

PROCEEDINGS OF SPIE

Vertical External Cavity Surface Emitting Lasers (VECSELs) IV

Jerome V. Moloney
Editor

2–4 February 2014
San Francisco, California, United States

Sponsored by
SPIE

Cosponsored by
Coherent, Inc. (United States)

Published by
SPIE

Volume 8966

Proceedings of SPIE 0277-786X, V. 8966

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

Vertical External Cavity Surface Emitting Lasers (VECSELs) IV, edited
by Jerome V. Moloney, Proc. of SPIE Vol. 8966, 896601 · © 2014 SPIE
CCC code: 0277-786X/14/\$18 · doi: 10.1117/12.2062799

Proc. of SPIE Vol. 8966 896601-1

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:

Author(s), "Title of Paper," in *Vertical External Cavity Surface Emitting Lasers (VECSELs) IV*, edited by Jerome V. Moloney, Proceedings of SPIE Vol. 8966 (SPIE, Bellingham, WA, 2014) Article CID Number.

ISSN: 0277-786X

ISBN: 9780819498793

Published by

SPIE

P.O. Box 10, Bellingham, Washington 98227-0010 USA

Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445

SPIE.org

Copyright © 2014, Society of Photo-Optical Instrumentation Engineers.

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is \$18.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at copyright.com. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher. The CCC fee code is 0277-786X/14/\$18.00.

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.



SPIDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon as they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc.

The CID Number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID Number.

Contents

ix Conference Committee

The previously unbelievable performance of ultrafast thin disk lasers

(Plenary Paper, Presentation Video) [8966-100]

U. Keller, ETH Zürich (Switzerland)

View the presentation on the SPIE Digital Library: <http://dx.doi.org/10.1117/12.2048382>

PLENARY PRESENTATION

- 8966 02 **The previously unbelievable performance of ultrafast thin disk lasers (Plenary Presentation Video)** [8966-100]
U. Keller, ETH Zürich (Switzerland)

SESSION 1 FUNDAMENTAL PHYSICS

- 8966 03 **Microscopic VECSEL modeling (Keynote Paper)** [8966-1]
S. W. Koch, Philipps-Univ. Marburg (Germany) and College of Optical Sciences, Univ. of Arizona (United States); J. Hader, J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States)
- 8966 04 **Exploring ultrafast negative Kerr Effect for self-mode-locking vertical external-cavity surface-emitting lasers (Invited Paper)** [8966-2]
A. R. Albrecht, The Univ. of New Mexico (United States); D. V. Seletskiy, Univ. Konstanz (Germany); Y. Wang, The Univ. of New Mexico (United States); J. G. Cederberg, Sandia National Labs. (United States); M. Sheik-Bahae, The Univ. of New Mexico (United States)

SESSION 2 ULTRAFAST VECSELS I

- 8966 06 **Carbon nanotube mode-locked vertical external-cavity surface-emitting laser (Invited Paper)** [8966-4]
K. Seger, N. Meiser, KTH Royal Institute of Technology (Sweden); S. Y. Choi, B. H. Jung, D.-I. Yeom, F. Rotermund, Ajou Univ. (Korea, Republic of); O. Okhotnikov, Tampere Univ. of Technology (Finland); F. Laurell, V. Pasiskevicius, KTH Royal Institute of Technology (Sweden)
- 8966 07 **Graphene modelocked VECSELS (Invited Paper)** [8966-5]
C. A. Zaugg, ETH Zürich (Switzerland); V. J. Wittwer, Z. Sun, D. Popa, S. Milana, T. S. Kulmala, R. S. Sundaram, Univ. of Cambridge (United Kingdom); M. Mangold, M. Golling, ETH Zürich (Switzerland); Y. Lee, J. H. Ahn, Yonsei Univ. (Korea, Republic of) and Sungkyunkwan Univ. (Korea, Republic of); A. C. Ferrari, Univ. of Cambridge (United Kingdom); U. Keller, ETH Zürich (Switzerland)

- 8966 08 **Graphene-based saturable absorbers in semiconductor lasers** [8966-6]
S. Husaini, R. G. Bedford, Air Force Research Lab. (United States)
- 8966 09 **Femtosecond MIXSEL (Invited Paper)** [8966-7]
M. Mangold, V. J. Wittwer, C. A. Zaugg, S. M. Link, M. Golling, B. W. Tilma, U. Keller, ETH Zürich (Switzerland)

