# Optical efficiency and gain dynamics of ultrafast semiconductor disk lasers

**Conference Poster**

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MIXSEL2 | RTD 2013

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# Optical efficiency and gain dynamics of ultrafast semiconductor disk lasers [1]


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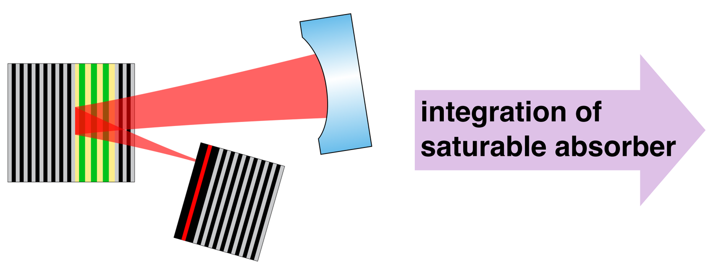
[1] C. G. E. Alfieri et al., Optics Express **25**, 6402-6420 (2017)

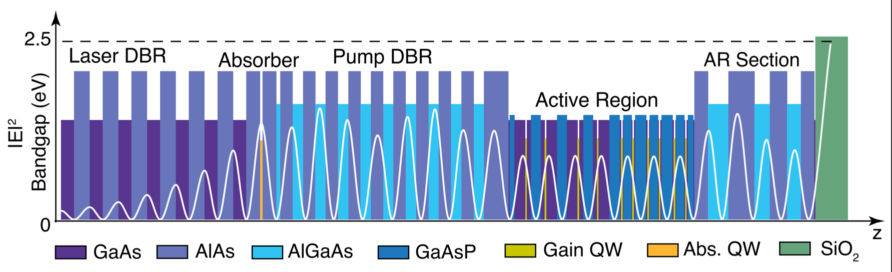

## Semiconductor disk lasers (SDLs)

### Diode pumped, passively modelocked VECSELs and MIXSELs

**Semiconductor based:**

✓ Compactness + Wavelength versatility + Cost efficiency + Mass scale production




**VECSEL** + **SESAM** = **MIXSEL**

**VECSEL**
Vertical External Cavity Surface Emitting Laser

- Distributed Bragg reflector (DBR)
- Active region
- **Low dispersion** antireflection (AR) section

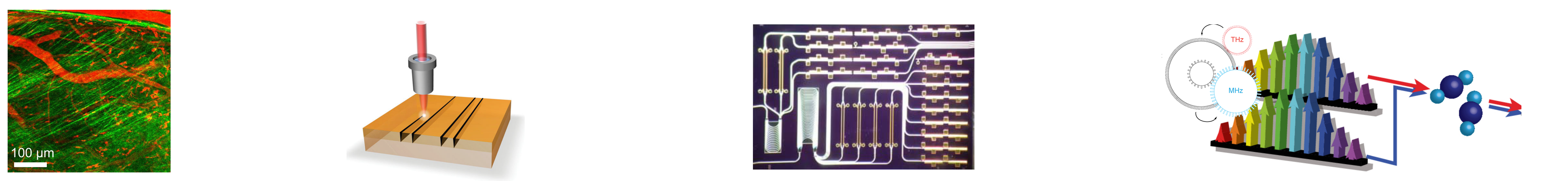
**SESAM**
SEmiconductor Saturable Absorber Mirror

- DBR + single **fast** saturable absorber
- Initiates and stabilizes modelocked operation

**MIXSEL**
Modelocked Integrated External-Cavity Surface Emitting Laser

- DBR for pump light
- Straight cavity for simplified **repetition rate scalability**
- Monolithic design

