PROCEEDINGS OF SPIE

SPIDigitalLibrary.org/conference-proceedings-of-spie

Front Matter Volume 8624

, "Front Matter Volume 8624," Proc. SPIE 8624, Terahertz, RF, Millimeter, and
Submillimeter-Wave Technology and Applications VI, 862401 (8 April 2013);
doi: 10.1117/12.2022480

SPIE.

Event: SPIE OPTO, 2013, San Francisco, California, United States

PROCEEDINGS OF SPIE

Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VI

**Laurence P. Sadwick
Créidhe M. O'Sullivan**
Editors

**5–7 February 2013
San Francisco, California, United States**

Sponsored and Published by
SPIE

Volume 8624

Proceedings of SPIE 0277-786X, V.8624

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

Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VI, edited by Laurence P. Sadwick,
Créidhe M. O'Sullivan, Proc. of SPIE Vol. 8624, 862401 · © 2013 SPIE · CCC code: 0277-786X/13/\$18
doi: 10.1117/12.2022480

Proc. of SPIE Vol. 8624 862401-1

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, RF, Millimeter, and Submillimeter-Wave Technology and Applications VI*, edited by Laurence P. Sadwick, Crdhe M. O'Sullivan, Proceedings of SPIE Vol. 8624 (SPIE, Bellingham, WA, 2013) Article CID Number.

ISSN: 0277-786X

ISBN: 9780819493934

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 © 2013, 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/13/\$18.00.

Printed in the United States of America.

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

SPIDigitalLibrary.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

ix	Conference Committee
xi	Introduction
xvii	Group IV photonics for the mid infrared (Plenary Paper) [8629-1] R. Soref, The Univ. of Massachusetts at Boston (United States)
xxxiii	Light in a twist: optical angular momentum (Plenary Paper) [8637-2] M. J. Padgett, Univ. of Glasgow (United Kingdom)

THZ TOPICS AND ADVANCEMENTS

8624 03	Active THz medical imaging using broadband direct detection (Invited Paper) [8624-2] Z. D. Taylor, J. Garritano, P. Tewari, E. Diebold, S. Sung, N. Bajwa, B. Nowroozi, Univ. of California, Los Angeles (United States); A. Stojadinovic, Walter Reed Army Medical Ctr. (United States) and Combat Wound Initiative Program (United States); N. Llombart, Wright State Univ. (United States); E. R. Brown, Technische Univ. Delft (Netherlands); W. S. Grundfest, Univ. of California, Los Angeles (United States)
---------	---

THZ AND SUBMILLIMETER GENERATION AND SOURCES

8624 06	Microfabrication and cold testing of copper circuits for a 50-watt 220-GHz traveling wave tube (Invited Paper) [8624-5] C. D. Joye, A. M. Cook, J. P. Calame, D. K. Abe, A. N. Vlasov, I. A. Chernyavskiy, U.S. Naval Research Lab. (United States); K. T. Nguyen, E. L. Wright, Beam-Wave Research, Inc. (United States)
8624 07	A tunable continuous-wave terahertz generator based on 1.3-μm dual-mode laser diode and travelling-wave photodiode [8624-6] H.-C. Ryu, N. Kim, J.-W. Park, S.-P. Han, H. Ko, K. Moon, Electronics and Telecommunications Research Institute (Korea, Republic of); M. Y. Jeon, Chungnam National Univ. (Korea, Republic of); K. H. Park, Electronics and Telecommunications Research Institute (Korea, Republic of)
8624 08	Sub-mm/THz wave generation/amplification using Cerenkov-transition based device [8624-7] A. I. Nashed, S. K. Chaudhuri, S. Safavi-Naeini, Univ. of Waterloo (Canada)
8624 09	Room temperature generation of THz radiation in GaN quantum wells structures [8624-8] A. Penot, J. Torres, P. Nouvel, L. Varani, Institut d'Electronique du Sud, Univ. Montpellier 2 (France); F. Teppe, C. Consejo, N. Dyakonova, W. Knap, Lab. Charles Coluomb, Univ. Montpellier 2 (France); Y. Cordier, S. Chenot, M. Chmielowska, Ctr. de Recherche sur l'Hétéro-Epitaxie et ses Applications (France); J.-P. Faurie, B. Beaumont, Lumilog (France); P. Shiktorov, E. Starikov, V. Gruzinskis, Semiconductor Physics Institute (Lithuania)

