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# ***Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications X***

**Laurence P. Sadwick  
Tianxin Yang**  
*Editors*

**30 January–2 February 2017  
San Francisco, California, United States**

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SPIE

**Volume 10103**

Proceedings of SPIE 0277-786X, V. 10103

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 X, edited by  
Laurence P. Sadwick, Tianxin Yang, Proc. of SPIE Vol. 10103, 1010301 · © 2017 SPIE  
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2276637

Proc. of SPIE Vol. 10103 1010301-1

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 [SPIDigitalLibrary.org](http://SPIDigitalLibrary.org).

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Please use the following format to cite material from these proceedings:

Author(s), "Title of Paper," in *Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications X*, edited by Laurence P. Sadwick, Tianxin Yang, Proceedings of SPIE Vol. 10103 (SPIE, Bellingham, WA, 2017) Seven-digit Article CID Number.

ISSN: 0277-786X  
ISSN: 1996-756X (electronic)

ISBN: 9781510606470  
ISBN: 9781510606487 (electronic)

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](http://SPIE.org)

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# Introduction

The 2017 Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VII Conference was divided into fourteen sessions reflecting specific categories as follows:

Session 1 THz Sources and Detectors I,

Session 2 Imaging and Security,

Session 3 Spectroscopy,

Session 4, RF-Submillimeter-Wave,

Session 5 Thickness Measurements using Terahertz Technologies I,

Session 6 Thickness Measurements using Terahertz Technologies II,

Session 7 RF-Submillimeter-Wave II,

Session 8 Metamaterials I,

Session 9 Biomedical Applications,

Session 10 Innovations,

Session 11 Metamaterials II,

Session 12 Terahertz Detectors and Sources II,

Session 13 Terahertz Detectors and Sources III, and

Session 14 Terahertz Detectors and Sources IV, and a poster session.

Session 1 began with an invited talk presented by Professor Robert Giles' research group on Terahertz source-receiver technologies: biomedical imaging followed by a talk on polarization dependent resonance manipulation by terahertz meta-molecules, with additional talks on plasmonics-enhanced large-area terahertz detectors by Professor Mona Jarrahi's research group and a high-sensitivity intensity correlation measurements for photon statistics at terahertz frequencies presented by Ileana-Cristina Benea-Chelmus who was a Best Student Paper Award winner.

Session 2 began with a talk on mechanically robust cylindrical metal terahertz waveguides for cryogenic applications, followed by talks on simplest passive millimeter wave discriminator for the finding of objects, sparse multistatic line-array-based 3D terahertz imaging system with real-time capability for industrial applications, a low noise readout integrated circuit for Nb5N6 microbolometer array detector and, completely the session, a talk on conception and realization of a semiconductor based 240GHz full 3D MIMO imaging system.

Session 3 began with a talk on material anisotropy effects in dielectric THz metamaterials, followed by presentations on temperature evolution of topological surface states in  $\text{Bi}_2\text{Se}_3$  thin films studied using terahertz spectroscopy, advanced temporal characterization of free electron laser pulses at European XFEL by THz photoelectron spectroscopy, InGaAs Schottky barrier diode array detectors integrated with broadband antenna, (012)-cut

chalcopyrite ZnGeP<sub>2</sub> as a high-bandwidth terahertz electro-optic detection crystal, and concluding with a talk on strong coupling of THz surface plasmon polaritons to complementary metasurfaces.

Session 4 began with a talk on picosecond-pulse generation over 10 GHz repetition rate based on cascaded semiconductor optical amplifiers, followed by talks on ultra-compact electromagnetic wave sensor featuring electro-optics polymer infiltrated one-dimensional photonic-crystal-slotted waveguide, 77 GHz radar for first responders, terahertz wireless communication based on InP-related devices, field-trial demonstration of an extended-reach GPON-supporting 60-GHz indoor wireless access, and concluding with a talk on radiation patterns of multimode feed-horn-coupled bolometers for FAR-IR space applications.

Session 5 was the first of two sessions on thickness measurements using terahertz technologies which included a number of talks from world experts on this subject and began with a Keynote presentation given by J.L.M. van Mechelen on towards the industrialization of THz technology: the case of quality control of paper during production followed by an invited talk on using terahertz-pulsed imaging (TPI) to study osmotic tablets, a talk on commercial perspective in THz spectroscopy, sensing and imaging, and concluding with a talk on thickness determination of wet coatings using self-calibration method.

