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MIXSEL2 RTD 2012

FNSNF

# Record Low Timing Jitter of a Free-Running and Actively Stabilized High-Power MIXSEL


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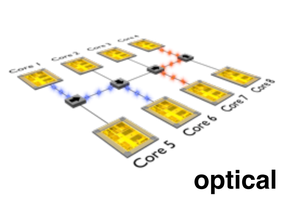
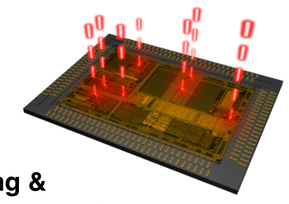
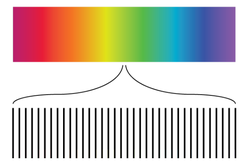
## Motivation

**Applications of SESAM-modelocked Vertical External Cavity Surface Emitting Lasers (VECSELs) and Modelocked Integrated eXternal-cavity Surface Emitting Lasers (MIXSELs)**

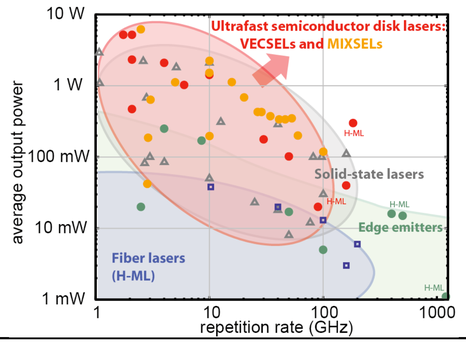



**optical clocking & interconnects**





**stabilized frequency comb?**




**first Watt-level femtosecond VECSEL [1]**

- 784-fs-pulses with >1 W output power in a 5.4 GHz V-cavity

**first femtosecond MIXSEL [2]**

- 620-fs-pulses with 101 mW output power in a 4.8 GHz straight cavity

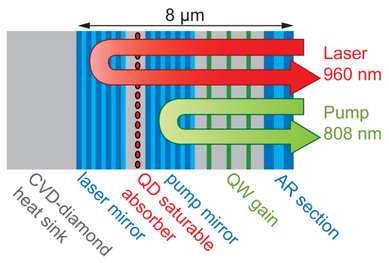

[1] M. Hoffmann, O. D. Sieber, V. J. Wittwer, I. L. Krestnikov, D. A. Livshits, T. Südmeyer, U. Keller, Optics Express (2011) vol. 19, pp. 8108-8116
[2] M. Mangold, V. J. Wittwer, C. A. Zaugg, S. M. Link, M. Golling, B. W. Tilma, U. Keller, Optics Express (2013) vol. 21, pp. 24904-24911


## High-power MIXSEL

### integration concept

- semiconductor based
- integrated QD absorber
- power scalable
- potential for monolithic design

**Modelocked Integrated eXternal-cavity Surface Emitting Laser**



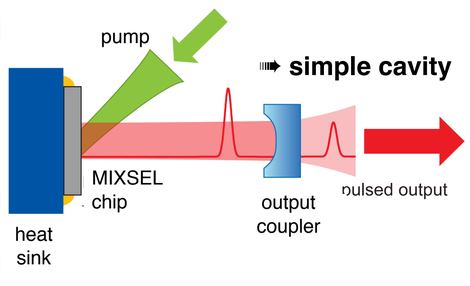

**anti-resonant MIXSEL concept**

### modelocking results

- **highest output power of a SESAM modelocked semiconductor laser [3]**

| 28.1 ps | 6.4 W | 2.5 GHz | 80 W |
|---|---|---|---|
| pulse duration | output power | repetition rate | peak power |
| 16.9 ps | 2.4 W | 10 GHz | 41 W |

