PROCEEDINGS OF SPIE

# *Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications X*

**Konstantin L. Vodopyanov**
*Editor*

**24–27 January 2011**
**San Francisco, California, United States**

*Sponsored and Published by*
SPIE

**Volume 7917**

Proceedings of SPIE, 0277-786X, v. 7917

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 *Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications X*, edited by Konstantin L. Vodopyanov, Proceedings of SPIE Vol. 7917 (SPIE, Bellingham, WA, 2011) Article CID Number.

ISSN 0277-786X
ISBN 9780819484543

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



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, 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

# Conference Committee

*Symposium Chairs*

**Friedhelm Dorsch,** TRUMPF GmbH & Company KG (Germany)
**Alberto Piqué,** U.S. Naval Research Laboratory (United States)

*Symposium Cochairs*

**Donald J. Harter,** IMRA America, Inc. (United States)
**Peter R. Herman,** University of Toronto (Canada)

*Conference Chair*

**Konstantin L. Vodopyanov,** Stanford University (United States)

*Conference Cochair*

**Yehoshua Y. Kalisky,** Nuclear Research Center Negev (Israel)

*Program Committee*

**Darrell J. Armstrong,** Sandia National Laboratories (United States)
**Pinhas Blau,** Soreq Nuclear Research Center (Israel)
**Majid Ebrahim-Zadeh,** ICFO - Instituto de Ciencias Fotónicas (Spain)
**Peter P. Günter,** ETH Zürich (Switzerland)
**Angus J. Henderson,** Lockheed Martin Aculight (United States)
**Baldemar Ibarra-Escamilla,** Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)
**Yun-Shik Lee,** Oregon State University (United States)
**Rita D. Peterson,** Air Force Research Laboratory (United States)
**Peter E. Powers,** University of Dayton (United States)
**Kenneth L. Schepler,** Air Force Research Laboratory (United States)
**Peter G. Schunemann,** BAE Systems (United States)
**Andrei V. Shchegrov,** Spectralus Corporation (United States)
**Wei Shi,** NP Photonics, Inc. (United States)
**Ramesh Shori,** Naval Air Warfare Center Weapons Division (United States)

*Session Chairs*

1 Visible Lasers I: Joint Session with Conference 7912
**W. Andrew Clarkson,** University of Southampton (United Kingdom)
**Andrei V. Shchegrov,** Spectralus Corporation (United States)

2 Visible Lasers II: Joint Session with Conference 7912
**Wolf R. Seelert,** Coherent Lübeck GmbH (Germany)

3 Visible and UV Lasers
**Darrell J. Armstrong,** Sandia National Laboratories (United States)

4 Terahertz Generation I
**Wei Shi,** NP Photonics, Inc. (United States)

5 Terahertz Generation II
**Peter P. Günter,** ETH Zürich (Switzerland)

6 Optical Parametric Devices I
**Pinhas Blau,** Soreq Nuclear Research Center (Israel)

7 Ultrafast Nonlinear Devices and Applications
**Darrell J. Armstrong,** Sandia National Laboratories (United States)

8 Nonlinear Fiber Devices and Applications
**Baldemar Ibarra-Escamilla,** Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

9 Optical Parametric Devices II
**Peter E. Powers,** University of Dayton (United States)

10 Mid-IR frequency Combs and Applications
**Konstantin L. Vodopyanov,** Stanford University (United States)

11 Nonlinear Materials and Characterization I
**Peter G. Schunemann,** BAE Systems (United States)

12 Nonlinear Materials and Characterization II
**Rita D. Peterson,** Air Force Research Laboratory (United States)

# Introduction

The span of electromagnetic frequencies, which can be achieved by means of nonlinear optics is impressive—more than four orders of magnitude: from the UV to THz—and this is reflected by a remarkable variety of current achievements in nonlinear optics presented in this volume.

In the realm of visible and UV generation, most hot topics are producing green, yellow and red colors by frequency conversion of the radiation of semiconductor lasers, the latter being known as efficient and inexpensive sources of near-infrared photons. For example, multi-watt orange light was generated by intracavity frequency doubling in a dual-gain quantum dot semiconductor disk laser (paper [7917-1]) and 1 Watt at 531 nm was generated in a ppMgO:LN planar waveguide by means of frequency doubling of a distributed Bragg reflector (DBR) tapered diode laser [7917-2]. Also, fiber-laser-pumped CW optical parametric oscillator (OPO) was shown to produce red, green, and blue laser light–all in one device [7917-5]. Vacuum UV light was produced at 193 nm by frequency conversion in quasi-phase-matched crystalline quartz that utilizes stress-induced twinning [7917-8].

On the other end of the spectrum, intense ultra-broadband (0.1 to 140 THz) terahertz waves with the field amplitude exceeding 100 MV/cm were produced via optical method using a hybrid Er:fiber-Ti:sapphire laser system. These pulses might be suitable for sub-cycle nonlinear optics [7917-11]. It has been demonstrated that ionized air plasma can be used as an emitter and a sensor for both generation and detection of broadband THz waves. In the case of THz generation, intense THz waves (peak THz field > 1.5 MV/cm) with a broadband spectrum, from 0.1 THz to 46 THz, were produced [7917-15]. Ultrasensitive room-temperature THz detection using parametric up conversion with a pulsed 1550-nm optical source was described in paper [7917-36].

In the field of ultrafast nonlinear devices, "light bullets" - Airy-Bessel wave packets which can be regarded as three-dimensionally localized light waves that do not spread in time or space as they propagate were reported and their applications highlighted [7917-26].

A new approach for generating ultra-broadband mid-infrared frequency combs in the difficult-to-access mid-infrared spectral region was implemented, based on degenerate (frequency-divide-by-two) optical parametric oscillation. This technique efficiently transfers the desirable properties of shorter wavelength mode-locked sources to the mid-infrared [7917-43].

As for new nonlinear optical materials, mid-infrared photonics based on silicon waveguides has been proposed. Low-loss (~4 dB/cm) waveguides appear to be suitable for microresonators operating at wavelengths around 5.5 μm, which can be used for sensing and nonlinear optics [7917-46]. In another paper, a new mixed LiGaInSe nonlinear optical crystal for the mid-IR was reported [7917-56]. Future directions in quasi-phase matched (QPM) semiconductors for mid-infrared lasers were highlighted and the properties, processing, and performance of orientation patterned GaAs (as a typical example of semiconductor QPM material) were compared to those of the next generation materials. In particular, gallium phosphide (GaP) was identified as the most promising material for near-term development [7917-50].

In short, the future of nonlinear optics looks bright. Laser outputs are converted to new wavelengths, from vacuum UV (or even XUV) to THz and sub-THz with time formats varying from continuous-wave operation to attosecond pulse regimes.

**Konstantin L. Vodopyanov**