Asia Pacific Microwave Conference, Kyoto, Japan Nov. 19-22, 2002
Invited

Terahertz Technology and Applications

Peter H. Siegel
California Institute of Technology Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91011
phs@merlin.jpl.nasa.gov

Abstract—*THz applications and instrument technology drivers are briefly reviewed. Emphasis is placed on the more prevalent science motivations: space, planetary and Earth remote sensing and spectroscopy. Some of the more unusual and more recent applications for THz instrumentation will be mentioned. An introduction to the THz field and a bit of historic background is also presented.*

I. INTRODUCTION

THz technology and applications have long been the province of molecular astronomers and chemical spectroscopists. However, recent advances in THz detectors and sources have started to open the field up to new applications. Not surprisingly, there have been many attempts to utilize some of the unique attributes of the submillimeter wavelength bands in applications as diverse as detecting the water content of bulk paper to measuring the radar cross section of enormous ships and aircraft on small scale models. In this brief presentation we will take a look at some of the ways THz technology has been applied in the past and some of the current and future potential of this expanding field.

II. BACKGROUND

It is interesting to note that the term *terahertz* did not come into popular use until the mid 1970's [1] where it was employed by spectroscopists to describe emission or absorption frequencies that fell below the far infrared (IR). Before this, THz frequencies were officially designated by the term MMc or megamegacycles [2]. Today *terahertz* or *THz* is broadly applied to submillimeter-wave energy that fills the wavelength range between 1000 and 100 microns (300 GHz to 3 THz). Below 300 GHz we cross into the millimeter-wave bands. Beyond 3 THz, and out to 30 microns (10 THz) is more or less unclaimed territory as few if any components exist. The border between far IR and submillimeter is still rather blurry and the designation is likely to follow the methodology (bulk or modal – photon or wave), which is dominant in the particular instrument.

Despite great scientific interest since at least the 1920's [3], the THz frequency range remains one of the least tapped regions of the electromagnetic spectrum. Sandwiched between traditional microwave and optical technologies where there is a limited atmospheric propagation path, little commercial emphasis has been placed on THz systems. This has, perhaps fortunately, preserved some unique science and applications for tomorrow's technologists. For over 25 years the sole niche for THz technology has been in the high resolution spectroscopy and remote sensing areas where heterodyne and Fourier transform techniques have allowed astronomers, chemists, Earth, planetary and space scientists to measure, catalog and map thermal emission lines for a wide variety of lightweight molecules. As it turns out, nowhere else in the electromagnetic spectrum do we receive so much information about these chemical species. In fact, the universe is bathed in THz energy; most of it going unnoticed and undetected.

Commercial uses for THz sensors and sources are just beginning to emerge as the technology enables new instrumentation and measurement systems. So called T-Ray imaging is tantalizing the interests of the medical community and promises to open the field up to the general public for the first time. Other less pervasive applications have been proposed, all of which would benefit from broader-based interest in the field. We will try to touch on some of the more popular applications in the course of this short review.