- **highest output power of any modelocked 10 GHz semiconductor laser [4]**

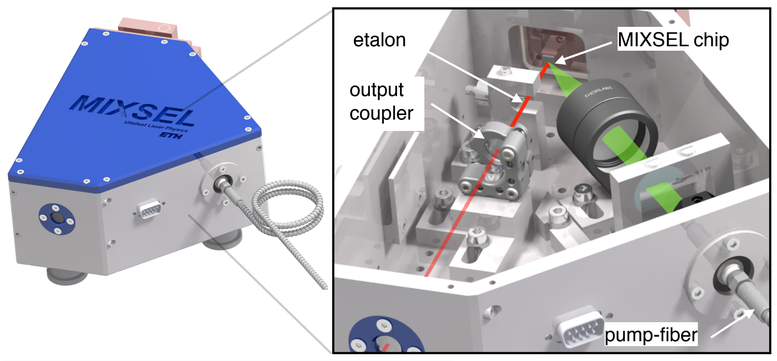



- **simple cavity**


[3] B. Rudin, V. J. Wittwer, D. J. H. C. Maas, M. Hoffmann, O. D. Sieber, Y. Barbarin, M. Golling, T. Südmeyer, and U. Keller, Opt. Express (2010) vol. 18, pp. 27582-27588
[4] V. J. Wittwer, M. Mangold, M. Hoffmann, O. D. Sieber, M. Golling, T. Südmeyer, U. Keller, Electronics Letters (2012), vol. 48, No. 18, pp. 1144

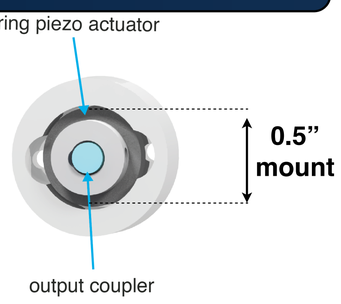

## Laser setup

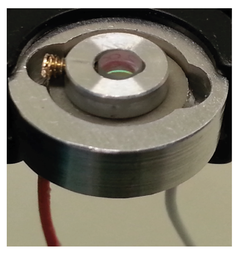
### stable and closed laser housing




- **water-cooling for high-power operation**
- **fiber-coupled pump (808 nm, 35 W)**
- **fix mounted pump optics & cavity optics**
- **straight cavity for gigahertz repetition rates**

### active cavity length stabilization

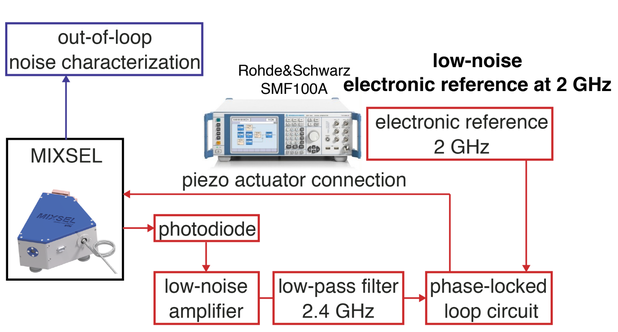


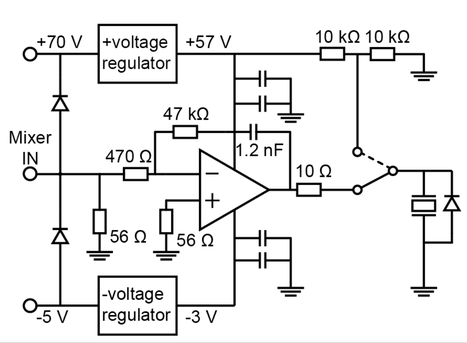
- **ring piezo actuator ($U_{max}$ = 200 V, $d_{max}$ = 2.7 $\mu$m)**
- **small output coupler (diameter: 2.5 mm, ROC: 200 mm, T = 0.5%)**
- **total weight: 230 mg**