THZ SMART MATERIALS AND IMAGING

- 8624 0B **Precise manipulation of light properties in optical domain by RF technology (Invited Paper)** [8624-49]
T. Yang, Z. Zhang, T. Wang, Z. Wang, Z. Wang, C. Ge, D. Jia, M. Sang, Tianjin Univ. (China)
- 8624 0C **Terahertz time-domain spectroscopy of organic semiconductors** [8624-11]
D. M. Hailu, H. Aziz, S. Safavi-Naeini, Univ. of Waterloo (Canada); D. Saeedkia, TeTechS Inc. (Canada)
- 8624 0D **3D terahertz beam profiling** [8624-12]
P. Klarskov, A. C. Strikwerda, T. Wang, M. Zalkovskij, P. U. Jepsen, Technical Univ. of Denmark (Denmark)
- 8624 0E **Imaging at 0.2 and 2.5 terahertz** [8624-13]
A. M. Melo, BR Labs. (Brazil); M. A. P. Toledo, Univ. Estadual de Campinas (Brazil); F. C. B. Maia, A. Rocha, M. B. Plotegher, BR Labs. (Brazil); D. Pereira, F. C. Cruz, Univ. Estadual de Campinas (Brazil)
- 8624 0F **Introducing a 384x288 pixel terahertz camera core** [8624-14]
C. Chevalier, L. Mercier, F. Duchesne, L. Gagnon, B. Tremblay, M. Terroux, F. Génèreux, J.-E. Paultre, F. Provençal, Y. Desroches, L. Marchese, H. Jerominek, C. Alain, A. Bergeron, INO (Canada)

RF DEVICES, SOURCES, AND COMPONENTS

- 8624 0H **Millimeter-wave and sub-millimeter-wave vacuum electronics amplifier development at the US Naval Research Laboratory (Invited Paper)** [8624-16]
D. K. Abe, J. P. Calame, C. D. Joye, A. M. Cook, J. A. Pasour, S. Cooke, A. N. Vlasov, I. A. Chernyavskiy, B. Levush, U.S. Naval Research Lab. (United States); K. T. Nguyen, D. E. Pershing, Beam-Wave Research, Inc. (United States); D. Chernin, SAIC (United States)
- 8624 0I **Integrated RF photonic devices based on crystal ion sliced lithium niobate** [8624-17]
V. Stenger, J. Toney, A. Pollick, J. Busch, J. Scholl, P. Pontius, S. Sriram, SRICO Inc. (United States)
- 8624 0J **IMDD microwave photonic link modeling using Optsim** [8624-18]
J. Haefner, T. Copenhaver II, J. Kurka, J. West, M. Maurer, C. Middlebrook, Michigan Technological Univ. (United States)
- 8624 0K **Toward a widely tunable narrow linewidth RF source utilizing an integrated heterogenous silicon photonic module** [8624-19]
D. W. Grund Jr., G. A. Ejzak, G. J. Schneider, J. Murakowski, S. Shi, D. W. Prather, The Univ. of Delaware (United States)

CONTINUOUS WAVE SOURCES, DEVICES, TECHNIQUES, AND TECHNOLOGY

- 8624 0L **Towards integrated continuous wave THz systems** [8624-20]
T. Göbel, D. Stanze, U. Troppenz, J. Kreissl, B. Sartorius, M. Schell, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)
- 8624 0M **Widely tunable opto-electronic oscillator based on a dual frequency laser** [8624-21]
J. Maxin, Thales Research and Technology (France); K. Saleh, Lab. d'Analyse et d'Architecture des Systèmes, CNRS, Univ. de Toulouse (France); G. Pillet, L. Morvan, Thales Research and Technology (France); O. Llopis, Lab. d'Analyse et d'Architecture des Systèmes, CNRS, Univ. de Toulouse (France); D. Dolfi, Thales Research and Technology (France)
- 8624 0O **Continuous wave terahertz reflection imaging of human colorectal tissue** [8624-23]
P. Doradla, The Univ. of Massachusetts Lowell (United States); K. Alavi, The Univ. of Massachusetts Medical School (United States); C. S. Joseph, R. H. Giles, The Univ. of Massachusetts Lowell (United States)