SESSION 3 SINGLE FREQUENCY/LOW NOISE

- 8966 0A **Intensity and frequency noise properties of multi-watt single frequency VECSEL with and without active stabilization (Invited Paper)** [8966-8]
A. Laurain, College of Optical Sciences, The Univ. of Arizona (United States); J. Hader, College of Optical Sciences, The Univ. of Arizona (United States) and Nonlinear Control Strategies Inc. (United States); S. W. Koch, College of Optical Sciences, The Univ. of Arizona (United States) and Philipps-Univ. Marburg (Germany); W. Stolz, Philipps-Univ. Marburg (Germany); J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States) and Nonlinear Control Strategies Inc. (United States)
- 8966 0C **Record-low noise performance of high-power picosecond MIXSEL** [8966-10]
S. M. Link, M. Mangold, V. J. Wittwer, A. Klenner, M. Golling, B. W. Tilma, U. Keller, ETH Zürich (Switzerland)

SESSION 4 NOVEL SOURCES/APPLICATIONS

- 8966 0D **High-efficiency tunable yellow-orange VECSEL with an output power of 20 W** [8966-28]
E. Kantola, T. Leinonen, S. Ranta, M. Tavast, M. Guina, Tampere Univ. of Technology (Finland)
- 8966 0E **Terahertz generation by difference frequency conversion of two single-frequency VECSELs in an external resonance cavity (Invited Paper)** [8966-12]
M. Scheller, J. R. Paul, Beam Technologies LLC (United States) and College of Optical Sciences, The Univ. of Arizona (United States); A. Laurain, College of Optical Sciences, The Univ. of Arizona (United States); A. Young, TeraVision Inc. (United States) and Steward Observatory, Univ. of Arizona (United States); S. W. Koch, Beam Technologies LLC (United States) and Philipps-Univ. Marburg (Germany); J. V. Moloney, Beam Technologies LLC (United States) and College of Optical Sciences, The Univ. of Arizona (United States)
- 8966 0G **Wafer-fused VECSELs emitting in the 1310nm waveband (Invited Paper)** [8966-14]
A. Sirbu, K. Pierscinski, A. Mereuta, V. Iakovlev, A. Caliman, Z. Micovic, N. Volet, Ecole Polytechnique Fédérale de Lausanne (Switzerland); J. Rautiainen, J. Heikkinen, J. Lyytikäinen, A. Rantamäki, O. Okhotnikov, Tampere Univ. of Technology (Finland); E. Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

SESSION 5 ELECTRICAL PUMPING

- 8966 0H **High power electrically pumped VECSELS and arrays (Invited Paper)** [8966-15]
H. Moench, Philips Technologie GmbH (Germany); A. Andreadaki, Philips Group Innovation (Netherlands); S. Gronenborn, J. S. Kolb, Philips Technologie GmbH (Germany); P. Loosen, RWTH Aachen Univ. (Germany); M. Miller, Philips Technologie GmbH (Germany); T. Schwarz, RWTH Aachen Univ. (Germany); A. van der Lee, Philips Group Innovation (Netherlands); U. Weichmann, Philips Technologie GmbH (Germany)
- 8966 0I **Coaxial tunnel junctions: a novel approach to reduce the current crowding effect in electrically pumped VECSELS** [8966-16]
J. Walczak, M. Wasiak, R. P. Sarzała, Technical Univ. of Lodz (Poland); A. Sirbu, E. Kapon, Ecole Polytechnique Fédérale de Lausanne (Switzerland); T. Czystanowski, Technical Univ. of Lodz (Poland)
- 8966 0J **SESAM-mode-locked electrically pumped VECSELS emitting 6.3-ps pulses** [8966-17]
C. A. Zaugg, W. P. Pallmann, M. Mangold, ETH Zürich (Switzerland); I. Dahhan, Univ. Kassel (Germany); M. Golling, B. W. Tilma, ETH Zürich (Switzerland); B. Witzigmann, Univ. Kassel (Germany); U. Keller, ETH Zürich (Switzerland)
- 8966 0K **216 MHz repetition rate passively mode-locked electrically pumped VECSEL** [8966-18]
A. Alhazime, M. Butkus, Univ. of Dundee (United Kingdom); C. J. Hamilton, M Squared Lasers Ltd. (United Kingdom); E. U. Rafailov, Univ. of Dundee (United Kingdom)

