

PROCEEDINGS OF SPIE

Next-Generation Optical Networks for Data Centers and Short-Reach Links III

Atul K. Srivastava

Editor

16–18 February 2016

San Francisco, California, United States

*Sponsored and Published by
SPIE*

Volume 9775

Proceedings of SPIE 0277-786X, V. 9775

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

Next-Generation Optical Networks for Data Centers and Short-Reach Links III, edited by Atul K. Srivastava,
Proc. of SPIE Vol. 9775, 977501 · © 2016 SPIE · CCC code: 0277-786X/16/\$18 · doi: 10.1117/12.2239357

Proc. of SPIE Vol. 9775 977501-1

The papers 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. Additional papers and presentation recordings may be available online in the SPIE Digital Library at SPIDigitalLibrary.org.

The papers 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 these proceedings:

Author(s), "Title of Paper," in *Next-Generation Optical Networks for Data Centers and Short-Reach Links III*, edited by Atul K. Srivastava, Proceedings of SPIE Vol. 9775 (SPIE, Bellingham, WA, 2016) Six-digit Article CID Number.

ISSN: 0277-786X
ISSN: 1996-756X (electronic)
ISBN: 9781510600102

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 © 2016, 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/16/\$18.00.

Printed in the United States of America.

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

SPIE. DIGITAL LIBRARY
SPIDigitalLibrary.org

Paper Numbering: *Proceedings of SPIE* follow an e-First publication model. A unique citation identifier (CID) number is assigned to each article at the time of 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 and print versions of the publication. SPIE uses a six-digit CID article numbering system structured as follows:

- 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.

Contents

v *Authors*
vii *Conference Committee*

OPTICAL COMMUNICATION PLENARY SESSION: JOINT SESSION WITH CONFERENCES 9772, 9774, AND 9775

- 9775 02 **Economics of data center optics (Invited Paper) [9775-2]**
- 9775 03 **Silicon-photonics-based optical transceivers for high-speed interconnect applications (Invited Paper) [9775-1]**

ADVANCED FIBERS FOR DATA CENTER, SDM, AND METRO APPLICATIONS: JOINT SESSION WITH CONFERENCES 9772, 9773, 9774, AND 9775

- 9775 04 **Next-generation wideband multimode fibers for data centers (Invited Paper) [9775-3]**

ADVANCED MODULATION FORMAT AND DSP I: JOINT SESSION WITH CONFERENCES 9774 AND 9775

- 9775 05 **Short-haul transmission links based on 25- and 56-Gbaud PAM4 modulation (Invited Paper) [9775-4]**
- 9775 06 **Scaling single-wavelength optical interconnects to 180 Gb/s with PAM-M and pulse shaping [9775-5]**

ADVANCED MODULATION FORMAT AND DSP II: JOINT SESSION WITH CONFERENCES 9774 AND 9775

- 9775 07 **Recent advances of emerging PAM4 signaling with real-time processing for 100/400Gbps data center connectivity (Invited Paper) [9775-6]**
- 9775 08 **Power penalties for multi-level PAM modulation formats at arbitrary bit error rates [9775-7]**

ADVANCED MODULATION FORMAT AND DSP III: JOINT SESSION WITH CONFERENCES 9773, 9774, AND 9775

- 9775 0A **112 Gb/s sub-cycle 16-QAM Nyquist-SCM for intra-datacenter connectivity [9775-9]**

DATACENTER NETWORK TRENDS

- 9775 0C **Recent standardization directions for high-speed client and line side components (Invited Paper)** [9775-11]
- 9775 0D **Optical interconnect technologies for high-bandwidth ICT systems** [9775-12]
- 9775 0E **Optoelectronic specifications of emerging coherent optical solutions for data center interconnect (Invited Paper)** [9775-13]
- 9775 0F **100 Gb/s optical discrete multi-tone transceivers for intra- and inter-datacenter networks** [9775-14]

COMPONENTS FOR DATACENTER NETWORKS

- 9775 0J **Demonstration of 720×720 optical fast circuit switch for intra-datacenter networks** [9775-18]
- 9775 0K **Adaptive gain, equalization, and wavelength stabilization techniques for silicon photonic microring resonator-based optical receivers** [9775-19]

Authors

Numbers in the index correspond to the last two digits of the six-digit citation identifier (CID) article numbering system used in Proceedings of SPIE. The first four digits reflect the volume number. Base 36 numbering is employed for the last two digits and indicates the order of articles within the volume. Numbers start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B...0Z, followed by 10-1Z, 20-2Z, etc.

