Noval ultrafast gigahertz high-power semiconductor lasers: MIXSELs and SESAM modelocked VECSELs

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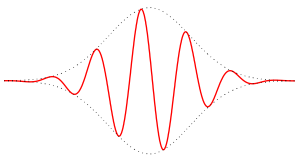
ETH Zurich, Switzerland

28.10.2010, IBM Research - Zurich, Ruschlikon

Ultrafast lasers

… generate well-controlled flashes of light with pico- or femtosecond duration

Access ultrashort time scales



⇨ Observe and use fast dynamics

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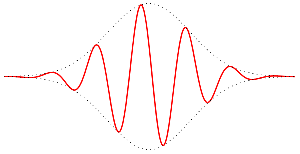
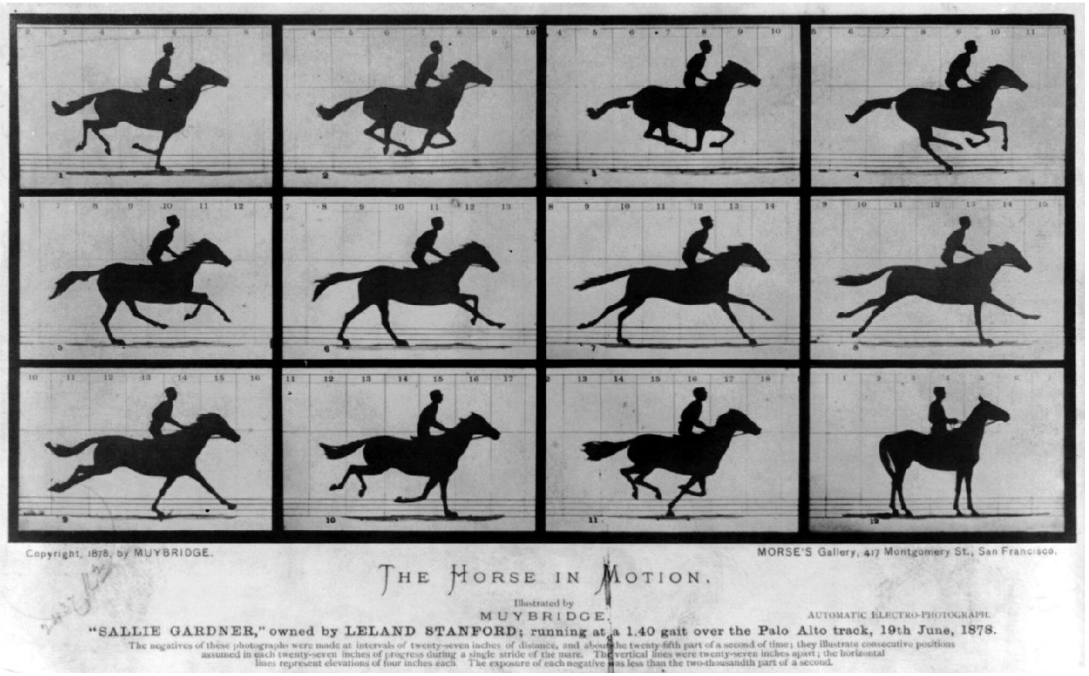


⇨ Observe and use fast dynamics

E. Muybridge in 1878:
understand horse gallop



Copyright, 1878, by MUYBRIDGE.

MORSE'S Gallery, 417 Montgomery St., San Francisco.

THE HORSE IN MOTION.

Illustrated by
MUYBRIDGE.

AUTOMATIC ELECTRO-PHOTOGRAPH.

"SALLIE GARDNER," owned by LELAND STANFORD; running at a 1.40 gait over the Palo Alto track, 19th June, 1878.

The negatives of these photographs were made at intervals of twenty-seven inches of distance, and about the twenty-fifth part of a second of time; they illustrate consecutive positions assumed in each twenty-seven inches of progress during a single stride of the mare. The vertical lines were twenty-seven inches apart; the horizontal lines represent elevations of four inches each. The exposure of each negative was less than the two-thousandth part of a second.

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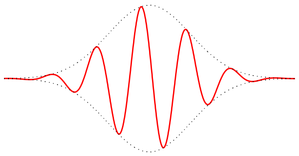
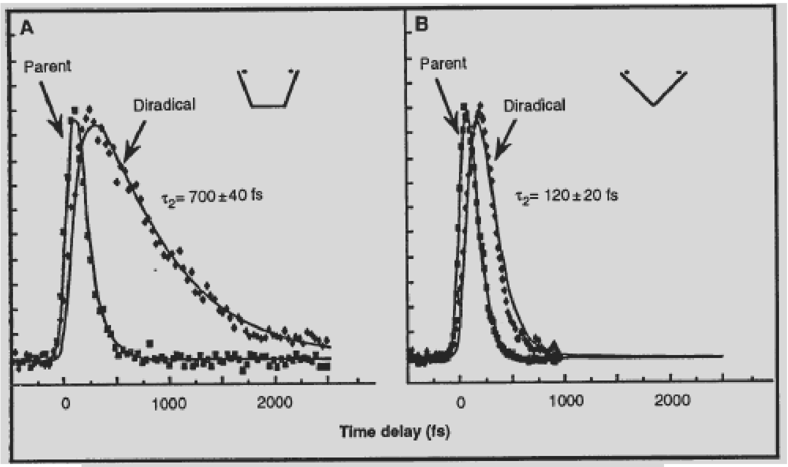


⇨ Observe and use fast dynamics

E. Muybridge in 1878:
understand horse gallop

A. H. Zewail in 1994:
understand transition states in chemical reactions



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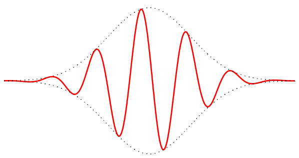
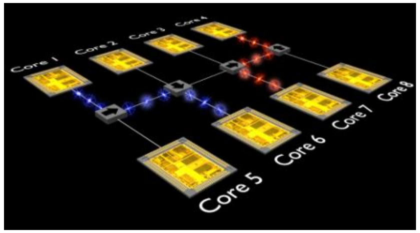
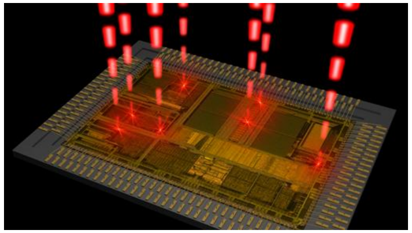


⇨ Observe and use fast dynamics
- understand chemical reaction dynamics
- fast communication
- …



interconnects

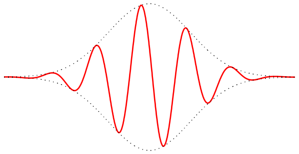


optical clocking

Ultrafast lasers

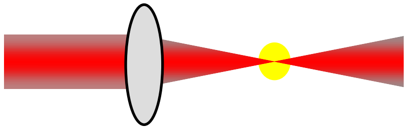
… generate well-controlled flashes of light with pico- or femtosecond duration

Access ultrashort time scales

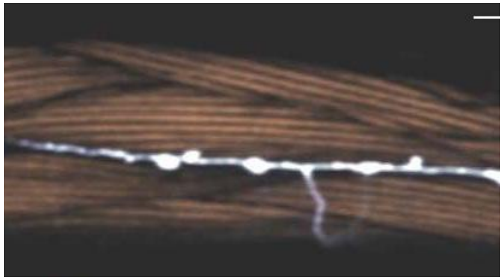


⇨ Observe and use fast dynamics
- understand chemical reaction dynamics
- fast communication
- …

Concentrate in time and space



⇨ Achieve extremely high intensities
- material processing
- multi-photon biomedical imaging
- …



2-photon image of
muscle tissue

Ultrafast lasers

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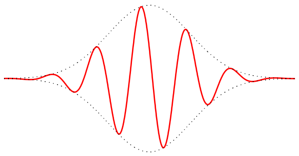

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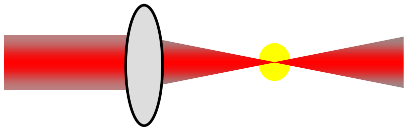
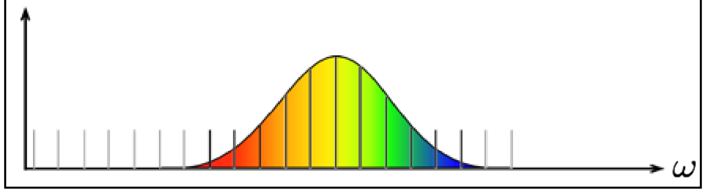


⇨ Achieve extremely high intensities
- material processing
- multi-photon biomedical imaging
- …

Broad optical spectrum



⇨ Generate ultrastable frequency combs
- high precision spectroscopy
- optical clocks
- …

Ultrafast semiconductor lasers

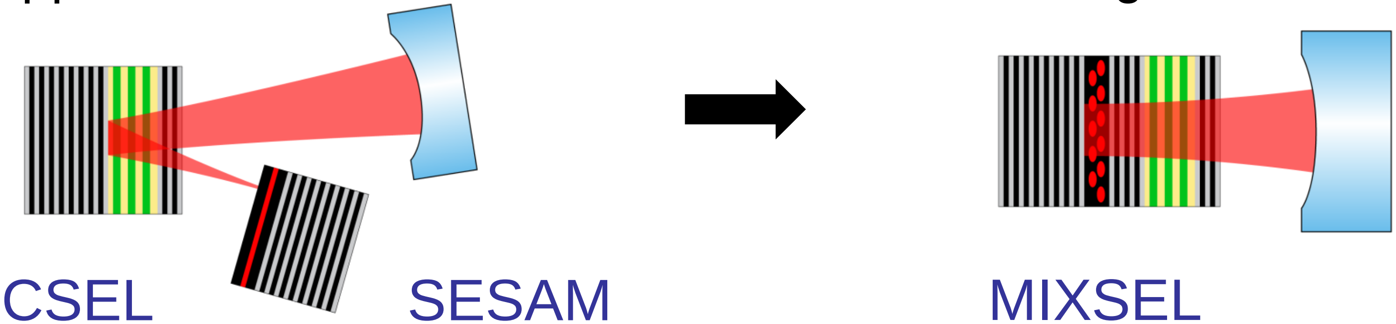
- Currently, typical ultrafast lasers are bulky and complex