SESSION 6 MULTI-FREQUENCY/APPLICATIONS

- 8966 0L **Generation of high-purity microwave signals from a dual-frequency OP-VECSEL (Invited Paper)** [8966-19]
F. Camargo, G. Lucas-Leclin, P. Dumont, P. Georges, Lab. Charles Fabry, CNRS, Univ. Paris-Sud 11 (France); J.-M. Danet, D. Holleville, S. Guerandel, LNE-SYRTE, CNRS, Observatoire de Paris (France); G. Pillet, G. Baili, L. Morvan, D. Dolfi, Thales Research & Technology (France); I. Gozhyk, G. Beaudoin, I. Sagnes, Lab. de Photonique et de Nanostructures, CNRS (France)
- 8966 0M **Experimental and theoretical study of noise in a dual-frequency VECSEL** [8966-20]
S. De, Lab. Aimé Cotton, CNRS, Univ. Paris Sud 11 (France); A. El Amili, Univ. de Rennes 1 (France); G. Pillet, G. Baili, Thales Research & Technology (France); F. Goldfarb, Lab. Aimé Cotton, CNRS, Univ. Paris Sud 11 (France); M. Alouini, Institut de Physique de Rennes, CNRS, Univ. de Rennes 1 (France) and Thales Research & Technology (France); I. Sagnes, Lab. de Photonique et de Nanostructures, CNRS (France); F. Bretenaker, Lab. Aimé Cotton, CNRS, Univ. Paris Sud 11 (France)

8966 ON **Systematic investigation of single- and multi-mode operation in vertical-external-cavity surface-emitting lasers** [8966-21]
M. Wichmann, M. K. Shakfa, Philipps-Univ. Marburg (Germany); M. Scheller, College of Optical Sciences, The Univ. of Arizona (United States) and Desert Beam Technologies LLC (United States); A. Rahimi-Iman, B. Heinen, Philipps-Univ. Marburg (Germany); J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States) and Desert Beam Technologies LLC (United States); S. W. Koch, Philipps-Univ. Marburg (Germany) and Desert Beam Technologies LLC (United States); M. Koch, Philipps-Univ. Marburg (Germany)

8966 OO **Picosecond MIXSEL for clocking applications (Best Student Paper Award)** [8966-22]
M. Mangold, V. J. Wittwer, C. A. Zaugg, S. M. Link, M. Golling, B. W. Tilma, U. Keller, ETH Zürich (Switzerland)

SESSION 7 ULTRAFAST VECSELS II

8966 OP **Femtosecond mode-locked red AlGaInP-VECSEL (Invited Paper)** [8966-23]
R. Bek, Univ. Stuttgart (Germany); N. S. Daghestani, Univ. of Dundee (United Kingdom) and STFC Rutherford Appleton Lab. (United Kingdom); H. Kahle, T. Schwarzbäck, M. Jetter, Univ. Stuttgart (Germany); M. A. Cataluna, Univ. of Dundee (United Kingdom); P. Michler, Univ. Stuttgart (Germany)

8966 OR **Femtosecond pulse mode-locked VECSELS (Invited Paper)** [8966-25]
A. H. Quarterman, K. G. Wilcox, Univ. of Dundee (United Kingdom)

SESSION 8 POWER SCALING

8966 OT **2- μ m high-brilliance micro-cavity VECSEL with >2W output power (Invited Paper)** [8966-27]
S. Kaspar, M. Rattunde, P. Holl, S. Adler, C. Schilling, A. Bächle, C. Manz, R. Aidam, K. Köhler, J. Wagner, Fraunhofer-Institut für Angewandte Festkörperphysik (Germany)

8966 OU **Generation of new spatial and temporal coherent states using VECSEL technology: VORTEX, high order Laguerre-Gauss mode, continuum source (Invited Paper)** [8966-11]
M. Sellahi, M. S. Seghilani, Institut d'Electronique du Sud, CNRS, Univ. Montpellier 2 (France); I. Sagnes, G. Beaudoin, X. Lafosse, Lab. de Photonique et de Nanostructures, CNRS (France); L. Legratiet, P. Lalanne, Lab. Photonique, Numérique et Nanosciences, CNRS (France); M. Myara, A. Garnache, Institut d'Electronique du Sud, CNRS, Univ. Montpellier 2 (France)

