Modelocking
by forcing all modes in a laser to operate phase-locked, "noise"
is turned into ideal ultrashort pulses

- axial modes in laser not phase-locked
- noise

Active Modelocking
acousto-optic loss modulator
needs RF power and water cooling
Innovation: before and after

acousto-optic modelocker

SESAM modelocker

needs RF power and water cooling

SESAM technology – ultrafast lasers for industrial application

IEEE JSTQE 2, 435, 1996
Progress in Optics 46, 1-115, 2004
Nature 424, 831, 2003

Output coupler

SESAM
SEmiconductor Saturable Absorber Mirror

self-starting, stable, and reliable modelocking of diode-pumped ultrafast solid-state lasers

SESAM solved Q-switching problem for diode-pumped solid-state lasers

20 years of SESAM – looking back

Why was it assumed that diode-pumped solid-state lasers cannot be passively modelocked?
How was the SESAM invented?
State-of-the-art performance and future outlook

Motivation for semiconductor lasers: Wafer scale integration


MIXSEL wafer scale integration

Development to the MIXSEL

Optically pumped ultrafast VECSELs / MIXSELs

More updates also on webpage of Prof. Keller:
www.ulp.ethz.ch/research/VecselMixsel
Comparison of Ultrafast GHz Lasers

10 - 160 GHz Nd:YVO₄ laser: quasi-monolithic cavity

L. Kainer et al., Electron. Lett. 35, 1160, 1999 (29 GHz)
APL 77, 2104, 2000 (up to 59 GHz), Electron. Lett. 36, 1846, 2000 (77 GHz)
IEEE J. Quant. Electron. 38, 1331, 2002 (10 to 160 GHz)

- Crystal lengths: 440 µm - 2.3 mm (FSR ~ 160 - 29 GHz)
- Nd:YVO₄ doping: 3 % (90 µm absorption length)

100 GHz Er:Yb:glass laser

1 GHz
2.8 GHz
1.1 ps
55 fs
162 fs
1.8 kW
1.5 kW
0.11 nJ
0.23 nJ

1 GHz
2.8 GHz
2.2 W
6.7 kW
2.2 nJ
1.6 ps
2.6 nm

10 W
1 W
100 mW
1 W
10 mW
100 mW
1 mW

Overview on high repetition rate DPSSLs 2011

<table>
<thead>
<tr>
<th>fᵣ</th>
<th>t₀</th>
<th>Pₐverage</th>
<th>material</th>
<th>λ_center</th>
<th>P_peak</th>
<th>E_p</th>
<th>reference</th>
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<tbody>
<tr>
<td>160 GHz</td>
<td>2.7 ps</td>
<td>110 mW</td>
<td>Nd:YVO₄</td>
<td>1064 nm</td>
<td>0.25 W</td>
<td>0.69 pJ</td>
<td>L. Kainer et al., IEEE J. Quant. Electron. 38, 1331 (2002)</td>
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<tr>
<td>1 GHz</td>
<td>55 fs</td>
<td>110 mW</td>
<td>Cr:LiSAF</td>
<td>865 nm</td>
<td>1.8 kW</td>
<td>0.11 nJ</td>
<td>D. Li et al., Opt. Lett. 35, 1446 (2010)</td>
</tr>
<tr>
<td>2.8 GHz</td>
<td>162 fs</td>
<td>880 mW</td>
<td>Yb:KYW</td>
<td>1045 nm</td>
<td>1.5 kW</td>
<td>0.23 nJ</td>
<td>S. Yamazoe et al., Opt. Lett. 35, 748 (2010)</td>
</tr>
<tr>
<td>1 GHz</td>
<td>290 fs</td>
<td>2.2 W</td>
<td>Yb:KGW</td>
<td>1042 nm</td>
<td>6.7 kW</td>
<td>2.2 nJ</td>
<td>Improved laser performance and frequency comb generation: Optics Express 19, 16491, 2011</td>
</tr>
</tbody>
</table>


Improved laser performance and frequency comb generation: Optics Express 19, 16491, 2011
**Most recent result from a GHz SEASM ML Yb:KGW**

Pumping with commercial fiber coupled multimode diode laser

- Reliable & robust pumping
- $f_{rep} = 1.1$ GHz
- $\tau_p = 125$ fs
- $P_a = 3.4$ W
- $P_{peak} = 22.7$ kW
- $\lambda_p = 1046$ nm

