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Laurence P. Sadwick
Créidhe M. O'Sullivan
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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.

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

<u>Session 2</u> 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.

<u>Session 3</u> 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.

<u>Session 4</u> 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.

<u>Session 5</u> 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.

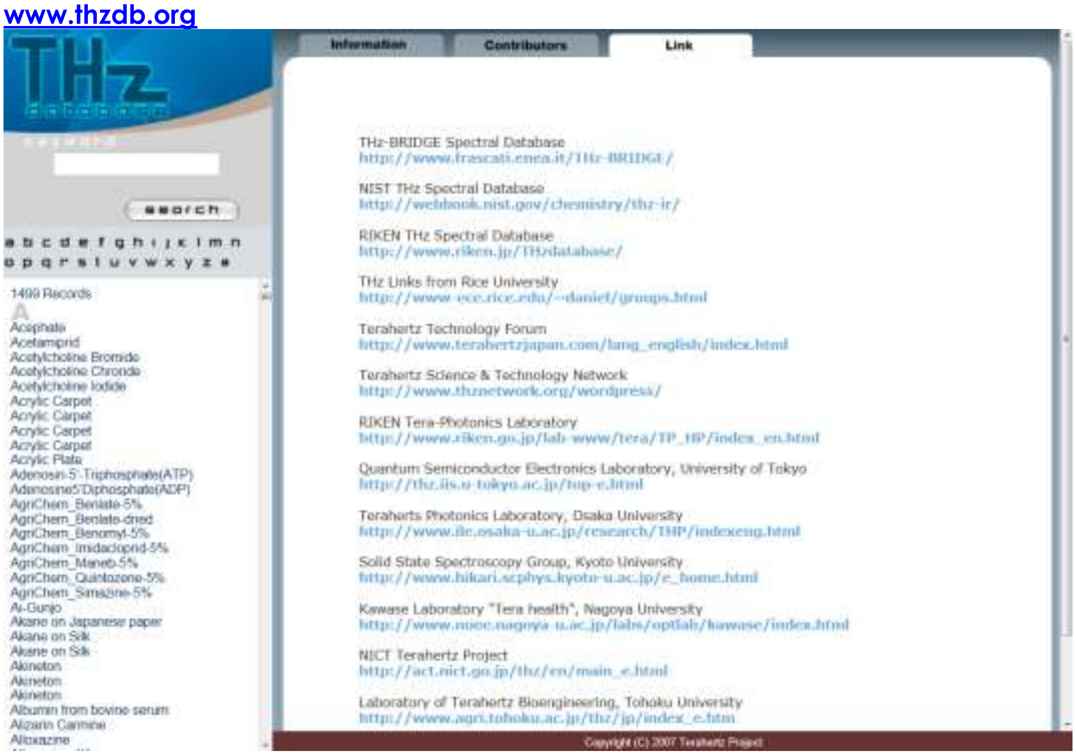
Session 9 began with a talk on metamaterial films as narrowband terahertz emitters, followed by a talk on a high sensitivity metamaterial based bi-material terahertz sensor, and concluding with a talk on the numerical simulation of terahertz plasmons in gated graphene structures.

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 Doctror 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



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	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.

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