THZ AND MM-WAVE CONDUCTIVITY, DETECTORS, RELATED MEASUREMENTS, AND TECHNIQUES

- 8624 0Q **Millimeter and terahertz detectors based on plasmon excitation in InGaAs/InP HEMT devices** [8624-25]
N. Nader Esfahani, Univ. of Central Florida (United States) and Solid State Scientific Corp. (United States); R. E. Peale, Univ. of Central Florida (United States); W. R. Buchwald, Solid State Scientific Corp. (United States) and Univ. of Massachusetts Boston (United States); J. R. Hendrickson, J. W. Cleary, Air Force Research Lab. (United States)
- 8624 0T **Frequency, amplitude, and phase measurements of GHz and THz sources using unstabilized THz frequency combs** [8624-28]
H. Füsler, M. Bieler, Physikalisch-Technische Bundesanstalt (Germany)

RF TO THZ MATERIALS, TECHNIQUES, TECHNOLOGY AND SOURCES, DETECTION AND DEVICES I

- 8624 0U **Fabrication and characterization of suspended graphene membranes for miniature Golay cells (Invited Paper)** [8624-29]
E. Ledwosinska, McGill Univ. (Canada); A. Guermoune, M. Sijj, Univ. du Québec à Montréal (Canada) and Univ. Laval (Canada); T. Szkopek, McGill Univ. (Canada) and Univ. de Montréal (Canada)
- 8624 0V **Design and fabrication of an RF GRIN lens using 3D printing technology** [8624-30]
J. W. Allen, B.-I. Wu, Air Force Research Lab. (United States)
- 8624 0W **An FBG sensor interrogation technique based on a precise optical recirculating frequency shifter driven by RF signals** [8624-31]
Z. Wang, T. Yang, D. Jia, Z. Wang, M. Sang, Tianjin Univ. (China)

- 8624 0Y **Progress towards dual vertical slot modulator for millimeter wave photonics** [8624-33]
S. T. Kozacik, M. Murakowski, M. Konkol, S. Addya, D. L. K. Eng, B. C. Olbricht, M. J. Zablocki, The Univ. of Delaware (United States); A. Sharkawy, EM Photonics, Inc. (United States); J. Murakowski, S. Shi, D. W. Prather, The Univ. of Delaware (United States)
- 8624 0Z **Flat pulse-amplitude rational-harmonic-mode-locking fiber lasers with GHz pulse repetition rates** [8624-34]
T. Wang, T. Yang, D. Jia, Z. Wang, M. Sang, Tianjin Univ. (China); N. Bai, G. Li, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

METAMATERIALS AND RELATED MATERIALS

- 8624 10 **Metamaterial films as narrowband terahertz emitters** [8624-35]
B. Kearney, F. Alves, D. Grbovic, G. Karunasiri, Naval Postgraduate School (United States)
- 8624 11 **High sensitivity metamaterial based bi-material terahertz sensor** [8624-36]
F. Alves, D. Grbovic, B. Kearney, G. Karunasiri, Naval Postgraduate School (United States)
- 8624 12 **Numerical simulation of terahertz plasmons in gated graphene structures** [8624-37]
A. Satou, V. Ryzhii, Tohoku Univ. (Japan); F. T. Vasko, V. V. Mitin, Univ. at Buffalo (United States); T. Otsuji, Tohoku Univ. (Japan)

RF TO THZ TRANSMISSION, SENSORS, SOURCES, AND DETECTION

- 8624 13 **Efficient horn antennas for next-generation terahertz and millimeter-wave space telescopes** [8624-39]
D. McCarthy, N. Trappe, A. Murphy, C. Bracken, S. Doherty, M. L. Gradziel, C. O'Sullivan, National Univ. of Ireland, Maynooth (Ireland)
- 8624 14 **Low-loss waveguides for THz guidance and devices** [8624-40]
B. M. A. Rahman, C. Themistos, H. Tanvir, M. Uthman, A. Quadir, C. Markides, City Univ. London (United Kingdom)
- 8624 15 **Ultra-broadband wavelength conversion sensor using thermochromic liquid crystals** [8624-41]
I. A. Chen, North Carolina State Univ. (United States); S. W. Park, G. Chen, C. Wang, Stevens Institute of Technology (United States); C. Bethea, Quantum Technology Consultants Inc. (United States); R. Martini, Stevens Institute of Technology (United States); D. Woolard, North Carolina State Univ. (United States)