### stabilization electronics

**active stabilization of cavity length**



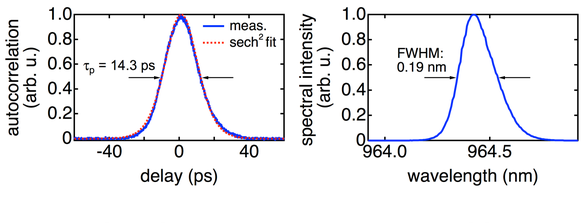

**specifically designed PLL**




## Noise characterization of a high-power MIXSEL

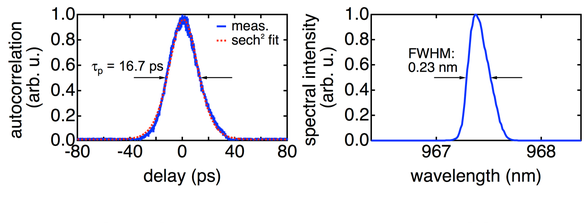
### laser performance

**free-running**




| pulse duration | output power | repetition rate |
|---|---|---|
| 14.3 ps | 645 mW | 1.99 GHz |

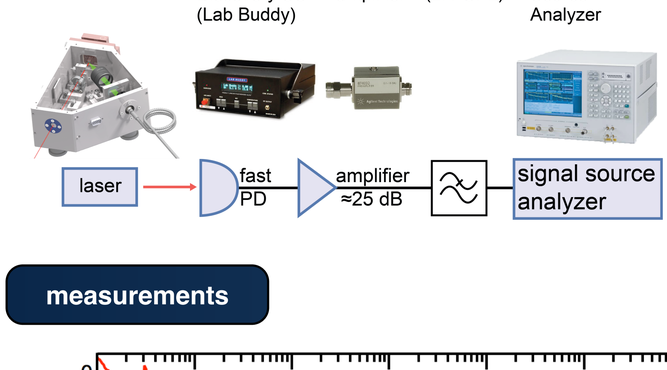
**stabilized repetition rate**




| pulse duration | output power | repetition rate |
|---|---|---|
| 16.7 ps | 701 mW | 2.00 GHz |

### measurement scheme

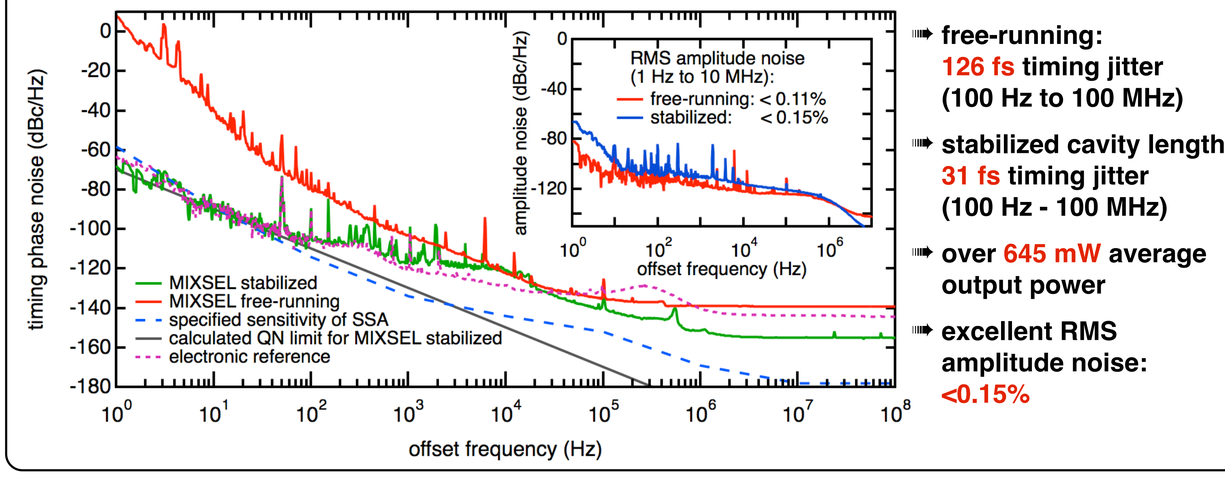
- **measurement in 13 s (1Hz to 100 MHz)**
- **extremely low noise floor (limit: shot-noise of photodetector)**




