

PROCEEDINGS OF SPIE

# ***Free-Space Laser Communications XXXI***

**Hamid Hemmati  
Don M. Boroson**  
*Editors*

**4–6 February 2019  
San Francisco, California, United States**

*Sponsored and Published by*  
SPIE

**Volume 10910**

Proceedings of SPIE 0277-786X, V. 10910

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

Free-Space Laser Communications XXXI, edited by Hamid Hemmati,  
Don M. Boroson, Proc. of SPIE Vol. 10910, 1091001 · © 2019 SPIE  
CCC code: 0277-786X/19/\$18 · doi: 10.1117/12.2531504

Proc. of SPIE Vol. 10910 1091001-1

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](http://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 *Free-Space Laser Communications XXXI*, edited by Hamid Hemmati, Don M. Boroson, Proceedings of SPIE Vol. 10910 (SPIE, Bellingham, WA, 2019) Seven-digit Article CID Number.

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

ISBN: 9781510624627  
ISBN: 9781510624634 (electronic)

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](http://SPIE.org)

Copyright © 2019, 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](http://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/19/\$18.00.

Printed in the United States of America by Curran Associates, Inc., under license from SPIE.

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

**SPIE. DIGITAL  
LIBRARY**

[SPIDigitalLibrary.org](http://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 seven-digit CID article numbering system structured as follows:

- The first five 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

ix *Authors*  
xiii *Conference Committee*

---

## LASER COMM DESIGNS I

---

- 10910 03 **Quantitative evaluation of a dual-band spacecraft communication concept for a 1000 AU interstellar pathfinder mission** [10910-77]
- 10910 04 **Bit error rate performance of a free space optical link using double clad fibers** [10910-2]
- 10910 05 **CubeSat lasercom optical terminals for near-Earth to deep space communications** [10910-3]
- 10910 06 **Optimizing the performance of space to ground optical communications (Invited Paper)** [10910-4]

---

## LASER COMM DESIGNS II

---

- 10910 07 **Optimization of the settings of the adaptive distributed frame repetition to the time-changing transmission link conditions** [10910-5]
- 10910 08 **Lifetime test results and polarization performance verification in fiber wrap for free space optical communications gimbals** [10910-6]
- 10910 09 **Characterization of a photon counting test bed for space to ground optical pulse position modulation communications links** [10910-7]
- 10910 0A **Approaching the ultimate capacity limit in deep-space optical communication** [10910-8]

---

## MODEM DESIGNS: RECEIVERS

---

- 10910 0D **Few-mode fiber coupled superconducting nanowire single-photon detectors for photon efficient optical communications** [10910-11]
- 10910 0F **Narrowband optical filtering for background-limited photon-counting free-space optical communications** [10910-13]
- 10910 0G **Single-mode fiber and few-mode fiber photonic lanterns performance evaluated for use in a scalable real-time photon counting ground receiver** [10910-14]

---

#### LASER COMM SYSTEM PROPOSALS

---

- 10910 0I **Research and development of highly secure free-space optical communication system for mobile platforms in NICT** [10910-16]
- 10910 0J **Optimization trades for a multi-aperture laser communications ground terminal** [10910-17]
- 10910 0K **HydRON: High throughput optical network** [10910-18]

---

#### MODEM DESIGNS: TRANSMITTERS

---

- 10910 0L **51W, 1.5 $\mu$ m, 7 WDM (25nm) channels PPM downlink transmitter and 500W, 1 $\mu$ m, uplink PPM transmitter for deep space lasercom** [10910-19]
- 10910 0M **High output power laser transmitter for high-efficiency deep-space optical communications** [10910-20]
- 10910 0N **Highly reliable low noise pump sources for solid state lasers in laser communication terminals** [10910-21]
- 10910 0O **Estimation of multimode pump ensemble reliability using Monte Carlo simulation to account for derating and variable stress profiles** [10910-22]

---

#### POINT, ACQUISITION, AND TRACK SUBSYSTEMS

---

- 10910 0P **Body pointing, acquisition and tracking for small satellite laser communication** [10910-23]
- 10910 0Q **Variable, two-color acquisition beam for free-space laser communication terminals** [10910-25]
- 10910 0R **Backend optical assembly module design for jitter rejection in the space environment** [10910-26]

---

#### SYSTEMS AND DEMOS

---

- 10910 0S **Update on DLR's OSIRIS program and first results of OSIRISv1 on Flying Laptop (Invited Paper)** [10910-27]
- 10910 0U **In orbit performance of tesat LCTs (Invited Paper)** [10910-29]
- 10910 0W **Optical technologies for very high throughput satellite communications (Invited Paper)** [10910-31]

