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4 Terahertz Detection and Imaging Systems
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Introduction

Terahertz and gigahertz electronics and photonics continue to make significant materials, device, and system development advances. This past year witnessed further advancements in modeling as well as demonstrations of improved device and system performance, as highlighted in this conference.

The proceedings from conference 6472 includes papers covering subjects that are arranged in four categories containing the following subjects:

(1) **High-Frequency Materials and Physics**: This session includes papers dealing with the performance of the cosmic microwave background telescope, studies of critical electric field and band offsets in semiconductors by use of terahertz radiation, as well as the theory of optical to terahertz conversion in non-linear materials. The session also features a theoretical and experimental article on artificially structured plasmonic materials (using micromachined pillars) for terahertz and gigahertz applications, in tune with the rapidly growing area of metamaterials.

(2) **Waveguides, Beams, and Modeling**: This session includes an invited paper reviewing the use of plastic fibers for terahertz waveguide applications. This session also deals with analytical modeling, and includes papers on electromagnetic scattering calculations for use in terahertz sensors, standing wave analysis in submillimeter optics — a problem that every experimenter working in the terahertz spectral region has encountered, Gaussian beam mode analysis in millimeter wave imaging and detection, high-finesse scanning Fabry-Perot filters for terahertz and gigahertz spectroscopy, and modeling of optical performance of millimeter wave instruments.

(3) **Terahertz Emitters and Detectors**: In this session, a widely tunable terahertz laser source using frequency mixing is presented, photoconductive antennas excited at telecommunication source wavelengths are presented, and terahertz applications of poled electro-optic polymers are reviewed.

(4) **Terahertz Detection and Imaging Systems**: This session includes papers on terahertz imaging of burn tissue through bandages, terahertz spectroscopy using transient mirror techniques, and high-speed modulators for millimeter wave detection and spectroscopy.

The general area of terahertz technology is still very much under development, and only limited options exist for sources, detectors, and imaging in general. For the reader's benefit, we here include a representative summary of currently used terahertz radiation sources and terahertz radiation detectors arranged in tabular form.

Table 1. Summary of the more common terahertz radiation sources. The top four entries are traveling electron sources, the fifth entry is a gas source laser with remarkably broad spectral coverage depending on the choice of gas, while the other entries are solid-state sources.

Terahertz radiation 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
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,	
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
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)	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.
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
Electrically pumped Ge	* 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
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
Direct multiplied mm waves	* Multiplied to low-THz region	Low power (uW level), available (VA Diodes)
		Used for heterodyne local oscillators in astronomy
Parametric generators	* Q-switched Nd:YAG pumps MgO:LiNbO3	High pulsed power, room temperature
	non-linear crystal	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, 2 to 4 THz	Not commercially available, require cryo-cooling
Transistor	* InGaAs channel HEMT with 60 nm gate	Under development at Inst. Elec. Micro, Lille
	* InGaAs with 12.5 nm gate, 0.845 THz	Univ. Illinois (Dec. 2006)

Table 2. Summary of the more common terahertz radiation detector types.

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
AlGaAs, InGaAs, & Si FET to 300K	* HEMT with 250 nm gate	Cryo and room temperature
	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.

Inevitably this summary is not all-inclusive. It is intended to present most of the commonly used terahertz source and detection components, representative features, advantages, disadvantages, relative performance, cost, and availability. As developments continue in this active field, we would like to update these tables on an ongoing basis, and suggestions for any additions or modifications to this list would be greatly appreciated, and can be sent to klinden@spirecorp.com.

In summary, this sixth conference on terahertz and gigahertz electronics and photonics demonstrates continued progress in both modeling and experimental demonstration areas, and touches on the rapidly evolving field of metamaterials for use in terahertz optics.

For individuals who wish to obtain a broader technical background in and deeper understanding of terahertz and gigahertz technologies, some representative review articles, including an article dealing with the rapidly evolving field of metamaterials, are listed in chronological order:

D.M. Mittlemen, R.H. Jacobson and M.C. Nuss, “T-Ray Imaging,” IEEE J. Sel. Topics in QE **2**, 679-692 (1996).

P.H. Siegel, “Terahertz Technology,” IEEE Trans. MTT **50**, 910-928 (2002).

D.L. Woolard, E.R. Brown, M. Pepper, and M. Kemp, “Terahertz Frequency Sensing and Imaging: A Time of Reckoning Future Applications?” Proc. IEEE **93**, 1722-1743 (2005).

C. Caloz and T. Itoh, "Metamaterials for High-Frequency Electronics," Proc. IEEE **93**, 1744-1752 (2005).

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