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

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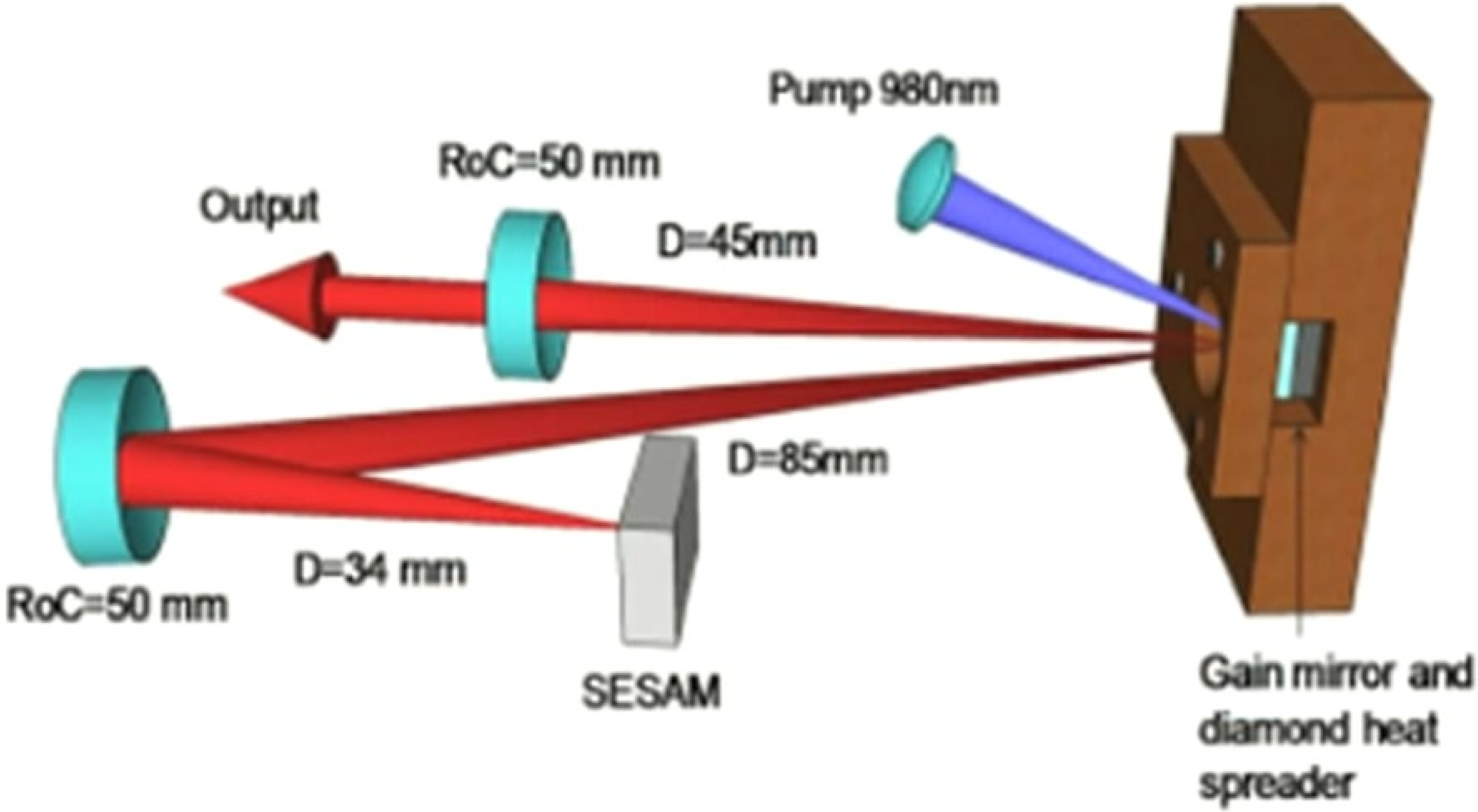
Ultrafast semiconductor lasers

- Currently, typical ultrafast lasers are bulky and complex

- Our approach: semiconductor laser with vertical integration

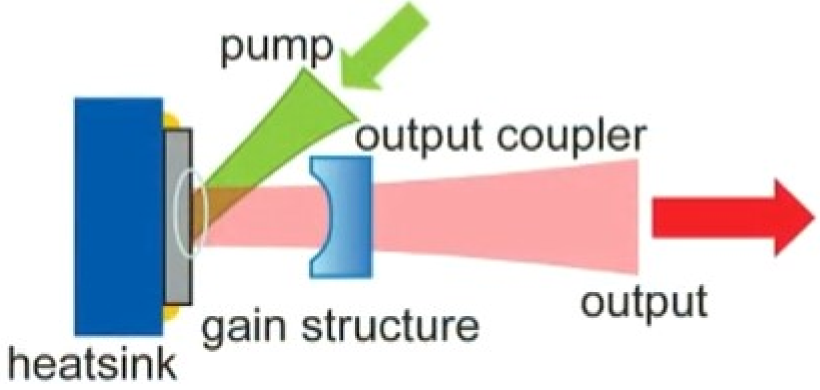
VECSEL	SESAM	MIXSEL
Vertical External Cavity Surface Emitting Laser	Semiconductor Saturable Absorber Mirror	Modelocked Integrated External-Cavity Surface Emitting Laser