~ 100 cm

Ultrafast semiconductor lasers

- Currently, typical ultrafast lasers are bulky and complex

- Our approach: semiconductor laser with vertical integration



VECSEL

Vertical External
Cavity Surface
Emitting Laser

SESAM

Semiconductor
Saturable Absorber
Mirror

MIXSEL

Modelocked Integrated
External-Cavity Surface
Emitting Laser

Outline

1. Introduction and Motivation
2. High power cw VECSELs
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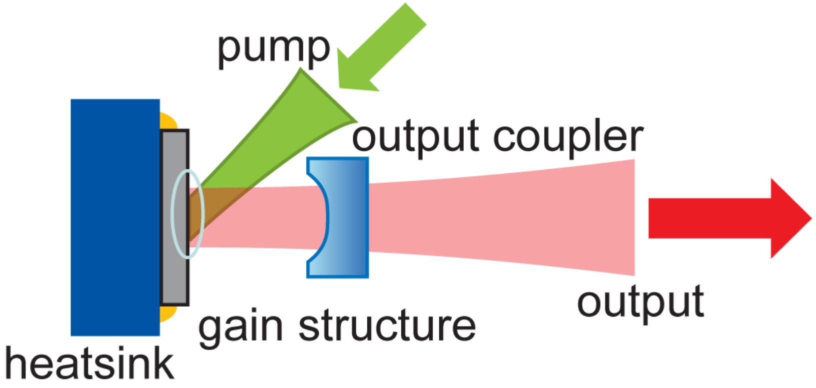
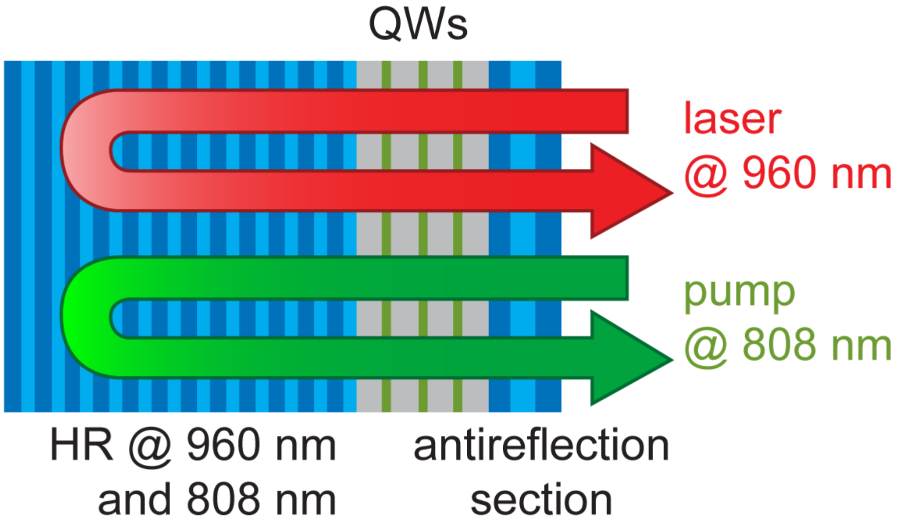
Optically pumped VECSEL

Combine the advantages of ion-doped DPSSL and semiconductor lasers





M. Kuznetsov et al., *IEEE Phot. Tech. Lett.* **9**, 1063 (1997)

Surface Emitter

- Power scalability

Optical Pumping

- Large area homogeous inversion

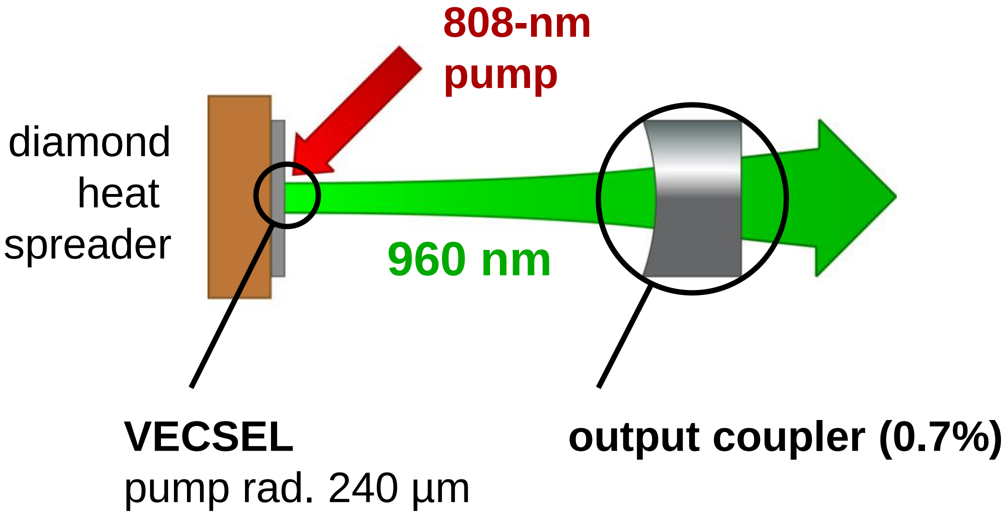
External cavity

- Excellent beam quality
- flexible: SHG, modelocking single-frequency

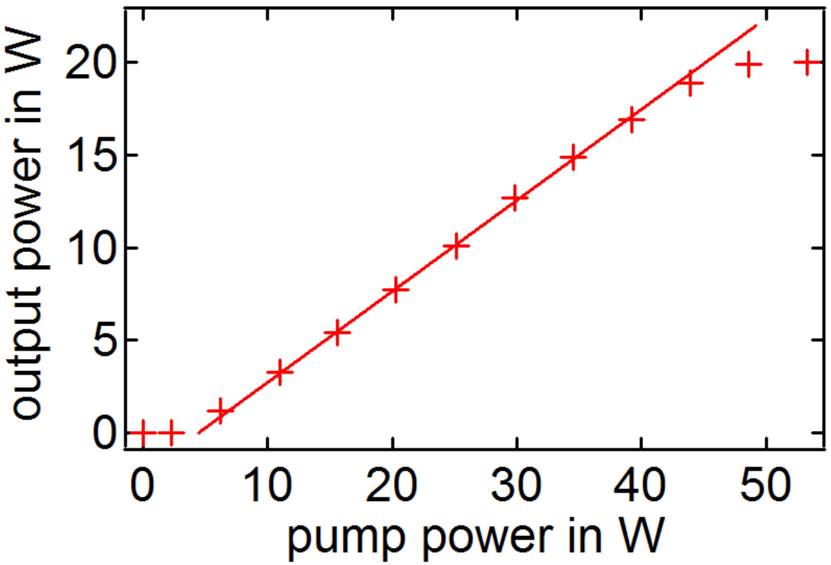
Semiconductor Gain

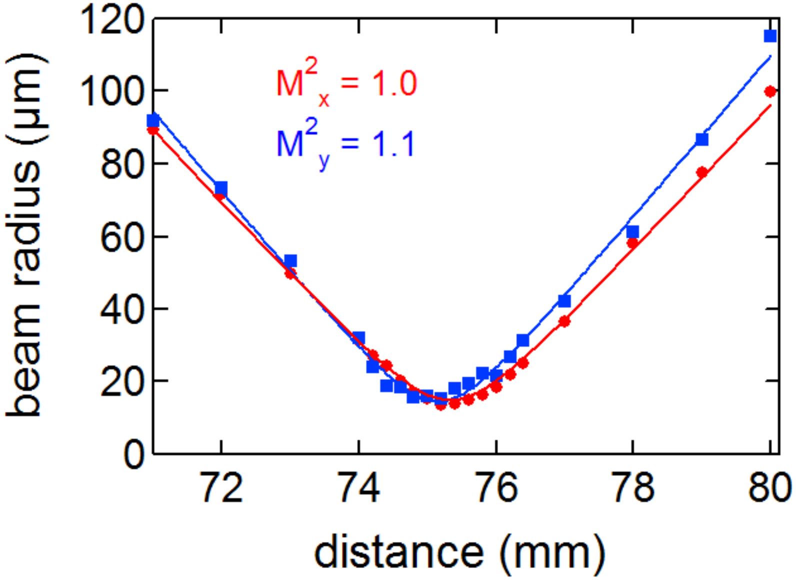
- bandgap engineering: so far 0.6 … 2.3 µm
- cost-efficient fabrication

High power CW-operation: 20 W TEM_{00}

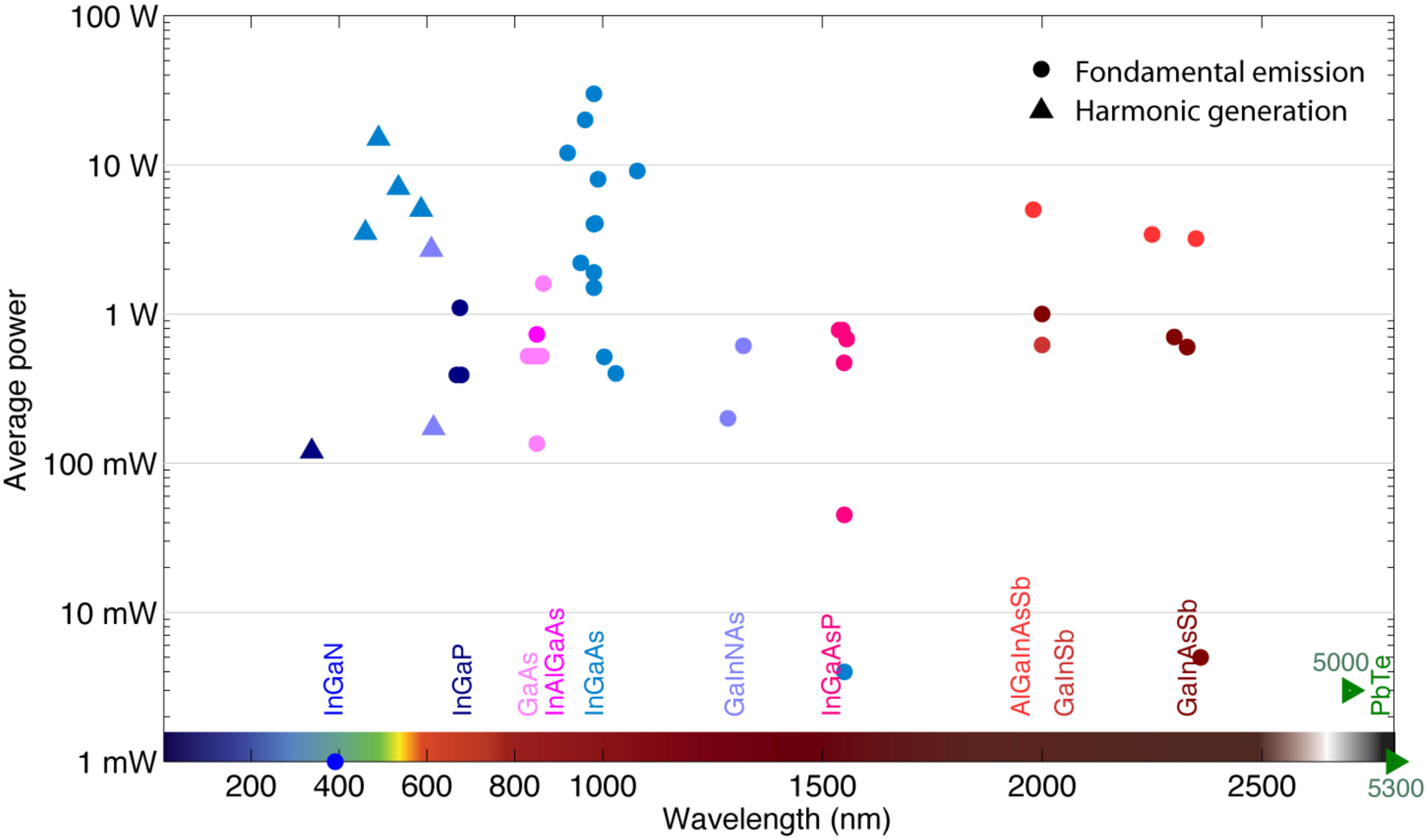


- Maximum power ***P* = 20.2 W**
- Up to $\eta_{\text{opt-opt}}$ **= 43%**
- $M^2 < 1.1$





