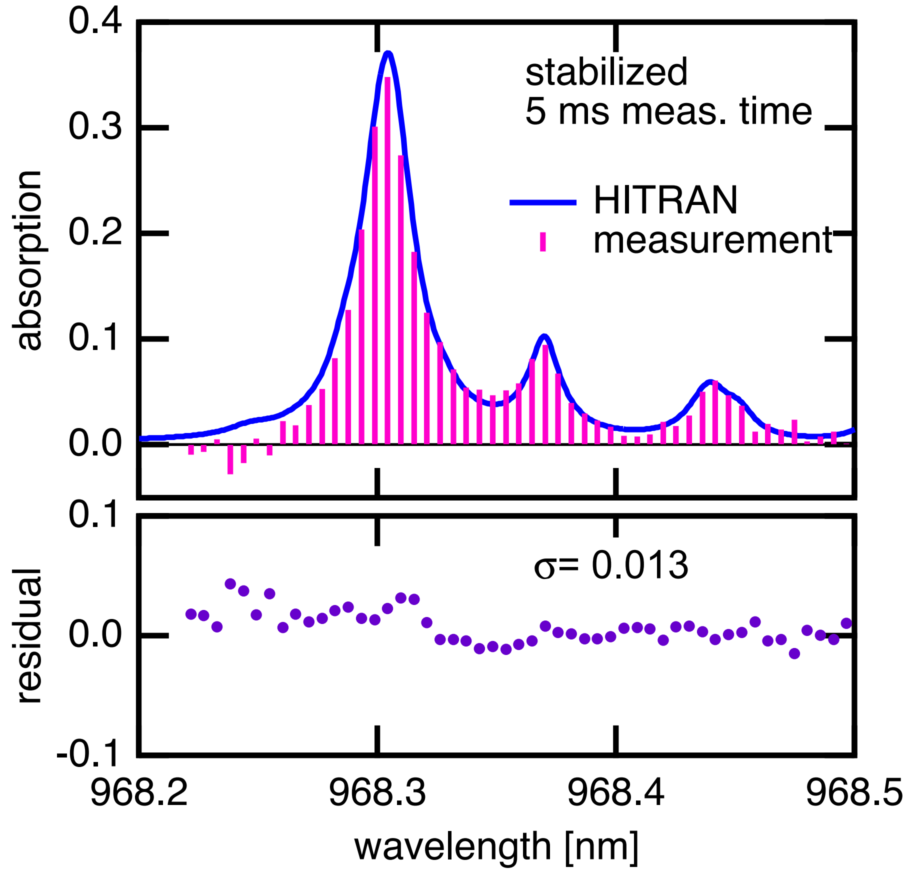
Dual-comb spectroscopy with dual-comb 968-nm MIXSEL



measurement with stabilized microwave comb of dual-comb MIXSEL!

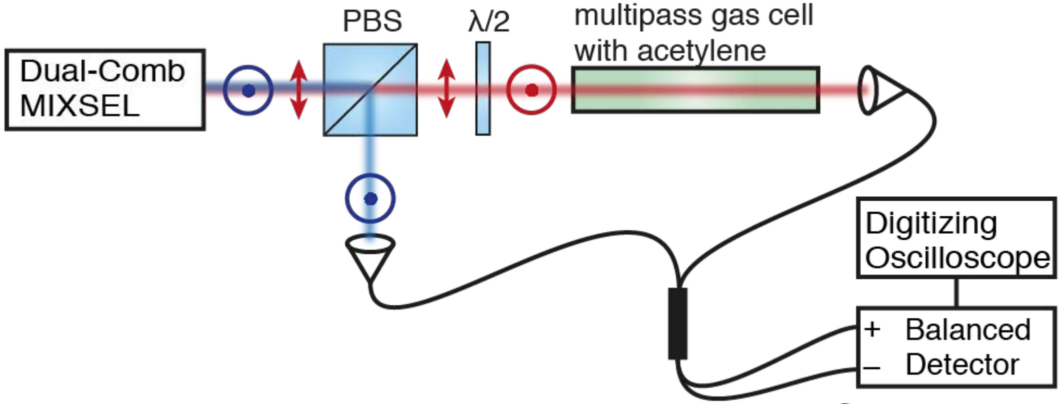
But also with free-running laser!





S. M. Link, D. J. H. C. Maas, D. Waldburger, U. Keller, "Dual-comb spectroscopy of water vapor with a free-running semiconductor disk laser", Science 356, 1164-1168 (16 Jun 2017)

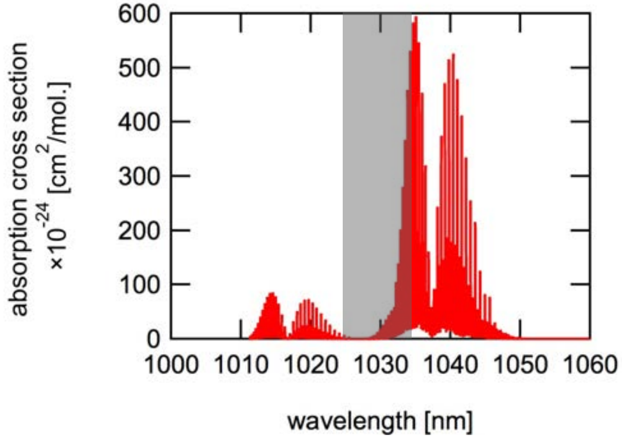
Dual-comb spectroscopy with dual-comb 1.03-μm MIXSEL



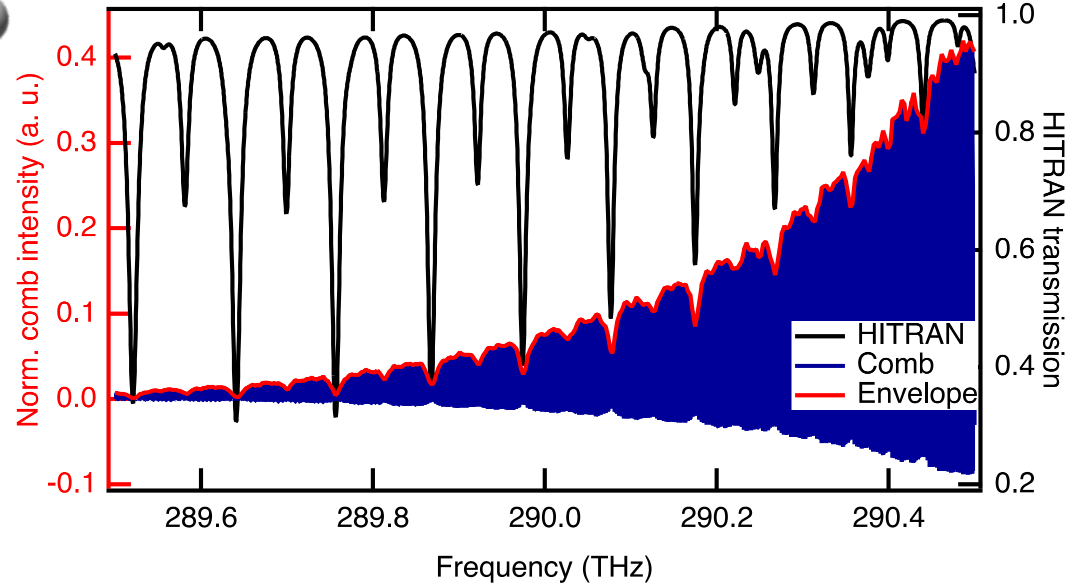
- Absorption in commercial fiber coupled multipass gas cell*
  *Manufacturer: Wavelength References
- 740 Torr pressure of acetylene (C_2H_2)
- 80 cm absorption path length

Jacob Nürnberg (2020)

Dual-comb spectroscopy of acetylene C_2H_2

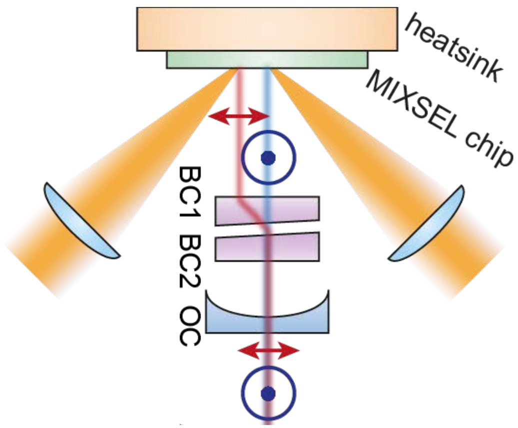


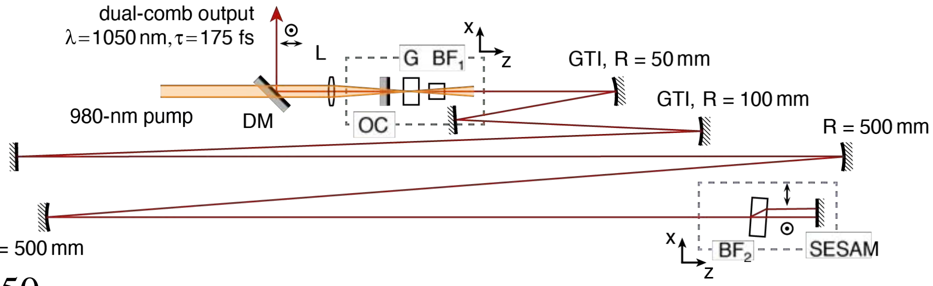
- Acetylene absorption lines (HITRAN 2016)
- Weak absorption in the near IR
- MIXSEL spectrum not perfectly matched



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

Dual-comb ranging with free-running lasers



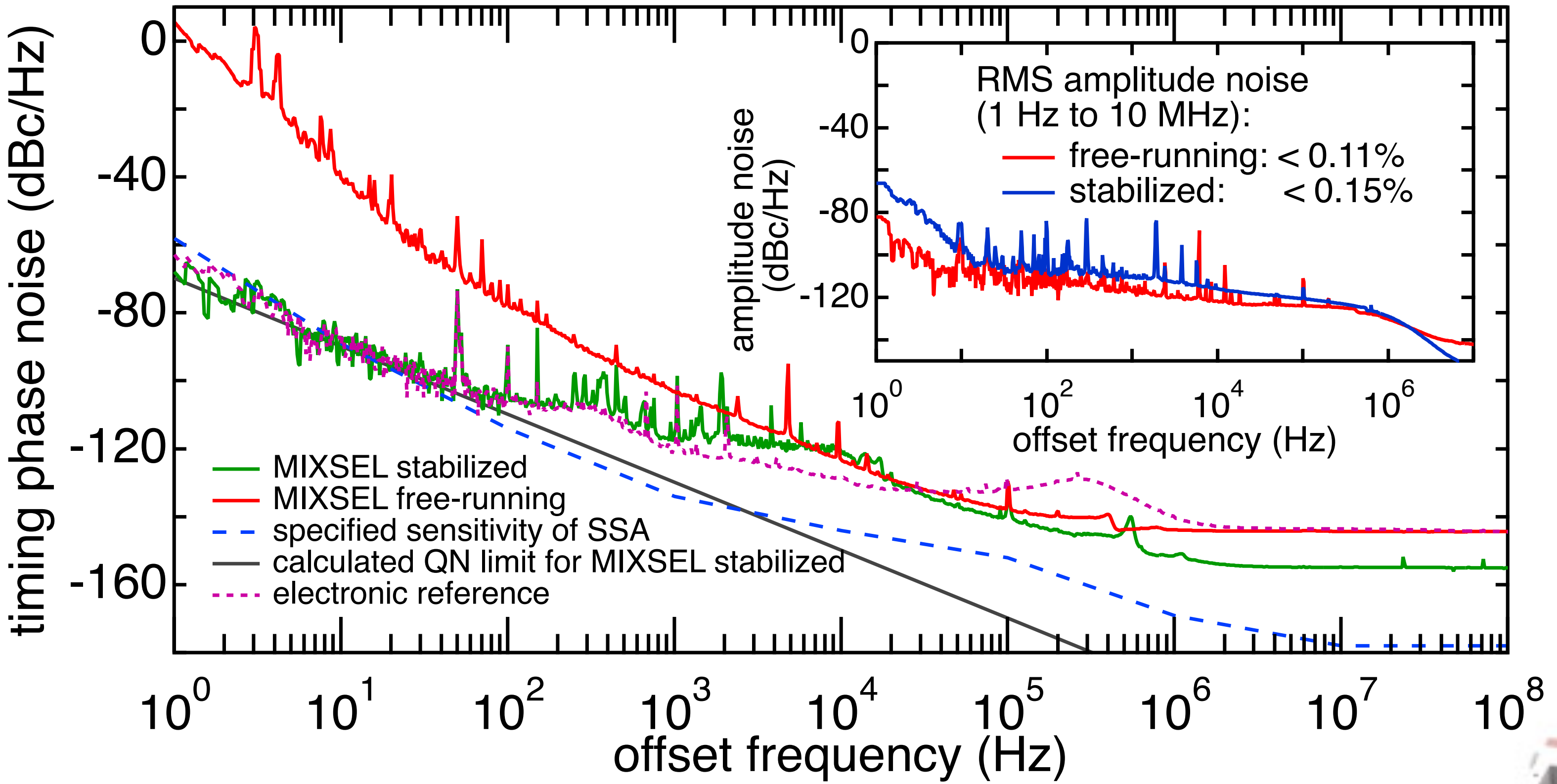


1028 nm	1050 nm
3 nm	6.9 nm
≈390 fs	≈175 fs

	Dual-comb MIXSEL	**Dual-comb Yb:CaF_2**
Update rate ($= \Delta f_{rep}$)	51 kHz	952 Hz
Ambiguity range (f_{rep})	**55 mm** (2.7 GHz)	**≈ 1 m** (136.5 MHz)
Precision	1.4 µm	0.5 µm
Theoretical ext. ambiguity range	2.8 km	**157 km**
Application	**Short range but fast**	**Long range but slower**
	Industrial and manufacturing	Satellite and spacecraft links

J. Nürnberg, et al. "Dual-comb ranging with frequency combs from single cavity free-running laser oscillators" *Optics Express* **29** (16) 24910, 2021

Picosecond MIXSEL noise characterization



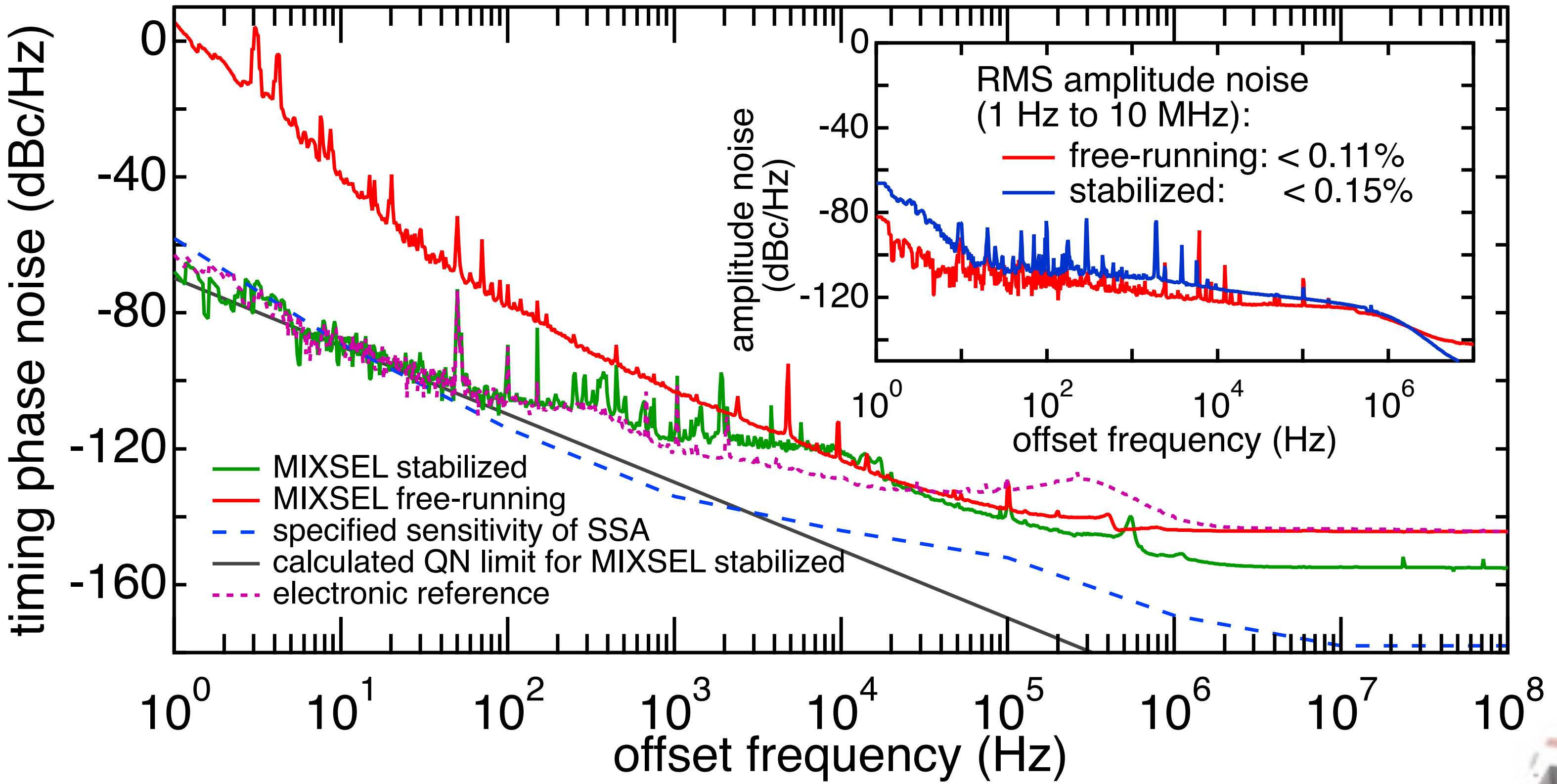
Mario Mangold (2015)

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



Mario Mangold (2015)

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)

MIXSEL frequency comb stabilization

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*

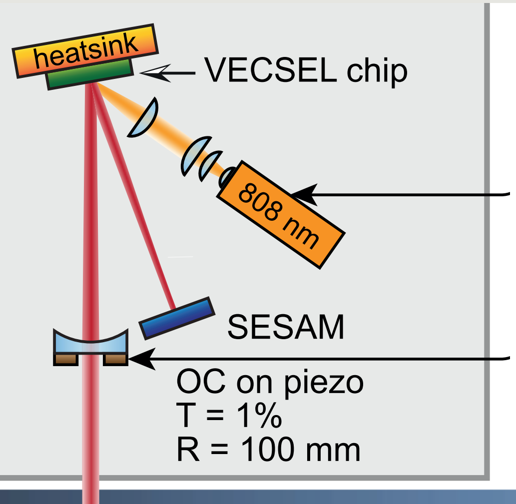
[3]*Department of Electrical Engineering, Columbia University, New York, New York 10027, USA*

**dominikw@phys.ethz.ch*

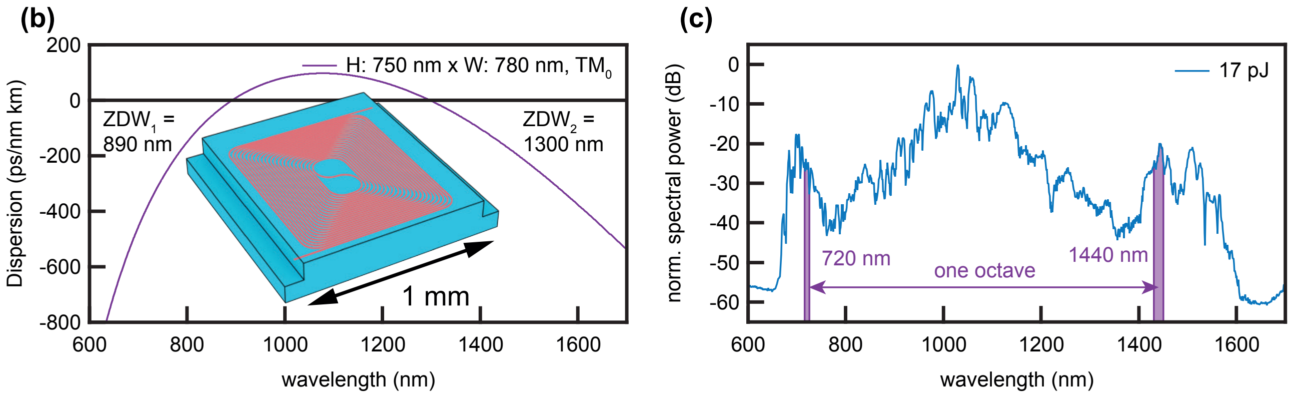
Dominik Waldburger (2018)

Aline Mayer (2018)

122-fs pulses &160-mW



No additional amplification and pulse compression with Silicon nitride waveguide



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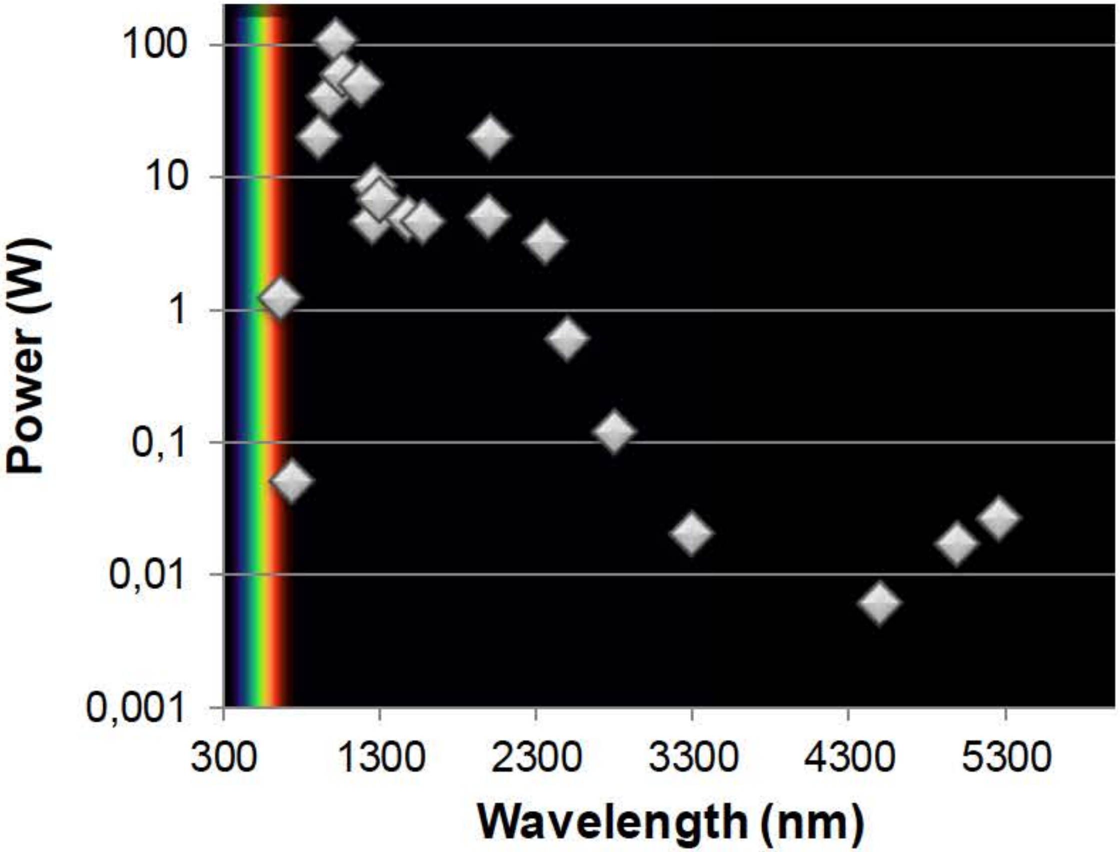
VECSELs: cw spectral coverage (Mircea Guina, 2017)

