

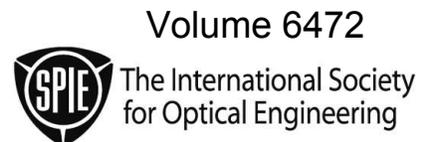
PROCEEDINGS OF SPIE

# ***Terahertz and Gigahertz Electronics and Photonics VI***

**Kurt J. Linden**  
**Laurence P. Sadwick**  
*Chairs/Editors*

**21–22 January 2007**  
**San Jose, California, USA**

*Sponsored and Published by*  
SPIE—The International Society for Optical Engineering



Proceedings of SPIE—The International Society for Optical Engineering, 9780819465856, v. 6472

SPIE is an international technical society dedicated to advancing engineering and scientific applications of optical, photonic, imaging, electronic, and optoelectronic technologies.

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 *Terahertz and Gigahertz Electronics and Photonics VI*, edited by Kurt J. Linden, Laurence P. Sadwick, Proceedings of SPIE Vol. 6472 (SPIE, Bellingham, WA, 2007) Article CID Number.

ISSN 0277-786X  
ISBN 9780819465856

Published by  
**SPIE—The International Society for Optical Engineering**  
P.O. Box 10, Bellingham, Washington 98227-0010 USA  
Telephone 1 360/676-3290 (Pacific Time) · Fax 1 360/647-1445  
<http://www.spie.org>

Copyright © 2007, The 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 <http://www.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/07/\$18.00.

Printed in the United States of America.

# Contents

v	Conference Committee
vii	Introduction

---

## SESSION 1 HIGH-FREQUENCY MATERIALS AND PHYSICS

---

- 647202 **The quasi-optical performance of CMB astronomical telescopes** [6472-01]  
C. O'Sullivan, J. A. Murphy, V. Yurchenko, G. Cahill, National Univ. of Ireland/Maynooth (Ireland); G. Curran, National Univ. of Ireland/Maynooth (Ireland) and Institute of Technology Blanchardstown (Ireland); M. Gradziel, J. Lavelle, F. Noviello, National Univ. of Ireland/Maynooth (Ireland)
- 647203 **Studies of the critical electric field and L valley offset of a semiconductor characterized by terahertz radiation** [6472-02]  
J. S. Hwang, H. C. Lin, C. K. Chang, T. S. Wang, K. I. Lin, L. S. Chang, Y. T. Lu, National Cheng Kung Univ. (Taiwan)
- 647206 **Artificial plasmonic materials for THz applications** [6472-05]  
A. J. Gallant, J. A. Levitt, M. Kaliteevski, D. Wood, M. C. Petty, R. A. Abram, S. Brand, G. P. Swift, D. A. Zeze, J. M. Chamberlain, Durham Univ. (United Kingdom)

---

## SESSION 2 WAVEGUIDES, BEAMS, AND MODELING

---

- 647208 **Sub-wavelength THz plastic fibers (Invited Paper)** [6472-07]  
J.-Y. Lu, H.-W. Chen, L.-J. Chen, C.-K. Sun, National Taiwan Univ. (Taiwan)
- 64720A **Electromagnetic scattering calculations for terahertz sensing** [6472-09]  
L. M. Zurk, B. Orlowski, G. Sundberg, Portland State Univ. (USA); D. P. Winebrenner, E. I. Thorsos, A. Chen, Univ. of Washington (USA)

---

**Pagination:** 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.

- 64720B **Analysis of standing waves in submillimeter-wave optics** [6472-10]  
N. Trappe, S. Kehoe, E. Butler, J. A. Murphy, T. Finn, National Univ. of Ireland/Maynooth (Ireland); S. Withington, Cavendish Lab. (United Kingdom);  
W. Jellema, Space Research Organisation Netherlands (Netherlands)
- 64720C **Analysis of millimeter-wave imaging and detection** [6472-11]  
W. Lanigan, E. Butler, E. Duffy, I. Mc Auley, L. Young, M. Gradziel, C. O'Sullivan, J. A. Murphy, R. May, N. Trappe, National Univ. of Ireland/Maynooth (Ireland)
- 64720D **Modelling of the optical performance of millimeter-wave instruments in MODAL** [6472-12]  
M. L. Gradziel, C. O'Sullivan, J. A. Murphy, G. Cahill, National Univ. of Ireland/Maynooth (Ireland); G. S. Curran, Institute of Technology Blanchardstown (Ireland); C. Pryke, Univ. of Chicago (USA); W. Gear, Univ. of Wales, Cardiff (United Kingdom); S. Church, Stanford Univ. (USA)
- 64720E **Scanning Fabry-Perot filter for terahertz spectroscopy based on silicon dielectric mirrors** [6472-13]  
J. W. Cleary, C. J. Fredricksen, A. V. Muravjov, J. Enz, M. V. Dolguikh, T. W. Du Bosq, R. E. Peale, Univ. of Central Florida (USA); W. R. Folks, S. Pandey, G. Boreman, CREOL, Univ. of Central Florida (USA); O. Edwards, Zyberwear Inc. (USA)