Bandgap engineering



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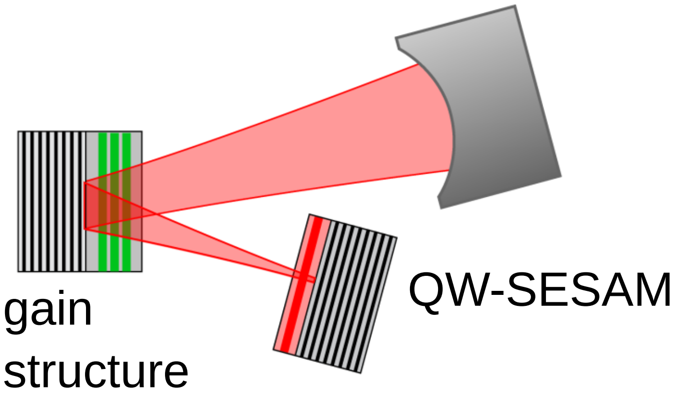
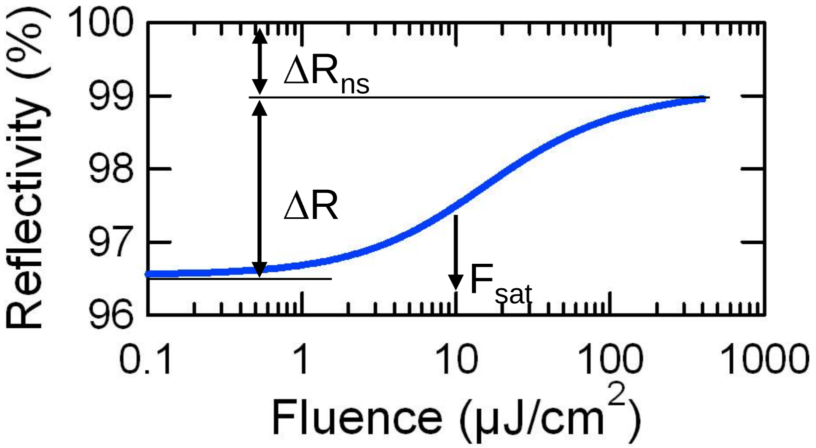
SESAM-VECSEL modelocking

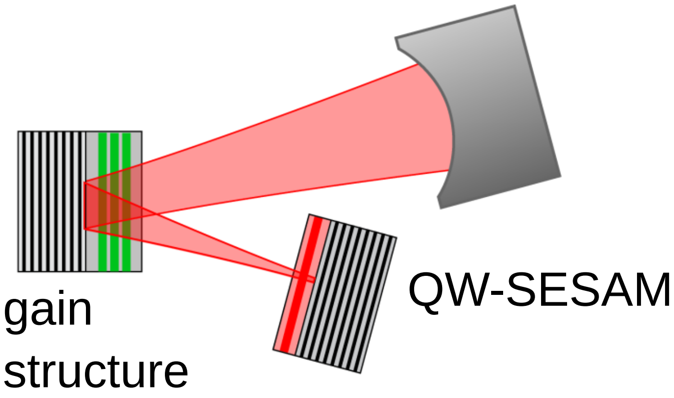


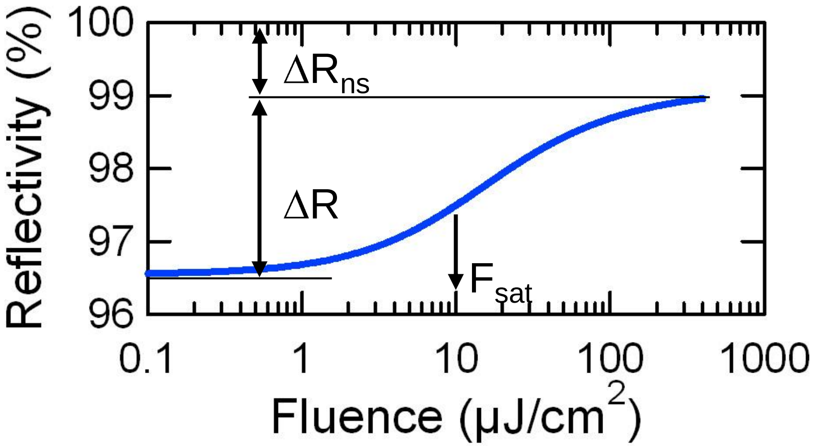


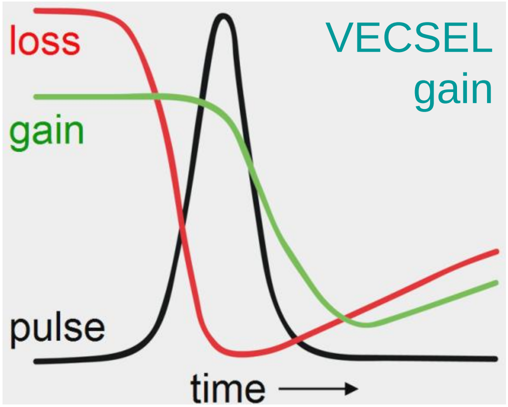
- Self-starting and reliable modelocking
- After each roundtrip a pulse is emitted
  - 1 GHz: $T_{roundtrip} = 1$ ns, $L_{cavity} = 15$ cm
  - 50 GHz: $T_{roundtrip} = 20$ ps, $L_{cavity} = 3$ mm

[#1] U. Keller et al., *Opt. Lett.* **17**, 505, 1992 [#2] U. Keller, *Nature* **424**, 831, 2003

SESAM-VECSEL modelocking







⇨ loss has to saturate faster

- Self-starting and reliable modelocking
- After each roundtrip a pulse is emitted
  - 1 GHz: $T_{\text{roundtrip}} = 1$ ns, $L_{\text{cavity}} = 15$ cm
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$$\frac{E_{sat,a}}{E_{sat,g}} = \frac{F_{sat,a}}{F_{sat,g}} \boxed{\frac{A_a}{A_g}} < 1$$

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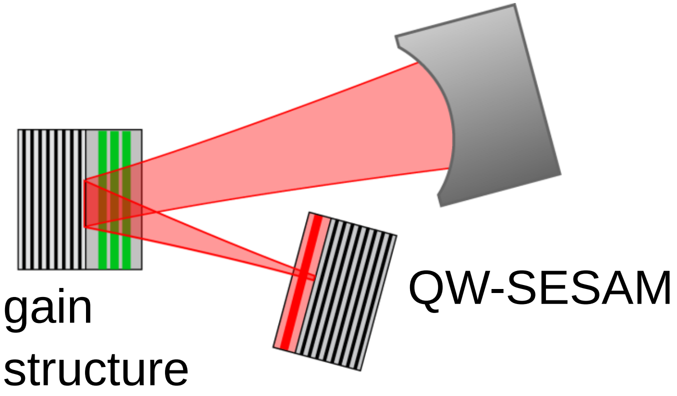
SESAM-VECSEL modelocking