---

#### ADAPTIVE OPTICS DESIGNS

---

10910 0Z **Demonstration of vehicle-to-vehicle optical pointing, acquisition, and tracking for undersea laser communications (Invited Paper)** [10910-35]

---

#### MODEM DESIGNS

---

10910 11 **Heavy Ion radiation assessment of a 100G/200G commercial optical coherent DSP ASIC** [10910-37]

10910 12 **Design and verification of a space-grade 10 Gbit/s high-speed transponder for an optical feeder link** [10910-38]

10910 13 **Lower frequency bands emerging as valid alternatives to free-space lasercom in terrestrial, aerial, and satellite links (Invited Paper)** [10910-39]

---

#### QUANTUM SYSTEMS

---

10910 14 **Low size, weight and power quantum key distribution system for small form unmanned aerial vehicles** [10910-40]

10910 15 **Studies on a time-energy entangled photon pair source and superconducting nanowire single-photon detectors for increased quantum system efficiency** [10910-41]

10910 16 **A space-suitable, high brilliant entangled photon source for satellite based quantum key distribution** [10910-42]

10910 17 **Information reconciliation (IR) for continuous variable quantum key distribution (QKD) over free space optics (FSO) channel** [10910-43]

---

#### OPTICAL UPLINKS

---

10910 18 **Transmitter diversity based on phase-division** [10910-44]

10910 1B **Opto-mechatronics system development for future intersatellite laser communications** [10910-47]

10910 1C **Towards optical data highways through the atmosphere** [10910-48]

## POSTER SESSION

---

- 10910 1F **A new laser beam pointing method using laser arrays** [10910-51]
- 10910 1G **Analysis of tip-tilt compensation for reflective free-space optical satellite communication** [10910-52]
- 10910 1H **Pre-correction adaptive optics performance for a 10 km laser link** [10910-53]
- 10910 1I **Laser transmitter for CubeSat-class applications** [10910-54]
- 10910 1J **Open architecture time-of-flight imaging leveraging highly efficient large area modulators** [10910-55]
- 10910 1K **Atmospheric fade probability in moderate aperture laser communication systems** [10910-56]
- 10910 1L **Anisoplanatic effects in moderate aperture laser communication system uplinks** [10910-57]
- 10910 1M **Study on a screening test process for quality assurance of optical communication devices for satellite** [10910-58]
- 10910 1N **Frequency comb-based one-way RF frequency transfer across a 880-m-long outdoor atmospheric link with  $10^{-16}$  instability** [10910-59]
- 10910 1O **Free space optical non-orthogonal multiple access experimentation** [10910-60]
- 10910 1P **Towards solid-state beam steering using a 7-emitter 1550 nm optical phased array** [10910-61]
- 10910 1Q **Optical software defined radio transmitter extinction ratio enhancement with differential pulse carving** [10910-62]
- 10910 1T **Corroboration of a multi-phase screen model** [10910-65]
- 10910 1U **Ultra-narrow linewidth diode laser based on resonant optical feedback** [10910-66]
- 10910 1X **Optical wireless power grid technology for extreme environments** [10910-69]
- 10910 1Y **Experimental analysis of the effects of atmospheric parameters on performance of an optical communication link** [10910-70]
- 10910 1Z **Initial high-intensity laser propagation experiments at the mobile ultrafast high-energy laser facility (MU-HELF)** [10910-71]
- 10910 2I **Weather limited short-range in-band full-duplex free-space optical transceiver** [10910-74]

- 10910 22     **A discriminant for on-orbit wavelength measurement** [10910-75]
- 10910 24     **Free space communication under scattering and scintillation effects** [10910-78]
- 10910 26     **Photonic integrated transmitter for space optical communications** [10910-80]





# Authors

Numbers in the index correspond to the last two digits of the seven-digit citation identifier (CID) article numbering system used in Proceedings of SPIE. The first five 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.