III. THZ APPLICATIONS

The wavelength range from 1mm to 100 μm corresponds to an approximate photon energy between 1.2 and 12.4 meV or to an equivalent black body temperature between 14 and 140 Kelvin, well below the ambient background on Earth. A quick look at the spectral signature of an interstellar dust cloud [4] however, explains why astronomers are so interested in THz sensor technology. Besides the continuum, interstellar dust clouds emit (upon a very non-quantitative survey) at least forty thousand individual spectral lines, only a few thousand of which have been resolved and many of these have not been identified. Much of the THz bands have yet to be mapped with sufficient resolution to avoid signal masking from spectral line clutter or obscuration from atmospheric absorption. Results from the NASA Cosmic Background Explorer (COBE) Diffuse Infrared Background Experiment (DIRBE) and examination of the spectral energy distributions in observable galaxies, indicate that approximately half of the total luminosity and 98% of the photons emitted since the Big Bang fall into the submillimeter and far infrared [5]. Much of this energy is being radiated by cool interstellar dust. Older galaxies, like our Milky Way, have a much greater abundance of dust [6], making submillimeter detectors true probes into the early universe. In addition, red shifted spectral lines from the early universe appear strongly in the far-IR where they are less obscured by intervening dust, that often hides our view of galactic centers. Individual emission lines such as C^+ at 158 microns (1.9 THz), the brightest line in the Milky Way submillimeter-wave spectrum, provide a detailed look at star forming regions where surrounding dust is illuminated by hot young ultraviolet emitting stars. Many other abundant molecules: water, oxygen, carbon monoxide, nitrogen, to name a few, can be probed in the THz regime. Since these signals are obscured from most Earth based observations (except from a very few high altitude observatories, aircraft or balloon platforms), they provide strong motivation for space astrophysics instruments worldwide, notably NASA's Submillimeter Wave Astronomy Satellite [7] ESA's Herschel [8] and Sweden's Odin [9]. For interstellar and intragalactic observations both high resolving power (large apertures) and high spectral resolution (1-100 MHz) are generally required. In the lower THz bands heterodyne detectors are generally preferred (although this is very application dependent). For the shorter wavelengths direct detectors offer significant sensitivity advantages. Probing inside star systems or galaxies requires extremely high angular resolution, obtainable only with untenably large diameter telescopes or from phase coherent interferometric techniques. In an apt comparison from [10], even a large submillimeter telescope like the James Clerk Maxwell 15m diameter telescope on Mauna Kea operating at 300 GHz has an angular resolution equivalent only to the human eye at 5000 Å. A ground-based (mountain top) interferometer ALMA (Atacama Large Millimeter Array) [11] based in Chile, which may have a baseline of 10 km or more and angular resolution better than 0.01 arc seconds is now being planned by NRAO and international partners and may well contain heterodyne spectrometers at frequencies as high as 1500 GHz.

Many of the same spectral signatures that are so abundant in interstellar and intragalactic space are also present in planetary atmospheres where background temperatures range from tens of Kelvin to several hundred K. Particularly important are thermal emission lines from gases that appear in the Earth's stratosphere and upper troposphere; water, oxygen, chlorine and nitrogen compounds, etc. that serve as pointers to the abundances, distributions and reaction rates of species involved in ozone destruction, global warming, total radiation balance and pollution monitoring. Many key species either have thermal emission line peaks or their first rotational or vibrational line emissions in the submillimeter, especially between 300 and 2500 GHz [12]. Again, these emission lines are best observed from platforms above the Earth's atmosphere. Several recent space instruments, in particular, NASA's Microwave Limb Sounder (MLS) [13], and Japan's Superconducting sub-MIllimeter wave Limb Emission Sounder (SMILES) on the Japanese Experimental Module of the International Space Station [14], have been designed to take advantage of the information content available through high resolution spectroscopic measurements of these gases at submillimeter-wave frequencies. Unlike the astrophysical sources, even modest diameter collecting surfaces are fully filled by the signal beam in atmospheric observations. Resolution requirements are set by the orbital path and speed or by the atmospheric processes themselves. In both limb sounding (scanning through the atmospheric limb along the tangent line) or nadir sounding (looking straight down through the atmosphere) precise spectral line shape information is required to separate out the effects of pressure and Doppler broadening at each altitude along the emission path. Spectral resolution of better than one part in a million is typically needed for line widths that range from tens of kHz in the upper stratosphere to 10 MHz or more lower down. In the lower stratosphere water and oxygen absorption makes the atmosphere optically thick in the THz bands and longer millimeter wavelengths must be used for chemical probing.