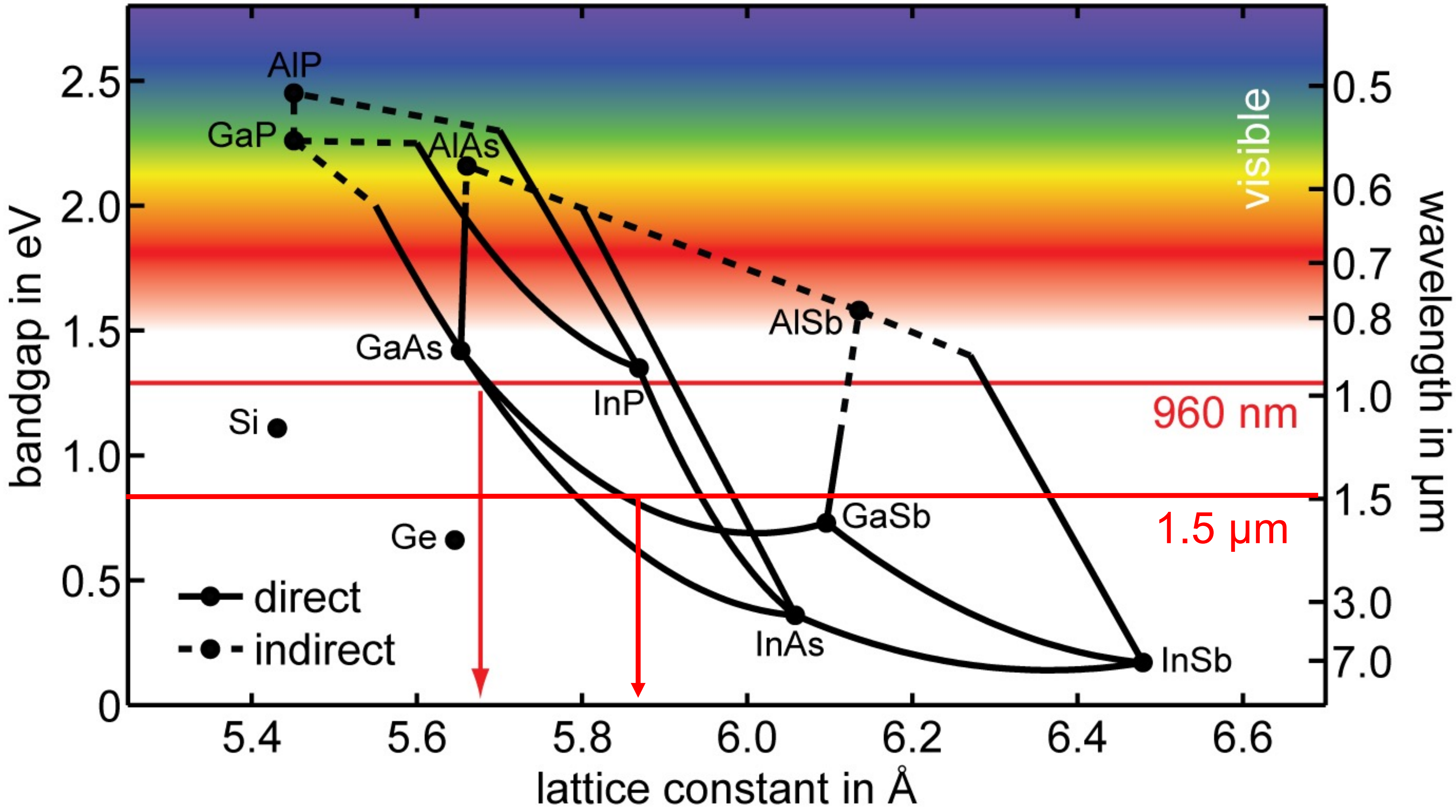


- 2-2.8 µm – GaInAs**Sb** / AlGaAs**Sb**
- 1.5 µm – InGaAs / InGaAsP
- **1.2-1.5 µm – AlGaInAs / InP (fused)**
- 1.2-1.3 µm – GaIn**N**As / GaAs
- 1-1.3 µm – InAs QDs
- **0.9-1.18 µm – InGaAs / GaAs**
- 850-870 nm – GaAs / AlGaAs
- 700-750 nm – InP QDs
- 640-690 nm – InGaP / AlGaInP
- **Frequency-doubled**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

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

SDLs = semiconductor disk lasers

LT InGaAs SESAMs



- GaAs/AlAs Distributed Bragg Reflectors (DBR) with near-perfect lattice match
- Low-temperature (LT) MBE grown for faster absorbers and strain-relaxed structures
- LT InGaAs SESAMs used up to 1.5 µm

LT grown SESAMs to reduce absorber recovery time

February 1, 1993 / Vol. 18, No. 3 / OPTICS LETTERS 217

Self-starting and self-*Q*-switching dynamics of passively mode-locked Nd:YLF and Nd:YAG lasers

U. Keller, T. H. Chiu, and J. F. Ferguson

AT&T Bell Laboratories, Crawfords Corner Road, Holmdel, New Jersey 07733

Received August 12, 1992

The semiconductor antiresonant Fabry–Perot saturable absorber (A-FPSA) has a bitemporal absorption response with a slow time component that is due to carrier recombination and a fast time component that is due to intraband thermalization. We demonstrate that the slow component provides the self-starting mechanism and without significant Kerr lens contribution the fast component is necessary for steady-state pulse formation in passively cw mode-locked solid-state lasers. The carrier lifetime of the bitemporal A-FPSA was varied by the molecular-beam-epitaxy growth temperature to characterize its inf[illegible] switching dynamics of cw mode-locked Nd:YLF and Nd:YAG lasers. T[illegible] reflector of the A-FPSA can be adjusted to optimize the self-starting perfo[illegible] of cw mode-locked solid-state lasers.

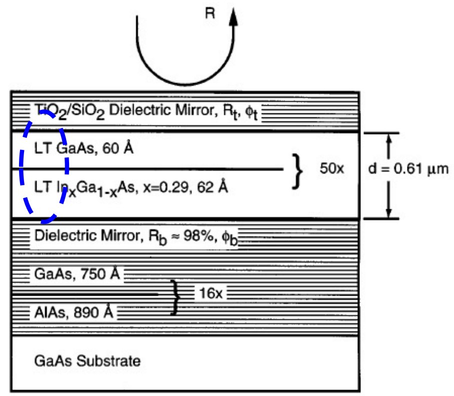


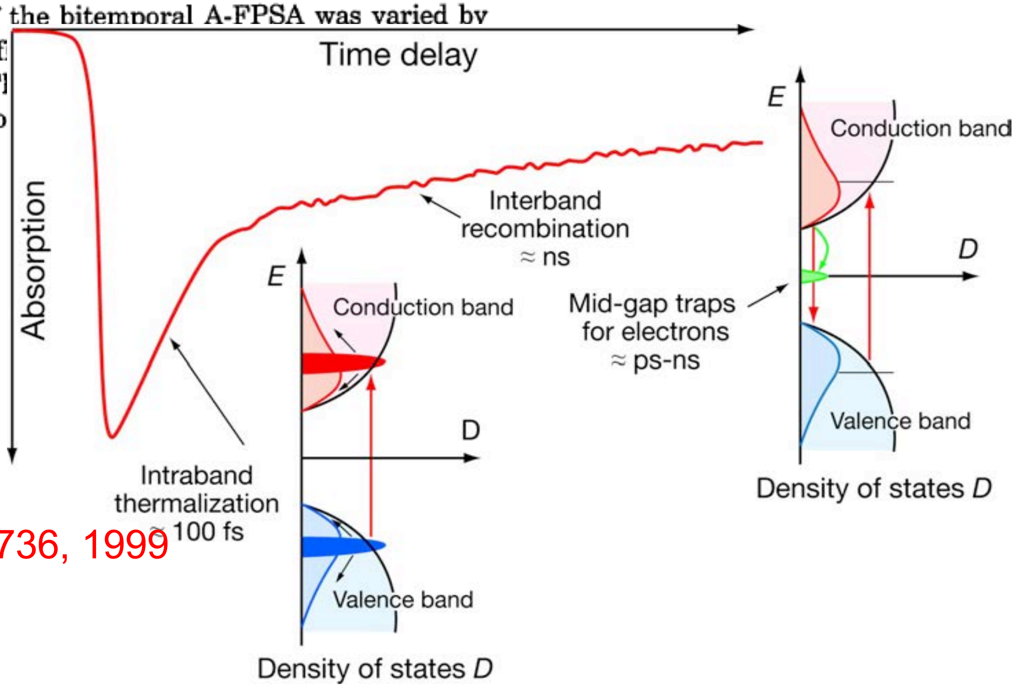
Fig. 1. Structure of an A-FPSA designed for an operation wavelength of ≈1 µm.

Adjustable parameter: absorber recovery time

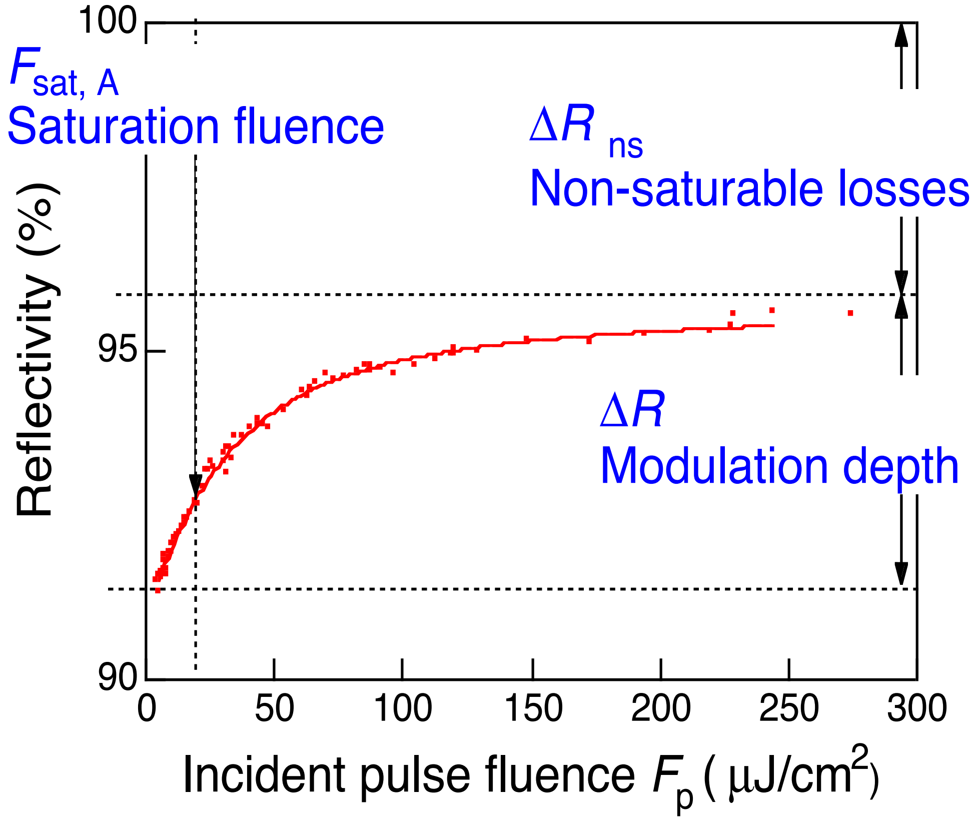
More on LT MBE growth and ion implantation to reduce recovery time of SESAMs:

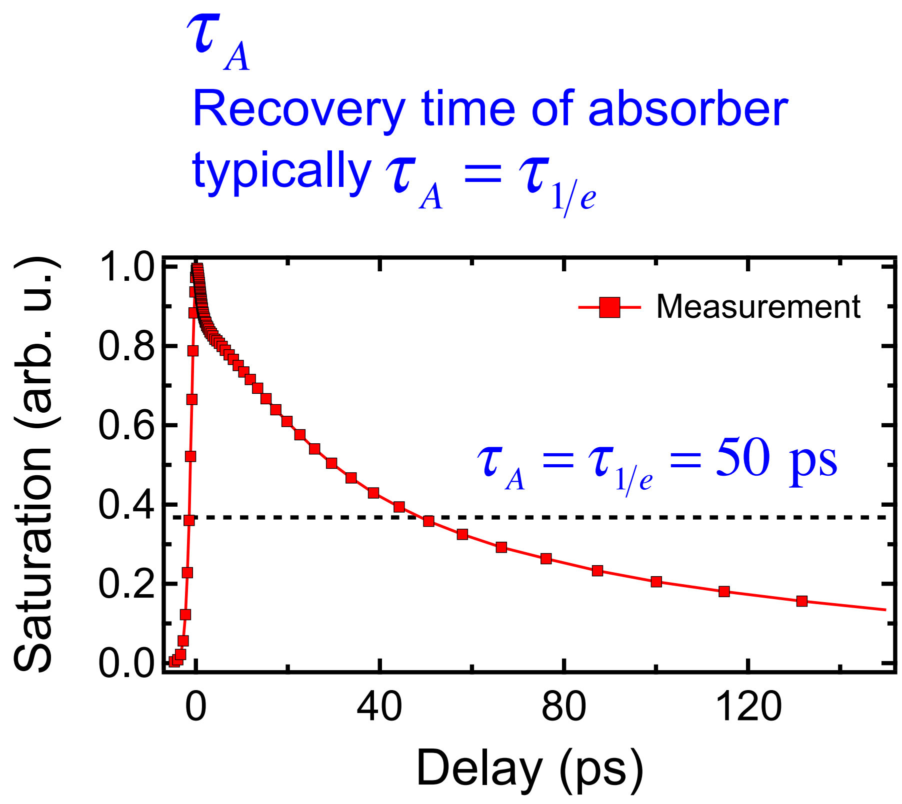
Appl. Phys. Lett., vol. 74, 3134-3136, 1999
Appl. Phys. Lett., vol. 74, pp. 1269-1271, 1999
Physica B: Condensed Matter, vol. 273-274, pp. 733-736, 1999

Appl. Phys. Lett., vol. 75, pp. 1437-1439, 1999
Appl. Phys. Lett., vol. 74, pp. 1993-1995, 1999



Basic SESAM Parameters





Guidelines how to measure these parameters:
M. Haiml, R. Grange, U. Keller, *Appl. Phys. B* **79**, 331, 2004
with improved accuracy: D. J. H. Maas, et al., *Optics Express* **16**, 7571, 2008

Recovery time: how short?
Depends on laser parameter. Soliton modelocking helps.

Low temperature MBE growth: LT GaAs

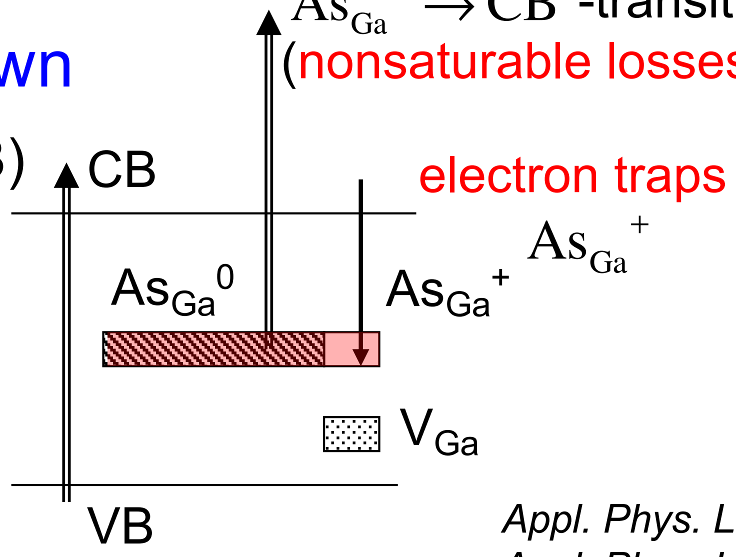
(a) LT GaAs: as grown

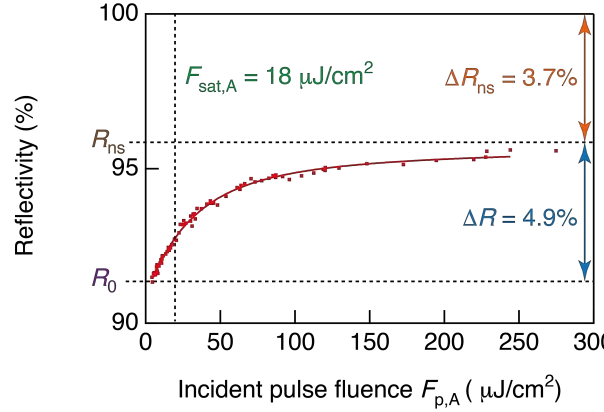
$As_{Ga}^{0} \rightarrow CB$ -transition strong (nonsaturable losses increased)

Conduction band (CB)

mid-gap defects: As antisites

Valence band (VB)



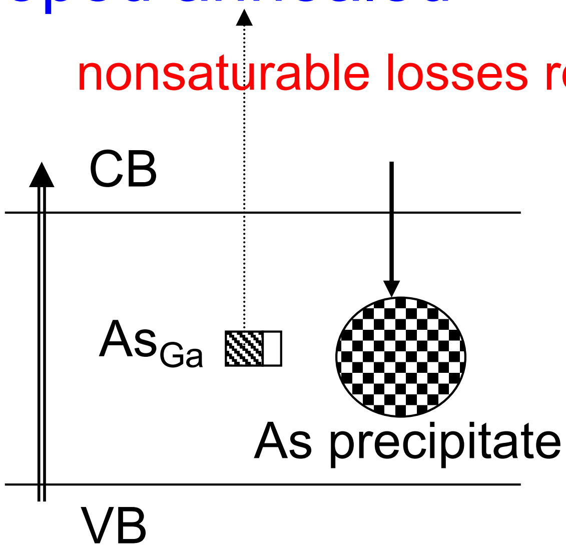


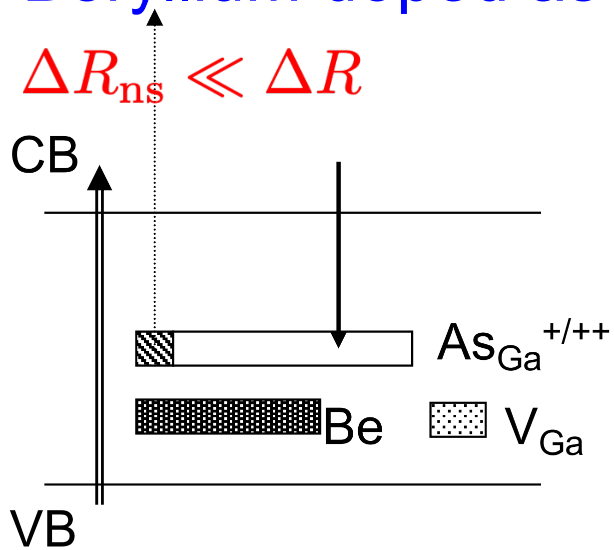
Appl. Phys. Lett. **74**, 3134, 1999
Appl. Phys. Lett. **74** 1269, 1999
Physica B: Condensed Matter **273-274**, 733,1999

(b) Undoped annealed

(c) Beryllium doped as grown

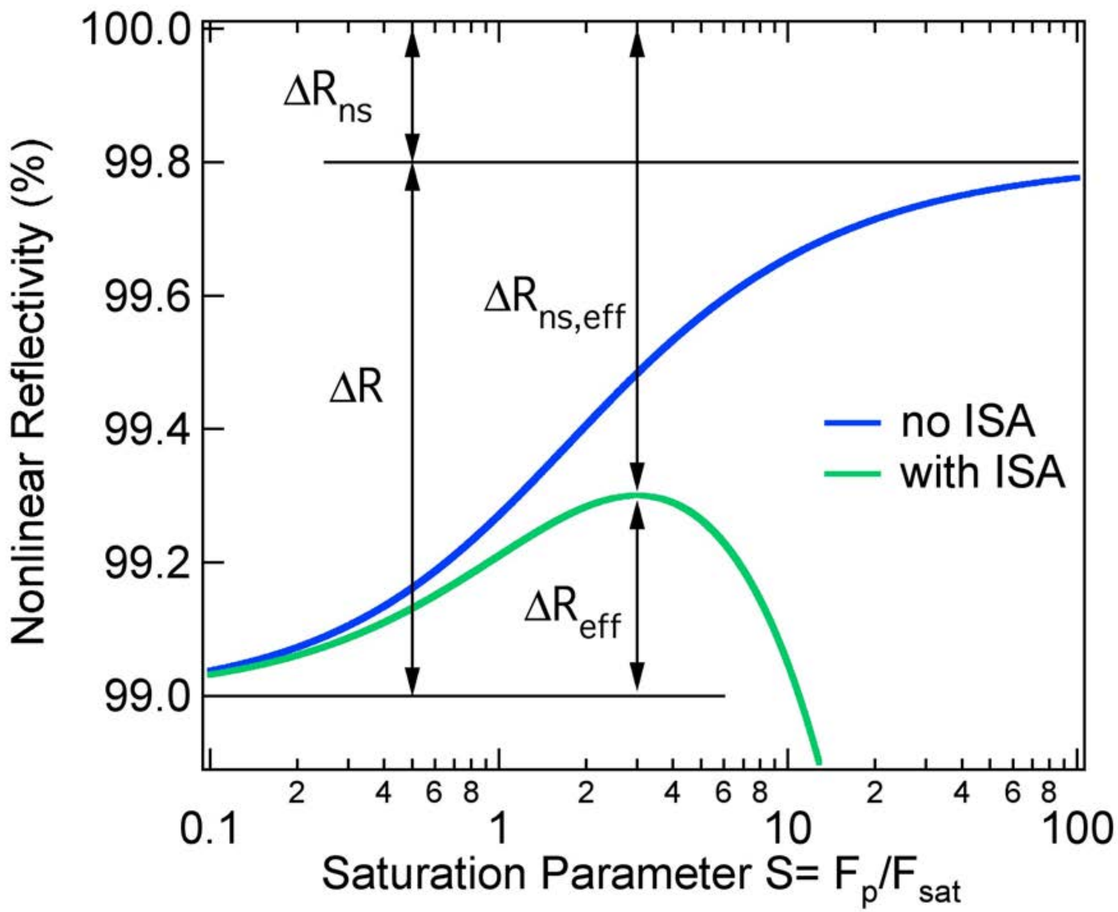
nonsaturable losses reduced: $\Delta R_{ns} \ll \Delta R$





Inverse saturable absorption (ISA)

SESAM reflectivity for a pulse fluence F_p



Reflectivity decreases with shorter pulses: two photon absorption

⬇

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

Fluence on absorber at maximum reflectivity and damage:

$$F_0 \approx \sqrt{\Delta R \cdot F_{sat,A} \cdot F_2} \qquad F_d \propto \sqrt{F_2}$$

R. Grange et al, *Appl. Phys. B* **80**, 151, 2005

C. J. Saraceno et al, *IEEE JSTQE* **18**, 29-41, 2012

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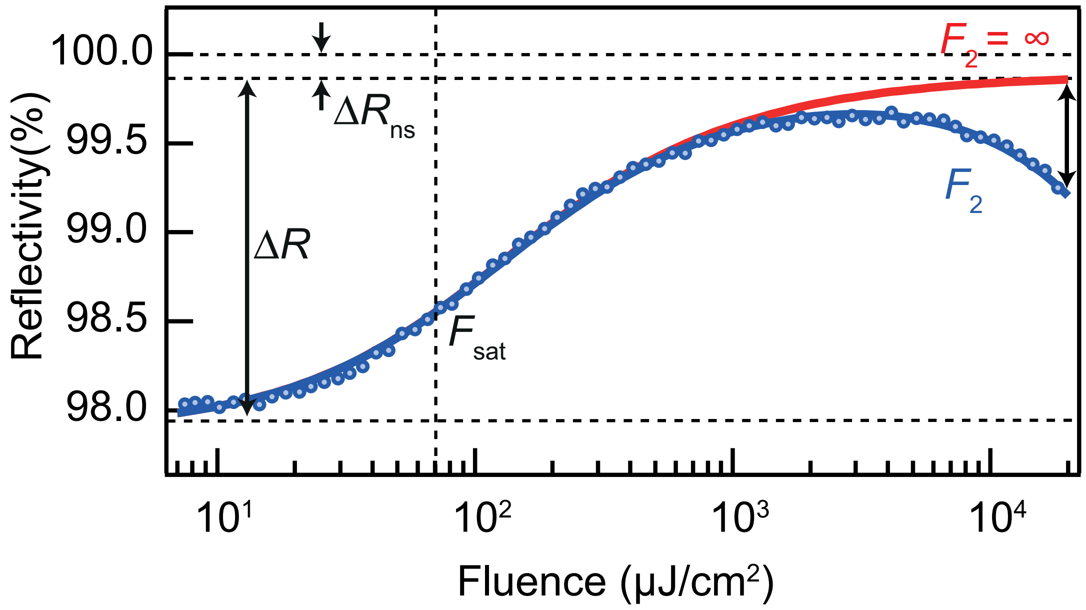

