

PROGRESS IN BIOMEDICAL OPTICS AND IMAGING

Vol. 17 No. 30

Quantitative Phase Imaging II

Gabriel Popescu

YongKeun Park

Editors

14–17 February 2016

San Francisco, California, United States

Sponsored and Published by
SPIE

Volume 9718

Proceedings of SPIE, 1605-7422, V. 9718

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

Quantitative Phase Imaging II, edited by Gabriel Popescu, YongKeun Park, Proc. of SPIE Vol. 9718, 971801
© 2016 SPIE · CCC code: 1605-7422/16/\$18 · doi: 10.1117/12.2239767

Proc. of SPIE Vol. 9718 971801-1

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 SPIEDigitalLibrary.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 *Quantitative Phase Imaging II*, edited by Gabriel Popescu, YongKeun Park, Proceedings of SPIE Vol. 9718 (SPIE, Bellingham, WA, 2016) Six-digit Article CID Number.

ISSN: 1605-7422

ISSN: 2410-9045 (electronic)

ISBN: 9781628419528

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 1605-7422/16/\$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**

SPIEDigitalLibrary.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

vii	<i>Authors</i>
ix	<i>Conference Committee</i>
xi	<i>Introduction</i>

SESSION 1	QPI METHODOLOGIES I
9718 02	The evolution of interferometry from metrology to biomedical applications (Keynote Paper) [9718-1]
9718 03	High resolution quantitative phase imaging of live cells with constrained optimization approach [9718-3]
9718 05	Non-iterative adaptive optical microscopy using wavefront sensing (Invited Paper) [9718-2]
9718 06	Holographic microscopy in low coherence [9718-5]
9718 07	Coherent label-free imaging through turbidity: a holographic approach [9718-8]
SESSION 2	QPI ALGORITHMS AND IMAGE PROCESSING
9718 0A	Phase microscope imaging in phase space (Invited Paper) [9718-10]
9718 0H	Enhanced lateral resolution for phase retrieval based on the transport of intensity equation with tilted illumination [9718-18]
SESSION 3	QPI OF CELLS AND TISSUES I
9718 0N	Prospects and challenges of quantitative phase imaging in tumor cell biology [9718-23]
9718 0O	Quantitative label-free sperm imaging by means of transport of intensity [9718-24]
9718 0R	Analyzing the texture changes in the quantitative phase maps of adipocytes [9718-27]
9718 0T	Highly sensitive kinesin-microtubule motility assays using SLIM [9718-29]
SESSION 4	QPI CLINICAL APPLICATIONS
9718 0U	Online quantitative phase imaging of vascular endothelial cells under fluid shear stress utilizing digital holographic microscopy [9718-30]

9718 0Y **Automatic Gleason grading of prostate cancer using SLIM and machine learning** [9718-34]

SESSION 5 QPI FROM LAB TO MARKET

9718 13 **HoloMonitor M4: holographic imaging cytometer for real-time kinetic label-free live-cell analysis of adherent cells (Invited Paper)** [9718-38]

9718 14 **Optical diffraction tomography using a digital micromirror device for stable measurements of 4D refractive index tomography of cells (Invited Paper)** [9718-39]

9718 16 **Coherence-controlled holographic microscopy principle embodiment into Q-PHASE microscope: story of a successful technology transfer (Invited Paper)** [9718-106]

POSTER SESSION

9718 17 **Automatic tissue segmentation of breast biopsies imaged by QPI** [9718-78]

9718 18 **Study of erythrocyte membrane fluctuation using light scattering analysis** [9718-79]

9718 19 **The study on RBC characteristic in paroxysmal nocturnal hemoglobinuria (PNH) patients using common path interferometric quantitative phase microscopy** [9718-80]

9718 1B **Phase-retrieved optical projection tomography for 3D imaging through scattering layers** [9718-82]

9718 1C **Quantitative measurement of displacement in photopolymer layers during holographic recording using phase shifting electronic speckle pattern interferometry** [9718-83]

9718 1F **White light phase shifting interferometry and color fringe analysis for the detection of contaminants in water** [9718-86]

9718 1R **Improvement of reconstructed phase distribution of fast moving phase object in digital holographic microscope** [9718-98]

9718 1S **Optical phase analysis in drilled cortical porcine bones using digital holographic interferometry** [9718-99]

9718 1T **Study of in-homogeneities in PMMA samples using a 3D-SD-OCT system** [9718-100]

9718 1Y **Coherence-controlled holographic microscopy for live-cell quantitative phase imaging in turbid media** [9718-105]

SESSION 6 QPI METHODOLOGIES II

9718 21 **Multi-modal digital holographic microscopy for wide-field fluorescence and 3D phase imaging** [9718-43]

