Terahertz Technology

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Invited Paper

***Abstract*—Terahertz technology applications, sensors, and sources are briefly reviewed. Emphasis is placed on the less familiar components, instruments, or subsystems. Science drivers, some historic background, and future trends are also discussed.**

***Index Terms*—Applications, submillimeter, technology, THz.**

I. Introduction

THESE DAYS, it is not possible to do justice to an entire field or give sufficient credit to all its deserving technical innovators in one short paper, even in a relatively narrow area of development like terahertz technology. If this were the case, we would not have such a plethora of journals to submit to, nor conferences to attend. One thing is certain, the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), through its journals and sponsored conferences, has played a major role in defining, distributing information on, and advancing the field of terahertz technology since the society's inception a half-century ago. During the course of this paper, we look back to the infancy of modern terahertz technology, beginning where Wiltse so ably left off in 1984 [1], pass through early childhood, and end up at adolescence. The field is perched on adulthood and perhaps, in another quarter-century, a more complete history can be written, hopefully by someone reading this paper today.

II. Background

The first occurrence of the term *terahertz* in this TRANSACTIONS is attributed to Fleming [2] in 1974, where the term was used to describe the spectral line frequency coverage of a Michelson interferometer. A year earlier, Kerecman [3] applied terahertz to the frequency coverage of point contact diode detectors in an IEEE MTT-S conference digest paper. Ashley and Palka [4] used the designation to refer to the resonant frequency of a water laser in the same digest. Spectroscopists had much earlier coined the term for emission frequencies that fell below the far infrared (IR).[1] Today, *terahertz* is broadly applied to submillimeter-wave energy that fills the wavelength range between 1000–100 μm (300 GHz–3 THz). Below 300 GHz, we cross into the millimeter-wave bands (best delimited in the author's opinion by the upper operating frequency of WR-3 waveguide—330 GHz). Beyond 3 THz, and out to 30 μm (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 1920s [5], the terahertz 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 [6] (Fig. 1), little commercial emphasis has been placed on terahertz systems. This has, perhaps fortunately, preserved some unique science and applications for tomorrow's technologists. For over 25 years, the sole niche for terahertz 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 terahertz energy; most of it going unnoticed and undetected.

This review will examine terahertz technology today with emphasis on frequencies above 500 GHz and on applications that may not be familiar to every reader. We will also try to do justice to molecular spectroscopy for Earth, planetary, and space science, the chief drivers of terahertz technology to-date. An excellent overview of lower frequency millimeter and submillimeter-wave technology can still be found in the review papers of Coleman [7], [8] and Wiltse [1]. Commercial uses for terahertz 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 cover some of these and anticipate others in the course of this paper.

We begin with a survey of terahertz applications in Section III, and follow this with some selected information on terahertz components in Section IV. More detailed discussions on terahertz components, materials, and techniques cannot be covered. We conclude with some fanciful applications and predictions in Section V.

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[1]The *Oxford English Dictionary* dates the term "terahertz" back to at least 1970 where it was used to describe the frequency range of an HeNe laser. In 1947, the International Telecommunications Union designated the highest official radio frequency bands [extremely high frequency (EHF)] as bands 12–14, 300 kMc–300 MMc (1 MMc = 1 THz).

