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Tianxin Yang
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Introduction

The 2017 conference on Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications XI was divided into 15 sessions reflecting specific categories as follows:

Session 1 Terahertz Sources
Session 2 Terahertz Detection and Sensing
Session 3 Terahertz Spectroscopy I
Session 4 Optical to Terahertz and Related Approaches and Concepts
Session 5 Thickness Measurements using Terahertz Technologies
Session 6 Terahertz Imaging and Volume Inspection
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Session 9 Radio Frequency to 300 GHz
Session 10 Wideband Communications
Session 11 Terahertz Spectroscopy II
Session 12 Terahertz Materials I
Session 13 Terahertz Materials II
Session 14 Materials, Detection, and Related Topics
Session 15 Radio Frequency Advances.

Session 1 began with an invited talk, "Terahertz radiation sources based on nano-antennas and plasmonic light concentrators," presented by SPIE Fellow, Professor Mona Jarrahi of Univ. of California Los Angeles (United States). Talks on "Ultra-broad generation of terahertz radiation from subwavelength lithium niobate waveguides" and "Development of THz quantum cascade lasers and hot electron bolometers for ultra-sensitive and ultra-compact heterodyne detection in astronomy applications" followed. Next, Professor René Beigang of Univ. Kaiserslautern (Germany) presented on "Spintronic terahertz emitters based on epitaxial-grown Fe/Pt bilayers," and was followed by Professor Mona Jarrahi's group presenting on "High-power pulsed terahertz radiation from terahertz nanoantenna arrays based on plasmonic nanocavities." The session closed with "High-repetition-rate tunable narrowband terahertz-wave generation based on nonlinear frequency-conversion pumped by dual fiber lasers in MgO: $LiNbO_3$," presented by researchers at Ricoh (Japan) and PHILUXi (Japan).

Professor Michael Shur from Rensselaer Polytechnic Institute (United States) opened Session 2 with his invited talk, "Subterahertz and terahertz sensing of biological objects and chemical agents." Shur was followed by talks on "An efficient terahertz detector based on an optical hybrid cavity," and "Enhanced performance of antenna-integrated Schottky barrier diodes for wave and photonic detection in the THz regime."

Session 3 began with a talk on "Terahertz spectroscopy and demonstration of visible transparent/terahertz-functional electromagnetic structures in La-doped $BaSnO_3$ films," by Sara Arezoomandan, a graduate student in Professor Berardi Sensale-Rodriguez's research group at the Univ. of Utah (United States). Arezoomandan's presentation was followed by a paper on "Recent progress of continuous-wave terahertz systems for spectroscopy, non-destructive testing, and telecommunication," presented by Simon Nellen from Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany). The third talk of the session was "Nondestructive evaluation of GFRP-wood sandwich structure composite using terahertz imaging," given by Professor Bala Pesala from CSIR Madras (India). Lukas Eng of TU Dresden (Germany) presented "Near-field THz nanoscopy at novel accelerator-based photon sources," and Dr Giacomo Mariani of Jet Propulsion Laboratory (United States) presented "Next-generation thermal Imagers for room-temperature far infrared detection." The session closed with "Optical modelling and analysis of the Q and U bolometric interferometer for cosmology," authored by researchers at the National Univ. of Ireland, Maynooth, and a diverse host of other universities and other groups.

Session 4 began with an invited talk on "Plasmonic nanowire optical to terahertz converter operating at telecommunication wavelengths," from the research team of Professor Diana L. Huffaker, from Univ. of California Los Angeles (United States), California NanoSystems Institute (United States), and Cardiff Univ. (United Kingdom), and Professor Mona Jarrahi from Univ. of California Los Angeles (United States). Varun Kamboj from the Univ. of Cambridge (United Kingdom) presented, "Probing the mobility and scattering rate of topological surface state in Bi_2Se_3 thin films using terahertz spectroscopy and magnetotransport." Xurong Li from the Univ. of California, Los Angeles (United States) presented "Polarization-insensitive plasmonic photoconductive terahertz emitters." Joseph Demers of Bakman Technologies (United States) presented "A UAV-mounted THz spectrometer for real-time gas analysis." Professor Jean-Paul Guillet of the Univ. of Bordeaux (France) closed the session with "Guided terahertz pulsed reflectometry: a remote probe for near-field imaging."