### Applications

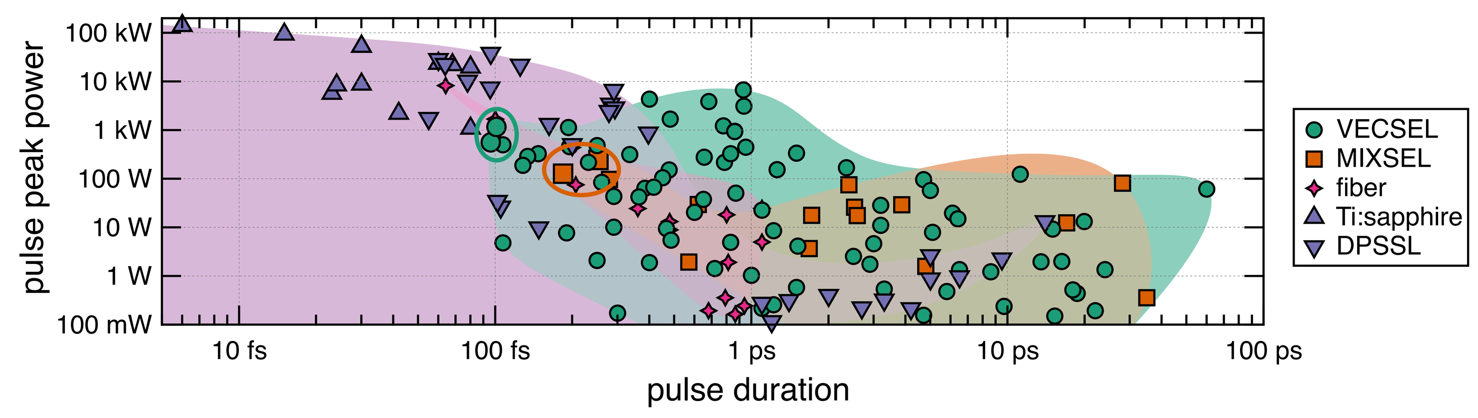


Microscopy[2] | Femtosecond Micromachining | Telecommunication | Comb metrology and spectroscopy[3]


[2] F. Voigt, F. Emaury et al., submitted to Biomedical Opt. Express (2017)
[3] S. M. Link et al., accepted in Science (2017)


## Gigahertz oscillator technologies

Many applications require combinations of **high pulse peak power** and **short femtosecond pulses**




- **Ti:Sapphire**: best performance for $f_{rep}$ < 10 GHz
- Diode pumped solid state lasers (**DPSSLs**): tens of kW of peak power, sub-100-fs pulses
- **SDLs**: **highest peak power for $f_{rep}$ > 10 GHz** [4]
  - **sub-200-fs MIXSELs**
  - **sub-100-fs VECSELs** [5] with **kW-level** pulse peak power **in the 1 μm emission range**

### Trade-offs of ultrafast SDLs

In sub-200-fs regime:

- **Power limitations: average output power < 1 W**
- **Multi-pulsing instabilities at high pump power**
- **Low efficiency, typically < 1%**

} **Fundamental problems related to the carrier dynamics in the saturable gain quantum wells?**

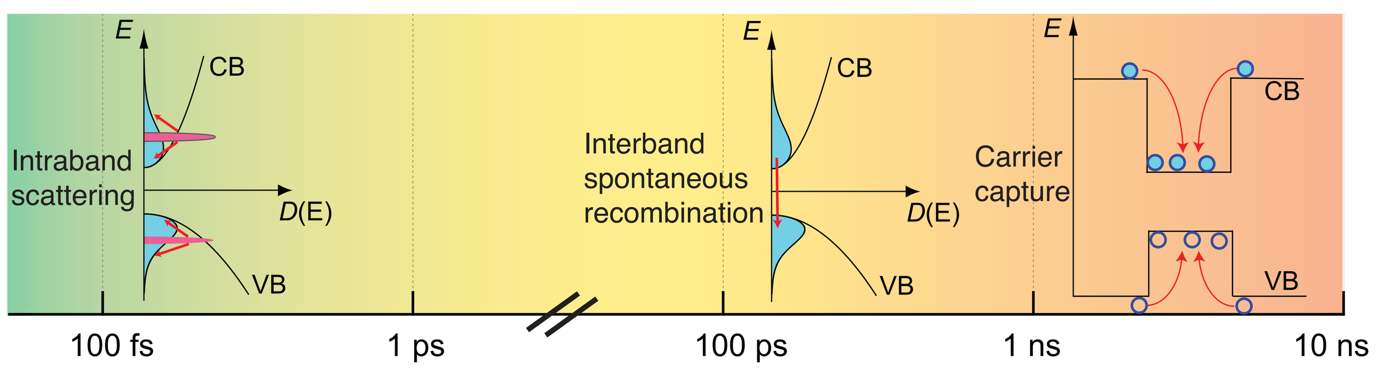

[4] M. Mangold et al., Opt. Express 22(5), 6099–6107 (2014)
[5] D. Waldburger et al., Optica 3(8), 844–852 (2016)


