## **PROCEEDINGS OF SPIE**

# Fiber Optic Sensors and Applications VI

Eric Udd Henry H. Du Anbo Wang Editors

15–17 April 2009 Orlando, Florida, United States

Sponsored and Published by SPIE

Volume 7316

Proceedings of SPIE, 0277-786X, v. 7316

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

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 Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proceedings of SPIE Vol. 7316 (SPIE, Bellingham, WA, 2009) Article CID Number.

ISSN 0277-786X ISBN 9780819475824

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 © 2009, 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/09/\$18.00.

Printed in the United States of America.

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



**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 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

- vii Conference Committee
- xi Introduction

SESSION 1	DISTRIBUTED SENSORS, RAMAN, AND BRILLOUIN SENSING

- 7316 02 Long-distance fiber optic sensing solutions for pipeline leakage, intrusion, and ground movement detection (Invited Paper) [7316-01]
   M. Nikles, Omnisens S.A. (Switzerland)
- 7316 03 Feasibility study of the automated detection and localization of underground tunnel excavation using Brillouin optical time domain reflectometer [7316-02] A. Klar, R. Linker, Technion-Israel Institute of Technology (Israel)
- 7316 04 Elimination of rain-induced nuisance alarms in distributed fiber optic perimeter intrusion detection systems [7316-03]
   S. S. Mahmoud, J. Katsifolis, Future Fibre Technologies Pty Ltd. (Australia)
- 7316 05 **Distributed temperature sensing via Brillouin-tailored optical fiber** [7316-04] P. D. Dragic, Neolight Technologies LLC (United States)
- Fiber optic distributed sensing applications in defense, security, and energy (Invited Paper)
   [7316-05]
   M. Jaaskelainen, SensorTran, Inc. (United States)
- 7316 07 **Tailoring of the Brillouin gain profile for fiber-based sensor systems and networks** [7316-06] P. D. Dragic, Neolight Technologies LLC (United States)
- 7316 08 Raman sensing of fuel gases using a reflective coating capillary optical fiber [7316-07] M. P. Buric, K. Chen, J. Falk, National Energy Technology Lab. (United States) and Univ. of Pittsburgh (United States); R. Velez, National Energy Technology Lab. (United States) and Univ. of Massachusetts (United States); S. Woodruff, National Energy Technology Lab. (United States)
- 7316 0A Distributed strain and temperature sensing in plastic optical fiber using Rayleigh scatter [7316-09]

S. T. Kreger, A. K. Sang, D. K. Gifford, M. E. Froggatt, Luna Innovations Inc. (United States)

#### SESSION 2 FIBER GRATING SENSORS I

7316 0B Through-the-jacket inscription of fiber Bragg gratings using femtosecond infrared radiation for sensor applications (Invited Paper) [7316-10]
 S. J. Mihailov, D. Grobnic, C. W. Smelser, R. B. Walker, Communications Research Ctr. Canada (Canada)

- 7316 0C Radiation sensitivity of Bragg gratings written with femtosecond IR lasers [7316-11]
   D. Grobnic, Communications Research Ctr. Canada (Canada); H. Henschel, S. K. Hoeffgen, J. Kuhnhenn, Fraunhofer-INT (Germany); S. J. Mihailov, Communications Research Ctr. Canada (Canada); U. Weinand, Fraunhofer-INT (Germany)
- 7316 0D Bragg gratings written in multimode borosilicate fibers using ultrafast infrared radiation and a phase mask [7316-12] D. Grobnic, S. J. Mihailov, C. W. Smelser, Communications Research Ctr. Canada (Canada)
- 7316 OE **Embedded fiber optic Bragg grating (FBG) detonation velocity sensor** [7316-13] J. Benterou, C. V. Bennett, G. Cole, D. E. Hare, C. May, Lawrence Livermore National Lab. (United States); E. Udd, Columbia Gorge Research (United States); S. J. Mihailov, P. Lu, Communications Research Ctr. Canada (Canada)