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R. Grange et al, *Appl. Phys. B* ***80***, 151, 2005

C. J. Saraceno et al, *IEEE JSTQE* **18**, 29-41, 2012

Strain compensation for InGaAs SESAM & MIXSEL

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

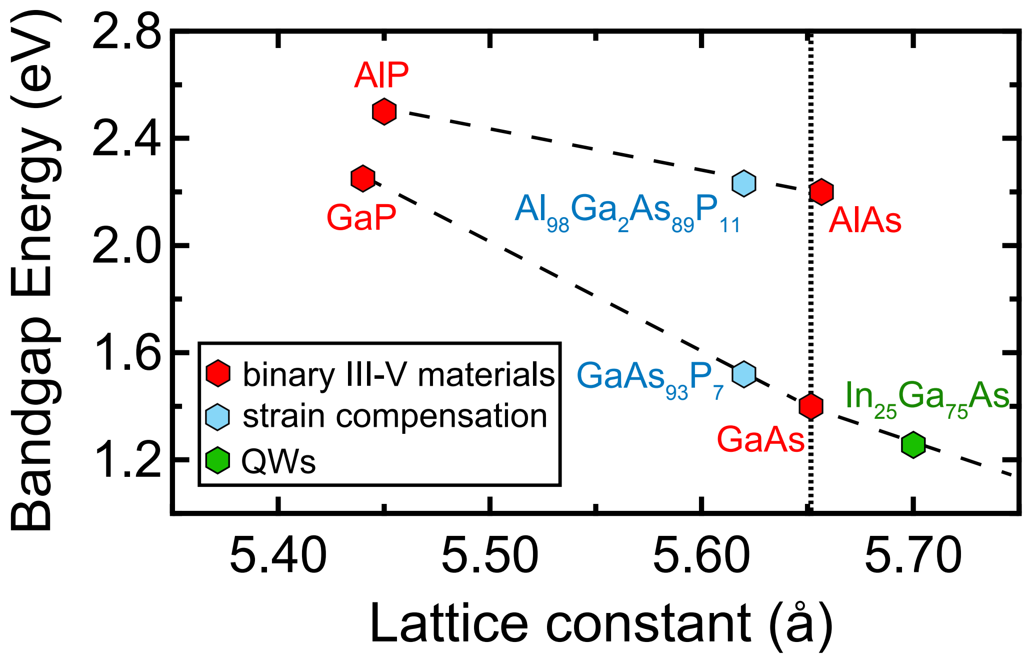
Dominik Waldburger (2018)

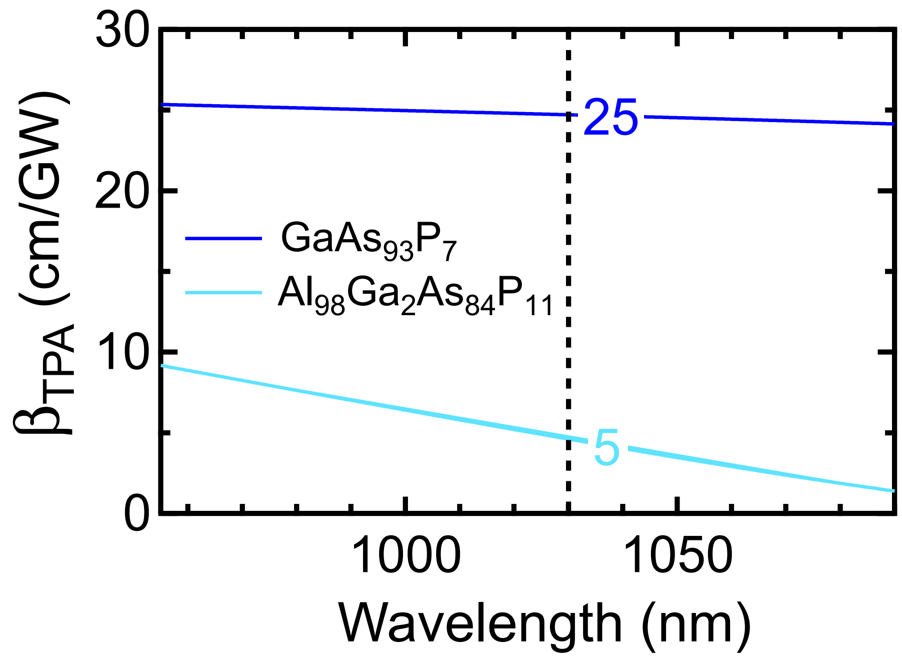
Cesare Alfieri (2018)

Large-bandgap AlAsP for strain-compensation for InGaAs SESAMs and MIXSELs:

For example allowed for 139-fs MIXSEL

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

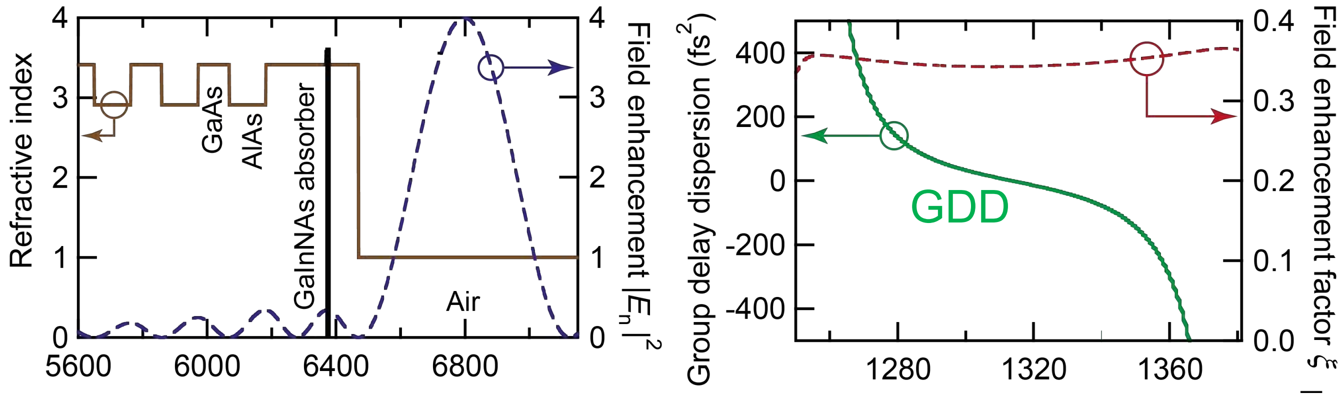




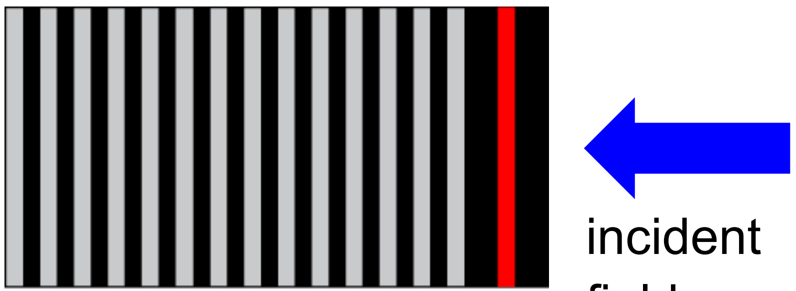
C. G. E. Alfieri, A. Diebold, F. Emaury, E. Gini, C. J. Saraceno, U. Keller. *Opt. Express* **24**, 27587-27599 (2016)

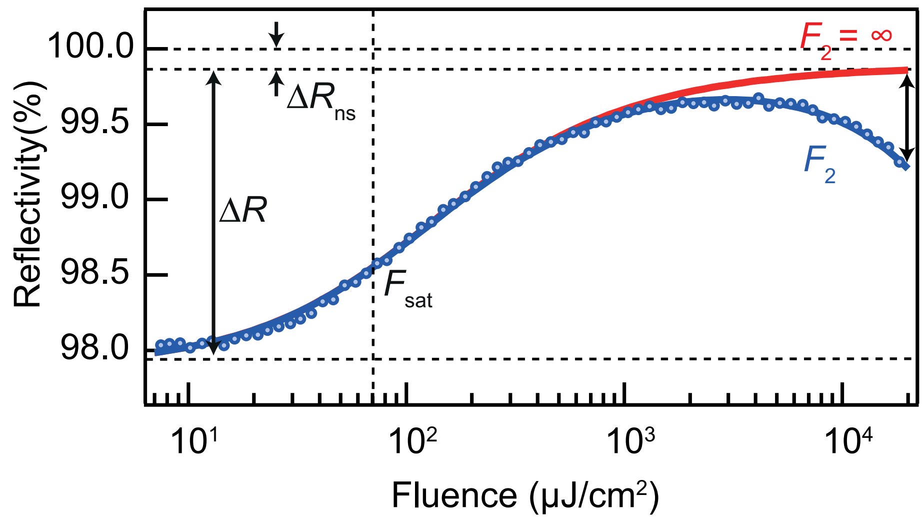
Antiresonant versus Resonant

antiresonant
SESAM



Very often need low saturation fluence F_{sat}





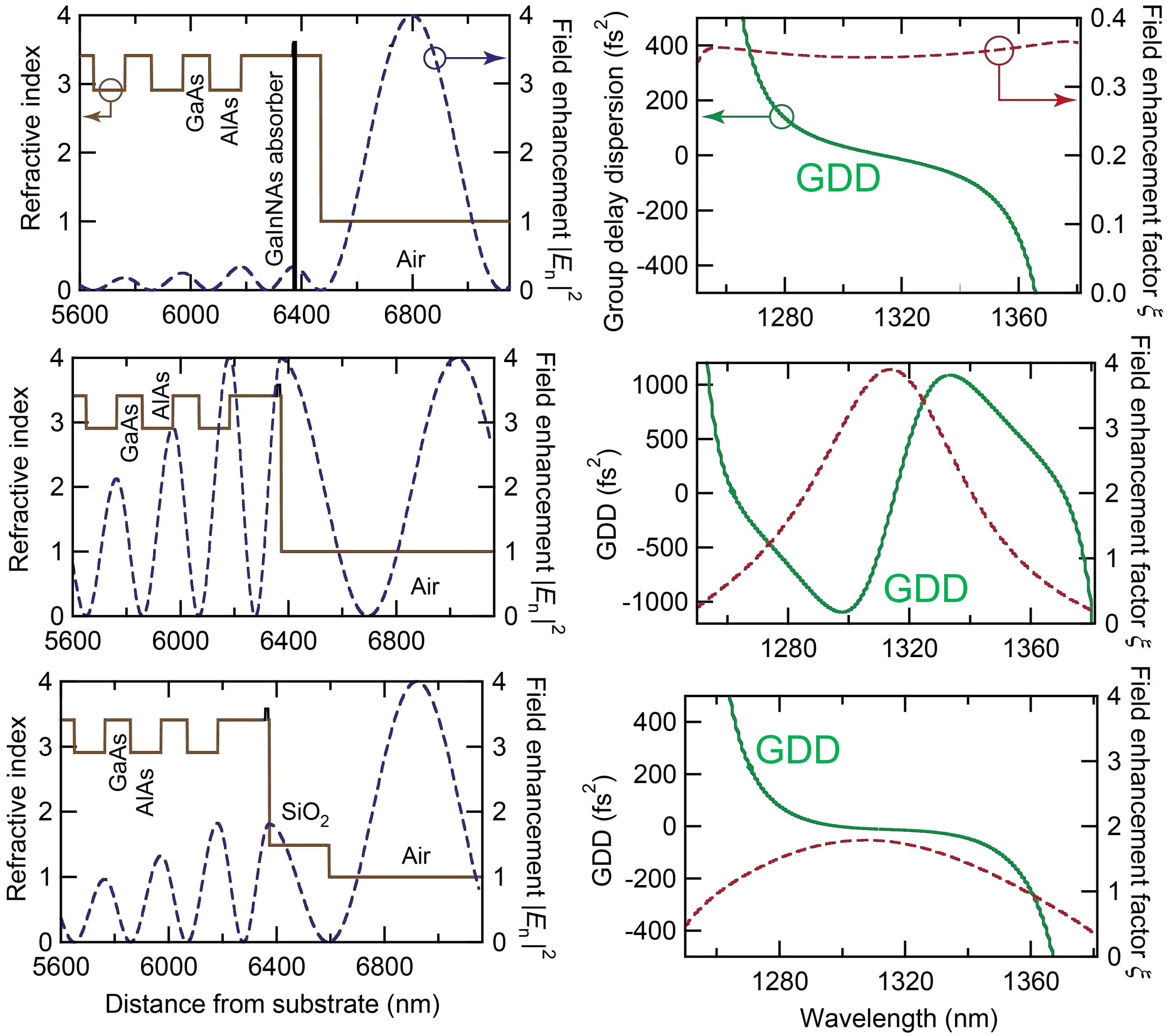
G. J. Spühler, K. J. Weingarten, R. Grange, L. Krainer, M. Haiml, V. Liverini, M. Golling, S. Schön, U. Keller
"Semiconductor saturable absorber mirror structure with low saturation fluence"
Appl. Phys. B, vol. 81, Nr. 1, pp. 27-32, 2005

Antiresonant versus Resonant

antiresonant SESAM

resonant SESAM ☹

"optimized" SESAM for low saturation fluence ☺



G. J. Spühler, K. J. Weingarten, R. Grange, L. Krainer, M. Haiml, V. Liverini, M. Golling, S. Schön, U. Keller
"Semiconductor saturable absorber mirror structure with low saturation fluence"
Appl. Phys. B, vol. 81, Nr. 1, pp. 27-32, 2005

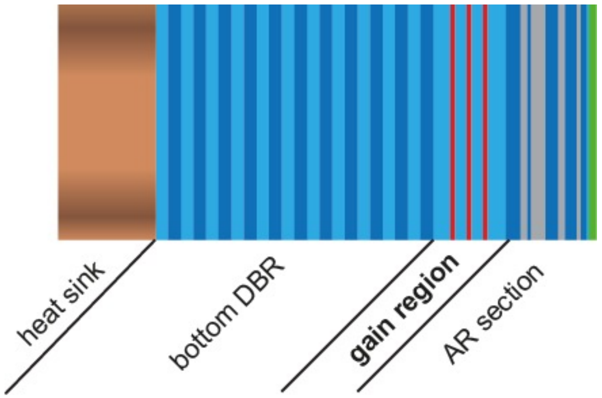
Outline

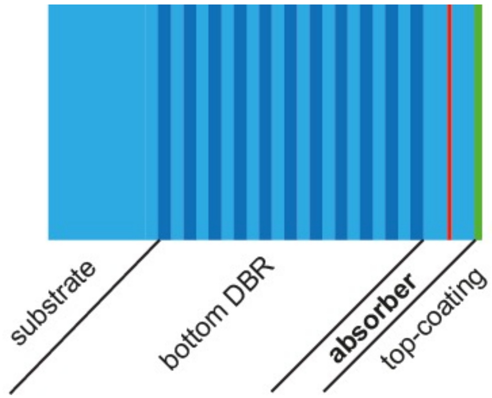
1. SESAM, VECSEL and MIXSEL basic device structure
2. Dual-comb modelocking and application demonstration
3. III-V semiconductor material
4. **MIXSEL and SESAM modelocked VECSEL**
5. Long wavelength SESAMs (> 2µm)
6. Outlook

Semiconductor disk lasers

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

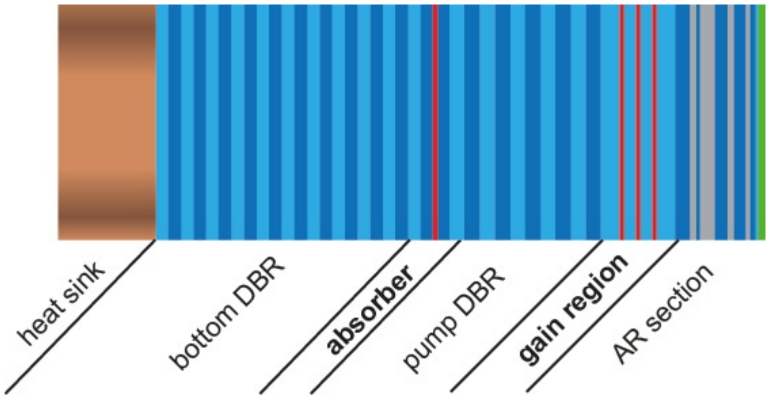
VECSEL & **SESAM**

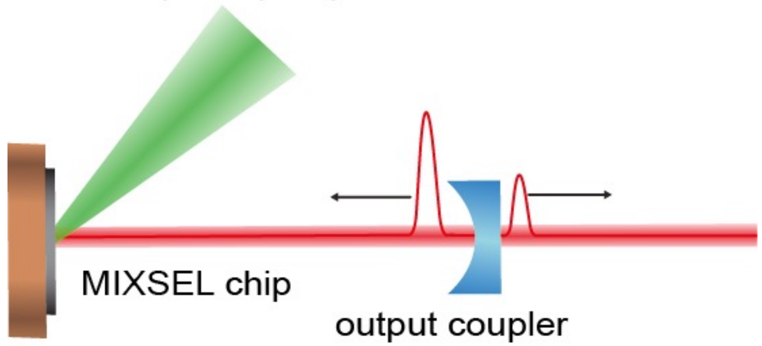




MIXSEL

modelocked integrated external-cavity surface-emitting laser



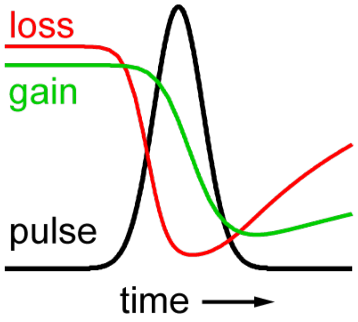


D. J. H. C. Maas et al., *Appl. Phys. B* **88**, 493, 2007

Low saturation fluence

Low saturation fluence $F_{sat,a}$ of saturable absorber

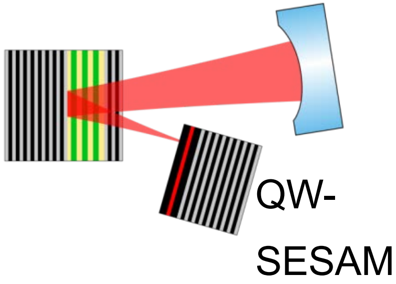
requirement for stable modelocking

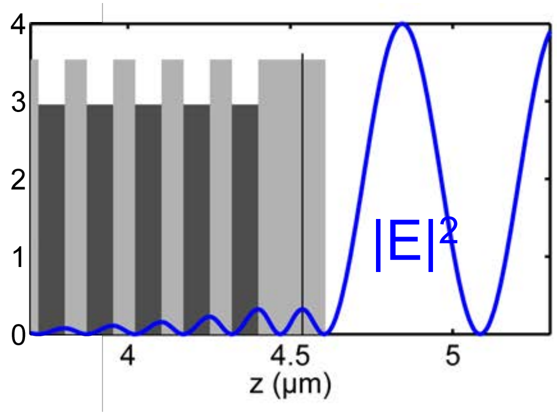


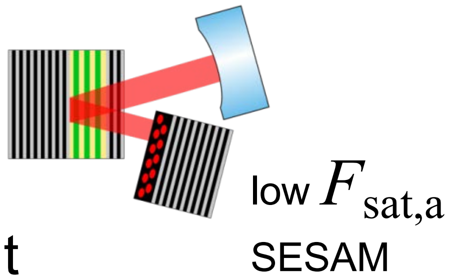
$$\frac{E_{sat,a}}{E_{sat,g}} = \frac{F_{sat,a}\,A_a}{F_{sat,g}\,A_g} < 0.1$$

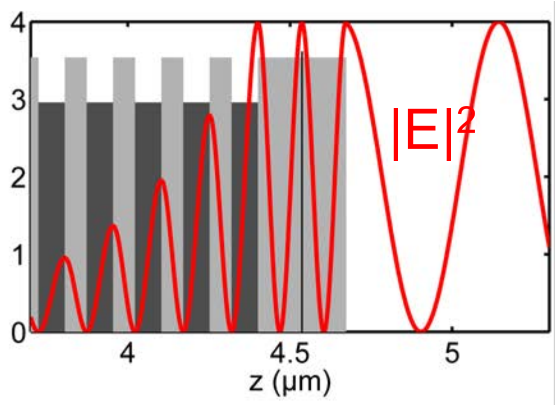
QW-SESAMs: $A_a < A_g$

- More difficult for MIXSEL integration!





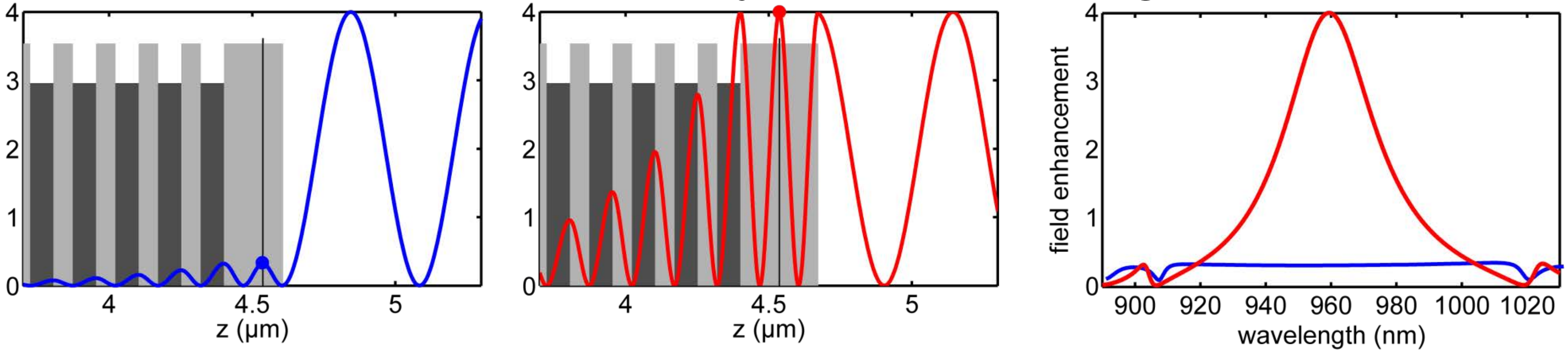




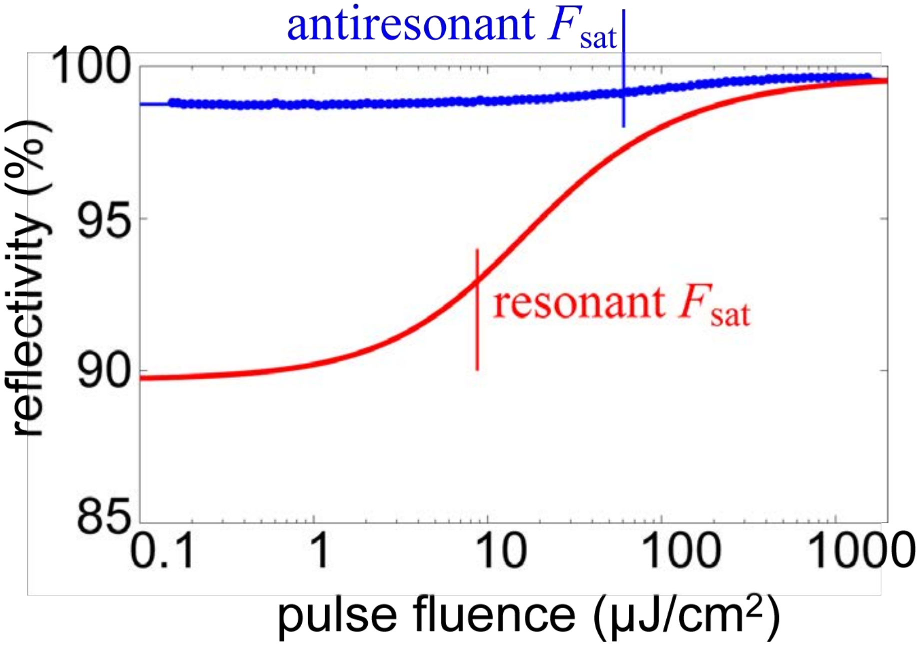
- Need: $F_{sat,a} < F_{sat,g}$
- increase field enhancement move from antiresonant to resonant

Antiresonant versus Resonant

- Increase field enhancement by resonant design[#1]



- Modulation depth increases



	ΔR (%)	F_{sat} (µJ/cm²)	$\Delta R\ F_{sat}$ (µJ/cm²)
antiresonant	1.16	60.5	0.70
resonant	10.03	8.7	0.87

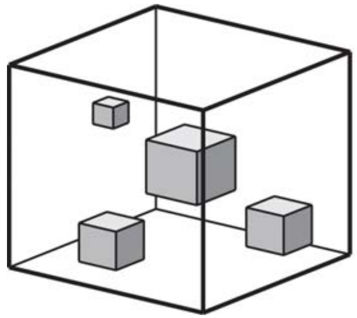
→ too large

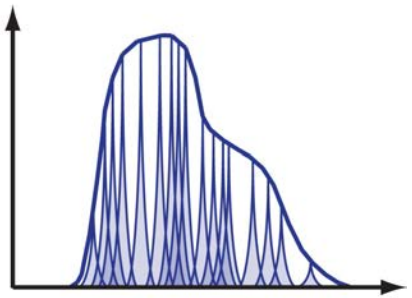
$\Delta R\ F_{sat}$ is independent of design!