A last major space application for THz sensors is in planetary and small body (asteroids, moons and comets) observations. Understanding the atmospheric dynamics and composition of these Earth companion bodies allows us to refine models of our own atmosphere as well as gaining insight into the formation and evolution of the solar system. Surface-based (landers) or orbital remote sensing observations of gaseous species in the Venutian, Martian and Jovian atmospheres as well as around Europa and Titan have all been proposed. ESA is launching a submillimeter-wave radiometer on its Rosetta orbiter that will rendezvous with the comet Wirtanen and measure water and carbon monoxide emissions [15]. An exciting new application for submillimeter wave planetary remote sensing has been proposed that takes advantage of newly available wide spectral coverage [16] of heterodyne local oscillator sources to search for life signatures in thin planetary atmospheres, such as on Mars. Abundances of several parts per trillion are measurable for some species in the Martian atmosphere [17]. As with the Earth sounders, short wavelengths allow for small antennas (and therefore smaller instruments) and still provide adequate spatial resolution for many atmospheric processes. The products of high resolution submillimeter-wave remote sensing, such as composition, temperature, pressure, and gas velocity (winds) offer the planetologist a wealth of information on a global scale.

Back on Earth, the two most pervasive applications for THz technology have been in the areas of plasma fusion diagnostics [18] and gas spectroscopy. Most of the measurements involve determination of the electron density profile as a function of position and time in the plasma core. Identification of the power spectrum can be through Thomson scattering or detection of synchrotron radiation (spiraling electrons emitted from plasma discharges in a confined magnetic field via electron cyclotron emission, ECE). The temperature of the plasma can be inferred from the equivalent blackbody intensity recorded in a narrowband radiometer pointing along a radial line of sight into the plasma core. Since the magnetic field intensity in a toroidal plasma varies linearly along a radial path, the ECE frequency changes correspondingly ($\omega_f \alpha B$). Using either a scanned LO or a wide IF bandwidth, one can obtain a profile of the temperature distribution along the plasma radius. Another phenomenon associated with fusion plasmas that has a large effect on power balance is electron temperature fluctuations in the core. These appear in the output signal as white noise riding on top of the simple thermal electron noise. However, this additional output noise is correlated with position within the plasma and can therefore be separated out using interferometric techniques. Since this involves a minimum of two radiometers and benefits from many more, it has been a major driver for the development of heterodyne imaging systems at millimeter and submillimeter-wave frequencies.

The title of grandfather of THz technology belongs to the molecular spectroscopists, especially early pioneers like W. King, W. Gordy, C.M. Johnson and C. H. Townes, to name a select few. Although many of the measurements were (and still are) performed with broadband Fourier transform spectrometers using thermal sources and bolometric detectors, much of the later heterodyne instrumentation (sources and detectors) as well as modern ultrasensitive direct detector technology owe their origins to this field. The draw of submillimeter-wave spectroscopy as opposed to more readily realized microwave spectroscopy, is in the strengths of the emission or absorption lines for the rotational and vibrational excitations of the lighter molecules. Since these lines tend to increase in strength as f^2 or even f^3 and often peak in the submillimeter, there is a strong natural sensitivity advantage in working at THz frequencies. Modern applications foreseen for THz spectroscopy (besides categorizing and compiling specific spectral line emissions) involve rapid scan and gas identification systems such as targeted molecule radar's for detecting and identifying noxious plumes [19] or very versatile systems like FASSST (FAst Scan Submillimeter Spectroscopic Technique) developed at Ohio State [20] and optical pulse terahertz time domain spectroscopy instruments [21] (the T-Ray imagers described shortly). Such systems could conceivably measure and rapidly identify such diverse spectral signatures as simple thermal absorption from an intervening gas to dangling molecular bonds on the surface of a solid. Following on this concept, proposals have been made for THz detection of DNA signatures through dielectric resonances (phonon absorption) [22] and for detection of hazardous bio and chemical plumes using active submillimeter wave systems. It is too early to tell what unique applications such systems will have, but the potential for interesting science as well as deployable instruments is certainly there.