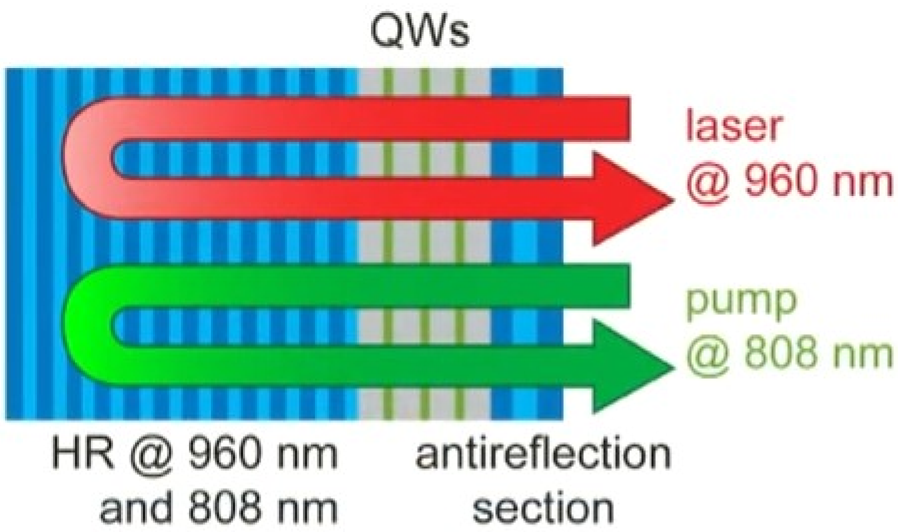


first wafer-fused modelocked VECSEL

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

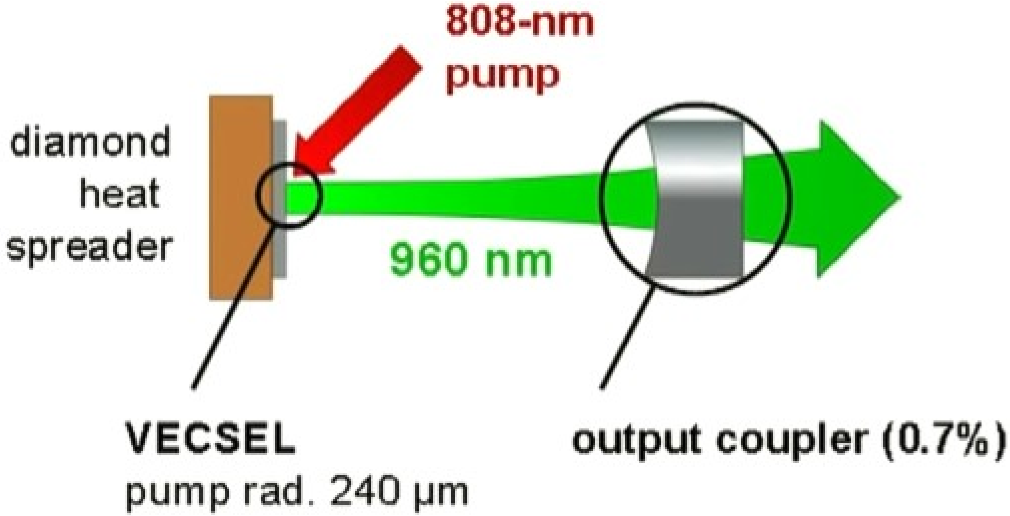
External cavity

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

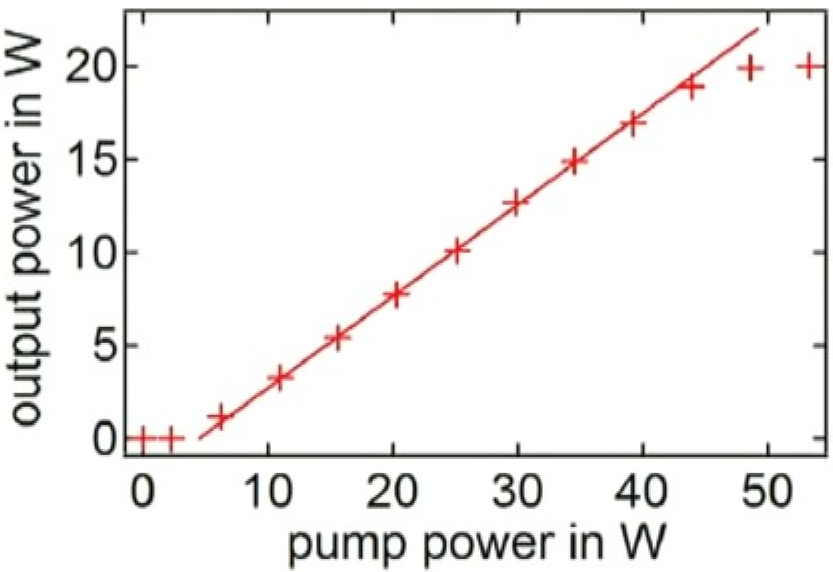
Semiconductor Gain