- 8624 16 **Antenna-coupled heterostructure field effect transistors for integrated terahertz heterodyne mixers** [8624-42]
A. Di Gaspere, Istituto di Fotonica e Nanotecnologie, CNR (Italy); V. Giliberti, Istituto di Fotonica e Nanotecnologie, CNR (Italy) and Univ. degli Studi di Roma La Sapienza (Italy); R. Casini, E. Giovine, Istituto di Fotonica e Nanotecnologie, CNR (Italy); F. Evangelisti, Univ. degli Studi di Roma Tre (Italy); D. Coquillat, Lab. Charles Coulomb, CNRS, Univ. Montpellier 2 (France); W. Knap, Institute of High Pressure Physics (Poland); S. Sadofev, R. Calarco, Paul-Drude-Institut für Festkörperelektronik (Germany); M. Dispenza, C. Lanzieri, Selex Sistemi Integrati S.p.A. (Italy); M. Ortolani, Istituto di Fotonica e Nanotecnologie, CNR (Italy) and Univ. degli Studi di Roma La Sapienza (Italy)
- 8624 17 **Realization of an ultra-broadband voltage pulse standard utilizing time-domain optoelectronic techniques** [8624-43]
M. Bieler, H. Füsler, Physikalisch-Technische Bundesanstalt (Germany)

RF TO THZ MATERIALS, TECHNIQUES, TECHNOLOGY AND SOURCES, DETECTION AND DEVICES II

- 8624 18 **Electric field sensor based on electro-optic polymer refilled silicon slot photonic crystal waveguide coupled with bowtie antenna** [8624-44]
X. Zhang, The Univ. of Texas at Austin (United States); A. Hosseini, Omega Optics, Inc. (United States); X. Xu, The Univ. of Texas at Austin (United States); S. Wang, Q. Zhan, The Univ. of Dayton (United States); Y. Zou, The Univ. of Texas at Austin (United States); S. Chakravarty, Omega Optics, Inc. (United States); R. T. Chen, The Univ. of Texas at Austin (United States)
- 8624 19 **Technological customization of uncooled amorphous silicon microbolometer for THz real time imaging** [8624-45]
S. Pocas, E. Deronzier, P. Brianceau, P. Imperinetti, G. Dumont, A. Roule, W. Rabaud, J. Meilhan, F. Simoens, V. Goudon, C. Vialle, A. Arnaud, CEA-LETI-Minatec (France)

POSTER SESSION

- 8624 1C **Tunable THz wave transmission using liquid metal based devices** [8624-48]
R. Zhou, J. Cheng, Y. Lin, H. Zhang, Univ. of North Texas (United States)

Author Index

Conference Committee

Symposium Chair

David L. Andrews, University of East Anglia Norwich (United Kingdom)

Symposium Cochairs

Alexei I. Glebov, OptiGrate Corporation (United States)

Klaus P. Streubel, OSRAM GmbH (Germany)

Program Track Chair

James G. Grote, Air Force Research Laboratory (United States)

Conference Chairs

Laurence P. Sadwick, InnoSys, Inc. (United States)

Créidhe M. O'Sullivan, National University of Ireland, Maynooth (Ireland)

Conference Program Committee

Antao Chen, University of Washington (United States)

Robert H. Giles, University of Massachusetts Lowell (United States)

R. Jennifer Hwu, InnoSys, Inc. (United States)

Anthony Murphy, National University of Ireland, Maynooth (Ireland)

Michael C. Wanke, Sandia National Laboratories (United States)

Tianxin Yang, Tianjin University (China)

Session Chairs

- 1 Silicon Photonics Meets EO-Polymers: Joint Keynote Session with Conferences 8622, 8624, and 8629
Robert A. Norwood, College of Optical Sciences, The University of Arizona (United States)
- 2 THz Topics and Advancements
Tianxin Yang, Tianjin University (China)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 3 THz and Submillimeter Generation and Sources
Robert H. Giles, University of Massachusetts Lowell (United States)
Laurence P. Sadwick, InnoSys, Inc. (United States)