#### SESSION 3 FIBER GRATING SENSORS II

- 7316 0G Chemical sensor using Bragg-grating-based optical ridge waveguide with polydimethysiloxane as top layer [7316-15]
   X. Dai, S. J. Mihailov, C. Blanchetiere, Communications Research Ctr. Canada (Canada)
- High-sensitivity pressure sensor based on fiber Bragg grating and metal bellows [7316-16]
   D. Song, J. Zou, Z. Wei, Stevens Institute of Technology (United States); S. Yang, Yantai Univ. (China); H.-L. Cui, Stevens Institute of Technology (United States)
- 7316 01 **Coupled resonator optical waveguide sensors: sensitivity and the role of slow light** [7316-52] M. A. Terrel, M. J. F. Digonnet, S. Fan, Stanford Univ. (United States)
- 7316 0M High reliability FBG interrogation analyzers [7316-50]
   W. Yang, C. Zhang, E. Bergles, BaySpec, Inc. (United States)

#### SESSION 4 ANALYSIS OF LIGHT AND EFFECTS ON SENSORS

- 7316 0N Fluoride glass fiber: state of the art (Invited Paper) [7316-49] M. Saad, IRphotonics Inc. (Canada)
- 7316 00 Advances in hyperspectral imaging technologies for multichannel fiber sensing [7316-20] J. Zakrzewski, K. Didona, Headwall Photonics, Inc. (United States)
- 7316 0Q A model for an omnidirectional radiometer [7316-22]
   M. E. Jansen, L. R. Gauthier, Jr., N. W. Rolander, The Johns Hopkins Univ. Applied Physics Lab. (United States)

#### SESSION 5 INTERFEROMETRIC SENSORS

- 7316 OR A personal tour of the fiber optic Sagnac interferometer (Invited Paper) [7316-23] E. Udd, Columbia Gorge Research (United States)
- 7316 0S Swept laser interferometric interrogation [7316-24] J. Bush, Optiphase, Inc. (United States)

7316 0T Temperature-independent strain sensor based on a core-offset multimode fiber interferometer [7316-25]
B. Dong, Wilfrid Laurier Univ. (Canada); L. Wei, Wilfrid Laurier Univ. (Canada) and Univ. of Waterloo (Canada); D.-P. Zhou, W.-K. Liu, Univ. of Waterloo (Canada); J. W. Y. Lit, Wilfrid Laurier Univ. (Canada)

- 7316 0U Low-cost lateral force sensor based on a core-offset multimode fiber interferometer with intensity-based interrogation technique [7316-26]
   D.-P. Zhou, Univ. of Waterloo (Canada); B. Dong, Wilfrid Laurier Univ. (Canada); L. Wei, Wilfrid Laurier Univ. (Canada) and Univ. of Waterloo (Canada); W.-K. Liu, Univ. of Waterloo (Canada); J. W. Y. Lit, Wilfrid Laurier Univ. (Canada)
- 7316 0X Low-noise planar external cavity laser for interferometric fiber optic sensors [7316-51] M. Alalusi, P. Brasil, S. Lee, P. Mols, L. Stolpner, A. Mehnert, S. Li, Redfern Integrated Optics, Inc. (United States)

#### SESSION 6 TEMPERATURE AND PRESSURE MEASUREMENTS AND HIGH-TEMPERATURE SENSORS

7316 OY Sapphire direct bonding as a platform for pressure sensing at extreme high temperatures [7316-28]

E. M. Lally, Y. Xu, A. Wang, Virginia Polytechnic Institute and State Univ. (United States)

- 7316 0Z **Reliability of optical fibers in a cryogenic environment** [7316-29] E. A. Lindholm, A. A. Stolov, R. S. Dyer, B. Slyman, D. Burgess, OFS Specialty Photonics Div. (United States)
- For the performance of a novel low-cost macro-bend fiber-based temperature sensor [7316-30]
   G. Rajan, J. Mathew, Y. Semenova, G. Farrell, Dublin Institute of Technology (Ireland)
- 7316 12 Light guide technology: using light to enhance safety [7316-32] W. S. Lerner, Consultant (United States)
- 7316 13 An integrated high-pressure, pressure temperature, and skin friction sensor [7316-33] A. K. Sang, C. Boyd, Luna Innovations Inc. (United States)