## Quantum well model

To understand the observed trade-offs and overcome them, we developed a **quantum well (QW) model based on rate equations** [4]

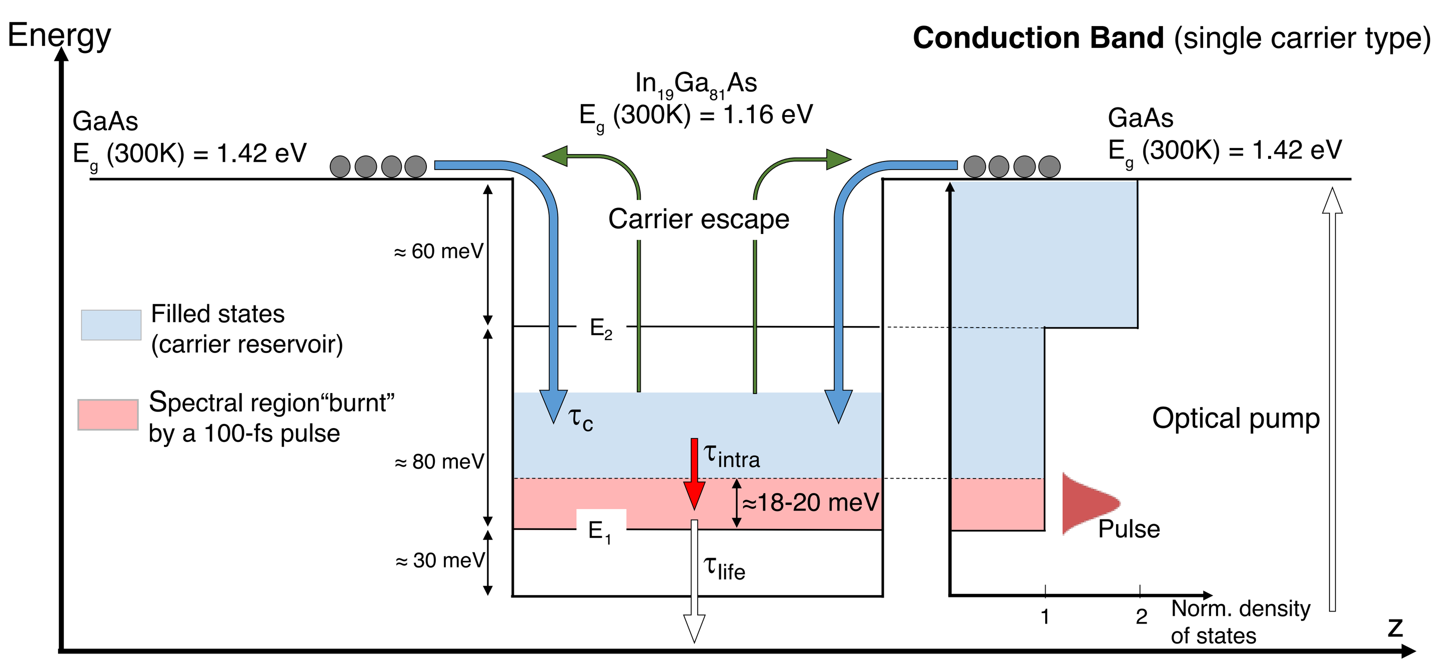
**Three time scales involved:**

Intraband: $\tau_{intra}$ ≈ **300 fs** — Interband: $\tau_{life}$ ≈ **150 ps** — Diffusion: $\tau_c$ ≈ **1-3 ns**

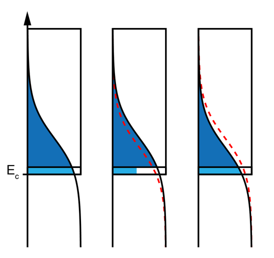



### Simulated carrier dynamics in gain QWs

- The pump photons are absorbed in the GaAs barriers and create $e^-/h^+$ pairs
- The generated carriers flow via **diffusion** until they are captured by the QW ($\tau_c$)




- The captured carriers **decay to the bottom of the band** ($\tau_{intra}$)
- The carriers continuously recombine via **spontaneous recombination** ($\tau_{life}$)
  - The modelocked pulse is amplified via stimulated recombination of the carriers at the bottom of the band