✓ < 20 GHz

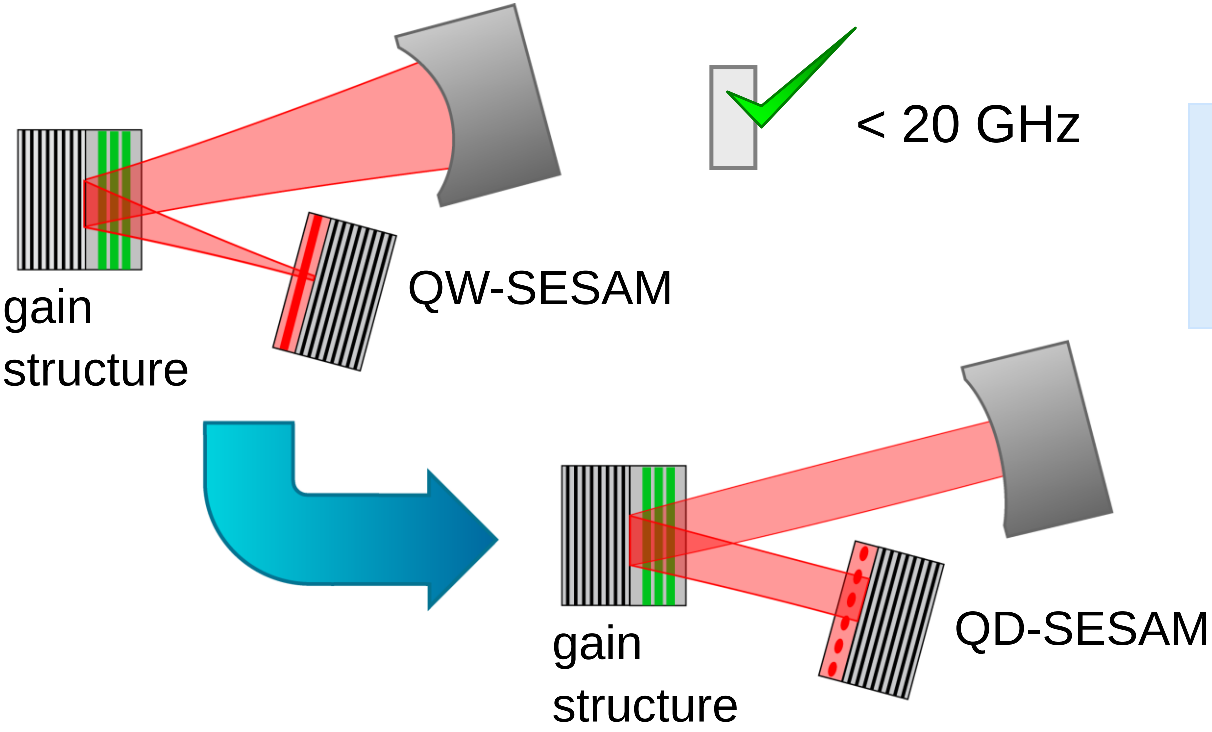
Quantum-Well SESAM ML

4 GHz	**2.1 W**	4.7 ps
10 GHz	**1.4 W**	6.1 ps

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

typically 1/4 – 1/20
for QW-SESAMs

SESAM-VECSEL modelocking



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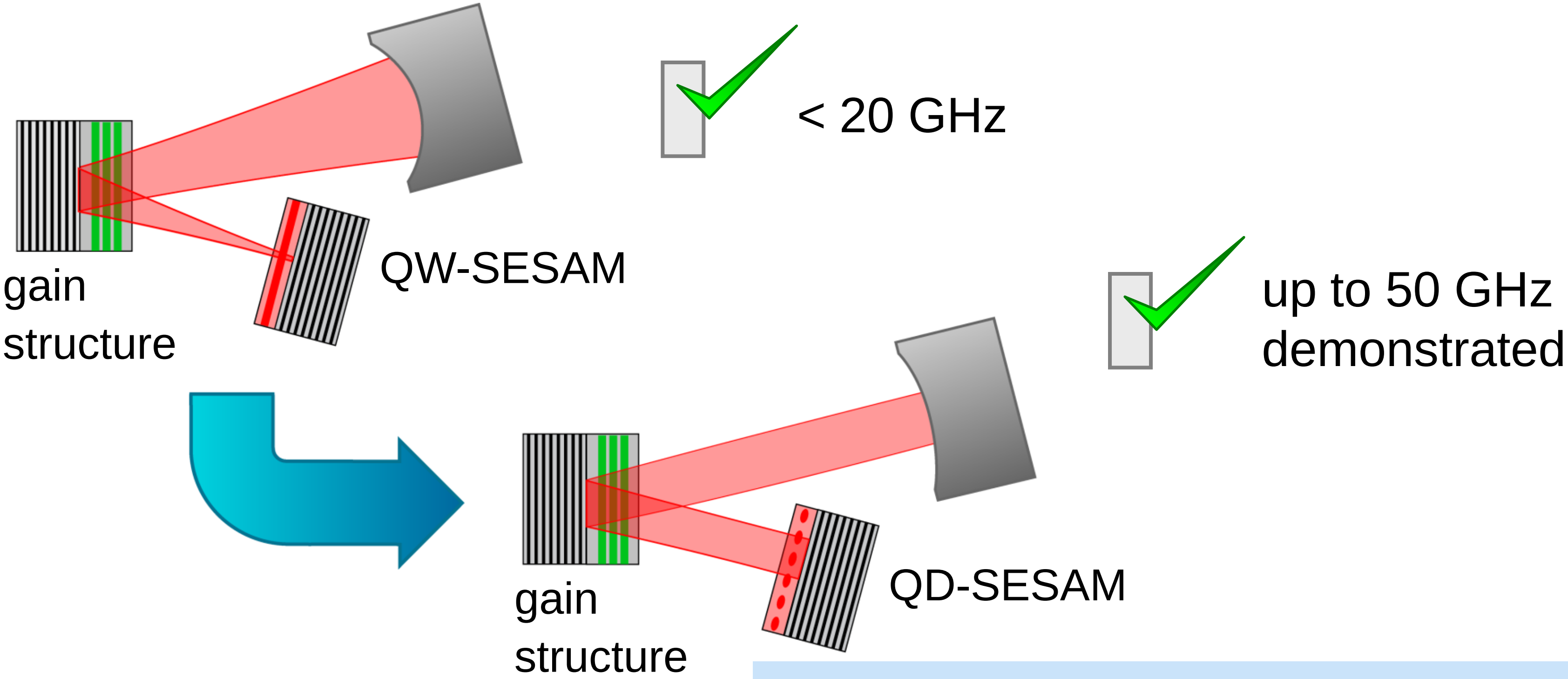
$$\frac{E_{sat,a}}{E_{sat,g}} = \boxed{\frac{F_{sat,a}}{F_{sat,g}}}\frac{A_a}{A_g} < 1$$

With lower saturation fluence
⇨ no focusing needed anymore!

SESAM-VECSEL modelocking



☑ < 20 GHz

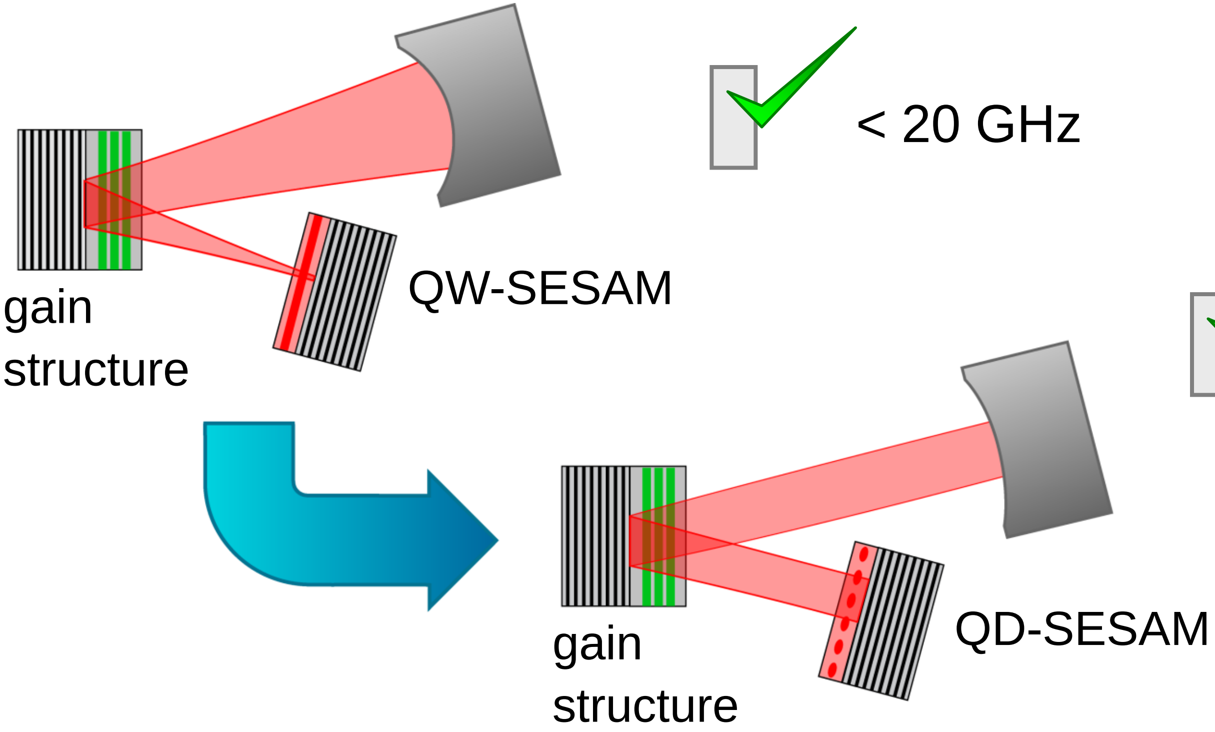
☑ up to 50 GHz demonstrated

Quantum-Dot SESAM

- modulation depth ΔR & F_{sat} decoupled
- resonant design to decrease F_{sat}
- low-T growth for fast recovery