9718 25 **Advances in design and testing of limited angle optical diffraction tomography system for biological applications** [9718-47]

9718 27 **Quantitative phase imaging of living cells with a swept laser source** [9718-49]

SESSION 7 QPI OF CELLS AND TISSUES II

9718 28 **Quantitative phase imaging of biological cells and tissues using singleshot white light interference microscopy and phase subtraction method for extended range of measurement** [9718-51]

9718 2B **Holographic microscopy for 3D tracking of bacteria** [9718-54]

9718 2C **Enlightening intracellular complexity of living cells with quantitative phase microscopy** [9718-55]

9718 2D **3D measurements of live cells via digital holographic microscopy and terahertz spectroscopy** [9718-56]

SESSION 8 QPI METHODOLOGIES III

9718 2H **Resolving the depth of fluorescent light by structured illumination and shearing interferometry** [9718-60]

9718 2I **Quantitative phase contrast imaging using a Nomarski microscope with variable shear distance** [9718-61]

9718 2J **Dual wavelength digital holographic imaging of embedded layered structures** [9718-62]

9718 2K **Unlimited field-of-view optofluidic quantitative phase imaging** [9718-63]

9718 2M **Shape measurements of microscopic objects using computational shear interferometry** [9718-67]

SESSION 9 QPI METHODOLOGIES IV

9718 2P **GPC and quantitative phase imaging (Invited Paper)** [9718-69]

9718 2Q **Extended synthetic wavelength phase imaging by multiwavelength digital holography** [9718-70]

SESSION 10 QPI MATERIAL APPLICATIONS

9718 2W **Through-the-objective holographic surface plasmon resonance imaging for quantitative measurement of thin film thickness** [9718-76]

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.

Agour, Mostafa, 2I, 2M	Kandel, Mikhail, 0T, 17
Ahmad, Azeem, 1F, 28	Kemper, Björn, 0N, 0U
Alm, Kersti, 13	Ketelhut, Steffi, 0N
Ancora, Daniele, 1B	Khare, Kedar, 03
Argoul, F., 2C	Khmaladze, Alexander, 2D, 2J
Arneodo, A., 2C	Kienle, Alwin, 2H
Awatsuji, Yasuhiro, 1R, 2I	Kim, Byungyeon, 19
Azucena, O., 05	Kim, Kyoo Hyun, 14
Balla, Andre K., 0Y, 17	Kim, Myung K., 2Q
Bañas, Andrew Rafael, 2P	Kim, Taeho, 14
Bavigadda, Viswanath, 1C	Kollárová, Věra, 06
Bedrossian, Manuel, 2B	Komrska, Jiří, 06
Bergmann, Ralf B., 2I, 2M	Kötter, Jonas, 2I
Berguiga, L., 2C	Kozacki, T., 0H
Bianco, V., 07, 2K	Krauter, Philipp, 2H
Boyer Provera, E., 2C	Krizova, A., 1Y
Briones R., Manuel de Jesús, 1S, 1T	Kubby, J., 05
Brodhag, Nicole, 2H	Kujawińska, M., 25
Chen, Shichao, 27	Kuś, A., 25
Chen, Xinzhang, 2J	Langberg, Anders, 13
Chmelík, Radim, 06, 16, 1Y	Laperrousaz, B., 2C
Cho, Yong Bin, 2B	Lee, Hoyoon, 18
Clark, David C., 2Q	Lee, Sangyun, 18
Čolláková, Jana, 06, 1Y	Lee, Seungrag, 19
De la Torre-L., Manuel H., 1S, 1T	Liapis, Evangelos, 1B
Di Battista, Diego, 1B	Lindensmith, Christian, 2B
Do, Minh N., 0Y, 17	Lindskov, Jens-Henrik, 13
Dostál, Zbyněk, 06	Lostak, M., 16, 1Y
Dubey, Vishesh, 1F, 28	Luna H., Juan M., 1S, 1T
Egelberg, Peter J., 13	Maguer-Satta, V., 2C
Elezgaray, J., 2C	Mahajan, Supriya, 2D
El-Kholy, Marwan, 2B	Majeed, Hassaan, 17
Elmaklizi, Ahmed, 2H	Makowski, P., 25
Falaggis, K., 0H	Mandracchia, B., 2W
Falldorf, Claas, 2I, 2M	Marchesano, V., 07, 2K
Ferraro, P., 07, 2K, 2W	Marcias, Virgilia, 0Y, 17
Flores M., J. Mauricio, 1S, 1T	Martinez Torres, C., 2C
Frenner, Karsten, 2H	Martinez-Carranza, J., 0H
Gefen, Amit, 0R	Matoba, Osamu, 1R, 2I
Giasafaki, Georgia, 1B	Mehta, Dalip Singh, 1F, 28
Glückstad, Jesper, 2P	Mehta, Shalin B., 0A
Götte, Martin, 0N	Memmolo, P., 07
Greve, Burkhard, 0N	Mendoza S., Fernando, 1S, 1T
Hohmann, Ansgar, 2H	Miccio, L., 07
Hong, Kihyun, 14	Moothanchery, Mohesh, 1C
Iapozzuto, Peter, 2D	Nadeau, Jay, 2B
Janicke, Birgit, 13	Nagahama, Naoya, 1R
Jayaraman, Varshini, 0O	Naydenova, Izabela, 1C
John, Renu, 03, 0O	Nguyen, Tan H., 0Y, 17