Aguilar, Alexa, 11  
Ahrens, R., 0M  
Alaluf, David, 1C  
Albert, Michael M., 05  
Alliss, Randall J., 06  
Andrie, Michael S., 0Q  
Aniceto, Raichelle J., 11  
Anwar, S. Mubashir, 03  
Aquino, K., 0P  
Arikawa, Manabu, 07  
Arnon, Shlomi, 17  
Aveta, Federica, 1O  
Banaszek, Konrad, 0A  
Barrios, Ricardo, 0W, 1H  
Beck, Adam L., 03  
Beckert, Erik, 16  
Bedi, Vijit, 1Y  
Bell, Teboho, 1T  
Bernath, Robert, 1Z  
Berry, M., 0M  
Bettters, Christopher, 0G  
Bigio, Victor, 22  
Bodnar, Nathan, 1Z  
Boone, B. G., 03  
Bu, Ting, 24  
Burnside, J. W., 0P  
Butler, Richard L., 22  
Cahoy, Kerri, 11  
Cao, He, 05, 0L  
Caplan, D. O., 0F  
Carrasco-Casado, Alberto, 0I  
Carrizo, Carlos, 0W  
Chang, J., 0P  
Chang, John, 0Q  
Chen, Nan, 24  
Child, Benjamin, 15  
Chuard, S., 14  
Clark, C., 14  
Cline, A., 08  
Colozzo, Ed, 0R  
Conrad, Stephen D., 0Z  
Crabb, Jonathan R., 1I  
Crowcombe, Will, 1B  
Cucchiaro, Paul, 0R  
Dailey, J. M., 0M  
Daneshgaran, Fred, 17  
de Lange, Dorus, 1B  
de Man, Harry, 1B  
den Breeje, Remco, 1H  
de Vries, Oliver, 16  
Dietz, Jonathan, 15  
Dinu, M., 0M  
Di Stasio, Francesco, 17  
Dochhan, Annika, 0W  
Doelman, Niek, 1H  
Driscoll, Dave, 0R  
Dugmore, Kirsten, 0R  
Edaibat, Mohammed, 03  
Ela, Carlo, 0K  
Endo, Hiroyuki, 0I  
Engelberth, J., 0M  
Engin, Doruk, 05, 0L  
Eppich, B., 0N  
Erry, G., 14  
Erven, C., 14  
Estrella, Steven, 26  
Faulkner, G., 14  
Ferrario, Ivan, 1H  
Floyd, Bertram M., 0G, 15  
Francis, Samuel P., 1P  
Fricke, J., 0N  
Fridlander, Joseph, 26  
Fritz, Erik, 1B  
Fuchs, Christian, 0S, 18  
Fujiwara, Mikio, 0I  
Gaißer, Steffen, 0S  
Garcia, Rafael A., 22  
Garham, J., 0J  
Gaschits, I., 0F  
Gebremicael, K., 14  
Giggenbach, Dirk, 0S, 18  
Gilaberte Basset, Martha, 16  
Goda, Takuo, 12, 1M  
Goorjian, P. M., 1F  
Gozzard, David R., 1P  
Gräfe, Markus, 16  
Greene, Daniel, 11  
Gruber, Michael, 1H  
Hamilton, Scott A., 0Z  
Haq, A F M Saniul, 21  
Hardy, Nicholas D., 0Z  
Hasegawa, Yohei, 07  
Hashimoto, Yoichi, 12, 1M  
Hasler, David, 0U  
Hauschildt, Harald, 0K  
Häusler, K., 0N  
Heine, Frank, 0U  
Hemmati, H., 13