---

### SESSION 3 TERAHERTZ EMITTERS AND DETECTORS

---

- 64720F **Terahertz science and applications based on poled electro-optic polymers** [6472-14]  
X. Zheng, C. V. McLaughlin, P. Cunningham, L. M. Hayden, Univ. of Maryland/Baltimore County (USA)
- 64720H **Widely tuneable ultra stable 1W two color THz laser source** [6472-17]  
S. Stry, J. R. Sacher, Sacher Lasertechnik GmbH (Germany)

---

### SESSION 4 TERAHERTZ DETECTION AND IMAGING SYSTEMS

---

- 64720K **Electro-optic polymer modulators as passive mm wave detectors** [6472-20]  
M. R. Fetterman, J. A. Grata, Penn State Electro-Optics Ctr. (USA); R. Dinu, M. Koenig, Lumera Corp. (USA); A. D. Visnansky, W. L. Kiser, Jr., Penn State Electro-Optics Ctr. (USA)
- 64720M **High-speed LiNbO<sub>3</sub> modulator for W-band millimeter-wave detection** [6472-22]  
C. J. Huang, C. A. Schuetz, R. Shireen, S. Shi, D. W. Prather, Univ. of Delaware (USA)
- 64720N **Terahertz imaging of burned tissue** [6472-23]  
J. P. Dougherty, G. D. Jubic, W. L. Kiser, Jr., Penn State Electro-Optics Ctr. (USA)
- 64720O **Terahertz micro-spectroscopy using a transient mirror technique** [6472-24]  
J. A. Levitt, A. J. Gallant, G. P. Swift, D. C. Dai, J. M. Chamberlain, Durham Univ. (United Kingdom)

*Author Index*

# Conference Committee

## *Symposium Chair*

**Yakov Sidorin**, Photineer Technology Group (USA)

## *Symposium Cochair*

**Ali Adibi**, Georgia Institute of Technology (USA)

## *Program Track Chair*

**James G. Grote**, U.S. Air Force Research Laboratory (USA)

## *Conference Chairs*

**Kurt J. Linden**, Spire Corporation (USA)

**Laurence P. Sadwick**, InnoSys, Inc. (USA)

## *Program Committee*

**Antao Chen**, University of Washington (USA)

**Alexander G. Davies**, University of Leeds (United Kingdom)

**R. Jennifer Hwu**, InnoSys, Inc. (USA)

**Michael C. Kemp**, Iconal Technology (United Kingdom)

**Edmund H. Linfield**, University of Leeds (United Kingdom)

**John A. Murphy**, National University of Ireland/Maynooth (Ireland)

## *Session Chairs*

- 1 High-Frequency Materials and Physics  
**Kurt J. Linden**, Spire Corporation (USA)
- 2 Waveguides, Beams, and Modeling  
**Créidhe M. O'Sullivan**, National University of Ireland/Maynooth (Ireland)
- 3 Terahertz Emitters and Detectors  
**Antao Chen**, University of Washington (USA)
- 4 Terahertz Detection and Imaging Systems  
**Lawrence P. Sadwick**, InnoSys, Inc. (USA)



# Introduction

Terahertz and gigahertz electronics and photonics continue to make significant materials, device, and system development advances. This past year witnessed further advancements in modeling as well as demonstrations of improved device and system performance, as highlighted in this conference.