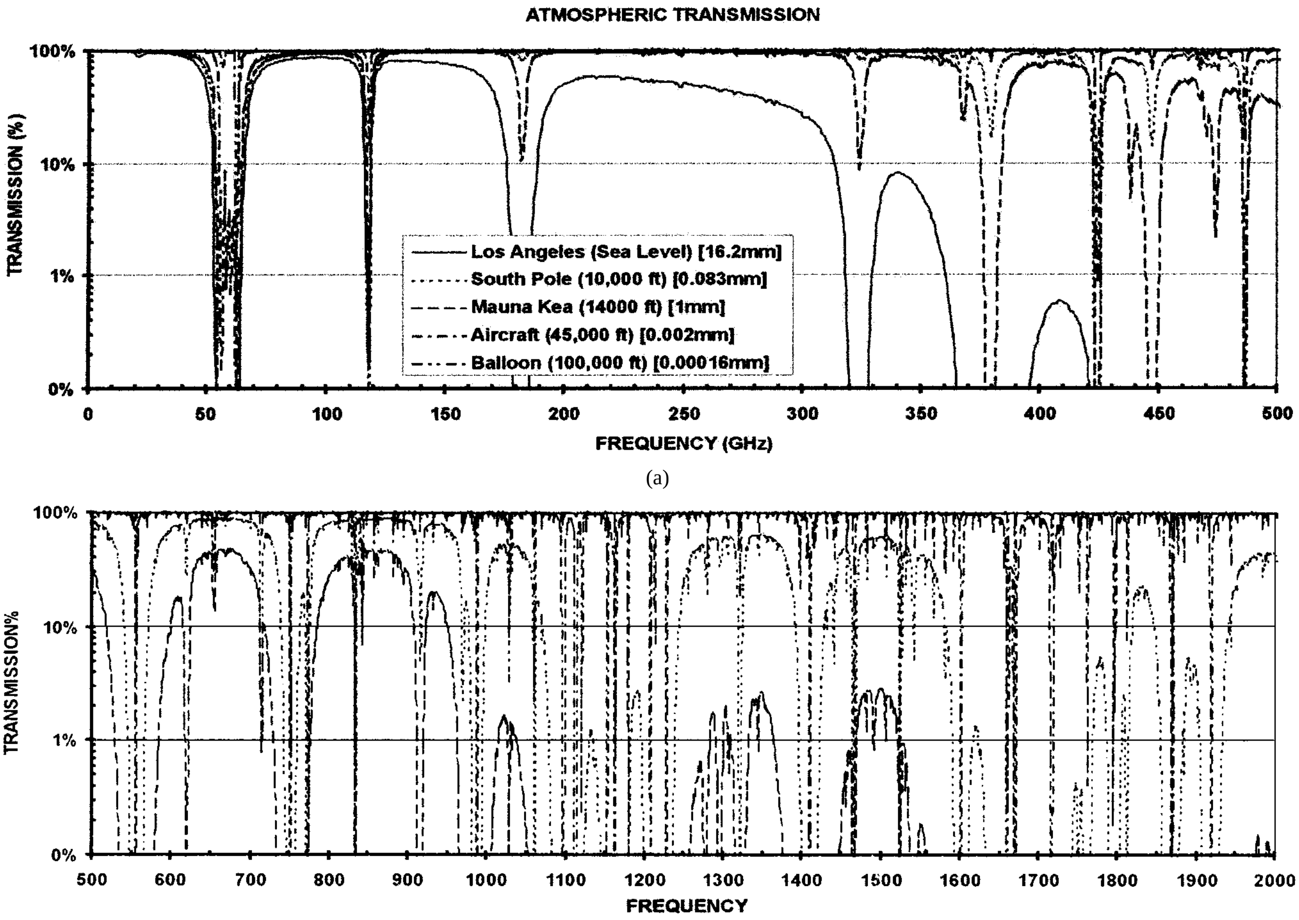


Fig. 1. Atmospheric transmission in the terahertz region at various locations and altitudes for given precipitable water vapor pressure (in millimeters). (a) 0–500 GHz. (b) 500–2000 GHz. Data from Erich Grossman using his "Airhead Software" [6].

III. Terahertz Applications

The wavelength range from 1 mm to 100 μm corresponds to an approximate photon energy between 1.2–12.4 meV or to an equivalent black body temperature between 14–140 K, well below the ambient background on Earth. A quick look at the spectral signature of an interstellar dust cloud (Fig. 2), however, explains why astronomers are so interested in terahertz sensor technology. An excellent science review can be found in Phillips and Keene [9]. Fig. 2 shows the radiated power versus wavelength for interstellar dust, light, and heavy molecules, a 30-K blackbody radiation curve, and the 2.7-K cosmic background signature. Besides the continuum, interstellar dust clouds likely emit some 40 000 individual spectral lines, only a few thousand of which have been resolved and many of these have not been identified. Much of the terahertz 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 one-half of the total luminosity and 98% of the photons emitted since the Big Bang fall into the submillimeter and far-IR [10]. Much of this energy is being radiated by cool interstellar dust. Older galaxies, like our Milky Way, have a much greater abundance

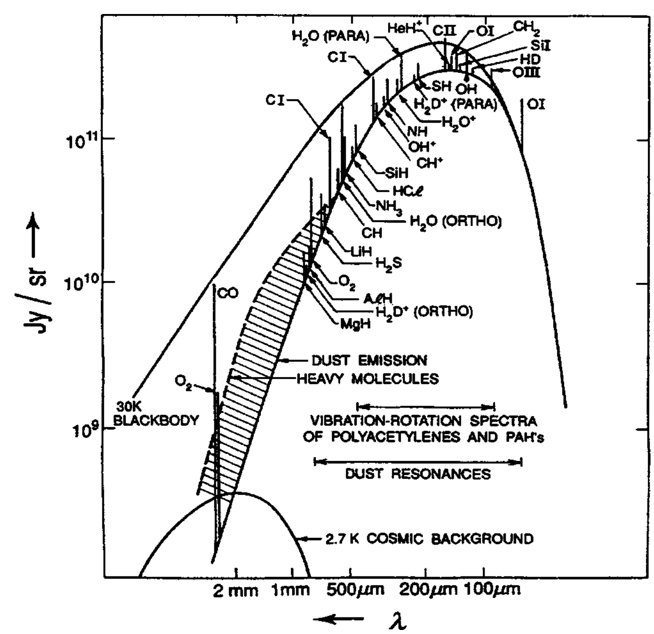


Fig. 2. Radiated energy versus wavelength showing 30-K blackbody, typical interstellar dust, and key molecular line emissions in the submillimeter (reprinted from [9]).

of dust (Figs. 3 and 4) making submillimeter detectors true probes into the early universe. In addition, red shifted spectral

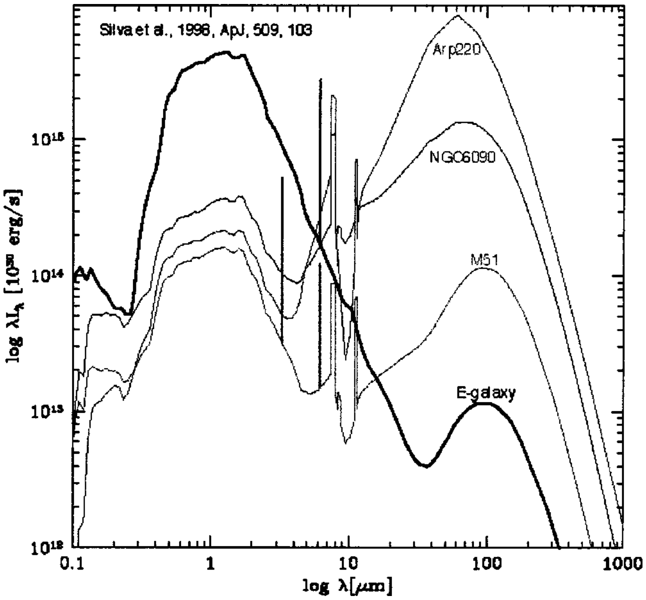


Fig. 3. Energy output versus wavelength for galaxies of ascending ages (E-galaxy = youngest, Arp220 = oldest) showing the advantages of terahertz detection systems for probing the early universe [courtesy of W. Langer, Herschel Space Observatory archive, Jet Propulsion Laboratory (JPL)].