Since so little instrumentation is commercially available for THz measurements, and what does exist is generally too costly for any but the most well funded institutions, other drivers for the technology have been very slow to take hold. Strong 183 and 557 GHz water lines have been proposed for many planetary and space sensor passive emission measurements including potential life detection, but these same spectral lines (or many others) can be used to determine water content of materials through transmission measurements. At least one application for characterizing the water content of newspaper print has been proposed [23] and patented. Another application that was demonstrated and actually made into a commercial system, came out of United Technologies Research Center in the early 1980's and involved using optically pumped far IR lasers to detect small voids in electric power cable [24]. Mie scattering from a focused far IR laser running methanol at 118 μm was used to detect voids with radii on the order of λ in a polyethylene-covered coax. The prototype seemed to work nicely and could detect both the size and position of the voids as well as defects in the inner conductor and particulate scattering. Unfortunately, before the application could take hold, the cable manufacturing process was changed to one in which a semiconducting outer coating was applied to the polyethylene sheath making the cable impenetrable at THz frequencies!

The atmospheric opacity severely limits radar and communications applications at THz frequencies, however some close-in systems have been proposed and studied [25]. Secure communications (through high attenuation outside the targeted receiver area) or secure intersatellite systems, benefit from the small antenna sizes needed to produce highly directional beams as well as the large information bandwidth allowed by THz carriers. Operation in the stratosphere (air-to-air links) is particularly advantageous for THz communications or radar systems because of the low scattering compared to IR and optical wavelengths (proportional to f^2 rather than f^4) and the much greater penetration through aerosols and clouds. Although concepts for ultrawide bandwidth "pocket" communications transceivers have been floated for years, the problems inherent in producing small and efficient THz transmitters or local oscillator sources to drive heterodyne systems have so far precluded any commercial development in this area, however new photoconductor components may soon change all of this.

Another rather clever application for the small spot size associated with THz wavelengths has been to use THz sources to illuminate scale models of large objects thereby simulating the radar scattering signatures (RCS) that would be obtained at much lower frequencies on actual equipment such as planes, tanks and battleships [26]. The savings in anechoic test chamber dimensions alone make the high cost of THz test systems attractive in comparison! Solid-state sources have been used in these test chambers up to 660 GHz and in earlier systems far IR lasers were employed at 1.2, 2.5, and 3.1 and 8 THz. Complete 3D synthetic aperture radar images can be processed with this system, by using dual polarization heterodyne transceivers and a special stepped CW scheme which gates out the effects of unwanted signals or chamber reflections.

Perhaps the most intriguing application for commercializing THz technology at this time is in the area of THz time domain spectroscopy or T-Ray imaging [27,28]. In this technique, pioneered by Martin Nuss and others at Bell Laboratories in the mid 1990's [29] and recently picked up by at least two commercial companies, Picometrix in the US and Teraview, a spin-off of Toshiba Research Europe Ltd. in the UK, in-situ measurements of the transmitted or reflected THz energy incident upon a small sample are processed to reveal spectral content (broad signatures only), time of flight data (refractive index determination, amplitude and phase, and sample thickness), and direct signal strength imaging. The principle involves generating and then detecting THz electromagnetic transients that are produced in a photoconductor or a crystal by intense femtosecond optical laser pulses. The laser pulses are beam split and synchronized through a scanning optical delay line and made to strike the THz generator and detector in known phase coherence. By scanning the delay line and simultaneously gating or sampling the THz signals incident on the detector a time dependent waveform proportional to the THz field amplitude and containing the frequency response of the sample is produced. Scanning either the THz generator or the sample itself allows a 2D image to be built up over time. Recent innovations are leading to both rapid scanning and true 2D sampling using CCD arrays. In the Picometrix and Lucent technologies systems the photoconductive effect in low temperature grown GaAs or radiation damaged silicon on sapphire is used for both the generator and detector. The Teraview system uses THz generation via difference frequency mixing in a nonlinear crystal (ZnTe) and detection via the electro-optical Pockels effect (measuring the change in birefringence of ZnTe induced by THz fields in the presence of an optical pulse) as first demonstrated by X.C. Zhang at RPI [30]. The femtosecond optical pulses are currently derived from expensive Ti:Sapphire lasers but much effort is being placed on longer wavelength, especially 1.5 micron, solid-state systems that can take better advantage of fiber technology. The RF signals produced by the optical pulses typically peak in the 0.5 to 2 THz range and have average power levels in the microwatt range and peak energies around a femtojoule. This makes T-Ray imaging a very attractive tool for the medical community (non-invasive sampling) as well as for nondestructive probing of biological materials or electronic parts. The technique is rapidly gaining an enormous following and is purged to be an exploding commercial success once the system can be made less costly (replacement of the Ti:Sapphire laser with solid-state devices), faster (through 2D imaging techniques) and somewhat more sensitive (with better sources and detectors). A wide range of applications already exist and many more will likely appear as commercial systems begin to disseminate.