**Highest peak power from a GHz DPSSL**

- $f_{rep} = 1.1$ GHz
- $\tau_p = 125$ fs
- $P_a = 3.4$ W
- $P_{peak} = 22.7$ kW
- $\lambda_p = 1046$ nm

**Outline**

- Continuous wave VECSEL
  - Bandgap engineering
  - Power scaling
- SESAM modelocking
  - SESAM-VECSEL modelocking
  - 1:1 modelocking
- MIXSEL
  - Integration challenges
  - Results
- QD-SESAM optimization
- Dispersion optimization
- Outlook & Conclusion

**CW optically pumped VECSEL**

**OP-VECSEL = Optically Pumped Vertical-External-Cavity Surface-Emitting Semiconductor Laser**

- Semiconductor gain structure with reduced thickness
- Pump: high power diode bar
- External cavity for diffraction-limited output

**VECSEL gain structure**

- Heat sink
- Gain structure
- Pump energy
- Bandgap energy

---


IEEE JQE 38, 1268 (2002)
In $0.13\text{Ga}_{0.87}\text{As}$ QWs (8 nm) in anti-nodes of standing-wave pattern, designed for gain at $\approx 960$ nm

- GaAs spacer layers
- Strain-compensating GaAs$_{0.94}$P$_{0.06}$ layers
- Pump at 808 nm

VECSEL gain structure

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

VECSELs: cw spectral coverage (Jennifer Hastie)

- 2-2.8 $\mu$m – GaInAsSb / AlGaAsSb
- 1.5 $\mu$m – InGaAs / InGaAsP
- 1.2-1.5 $\mu$m – AlGaInAs / InP (fused)
- 1.2-1.3 $\mu$m – GaInNAs / GaAs
- 1-1.3 $\mu$m – InAs QDs
- 0.9-1.18 $\mu$m – 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

updated by Jennifer Hastie, University of Strathclyde, group of Prof. Martin Dawson
**Power scaling in the thin disk geometry**

*Increase output power by increasing pump power and mode size*

- Pump spot (typical diameter >100 µm)
- Thin semiconductor structure (~8 µm)
- 1D heat flow
- Copper or diamond heat sink
- 3D heat flow

**First room temperature VECSEL:**
- High-power cw operation:
  - 0.5 W in TEM₀₀₀₀ beam: M. Kuznetsov et al., IEEE Photon. Technol. Lett. 9, 1063 (1997)

**High power TEM₀₀ cw-operation**

- MBE or MOVPE growth of structure in reverse order
- Cleaning of small pieces
- Metalization for soldering
- Flipping over
- Soldering on heat spreader with high thermal conductivity
- Substrate removal by selective wet etching

**High power TEM₀₀ cw-operation**

- Maximum power $P = 20.2$ W
- Opt.-to-opt. efficiency up to 43%
- $M² < 1.1$

**OP-VECSEL milestones**

- First room temperature VECSEL:
- High-power cw operation:
  - 0.5 W in TEM₀₀₀₀ beam: M. Kuznetsov et al., IEEE Photon. Technol. Lett. 9, 1063 (1997)
  - 20 W in TEM₀₀₀₀ beam: B. Rudin et al., Optics Lett. 33, 2719, 2008
2.62 W wafer fused VECSEL at 1550 nm

- Combine advantages of InP-based active medium with GaAs/AlGaAs reflector
- Intra-cavity diamond for good heat dissipation


Continuous wave VECSEL
- Bandgap engineering
- Power scaling

SESAM modelocking
- SESAM-VECSEL modelocking
- 1:1 modelocking

MIXSEL
- Integration challenges
- Results

QD-SESAM optimization
- Dispersion optimization

Outlook & Conclusion

Outline

Ultrafast VECSELs: Modelocking with SESAMs


SESAM-VECSEL modelocking

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

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

$$\frac{E_{\text{sat, in}}}{E_{\text{sat, g}}} \frac{A_g}{A_s} < 1$$

SESAM-VECSEL modelocking

- Quantum-Well SESAM ML
  - 1.5 GHz: 2.2 W, 6 ps
  - 4 GHz: 2.1 W, 4.7 ps
  - 10 GHz: 1.4 W, 6.1 ps

$$\frac{E_{\text{sat, in}}}{E_{\text{sat, g}}} \frac{A_g}{A_s} < 1$$

Modelocking with quantum well (QW) SESAM

- QW SESAM
- etalon for dispersion management

$$\frac{E_{\text{sat, in}}}{E_{\text{sat, g}}} \frac{A_g}{A_s} < 0.1$$

- Cavity close to stability limit:
  - mode radius on gain: 175 $\mu$m
  - mode radius on SESAM: 40 $\mu$m
  - $A_s = A_g \left( \frac{40 \mu m}{175 \mu m} \right) = 0.052$

2.2 W in 6.0 ps pulses at 1.5 GHz

With lower saturation fluence, no focusing needed anymore!