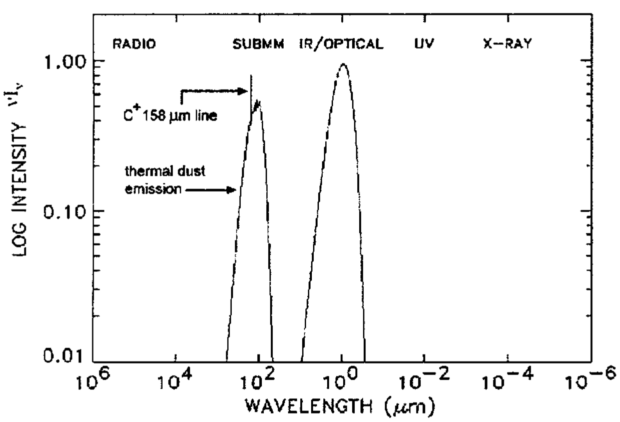


Fig. 4. Spectrum of our Milky Way galaxy showing that at least one-half of the luminous power is emitted at submillimeter wavelengths. The intensity of the ionized carbon emission line at 1.9 THz shows how incredibly abundant this element is (the most after hydrogen, helium, and oxygen) (courtesy of D. Leisawitz *et al.* [10] and W. Langer, Herschel Space Observatory archive, JPL).

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 μm (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, e.g., water, oxygen, carbon monoxide, nitrogen, to name a few, can be probed in the terahertz 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 a number of existing or upcoming space astrophysics instruments, most notably the Submillimeter Wave Astronomy Satellite (SWAS) [11], launched in December 1998, and currently sending back data on water, oxygen, neutral carbon, and carbon monoxide in interstellar space; and in the near future, the European Space Agency's (ESA) Herschel [12] [formerly the Far InfraRed and Submillimeter space Telescope (FIRST)] scheduled for 2007 and NASA's proposed Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) [13], SPace InfraRed Interferometric Telescope (SPIRIT) [10], and Filled Aperture InfraRed telescope (FAIR) [14], which will examine this spectral region in great detail in the decade beyond 2010. For interstellar and intragalactic observations, both high resolving power (large apertures) and high spectral resolution (1–100 MHz) are generally required. In the lower terahertz 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 such as planned for SPIRIT and SPECS. In an apt comparison from [13], even a large submillimeter telescope like the James Clerk Maxwell 15-m-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 Atacama Large Millimeter Array (ALMA) [15] based in Chile, which may have a baseline of 10 km or more and angular resolution better than 0.01 arc/s is now being planned by the National Radio Astronomy Observatory (NRAO) and several international partners and may well contain heterodyne spectrometers at frequencies as high as 1500 GHz [16].

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 kelvin. 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 300–2500 GHz (Fig. 5) [17], [18]. Again, these emission lines are best observed from platforms above the Earth's atmosphere. Several recent space instruments, in particular, the Earth observing system microwave limb sounder (EOS-MLS) launching on Aura in 2003 with high-resolution heterodyne receivers at 118, 190, 240, 640, and 2520 GHz [19], 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

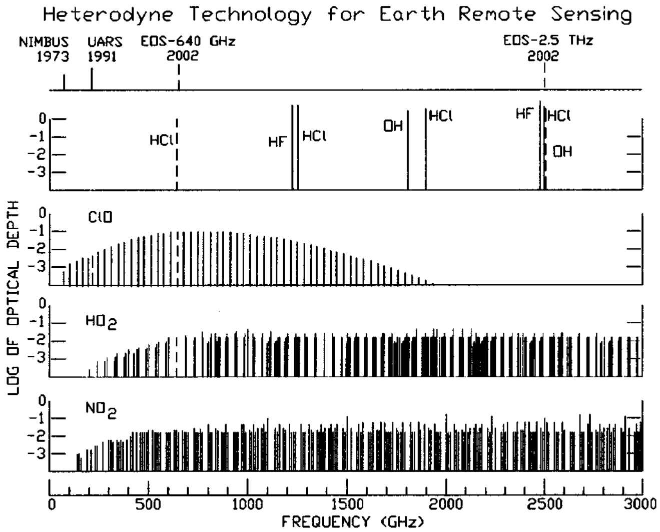


Fig. 5. Spectra of some important molecules in the Earth's upper atmosphere and measurements being addressed by NASA heterodyne instruments. The peak power or minimum frequency for many emission lines occurs in the terahertz region. Figure based on J. Waters, EOS Atmospheres presentation [17].

resolution of better than one part in a million is typically needed for linewidths that range from tens of kilohertz 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 terahertz bands and longer millimeter wavelengths must be used for chemical probing. Following a very successful deployment in September 1991 and many years of continuous data collection from the UARS microwave limb sounder [20], which carried heterodyne limb scanning spectrometers at 63, 183, and 205 GHz, several additional Earth sounders are planned for millimeter and submillimeter-wave observations over the next decade. Besides NASA's EOS-MLS, these include Sweden's Odin (astrophysics and Earth sounding at 118, 490, and 557 GHz) launched in February 2001 [21], the Japanese SMILES, Superconducting subMillimeter wave Limb Emission Sounder on the Japanese Experimental Module of the International Space Station (JEMS) planned for 2005 with a superconducting receiver at 640 GHz [22], [23], and still in study phase, the ESA's Submillimeter Observation of PRocesses in the Atmosphere Noteworthy for Ozone (SOPRANO) [24] and NASA's follow up to EOS-MLS, the Advanced Microwave Limb Sounder (AMLS) [25].

A last major space application for terahertz 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 [26]. 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 [27]. A soon to be launched (2003) ESA cornerstone observatory mission, Rosetta, contains a submillimeter-wave radiometer on Microwave Imager on the Rosetta Orbiter (MIRO) at 562 GHz, which will look at water vapor and carbon monoxide in the head and tail of comet Wirtanen [29]. 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. It is not unreasonable to suppose that the first detection of planets containing atmospheric conditions (temperature, pressure, composition) suitable for extraterrestrial life forms will be confirmed by terahertz spectroscopy. Such a discovery would surely justify the technology investment in this field. An excellent, but short, overview of terahertz applications for space can be found in [30].