Argyris, Nikolaos, 06, 0A
Arimoto, Hideo, 0D
Armijo, G., 03
Avramopoulos, Hercules, 06, 0A
Bai, Rui, 0K
Bakopoulos, Paraskevas, 06, 0A
Balardeta, J., 03
Balemorthy, Kasyapa, 04
Beausoleil, Ray, 0K
Chan, Trevor K., 05
Chang, Frank, 07
Chase, B., 03
Chen, Chin-Hui, 0K
Chi, Y., 03
Chiang, Patrick, 0K
Chiuchiarelli, Andrea, 0E
Chujo, Norio, 0D
Dahl, A., 03
De Dobbelaere, P., 03
De Koninck, Y., 03
Denton, S., 03
Downie, John D., 08
Dris, Stefanos, 06, 0A
Eker, M., 03
Fathpour, S., 03
Fiorentino, Marco, 0K
Foltz, D., 03
Gholami, F., 03
Gloeckner, S., 03
Hasegawa, Hiroshi, 0J
Hon, K. Y., 03
Hovey, S., 03
Huff, Lisa, 02
Hurley, Jason, 08
Ishii, Kiyo, 0J
Isono, Hideki, 0C
Jackson, S., 03
Kai, Yutaka, 0F
Kaliteevskiy, Nikolay A., 08
Kuwatsuka, Haruhiko, 0J
Lebedev, Alexander, 05
Li, Cheng, 0K
Li, Hao, 0K
Li, Lei, 0F
Li, W., 03
Liang, Y., 03
Liu, Bo, 0F
Mack, M., 03
Masini, G., 03
Matsuoka, Yasunobu, 0D
Matsushima, Naaki, 0D
Matsuura, Hiroyuki, 0J
McGee, G., 03
Mekis, A., 03
Mizushima, Akiko, 0D
Mori, Yojiro, 0J
Namiki, Shu, 0J
Nishihara, Masato, 0F
Okabe, Ryo, 0F
Oliveira, Juliano R. F., 0E
Palermo, Samuel, 0K
Pang, S., 03
Peterson, M., 03
Pinguet, T., 03
Pivem, Tatiani, 0E
Planchon, L., 03
Rasmussen, Jens C., 0F
Reis, Jacklyn D., 0E
Roberson, K., 03
Rozental, Valery N., 0E
Sahni, S., 03
Sato, Ken-ichi, 0J
Schramm, J., 03
Shafik, Ayman, 0K
Sharp, M., 03
Shubochkin, Roman, 04
Sohn, C., 03
Souza, André L. N., 0E
Spatharakis, Christos, 06, 0A
Stechschulze, K., 03
Sterlingov, Petr, 08
Sun, P., 03
Sun, Yi, 04
Takahara, Tomoo, 0F
Takai, Toshiaki, 0D
Tanaka, Toshiki, 0F
Tao, Zhenning, 0F
Titriku, Alex, 0K
Ueda, Koh, 0J
Vastola, G., 03
Wang, S., 03
Way, Winston I., 05
Weber, B., 03
Wong, G., 03
Wood, William A., 08
Yamashita, Hiroki, 0D
Yokoyama, K., 03
Yu, Kunzhi, 0K

Yu, S., 03
Zhou, R., 03

Conference Committee

Symposium Chairs

Jean-Emmanuel Broquin, IMEP-LAHC (France)
Shibin Jiang, AdValue Photonics, Inc. (United States)

Symposium Co-chairs

David L. Andrews, University of East Anglia (United Kingdom)
Alexei L. Glebov, OptiGrate Corporation (United States)

Program Track Chair

Benjamin B. Dingel, Nasfina Photonics, Inc. (United States)

Conference Chair

Atul K. Srivastava, NEL America, Inc. (United States)

Conference Program Committee

Philippe P Absil, IMEC (Belgium)
Juliano Rodrigues Fernandes de Oliveira, CpqD (Brazil)
Benjamin B. Dingel, Nasfina Photonics, Inc. (United States)
Mitchell H. Fields, Avago Technologies Ltd. (United States)
Hideki Isono, Fujitsu Ltd. (Japan)
Hai-Feng Liu, Intel Corporation (United States)
B. Jonathan Luff, Mellanox Technologies, Inc. (United States)
Takahiro Nakamura, Photonics Electronics Technology Research
Association (Japan)
Takashi Saida, NTT Photonics Laboratories (Japan)
Ivan Shubin, Oracle (United States)
Takashi Takemoto, Hitachi, Ltd. (Japan)

Session Chairs

Optical Communication Plenary Session: Joint Session with
Conferences 9772, 9774, and 9775
Benjamin B. Dingel, Nasfina Photonics, Inc. (United States)
Guifang Li, CREOL, The College of Optics and Photonics, University
of Central Florida (United States)

Advanced Fibers for Data Center, SDM, and Metro Applications: Joint Session with Conferences 9772, 9773, 9774, and 9775

Atul K. Srivastava, NEL America, Inc. (United States)

Guifang Li, CREOL, The College of Optics and Photonics, University of Central Florida (United States)

Post Deadline Session

Benjamin B. Dingel, Nasfine Photonics, Inc. (United States)

Advanced Modulation Format and DSP I: Joint Session with Conferences 9774 and 9775

Guifang Li, CREOL, The College of Optics and Photonics, University of Central Florida (United States)

Andrea Chiuchiarelli, CPqD (Brazil)

Advanced Modulation Format and DSP II: Joint Session with Conferences 9774 and 9775

Hideki Isono, Fujitsu Optical Components Ltd. (Japan)

Xiang Zhou, Google (United States)

Advanced Modulation Format and DSP III: Joint Session with Conferences 9773, 9774, and 9775

Benny Mikkelsen, Mintera Corporation (United States)

Idelfonso Tafur Monroy, DTU Fotonik (Denmark)

Datacenter Network Trends

Philippe P. Absil, IMEC (Belgium)

Hai-Feng Liu, Intel Corporation (United States)

Components for Datacenter Networks

Hideki Isono, Fujitsu Optical Components Ltd. (Japan)

Andrea Chiuchiarelli, CPqD (Brazil)