Session 5 began with a keynote presentation by Professor Frank Ellrich from Technischen Hochschule Bingen (Germany) on "Terahertz thickness determination for industrial applications: challenges and solutions." Ellrich's talk was followed by an invited paper on "Terahertz time-domain spectroscopy for nondestructive testing," given by Professor Björn Globisch of the Fraunhofer-Institut fur Nachrichtentechnik Heinrich-Hertz-Institut (Germany). The session closed with a paper on "Multilayer thickness inspection with millimeter-waves," presented by Dr. Fabian Friederich from Fraunhofer ITWM (Germany).

Session 6 began with the invited talk, "3D-additive manufacturing non-destructive characterization with terahertz waves," from a team of researchers from a number of institutes and organizations in France. The session's second presentation was an invited talk on "Millimeter-wave imaging solutions for non-destructive testing," given by Dr. Fabian Friederich from Fraunhofer ITWM (Germany). Dr. Richard Al Hadi from Univ. of California, Los Angeles (United States) presented his invited talk on "Multispectral terahertz imaging in CMOS technology." The session concluded with "Towards industrial applications of terahertz real-time imaging," from a collective of institutes and organizations in France.

Professor Dmitry Turchinovich of the Max-Planck-Institut für Polymerforschung (Germany) opened Session 7 with his invited talk on "Terahertz response of graphene is governed by basic thermodynamics." Turchinovich's presentation was followed by an invited talk, "Accurate measurement and generation of linearly chirped optical waves over broad frequency ranges," from Professor Tianxin Yang of Tianjin Univ. (China). Jinghui Yang, a student of Professor Mona Jarrahi's research group at the Univ. of California, Los Angles (United States), presented the invited paper, "Chip-scale microresonator Turing pattern formation for coherent high-power THz radiation," Concluding the session was "Generation of optical Nyquist pulses with pre-programmed rectangular-shape spectrum," by Cheng Guo of Tianjin Univ. (China).

Session 8 began with an invited paper on "Nano-absorbers on InP multiplication region: a platform for mid-wavelength infrared separate absorption and multiplication avalanche photodiodes," by Dingkun Ren of the Univ. of California, Los Angeles (United States). The second paper in the session was an invited talk on "Measuring electric fields with nitrogen-vacancy ensembles for neutron electric dipole moment experiments," presented by Dr. David Hovde, of Southwest Sciences, Inc. (United States). The next presentation was "Integrated silicon-organic hybrid electromagnetic wave sensor," followed by Dr. Fabio Alves of the Naval Postgraduate School (United States) presentation of "MEMS THz sensors using metasurface structures." Dr. Wei-Chih Wang, Univ. of Washington (United States), presented "Tunable terahertz filter using PDLC fishnet metamaterial," and Professor Xuecou Tu of Nanjing Univ. (China) gave a talk on "Investigation of antenna coupled Nb_5N_6 microbolometer THz detector."

Dr. Haruichi Kanaya opened Session 9 with his presentation, "Development of 4×4 phased array antenna on chip for 300GHz band application." This was followed by "Study of high power generation in UTC-PD at 110-210 GHz," by Toshimasa Umezawa of the National Institute of Information and Communications Technology (Japan). Next in this session was "SBD detector-based THz receiver module operating at 220~320GHz," presented by Jeong-Woo Park of Electronics and Telecommunications Research Institute (Korea, Republic of).