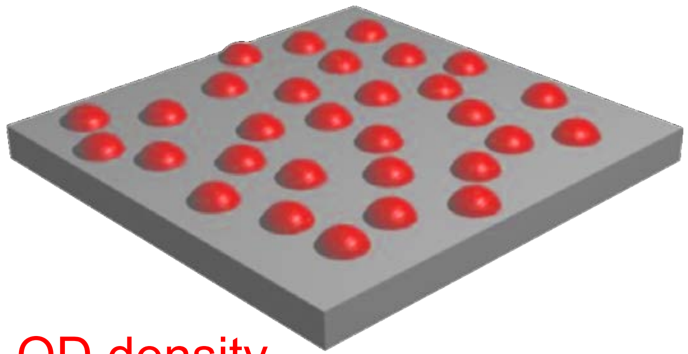
[#1] Spühler et al., Appl. Phys. B **81**, 27-32 (2005)

Towards Absorber Integration: Quantum Dots (QDs)

QDs absorbers offer more growth parameters than QWs absorbers







Deran Maas (2008)

QD size and size distribution

→ determine absorption spectrum

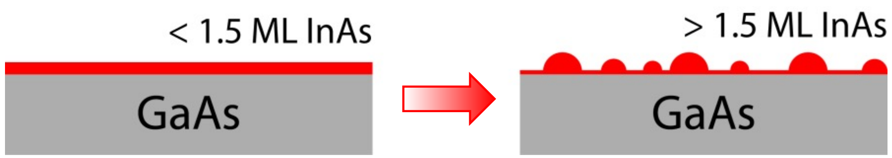
QD density

→ determines modulation depth

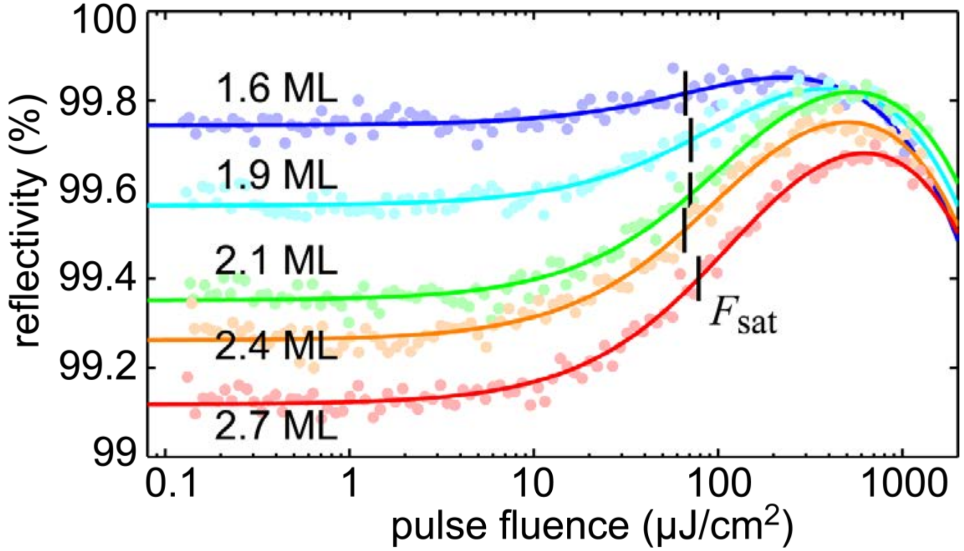
QD growth

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

Self-assembled QD formation:

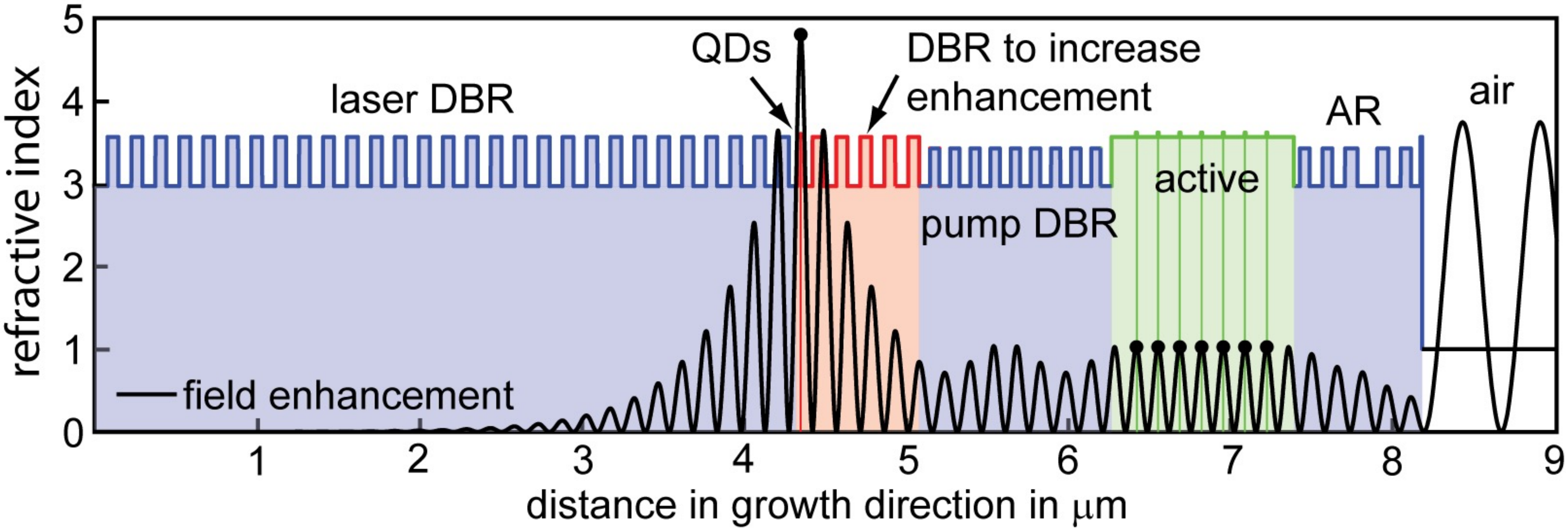


ΔR can be tuned with dot density, while F_{sat} stays constant!



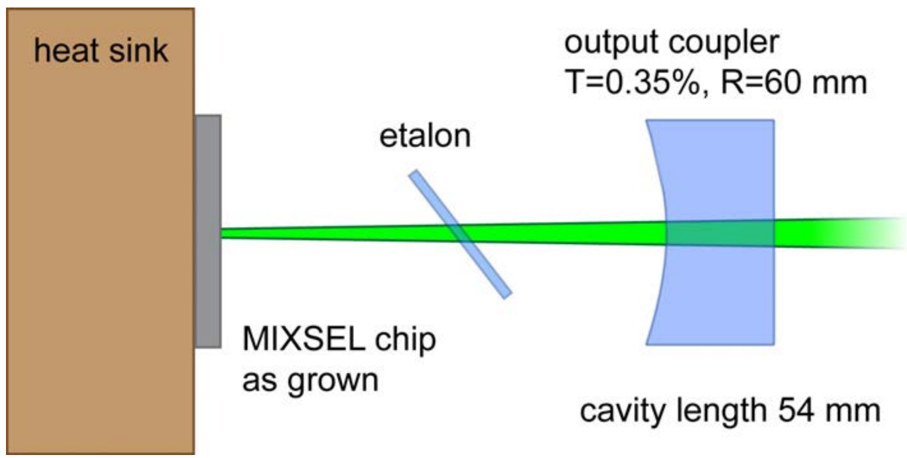
First MIXSEL demonstration: 35 ps, 40 mW, 2.8 GHz

Resonant design



Sections:

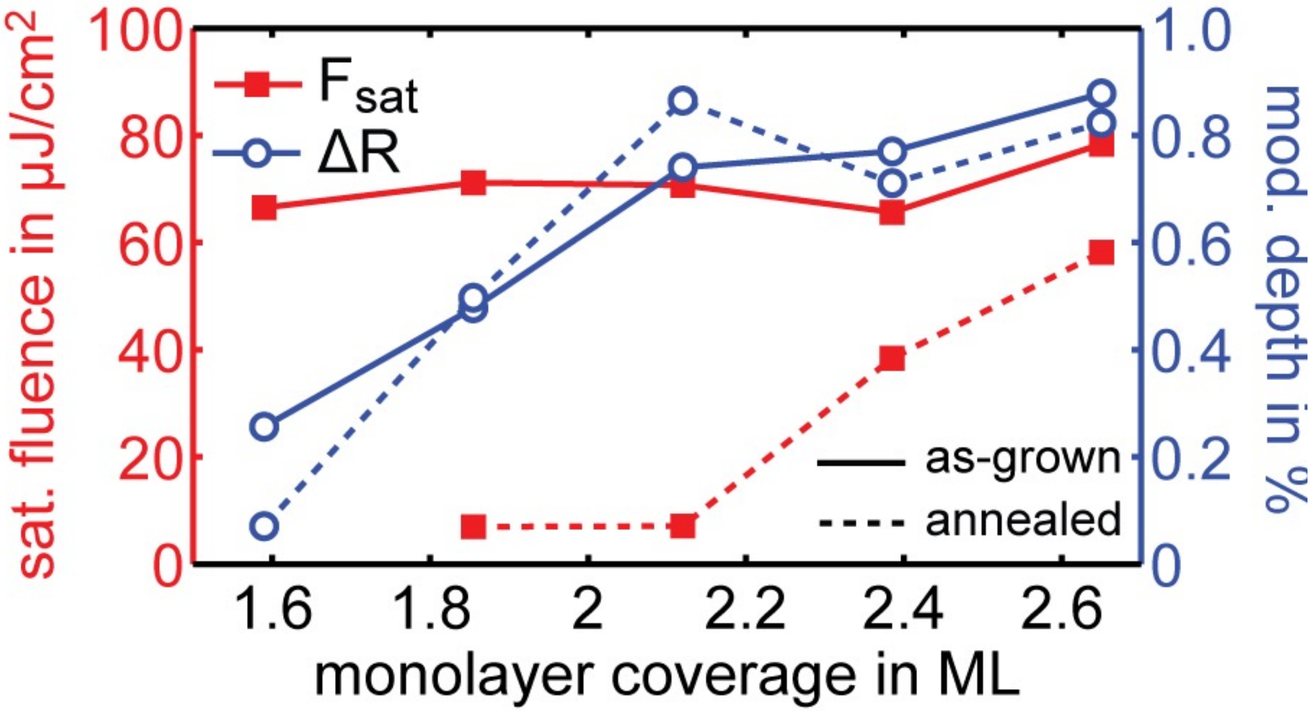
- 30 pair bottom mirror for the laser
- 1 layer of self-assembled InAs QD
- DBR to increase field in absorber
- 9 pair mirror for the pump
- active region with 7 InGaAs QWs
- AR coating



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

QD-SESAM annealing benefits: lower F_{sat}

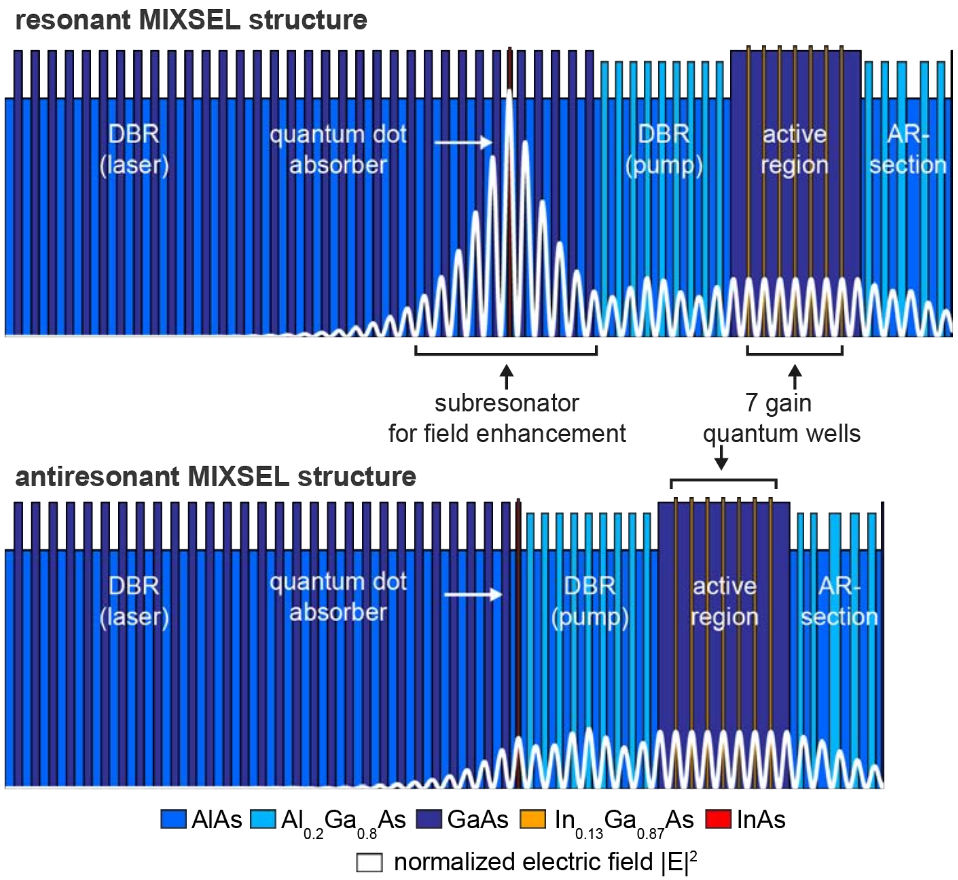
Optics Express **16**, 18646 (2008)

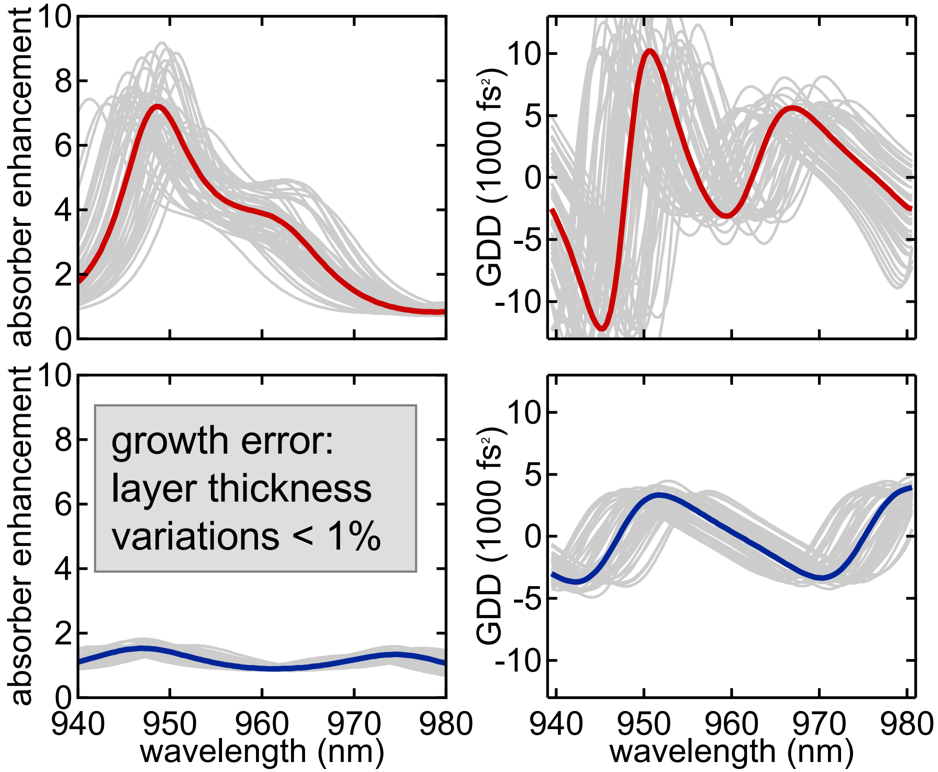


Deran Maas (2008)

→ F_{sat} decreased by annealing and $\Delta R \approx$ constant

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

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)

High Power MIXSEL

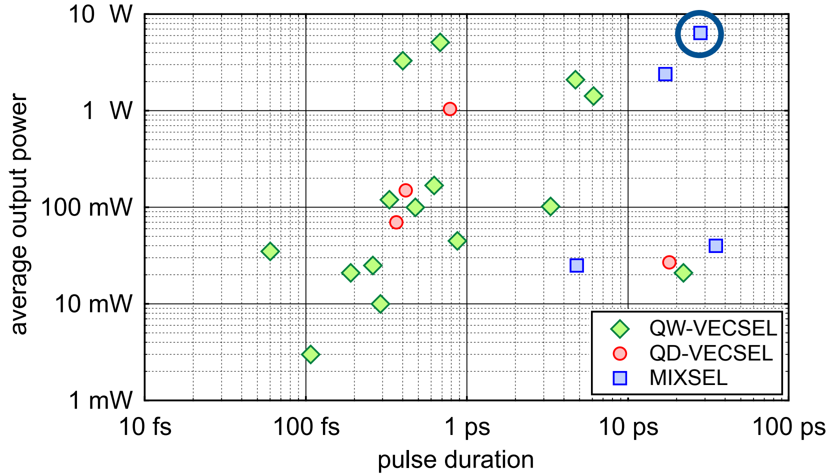
Benjamin Rudin (2010

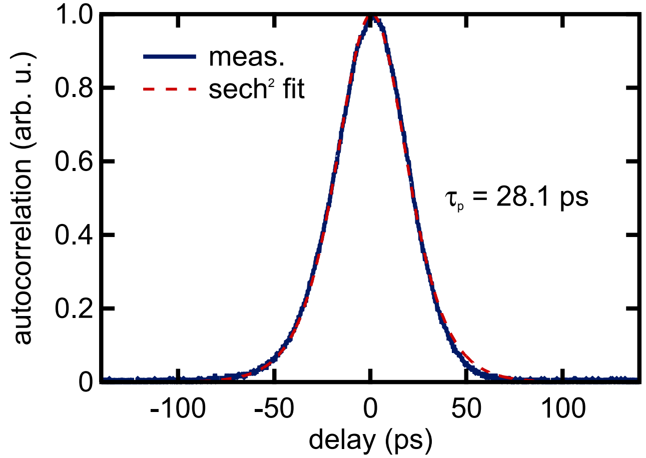
Average power	**6.4 W**
Center wavelength	959.1 nm
Pulse duration	28.1 ps
FWHM spectral width	0.15 nm

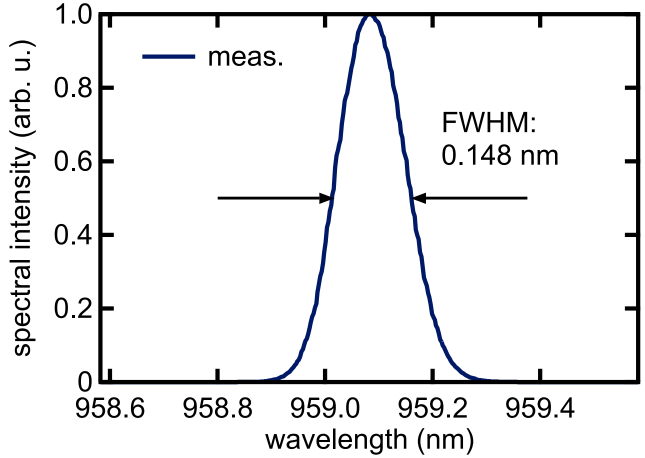
- optical pumping **36.7 W** at **808 nm**
- pump / laser spot radius: **≈215 µm**
- cavity length: **60.8 mm ⇨ 2.47 GHz**
- fluence on the MIXSEL : **252 µJ/cm^2**

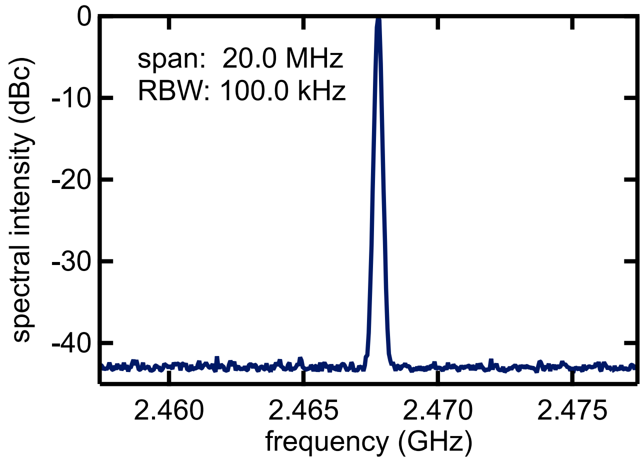
highest average power from an ultrafast semiconductor laser

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





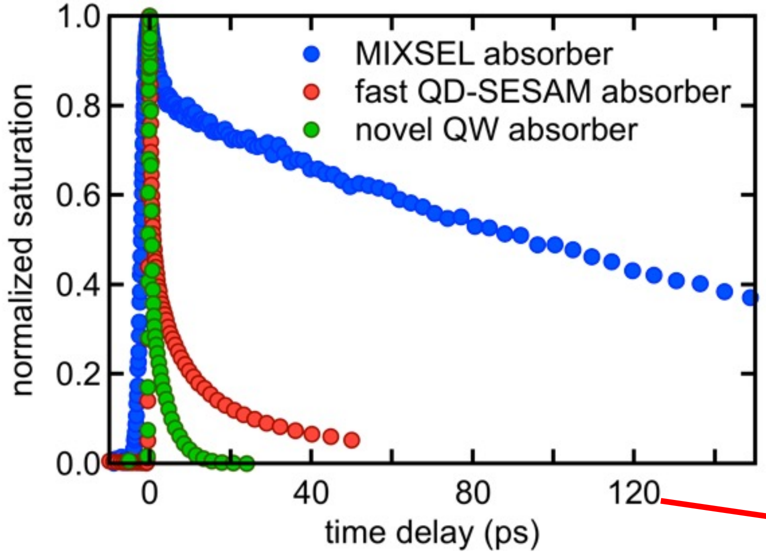




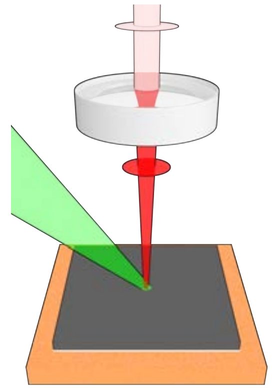
B. Rudin, V.J. Wittwer, D.J.H.C. Maas, M. Hoffmann, O.D. Sieber, Y. Barbarin, M. Golling, T. Südmeyer, U. Keller, OE **18**, 27582 (2010)