Finally, there are several new and untested applications that might evolve from advances in THz component technology. At JPL, a room temperature THz heterodyne camera has been proposed that would have many times the sensitivity of the T-Ray imager, as well as the frequency resolution of the scanning spectrometer or single pixel receivers now in common use for Earth science applications. Similarly cryogenic direct detector cameras have been proposed for the submillimeter [31] with extremely low NEP (noise equivalent power) capability. These next generation instruments should enhance the T-Ray applications as well as opening up new opportunities. Leaving the sensors world, microminiature THz power converters (microrectifiers) that might be incorporated onto microrobots and operate in-vivo or in hostile environments are being developed [32]. These microrectennas could give new meaning to the term miniature power supply! These applications as well as many others might be enabled by THz vacuum nanotube sources [33]. A web search for other applications will turn up several curious articles that should be of interest to the adventurous reader!

IV. SUMMARY

In this short review the author has attempted to give the reader a flavor of several of the major factors driving THz technology development. As THz components become commercially available new applications will open up. There is still an enormous gap in the source area that remains to be filled, but progress is being made on several fronts, including solid-state and gas based lasers, frequency multipliers and amplifiers, photoconductive and photoconversion techniques and even direct oscillators based on vacuum tubes. THz sensors are remarkably mature and single photon counting direct detection is now a reality [34]. As these sensors and sources become more available, more complex circuits and eventually complete instruments will follow. We have not even scratched the surface in this area and many more pages would be needed to do justice to the component developments that have taken place already at THz frequencies. On the instrument side we are just beginning to see emerging systems. A THz network analyzer is commercially available [35], near field antenna measurements have been performed at 640 GHz at JPL, a recently demonstrated millimeter-wave near field microscope technique [36] promises micron resolution THz imaging once sources have been developed, the T-Ray system is now being employed on a wide variety of samples from the electronics industry to medical diagnostics and will likely be the medium for introducing the public to THz wavelengths for the first time. As laser systems advance so that the pulsed and higher power bench-top models are replaced by solid-state semiconductor devices there will be dramatic reductions in the instrument envelopes as well as tremendous cost savings. In the space science community, submillimeter waves have already reached their golden era and the groundwork for a long string of astrophysics, Earth and planetary sensor systems has been laid. Ultimately, the author hopes that submillimeter systems will complement near IR and optical sensors for measurements in the search for extraterrestrial life. All of these exciting applications and countless undiscovered ones remain in wait while THz applications continue to expand.

V. ACKNOWLEDGEMENTS

This article could not have been written without the many conversations and contributions the author had from his friends and colleagues in the submillimeter-wave field. Due to space limitations only a few of the many references that the author has tapped have been explicitly listed. For a more comprehensive list the reader is referred to [37]. Finally, the author would like to thank all the members of the JPL Submillimeter Wave Advanced Technology (SWAT) team for their many contributions to NASA applications and to THz technology This task was supported by the California Institute of Technology Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration.

VI. REFERENCES

1 The Oxford English Dictionary dates the term terahertz back to at least 1970 where it was used to describe the frequency range of a HeNe laser.

2 In 1947, the Int. Telecommunications Union designated the highest official radio frequency bands (EHF-extremely high frequency) as bands 12-14, 300kMc-300MMc (1 MMc=1 THz).

3 E.J. Nichols and J.D. Tear, "Joining the Infrared and Electric Wave Spectra," Astrophysical Journal, vol. 61, pp. 17-37, 1925.