The proceedings from conference 6472 includes papers covering subjects that are arranged in four categories containing the following subjects:

(1) **High-Frequency Materials and Physics:** This session includes papers dealing with the performance of the cosmic microwave background telescope, studies of critical electric field and band offsets in semiconductors by use of terahertz radiation, as well as the theory of optical to terahertz conversion in non-linear materials. The session also features a theoretical and experimental article on artificially structured plasmonic materials (using micromachined pillars) for terahertz and gigahertz applications, in tune with the rapidly growing area of metamaterials.

(2) **Waveguides, Beams, and Modeling:** This session includes an invited paper reviewing the use of plastic fibers for terahertz waveguide applications. This session also deals with analytical modeling, and includes papers on electromagnetic scattering calculations for use in terahertz sensors, standing wave analysis in submillimeter optics — a problem that every experimenter working in the terahertz spectral region has encountered, Gaussian beam mode analysis in millimeter wave imaging and detection, high-finesse scanning Fabry-Perot filters for terahertz and gigahertz spectroscopy, and modeling of optical performance of millimeter wave instruments.

(3) **Terahertz Emitters and Detectors:** In this session, a widely tunable terahertz laser source using frequency mixing is presented, photoconductive antennas excited at telecommunication source wavelengths are presented, and terahertz applications of poled electro-optic polymers are reviewed.

(4) **Terahertz Detection and Imaging Systems:** This session includes papers on terahertz imaging of burn tissue through bandages, terahertz spectroscopy using transient mirror techniques, and high-speed modulators for millimeter wave detection and spectroscopy.

The general area of terahertz technology is still very much under development, and only limited options exist for sources, detectors, and imaging in general. For the reader's benefit, we here include a representative summary of currently used terahertz radiation sources and terahertz radiation detectors arranged in tabular form.

Table 1. Summary of the more common terahertz radiation sources. The top four entries are traveling electron sources, the fifth entry is a gas source laser with remarkably broad spectral coverage depending on the choice of gas, while the other entries are solid-state sources.

Terahertz radiation sources		
THz source type	Details	Characteristics
<b>Synchrotron</b>	* Coherent synchrotron produces very high photon flux, including THz region	E-beam, very broadband source, limited instrument availability, very large size
<b>Free electron laser</b>	* Benchtop design at Univ. Essex, UK Elec beam moves over alternate H-field regions	Tunable over entire THz region, under development 0.1 - 4.8 THz, 0.5 - 5 kW, 1 - 20 us pulses at 1 Hz
<b>Smith-Purcell emitters</b>	* E-beam travels over metal grating surface,	
<b>Backward-wave oscillators</b>	* Vacuum tube, requires homog H-field~10 kG "Carcinotron", room temperature, to 1.2 THz	Tunable output possible. Under development and commercially available, 10 mW power level, <1 THz
<b>Optically pumped gas cell laser</b>	* Grating-tuned CO <sub>2</sub> laser and far-IR gas cell such as methane. Most mature laser.	> 100 mW, 0.3-10 THz, discrete lines, CW/pulsed Commercially avail - Coherent (\$400K - \$1M)
<b>Opt pump GaAs, p-InAs, Si, ZnTe, InGaAs (fiber laser pump)</b>	* Mode locked Nd:YAG or Ti:sapphire laser creates short across biased spiral antenna gap * Also As-doped Si, CO <sub>2</sub> laser pump	Imaging apparatus produced, 0.1 to 3 THz Commercially available, CW uW range, \$50K-500K 6 THz stim emission from As, Liq He temp.
<b>Photomixing of near-IR lasers</b>	* Mixing tunable Ti-sapphire laser and diode laser in LT-grown GaAs photomixer. * GaSe crystal, Nd:YAG/OPO difference freq * Single 835 nm diode laser, external cavity	Tens of nW, tunable. Requires antenna pattern Not commercial. GaP gave 480 mW @ 1.3 THz Tunable 58-3540um (5-0.1THz), 209 W pulse 1.5THz 2-freq mix& 4-wave mixing, RT, sub-nW, 0.3-4.2THz
<b>Electrically pumped Ge</b>	* Electric field injects electrons, magnetic field splits hole levels for low-E transitions	Requires electric and magnetic fields Output up to hundreds of mW, cryogenic cooling
<b>Electrically pumped Si:B or As</b>	* Transitions between impurity levels 100 x 200 um rectangle mesas, biased	31 uW output at 8.1 THz, slightly polarized Cryogenic cooling needed
<b>Direct multiplied mm waves</b>	* Multiplied to low-THz region	Low power (uW level), available (VA Diodes) Used for heterodyne local oscillators in astronomy
<b>Parametric generators</b>	* Q-switched Nd:YAG pumps MgO:LiNbO <sub>3</sub> non-linear crystal	High pulsed power, room temperature Commercially available ~ \$30K
<b>Quantum cascade (QC) laser</b>	* First announced in 2002, semiconductor, AlGaAs/GaAs-based, MBE grown, 2 to 4 THz	Operated at mW power, and up to 164K pulsed Not commercially available, require cryo-cooling
<b>Transistor</b>	* InGaAs channel HEMT with 60 nm gate * InGaAs with 12.5 nm gate, 0.845 THz	Under development at Inst. Elec. Micro, Lille Univ. Illinois (Dec. 2006)