Session 6 was the second of two sessions on thickness measurements using terahertz technologies which included a number of talks from world experts on this subject and began with an invited talk on film thickness determination using ultrashort terahertz pulses by Professor Kodo Kawase and his research group, online terahertz thickness measurement in films and coatings by Irl Duling, followed by talks on terahertz thickness measurements for real industrial applications: from automotive paints to aerospace industry, and concluding with a talk on an accurate frequency-modulated continuous-wave method for fast terahertz thickness measurements.

Session 7 began with a talk on Nyquist pulse generator by techniques of frequency synthetization, followed by talks on microwave photonic filter with continuous tunability using a wavelength-spacing-tunable multiwavelength fiber laser, analogue RF over fibre links for future radar systems, analogue RF over fibre links for future radar systems, multicore fiber beamforming network for broadband satellite communications, and concluding with a talk on wireless chemical sensor system based on electromagnetically energy-harvesting metamaterials.

Session 8 was the first of two sessions on metamaterials and had a number of world recognized leaders in the field and began with an invited talk on applications of spatially varying conductivity in plasmonics and metamaterials by Professor Ajay Nahata's research group and was followed by invited talks

on large dynamic range terahertz spectrometers based on plasmonic photomixers by Professor Mona Jarrahi's research group, analysis of tuning methods in semiconductor frequency-selective surfaces by Professor Marco Rahm's research group, and completing the session an invited talk on broadband terahertz generation from metamaterials and their hybrid quantum structures by Professor Jigang Wang's research group.

Session 9 began with an invited talk on development of terahertz endoscopic system for cancer detection by Dr. Pallavi Doradla and Professor Robert Giles' research group, followed by a talk on one-dimensional photonic crystals for eliminating cross-talk in mid-IR photonics-based respiratory gas sensing that was presented by Lewis S. Fleming who was a Best Student Paper winner, and concluded with a talk on tissue characterization by using phase information of terahertz time domain spectroscopy.

Session 10 began with a talk on terahertz chiral structures with large optical activity, followed by talks on Improvement of terahertz time-domain spectroscopy precision by interferometrically tracked delay lines, tunable flexible metasurfaces, and concluded with a talk on demultiplexing method of terahertz-wave OFDM sub-carrier channels using integrated-optic DFT circuit.

Session 11 was the second session on metamaterials and began with an invited talk on metamaterial reconfigurable spatio-temporal modulators for terahertz sensing and imaging by Professor Willie J. Padilla and his research group, followed by a talk on ultrathin wide bandwidth metamaterial absorber using randomly distributed scatterers, an invited talk on high-performance terahertz metasurface lenses by Dr. Hou-Tong Chen, and concluded with a talk on a talk on tunable THz metamaterials based on phase-changed materials (VO<sub>2</sub>) triggered by thermal and electrical stimuli.

Session 12 began with an invited talk on resonant tunnelling diode terahertz sources for broadband wireless communications by Professor Edward Wasige and his research group, followed by talks on properties of cellulose nanocrystal films and powder in the terahertz frequency regime, gas spectroscopy system with 245 GHz transmitter and receiver in SiGe BiCMOS, a metamaterial-coupled hot-electron-bolometer working at THz frequencies, and concluded with a talk on 4x4 planar array antenna on indium phosphide substrate for 0.3-THz band application.

Session 13 began with an invited talk on terahertz monolithic solution for biosensing applications by Dr. Richard Al Hadi and others at UCLA, followed by talks on generations of linear frequency modulation continuous waves, THz wave generation through 2nd order non-linear excitonic effects in GaAs/AlAs MQWs at room temperature, and concluded with a talk on a sensitive Nb<sub>5</sub>N<sub>6</sub> microbolometer with a composite coupling structure for THz detection.

Session 14 began with a talk waveguide development using wafer fused GaP/GaAs in THz quantum cascade lasers, followed by talks on printing sub-THz wire grid polarizers using a composite liquid metal ink, printing sub-THz wire grid polarizers using a composite liquid metal ink, and concluded with a talk on a broadband ultrathin metamaterial absorber using tilted parallel strips.

There were also a number of excellent poster presentations at this conference. The poster presentations were on precisely tunable multi-wavelength fiber laser source for phased array antenna, a linearly frequency-swept high-speed-rate multi-wavelength laser for optical coherence tomography, ultra-flattened nearly zero-dispersion THz waveguide using photonic quasi-crystal porous core fiber, slot-shaped porous core THz photonic crystal fiber with broadband high birefringence and nearly zero flat-dispersion, self-oscillating optical comb generator based on optoelectronic oscillator, an inset-fed slot ring antenna integrated with a terahertz photomixer based on a uni-traveling-carrier photodiode, and analysis of quantum well optical modulation in light-emitting transistors.