Back on Earth, the two most pervasive applications for terahertz technology have been in the areas of plasma fusion diagnostics and gas spectroscopy. An excellent review of terahertz techniques in the fusion field with close to 400 references can be found in the paper by Luhmann and Peebles [31]. Most of the measurements involve determination of the electron density profile as a function of position and time in the plasma core [32]. 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 narrow-band radiometer pointing along a radial line of sight into the plasma core [33]. 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 local oscillator (LO) or a wide IF bandwidth, one can obtain a profile of the temperature distribution along the plasma radius [34]. 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 [35]. 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 [36]. Two-dimensional (2-D) and now three-dimensional (3-D) snapshot systems are being developed [34]. Typical tokamak systems have fundamental ECE resonances in the millimeter bands (100–150 GHz), however, much can be gained from terahertz measurements of the ECE harmonics and in regions where strong magnetic fields are found. A schematic of an operating 2-D imaging array using a 1-D line detector arrangement is shown in Fig. 6 [36]. The 2-D image is obtained by varying frequency (and, hence, penetration into the plasma).

The title of grandfather of terahertz technology belongs to the molecular spectroscopists, especially early pioneers like King, Gordy, Johnson, and Townes, to name a select few. Although many of the measurements were (and still are) performed with broad-band 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, owes

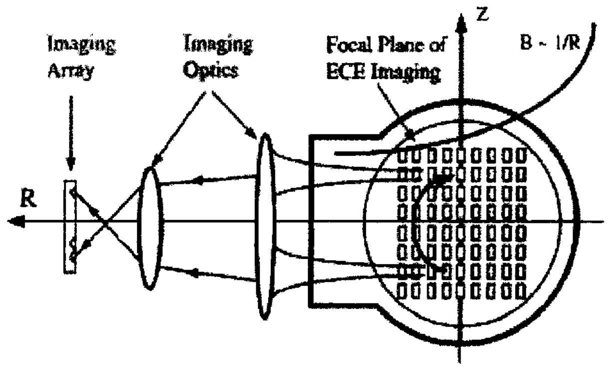


Fig. 6. Diagram of 2-D plasma ECE heterodyne imager using linear array of receive antennas for ∼100 GHz. LO power is incident from the rear of the array and distributed to each element by a cylindrical mirror (courtesy of [36], American Institute of Physics).

its origins to this field. The history of submillimeter-wave spectroscopy is well covered in [1] and the general field fills several texts [37]–[40], as well as over 50 years of annual conferences at Ohio State University, Athens.[2] 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 terahertz frequencies. Modern applications foreseen for terahertz 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 [41] or very versatile systems like the FAst Scan Submillimeter Spectroscopic Technique (FASSST) developed at Ohio State University [42], [43] and optical pulse terahertz time-domain spectroscopy instruments [44] (the T-ray imagers, which will be 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. A schematic and sample plots from FASSST appear in Fig. 7. The resolution of this system is in the 100-kHz range, it can scan and record ∼10 000 lines/s, and has a bandwidth of over 100 GHz (based around available voltage tunable backward-wave oscillators). The identification of signature gases can be done in milliseconds through lookup tables once an exact determination of the spectral line frequency has been made. Following on this concept, proposals have even been made for terahertz detection of DNA signatures through dielectric resonances (phonon absorption) ([45], [46], and Fig. 8). 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 terahertz measurements, and what does exist is generally too costly for any but the most well-funded institutions (if any still exist), other drivers for the technology have been very slow

[2]The Ohio State University International Symposium on Microwave Spectroscopy is currently in its 56th year.

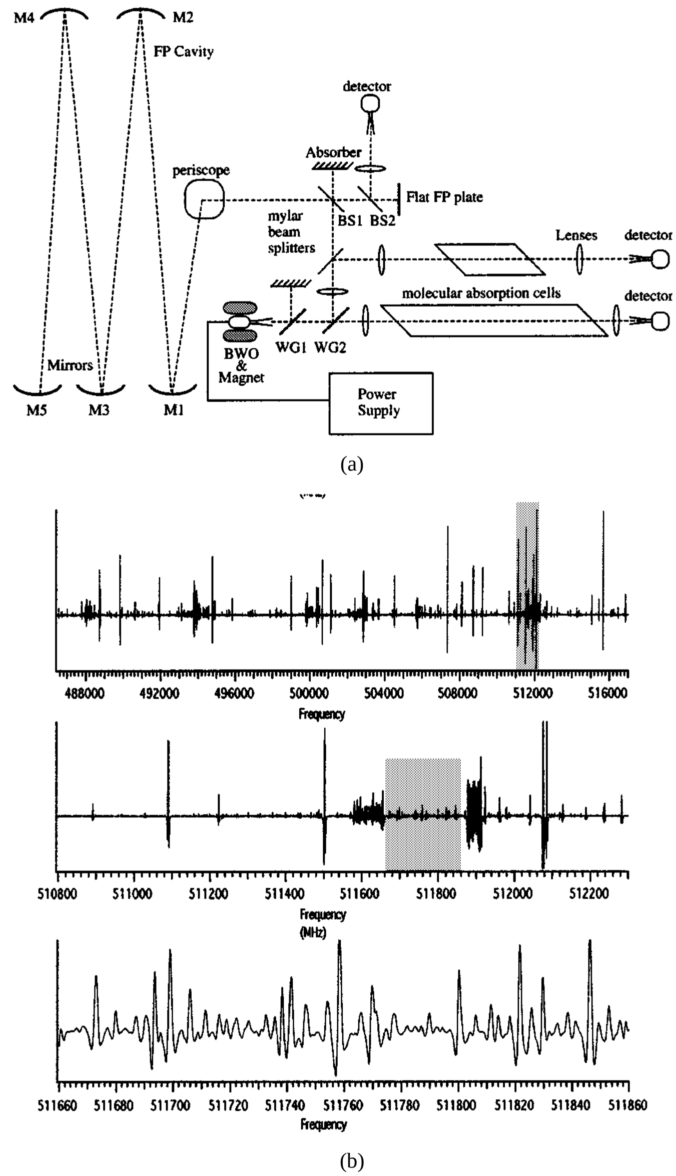


Fig. 7. (a) FASSST schematic. (b) Spectral plots at 500 GHz in increasing frequency resolution sweeps (top to bottom) for a combination of pyrrole, pyridine, and sulfur dioxide at 10 mTorr each (courtesy of [43]).