Quantum-Dot SESAM
- modulation depth and $F_{\text{sat}}$ decoupled
- resonant design to decrease $F_{\text{sat}}$
- low-T growth for fast recovery ($\approx 10$-fold $F_{\text{sat}}$ reduction)

Modelocking with identical mode sizes on gain and absorber:
- Resonant QD SESAM: $\Delta R = 1\%$, $F_{\text{sat}} = 2 \mu \text{J/cm}^2$
- Laser output: $P_{\text{out}} = 102 \text{ mW}$, $f_{\text{rep}} = 3.3 \text{ ps}$, $f_{\text{rep}} = 50 \text{ GHz}$

Integration of absorber is now conceptually possible!

SESAM-VECSEL modelocking and MIXSEL

- SESAM-VECSEL modelocking and MIXSEL
  - Gain structure: QW-SESAM < 20 GHz, QD-SESAM up to 50 GHz demonstrated
  - MIXSEL

OP-VECSEL milestones

- First room temperature VECSEL:
  - 20 µW average power:
- High-power cw operation:
  - 0.5 W in TEM$_{00}$ beam: M. Kuznetsov et al., IEEE Photon. Technol. Lett. 9, 1063 (1997)
  - 20 W in TEM$_{00}$ beam: B. Rudin et al., Optics Lett. 33, 2719, 2008
- Passive mode locking with SESAM:
  - 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

Modelocked VECSEL review: Physics Reports 429, 67, 2006

First wafer-fused modelocked VECSEL at 1550 nm

- First wafer-fused passively modelocked VECSEL at 1550 nm!
- Combine advantages of InP-based active medium with GaAs/AlGaAs reflector
- Intracavity diamond for good heat dissipation
- Beam-spot diameters: 210 µm on gain chip; 50 µm on GainNAs-based SESAM
- 600 mW in 16 ps pulses at 1.29 GHz with 10 W pump power

Optically pumped ultrafast VECSELs / MIXSELs

Continuous wave VECSEL
- Bandgap engineering
- Power scaling

SESAM modelocking
- SESAM-VECSEL modelocking
- 1:1 modelocking

MIXSEL
- Integration challenges
- Results

QD-SESAM optimization

Dispersion optimization

Outlook & Conclusion

Outline

Femtosecond all quantum dot VECSEL

Separate pump mirror DBR separation tuning for maximum absorption
- higher efficiency

Active region
- chirped QD-layer positions
- each layer stack resonant for different laser wavelength
- according to absorption intensity
- broader gain

è higher efficiency

Active region

Heat sink: thinned QD gain structure on CVD substrate
- output coupler: 100 mm
- output coupler transmission: 2.5%
- laser mode radius on QD-VECSEL: 115 µm
- laser mode radius on QD-SESAM: 115 µm
- heat sink temperature: -20°C


Continuous wave VECSEL

Bandgap engineering
- Power scaling

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Dispersion optimization

Outlook & Conclusion

MIXSEL Concept

- gain and absorber in one chip
- same mode size on absorber and gain (1:1 mode-locking)
- simple linear cavity
- potential for quasi-monolithic cavity

First MIXSEL demonstration in 2007
- 40 mW in 35 ps pulses (at -10°C) and 185 mW in 32 ps pulses (at -50°C)
- complex growth → limited power

MIXSEL concept

MIXSEL cavity
- simple linear cavity
- optical pumping:
  inherit good performance OP-VECSEL
  (power scaling, good beam quality)

MIXSEL chip
- gain region with 7 QWs
- QD-saturable absorber layer
  enables modelocking
- intermediate pump mirror
  (HR pump, HT laser)
  avoids pre-saturation by pump

Integration challenges
- spot size on absorber and gain is the same


Towards Absorber Integration

Challenge 1
Reduction of saturation fluence
Increase field in absorber

\[ \frac{E_{\text{sat, d}}}{E_{\text{sat, g}}} < 0.1 \]