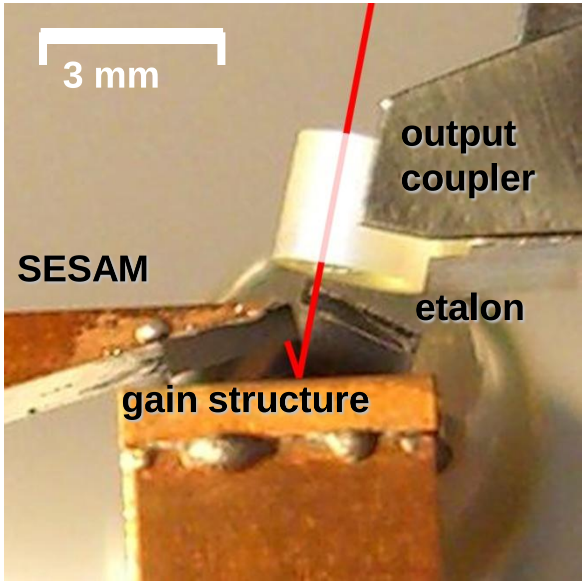
⇨ ~10-fold F_{sat} reduction

SESAM-VECSEL modelocking



☑ < 20 GHz

☑ up to 50 GHz demonstrated

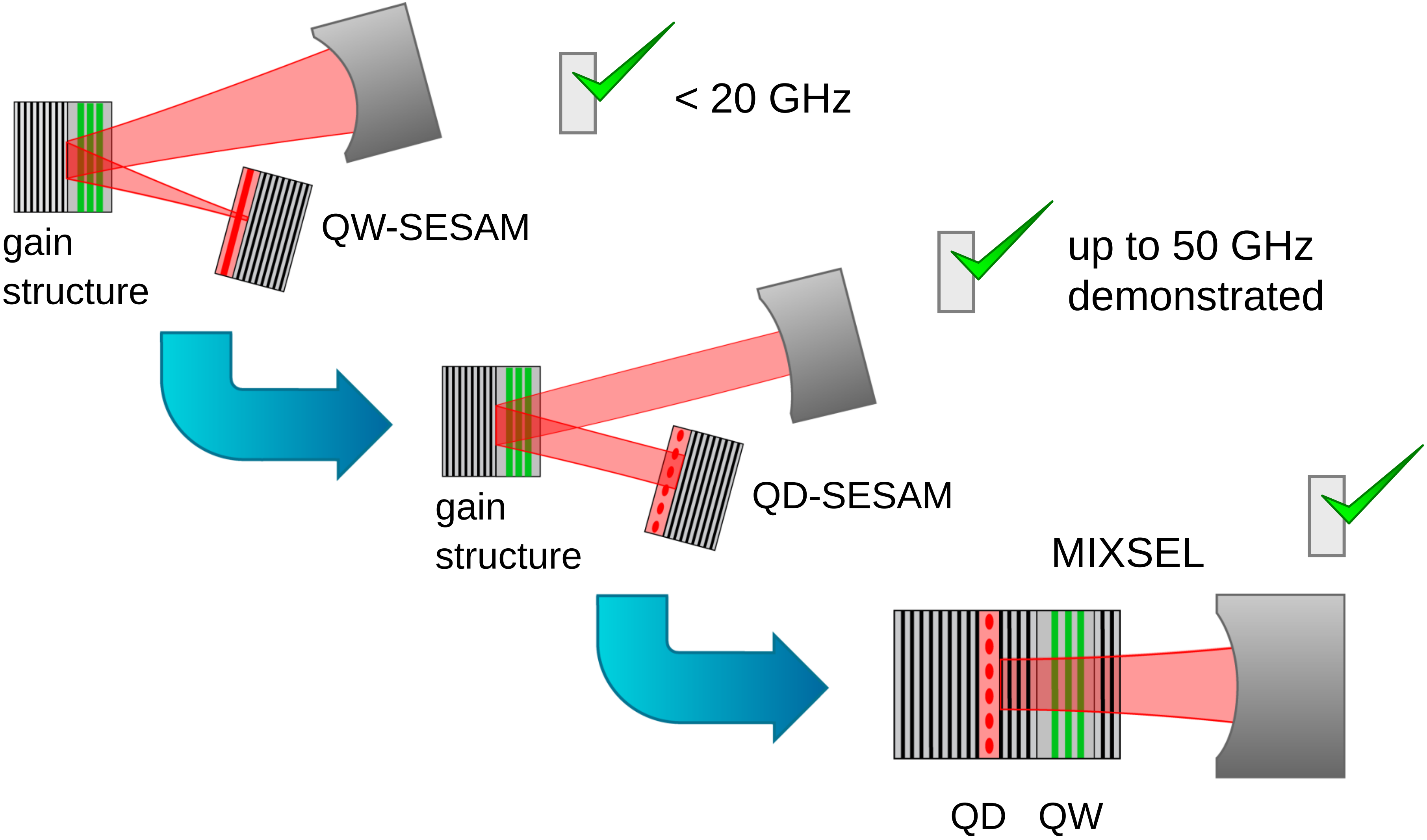


QD-SESAM modelocking: up to 50 GHz repetition rate

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

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

SESAM-VECSEL modelocking



gain structure

QW-SESAM

☑ < 20 GHz

gain structure

QD-SESAM

☑ up to 50 GHz demonstrated

MIXSEL ☑

QD QW

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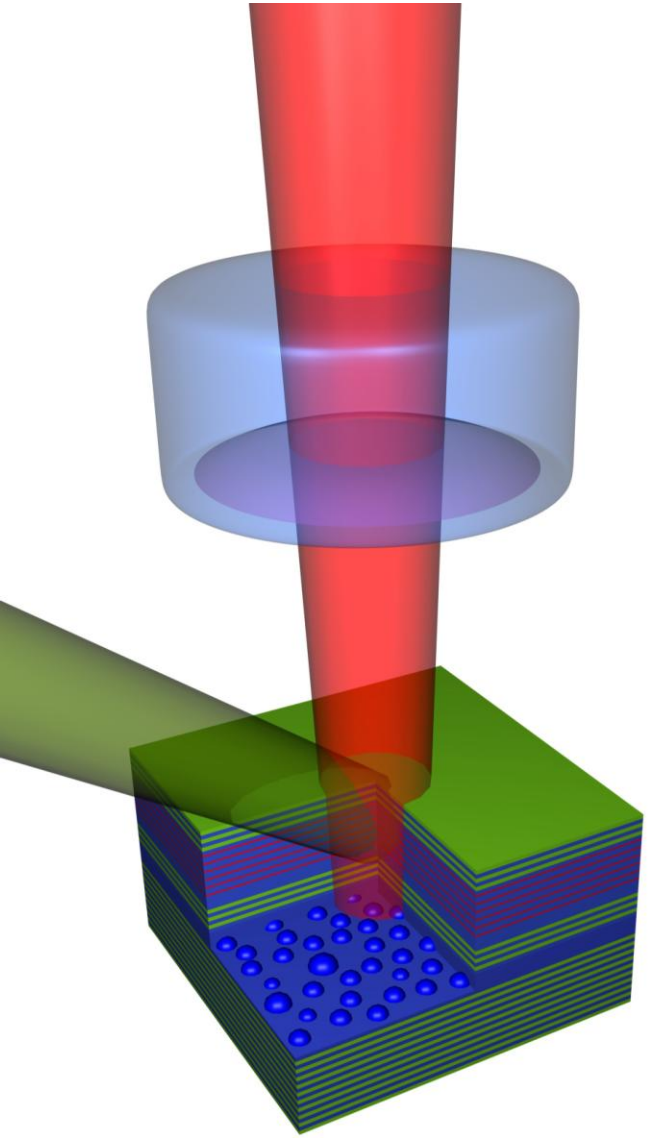
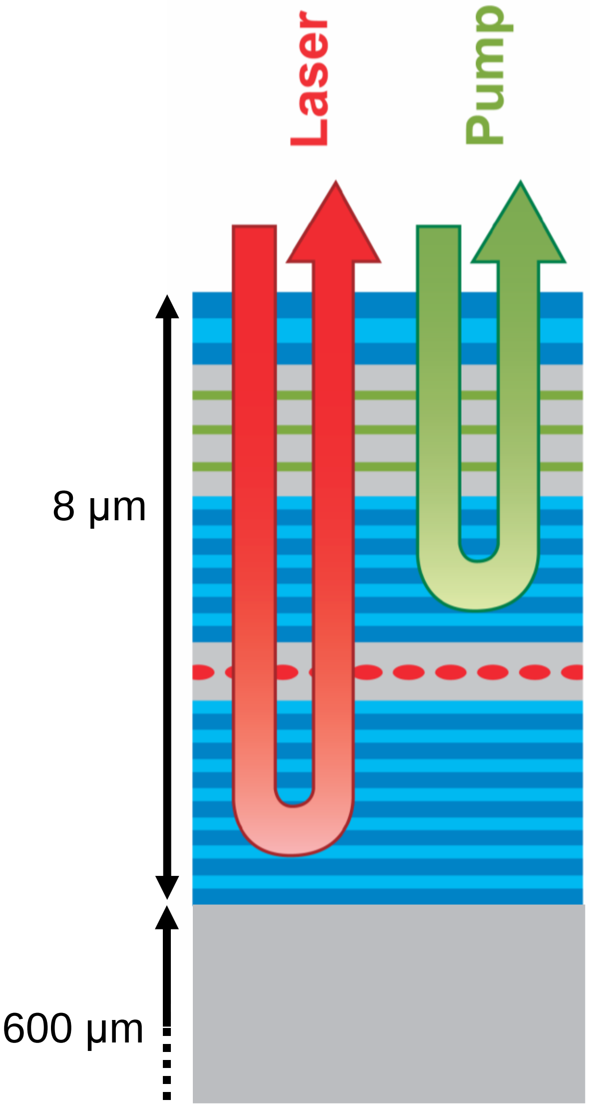
MIXSEL concept





AR

7 QW gain layers

Pump DBR

QD saturable absorber

Laser DBR

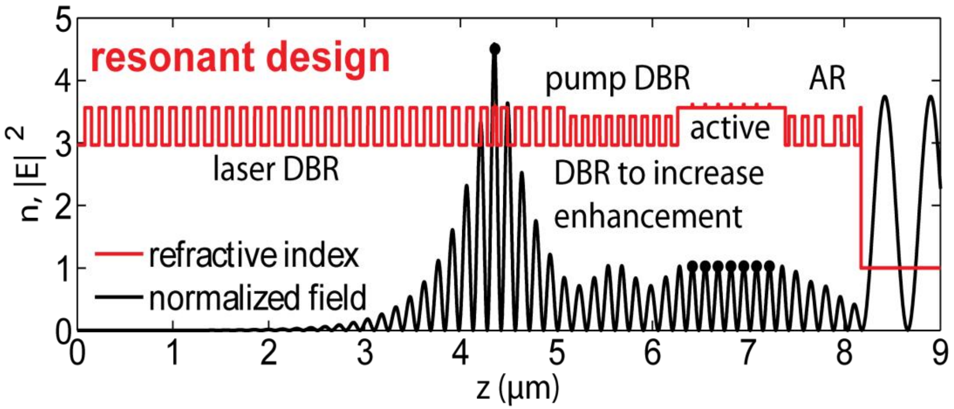
Substrate GaAs

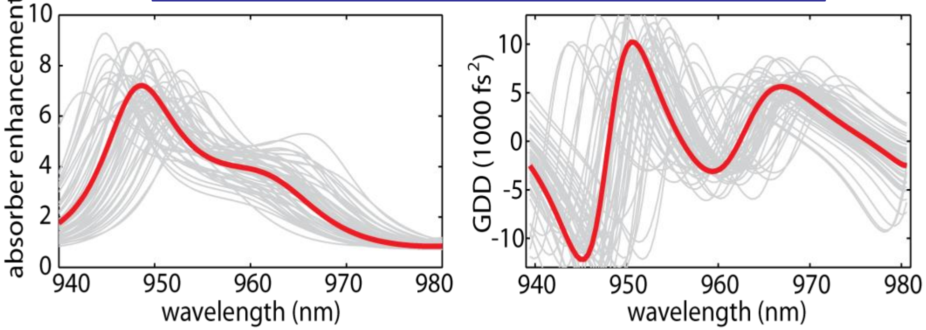
Resonant vs. antiresonant design

Initial MIXSEL demonstration had a **resonant design:**

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

- sensitive to growth errors
- high GDD - long pulses

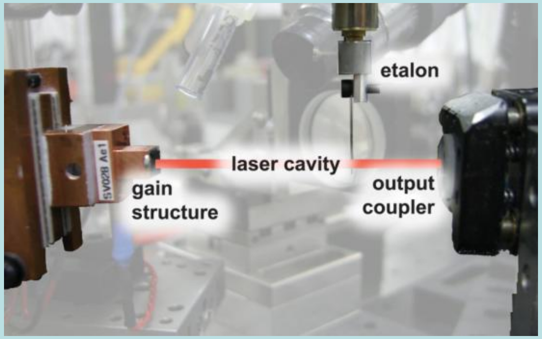




growth error simulation:
layer thickness variations < 1%

- Field enhancement in QD-layer by resonant sub-cavity
  - low saturation fluence <10 µJ/cm²

pulse repetition rate:	**2.8 GHz**
average output power:	**185 mW**
pulse duration:	**32 ps**
heat sink temperature:	**-50˚C**