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 [47] and a patent filed [48]. Another application that was demonstrated and actually made into a commercial system, came out of United Technologies Research Center in the early 1980s and involved using optically pumped far-IR lasers to detect small voids in electric power cable [49]. 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, as shown by the data in Fig. 9, and could detect both the size and position of the voids, as well as defects in the inner conductor and particulate scattering. Unfortunately,

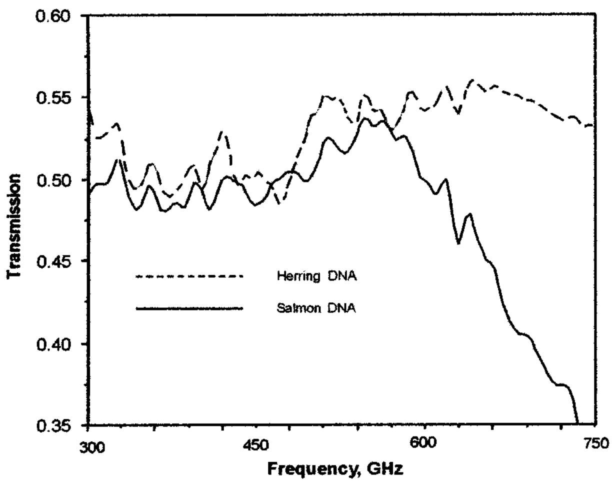


Fig. 8. Comparison of Herring and Salmon DNA transmission spectra using an FTS system (courtesy of [46]).

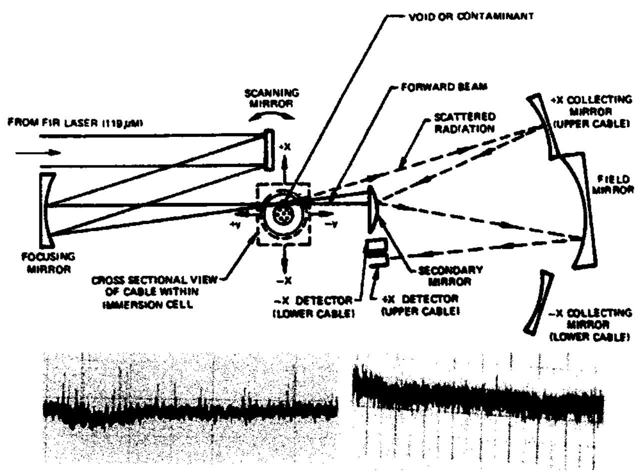


Fig. 9. 2.5-THz cable void inspection system and plots of scattered power from: (a) void-filled and (b) solid cable. Peaks are indicative of void size (courtesy of [49]).

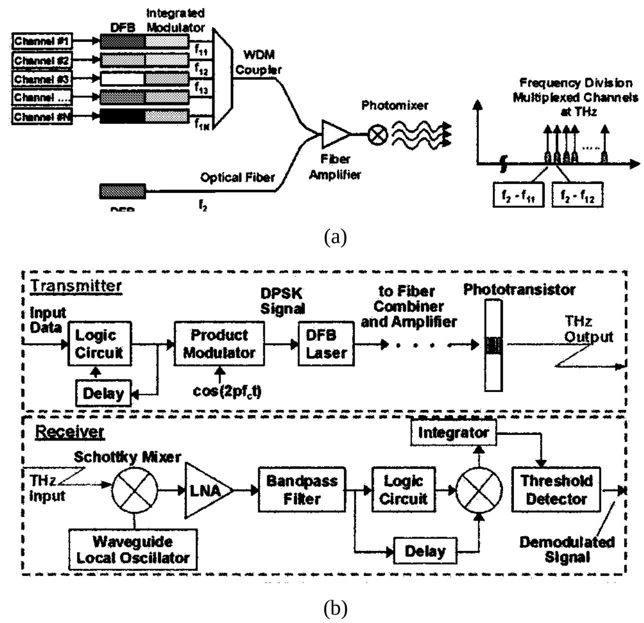


Fig. 10. (a) Optically diplexed terahertz transmitter source based on 1.5-μm fiber technology and terahertz power generation through photomixing. (b) Gigabit data-rate transmit/receive module based on this technology (courtesy of [52]).

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 terahertz frequencies [50].

The atmospheric opacity severely limits radar and communications applications at terahertz frequencies; however, some close-in systems have been proposed and studied [51]. 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 terahertz carriers. Operation in the stratosphere (air-to-air links) is particularly advantageous for terahertz 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. As can be seen from Fig. 1, stratospheric windows abound. A novel scheme for markedly increasing the bandwidth, number of discrete channels, and even adding track and scan capability to a terahertz communications system was proposed by Brown [52], taking advantage of optical keying techniques and terahertz power generation via photomixer arrays (Fig. 10). Airways data rates in the tens of gigabits per second are possible in such a system. Although concepts for ultrawide-bandwidth "pocket" communications transceivers have been floated for years, the problems inherent in producing small and efficient terahertz transmitters or LO sources to drive heterodyne systems have thus far precluded any commercial development in this area; however, new photoconductor components may soon change all of this (see Section IV).