- The pulse creates a **spectral hole** at the bottom of the band
  - If the pulse is shorter than $\tau_{intra}$, the gain is **saturated** fast since the carriers in the reservoir cannot be used

**Short pulses saturate the gain at low pulse energies**

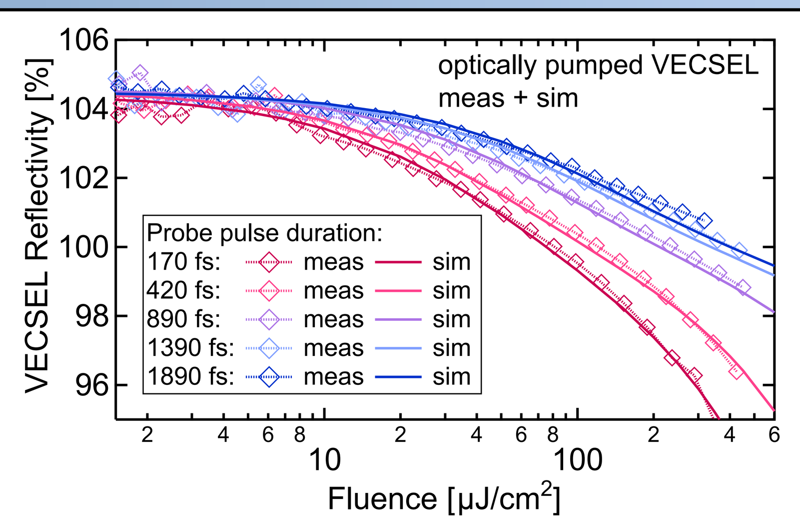
## Gain and efficiency calculation

Two mechanisms decrease the net gain for energetic short pulses:

- Spectral hole burning (SHB)
- Two-photon absorption (TPA)

Longer stretched pulses (same spectrum) experience significantly higher VECSEL gain saturation fluence

**The QW model can quantitatively predict this behaviour.**




### Cavity reflectivity simulations

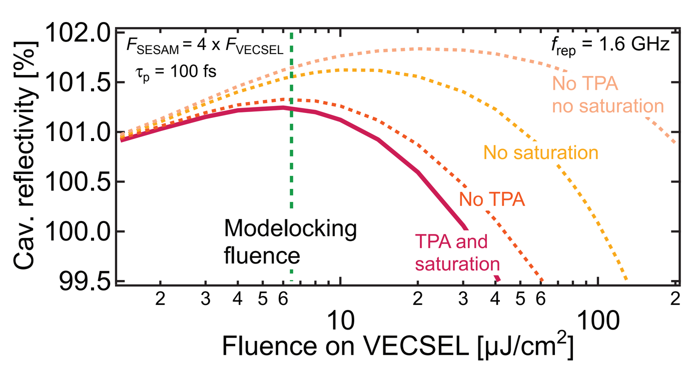
$R_{cav}$ = reflectivity seen by the pulse after a cavity roundtrip, before output coupling (OC)

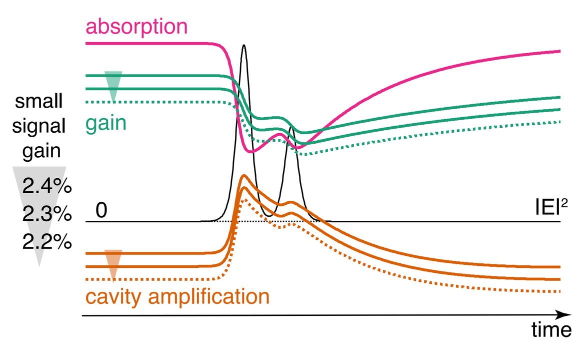
$F_0$ = pulse fluence maximizing $R_{cav}$. **SDLs modelock close to $F_0$**

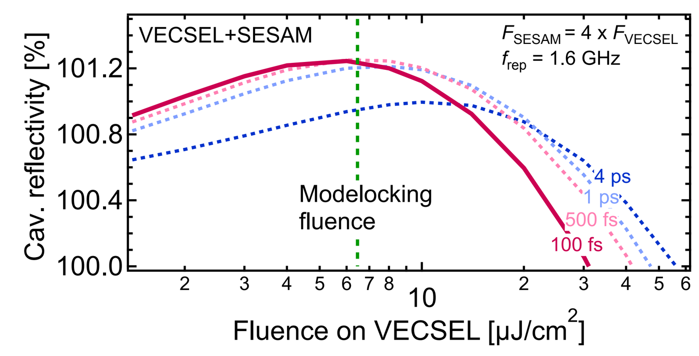
OC = $R_{cav}$ - 100% - cavity losses = **available output coupling ratio**