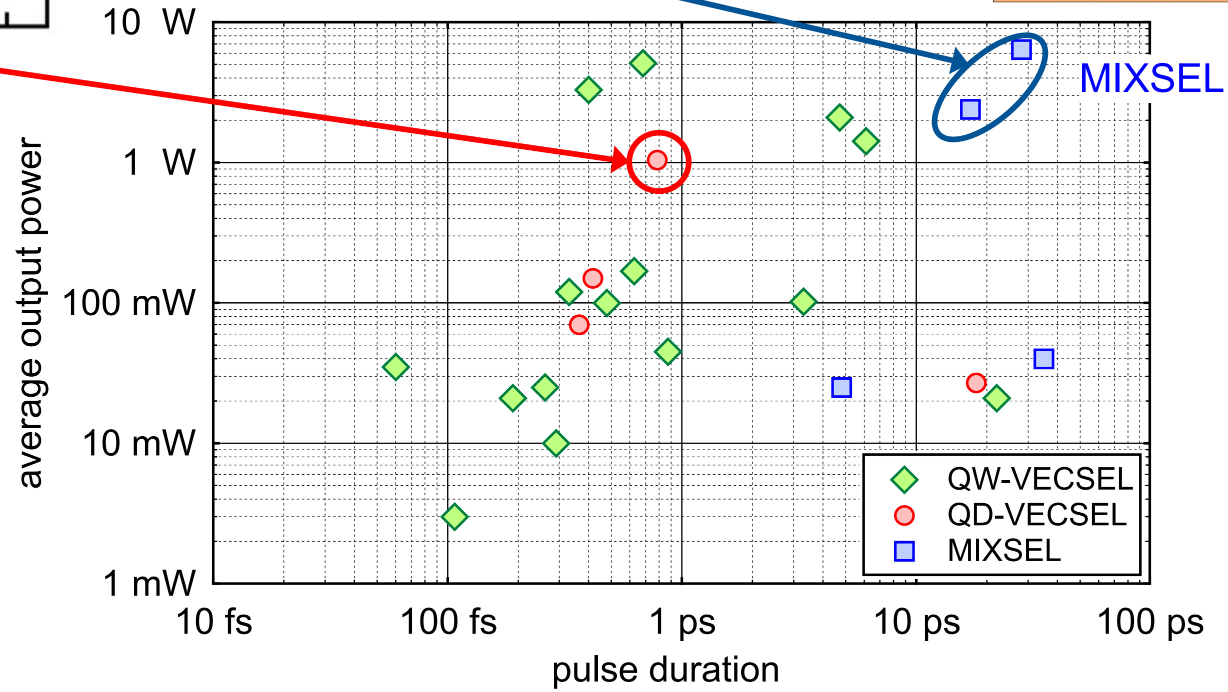
Pulse Shortening

absorber recombination

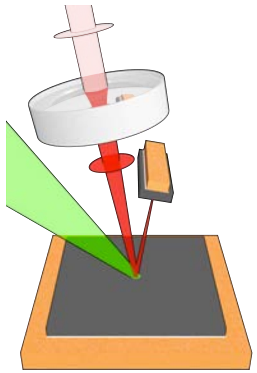


- slow recombination of the QD absorber in the MIXSEL *Optics Express* **18**, 27582 (2010)



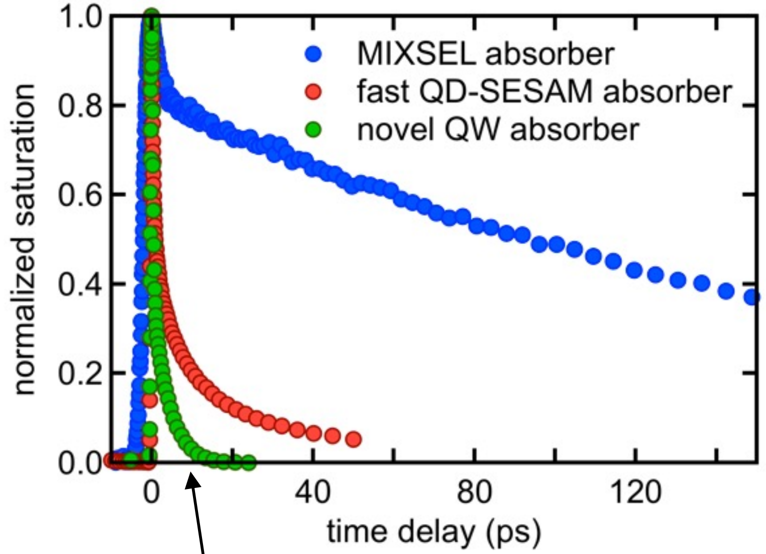


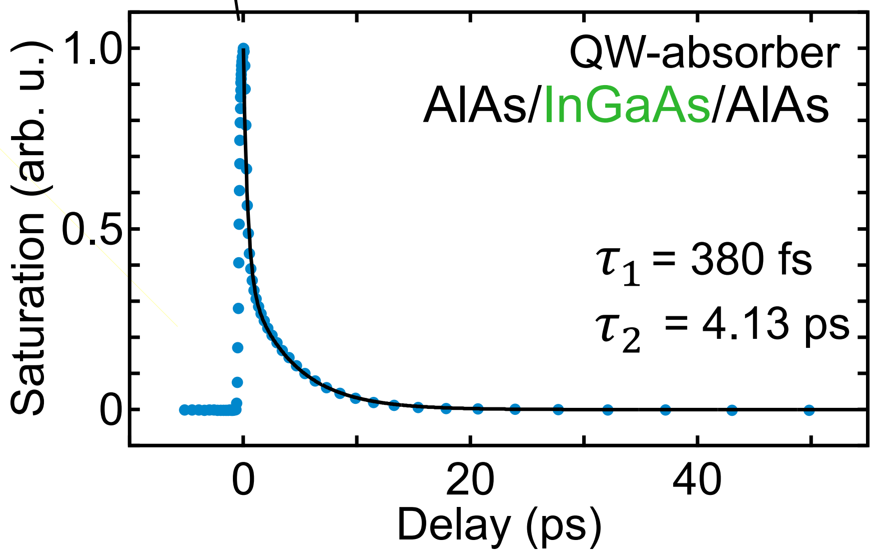
SESAM-modelocked QD-VECSEL:
M. Hoffmann et al.,
Opt. Express **19**, 8108 (2011)



Martin Hoffmann
(2011)

LT AlAs defects more robust with annealing





Saturable absorber

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

- Single LT **InGaAs quantum well**
- Embedded in LT **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	–	+

LT AlAs defects more robust with annealing

Journal of Applied Physics

Lattice parameter changes and point defect reactions in low temperature electron irradiated AlAs

A. Gaber, H. Zillgen, P. Ehrhart, P. Partyka, and R. S. Averback

Journal of Applied Physics **82**, 5348 (1997)

In AlAs defects are rather fixed at their positions and cannot be easily moved by annealing.

Jiang *et al. Nanoscale Research Letters* (2018) 13:301 Nanoscale Research Letters
https://doi.org/10.1186/s11671-018-2719-7

NANO EXPRESS **Open Access**

First-Principles Study of Point Defects in GaAs/AlAs Superlattice: the Phase Stability and the Effects on the Band Structure and Carrier Mobility

Ming Jiang[1], Haiyan Xiao[1*], Shuming Peng[2], Liang Qiao[1], Guixia Yang[2], Zijiang Liu[3] and Xiaotao Zu[1]

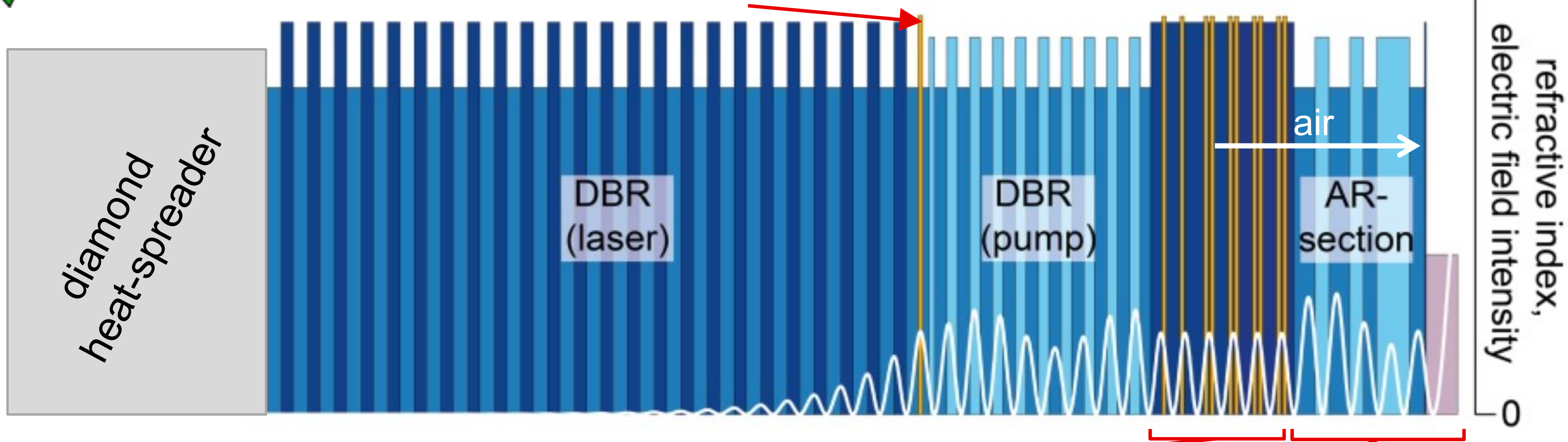
Antisite defects

i.e. Ga_{As}, Al_{As}, As_{Ga}

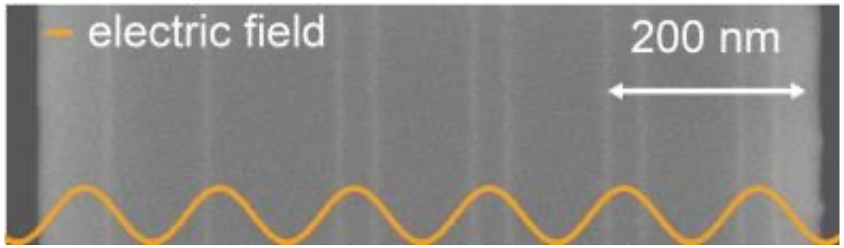
are energetically more favorable than vacancy and interstitial defects in GaAs/AlAs superlattices

2013 NIR MIXSEL structure

Low saturation fluence InGaAs/AlAs QW-absorber (operated closer to the bandedge)

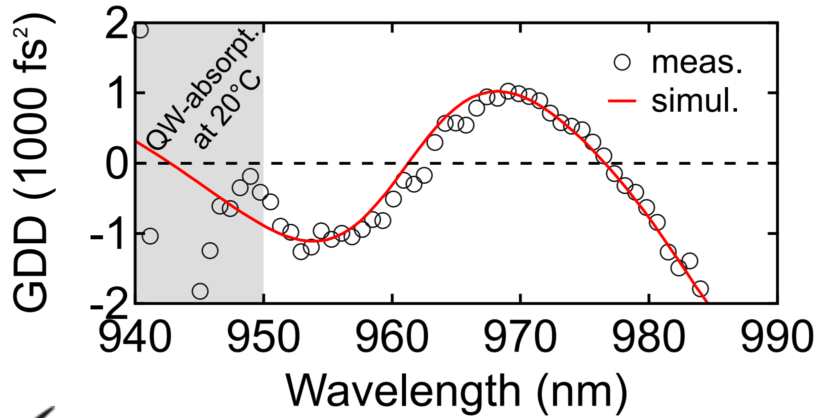


10 quantum well active region



Higher gain saturation fluence and more broadband gain

Anti-reflection section

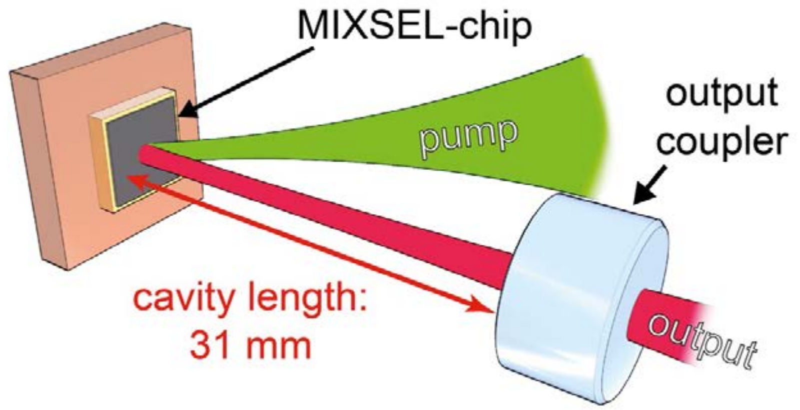


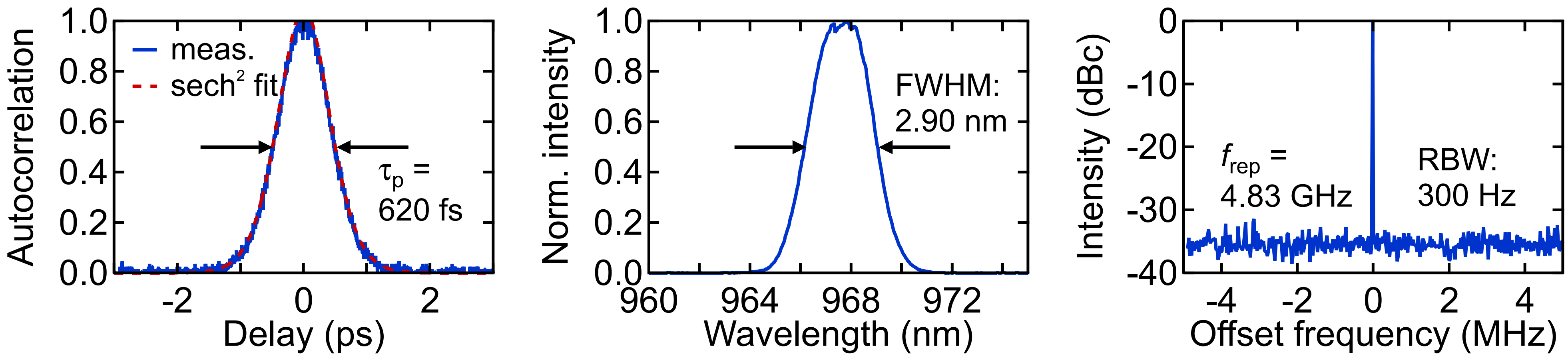
Low and flat group-delay dispersion

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



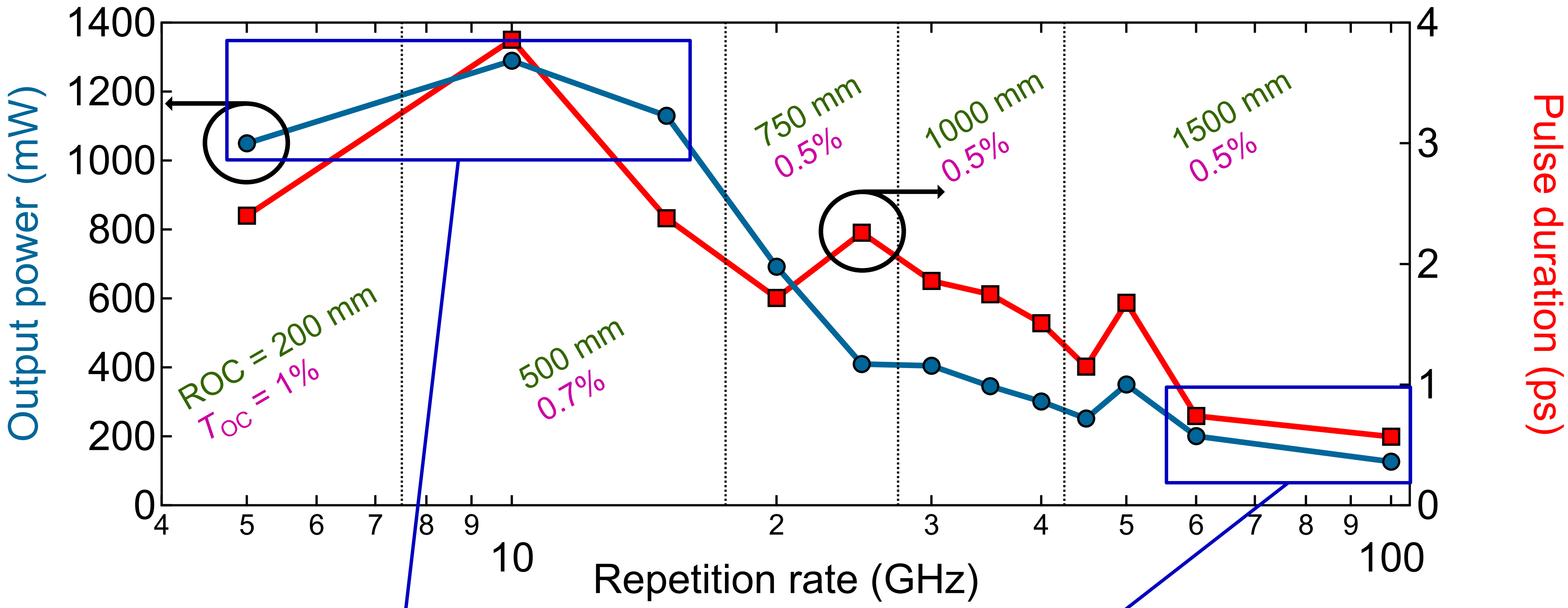


- Optical pumping **24.9 W** at **808 nm**
- Heat sink temperature: **+ 11 ° C**
- Output coupling: **0.35 % (ROC 200 mm)**
- Beam quality: **M^2 < 1.05**

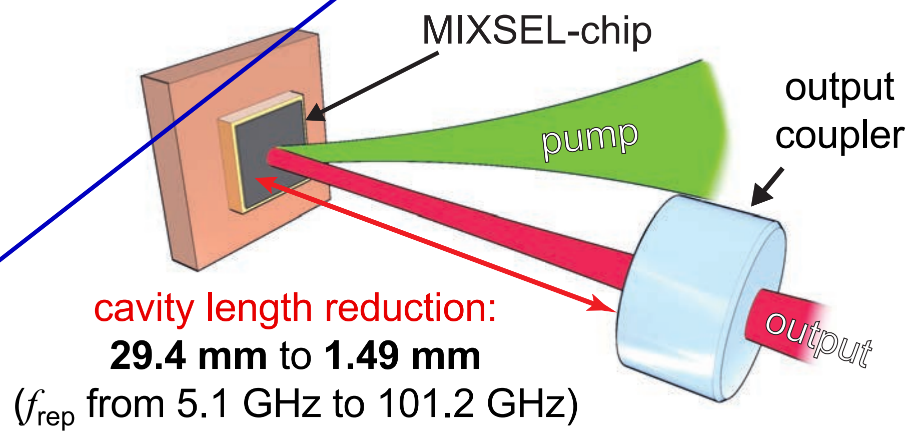
Shorter pulse duration enable scaling to higher repetition rates

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

Repetition-rate scaling of MIXSEL

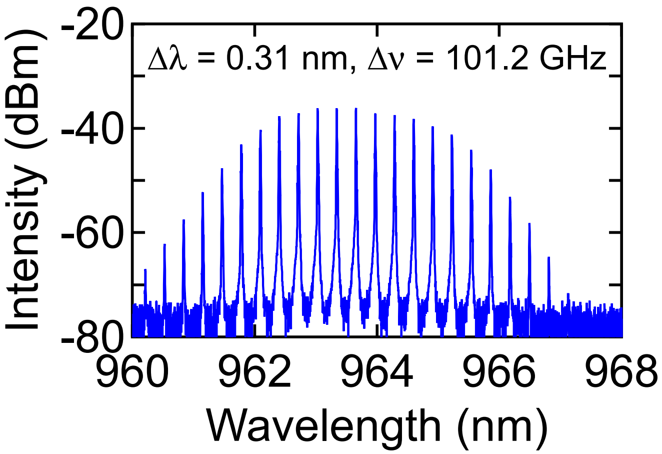


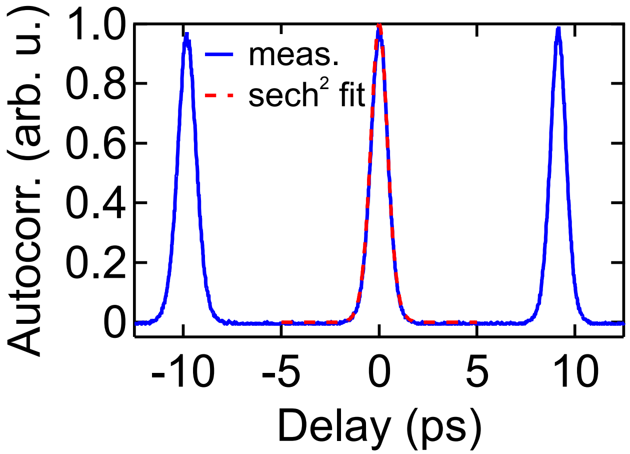
- Repetition rate-tuning from 5 GHz to 101 GHz with single MIXSEL structure
- Watt-level operation up to 15 GHz
- Femtosecond operation at 60 GHz and 101 GHz
- $M^2 < 1.1$ for all measurements

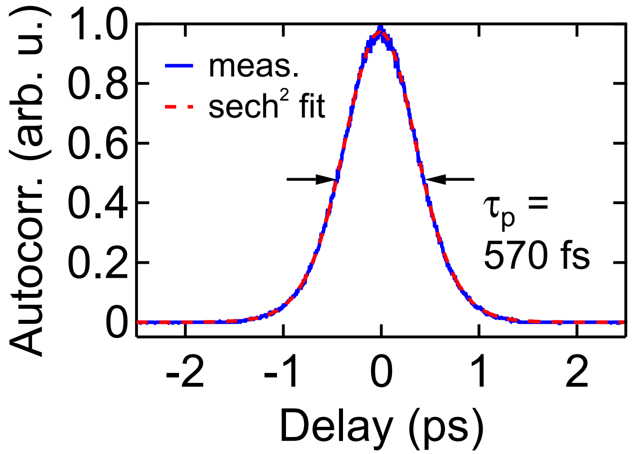


M. Mangold et al., *Opt. Express* **22**, pp. 6099 (2014)

Femtosecond 100-GHz MIXSEL





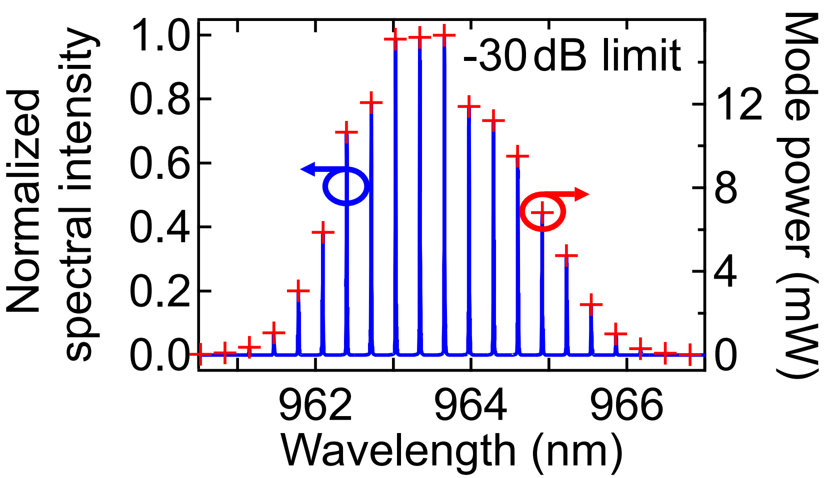


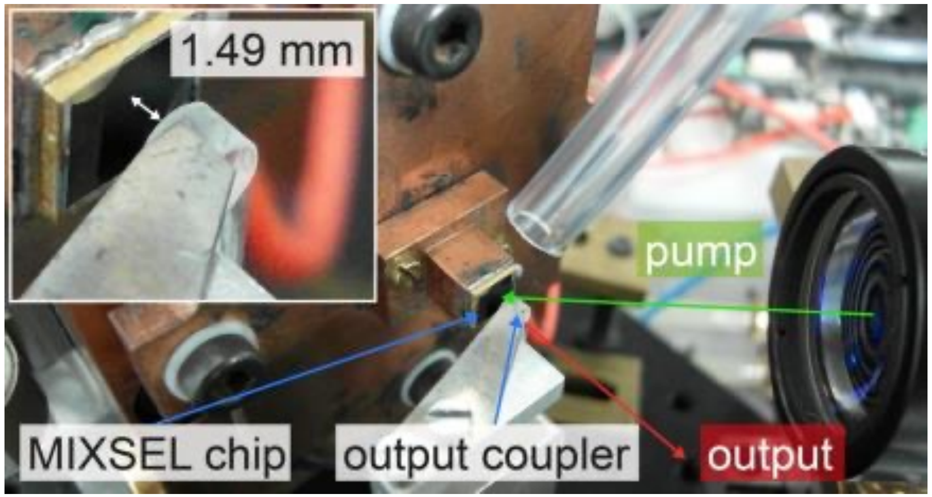
Pulse duration: **570 fs**

Average output power: **127 mW**

Repetition rate: **101.2 GHz**

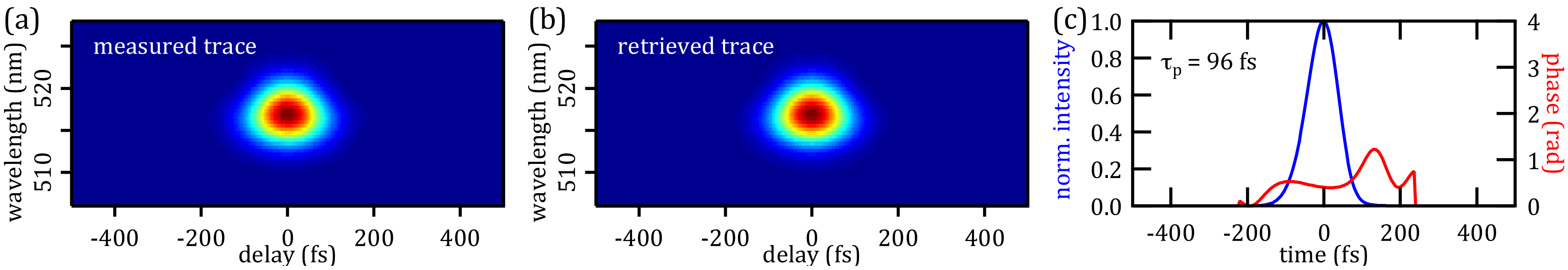
Av. mode power (-30 dB): **7.5 mW**





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

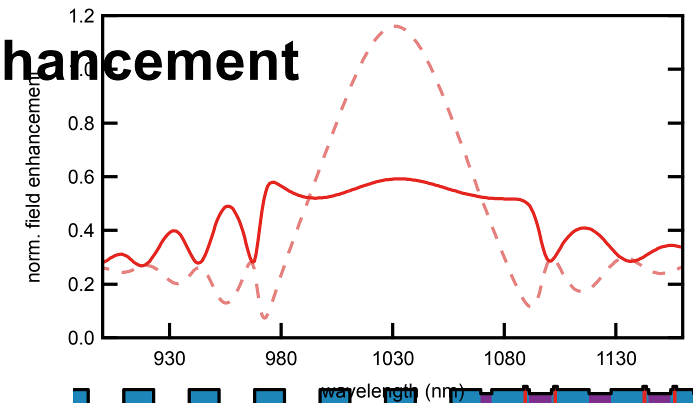
World-record 100-fs 100-mW 1.63-GHz VECSEL



