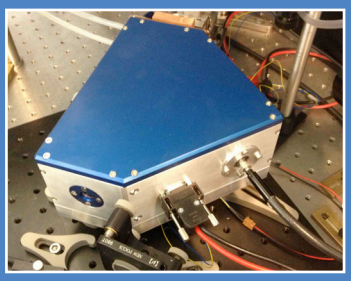
Prof. Ursula Keller, ETHZ

MIXSEL

VERTICAL INTEGRATION OF ULTRAFAST SEMICONDUCTOR LASERS FOR WAFER-SCALE MASS PRODUCTION



Prof. Eli Kapon, EPFL

Prof. Thomas Südmeyer, UniNE

Prof. Bernd Witzigmann, Uni Kassel

What it's about…

Developing a new class of semiconductor lasers generating ultrashort pulses (in the pico- and femtosecond regime) to enable new industrial applications.

Context and project goals

The project expands the SESAM modelocking approach to a new class of semiconductor lasers with wafer-scale integration of both the gain and the absorber into a vertical emitting structure. The goal is to scale both power and pulse duration to new regimes that enable for example stable frequency comb generation.

How the project differentiates from similar competition in the field

The OP-MIXSEL/VECSEL results obtained are all world leading. The consortium is pushing the average power of this technology. A picosecond MIXSEL generated more than 6 W average power, a femtosecond MIXSEL generated more than 100 mW average power, a femtosecond SESAM modelocked VECSEL generated more than 1 W average output power and extremely low noise level performance was demonstrated both for the SESAM modelocked VECSEL as well as for the MIXSEL. Frequency combs based on DPSSLs show superior performance, but are more complex and not producible in a wafer-scale approach.

Quick summary of the project status and key results

The semiconductor disk laser technology was moved into the femtosecond domain. With a SESAM modelocked VECSEL, 1W of output power was achieved with sub-picosecond pulses. The MIXSEL was demonstrated with 570 fs pulses and an output power of 127 mW. A record high average output power of 6.4 W was achieved in 28 ps pulses from a MIXSEL. Both the SESAM modelocked VECSEL and the MIXSEL show excellent noise performance comparable to DPSSL. This makes them highly suitable for further frequency comb stabilization.

Full stabilization of a frequency comb (CEO beat and laser repetition rate) has been demonstrated with a SESAM modelocked diode-pumped Er:Yb:glass laser.

Extensive modeling and a well considered design of an EP-VECSEL structure has lead to the shortest pulses from a SESAM modelocked VECSEL reported so far. 6.3 ps pulses were recorded with a 6.2 mW average output power.

Patent

A. Sirbu, A. Mereuta, A. Caliman, Vertical cavity surface emitting devices incorporating wafer-fused reflectors, European patent 2449638, 2013.

Success stories

The wafer fused gain mirrors, developed at EPFL, were implemented into products of a leading industrial player in the VECSEL technology. This one year collaborative project was supported by the Nano-Tera Program and internal resources of the industrial partner.

Mario Mangold and Alexei Sirbu are invited to give a presentation at SPIE Photonics WEST 2014 about the latest femtosecond MIXSEL results and about wafer fused VECSELs in the 1310 nm region (besides a number of contributed talks).

Two European workshops in the field of the MIXSEL project: European laser workshop and European VCSEL day were organized by the EPFL MIXSEL team in Lausanne in 2011 and 2013.

The research also received strong media interest: it was covered by several news articles including two articles in the Photonik International magazine, an article in the SPIE Newsroom and an article in Compound Semiconductors magazine.

Main publications

M. C. Stumpf, S. Pekarek, A. E. H. Oehler, T. Südmeyer, J. M. Dudley, and U. Keller, Self-referencable frequency comb from a 170-fs, 1.5-µm solid-state laser oscillator, Applied Physics B: Lasers and Optics 99, 401-408 (2009).

B. Rudin, V. J. Wittwer, D. J. H. C. Maas, M. Hoffmann, O. D. Sieber, Y. Barbarin, M. Golling, T. Südmeyer, U. Keller, High-power MIXSEL: an integrated ultrafast semiconductor laser with 6.4 W average power, Optics Express, vol. 18, pp. 27582-27588, 2010

M. Hoffmann, O. D. Sieber, V. J. Wittwer, I. L. Krestnikov, D. A. Livshits, T. Südmeyer, U. Keller, Femtosecond high-power quantum dot vertical external cavity surface emitting laser, Optics Express, vol. 19, No. 9, pp. 8108-8116, 2011

V. J. Wittwer, R. van der Linden, B. W. Tilma, B. Resan, K. J. Weingarten, T. Südmeyer, U. Keller, Sub-60-fs timing jitter of a SESAM modelocked VECSEL, IEEE Phot. Journal, vol. 5, No.1, pp. 1400107, 2013

W.P. Pallmann, C.A. Zaugg, M. Mangold, V.J. Wittwer, H. Moench, S. Gronenborn, M. Miller, B.W. Tilma, T. Südmeyer, U. Keller, Gain characterization and passive modelocking of electrically pumped VECSELs, Opt. Express 20(22), 24791-24802 (2012)

V. J. Wittwer, M. Mangold, M. Hoffmann, O. D. Sieber, M. Golling, T. Südmeyer, U. Keller, High-power integrated ultrafast semiconductor disk laser: multi-watt 10-GHz pulse generation, Electronics Lett., vol. 48, No. 18, pp. 1144, 2012