Nicolini, F. E., 2C
 Nitta, Koichi, 1R, 21
 Norbury, Sean, 2D
 Odenthal-Schnittler, Maria, 0U
 Oser, Dorian, 2D
 Osten, Wolfgang, 2H
 Pagliarulo, V., 2W
 Palima, Darwin, 2P
 Pandiyan, Vimal Prabhu, 03, 0O
 Park, Byung Jun, 19
 Park, Jinah, 14
 Park, Jun Yong, 2D, 2J
 Park, YongKeun, 14, 18
 Paturzo, M., 07, 2K, 2W
 Petráček, Jiří, 06
 Poola, Praveen Kumar, 0O
 Popescu, Gabriel, 0T, 0Y, 17
 Pramanik, Manojit, 1C
 Psycharakis, Stylianos, 1B
 Quan, Xiangyu, 1R, 21
 Rider, Stephanie, 2B
 Roitshtain, Darina, 0R
 Schau, Philipp, 2H
 Schindler, Johannes, 2H
 Schnittler, Hans Joachim, 0U
 Sebesta, Mikael, 13
 Selvin, Paul R., 0T
 Shaked, Natan T., 0R
 Sharabani-Yosef, Orna, 0R
 Sharikova, Anna, 2D, 2J
 Sharma, Anuradha, 28
 Sheppard, Colin J. R., 0A
 Shin, Sehyun, 18
 Shin, Seungwoo, 14
 Singh, Gyanendra, 1F
 Singh, Veena, 1F, 28
 Slabá, Michala, 06
 Slabý, Tomáš, 06, 1Y
 Sridharan, Shamira, 0Y
 Tangella, Krishnarao, 17
 Tao, X., 05
 Tavera R., César G., 1S, 1T
 Teng, Kai Wen, 0T
 Toal, Vincent, 1C
 Upputuri, Paul Kumar, 1C
 Veselý, Pavel, 06, 1Y
 Villangca, Mark Jayson, 2P
 Voit, Florian, 2H
 Wallace, J. Kent, 2B
 Won, Youngjae, 19
 Wyant, James C., 02
 Xia, Peng, 1R, 21
 Yoon, Jonghee, 14
 Zacharakis, Giannis, 1B
 Zacharopoulos, Athanasios, 1B
 Zhu, Yizheng, 27

Conference Committee

Symposium Chairs

James G. Fujimoto, Massachusetts Institute of Technology
(United States)

R. Rox Anderson, Wellman Center for Photomedicine, Massachusetts
General Hospital (United States) and Harvard School of Medicine
(United States)

Program Track Chairs

Ammasi Periasamy, University of Virginia (United States)

Daniel L. Farkas, University of Southern California (United States) and
Spectral Molecular Imaging, Inc. (United States)

Conference Chairs

Gabriel Popescu, University of Illinois at Urbana-Champaign
(United States)

YongKeun Park, Korea Advanced Institute of Science and
Technology (Korea, Republic of)

Conference Program Committee

George Barbastathis, Massachusetts Institute of Technology
(United States)

Audrey K. Ellerbee, Stanford University (United States)

Pietro Ferraro, Istituto di Scienze Applicate e Sistemi Intelligenti (Italy)

Björn Kemper, Westfälische Wilhelms-Universität Münster (Germany)

Myung K. Kim, University of South Florida (United States)

Theo Lasser, École Polytechnique Fédérale de Lausanne (Switzerland)

Jerome Mertz, Boston University (United States)

Aydogan Ozcan, University of California, Los Angeles (United States)

Demetri Psaltis, École Polytechnique Fédérale de Lausanne
(Switzerland)

Colin James Richard Sheppard, Istituto Italiano di Tecnologia (Italy)

Peter T. C. So, Massachusetts Institute of Technology (United States)

Laura Waller, University of California, Berkeley (United States)

Changhuei Yang, California Institute of Technology (United States)

