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

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

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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

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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 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)
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, 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.
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:LiNbO3 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 WHz ^{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 WHz ^{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.

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