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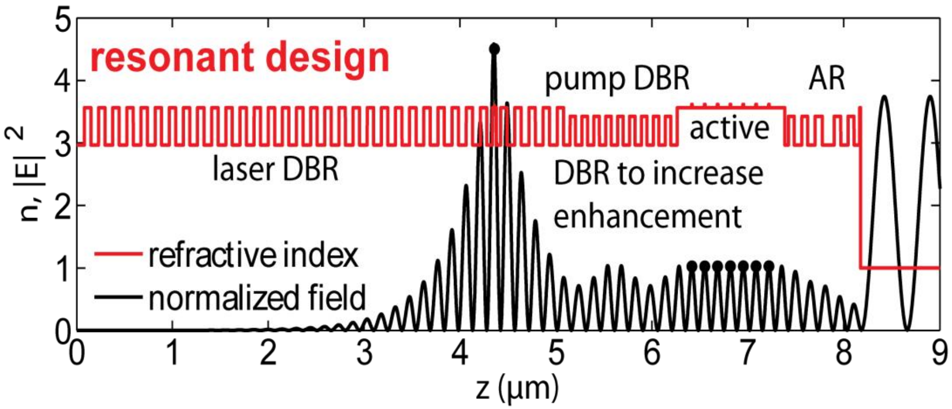

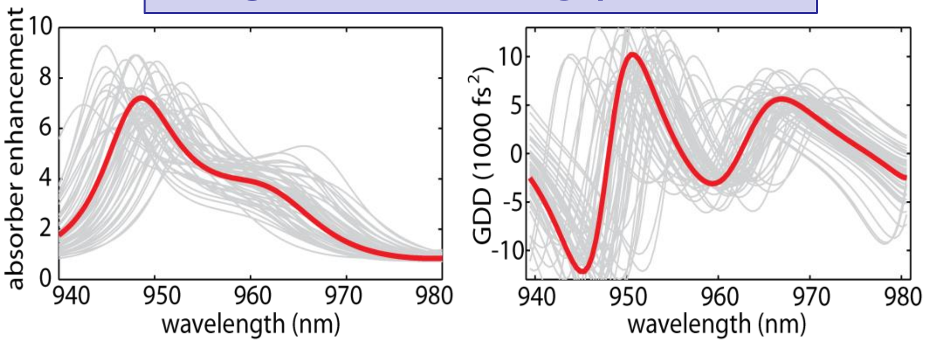

growth error simulation:

layer thickness variations < 1%

- Field enhancement in QD-layer by resonant sub-cavity
  - low saturation fluence <10 µJ/cm²
- Recently: detailed study on QD-growth parameters
  - optimization of growth temperature and post-growth annealing
  - achieved first 1:1 SESAM-VECSEL modelocking from antiresonant SESAM

A.-R. Bellancourt, Y. Barbarin, D. J. H. C. Maas, M. Shafiei, M. Hoffmann, M. Golling, T. Südmeyer and U. Keller, OE, 17, 12, 9704 (2009)

D. J. H. C. Maas, A. R. Bellancourt, M. Hoffmann, B. Rudin, Y. Barbarin, M. Golling, T. Südmeyer and U. Keller, OE, 16, 23, 18646 (2008)

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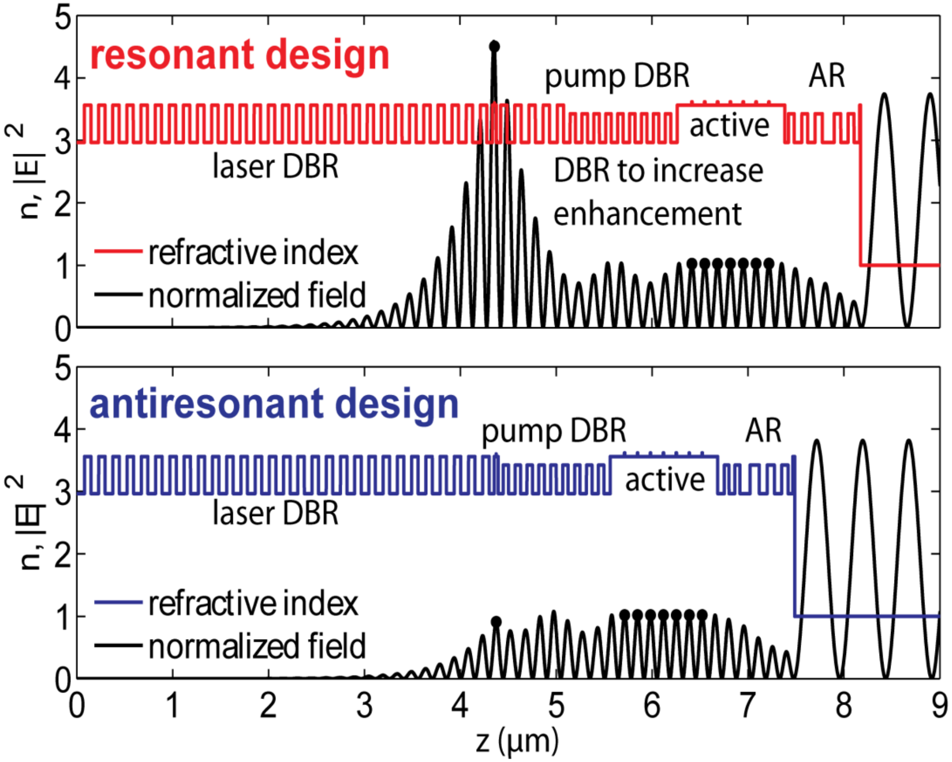
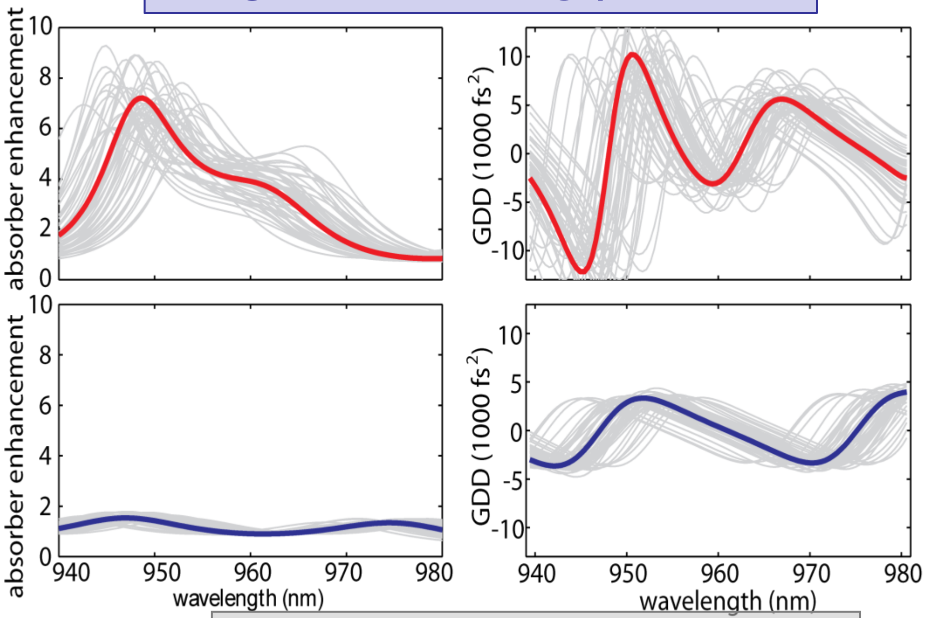




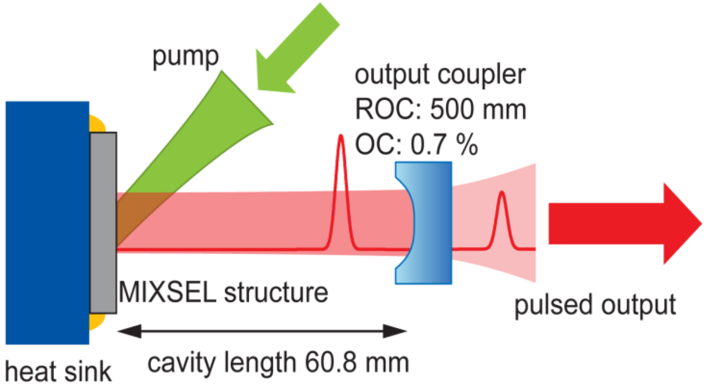
growth error simulation:
layer thickness variations < 1%

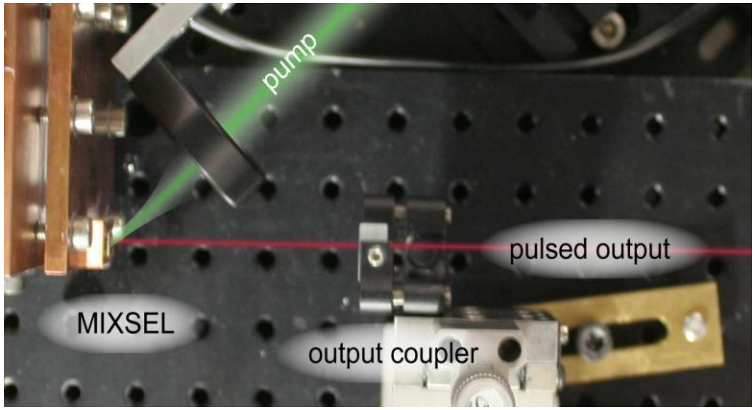
New: MIXSEL demonstration with **antiresonant design**

- tolerant to growth errors
- low GDD - short pulses

MIXSEL on diamond heat sink

- First MIXSEL with diamond heat sink instead of GaAs wafer
- Increase pump spot from 80 µm radius to ~215 µm
- Achieve new power record: 6.4 W in 28 ps at 2.5 GHz





average output power: **6.4 W**
pulse duration: 28.1 ps
center wavelength: 959.1 nm
FWHM spectral width: 0.15 nm
optical pumping 36.7 W at 808 nm

pump / laser spot radius: ~215 µm
TBP: 1.35 (4.2 times sech^2)
efficiency (opt-opt): 17.4 %