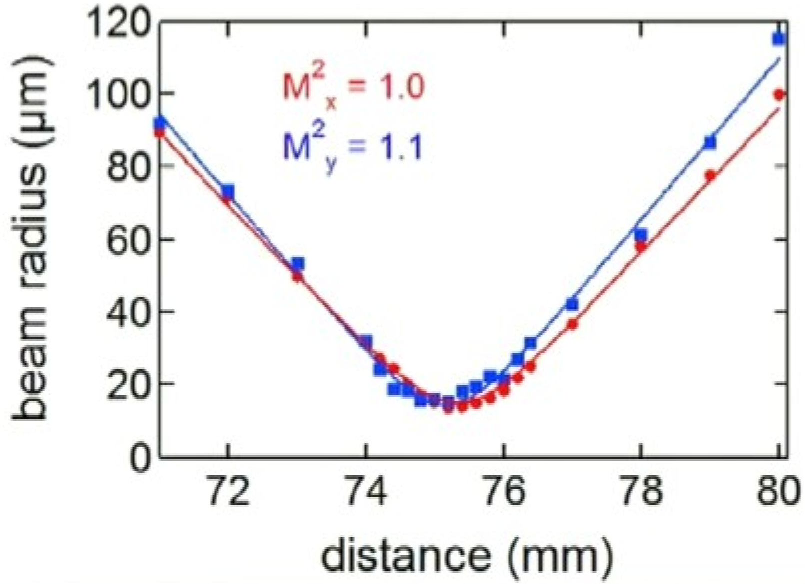
- bandgap engineering: so far 0.6 … 2.3 µm
- cost-efficient fabrication

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

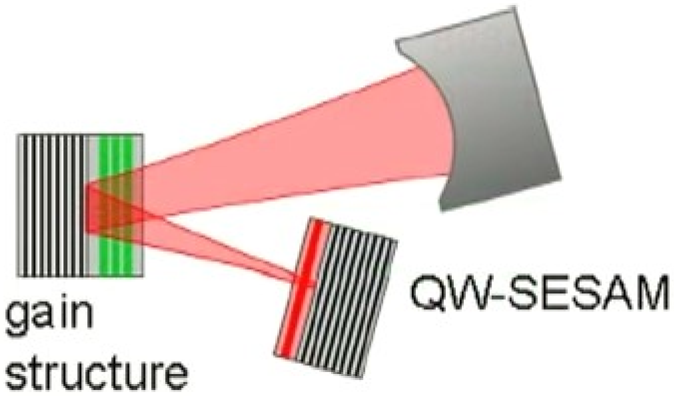


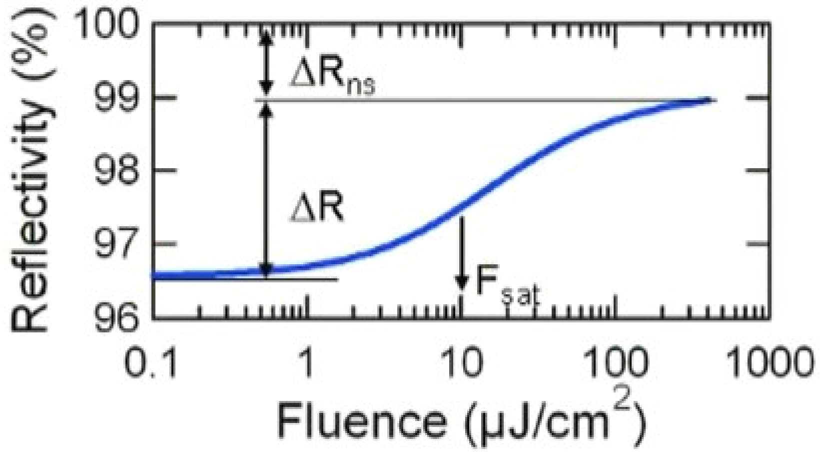
- Maximum power P = 20.2 W
- Up to $\eta_{opt\text{-}opt}$ = 43%
- $M^2 < 1.1$