4 T.G. Phillips and J. Keene, "Submillimeter Astronomy," Proceedings of the IEEE, vol. 80, no. 11, pp. 1662-1678, Nov. 1992.

5 D. Leisawitz et.al., "Scientific motivation and technology requirements for the SPIRIT and SPECS far-infrared/submillimeter space interferometers," Proceedings of the SPIE: UV, Optical and IR Space Telescopes and Instruments, vol. 4013, Munich, Germany, pp.36-46, March 29-31, 2000.

6 L..Silva, G. L. Granato, A. Bressan, & L. Danese , "Modeling the Effects of Dust on Galactic Spectral Energy Distributions

from the Ultraviolet to the Millimeter Band," Astrophysical Journal, vol. 509, no.1, pp. 103-117, Dec. 10, 1998.

7 G. Melnick et.al., "The Submillimeter Wave Astronomy Satellite: Science Objectives and Instrument Description," Astrophys. J. Lett., vol. 539, Number 2, Part 2, pp.L77-L85, August 20, 2000.

8 N. Wyborn, "The HIFI Heterodyne Instrument for FIRST: Capabilities and Performance," ESA Symposium: The Far InfraRed and Submillimetre Universe, Grenoble, France, pp. 19-24, 15-17 April 1997.

9 F. von Schéele, "The Swedish Odin Satellite to Eye Heaven and Earth," Swedish Space Corporation, © 1996. http://www.ssc.se/ssd/papers/odeye/odeye.html

10 John C. Mather, S. Harvey Moseley, Jr., David Leisawitz, et. al., "The Submillimeter Frontier: A Space Science Imperative," preprint available from: http://xxx.lanl.gov/abs/astro-ph/9812454

11 R.L. Brown, "Technical Specification of the Millimeter Array," Proceedings of the SPIE, no. 3357, pp. 231-441, 1998.

12 J.W. Waters, "Submillimeter-Wavelength Heterodyne Spectroscopy and Remote Sensing of the Upper Atmosphere," Proceedings of the IEEE, vol. 80, no. 11, pp. 1679-1701, Nov. 1992.

13 J. W. Waters et.al., "The UARS and EOS Microwave Limb Sounder (MLS) Experiments," J. of the Atmospheric Sciences, vol. 56, No. 2, pp. 194–218, Feb. 1999.

14 J. Inatani, et.al. "Submillimeter limb-emission sounder JEM/SMILES aboard the Space Station," Proceedings of SPIE, "Remote Sensing of the Atmosphere, Environment and Space," vol. 4152, Nara, Japan, session 4152-36, 9-12 October, 2000.

15 S. Gulkis, M. Frerking, G. Beaudin , P. Hartogh , M. Janssen, C. Kahn, T. Koch and Y. Salinas, "Microwave Instrument For The Rosetta Orbiter (MIRO)," ESA-SP 1165, (special publication) Noordwijk, Netherlands, in Press 2002.

16 Imran Mehdi, Erich Schlecht, Goutam Chattopadhyay and Peter H. Siegel, "THz Local Oscillator Sources," presented at the NASA/Ames Far IR, Sub-MM and MM Detector Workshop, Monterey, CA, April 1-3, 2002.

17 P.H. Siegel, J.E. Oswald, G. Chin and M. Allen, "SIGNAL: Submillimeter Instrument for Gauging the Natural Abundance of Life," proposal to NASA Scout program, June 2002.

18 N.C. Luhmann and W.A. Peebles, "Instrumentation for magnetically confined fusion plasma diagnostics. Review of Scientific Instruments, vol.55, (no.3), pp. 279-331, March 1984.

19 N. Gopalsami and A.C. Raptis, "Remote detection of chemicals by millimeter wave spectroscopy," Proc. SPIE Int. Conf. on Millimeter and Submm. Waves and Applications IV, San Diego, CA, pp.254-265, July 1998.

20 F. DeLucia and S. Albert, "Fast-scanning spectroscopic method for the submillimeter: the FASSST spectrometer," SPIE Proceedings Vol. 3465, Millimeter and Submillimeter Waves IV, San Diego, CA, pp.236-246, 1998.