- 4 THz Smart Materials and Imaging
Darragh McCarthy, National University of Ireland, Maynooth (Ireland)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 5 RF Devices, Sources, and Components
Tianxin Yang, Tianjin University (China)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 6 Continuous Wave Sources, Devices, Techniques, and Technology
Robert H. Giles, University of Massachusetts Lowell (United States)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 7 THz and MM-Wave Conductivity, Detectors, Related Measurements, and Techniques
R. Jennifer Hwu, InnoSys, Inc. (United States)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 8 RF to THz Materials, Techniques, Technology and Sources, Detection and Devices I
Antao Chen, University of Washington (United States)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 9 Metamaterials and Related Materials
Tianxin Yang, Tianjin University (China)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 10 RF to THz Transmission, Sensors, Sources, and Detection
Michael C. Wanke, Sandia National Laboratories (United States)
Laurence P. Sadwick, InnoSys, Inc. (United States)
- 11 RF to THz Materials, Techniques, Technology and Sources, Detection and Devices II
Darragh McCarthy, National University of Ireland, Maynooth (Ireland)
Laurence P. Sadwick, InnoSys, Inc. (United States)

Introduction

The 2013 Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VI Conference was divided into eleven sessions reflecting specific categories as follows; Session 1—Silicon Photonics Meets EO-Polymers: Joint Keynote Session with Conferences 8622, 8624, and 8629; Session 2—THz Topics and Advancements; Session 3—THz and Submillimeter Generation and Sources; Session 4—THz Smart Materials and Imaging; Session 5—RF Devices, Sources, and Components; Session 6—Continuous Wave Sources, Devices, Techniques, and Technology; Session 7—THz and MM-Wave Conductivity, Detectors, Related Measurements, and Techniques; Session 8—RF to THz Materials, Techniques, Technology and Sources, Detection and Devices I; Session 9—Metamaterials and Related Materials; Session 10—RF to THz Transmission, Sensors, Sources, and Detection; and Session 11—RF to THz Materials, Techniques, Technology and Sources, Detection and Devices II.

Session 1 was a joint session on photonic circuits, organic and plastic photocells and other optoelectronic devices.

Session 2 began with an invited talk by Professor Elliott Brown covering a powerful new THz photoconductive source driven at 1550 nm, followed by an invited talk by Dr. Zachary Taylor on THz imaging using broadband direct detection and a contributed talk on strong optical forces in the mid-IR and terahertz mediated by coupled spoof surface plasmons.

Session 3 began with an invited paper on the microfabrication and cold testing of copper circuits for a 50-watt 220-GHz traveling wave tube from the US Naval Research Laboratory and also included contributed papers on a tunable continuous-wave terahertz generator based on 1.3 μm dual-mode laser diode and travelling-wave photodiode, a tunable continuous-wave terahertz generator based on 1.3 μm dual-mode laser diode and travelling-wave photodiode, room temperature generation of THz radiation in GaN quantum wells structures, and an improved design of THz radiation device with hybrid waveguide structures compatible with latest technique of monolithic integration fabrication.

Session 4 began with an invited paper by Professor Tianxin Yang on precise manipulation of light properties in optical domain by RF technology followed by a talk on terahertz time-domain spectroscopy of organic semiconductors, a talk on 3D terahertz beam profiling, followed by a talk on imaging at 0.2 and 2.5 terahertz, and concluding with a talk on new developments in a 384x288 pixel terahertz camera core.

Session 5 began with an invited paper on millimeter-wave and sub-millimeter-wave vacuum electronics amplifier development at the US Naval Research

Laboratory given by Doctor David Abe of the US Naval Research Laboratory, followed by a talk on integrated RF photonic devices based on crystal ion sliced lithium niobate, continuing with a talk on IMDD microwave photonic link modeling using Optsim, and concluding with a talk on a progress toward a widely tunable narrow linewidth RF source utilizing an integrated heterogenous silicon photonic module.

Session 6 began with a talk on widely tunable opto-electronic oscillator based on a dual frequency laser, followed by talks that included a continuous wave terahertz reflection imaging of human colorectal tissue.

Session 7 began with a talk on Millimeter and terahertz detectors based on plasmon excitation in InGaAs/InP HEMT devices, followed by talks dealing with the topic of conductivities.

Session 8 began with an invited talk on the fabrication and characterization of suspended graphene membranes for miniature Golay cells by Elizabeth Ledwosinska, the invited talk was followed by talks on the design and fabrication of an RF GRIN lens using 3D printing technology, an FBG sensor interrogation technique based on a precise optical recirculating frequency shifter driven by RF signals, an enhanced terahertz emission from photoconductive emitters using plasmonic contact electrodes, a talk on the progress being made toward dual vertical slot modulator for millimeter wave photonics, and concluding with a talk on flat pulse-amplitude rational-harmonic-mode-locking fiber lasers with GHz pulse repetition rates.