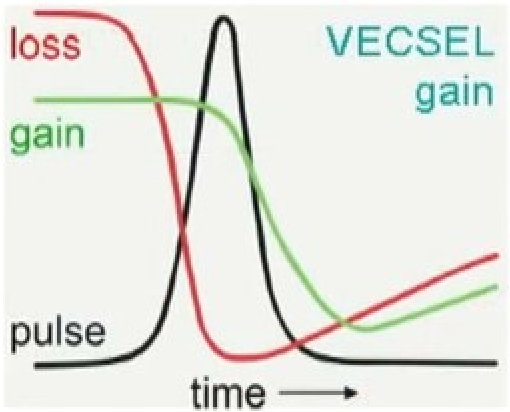




SESAM-VECSEL modelocking







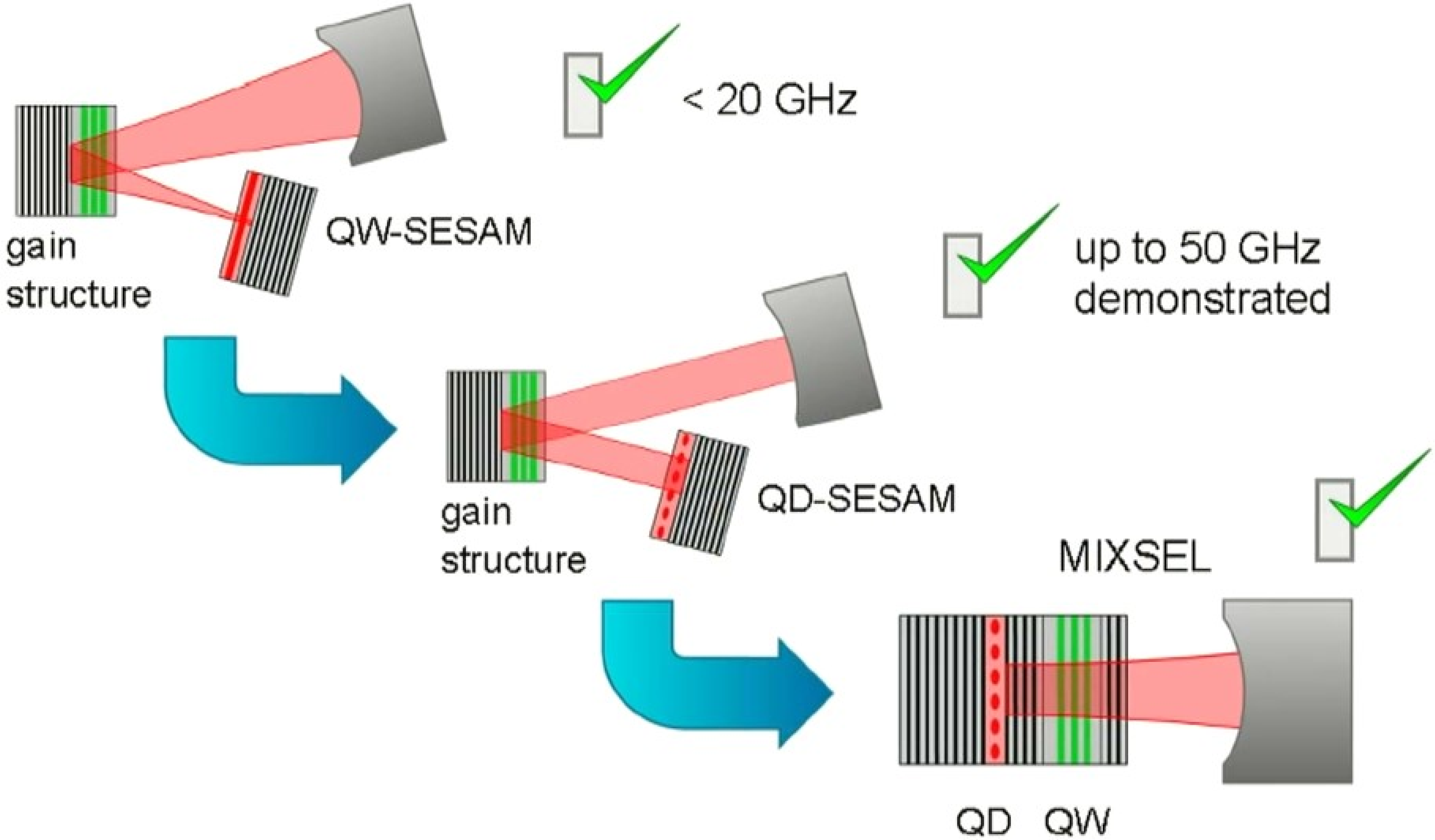
⇨ loss has to saturate faster

- 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

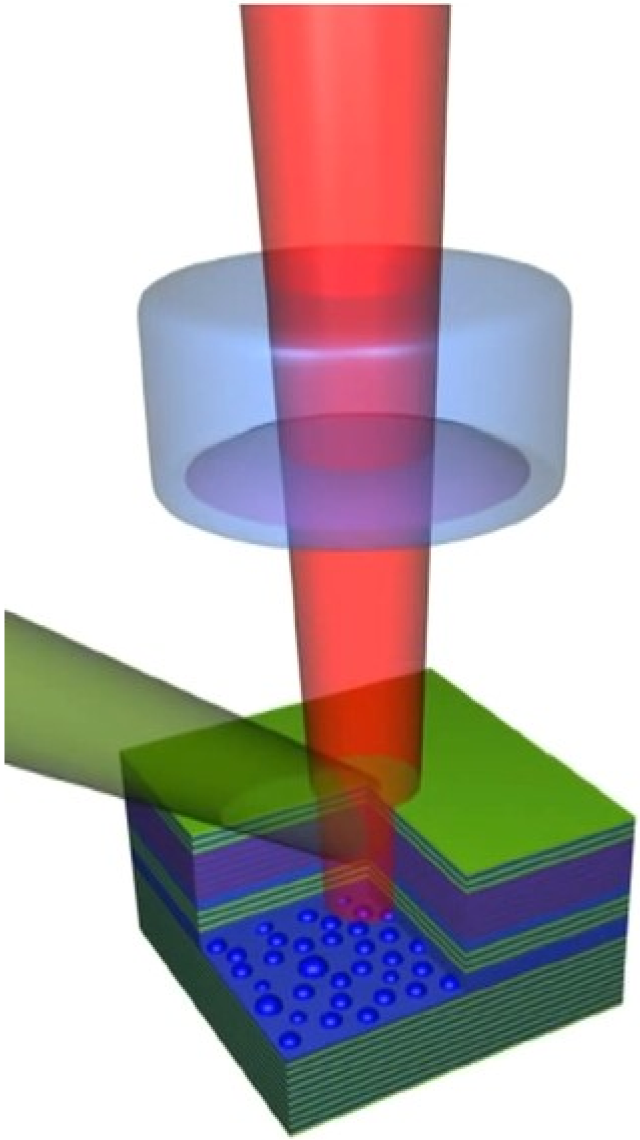
$$\frac{E_{sat,a}}{E_{sat,g}} = \frac{F_{sat,a}}{F_{sat,g}} \frac{A_a}{A_g} < 1$$