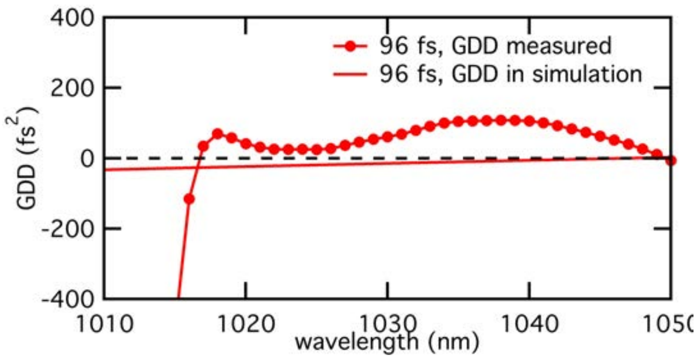
Pulse duration	96 fs
Pulse repetition rate	1.63 GHz
Average power	100 mW

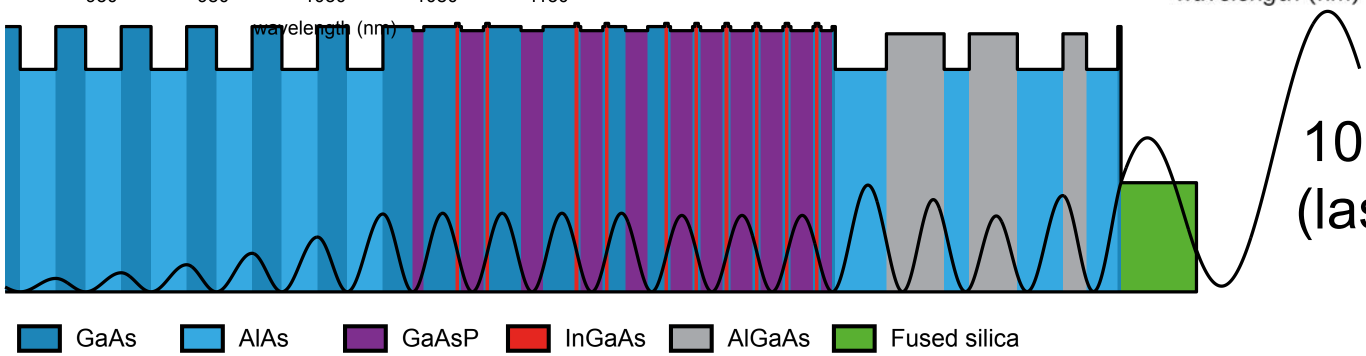
D. Waldburger et al., *Optica* **3**, 844–852 (2016)

Field enhancement



Group delay dispersion

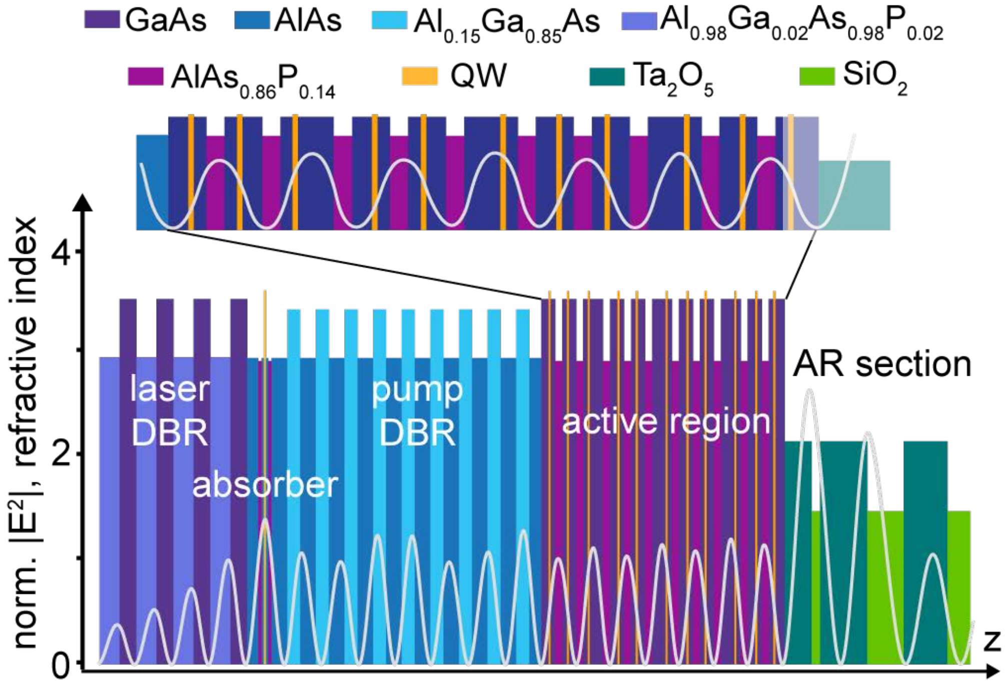


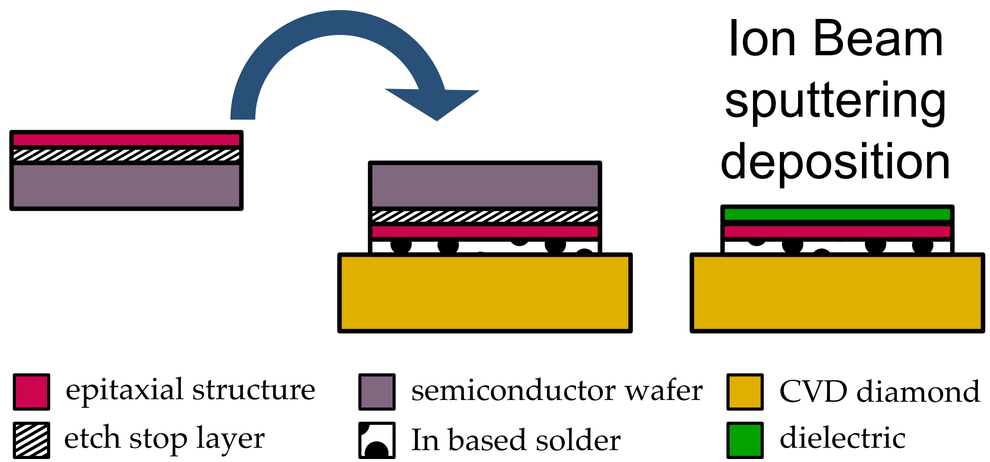


1030 nm
(laser)

139-fs MIXSEL at 1.03 µm

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





Design optimization

⇒ **Quaternary GaAs/AlGaAsP DBR**

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

⇒ **Strain-compensated absorber**

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

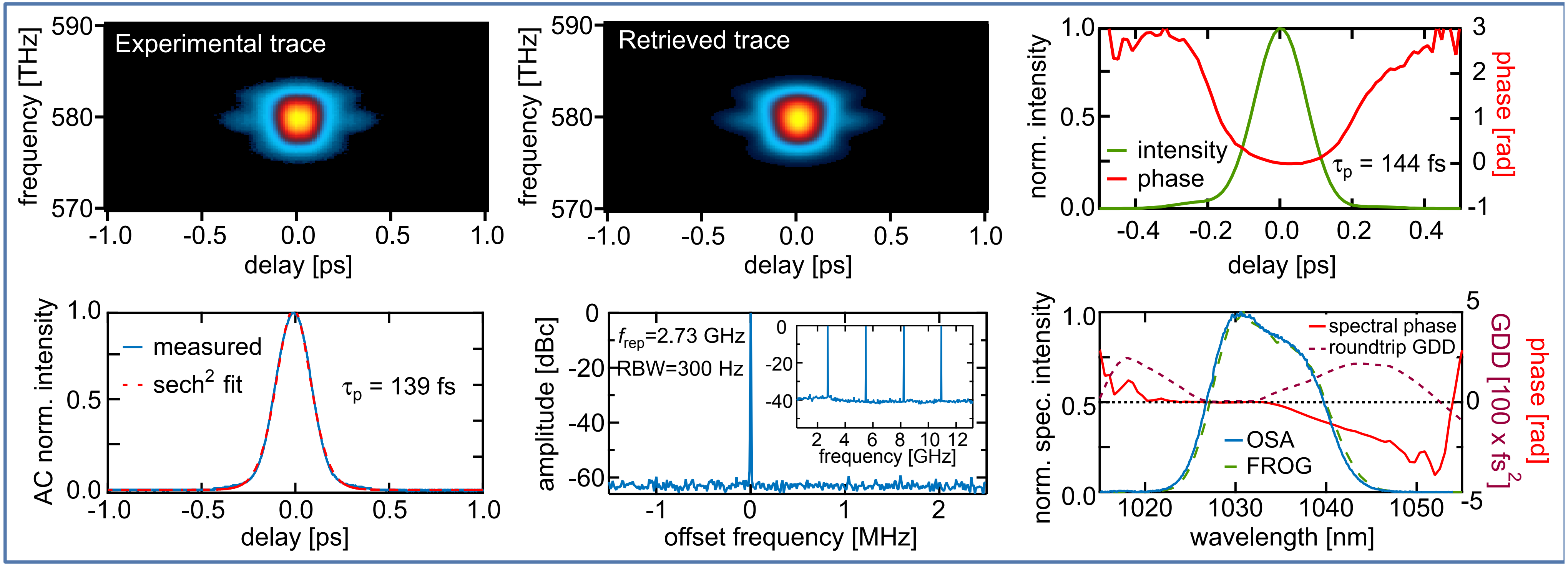
- ⇒ Reduced TPA losses
- ⇒ Optimized pump absorption
- ⇒ Better carrier confinement
- ⇒ No spectral filtering (broad gain)

⇒ **Dielectric IBS top coating (GDD):**

- ⇒ Precise layer thickness
- ⇒ Protection against oxidation
- ⇒ Reduced TPA losses

139-fs MIXSEL at 1.03 µm

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

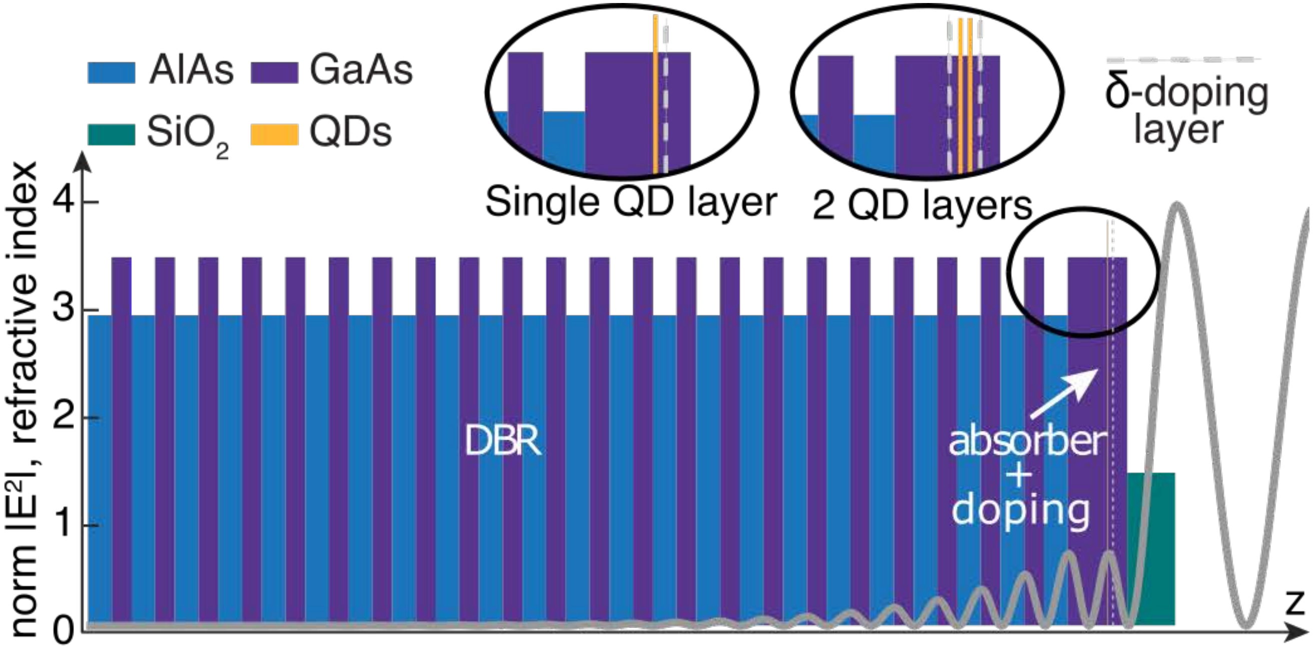


center wavelength [nm]	1033
bandwidth [nm]	13
pulse duration [fs]	139
average output power [mW]	30
pulse repetition rate [GHz]	2.73
Dual-comb operation	✓

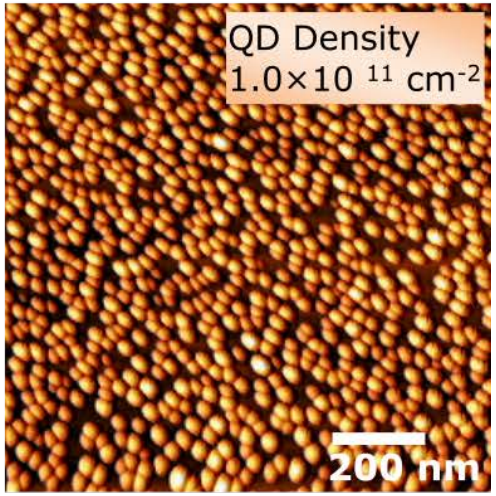
- ✓ 13 nm of FWHM bandwidth (prev. 7.4 nm)
- ✓ Central wavelength tuned to C_2H_2
- ✓ First sub-150-fs MIXSEL
- ✓ Sufficient output power for spectroscopy
- ✓ Sufficient resolution for spectroscopy
- ✓ Turn-key for hundreds of hours

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

Novel concepts for fast saturable absorbers



a)



b)

- High quality InGaAs quantum dots (QDs)
- Radiative recombination is enhanced with high hole density in QDs with modulation doping (using p-typed δ-doping)
- Low saturation fluence <10 μJ/cm²

T. Finke, J. Nürnberg, V. Sichkovskyi, M. Golling, U. Keller, J. P. Reithmaier,
“Temperature resistant fast $In_xGa_{1-x}As$/GaAs quantum dot saturable absorber for epitaxial integration into semiconductor surface emitting lasers”
Optics Express, vol. 28, No. 14, pp. 20954-20965, 2020

Outline

1. SESAM, VECSEL and MIXSEL basic device structure
2. Dual-comb modelocking and application demonstration
3. III-V semiconductor material
4. MIXSEL and SESAM modelocked VECSEL
5. Long wavelength SESAMs (> 2µm)

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This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme grant agreement No 787097

started 1. Jan. 2019

Dr. Özgür Alaydin

Dr. Matthias Golling

M. Rattunde, P. Holl, S. Adler, E. Diwo-Emmer, R. Aidam, J. Wagner

Fraunhofer-Institut for Applied Solid State Physics
Tullastrasse 72, D-79108 Freiburg, Germany

Invited Talk
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  - 1W at 3 µm
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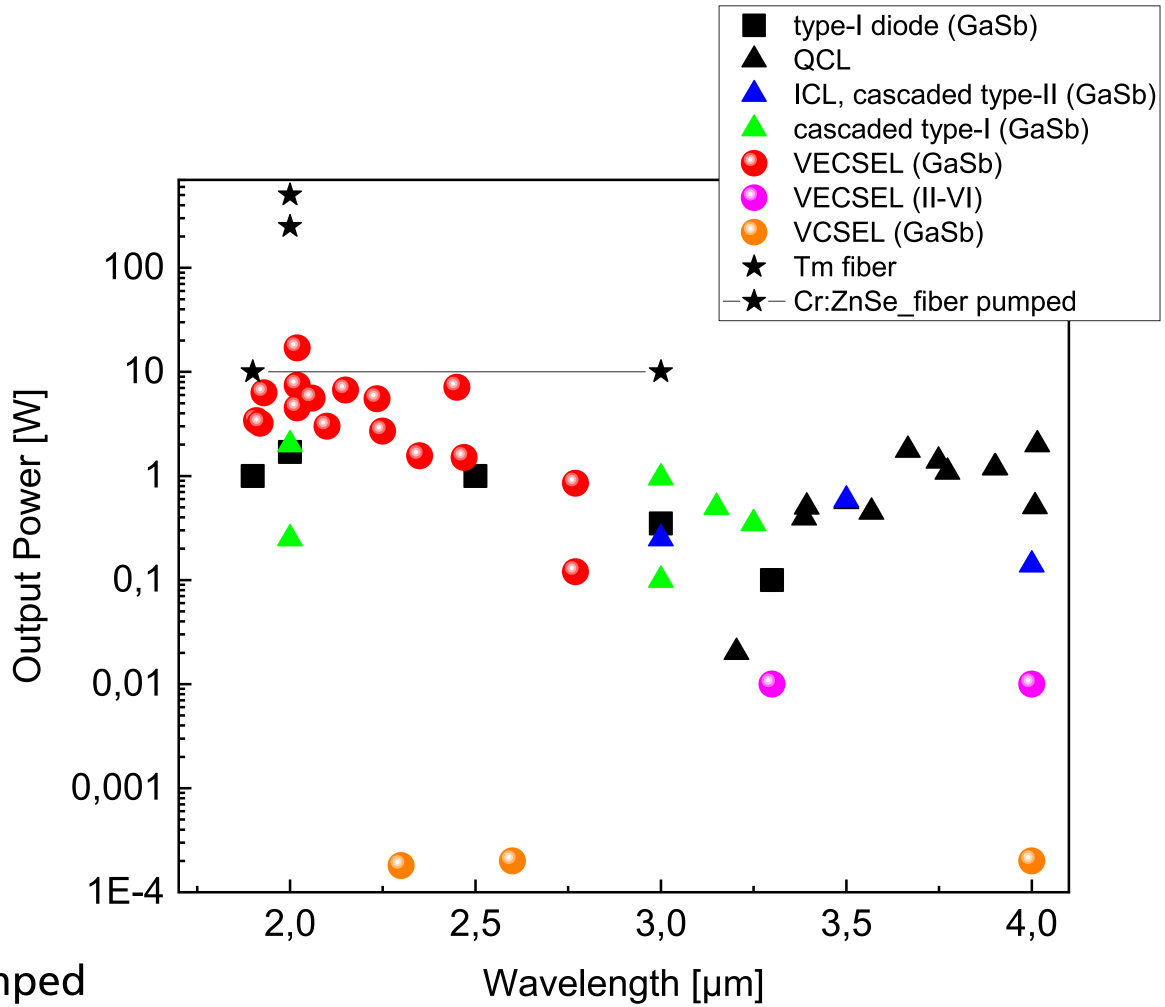
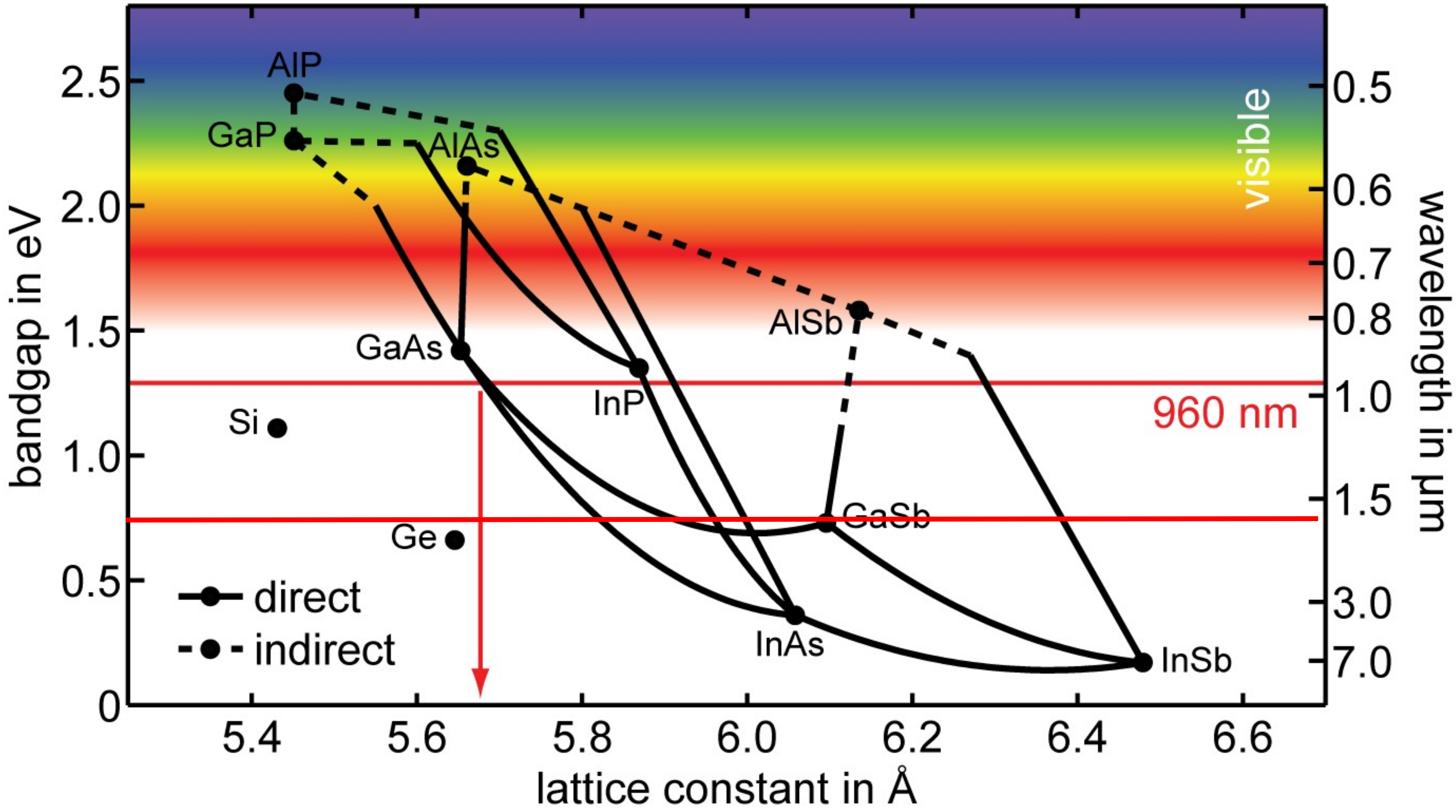
  - Up to 17 W CW @ RT
  - High beam quality
- II-VI-based VECSEL
  - 3 – 5 µm
- Electrically pumped VCSEL
  - GaSb, type-I, type-II
  - 2 – 4 µm
- Tm fiber laser / Cr:ZnSe, Tm-fiber pumped