Session 9 began with a talk on metamaterial films as narrowband terahertz emitters, followed by a talk on a high sensitivity metamaterial based bi-material terahertz sensor, and concluding with a talk on the numerical simulation of terahertz plasmons in gated graphene structures.

Session 10 began with a talk on efficient horn antennas for next-generation terahertz and millimeter-wave space telescopes, and included a talk on antenna-coupled heterostructure field effect transistors for integrated terahertz heterodyne mixers, and concluded with a realization of an ultra-broadband voltage pulse standard utilizing time-domain optoelectronic techniques.

Session 11 began with a talk on electric field sensor based on electro-optic polymer refilled silicon slot photonic crystal waveguide coupled with bowtie antenna, followed by a talk on technological customization of uncooled amorphous silicon microbolometer for THz real time imaging, and included a talk on the generation of frequency tunable and broadband THz pulses in the frequency range 1-20 THz with organic electro-optic crystals OH1 and DSTMS.

As in prior Terahertz Technology and Applications Conferences, these papers represent a cross section of much of the research work that is being pursued in

the technically challenging terahertz spectral region. The Conference now includes talks and topics covering the Terahertz, RF, Millimeter, and Submillimeter-Wave frequency regions as well as related and associated technologies. In the prior five years of the proceedings of this conference (Conferences 6472, 6893 7215, 7601, 7938, and 8261, respectively), we (including Doctor Kurt Linden) presented a list of recent technical articles describing significant advances in the terahertz technology. This year, for the interested reader, we also include a list that points to a rather extensive and growing database on the terahertz absorption characteristics of a large number of chemicals given on the website www.thzdb.org. That website, in turn, provides links to related terahertz technology database websites as shown in Table 1.

Table 1. List of terahertz technology database websites as found at www.thzdb.org

Information	Contributors	Link
THz-BRIDGE Spectral Database		http://www.frascati.enea.it/THz-BRIDGE/
NIST THz Spectral Database		http://webbook.nist.gov/chemistry/thz-ir/
RIKEN THz Spectral Database		http://www.riken.jp/THzdatabase/
THz Links from Rice University		http://www.ece.rice.edu/~daniel/groups.html
Terahertz Technology Forum		http://www.terahertzjapan.com/lang_english/index.html
Terahertz Science & Technology Network		http://www.thznetwork.org/wordpress/
RIKEN Tera-Photonics Laboratory		http://www.riken.go.jp/lab-www/tera/TP_HP/index_en.html
Quantum Semiconductor Electronics Laboratory, University of Tokyo		http://thz.its.u-tokyo.ac.jp/top-e.html
Terahertz Photonics Laboratory, Osaka University		http://www.its.osaka-u.ac.jp/research/THP/indexeng.html
Solid State Spectroscopy Group, Kyoto University		http://www.hikari.scphys.kyoto-u.ac.jp/e_home.html
Kawase Laboratory "Tera health", Nagoya University		http://www.moe.nagoya-u.ac.jp/labs/optlab/kawase/index.html
NICT Terahertz Project		http://act.nict.go.jp/thz/en/main_e.html
Laboratory of Terahertz Bioengineering, Tohoku University		http://www.agri.tohoku.ac.jp/thz/jp/index_e.htm

Copyright (C) 2007 Terahertz Project

In the last five years' introduction to SPIE Proceedings, Volumes 6893, 7215, 7601, 7938, and 8261 respectively, two tables were included, one summarizing the more common terahertz radiation sources, and the other summarizing the more common terahertz detector types. For the interest of the general reader we again include these tables without updates other than to note that recent advancements in vacuum electronics BWOs coupled with solid state multipliers have now produced usable power above 2 THz and that devices such as quantum cascade lasers continue to make improvements that encroach upon

established high power sources such as carbon dioxide lasers. Due to such advancements, any values listed in Tables 2 and 3 are likely to be bested by new records in a very short time period; however the sources and detectors listed in Tables 2 and 3 still comprise the majority of those used in the THz regime. Readers of this volume may send additions and enhancements to these tables so that future volumes can continue to provide readers with relevant information on the availability of terahertz sources and detectors. Such suggestions can be sent to sadwick@innosystech.com.