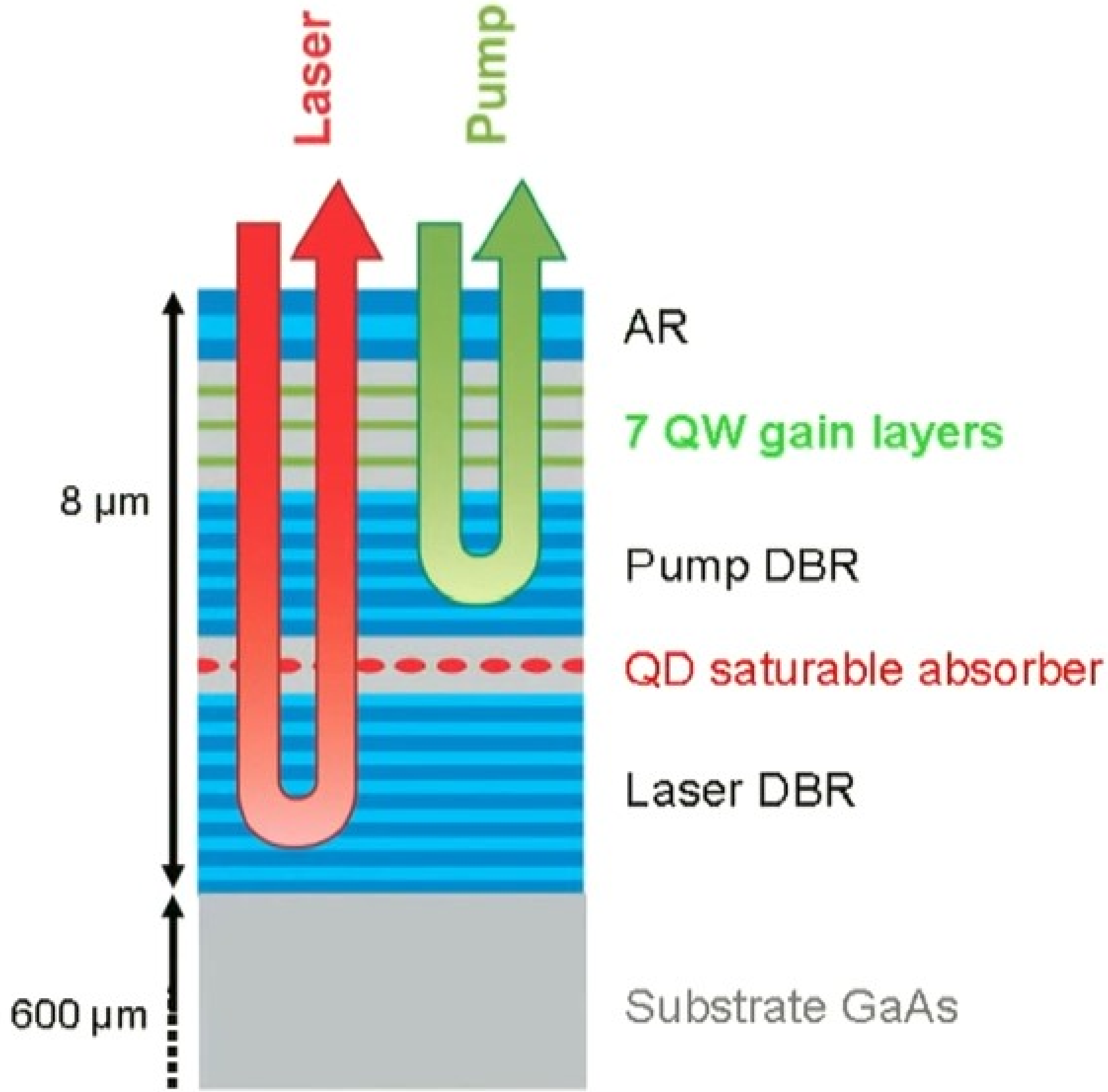
[#1] U. Keller et al., *Opt. Lett.* **17**, 505, 1992 [#2] U. Keller, *Nature* **424**, 831, 2003