#### SESSION 7 ELECTROMAGNETIC RADIATION AND PARTICLE SENSORS

- 7316 14 **Compact super-wideband optical antenna** [7316-34] W. C. Wang, R. Forber, IPITEK, Inc. (United States); K. Bui, U.S. Army Communications-Electronics Command (United States)
- 7316 16 Ce-doped SiO<sub>2</sub> optical fibers for remote radiation sensing and measurement [7316-36]
   N. Chiodini, A. Vedda, M. Fasoli, F. Moretti, A. Lauria, Univ. degli Studi di Milano-Bicocca (Italy); M. C. Cantone, I. Veronese, Univ. degli Studi di Milano (Italy); G. Tosi, Istituto Europeo di Oncologia (Italy); M. Brambilla, B. Cannillo, E. Mones, Azienda Ospedaliera Maggiore della Carità (Italy); G. Brambilla, M. Petrovich, Univ. of Southampton (United Kingdom)

7316 17 Vulnerability of rare-earth-doped fibers for space missions: origins of radiation-induced attenuation [7316-37]
Y. Ouerdane, LAHC, Univ. Jean Monnet Saint-Etienne (France); S. Girard, CEA DAM IIe de France (France); B. Tortech, LAHC, Univ. Jean Monnet Saint-Etienne (France); T. Robin, iXFiber SAS (France); C. Marcandella, CEA DAM IIe de France (France); A. Boukenter, LAHC,

Univ. Jean Monnet Saint-Etienne (France); B. Cadier, iXFiber SAS (France); J.-P. Meunier, LAHC, Univ. Jean Monnet Saint-Etienne (France); P. Crochet, iXFiber SAS (France)

7316 18 **Characterization of a triboluminescent optical sensor for detecting particles** [7316-38] L. R. Gauthier, Jr., M. E. Jansen, J. R. Meyer, The Johns Hopkins Univ. Applied Physics Lab. (United States)

#### SESSION 8 PHOTONIC CRYSTAL FIBERS AND SENSORS

- Multi-channel surface-enhanced Raman scattering probe based on photonic crystal fiber [7316-39]
  H. Yan, Z. Zhang, J. Liu, M. Li, S. Liao, C. Yang, Tsinghua Univ. (China); L. Hou, Yanshan Univ. (China)
- High-sensitivity photonic crystal fiber interferometer for chemical vapors detection [7316-40]
   J. Villatoro, M. P. Kreuzer, R. Jha, Institut de Ciències Fotòniques (Spain); V. P. Minkovich, Ctr. de Investigaciones en Óptica, A.C. (Mexico); V. Finazzi, G. Badenes, Institut de Ciències Fotòniques (Spain); V. Pruneri, Institut de Ciències Fotòniques (Spain) and Institució Catalana de Recerca i Estudis Avançats (Spain)
- 7316 1B **Photonic crystal fiber modal interferometers for accurate refractometry** [7316-41] J. Villatoro, R. Jha, G. Badenes, Institut de Ciències Fotòniques (Spain)
- Design of photonic crystal fiber long-period grating refractive index sensor [7316-43]
   J. Kanka, Institute of Photonics and Electronics (Czech Republic); Y. Zhu, Z. He, H. Du, Stevens Institute of Technology (United States)
- 7316 1E **Tunable properties of liquid crystal filled photonic crystal fibers** [7316-44] S. Mathews, Y. Semenova, G. Rajan, G. Farrell, Dublin Institute of Technology (Ireland)

#### POSTER SESSION

7316 1F All-fiber multimode interference refractometer sensor [7316-47]
 J. E. Antonio-Lopez, D. Lopez-Cortes, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); M. A. Basurto-Pensado, Univ. Autónoma del Estado de Morelos (Mexico); D. A. May-Arrioja, J. J. Sanchez-Mondragon, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

Author Index

### **Conference Committee**

Symposium Chair

Ray O. Johnson, Lockheed Martin Corporation (United States)

Symposium Cochair

Michael T. Eismann, Air Force Research Laboratory (United States)

#### **Conference** Chairs

Eric Udd, Columbia Gorge Research (United States)
Henry H. Du, Stevens Institute of Technology (United States)
Anbo Wang, Virginia Polytechnic Institute and State University (United States)

