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# Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VIII

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# Introduction

The 2015 Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VIII conference was divided into 11 sessions reflecting specific categories as follows: Session 1, Terahertz I; Session 2, Terahertz II; Session 3, Terahertz III; Session 4, New Developments in THz, RF, Millimeter-waves, and Sub-Milimeter Waves I; Session 5, New Developments in THz, RF, Millimeter-waves, and Sub-Millimeter-waves II; Session 6, New Developments in THz, RF, Millimeter-waves, and Sub-Millimeter-waves III; Session 7, New Developments in THz, RF, Millimeter-waves, and Sub-Millimeter-waves IV; Session 8, New Developments in THz, RF, Millimeter-waves, and Sub-Millimeter-waves V; Session 9, New Developments in THz, RF, Millimeter-waves, and Sub-Millimeter-waves VI; and a poster session.

Session 1 began with a talk presented by Dr. Alessia Portieri on a terahertz probe for detection of breast cancer followed by "Numerical studies of supercontinuum generation based on quasi-rectangle wave pumping" by Professor Tianxin Yang, with additional talks on "Incoherent sub-terahertz radiation source with a photomixer array for active imaging in smoky environments," and an invited paper, "Structured-surface-plasmon-inspired THz components and devices," by Professor Elliot Brown.

Session 2 began with an invited talk by Professor Sundaram on "Glasses and ceramics for THz photonics" with additional talks on **"**Photoconductive materials for THz generation at 1550 nm: ErAs:GaAs vs InGaAs based materials," "Terahertz wavefront assessment based on 2D electro-optic imaging," "Terahertz plasmonic channel waveguide based on metallic rod arrays," with the final talk of the session on **"**Terahertz photonic crystals based on two-dimensional rod array**."**

Session 3 began with an invited talk on **"**Preliminary results of non-contact THz imaging of cornea," followed by talks that included "Flexible waveguide enabled single-channel terahertz endoscopic system," "A new scheme for ultra-intense terahertz pulse production and nonlinear THz science," "Room-temperature zero-bias plasmonic THz detection by asymmetric dual-grating-gate HEMT," and concluding with a talk on "Enhancing the low frequency THz resonances (< 1 THz) of organic molecules via electronegative atom substitution."

Session 4 began with an invited talk on "Deep sub-wavelength structure empowered THz components," by Professor Jinghua Teng of A*STAR Institute of Materials Research and Engineering in Singapore followed by talks on "Video rate imaging of narrow band THz radiation based on frequency upconversion," "Novel method of generation of linear frequency modulation optical waveforms with swept range of over 200 GHz for LIDAR systems," and concluding with a talk on liquid crystal device into THz phase imaging.

Session 5 began with an invited talk by Mona Jarrahi on "Plasmonic photomixers for high-power continuous-wave terahertz generation," followed by talks on "Optical multi-coset sampling of GHz-band chirped signals" and "Optical and quasi-optical analysis of system components for a far-infrared space interferometer." Mr. Xingyu Zhang, a graduate student at the University of Texas at Austin, presented the session's last two talks on "Antenna-coupled silicon-organic hybrid integrated photonic crystal modulator for broadband electromagnetic wave detection" (winner of the Best Student Paper Award) and "Integrated broadband bowtie antenna on transparent substrate."

Session 6 began with a talk on the **"**Demonstration of high-resolution doping profile mapping using terahertz time domain spectroscopy with electrochemical anodization," followed by "Performance of microwave optoelectronic oscillators based on crystalline whispering-gallery mode resonators," and concluding with **"**High-performance PIN photodetector at 67GHz and beyond for radio-over-fiber applications**."**

Session 7 began with "Frequency tuning of THz quantum cascade lasers," by Professor Xifeng Qian, followed by an invited talk on "Development of portable terahertz scanner for imaging and spectroscopy using InP-related devices," by Dr. Kyung Hyun Park of the Electronics and Telecommunications Research Institute in the Republic of Korea, with other talks on "Multiple-angle approach for enhanced terahertz spectroscopic pattern recognition," "High-power photodetector modules for microwave photonic applications," "Wavelength-spacing tunable multiwavelength erbium-doped fiber laser using polarization-differential time delay for photonic microwave filter," and concluded with a talk on "Recent developments in electroabsorption modulators at Acreo Swedish ICT**."**

Session 8 began with a talk on "Compensating the carrier screening effect in plasmonic photoconductive terahertz sources," followed by talks on "Hydration kinetics of cement composites with varying water-cement ratio using terahertz spectroscopy," "Design of hybrid optical delay line for automotive radar test system**,"** and concluded with a talk on "Broadband receiver-based distortion elimination in phase-modulated analog optical links using four-wave mixing."

Session 9 began with a talk on "Reconfigurable thermo-optic polymer switch based true-time-delay network utilizing imprinting and inkjet printing," followed by talks on "Fourier transform molecular rotational resonance spectroscopy for reprogrammable chemical sensing," "Design and characterization of evanescently-coupled dual-photodiodes for 1.3 μm wavelength," and concluded with a talk on "Aluminum-doped zinc-oxide for radio frequency applications."

There were also a number of excellent poster presentations at this conference.

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 seven years of these Proceedings (SPIE Volumes 6472, 6893 7215, 7601, 7938, 8621, 8624, and 8985, 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
- Teraherts Photonics Laboratory, Osaka University
  http://www.ile.osaka-u.ac.jp/research/THP/indexeng.html
- Kawase Laboratory "Tera health", Nagoya University
  http://www.nuee.nagoya-u.ac.jp/labs/optlab/kawase/index.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/
- 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.

**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, InGaAs (fiber laser pump), Ge photoconducting (PC) switch** | * Mode locked Nd:YAG or Ti:sapphire laser | Imaging apparatus produced, 0.1 to 3 THz |
| | creates short across biased spiral antenna gap | Commercially available, CW uW range, $50K-500K |
| | * 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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