Another rather clever application for the small spot size associated with terahertz wavelengths has been to use terahertz sources to illuminate scale models of large objects, thereby simulating the radar scattering signatures (RCSs) that would be obtained at much lower frequencies on actual equipment such as planes, tanks, and battleships [53], [54]. The savings in anechoic test chamber dimensions alone make the high cost of terahertz test systems attractive in comparison. An example of such a system, pioneered at the Massachusetts Institute of Technology (MIT), Cambridge, and the University of Lowell, Lowell, MA, is shown as Fig. 11. Solid-state sources have been used up to 660 GHz [54] and, in earlier systems, far-IR lasers were employed at 1.2, 2.5, 3.1, and 8 THz [53]. Complete 3-D synthetic aperture radar images can be processed with this system (see images of Fig. 11) by using dual polarization heterodyne transceivers and a special stepped continuous wave (CW) scheme, which gates out the effects of unwanted signals or chamber reflections.

Perhaps the most intriguing application for commercializing terahertz technology at this time is in the area of terahertz time-domain spectroscopy or T-ray imaging [55], [56]. In this technique, pioneered by Nuss and others at Bell Laboratories in the mid-1990s [57], [58] and recently picked up by at least two commercial companies, Picometrix in the U.S. [59] and

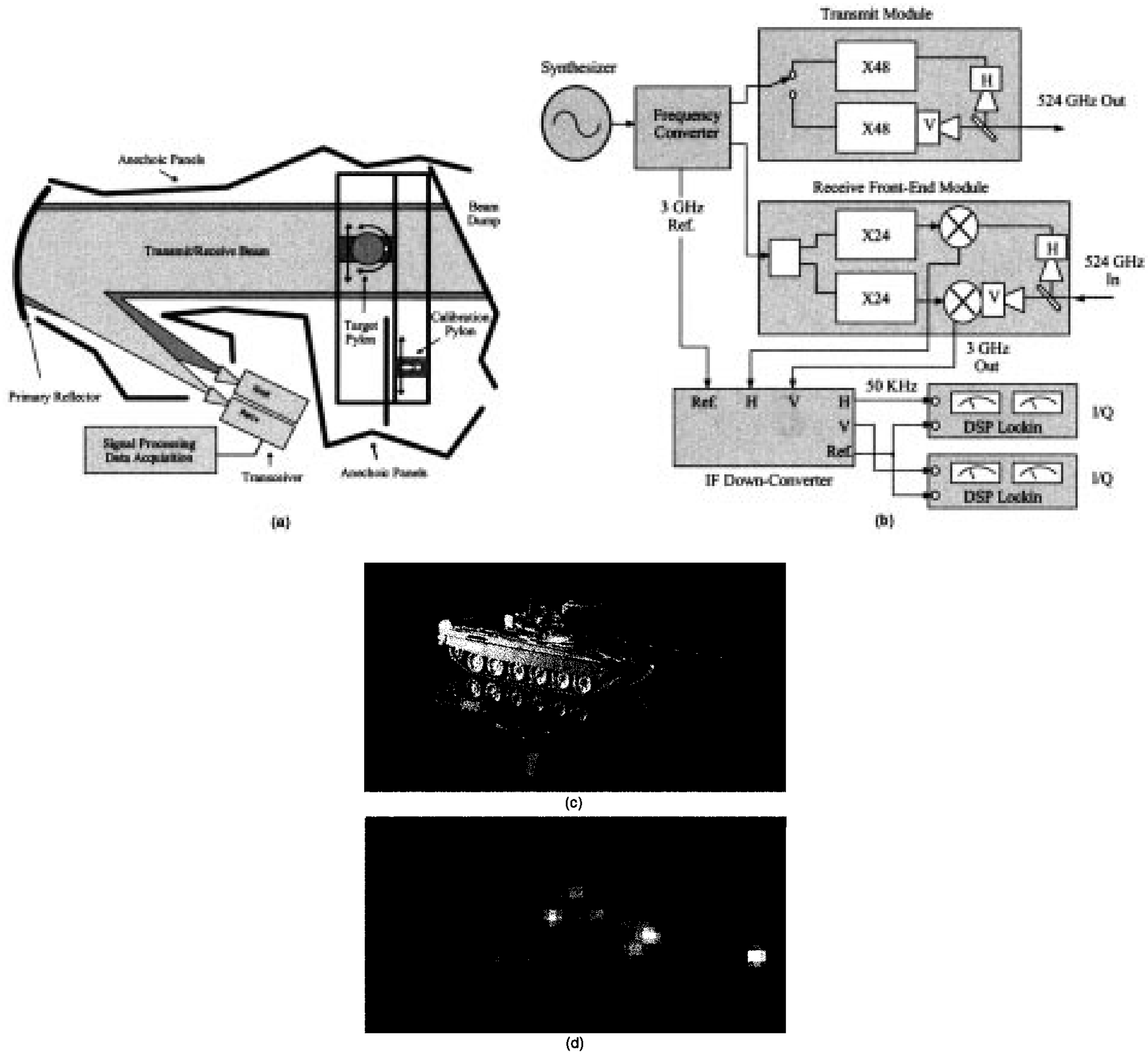


Fig. 11. Terahertz RCS system. (a) Compact range layout and submillimeter-wave transmit/receive arrangement. (b) Transceiver block diagram. (c) Optical image of scale model tank. (d) Processed submillimeter-wave radar image—cross section of 3-D image (courtesy of [54]).