SESAM-VECSEL modelocking



MIXSEL concept



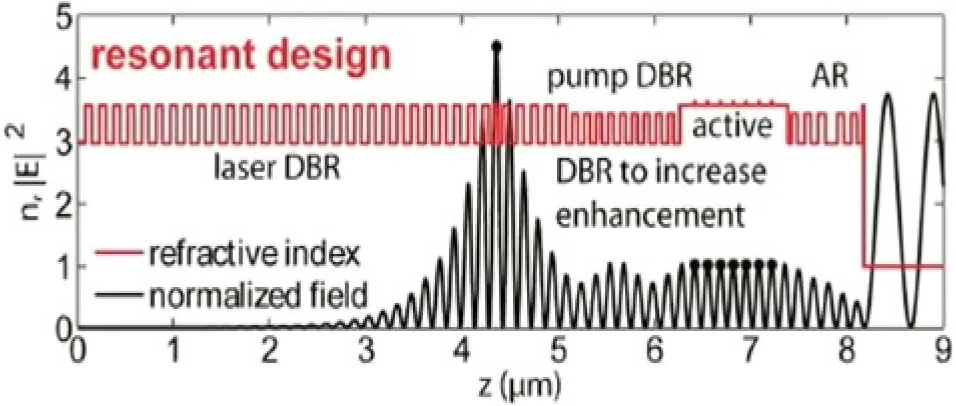


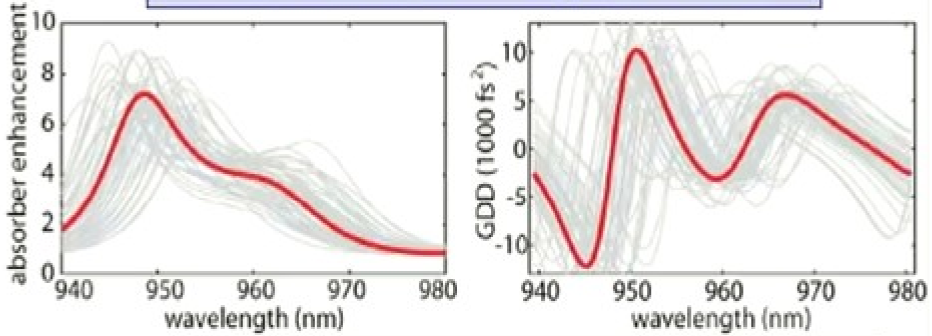
Resonant vs. antiresonant design

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



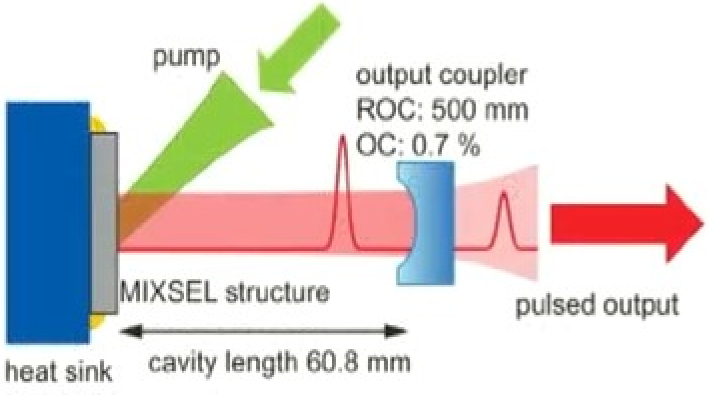


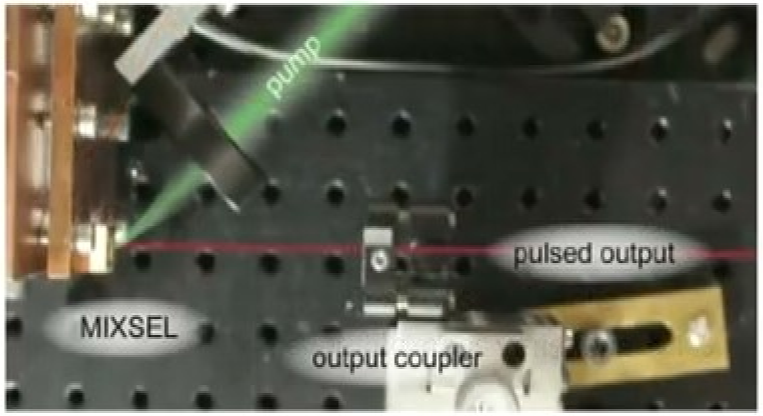
growth error simulation:
layer thickness variations < 1%