} **To improve performance: increase $F_0$ and OC**

**Power limiting effect** | **Multipulse instabilities** | **Chirped pulse formation**

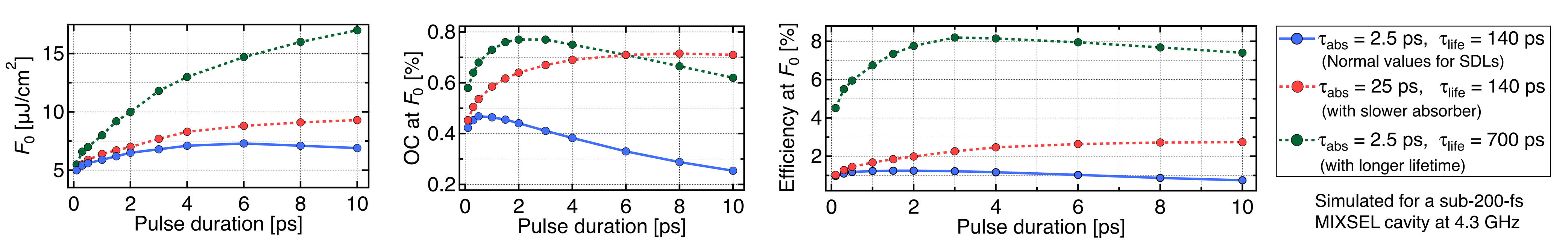



- **Gain saturation** due to SHB is limiting power scaling **more than TPA**
- High VECSEL gain "opens" a **net gain window** after a short pulse if the SESAM recovery is too slow
- **Increased $F_0$**: no SHB
- **Decreased OC**: more losses in fast SESAM (recovery in ≈ 2 ps)
- **No fast SESAM required** for ps pulses

### Solutions for higher efficiency




**To achieve higher efficiency:**

- Long pulse duration
- Slow absorber ($\tau_{abs}$ ≈ 10 $\tau_{pulse}$)

OR

**Significantly increased carrier lifetime in the gain**

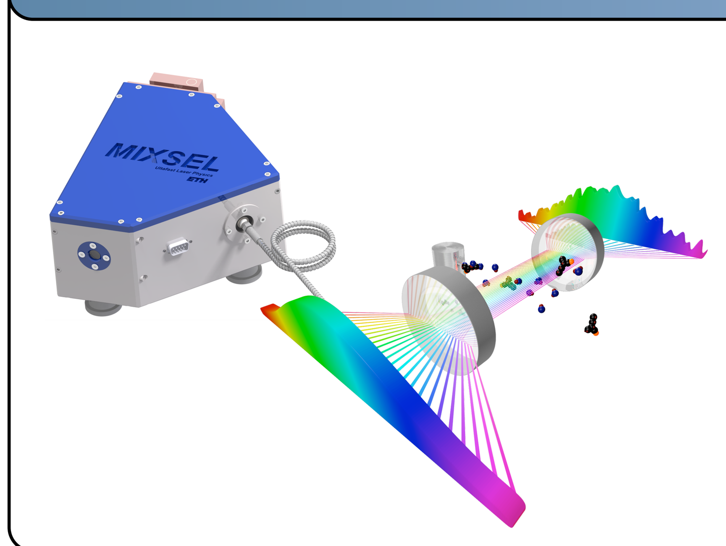
## Conclusions

- SDLs are limited by spectral hole burning effects in the gain QWs
- Efficiency scaling is prevented by the short carrier lifetime in the QWs

- Chirped pulse formation can provide **higher pulse energies** when combined with a slow absorber
- Efficiency is increased by **longer carrier lifetimes**
  - **Epitaxial improvement** of the gain structures
  - New gain materials based on **intrinsically slower quantum dots** (QDs)

**There is still room for significant improvement in ultrafast SDL technology**

## Outlook



**next steps:** **Development of QD gain materials and chirped pulse formation**

**ultimate goal:** **Efficient sub-100-fs SDLs with multi-kW pulse peak power for supercontinuum generation and dual comb spectroscopy**