Challenge 2
Problem: increase of modulation depth
\[ F_{\text{sat}} \cdot \Delta R = \text{const.} \]

No possibility for uncoupled \( F_{\text{sat}} \) and \( \Delta R \) 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

\[ \Delta R \text{ can be tuned with dot density, while } F_{\text{sat}} \text{ stays constant!} \]

Self-assembled QD formation:
- Stranski-Krastanov growth on MBE
- InAs on GaAs substrate
- In ML coverage determines density

QD growth
- \( \Delta R \) can be tuned with dot density, while \( F_{\text{sat}} \) stays constant!
First MIXSEL demonstration: 35 ps, 40 mW, 2.8 GHz

Optically pumped ultrafast VECSELs / MIXSELs

Antiresonant MIXSEL 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


Average output power: 40 mW
Pulse duration: 35 ps
Pulse repetition rate: 2.8 GHz
Center wavelength: 953.4 nm
FWHM spectral width: 0.11 nm

Low output power compared to former VECSEL-SESAM modelocking: structure was used as-grown


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


-10
-5
0
5
10
GDD (1000 fs^2)

-10
-5
0
5
10
GDD (1000 fs^2)
**MIXSEL: improved thermal management**

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Sink Conductivity (W m⁻¹ K⁻¹)</th>
<th>Estimated Heating Power (pump power)</th>
<th>Pump/laser Mode Radius</th>
<th>Temp. Rise (FE sim.)</th>
<th>Heat Sink Temperature</th>
<th>Output Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>45</td>
<td>1.5 W (1.7 W)</td>
<td>80 µm</td>
<td>149 K</td>
<td>15 °C</td>
<td>41.5 mW</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
<td>3.2 W (4.3 W)</td>
<td>80 µm</td>
<td>98 K</td>
<td>10 °C</td>
<td>660 mW</td>
</tr>
<tr>
<td>Diamond</td>
<td>1800</td>
<td>26.6 W (36.7 W)</td>
<td>215 µm</td>
<td>100 K</td>
<td>15 °C</td>
<td>6400 mW</td>
</tr>
</tbody>
</table>

- exchange the copper with CVD diamond: reasonable temperatures
- leads to highest output power from a ultrafast semiconductor laser

**High Power MIXSEL Structure**

- MBE-grown in FIRST at ETH Zurich (at 580 °C on 600 µm GaAs wafer)
- laser DBR (AlAs/GaAs) at 960 nm
- self-assembled InAs quantum dot absorber embedded in GaAs
  - grown at 420 °C Stranski–Krastanov
- pump DBR (Al<sub>0.4</sub>Ga<sub>0.6</sub>As/AlAs) to reflect the pump at 808 nm
- avoids absorber presaturation by the pump
- gain section: 7 In<sub>0.8</sub>Ga<sub>0.2</sub>As Quantum wells (5 nm) separated by GaAs
- 8-µm structure directly soldered on a CVD diamond heat sink

**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: 66.8 mm ≈ 2.47 GHz
- fluence on the MIXSEL: 252 µJ/cm²

**10 GHz – 2.4 W MIXSEL**

- Repetition rate: 10 GHz
  - Average output power: 2.4 W
  - Pulse duration: 17.0 ps
  - Center wavelength: 963 nm
- Optical pumping 25.4 W at 808 nm
- Pump / laser spot radius: ≈193 µm
- Cavity length: 15.0 mm ≈ 10.0 GHz
- Output coupling: 0.5% (ROC 1.0 m)

**Autocorrelation (arb. u.):**

<table>
<thead>
<tr>
<th>Time (ps)</th>
<th>Autocorrelation (arb. u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0.05</td>
</tr>
<tr>
<td>20</td>
<td>0.15</td>
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<tr>
<td>30</td>
<td>0.25</td>
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<td>40</td>
<td>0.35</td>
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<tr>
<td>50</td>
<td>0.45</td>
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<tr>
<td>60</td>
<td>0.55</td>
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<tr>
<td>70</td>
<td>0.65</td>
</tr>
<tr>
<td>80</td>
<td>0.75</td>
</tr>
<tr>
<td>90</td>
<td>0.85</td>
</tr>
<tr>
<td>100</td>
<td>0.95</td>
</tr>
</tbody>
</table>