Table 2. Summary of common terahertz sources

THz source type	Details	Characteristics
Synchrotron	* Coherent synchrotron produces very high photon flux, including THz region	E-beam, very broadband source, limited instrument availability, very large size, 20 W pulsed
Free electron laser	* 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
Smith-Purcell emitters	* E-beam travels over metal grating surface,	Requires vacuum, has low efficiency
Backward-wave oscillators	* 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
Mercury lamp	* Water cooled housing, low press. 1E-3 Torr 75-150 W lamp, broad emission	Sciencetech SPS-200,300, low power density Low-cost, used in THz spectroscopy
Optically pumped gas cell laser	* Grating-tuned CO ₂ 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)
Opt pump GaAs, p-InAs, Si, ZnTe, InGaAs (fiber laser pump), Ge photoconducting (PC) switch	* Mode locked Nd:YAG or Ti:sapphire laser creates short across biased spiral antenna gap * Also As-doped Si, CO ₂ 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.
Laser-induced air plasma	* Ti-saph laser induces air plasma	Remote THz generation possible, very low power Possibility of power increase in multiple plasmas
Photomixing of near-IR lasers	* 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 * Diff-freq generation with 2 monolith QCLs	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 7.6 u & 8.7 u -> 5 THz, 60 nW pulsed output
Electrically pumped Ge in H-field	* 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, 1.5 ~ 4 THz
Electrically pumped Si:B or As	* Transitions between impurity levels 100 x 200 um rectangle mesas, biased	31 uW output at 8.1 THz, slightly polarized Cryogenic cooling needed
Electrically pulsed InGaAs RTD	* Harmonically generated by electrical pulses RTD integrated into slot antenna	0.6 uW, 1.02 THz harmonic from InGaAs/AlAs RTD pulsed at 300 Hz
Direct multiplied mm waves	* Multiplied to low-THz region up-multiplied from mm-wave	Low power (uW level), available (VA Diodes) Coherent, heterodyne local oscillators in astronomy
Parametric generators	* Q-switched Nd:YAG pumps MgO:LiNbO ₃ non-linear crystal, Phase matched GaAs, GaP	200 W pulsed power, room temp., 0.1-5 THz tunable some commercially available ~ \$30K
Quantum cascade (QC) laser	* First announced in 2002, semiconductor, AlGaAs/GaAs-based, MBE grown, 1.6 to 4 THz	Operated at mW power, and up to 164K pulsed THz not commercially available, require cryo-cooling
Josephson junction cascades	Research stage	0.4-0.85 THz, microwatts
Transistor	* InGaAs channel PHEMT with 35 nm gate * InGaAs with 12.5 nm gate, 0.845 THz	1.2 THz, development at Northrop Grumman Univ. Ill (Dec 2006)
Grating-bicoupled plasmon-FET	* GaAs based double interdigitated grating	with 1.5um laser illum., Tohoku/Hokkaido Univ.

Table 3. Summary of common terahertz radiation detectors

THz detector type	Details	Characteristics
Si bolometer	* Most sensitive (10 pW Hz ^{1/2}) THz detector at liquid He temp., slow response time	Responsivity 2E9V/W, NEP=1E-17 W/Hz ^{1/2} , 100 mK Requires liquid He dewar, commercially avail.
Superconducting hot elec bolom	* Highest sensitivity Fast (1 us) response time	Requires cooling to 0.3 K, NEP=1E-17 W/Hz ^{1/2} Commercially available, expensive, bulky
Pyroelectric detectors	* 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
Schottky diodes	* ~ 1 THz cutoff frequency Fast response, but low THz sensitivity	Commercially available ((VA Diodes) with corner ref. Room temp operation, good for mixers
PC dipole antennas	* signal gen across biased spiral antenna gap Short pulsed detection only	Analogous to optically pumped THz PC switch but in detection mode. Commercially available
Antenna coupled inter-subband	* 4-terminal phototransistor, 1.6 THz	Under development UCSB
III-V HEMT & Si FET to 300K	* HEMT with 250 nm gate plasma wave-based detection	20 K, 50 mV/W at 420 GHz, still in development Univ research, Si NEP to 1E-10 W/Hz ^{1/2} at 300 K
Quantum dot photon detector	* Demo-photon counting terahertz microscopy imaging, requires 0.3 K temp, research only	Under development, 1E-19 W = 100 photons/sec, Tokyo Univ.

**Laurence P. Sadwick
Creidhe M. M. O'Sullivan**