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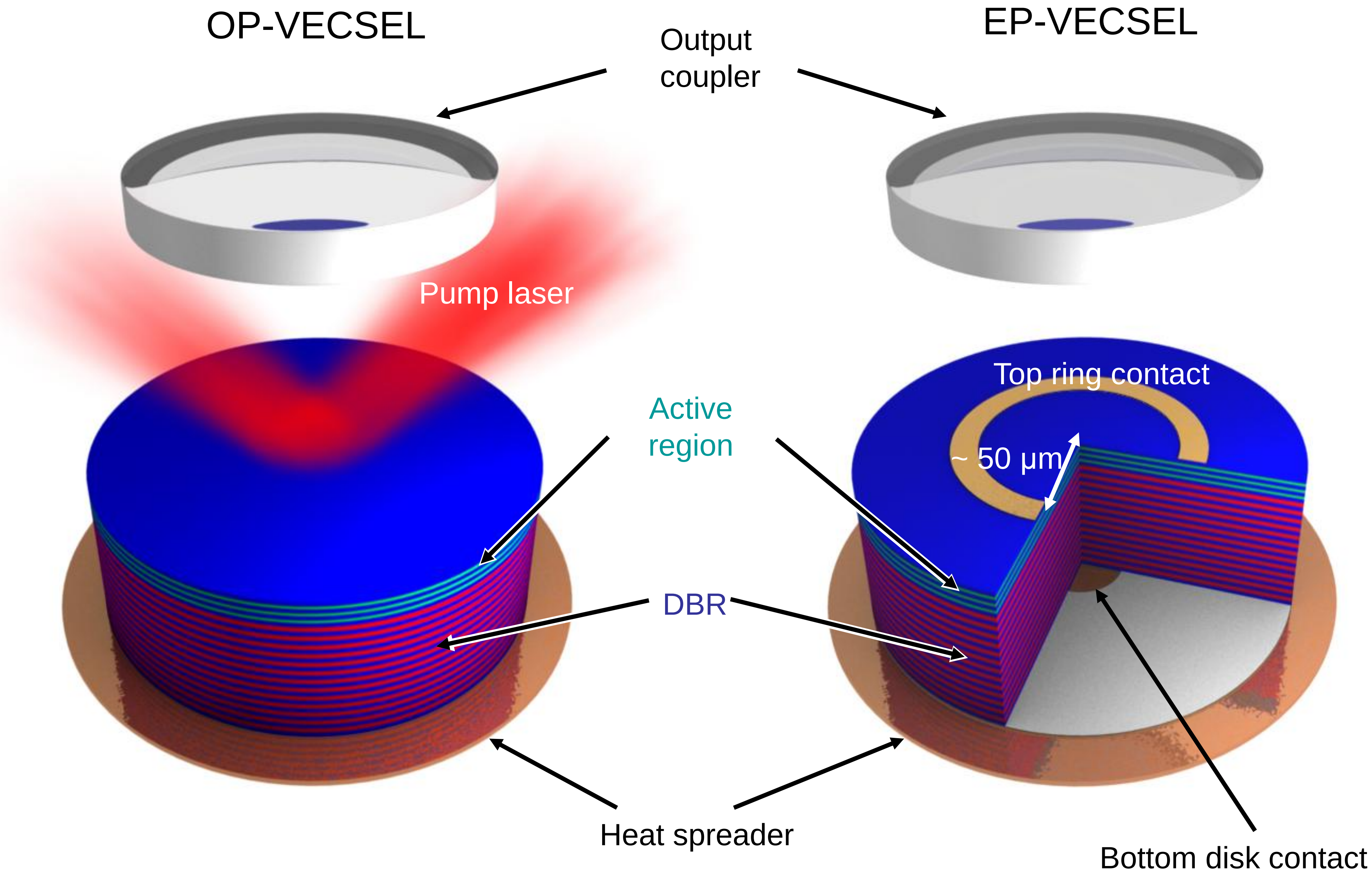
Electrical vs. optical pumping



OP-VECSEL

EP-VECSEL

Output coupler

Pump laser

Top ring contact

Active region

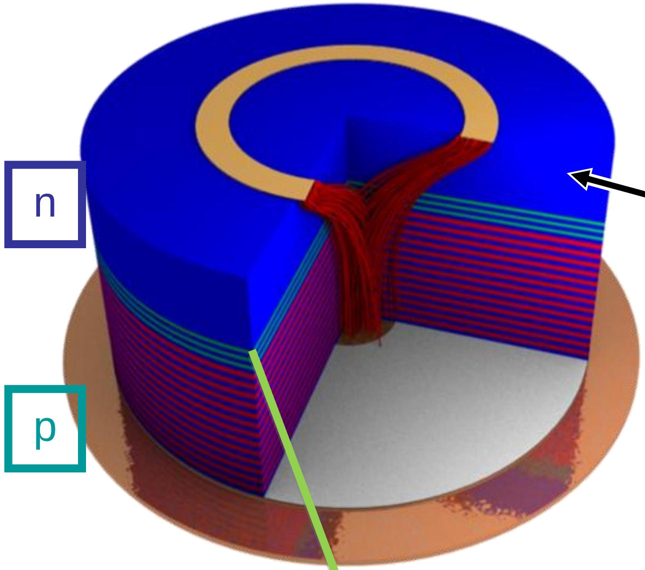
~ 50 µm

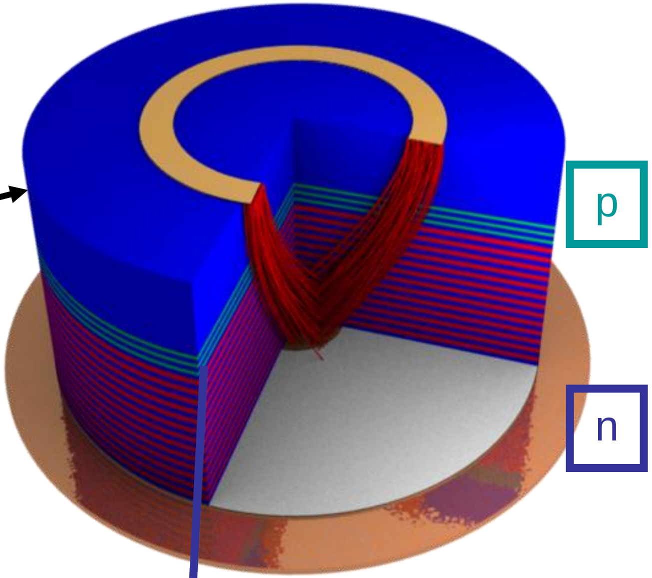
DBR

Heat spreader

Bottom disk contact

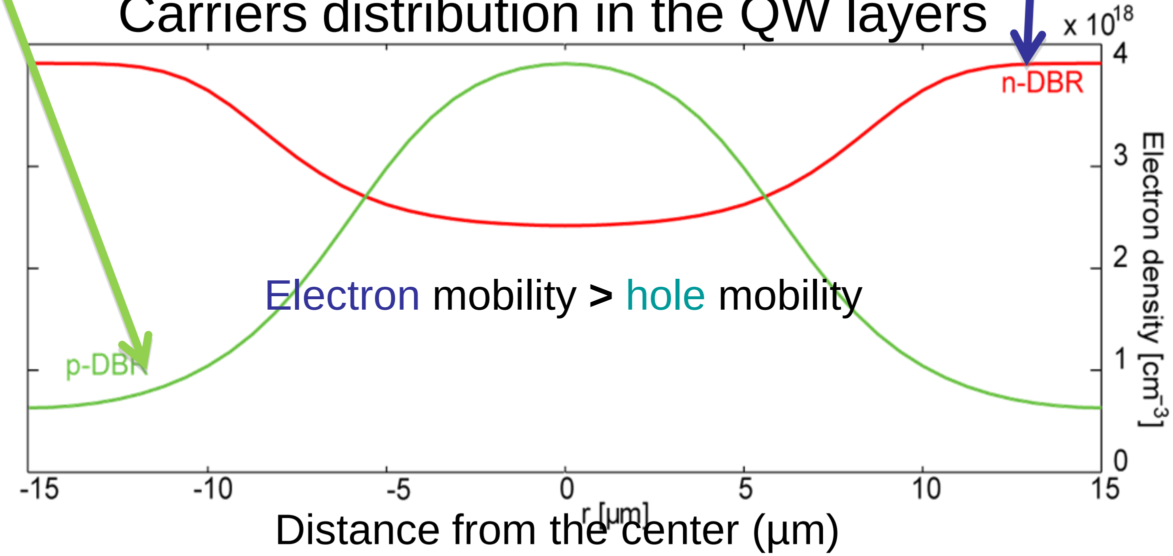
Simulations for EP-VECSEL Design





Current spreading layer

Carriers distribution in the QW layers



Electron mobility **>** hole mobility

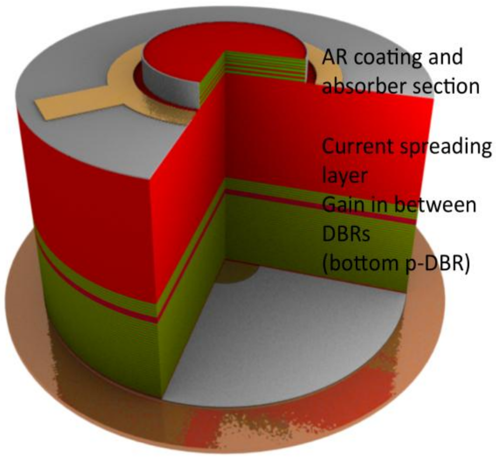
Distance from the center (μm)

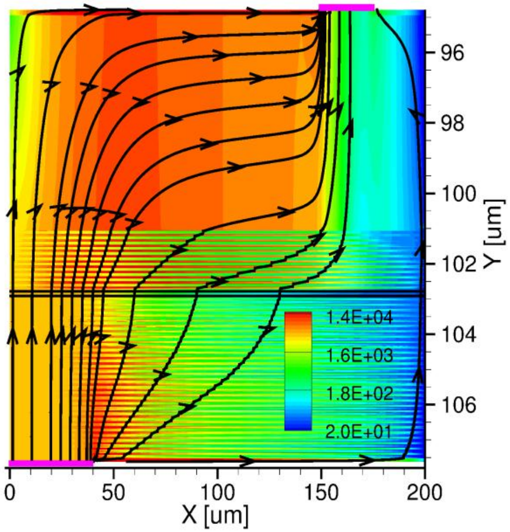
p-DBR design favorable for large output beam with fundamental transverse mode

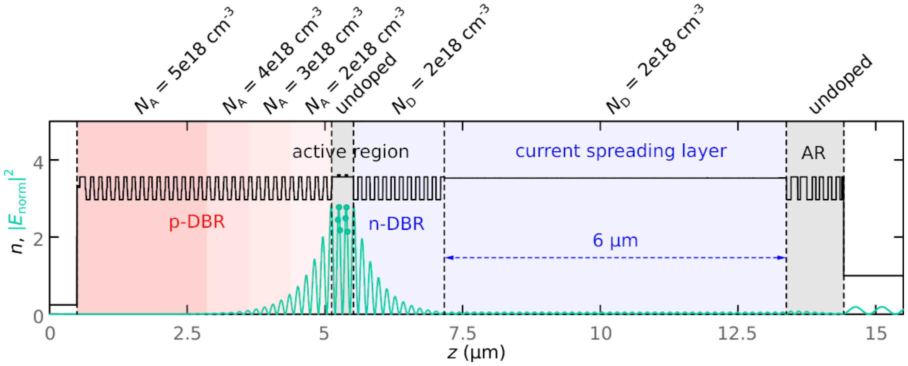
P. Kreuter et al., *Appl. Phys. B*, **91**, 257, 2008