21 R.H. Jacobsen, D.M. Mittleman and M.C. Nuss, "Chemical recognition of gases and gas mixtures with terahertz waves," Optics Letters, vol. 21, no. 24, pp. 2011-2013, Dec. 1996.

22 D. Woolard, R. Kaul, R. Suenram, A.H. Walker, T. Globus and A. Samuels, "Terahertz Electronics for Chemical and Biological Warfare Agent Detection," 1999 IEEE MTT-S Int. Micr. Sym. Digest, Anaheim, CA, pp. 925-928, June 13-19, 1999.

23 R. Boulay, R. Gagnon, D. Rochette and J.R. Izatt, "Paper sheet moisture measurements in the far infrared," Int. Journal of Infrared and Millimeter Waves, vol. 5, no. 9, pp. 1221-34, 1984.

24 A. J. Cantor, P. Cheo, M. Foster and L. Newman, "Application of submillimeter wave lasers to high voltage cable inspection," IEEE Journal of Quantum Electronics, vol. QE-17, no. 4, pp.477-489, April 1981.

25 D. Woolard, "Terahertz electronic research for defense: novel technology and science," Eleventh Int. Sym. on Space THz Technology, Ann Arbor, MI, pp.22-38, May 1-3, 2000.

26 J. Waldman, H. R. Fetterman, P. E. Duffy, T. G. Bryant, P. E. Tannenwald, "Submillimeter Model Measurements and Their Applications to Millimeter Radar Systems," Proc. Fourth Int. Conf. Infrared & Near-Millimeter Waves, pp. 49-50, Dec. 1979.

27 S. Hunsche and M.C. Nuss, "Terahertz 'T-Ray' Tomography," Proc. SPIE Int. Conf. on Millimeter and Submm. Waves and Applications IV, San Diego, CA, pp. 426-433, July 1998.

28 D.D. Arnone, et.al. "Applications of Terahertz (THz) Technology to Medical Imaging," Proc. SPIE: Terahertz Spectroscopy and App. II, v. 3823, Munich, Germany, pp. 209-219, 1999.

29 B.B. Hu and M.C. Nuss, "Imaging with terahertz waves," Optics Letters, vol. 20, no. 16, pp. 1716-1718, Aug. 15, 1995.

30 Q. Wu, T.D. Hewitt and X-C. Zhang, "Two-Dimensional Electro-optic Imaging of THz Beams," Applied Physics Letters, vol. 69, no. 8, pp. 1026-1028, 19 August 1996.

31 S. Ariyoshi, H. Matsuo, M. Takeda and T. Noguchi, "Design of submillimeter-wave camera with superconducting direct detectors," Twelfth Int. Sym. on Space THz Technology, San Diego, CA, paper 5.9, Feb. 14-16, 2001.

32 P.H. Siegel, "Nanoconverters: Remote DC Power for Nanodevices." JPL New Technology Report, November 27, 2000.

33 P.H. Siegel, "A Frequency Agile Nanoklystron," JPL New Technology Report, NPO 21033, March 31, 2000.

34 S. Komiyama, O. Astafiev, V. Antonov, H. Hirai and T. Kutsuwa, "A single-photon detector in the far-infrared range," Nature vol. 405, pp. 405-407, 27 Jan. 2000.

35 P. Goy, S. Caroopen and M. Gross, "Dual-frequency vector measurements up to the THz and beyond, with a single detector," Twelfth Int. Conf. on Space THz Tech., San Diego, CA, paper 5.7, Feb. 14-16, 2001.

36 T. Nozokido, J. Bae and K. Mizuno, "Scanning near field millimeter-wave microscopy using a metal slit as a scanning probe," IEEE Trans. MTT., v.49, no.3, pp. 491-499, March 2001.

37 P.H. Siegel, "Terahertz Technology," IEEE Trans. MTT, vol. 80, no.3, pp.910-928, March 2002.