Session 10 began with a talk on "Low-loss silicon nitride integrated optical beamforming network for wideband communication," by Dr. Yuan Liu, Univ. of California Santa Barbara (United States). Dr. Hyun-Soo Kim, Electronics and Telecommunications Research Institute (Korea, Republic of), presented "Terahertz wireless communication using 1.3μm photonic-based modules," and Dr. Simon Ayotte from TeraXion Inc. (Canada) presented, "Compact optical coherent receiver for avionics applications." Dr. Yanne Chembo of FEMTO-ST (France) presented, "Novel architectures of optoelectronic oscillators." The session concluded with "Multicomponent- multilayer hybrid plasmonic leaky-wave optical antenna with improved directivity and matching," given by Zahra Manzoor, Missouri Univ. of Science and Technology (United States).

Session 11 started with an invited talk on "Metamaterial absorber for THz polarimetric sensing," by Dr. Bingnan Wang of Mitsubishi Electric Research Labs (Japan). Wang's talk was followed by "Towards swept source spectroscopy using THz emission from 2nd-order nonlinear optical effects in GaAs/AlGaAs multi-quantum well excitons at room temperature," given Richard Hogg, Univ. of Glasgow (United Kingdom). Wonjong Ryu of KAIST (Korea, Republic of) presented "Compact and portable terahertz imaging system using single-mode Fabry-Perot laser diode photomixer," followed by "Understanding the effect of nanosilica incorporation on dicalcium silicate hydration using terahertz spectroscopy," presented by Dr. Bala Pesala from CSIR—Structural Engineering Research Center (India) and the Academy of Scientific and Innovative Research (India).

Wednesday evening's poster session had a number of excellent poster presentations, including "Terahertz spectroscopy using an injection-seeded terahertz parametric generator for quantitative analysis and inspection of over-the-counter medicine tablets," from Hitachi High-Technologies Corporation (Japan) and Nagoya Univ. (Japan); "Effect of thin-film interference on resonance spectra of distorted metamaterials," "Terahertz frequency modulated continuous wave imaging for nondestructive evaluation of painting and multilayer parts," and "The fabrication and application of ultrasensitive Nb_5N_6 microbolometer detector for 0.3 THz detection."

Session 12 began with "Strong terahertz plasmonic resonances in thin-film cadmium arsenide: a 3D topological Dirac semimetal," an invited talk by Ajay Nahata's and Berardi Sensale-Rodriguez's groups at the Univ. of Utah (United States). This was followed by "One-dimensional photonic-crystal waveguide-based true time delay line," by Chi-Jui Jung, The Univ. of Texas at Austin (United States). Dr. Takahiro Kaji from the National Institute of Information and Communications Technology (Japan) presented "Fabrication of electro-optic polymer waveguide devices with terahertz-wave low-loss materials," and was followed by "Numerical study of resonance modes in terahertz metamaterials for thin film sensing perspective," presented by S. Jagan Mohan Rao from the Indian Institute of Technology Guwahati (India). The session closed with "Terahertz-frequency dielectric anisotropy in three-dimensional methacrylates fabricated by stereolithography," presented by Dr. Tino Hofmann of The Univ. of North Carolina at Charlotte (United States).

Professor Richard Averitt of the Univ. of California, San Diego (United States) opened Session 13 with an invited talk on "Terahertz quantum metamaterials." S. Jagan Mohan Rao from the Indian Institute of Technology Guwahati (India) presented "Tuning near-field capacitive coupling in planar terahertz metamaterials," and was followed by "Energy-harvesting metamaterial-based wireless chemical sensor system," by Wonwoo Lee from Soongsil Univ. (Korea, Republic of). Brett Carnio of the Univ. of Alberta (Canada) presented, "Birefringent and optical rectification characteristics of a chalcopyrite $CdSiP_2$ crystal in the terahertz frequency regime." The session ended with "Electrically controllable THz high-Q metamaterials based on vanadium dioxide thin film," presented by Prof. Han-Cheol Ryu from Sahmyook Univ. (Korea, Republic of).