M. Mangold, V. J. Wittwer, O. D. Sieber, M. Hoffmann, I. L. Krestnikov, D. A. Livshits, M. Golling, T. Südmeyer, U. Keller, VECSEL gain characterization, Optics Express, vol. 20, No. 4, pp. 4136-4148, 2012

Y. Barbarin, M. Hoffmann, W. P. Pallmann, I. Dahhan, P. Kreuter, M. Miller, J. Baier, H. Moench, M. Golling, T. Südmeyer, B. Witzigmann, U. Keller, Electrically pumped vertical external cavity surface emitting lasers suitable for passive modelocking, IEEE J. Selected Topics in Quantum Electronics (JSTQE), vol. 17, No. 6, pp. 1779-1786, 2011

O. D. Sieber, V. J. Wittwer, M. Mangold, M. Hoffmann, M. Golling, T. Südmeyer, U. Keller, Femtosecond VECSEL with tunable multi-Gigahertz repetition rate, Optics Express, vol. 19, No. 23, pp. 23538-23543, 2011

A. Sirbu, N. Volet, A. Mereuta, J. Lyytikäinen, J. Rautiainen, O. Okhotnikov, J. Walczak, M. Wasiak, T. Czyszanowski, A. Caliman, V. Iakovlev, E. Kapon, Wafer-Fused Optically Pumped VECSELs Emitting in the 1310-nm and 1550-nm Wavebands, Advances in Optical Technologies, vol. 2011, pp. 1-8, 2011

S. Schilt, N. Bucalovic, V. Dolgovskiy, C. Schori, M. C. Stumpf, G. Di Domenico, S. Pekarek, A. E. H. Oehler, T. Südmeyer, U. Keller, P. Thomann, Fully stabilized optical frequency comb with sub-radian CEO phase noise from a SESAM-modelocked 1.5-µm solid-state laser, Opt. Express 19(24), 24171-24181 (2011)

S. Schilt, N. Bucalovic, L. Tombez, C. Schori, V. Dolgovskiy, C. Schori, G. Di Domenico, M. Zaffalon, P. Thomann, Frequency discriminators for the characterization of narrow-spectrum heterodyne beat signals: application to the measurement of a sub-hertz carrier-envelope-offset beat in an optical frequency comb, Rev. Scient. Instr. 82(12), 123116 (2011)

S. Schilt, N. Bucalovic, V. Dolgovskiy, C. Schori, G. Di Domenico, M. C. Stumpf, S. Pekarek, A. E. H. Oehler, T. Südmeyer, U. Keller, P. Thomann, Noise properties of an optical frequency comb from a SESAM-modelocked 1.5-µm solid-state laser stabilized to the 10-13 level, Appl. Phys. B 109 (3), 391-402 (2012), DOI 10.1007/s00340-012-5072-z

L. Tombez, S. Schilt, J. Di Francesco, T. Führer, B. Rein, T. Walther, G. Di Domenico, D. Hofstetter, P. Thomann, Linewidth of a quantum cascade laser assessed from its frequency noise spectrum and impact of the current driver, Appl. Phys. B 109 (3), 407-414 (2012), DOI 10.1007/s00340-012-5005-x

N. Bucalovic, V. Dolgovskiy, C. Schori, P. Thomann, G. Di Domenico, S. Schilt, Experimental Validation of a Simple Approximation to Determine the Linewidth of a Laser from its Frequency Noise Spectrum, Appl. Optics 51 (20), 4582-4588 (2012)

N. Bucalovic, V. Dolgovskiy, M.C. Stumpf, C. Schori, G. Di Domenico, U. Keller, S. Schilt, T. Südmeyer, Effect of the Carrier-Envelope-Offset Dynamics on the Stabilization of a Diode-Pumped Solid-State Frequency Comb, Optics Letters 37 (21), 4428-4430 (2012)

L. Tombez, S. Schilt, J. Di Francesco, P. Thomann, D. Hofstetter, Temperature dependence of the frequency noise in a mid-IR DFB quantum cascade laser from cryogenic to room temperature, Opt. Express 20 (7), 6851-6859, (2012)

V. Dolgovskiy, N. Bucalovic, P. Thomann, C. Schori, G. Di Domenico, S. Schilt, Cross-influence between the two servo-loops of a fully-stabilized Er:fiber optical frequency comb, J. Opt. Soc. America B, 29 (10), 2944-2957 (2012)

O. D. Sieber, M. Hoffmann, V. J. Wittwer, M. Mangold, M. Golling, B. W. Tilma T. S. udmeyer, U. Keller, Experimentally verified pulse formation model for high-power femtosecond VECSELs, Appl. Phys. B, published online April 2013, DOI 10.1007/s00340-013-5449-7

W.P Pallmann, C.A. Zaugg, M. Mangold, I. Dahhan, M. Golling, B.W. Tilma, B. Witzigmann, U. Keller, Ultrafast Electrically Pumped VECSELs, IEEE Phot. Journal, Vol. 5, No. 4, pp. 1501207, 2013

A. Rantamäki, J. Rautiainen, A. Sirbu, A. Mereuta, E. Kapon, and O. Okhotnikov, 1.56 1 watt single frequency semiconductor disk laser, Opt. Express 21, 2355-2360, 2013

A. Caliman, A. Sirbu, A. Mereuta, K. Pierscinski, V. Iakovlev, and E. Kapon, , 14XX nm-wavelength electrically-pumped VECSELs fabricated by wafer fusion, Opt. Express 21, 13668-13674 (2013).