**Finite Element (FE) temperature simulations:***

- 0.2 W
- 0.4 W
- 0.6 W
- 0.8 W
- 1.0 W

**Cavity length:**

- 6400 mW
- 660 mW
- 41.5 mW

**Gain section:**

- Average output power
- Repetition rate
- Center wavelength
Outline

Continuous wave VECSEL
- Bandgap engineering
- Power scaling

SESAM modelocking
- SESAM-VECSEL modelocking
- 1:1 modelocking

MIXSEL
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Quantum Dot (QD) SESAM

Reduce saturation fluence of saturable absorber
- $DR_{sat}$ is proportional to the transparency density $N_0$
- try to reduce the density of states $D(E)$

$< 1.5 \text{ ML InAs}$

GaAs

$> 1.5 \text{ ML InAs}$

GaAs

Photoluminescence (PL) shift during annealing

Case with 1.6 ML InAs coverage

- Strong blueshift of the PL peak.
- The QDs are annealed in the growth of a MIXSEL


QD-SESAM annealing benefits: lower $F_{sat}$

Optics Express 16, 18646 (2008)
QD SESAM annealing benefits: summary

→ $F_{\text{sat}}$ decrease by annealing and $D_R \approx$ constant
→ $A$ decreases by annealing but $t_{\text{slow}} \approx$ constant


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Outlook

Outlook & Conclusion

Pulse Formation Mechanism

solid-state lasers

soliton modelocking

$\Delta \phi(t) = \gamma P(t)$

SPM coefficient $\gamma$

pulse power $P(t)$

SPM ($n_2>0$) = negative GDD

solitons


Soliton modelocking: GDD negative, $n_2 > 0$

Master equation:

$T_s \frac{2}{\partial t} A(T,t) = \left[ iD \frac{\partial^2}{\partial t^2} - i\Delta A(T,t) \right] A(T,t) + g - I + D_s \frac{\partial^2}{\partial t^2} - q(t) A(T,t) = 0$

$A(T,t) = \left[ A_0 \ \text{sech} \left( \frac{t}{\tau} \right) \right] \exp \left[ i \phi \frac{T}{T_s} \right] + \text{continuum}$

$\tau = \frac{\sqrt{IP}}{\delta F_p}$

Outline

Continuous wave VECSEL

- Bandgap engineering
- Power scaling

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MIXSEL

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Dispersion optimization

Outlook & Conclusion
Pulse Formation Mechanism

1. **Solid-state Lasers**
   - **VECSELs**
     - **SPM** ($n_2 > 0$) + **negative GDD** ➜ **solitons**
     - **Saturation** ($n_2 < 0$) + **positive GDD** ➜ **quasi-solitons**

2. **Saturation**
   - $\Delta \psi(t) = \gamma P(t)$
   - SPM coefficient
   - Pulse power $P(t)$

3. **Gain**
   - $g(t)$
   - Power gain

4. **Width Enhancement Factor**
   - $\alpha$

Experimental Verification

- **Stabilization**: Dispersion spreads continuum out where it sees more loss

Low-Dispersion Top Coating

- **old VECSEL structures**
  - Top coating optimized for minimal reflection
  - Strongly wavelength dependent GDD
  - Also high negative GDD of down to -5000 fs$^2$
- **new low-dispersion top coating**
  - 6 AlAs/AlGaAs pairs with fused silica (quarter-wave layer) top coating
  - Monte Carlo simulation
  - Local GDD optimization

- **Measurement vs. Simulation**
  - 955 nm, 995 nm, 998 nm wavelength
  - Positive GDD supports shorter pulses
  - Minimum achieved with slightly positive GDD
  - Soliton-like pulse shaping mechanism in passively modelocked VECSELs
  - Pulse duration limited to picosecond regime due to etalon

- **GDD (1000 fs$^2$)**
  - ±30 fs$^2$

- **old structure**
  - $\Delta$GDD (nm)
  - $\Delta$GDD (fs$^2$)

- **new structure**
  - $\Delta$GDD (nm)
  - $\Delta$GDD (fs$^2$)

- **Wavelength (nm)**
  - > 30 nm

- **Wavelength (nm)**
  - 920, 953, 960, 965, 970 nm

- **old structure**
  - 955 nm, 995 nm, 998 nm wavelength

- **new structure**
  - 955 nm, 995 nm, 998 nm wavelength
**Modelocked QD-VECSEL - Setup**