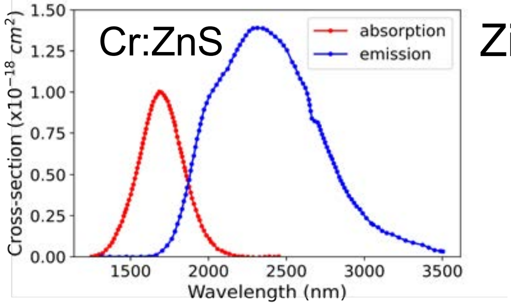
Fraunhofer
IAF

Long-wavelength SESAMs (> 2 µm)



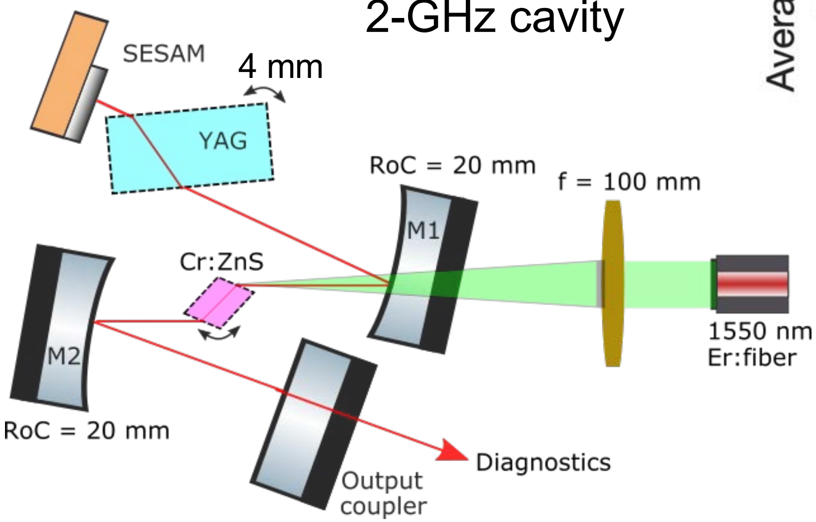
- GaSb Substrate, GaSb/AlAsSb DBR
- InGaSb saturable absorbers (exploring both type I and type II structures)
- 2.07-µm SESAMs demonstrated, Phys. Status Solidi C 9, No. 2, 294–297 (2012)

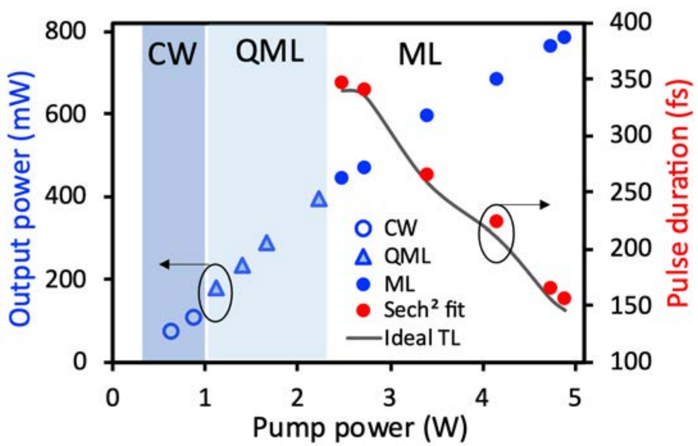
2.4-µm type-I InGaSb SESAM

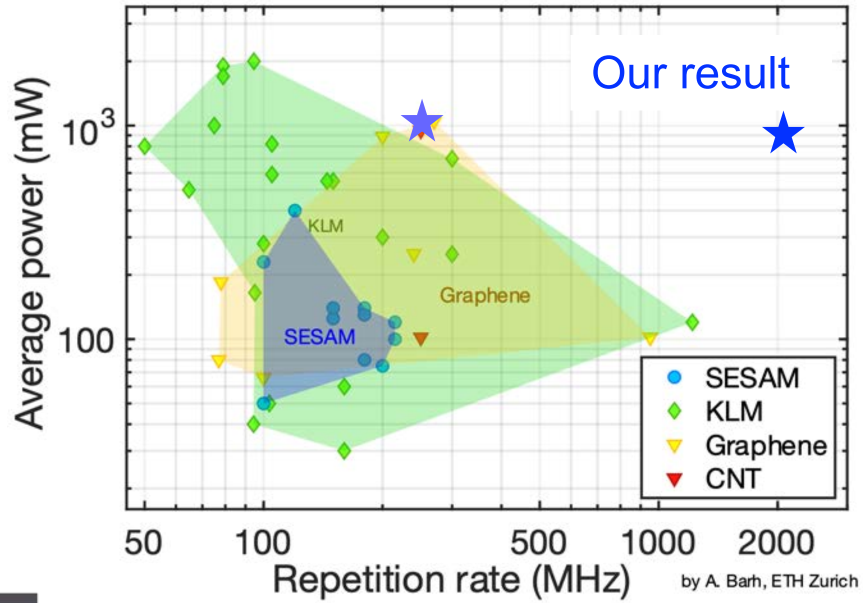


Zinc sulfide

2-GHz cavity



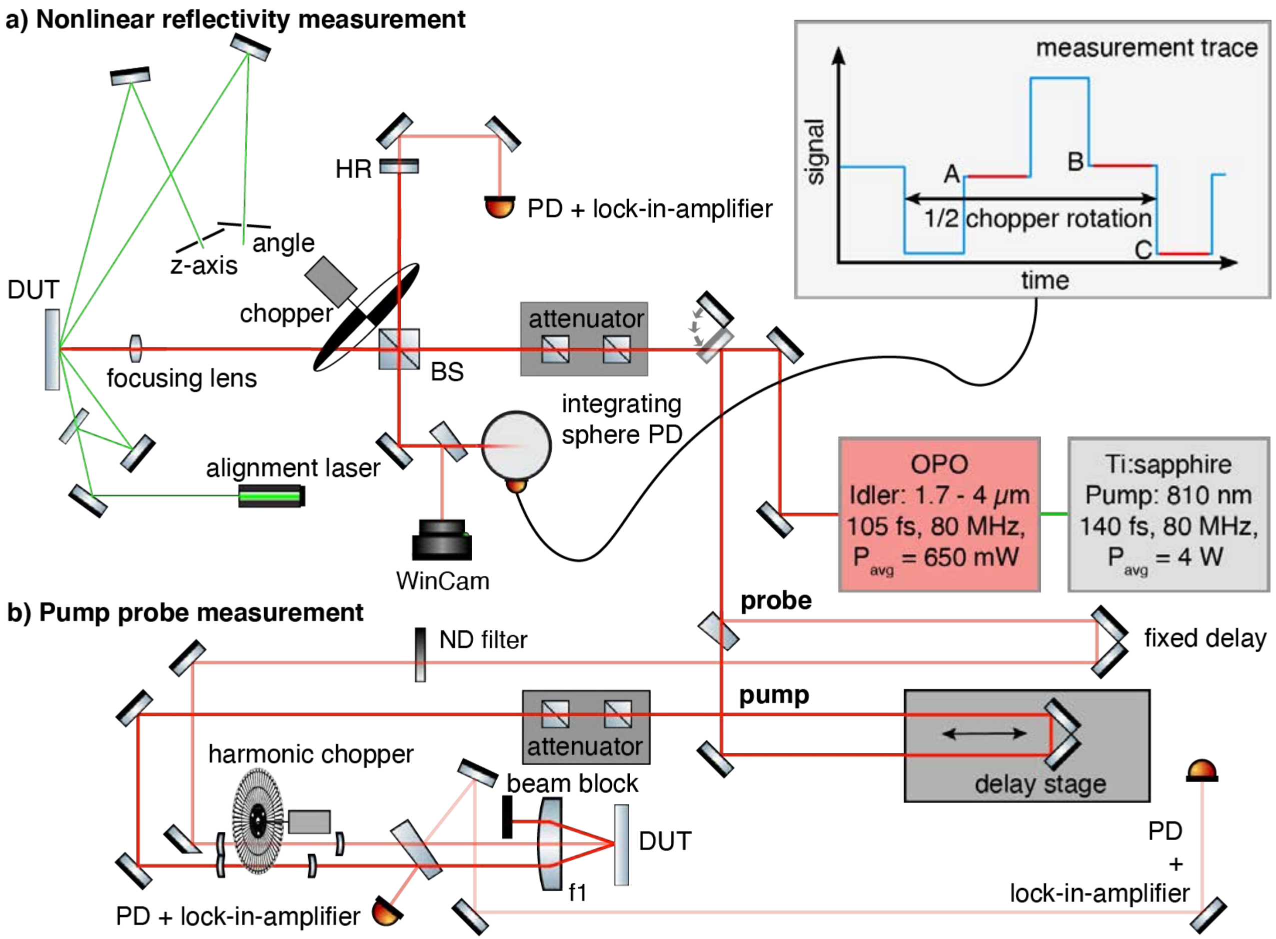


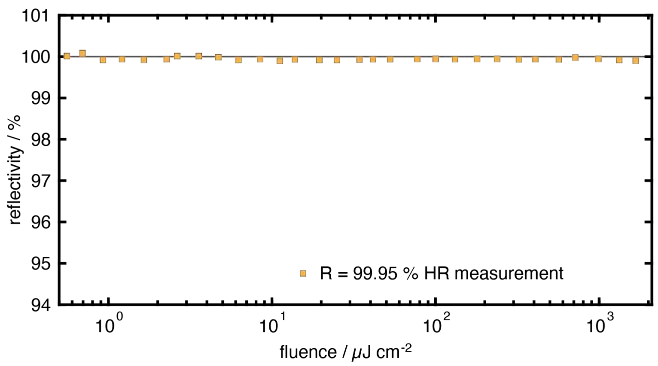


Dr. Ajanta Barh

- Soliton modelocking with transform-limited pulses
  SESAM only starts and stabilizes modelocking!
  4 mm YAG gives negative GDD (-1300 fs^2)
  ZnS gain crystal gives positive SPM
- **250-MHz Cr:ZnS laser:**
  A. Barh et al., *Optics Express*, 29, 5934 (2021)
  5% output coupler, **0.8 W (1 W)** average output power with **79 fs (120 fs)** pulses**,** peak power **39 kW (32 kW)**
- **2-GHz Cr:ZnS laser (CLEO postdeadline paper):**
  3% output coupler, **0.8 W** average output power with **157 fs** pulses at **2.04 GHz,** peak power **2.5 kW**

Long-wavelength SESAM characterization





High reflector (HR)
precision measurement:
$\sigma_R \leq 0.04\%$

over ≈ 4 orders of magnitude

Wavelength range for device unter test (DUT): 1.9 µm to 3 µm

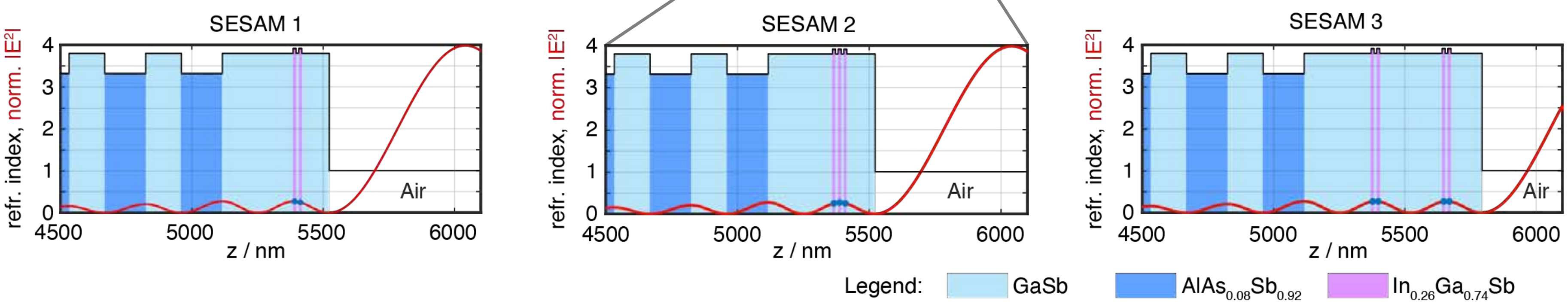
Jonas
Heidrich

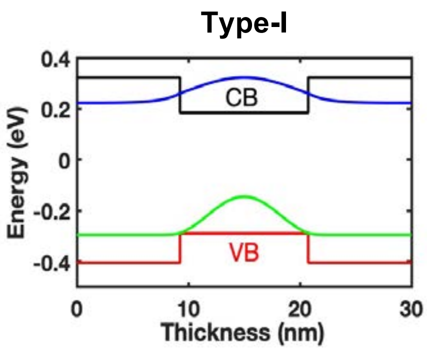
Marco
Gaulke

J. Heidrich, M. Gaulke, B. O. Alaydin, M. Golling, A. Barh, U. Keller,
Full optical SESAM characterization methods in the 1.9 to 3-µm wavelength regime, *Opt. Express* **29**, 6647 (2021)

2-µm InGaSb SESAM

- SESAM = Distributed Bragg reflector (DBR) + QW absorber section
- 20 pair $AlAs_{0.08}Sb_{0.92}$/GaSb DBR growth with molecular beam epitaxy at 525 °C
- 11.5 nm thick $In_{0.26}Ga_{0.74}Sb$ quantum wells (type I) grown at 455 °C





	QWs	F_{Sat} (µJ/cm^2)	ΔR (%)	ΔR_{ns} (%)	F_2 (mJ/cm^2)
SESAM 1	2	5	1	0.18	70.6
SESAM 2	3	2.9	1.8	0.15	50.8
SESAM 3	4	2.6	2.4	0.23	29.3

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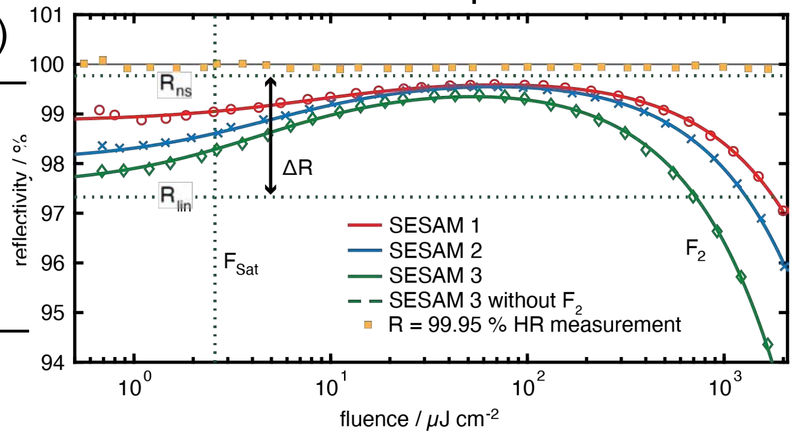
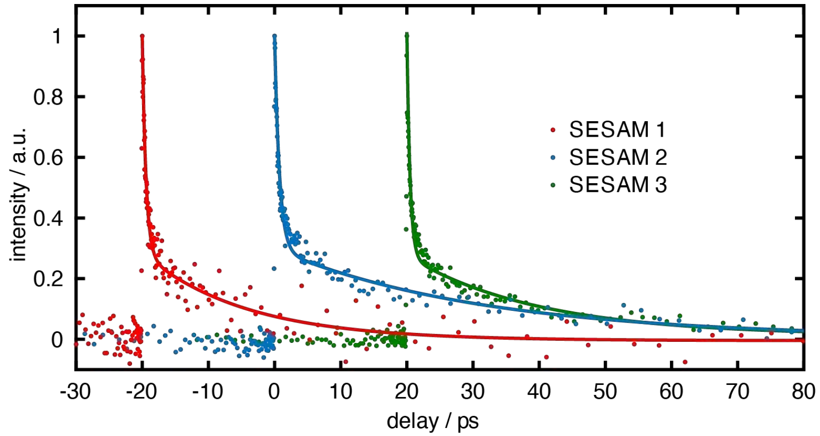
Measured with 100-fs pulses:



Recovery times fit with a bi-exponential decay model

$$\Delta R(\tau) = A\, e^{-\tau/\tau_1} + (1-A)\, e^{-\tau/\tau_2}$$

	SESAM 1	SESAM 2	SESAM 3
Weighting factor A (%)	71	71	74
τ_1 (ps)	0.56	0.73	0.47
τ_2 (ps)	16	32	20



Collaboration with Prof. Clara Saraceno:

SESAM-modelocked Ho-YAG thin-disk laser

- 40.5 W output power
- Sub-ps pulses at 2.09 µm

CLEO SF2M.3 Thu 07/14/21 07:45

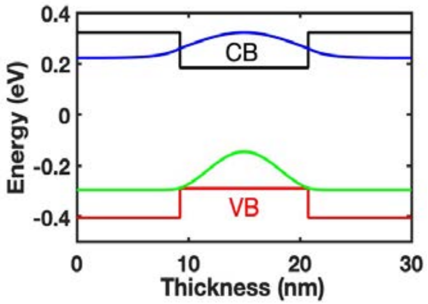
FIRST Center for Micro- and Nanoscience

2.4-μm InGaSb/GaSb SESAM

General remark

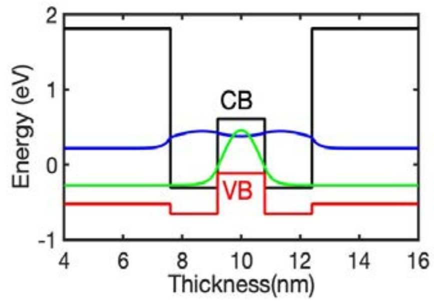
- Structure is **all-semiconductor**, **monolithic** growth
- Absorber section: **Quantum-well** layers

Type-I



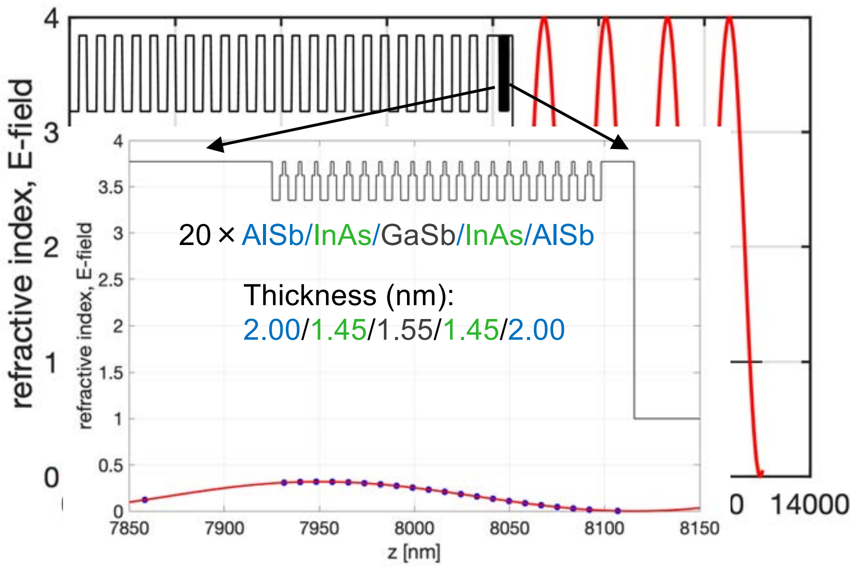
2– 2.4 μm

Type-II

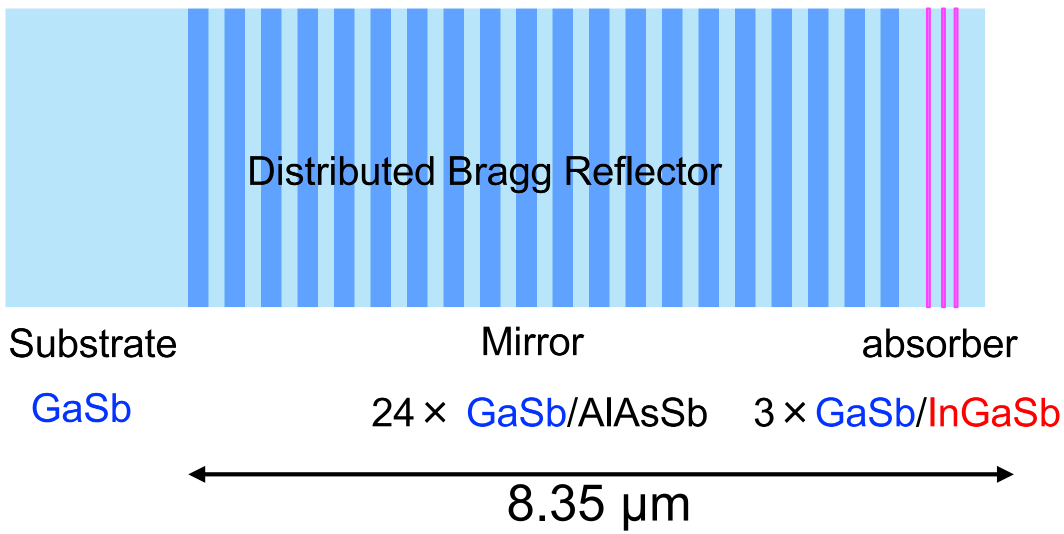


2 – 4.5 μm

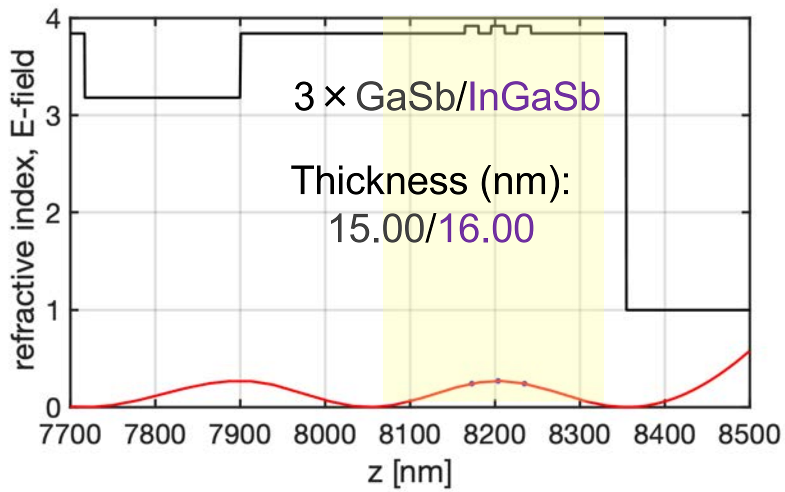
Type-II



2.4-μm type-I InGaSb SESAM



Type-I



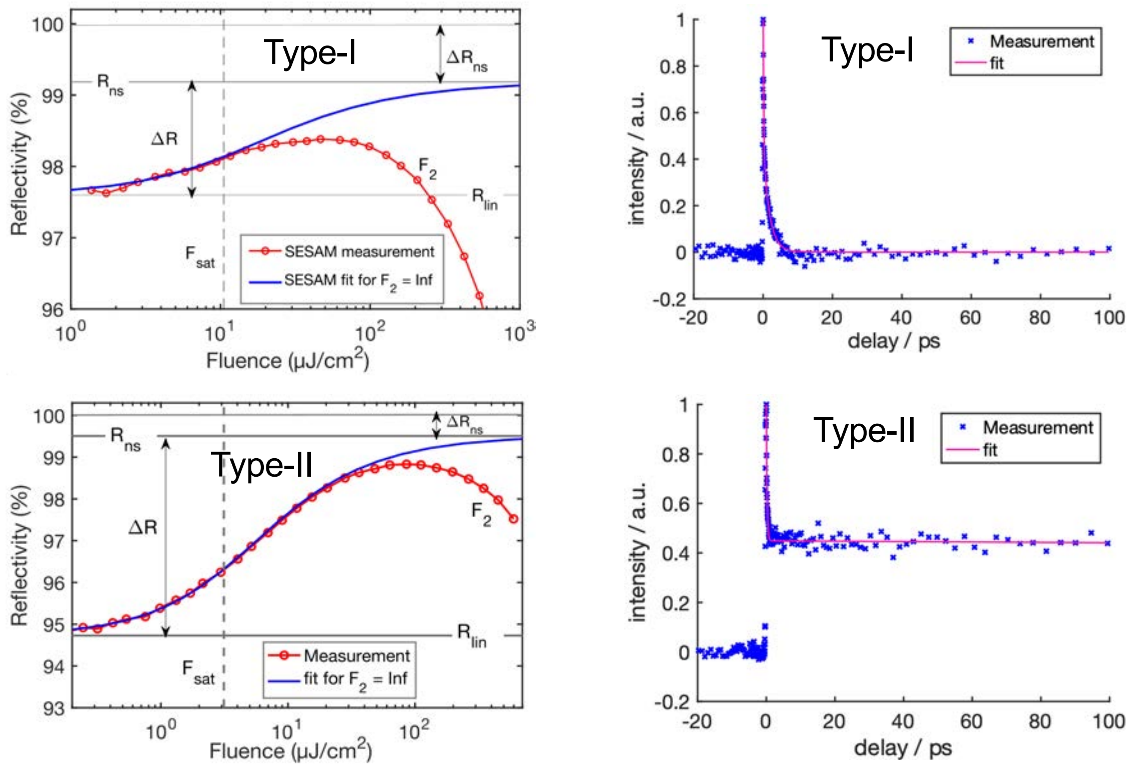
2.4-µm InGaSb/GaSb SESAM

SESAM	Type-I	Type-II
Modulation depth ∆R	1.59 %	4.78 %
Saturation fluence **Fsat**	10.51 µJ/cm²	3.13 µJ/cm²
Non-saturable loss ΔR_{ns}	0.8 %	0.5 %
F_2	18 mJ/cm²	31 mJ/cm²
Absorber recovery dynamics		
τ_1	160 fs	300 fs
τ_2	1.9 ps	> 10^3 ps
A_{slow}	0.45	0.58