Session 14 began with a talk on "Characterization of Si-MOSFET CMOS devices for detection at 170 to 250 GHz," presented by Katherine Seery from the Rochester Institute of Technology (United States), followed by a talk on the "Effects of polyimide layer under electrical contact pads on the response bandwidth of UTC-PD," by Siwei Sun of the Institute of Semiconductors (China). The session closed with "Broadband terahertz wave plates based on cross polarization metasurfaces," presented by Ji Hyun Hwang of the Gwangju Institute of Science and Technology (Korea, Republic of).

Session 15 started with a talk on "Experimental investigations for designing low-phase noise 10-GHz coupled optoelectronic oscillator," by Oriane Lelievre of Thales Research &Technology (France), followed by a talk on "Silicon-photonic-assisted on-chip RF signal processing," by Vadivukkarasi Jeyaselvan from Indian Institute of Science (India). Next in the session was a talk on "Photonic generation of a dual nonlinear chirp microwave waveform in Ku-band and its comparative study with dual linear chirping capability to distinguish rang-Doppler coupling in radar application," given by Manish Kumar of the Indian Institute of Technology (Indian School of Mines). Jingliang Liu from Beijing Univ. of Posts and Telecommunications (China) presented "Generation and stabilization of optoelectronic oscillation millimeter-wave signal employing frequency sextupling technique and phase-locked loop." The final talk of the session and conference was "Monolithic mmW/THz optical heterodyne source based on dual wavelength DFB laser integrated with high-speed PIN diode using InP generic foundry platform," by researchers at the Univ. of Carlos III de Madrid (Spain).

As with 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 11 years of the Proceedings of this conference (SPIE Volumes 6472, 6893, 7215, 7601, 7938, 8621, 8624, 8985, 9362, 9747 and 10103, 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. 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

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.iis.u-tokyo.ac.jp/top-e.html

Teraherts Photonics Laboratory, Osaka University
http://www.ile.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.nuee.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

Infrared and Raman Users Group
http://www.irug.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/
- Terahertz Technology Forum
  http://www.terahertzjapan.com/lang_english/index.html
- Kawase Laboratory "Tera health", Nagoya Univ.
  http://www.nuee.nagoya-u.ac.jp/labs/optlab/kawase/index.html
- Laboratory of Terahertz Bioengineering, Tohoku Univ.
  http://www.agri.tohoku.ac.jp/thz/jp/index_e.htm
- Infrared and Raman Users Group
  http://www.irug.org/
- Kyoto Univ., Terahertz Optical Science Group
  http://www.icems.kyoto-u.ac.jp/e/ppl/grp/tanaka.html
- Kyoto Univ., Laboratory of Bio-Sensing Engineering
  http://www.aptech.kais.kyoto-u.ac.jp/e/index.html