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

MIXSEL on diamond heat sink

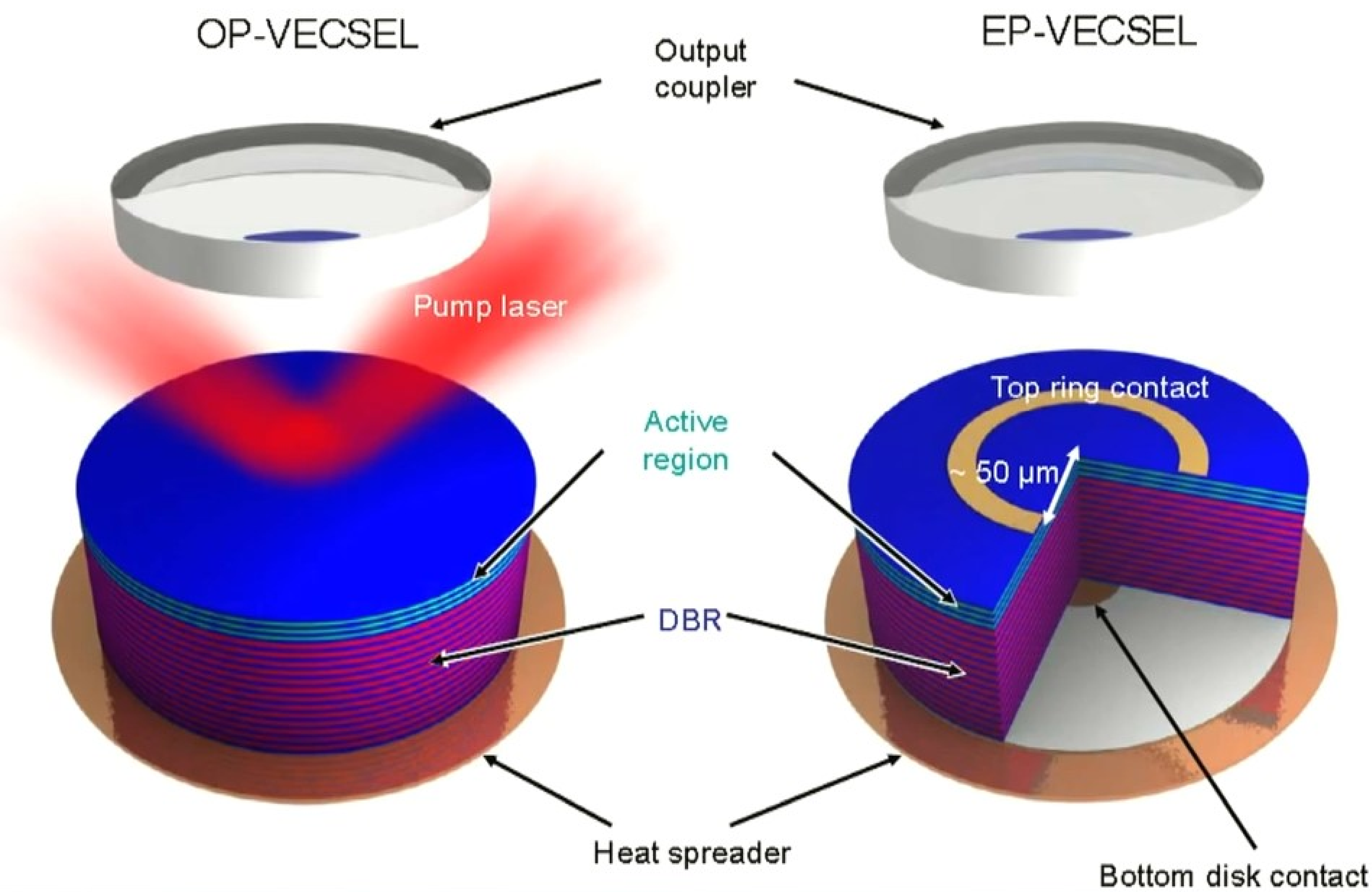
- First MIXSEL with diamond heat sink instead of GaAs wafer
- Increase pump spot from 80 µm radius to ~215 µm
- Achieve new power record: 6.4 W in 28 ps at 2.5 GHz



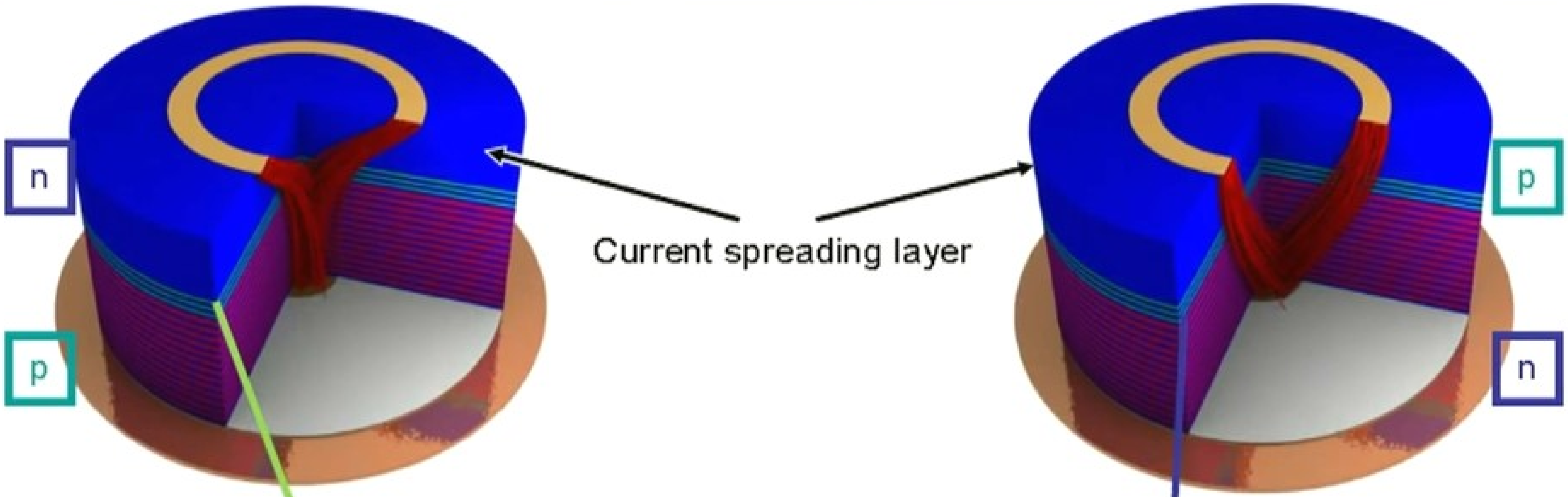


average output power: **6.4 W**
pulse duration: 28.1 ps
center wavelength: 959.1 nm
FWHM spectral width: 0.15 nm
optical pumping 36.7 W at 808 nm
pump / laser spot radius: ~215 µm
TBP: 1.35 (4.2 times sech^2)
efficiency (opt-opt): 17.4 %