Teraview (a spinoff of Toshiba Research Europe in the U.K.) [60], *in situ* measurements of the transmitted or reflected terahertz 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 terahertz 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 terahertz generator and detector in known phase coherence. By scanning the delay line and simultaneously gating or sampling the terahertz signals incident on the detector, a time-dependent waveform proportional to the terahertz field amplitude and containing the frequency response of the sample is produced (Fig. 12). Scanning either the terahertz generator or the sample itself allows a 2-D image to be built up over time. Recent innovations are leading to both rapid scanning [55] and true 2-D sampling using charge-coupled device (CCD) arrays [61]. In the Picometrix and Lucent Technologies systems, the photoconductive effect in low-temperature-grown (LTG) GaAs or radiation-damaged silicon on sapphire is used for both the generator and detector. The Teraview system uses terahertz generation via difference frequency mixing in a nonlinear crystal (ZnTe) and detection via the electrooptical Pockels effect (measuring the change in birefringence of ZnTe induced by terahertz fields in the presence of an optical pulse) as first demonstrated by Zhang at the Rensselaer Polytechnic Institute (RPI), Troy, NY [62]. The femtosecond optical pulses are currently derived from expensive Ti : Sapphire lasers, but much effort is being placed on longer wavelength, especially 1.5 μm, solid-state systems that can take better advantage of fiber technology [58]. The RF signals produced by the optical pulses typically peak in the 0.5–2-THz range and have average

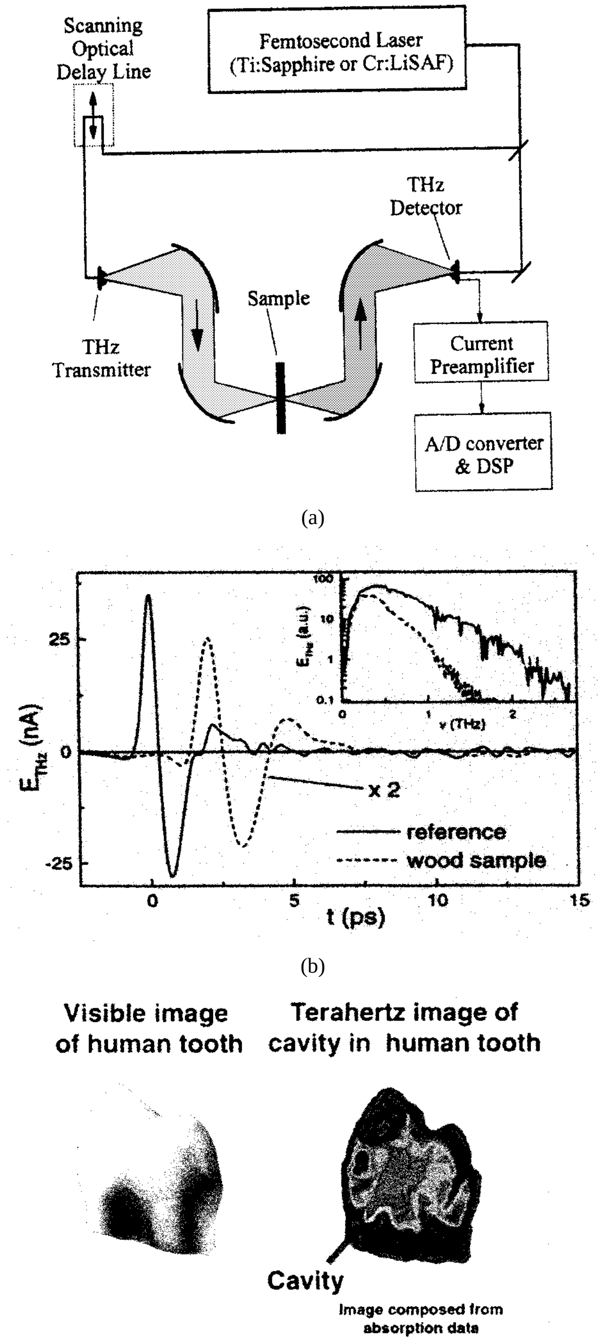


Fig. 12. (a) T-ray imager schematic [58]. (b) Time- and frequency-domain images of terahertz transmission through a piece of wood [55]. (c) 2-D contour plot of terahertz transmission through extracted tooth [56] (courtesy of [55], [56], and [58]).

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 (noninvasive 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 2-D imaging techniques) and somewhat more sensitive (with better sources and detectors). A wide range of applications already exist [56], [63] 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 terahertz technology. A room-temperature terahertz heterodyne camera has been proposed [64] 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 [65] with extremely low noise equivalent power (NEP) capability. These next-generation instruments should enhance the T-ray applications, as well as opening up new opportunities. Leaving the sensors world, microminiature terahertz power converters (nanorectifiers) that might be incorporated onto nanorobots and operate *in vivo* or in hostile environments have been suggested [66]. These nanorectennas could give new meaning to the term miniature power supply. These applications, as well as many others might be enabled by terahertz vacuum nanotube sources [67]. A search for other applications has turned up a couple of curious papers that should be of interest to the adventurous reader [68], [69].

In the following sections, we will briefly highlight specific components that are employed for the applications mentioned here and some of the instrumentation that has been constructed from these components for measurement and test. In some cases, particularly in the astronomy and spectroscopy areas, a wealth of published information already exists, including several special issues of this TRANSACTIONS and the PROCEEDINGS OF THE IEEE [70]–[76], and we cannot hope to cover all the technologies that are being brought to bear. Instead, we will select a few of the more recent innovations and techniques and leave the remainder to the references. For keeping abreast of advances in this rapidly changing field, the interested reader should be sure to scan a few of the now many annual terahertz conference proceedings, especially the NASA International Symposium on Space Terahertz Technology, the IEEE International Conference on Terahertz Electronics, the SPIE International Conference on Millimeter and Submillimeter Waves, and the original Ken Button MIT Magnet Laboratory conference and associated journal *International Conference on Infrared and Millimeter Waves*, now in its 26th year. It is also worthwhile keeping an eye on the *Applied Physics Letters*, where much of the solid-state device and component work appears.