- **Output coupler radius:** 100 mm
- **Output coupler transmission:** 2.5%
- **Laser mode on QD-VECSEL:** 115 µm
- **Laser mode on QD-SESAM:** 115 µm
- **Heat sink temperature:** -20°C

**SESAM parameters**

- **DBR:** 30 pairs AlAs/GaAs
- **Saturable absorber:** single InAs QD layer in GaAs
- **Top coating:** fused silica
- **Anti-resonant design:** GDD below 200 fs²

**Cavity parameters**

- **Saturation parameters:**
  - Saturation fluence: ≈ 3.8 µJ/cm²
- **Recombination parameters:**
  - Fast relaxation: ≈ 0.5 ps
  - Slow relaxation: ≈ 15.9 ps

**Simulations for EP-VECSEL Design**

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

**Outline**

- **Continuous wave VECSEL**
  - Bandgap engineering
  - Power scaling
- **SESAM modelocking**
  - SESAM-VECSEL modelocking
  - 1:1 modelocking
- **MIXSEL**
  Integration challenges
  Results
- **QD-SESAM optimization**
- **Dispersion optimization**
- **Outlook & Conclusion**

**Electrically pumped (EP) VECSELs**

- **Optical pumping:**
- **Electrical pumping:**

**References**


Suitable for modelocking
- Relatively low GDD: AR section
- Confined current injection for good beam profile
- 6 µm current spreading layer
- Bottom p-doped, top n-doping
- Small bottom disk p-contact

Power scalability
- Wafer removal
- Large apertures possible

Trade off between electrical and optical losses
- Optimized doping profile
- High doping → high free carrier absorption
- Low doping → high resistivity
- Intermediate n-DBR for increased gain

Experimental results:
- Pulse duration: 9.5 ps
- Average output power: 7.6 mW
- Center wavelength: 975.1 nm
- FWHM spectral width: 0.43 nm
- Pump current: 480 mA
- VECSEL / SESAM temperature: -17.8°C / 37.2°C
- Transmission OC: 4%
S/N in nearly all applications is limited by available power per comb line

Increasing repetition rate leads to larger line spacing

Frequency comb with larger spacing:
- higher power per mode
- easier to access individual lines
- more compact system

Coherence requirement for SCG:

\[ N = \frac{\tau_1 \cdot P_p \cdot \left| f_{CEO} \right|}{0.322} < 10 \]
GHz oscillators without compression or amplification

Mhz-DPSSL vs. Mhz-fiber laser

20-fold better fractional frequency stability for Diode-Pumped Solid-State Laser (DPSSL)

>1 GHz

<200 fs

>6 kW

N=10 octave-spanning spectrum

PCF

1 octave-spanning spectrum

20-fold better fractional frequency stability for Diode-Pumped Solid-State Laser (DPSSL)

GOAL: GHz-DPSSL frequency comb

S. Schliß et al., Opt. Express 18, 24171 (2011)

Pulse duration (fs)

Conclusion

First CEO-beat detection of a GHz DPSSL without pulse compression


• Further investigations on the requirements for stable frequency comb generation

• Full stabilization of the 1 GHz Yb:KGW laser

Promising alternatives:

VECSEL: Vertical External Cavity Surface Emitting Laser

MIXSEL: Mode-locked Integrated External-Cavity Surface Emitting Laser

for more compact and low noise frequency combs


Pulse duration (fs)

Outlook

More info on the web ...

• Web page of Prof. Ursula Keller at ETH Zurich: http://www.ulp.ethz.ch

• All papers are available to download as PDFs: http://www.ulp.ethz.ch/publications/paper

• SESAM milestones: http://www.ulp.ethz.ch/research/Sesam

• Ultrafast solid-state laser: get started with the book chapter ... http://www.ulp.ethz.ch/research/UltrafastSolidStateLasers

• VECSEL and MIXSEL: http://www.ulp.ethz.ch/research/VecselMixsel

• Frequency combs: http://www.ulp.ethz.ch/research/FrequencyComb

• Attoscience, Attoclock, Attoline:

• http://www.ulp.ethz.ch/research/Attosecondscience

• http://www.ulp.ethz.ch/research/Attoline

• Viewgraphs to graduate lecture course: Ultrafast Laser Physics http://www.ulp.ethz.ch/education/ultrafastlaserphysics/viewgraphs