Heo, Myoung-Sun, 1N  
 Hohne, Andrew, 15  
 Höpcke, Nils, 0U  
 Howe, Thomas R., 0Z  
 Human, Jet, 1H  
 Hummel, David, 1Y  
 Hwang, Jacob, 05  
 Ismail, T., 14  
 Ito, Toshiharu, 07  
 Jachura, Michal, 0A  
 Jaques, J., 0M  
 Jarzyna, Marcin, 0A  
 Jiao, Hua, 22  
 Jo, Jino, 0R  
 Johansson, Leif, 26  
 Johnstone, W., 1I  
 Kaminsky, Richard D., 0Z  
 Katz, Evan J., 0D, 15  
 Kehayas, E., 1I  
 Keim, Jonas, 0S  
 Kelemu, Helawae Friew, 0W  
 Kennard, J., 14  
 Kerrigan, Haley, 1Z  
 Kim, Jungwon, 1N  
 King, Alexander J., 0Q  
 Kingston, E., 14  
 Kitamura, Mitsuo, 0I  
 Klamkin, Jonathan, 26  
 Klop, Wimar, 1H  
 Knigge, A., 0N  
 Kolchmeyer, J., 0M  
 Kotake, Hideaki, 12, 1M  
 Kramer, Lukas, 1B  
 Kremsner, Peter, 1G  
 Kubo-oka, Toshihiro, 0I  
 Kufahl, Katelyn, 03  
 Kuiper, Stefan, 1B  
 Kumar, Prajnesh, 24  
 Kunz, Ludwig, 0A  
 Kupferman, Judy, 17  
 Lafon, Robert, 0G  
 Lantz, Nicholas C., 09, 1Q  
 Le, Khoa, 05, 0L  
 Lee, Jaegoan, 1N  
 Le Grange, J., 0M  
 Lekki, John D., 15  
 Lengowski, Michael, 0S  
 Leon-Saval, Sergio, 0G  
 Litvinovitch, Slava, 05  
 Luetke, Wolfram, 0W  
 Mabena, Chemist M., 1T  
 Maliakal, A., 0M, 0O  
 Malowicki, John, 1Y  
 Martini, Rainer, 24  
 Martin-Pimentel, Patricia, 0U  
 Mata Calvo, Ramon, 0W, 18, 1H  
 Mathason, Brian, 05, 0L  
 Matsumoto, Atsushi, 1X  
 McClelland, David E., 1P  
 McClure, Steve, 1I  
 McNally, J., 08, 0J  
 McNutt, R. L., 03  
 Michie, C., 1I  
 Milanowski, Randall, 1I  
 Milby, Ezra, 0R  
 Miller, Eric D., 1I  
 Moeller, Hermann Ludwig, 0K  
 Moens, Thijs, 1H  
 Mohseni, Hooman, 1J  
 Moll, Florian, 0S  
 Mondin, Marina, 17  
 Monte, A., 0M  
 Moro, Slaven, 1I  
 Munemasa, Yasushi, 0I  
 Murphy, Robert J., 0Q  
 Nakamura, Junichi, 12, 1M  
 Nappier, Jennifer M., 09, 0D, 1Q  
 Nemitz, Ian, 15  
 Nicholson, Neal, 1I  
 Nicklaus, Kolja, 1C  
 Nikulin, Vladimir, 1Y  
 O'Brien, D., 14  
 Ono, Yoshimasa, 07  
 Oshima, Yutaka, 12, 1M  
 Parenti, Ronald R., 0Q  
 Park, Sang Eon, 1N  
 Peña, Jessica, 1Z  
 Perdigues Armengol, Josep Maria, 0K, 1C  
 Petrillo, Keith G., 05  
 Pettazzi, Federico, 1H  
 Piccirilli, A., 0M  
 Pinna, Sergio, 26  
 Poliak, Juraj, 0W, 1H  
 Prego, R., 0M  
 Puffenberger, Kent, 05, 0L  
 Quintana, C., 14  
 Rajavel, Rajesh, 0R  
 Ramakrishnan, Shankararaman, 0Q  
 Rao, Hemonth G., 0Z  
 Rarity, J., 14  
 Rauch, Stephen, 0Q  
 Reeves, Andrew, 0W  
 Refai, Hazem H., 1O  
 Rein, Fabian, 0W  
 Reyes, Danielle, 1Z  
 Reyes, P., 08  
 Reynolds, Brett, 0Q  
 Richardson, Martin C., 1Z  
 Richerzhagen, Matthias, 0W, 1H  
 Riel, Thomas, 1G  
 Riesing, K. M., 0P  
 Roberts, Lyle E., 1P  
 Roberts, Tony D., 15  
 Robinson, B. S., 0P  
 Rödiger, Benjamin, 0S  
 Rodrigues, Tim, 0R  
 Romayah, Patrick, 1Z  
 Rosborough, Victoria, 26  
 Rosenkranz, Werner, 18  
 Rostami Fairchild, Shermineh, 1Z