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 and other electromagnetic regions.

In the prior ten years of the Proceedings of this conference (Conferences 6472, 6893 7215, 7601, 7938, 8621, 8624, 8985, 9362 and 9747, respectively), we (including Dr. 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](http://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](http://www.thzdb.org)

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](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](http://www.riken.go.jp/lab-www/tera/TP_HP/index_en.html)

Quantum Semiconductor Electronics Laboratory, University of Tokyo  
<http://thz.iis.u-tokyo.ac.jp/top-e.html>

Terahertz Photonics Laboratory, Osaka University  
<http://www.ile.osaka-u.ac.jp/research/THP/indexeng.html>

Solid State Spectroscopy Group, Kyoto University  
[http://www.hikari.sc.phys.kyoto-u.ac.jp/e\\_home.html](http://www.hikari.sc.phys.kyoto-u.ac.jp/e_home.html)

Kawase Laboratory "Tera health", Nagoya University  
<http://www.nuee.nagoya-u.ac.jp/labs/optlab/kawase/index.html>

NICT Terahertz Project  
[http://act.nict.go.jp/thz/en/main\\_e.html](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](http://www.agri.tohoku.ac.jp/thz/jp/index_e.htm)

Infrared and Raman Users Group  
<http://www.irug.org/>

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- Infrared and Raman Users Group  
<http://www.irug.org/>
- Kyoto University, Terahertz Optical Science Group  
<http://www.icems.kyoto-u.ac.jp/e/ppl/grp/tanaka.html>

- Kyoto University, Laboratory of Bio-Sensing Engineering  
<http://www.aptech.kais.kyoto-u.ac.jp/e/index.html>
- Spectra Design  
<http://spectra-dsn.co.jp/english/thz.html>

In the last eight years' introduction to SPIE Proceedings, Volumes 6472, 6893, 7215, 7601, 7938, 8621, 8624, and 8985, 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](mailto:sadwick@innosystech.com).

**Table 2. Summary of common terahertz 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, 20 W pulsed
<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,	Requires vacuum, has low efficiency
<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>Mercury lamp</b>	* 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
<b>Optically pumped gas cell laser</b>	* Grating-tuned CO2 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), Ge photoconducting (PC) switch</b>	* Mode locked Nd:YAG or Ti:sapphire laser creates short across biased spiral antenna gap * Also As-doped Si, CO2 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>Laser-induced air plasma</b>	* Ti-saph laser induces air plasma	Remote THz generation possible, very low power Possibility of power increase in multiple plasmas
<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 * 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
<b>Electrically pumped Ge in H-field</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, 1.5 ~ 4 THz
<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>Electrically pulsed InGaAs RTD</b>	* 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
<b>Direct multiplied mm waves</b>	* Multiplied to low-THz region up-multiplied from mm-wave	Low power (uW level), available (VA Diodes) Coherent, heterodyne local oscillators in astronomy
<b>Parametric generators</b>	* Q-switched Nd:YAG pumps MgO:LiNbO3 non-linear crystal, Phase matched GaAs, GaP	200 W pulsed power, room temp., 0.1-5 THz tunable some commercially available ~ \$30K
<b>Quantum cascade (QC) laser</b>	* 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
<b>Josephson junction cascades</b>	Research stage	0.4-0.85 THz, microwatts
<b>Transistor</b>	* 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)
<b>Grating-bicoupled plasmon-FET</b>	* 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
<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 ((VA 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>III-V HEMT &amp; Si FET to 300K</b>	* 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 <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.

We would also to acknowledge Miss Sahar Mirzaei, a graduate student pursuing her Ph.D. degree at University of Southampton in England who was unfortunately not able to attend the conference due to a temporary ban that was later lifted by the U.S. Courts. Her paper is among those published herein.

Finally, we would like to thank the Conference Program Committee: René Beigang, Jianji Dong, Frank Ellrich, Robert H. Giles, R. Jennifer Hwu, J. Anthony Murphy, Créidhe O'Sullivan, Kyung Hyun Park, Alessia Portieri, Jinghua Teng, Michael Weibel, and Jiangfeng Zhou.

We would also like to thank the SPIE Program and Proceedings staff who worked on this conference and proceedings.

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