In the last 10 years, the introductions to *Proceedings of SPIE* volumes 6472, 6893, 7215, 7601, 7938, 8621, 8624, 8985, 9362, 9747 and 10103, respectively, included two tables, 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	E-beam, very broadband source, limited instrument
	photon flux, including THz region	availability, very large size, 20 W pulsed
Free electron laser	* Benchtop design at Univ. Essex, UK	Tunable over entire THz region, under development
	Elec beam moves over alternate H-field regions	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	Tunable output possible. Under development and
	"Carcinotron", room temperature, to 1.2 Thz	commercially available, 10 mW power level, <1 THz
Mercury lamp	* Water cooled housing, low press. 1E-3 Torr	Sciencetech SPS-200,300, low power density
	75-150 W lamp, broad emission	Low-cost, used in THz spectroscopy
Optically pumped gas cell laser	* Grating-tuned CO2 laser and far-IR gas	> 100 mW, 0.3-10 THz, discrete lines, CW/pulsed
	cell such as methane. Most mature laser.	Commercially avail - Coherent ($400K - $1M)
Opt pump GaAs, p-InAs, Si, ZnTe,	* Mode locked Nd:YAG or Ti:sapphire laser	Imaging apparatus produced, 0.1 to 3 THz
InGaAs (fiber laser pump), Ge	creates short across biased spiral antenna gap	Commercially available, CW uW range, $50K-500K
photoconducting (PC) switch	* Also As-doped Si, CO2 laser pump	6 THz stim emission from As, Liq He temp.
Laser-induced air plasma	* Ti-saph laser induces air plasma	Remote THz generatiion possible, very low power
		Possibility of power increase in multiple plasmas
Photomixing of near-IR lasers	* Mixing tunable Ti-sapphire laser and diode	Tens of nW, tunable. Requires antenna pattern
	laser in LT-grown GaAs photomixer.	Not commercial. GaP gave 480 mW @ 1.3 THz
	* GaSe crystal, Nd:YAG/OPO difference freq	Tunable 58-3540um (5-0.1THz),209 W pulse 1.5THz
	* Single 835 nm diode laser, external cavity	2-freq mix& 4-wave mixing, RT, sub-nW,0.3-4.2THz
	* Diff-freq generation with 2 monolith QCLs	7.6 u & 8.7 u -> 5 THz, 60 nW puled output
Electrically pumped Ge in H-field	* Electric field injects electrons, magnetic	Requires electric and magnetic fields Output up to
	field splits hole levels for low-E transitions	hundres of mW, cryogenic cooling, 1.5 ~ 4 THz
Electrically pumped Si:B or As	* Transitions between impurity levels	31 uW output at 8.1 THz, slightly polarized
	100 x 200 um rectangle mesas, biased	Cryogenic cooling needed
Electrically pulsed InGaAs RTD	* Harmonically generated by electrical pulses	0.6 uW, 1.02 THz harmonic from InGaAs/AlAs RTD
	RTD integrated into slot antenna	pulsed at 300 Hz
Direct multiplied mm waves	* Multiplied to low-THz region	Low power (uW level), available (VA Diodes)
	up-multiplied from mm-wave	Coherent, heterodyne local oscillators in astronomy
Parametric generators	* Q-switched Nd:YAG pumps MgO:LiNbO3	200 W pulsed power, room temp., 0.1-5 THz tunable
	non-linear crystal, Phase matched GaAs, GaP	some commercially available ~ $30K
Quantum cascade (QC) laser	* First announced in 2002, semiconductor,	Operated at mW power, and up to 164K pulsed
	AlGaAs/GaAs-based, MBE grown, 1.6 to 4 THz	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	1.2 THz, development at Northrop Grumman
	* InGaAs with 12.5 nm gate, 0.845 THz	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 Hz1/2) THz detector	Responsivity 2E9V/W,NEP=1E-17 WHz1/2,100 mK
	at liquid He temp., slow response time	Requires liquid He dewar, commercially avail.
Superconducting hot elec bolom	* Highest sensitivity	Requires cooling to 0.3 K, NEP=1E-17 WHz1/2
	Fast (1 us) response time	Commercially available, expensive, bulky
Pyroelectric detectors	* Slow response t, 220 nW sensitiv at 24 Hz	Room temp operation, commercially available,
	Requires pulsed signals or mechanical chopper	Low cost, imagers available ~ $10K
Schottky diodes	* ~ 1 THz cutoff frequency	Commercially available ((VA Diodes) with corner ref.
	Fast response, but low THz sensitivity	Room temp operation, good for mixers
PC dipole antennas	* signal gen across biased spiral antenna gap	Analogous to optically pumped THz PC switch but
	Short pulsed detection only	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	20 K, 50 mV/W at 420 GHz, still in development
	plasma wave-based detection	Univ research, Si NEP to 1E-10 W/Hz1/2 at 300 K
Quantum dot photon detector	* Demo-photon counting terahertz microscopy	Under development, 1E-19 W = 100 photons/sec,
	imaging, requires 0.3 K temp, research only	Tokyo Univ.

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