Measured @ 2.36 µm with 100-fs pulses

Nonlinear reflectivity measurement

Pump-probe measurement



A. Barh, J. Heidrich, B. O. Alaydin, M. Gaulke, M. Golling, C. R. Phillips, U. Keller
"Watt-level and sub-100-fs self-starting modelocking Cr:ZnS oscillator enabled by GaSb-SESAMs"
Optics Express, vol. 29, No. 4, pp. 5934-5946, 2021

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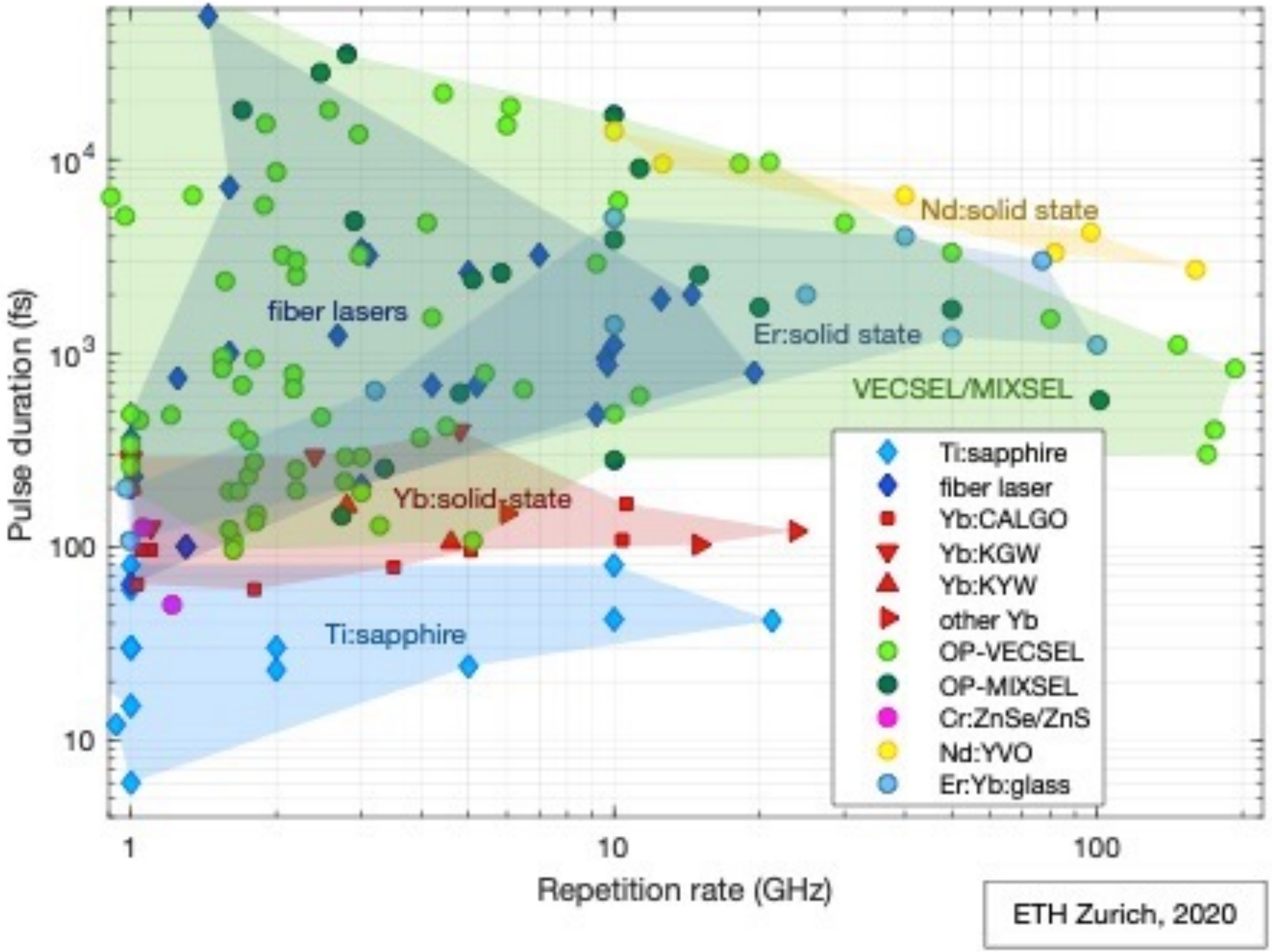
6. Outlook

Overview near infrared results



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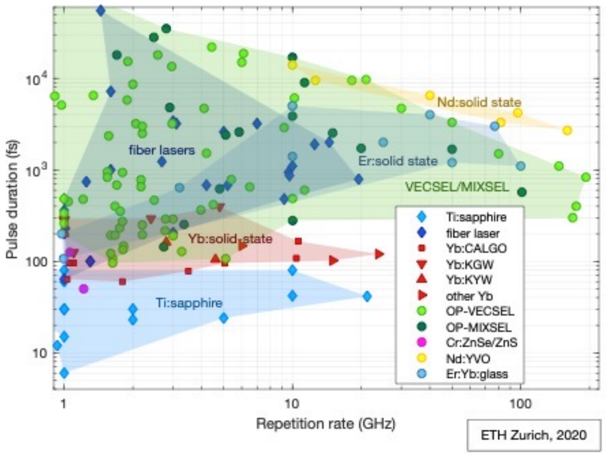

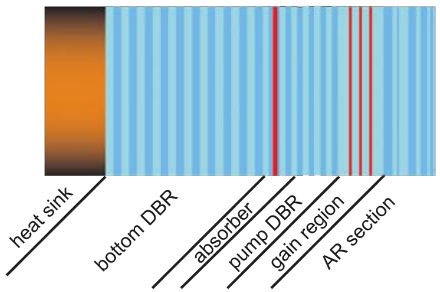

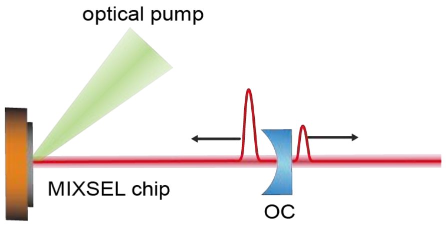

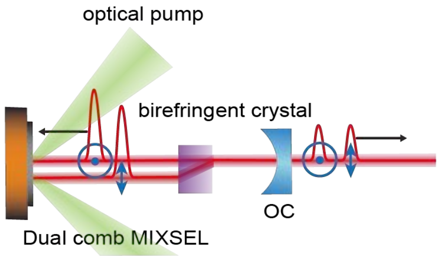

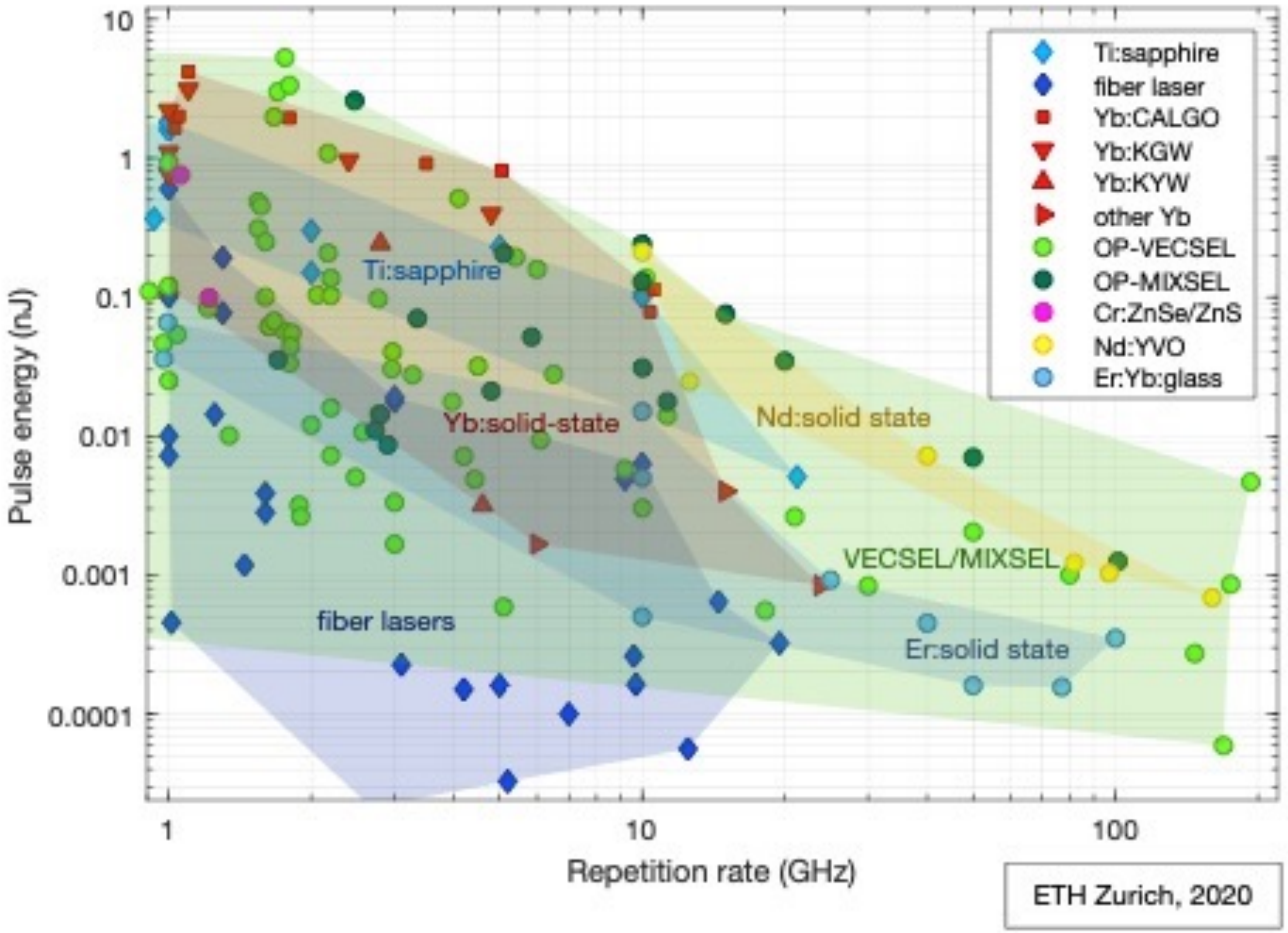

MIXSEL
modelocked integrated external-cavity surface-emitting laser

M. Rattunde, P. Holl, S. Adler, E. Diwo-Emmer, R. Aidam, J. Wagner

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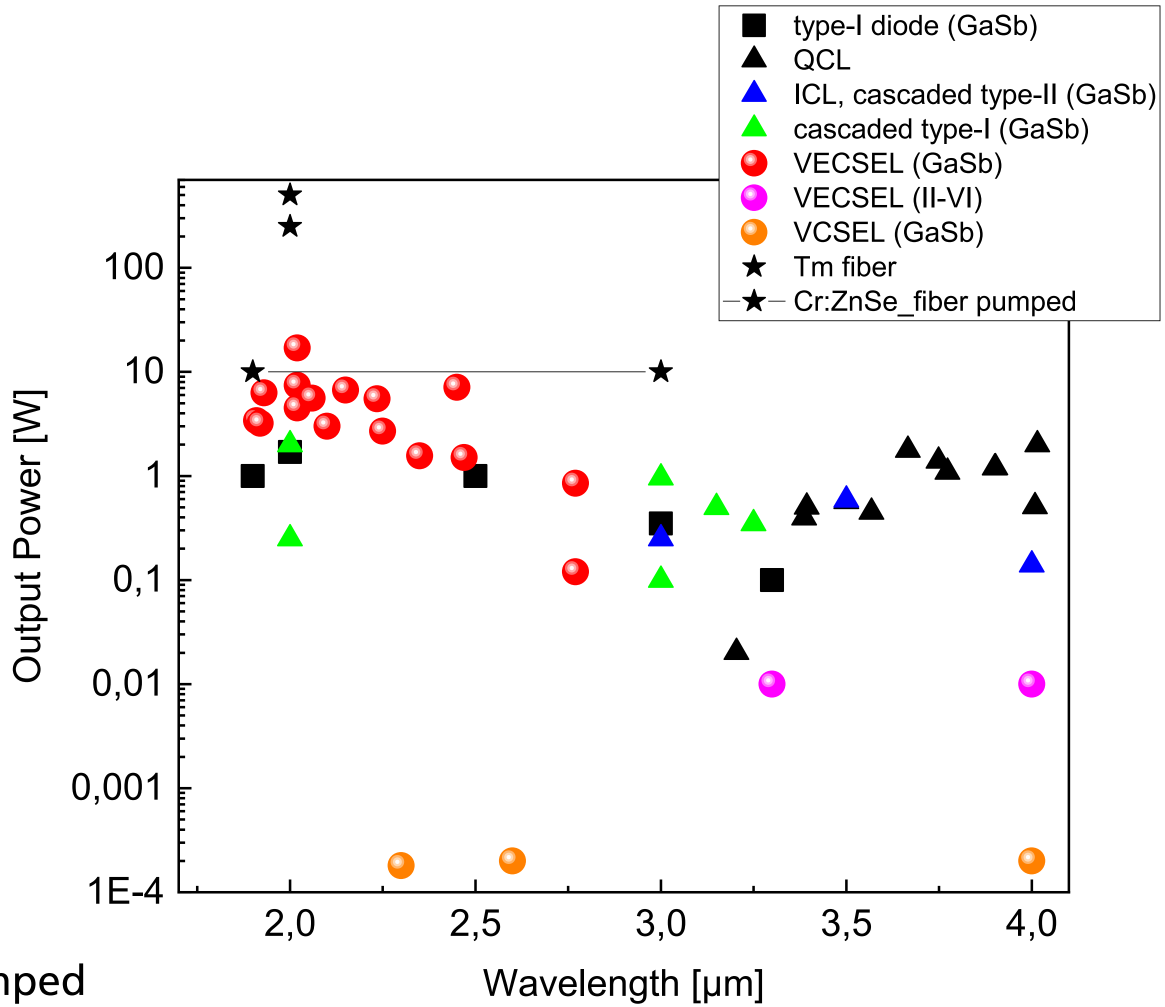

Fraunhofer IAF

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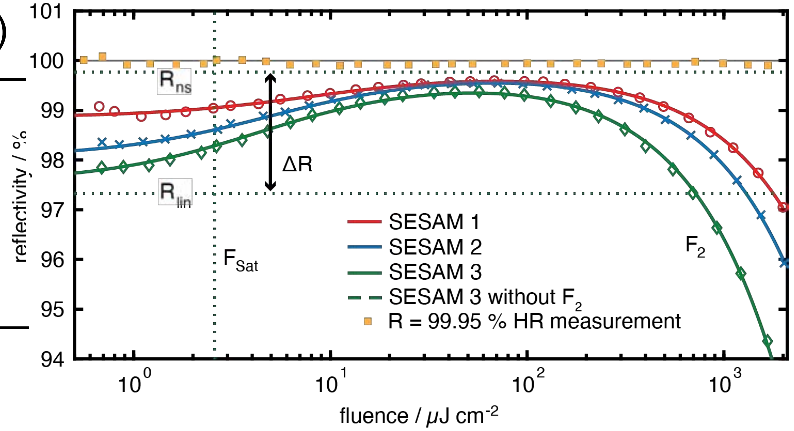

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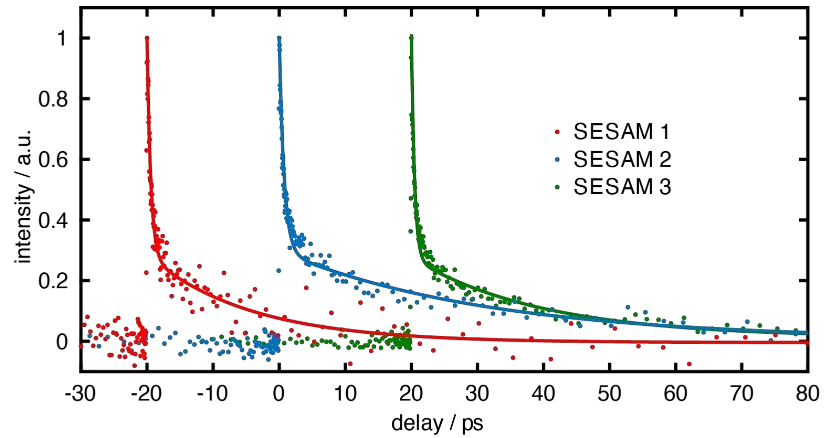

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- SESAM modelocked VECSEL
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CLEO SF2M.3 Thu 07/14/21 07:45

FIRST Center for Micro- and Nanoscience

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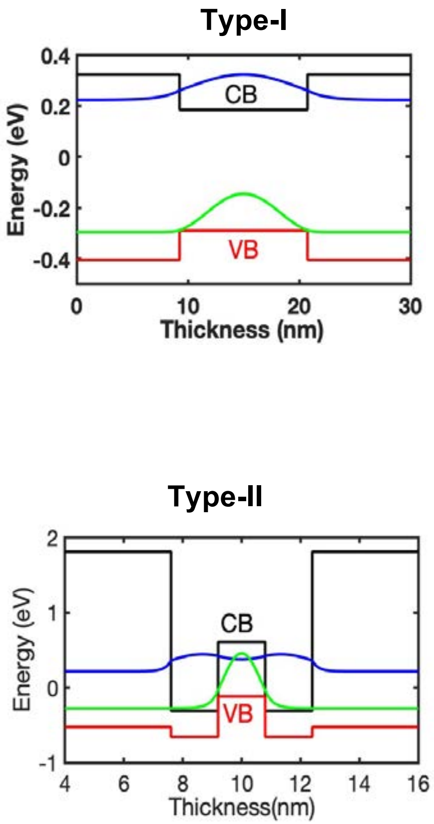

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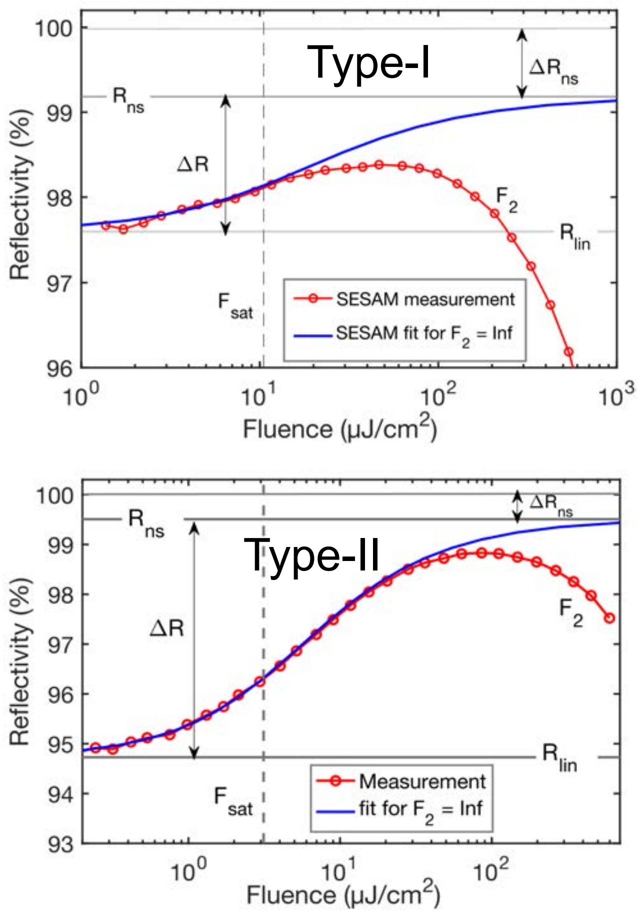
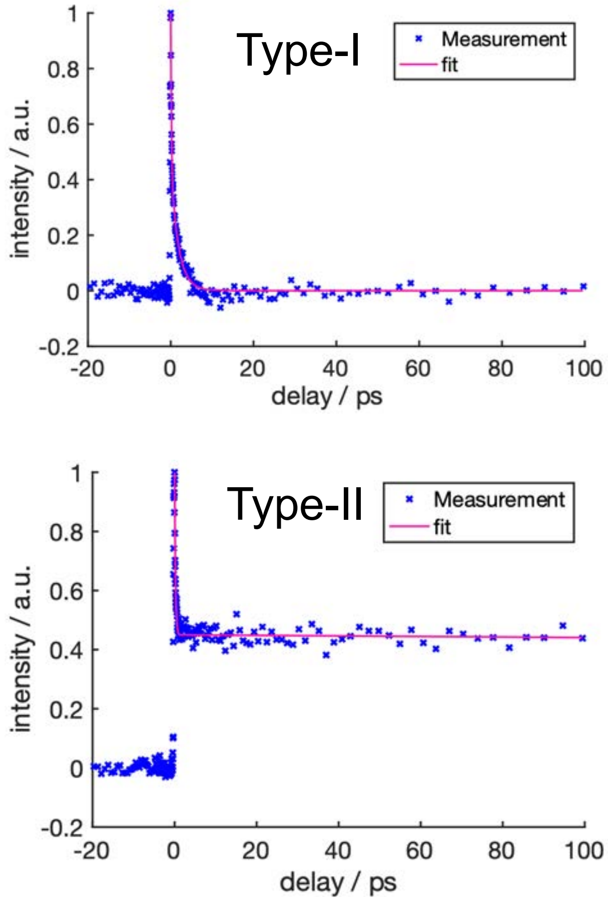


Pump-probe measurement



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This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme grant agreement No 787097

New textbook for ultrafast lasers

U. Keller

Ultrafast Lasers

April 29, 2021

Springer

Partial lab shut down and home office made it possible

≈800 pages

Detailed derivations

Focus on diode-pumped solid-state lasers

Hopefully to be published end of 2021