#### Program Committee

Christopher S. Baldwin, Aither Engineering, Inc. (United States) Jeremy J. Baumberg, University of Cambridge (United Kingdom) Jerry J. Benterou, Lawrence Livermore National Laboratory (United States) Eric A. Bergles, BaySpec, Inc. (United States) Jeff Bush, Optiphase, Inc. (United States) Steven D. Christesen, U.S. Army Edgewood Chemical Biological Center (United States) **Brian Culshaw**, University of Strathclyde (United Kingdom) Robert P. Dahlgren, University of California, Santa Cruz (United States) John P. Dakin, University of Southampton (United Kingdom) Wolfgang Ecke, IPHT Jena (Germany) Yoel Fink, Massachusetts Institute of Technology (United States) Hiroshi Fudouzi, National Institute for Materials Science (Japan) Tom W. Graver, Micron Optics, Inc. (United States) Hajime Haneda, National Institute for Materials Science (Japan) Kazuo Hotate, The University of Tokyo (Japan) Jesper B. Jensen, Danmarks Tekniske Universitet (Denmark) **Desheng Jiang**, Wuhan University of Technology (China) Jiri Kanka, Institute of Photonics and Electronics (Czech Republic) Steven T. Kreger, Luna Innovations Inc. (United States) Paul Lefebvre, LxDATA (Canada) Alexis Mendez, MCH Engineering LLC (United States) Stephen J. Mihailov, Communications Research Center Canada (Canada)

Gary Pickrell, Virginia Polytechnic Institute and State University (United States)
Devanand K. Shenoy, Defense Advanced Research Projects Agency (United States)
Ping Shum, Nanyang Technological University (Singapore)
Svetlana A. Sukhishvili, Stevens Institute of Technology (United States)
Dennis J. Trevor, OFS Fitel, LLC (United States)
Michael J. Wardlaw, Naval Surface Warfare Center (United States)
Younan Xia, University of Washington (United States)
Hai Xiao, Missouri University of Science and Technology (United States)

#### Session Chairs

- Distributed Sensors, Raman, and Brillouin Sensing
   Anbo Wang, Virginia Polytechnic Institute and State University (United States)
   Alexis Mendez, MCH Engineering LLC (United States)
- Fiber Grating Sensors I
   Jerry J. Benterou, Lawrence Livermore National Laboratory (United States)

   Stephen J. Mihailov, Communications Research Center Canada (Canada)
- Fiber Grating Sensors II
   Eric Udd, Columbia Gorge Research (United States)
   Paul Lefebvre, LxDATA (Canada)
- Analysis of Light and Effects on Sensors
   Robert P. Dahlgren, University of California, Santa Cruz (United States)
   Jeff Bush, Optiphase, Inc. (United States)
- Interferometric Sensors
   Jeff Bush, Optiphase, Inc. (United States)
   Robert P. Dahlgren, University of California, Santa Cruz (United States)
- Temperature and Pressure Measurements and High-Temperature Sensors
   Gary Pickrell, Virginia Polytechnic Institute and State University (United States)

Anbo Wang, Virginia Polytechnic Institute and State University (United States)

- 7 Electromagnetic Radiation and Particle Sensors
   Gary Pickrell, Virginia Polytechnic Institute and State University (United States)
   Anbo Wang, Virginia Polytechnic Institute and State University (United States)
- 8 Photonic Crystal Fibers and Sensors Henry H. Du, Stevens Institute of Technology (United States)

## Introduction

SPIE has been sponsoring conferences on fiber optic sensor technology for over 30 years, and the Fiber Optic Sensors and Applications VI conference continues this tradition. Three fiber optic sensor conferences have been combined in an effort to provide a more comprehensive overview of the technology and its applications than could have been provided by a single conference. It is hoped that in the future this conference will offer a yearly venue for useful discussions between researchers and developers of this technology, as well as those who are striving to apply it to the real world.

Over the past 30 years, some of the technology has reached considerable maturity with the widespread deployment of fiber optic gyro technology, the usage of fiber optic acoustic sensors for undersea applications, fiber optic current sensors used to support electrical grids, and widespread deployment of fiber optic sensors on civil structures worldwide. This maturity has lead to an increase in the number of companies offering fiber optic sensor products and the overall size of the market. At the same time, there are many application areas that have yet to be explored which has resulted in a number of new fiber optic sensor designs that offer promise of new markets in the future. It is also apparent that each new application brings new sets of challenges as well as opportunities.

The result has been a continuing revitalization of the fiber optic sensor field that is apparent in the papers that are contained in these proceedings.

Eric Udd Anbo Wang Henry Du