**rms timing jitter:** $\sigma_T = \frac{\sqrt{2\int_{f_{low}}^{f_{high}} P_F(\Delta f)\,d\Delta f}}{2\pi f_{rep}}$

**integration span:** ( $f_{low}$ to $f_{high}$ )

### measurements




- **free-running: 126 fs timing jitter (100 Hz to 100 MHz)**
- **stabilized cavity length: 31 fs timing jitter (100 Hz - 100 MHz)**
- **over 645 mW average output power**
- **excellent RMS amplitude noise: <0.15%**

## Timing jitter results in comparison

| laser | repetition rate (GHz) | output power (mW) | *f* (Hz) | *f* (MHz) | RMS timing jitter (fs) |
|---|---|---|---|---|---|
| **MIXSEL** | | | | | |
| free-running [5] | 1.985 | 645 | 1 | 100 | 141721 |
| | | | 100 | 100 | 145 |
| | | | 100 | 1.56 | 128 |
| | | | 300 | 1.5 | 56 |
| | | | 1000 | 15 | 43.1 |
| | | | 100 | 10 | 129 |
| stabilized [5] | 2.004 | 701 | 1 | 100 | 69 |
| | | | 100 | 100 | 32 |
| | | | 6 | 1.56 | 45 |
| | | | 300 | 1.5 | 24 |
| | | | 1000 | 15 | 25 |
| | | | 100 | 10 | 31 |
| **VECSEL** | | | | | |
| free-running [6] | 2 | 40 | 100 | 10 | 200 |
| | | | 100 | 100 | 201 |
| stabilized [7] | 2 | 40 | 1 | 100 | 58 |
| | | | 100 | 100 | 47 |
| free-running [7] | 0.897 | 40 | 1000 | 15 | 410 |
| stabilized [7] | 0.897 | | 1000 | 15 | 160 |
| stabilized [8] | 1 | 40 | 300 | 1.5 | 190 |
| free-running [9] | 1.68 | 21 | 100 | 10 | 8000 |
| stabilized [9] | 1.68 | | 100 | 10 | 423 |
| **Er:Yb:glass laser** | | | | | |
| free-running [10] | 10 | 15 | 100 | 1.56 | 190 |
| stabilized [10] | 10 | | 6 | 1.56 | 26 |

**VECSELs and MIXSELs**

+ high-Q cavity
+ short interaction length with semiconductor gain
+ class-A behavior
+ convenient and robust, cost efficient

**DPSSLs (Diode Pumped Solid State Lasers)**

+ high-Q cavity, low nonlinearities
  ➡ low intrinsic noise
+ convenient and robust

ERGO (Er:Yb:glass laser) [9]

ERGO-XG, *Time-Bandwidth Products AG*


[5] M. Mangold, S. M. Link, A. Klenner, C. A. Zaugg, M. Golling, B. W. Tilma and U. Keller, IEEE Photonics Journal (2013), vol. 6, ArticleNr. 1500309
[6] V. J. Wittwer, R. van der Linden, B. W. Tilma, B. Resan, K. J. Weingarten, T. Sudmeyer, and U. Keller, IEEE Photonics Journal (2013), vol. 5, pp. 1400107-1400107
[7] K. G. Wilcox, H. D. Foreman, J. S. Roberts, and A. C. Tropper, Electronics Letters (2006), vol. 42, pp. 159-160
[8] A. H. Quarterman, K. G. Wilcox, S. P. Elsmere, Z. Mihoubi, and A. C. Tropper, Electronics Letters (2008), vol. 44, pp. 1135-1137
[9] G. Baili, M. Alouini, L. Morvan, D. Dolfi, A. Khadour, S. Bouchoule, and J. L. Oudar, IEEE Photonics Technology Letters (2010), vol. 22, pp. 1434-1436
[10] A. Schlatter, B. Rudin, S. C. Zeller, R. Paschotta, G. J. Spühler, L. Krainer, N. Haverkamp, H. R. Telle, and U. Keller, Optics Letters (2005), vol. 30, pp. 1536-1538


## Outlook

**next steps:** sub-200-fs pulses with high average power ( > 1W) from a mode-locked MIXSEL

**ultimate goal:** fully stabilized frequency comb (repetition rate & CEO-frequency) from a compact, low cost MIXSEL