Roth, Jeffrey M., 0Q	Yamamoto, Naokatsu, 1X
Roux, Filippus S., 1T	Yu, Dai-Hyuk, 1N
Rudd, Joe, 0L	Yuksel, Murat, 2I
Russchenberg, Tjeerd, 1H	Zech, Herwig, 0U
Saathof, Rudolf, 1B, 1H	Zhang, Dayu, 24
Saito, Yoshihiko, 0I	
Sánchez-Tercero, Alicia, 0U	
Sang, Fengqiao, 26	
Sasaki, Masahide, 0I	
Saucke, Karen, 0W	
Sawruk, Nick, 0L	
Scheinbart, Marvin S., 0Z	
Schieler, C. M., 0P	
Schiemangk, Max, 1U	
Schitter, Georg, 1G	
Schmidt, Christopher, 0S	
Schober, Andrew, 0L	
Schoenholz, Bryan, 04	
Schwartz, Jay, 0R	
Shaddock, Daniel A., 1P	
Shaw, Rebecca R., 03	
Shin, Junho, 1N	
Shtyrkova, K., 0F	
Shubert, Paul D., 08, 0J, 1K, 1L	
Sibley, Paul G., 1P	
Sibson, P., 14	
Sinn, Andreas, 1G	
Sochor, T., 0M	
Sodnik, Zoran, 1C	
Spollard, James T., 1P	
Staffa, Jeremy, 0G	
Staske, R., 0N	
Steinlechner, Fabian-Oliver, 16	
Stevens, G., 1I	
Storm, Mark, 05, 0L	
Sullivan, Joseph, 04	
Surof, Janis, 0W	
Takenaka, Hideki, 0I	
Takeoka, Masahiro, 0I	
Taylor, John A., 0Q	
Tedder, Sarah A., 04, 09, 0D, 0G, 1Q	
Thueux, Y., 14	
Thul, Daniel, 1Z	
Toyoshima, Morio, 0I	
Tränkle, Günther, 1U	
Trinh, Phuc V., 0I	
Ulmer, Todd G., 0Q	
Umezawa, Toshimasa, 1X	
Ursin, Rupert, 16	
Utano, Richard, 05	
van der Valk, Nick, 1B	
Vedrenne, Nicolas, 1C	
Voland, Christoph, 1C	
Volpicell, Alicia M., 0Q	
Vyhnaiek, Brian E., 09, 0D, 0G, 15, 1Q	
Watson, M., 14	
Wheaton, Skyler, 1J	
Wicht, Andreas, 1U	
Wolf, Raphael, 0W	
Wright, M. W., 0M	



# Conference Committee

## *Symposium Chairs*

**Beat Neuenschwander**, Berner Fachhochschule Technik und Informatik  
(Switzerland)

**Xianfan Xu**, Purdue University (United States)

## *Symposium Co-chairs*

**Koji Sugioka**, RIKEN Center for Advanced Photonics (Japan)

**Reinhard Poprawe**, Fraunhofer-Institut für Lasertechnik (Germany)

## *Program Track Chairs*

**Bo Gu**, Bos Photonics (United States)

**Stefan Kaierle**, Laser Zentrum Hannover e.V. (Germany)

## *Conference Chairs*

**Hamid Hemmati**, Facebook Inc. (United States)

**Don M. Boroson**, MIT Lincoln Laboratory (United States)

## *Conference Program Committee*

**Abhijit Biswas**, Jet Propulsion Laboratory (United States)

**Donald M. Cornwell Jr.**, NASA Goddard Space Flight Center  
(United States)

**Frank F. Heine**, Tesat-Spacecom GmbH & Company KG (Germany)

**William S. Rabinovich**, U.S. Naval Research Laboratory (United States)

**Zoran Sodnik**, European Space Research and Technology Center  
(Netherlands)

**Linda M. Thomas**, U.S. Naval Research Laboratory (United States)

**Morio Toyoshima**, National Institute of Information and Communications  
Technology (Japan)

## *Session Chairs*

1 Laser Comm Designs I  
**Hamid Hemmati**, Facebook Inc. (United States)

2 Laser Comm Designs II  
**Don M. Boroson**, MIT Lincoln Laboratory (United States)

3 Modem Designs: Receivers  
**Hamid Hemmati**, Facebook Inc. (United States)

- 4 Laser Comm System Proposals  
**Christoph Volland**, European Space Research and Technology Centre  
(Netherlands)
- 5 Modem Designs: Transmitters  
**William S. Rabinovich**, U.S. Naval Research Laboratory (United States)
- 6 Point, Acquisition, and Track Subsystems  
**Linda M. Thomas**, U.S. Naval Research Laboratory (United States)
- 7 Systems and Demos  
**Frank F. Heine**, Tesat-Spacecom GmbH & Company KG (Germany)
- 8 Adaptive Optics Designs  
**Hamid Hemmati**, Facebook Inc. (United States)
- 9 Modem Designs  
**Don M. Boroson**, MIT Lincoln Laboratory (United States)
- 10 Quantum Systems  
**Hamid Hemmati**, Facebook Inc. (United States)
- 11 Optical Uplinks  
**Don M. Boroson**, MIT Lincoln Laboratory (United States)