EP-VECSEL: some design features

Trade off between optical losses and electrical resistance



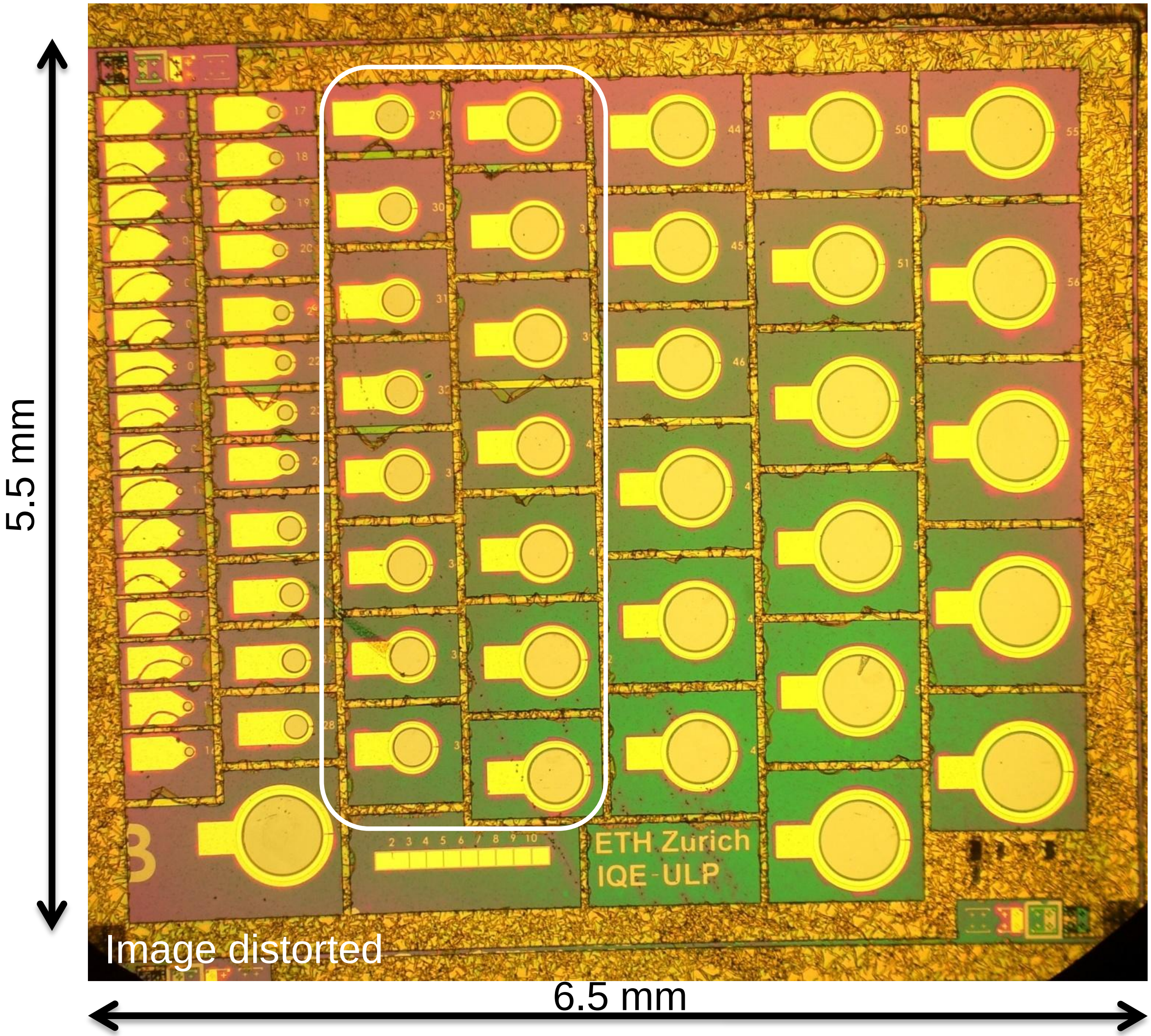




- **Suitable for modelocking**
  ⇨no excessive resonances, low dispersion
- **Low-loss, high conductivity p-DBR**
  ⇨ large aperture possible
  ⇨ high power achievable
- **Use wafer bonding on CuW wafer**
- **Good electrical contacts**
  - Donut n-contact
  - Small disk p-contact
- **Uniform current injection**
  by thick spreading layer (shown in red)
- **Increased gain**
  by intermediate DBR
- **AR coating etched for lower resistance**

P. Kreuter et al., *Appl. Phys. B*, **91**, 257, 2008

EP-VECSEL chip

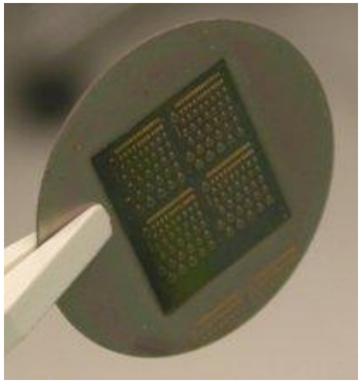


EP-VECSEL target:

Bottom contact diameter : 50-100 µm

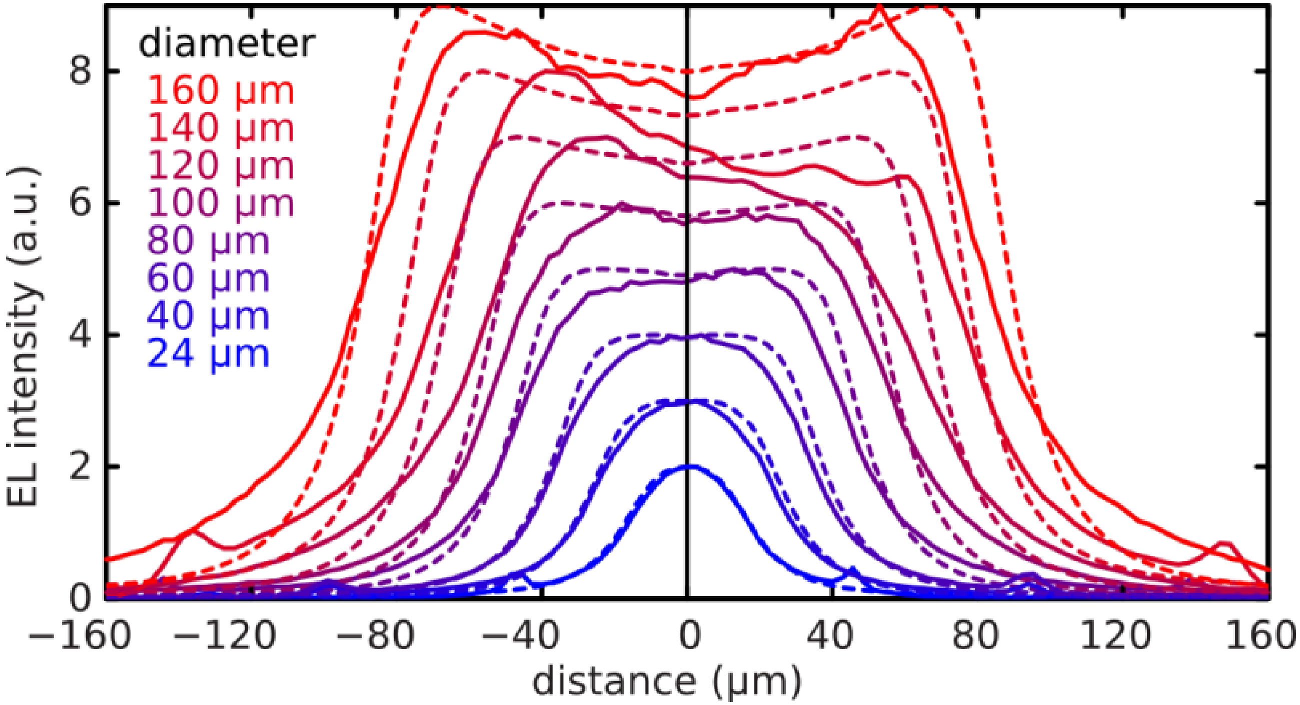
Top ring contact diameter: 100-300 µm

Larger EP-VECSEL
⇒ multimode output beam expected

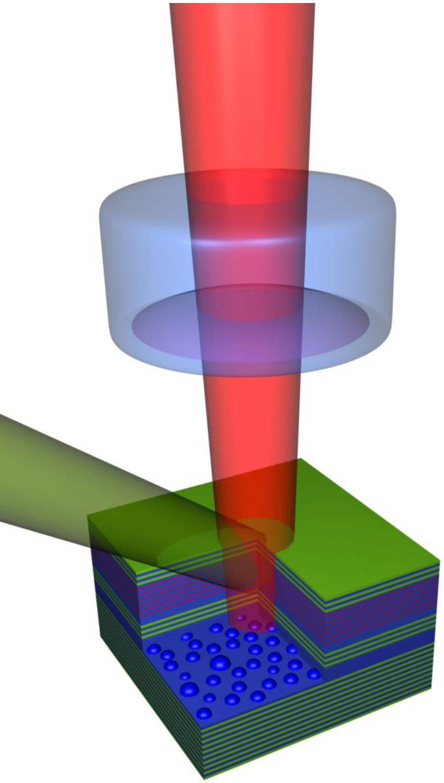


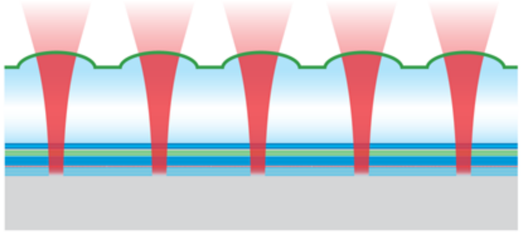
First EP-VECSEL results

- ✓ Growth, processing, and evaluation implemented
- ✓ 60 different EP-VECSEL lasing in cw
- ✓ Output power up to 120 mW (cw) achieved
- ✓ Good homogenous electroluminescence profiles measured for devices up to 100 µm (excellent agreement with our simulations)



Conclusions





Passively modelocked VECSEL with an integrated saturable absorber:

MIXSEL (Modelocked Integrated External-Cavity Surface Emitting Laser)

- modelocking with **6.4 W** was obtained at 2.5 GHz
- modelocking with 200 mW at 10 GHz (not yet optimized)

Next steps

➡ Optimization dispersion and SESAM recovery time:

- Reduce pulse duration

➡ Electrical pumping:

- Simple, compact, cost-efficient device

MIXSEL nano-tera.ch

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