Session Chairs

- 1 QPI Methodologies I
Gabriel Popescu, University of Illinois at Urbana-Champaign (United States)
YongKeun Park, Korea Advanced Institute of Science and Technology (Korea, Republic of)
- 2 QPI Algorithms and Image Processing
George Barbastathis, Massachusetts Institute of Technology (United States)
Colin James Richard Sheppard, Istituto Italiano di Tecnologia (Italy)
- 3 QPI of Cells and Tissues I
Björn Kemper, Westfälische Wilhelms-Universität Münster (Germany)
Peter T. C. So, Massachusetts Institute of Technology (United States)
- 4 QPI Clinical Applications
Aydogan Ozcan, University of California, Los Angeles (United States)
- 5 QPI from Lab to Market
Gabriel Popescu, University of Illinois at Urbana-Champaign (United States)
- 6 QPI Methodologies II
Jerome Mertz, Boston University (United States)
Demetri Psaltis, École Polytechnique Fédérale de Lausanne (Switzerland)
- 7 QPI of Cells and Tissues II
Gabriel Popescu, University of Illinois at Urbana-Champaign (United States)
- 8 QPI Methodologies III
YongKeun Park, Korea Advanced Institute of Science and Technology (Korea, Republic of)
David C. Clark, University of South Florida (United States)
- 9 QPI Methodologies IV
Audrey K. Ellerbee, Stanford University (United States)
Pietro Ferraro, Istituto di Scienze Applicate e Sistemi Intelligenti (Italy)
- 10 QPI Material Applications
Pietro Ferraro, Istituto di Scienze Applicate e Sistemi Intelligenti (Italy)

Introduction

After the launch of the first conference in 2015, the second conference on Quantitative Phase Imaging (QPI II) at Photonics West BIOS has continued its success. For four full days, 14–17 February, the QPI conference hosted a dense program of oral presentations, covering both novel methodologies and applications in diverse fields. The conference was kicked-off with the keynote presentation by James C. Wyant from University of Arizona (United States), highlighting the evolution of interferometry from metrology to biomedical applications and commenting on the exciting future of QPI. Each presentation throughout the conference was followed by insightful comments and questions, truly engaging discussions about the state of the art and future directions of the field. This year QPI II received 107 abstract submissions, making it one of the largest conferences at Photonics West. Recognizing the importance of transferring the QPI technology to the hands of the biomedical users, this year we inaugurated a special session on entrepreneurship, "From lab to market," inviting start-up companies operating in the QPI market to tell their stories. The keynote of this special session was given by Jim Sharp, President of Carl Zeiss Microscopy, LLC (United States) and President and CEO of Carl Zeiss, Inc. (Germany).

Together, this growing event gives a strong message that the QPI field has become one of the most active fields in biophotonics.

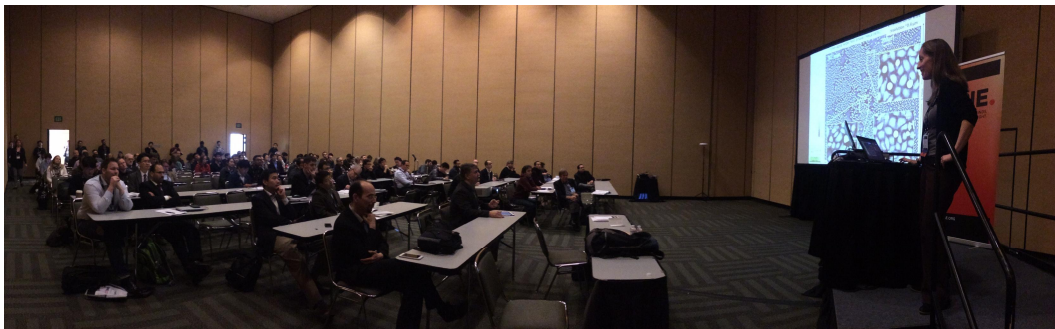


Figure 1. A morning session during the QPI Conference at Photonics West, BIOS (San Francisco, 7-10 Feb. 2015)

The papers published in this issue, proceedings volume on Quantitative Phase Imaging II, cover the latest developments and applications. The objective of this volume is to highlight recent progress and trends in novel optical technology developments as well as their biological, clinical, and industrial applications. The papers published here can be categorized into the following major topics:

1. QPI Methodologies
2. QPI Algorithms and Image Processing
3. QPI of Cells and Tissues
4. QPI Clinical Applications
5. QPI Material Applications

These topics are discussed in the contributed papers, covering original results and recent developments. Many of the papers published in this special issue represent an in-depth elaboration of topics presented at the Quantitative Phase Imaging II, Photonics West, BIOS, 2016. As chairs of the QPI II Conference, we are grateful to the contributors to this Volume and all the conference participants who have helped shape this exciting field of quantitative phase imaging.

Gabriel Popescu
YongKeun Park