Table 2. Summary of the more common terahertz radiation detector types.

THz detector type	Details	Characteristics
<b>Si bolometer</b>	* Most sensitive (10 pW Hz <sup>1/2</sup> ) THz detector at liquid He temp., slow response time	Responsivity 2E9V/W, NEP=1E-17 W/Hz <sup>1/2</sup> , 100 mK Requires liquid He dewar, commercially avail.
<b>Superconducting hot elec bolom</b>	* Highest sensitivity Fast (1 us) response time	Requires cooling to 0.3 K, NEP=1E-17 W/Hz <sup>1/2</sup> Commercially available, expensive, bulky
<b>Pyroelectric detectors</b>	* Slow response t, 220 nW sensitiv at 24 Hz Requires pulsed signals or mechanical chopper	Room temp operation, commercially available, Low cost, imagers available ~ \$10K
<b>Schottky diodes</b>	* ~ 1 THz cutoff frequency Fast response, but low THz sensitivity	Commercially available (V/A Diodes) with corner ref. Room temp operation, good for mixers
<b>PC dipole antennas</b>	* signal gen across biased spiral antenna gap Short pulsed detection only	Analogous to optically pumped THz PC switch but in detection mode. Commercially available
<b>Antenna coupled inter-subband</b>	* 4-terminal phototransistor, 1.6 THz	Under development UCSB
<b>AlGaAs, InGaAs, &amp; Si FET to 300K</b>	* HEMT with 250 nm gate plasma wave-based detection	Cryo and room temperature Univ research, Si NEP to 1E-10 W/Hz <sup>1/2</sup> at 300 K
<b>Quantum dot photon detector</b>	* Demo-photon counting terahertz microscopy imaging, requires 0.3 K temp, research only	Under development, 1E-19 W = 100 photons/sec, Tokyo Univ.

Inevitably this summary is not all-inclusive. It is intended to present most of the commonly used terahertz source and detection components, representative features, advantages, disadvantages, relative performance, cost, and availability. As developments continue in this active field, we would like to update these tables on an ongoing basis, and suggestions for any additions or modifications to this list would be greatly appreciated, and can be sent to [klinden@spirecorp.com](mailto:klinden@spirecorp.com).

In summary, this sixth conference on terahertz and gigahertz electronics and photonics demonstrates continued progress in both modeling and experimental demonstration areas, and touches on the rapidly evolving field of metamaterials for use in terahertz optics.

For individuals who wish to obtain a broader technical background in and deeper understanding of terahertz and gigahertz technologies, some representative review articles, including an article dealing with the rapidly evolving field of metamaterials, are listed in chronological order:

D.M. Mittlemen, R.H. Jacobson and M.C. Nuss, "T-Ray Imaging," IEEE J. Sel. Topics in QE **2**, 679-692 (1996).

P.H. Siegel, "Terahertz Technology," IEEE Trans. MTT **50**, 910-928 (2002).

D.L. Woolard, E.R. Brown, M. Pepper, and M. Kemp, "Terahertz Frequency Sensing and Imaging: A Time of Reckoning Future Applications?" Proc. IEEE **93**, 1722-1743 (2005).

C. Caloz and T. Itoh, "Metamaterials for High-Frequency Electronics," Proc. IEEE **93**, 1744-1752 (2005).

**Kurt J. Linden**  
**Laurence P. Sadwick**