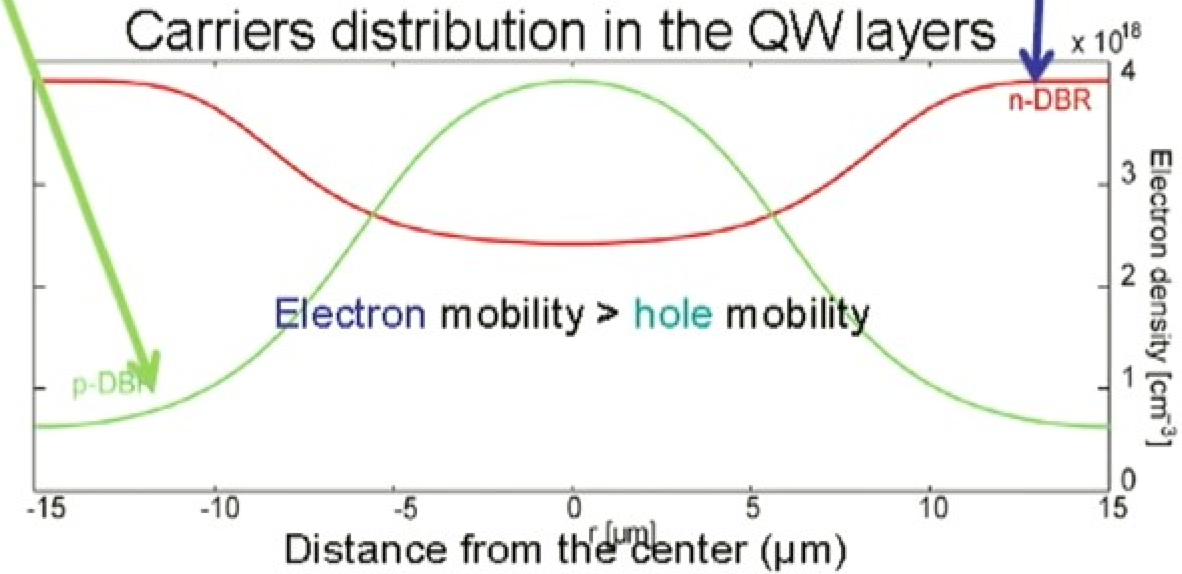
Electrical vs. optical pumping



Simulations for EP-VECSEL Design



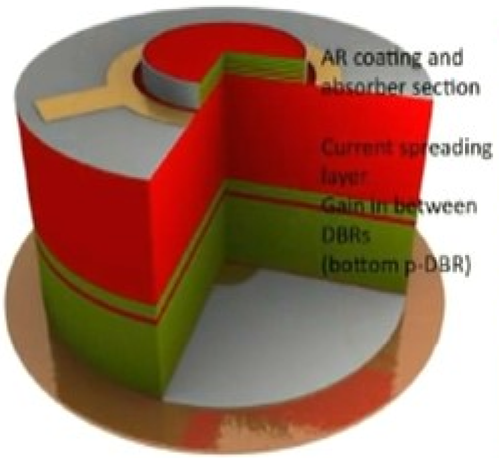
p-DBR design favorable for large output beam with fundamental transverse mode

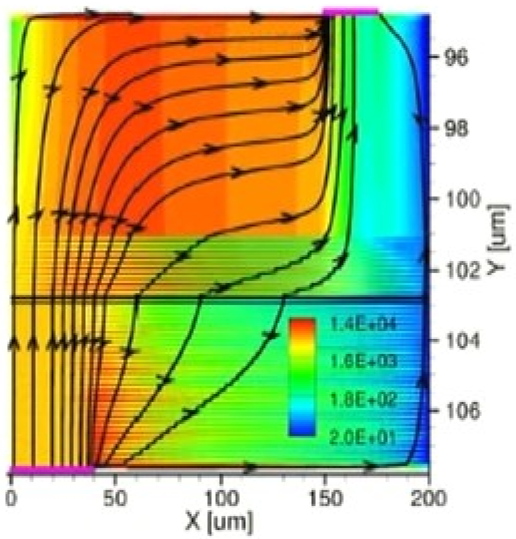


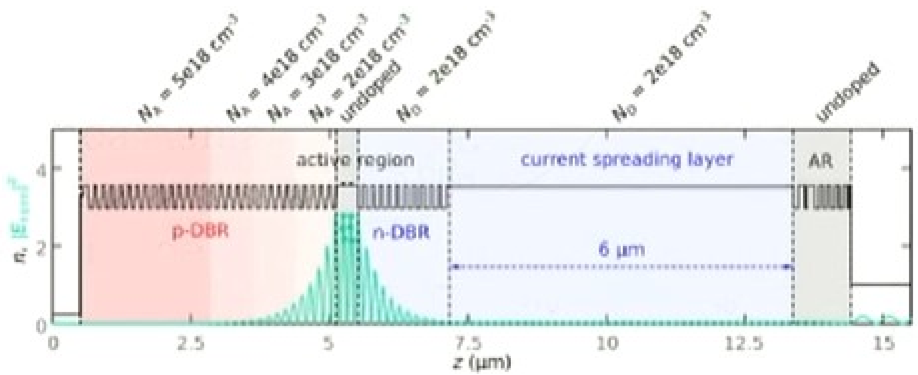
P. Kreuter et al., *Appl. Phys. B*, **91**, 257, 2008

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