8966 OV **Industrial integration of high coherence tunable VECSEL in the NIR and MIR** [8966-29]
A. Garnache, Institut d'Electronique du Sud, CNRS, Univ. Montpellier 2 (France); V. Lecocq, L. Ferrières, Innoptics SAS (France); A. Benselama, Innoptics SAS (France) and Institut d'Electronique du Sud, CNRS, Univ. Montpellier 2 (France); M. Myara, L. Cerutti, Institut d'Electronique du Sud, CNRS, Univ. Montpellier 2 (France); I. Sagnes, Lab. de Photonique et de Nanostructures, CNRS (France); S. Denet, Innoptics SAS (France)

- 8966 OW **Demonstration of an in-phase, coherently coupled 37-element VECSEL array** [8966-30]
A. C. Sills, G. N. West, Rose-Hulman Institute of Technology (United States); E. A. Fennig, Rose-Hulman Institute of Technology (United States) and Univ. of Rochester (United States); J. W. Braker, Rose-Hulman Institute of Technology (United States) and DILAS Diode Laser, Inc. (United States); M. P. Grimshaw, M. Kanskar, nLIGHT Corp. (United States); M. T. Johnson, K. D. Choquette, Univ. of Illinois at Urbana-Champaign (United States); P. O. Leisher, Rose-Hulman Institute of Technology (United States)

POSTER SESSION

- 8966 OX **Graphene saturable absorbers for VECSELS** [8966-31]
V. J. Wittwer, Univ. of Cambridge (United Kingdom); C. A. Zaugg, ETH Zürich (Switzerland); Z. Sun, D. Popa, S. Milana, T. S. Kulmala, R. S. Sundaram, Univ. of Cambridge (United Kingdom); M. Mangold, M. Golling, ETH Zürich (Switzerland); Y. Lee, J. H. Ahn, Yonsei Univ. (Korea, Republic of) and Sungkyunkwan Univ. (Korea, Republic of); U. Keller, ETH Zürich (Switzerland); A. C. Ferrari, Univ. of Cambridge (United Kingdom)
- 8966 OY **Beam combination of multiple vertical external cavity surface emitting lasers via volume Bragg gratings** [8966-32]
C. A. Lu, W. P. Roach, Air Force Research Lab. (United States); G. Balakrishnan, A. R. Albrecht, The Univ. of New Mexico (United States); J. V. Moloney, College of Optical Sciences, The Univ. of Arizona (United States); L. B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)
- 8966 OZ **Injection-locked optically pumped vertically external cavity surface emitting laser (VECSEL)** [8966-33]
Y.-Y. Lai, K. Winn, J. M. Yarborough, Y. Merzlyak, Y. Kaneda, College of Optical Sciences, The Univ. of Arizona (United States) and ERATO, Katori Innovative Space-Time Project (Japan)

Author Index

Conference Committee

Symposium Chairs

Bo Gu, Bos Photonics (United States)
Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und
Feinmechanik (Germany) and Friedrich-Schiller-Universität Jena
(Germany)

Symposium Co-chairs

Guido Hennig, Daetwyler Graphics AG (Switzerland)
Yongfeng Lu, University of Nebraska-Lincoln (United States)

Program Track Chair

Klaus P. Streubel, OSRAM AG (Germany)

Conference Chair

Jerome V. Moloney, College of Optical Sciences, The University of
Arizona (United States)

Conference Program Committee

Juan L. Chilla, Coherent, Inc. (United States)
Arnaud Garnache, Université Montpellier 2 (France)
Mircea Guina, Tampere University of Technology (Finland)
Jennifer E. Hastie, University of Strathclyde (United Kingdom)
Elyahou Kapon, Ecole Polytechnique Fédérale de Lausanne
(Switzerland)
Ursula Keller, ETH Zürich (Switzerland)
Anne C. Tropper, University of Southampton (United Kingdom)

Session Chairs

- 1 Fundamental Physics
Jerome V. Moloney, College of Optical Sciences, The University of
Arizona (United States)
- 2 Ultrafast VECSELS I
Stephan W. Koch, Philipps-Universität Marburg (Germany)
- 3 Single Frequency/Low Noise
Mircea Guina, Tampere University of Technology (Finland)

- 4 Novel Sources/Applications
Juan L. Chilla, Coherent, Inc. (United States)
- 5 Electrical Pumping
Mircea Guina, Tampere University of Technology (Finland)
- 6 Multi-Frequency/Applications
Keith G. Wilcox, University of Dundee (United Kingdom)
- 7 Ultrafast VECSELS II
John-Mark Hopkins, Fraunhofer Centre for Applied Photonics
(United Kingdom)
- 8 Power Scaling
Ursula Keller, ETH Zürich (Switzerland)