IV. TERAHERTZ COMPONENTS

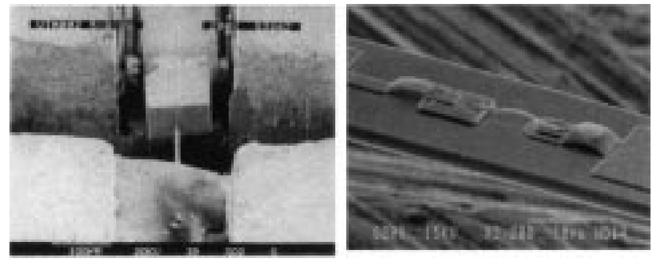
In this section, we highlight a few of the major component technologies that have been developed for terahertz applications. They broadly fall into two categories: sensors and sources. Space does not permit us to examine other terahertz component building blocks such as guiding structures, quasi-optics, antennas, filters, or submillimeter-wave materials. Some of these are reviewed in companion papers in this TRANSACTIONS. Terahertz component fabrication techniques and device processing are also fields in and of themselves and will not be covered here. These topics may be addressed in an upcoming text on terahertz technology [77].

A. Sensors

Terahertz sensors have progressed faster than any other submillimeter-wave technology. Today, there are near-quantum-limited detectors that can measure both broad-band or extremely narrow-band signals up to or exceeding 1 THz. There soon promises to be available individual photon counters that should do for the submillimeter what photomultipliers have done for optical wavelengths. The critical differences between detection at terahertz frequencies and detection at shorter wavelengths lies in the low photon energies (1–10 meV) and in the rather large Airy disk diameter (hundreds of micrometers). The former condition means that ambient background thermal noise almost always dominates naturally emitted narrow-band signals requiring either cryogenic cooling of the detector elements or long-integration-time radiometric techniques or both. The latter condition almost always imposes a mode converter or matched director (antenna) between the signal and sensor element. Note that the crossover frequency at which an ideal thermal noise limited detector (such as a room-temperature Schottky barrier diode) surpasses the sensitivity (power spectral density) of an ideal quantum detector (like a photodiode), occurs between 1–10 THz, a sometimes under-appreciated advantage of RF over optical detection [78, Fig. 5.4].[3] On the other hand, in comparison to longer wavelength radio techniques, terahertz sensors suffer from a lack of available electronic components—lumped resistors, capacitors, and inductors, as well as amplifiers and low-loss transmission media. To date, the most common terahertz sensors have been heterodyne detectors since applications have been centered on high-resolution spectroscopy. This may be changing, however, and more and more emphasis is now being focused toward direct detection techniques and components. For this paper, we will look at heterodyne and direct detector technologies, each of which has both room-temperature and cryogenic realizations. Since the field is vast, only a surface skim can be accommodated. The interested reader will have to track down additional details via this paper's references.

1) Heterodyne Semiconductor: For applications involving Earth science and planetary or some *in situ* measurements (e.g., plasma diagnostics), the sensitivity offered by semiconductor sensors is generally adequate for reasonable science return. For passive systems, heterodyning is used to increase signal-to-noise by reducing bandwidth. Since low-noise amplifiers are not yet available above approximately 150 GHz (this may soon be changing [79]), signal acquisition is accomplished through frequency downconversion (crystal rectification) and post or IF amplification. The figure-of-merit (ignoring antenna noise) is the receiver noise figure or equivalent input noise temperature $T_r = T_m + LT_{if}$, where T_m represents the downconverter or mixer added noise (shot and thermal contributions), L is the difference frequency conversion loss, and T_{if} is the noise added by the first-stage amplifier. This determines the minimum detectable temperature difference δT for a given

[3]The author thanks Hamid Hemmati, JPL, Pasadena, CA, for [78].



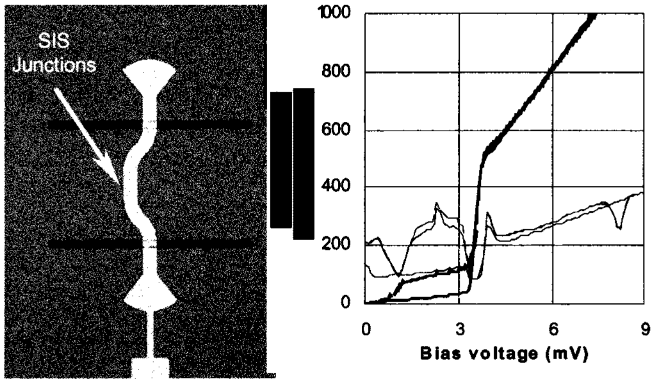
(a) (b)

Fig. 13. (a) Whisker-contacted Schottky honeycomb diode circa 1980 for 200-GHz operation in waveguide downconverter. Chip width is 125 μm. (b) Planar integrated submicrometer area Schottky diode on 3-μm-thick $\times$ 30-μm-wide GaAs membrane for operation at 2500 GHz, also coupled to a waveguide mount.

predetection bandwidth B and post-detection integration time τ, $\delta T = T_r/\sqrt{(B\tau)}$ (noise power $P_n = kT_rB$). Radiometric techniques in use since the 1940s [80]–[83], are still employed for acquiring weak signals embedded in background noise.

For applications where the sensitivity of room-temperature detectors is adequate, the basic single Schottky diode mixer is the preferred downconverter in the terahertz frequency range. Over the past 50 years, this component has transitioned from the "cat-whisker" point contact crystal technology prevalent since the beginning of the IEEE MTT-S to the "honeycomb diode" [84] of Fig. 13(a) to a fully integrated planar geometry with much greater flexibility and reliability, as well as superior performance [see Fig. 13(b)]. Planar diode mixers have been constructed and space qualified at frequencies as high as 2500 GHz [85] with noise performance below 5000-K double sideband. LO power is still a serious issue, as semiconductor downconverters that rely on the nonlinear resistance of an exponential diode require ≈0.5 mW of RF drive level at frequencies close to that of the observed signal. Multiple diode configurations, such as balanced and subharmonically pumped circuits, require even more LO power (≈3–5 mW) at submillimeter wavelengths [86]. Receivers based on room-temperature Schottky diode mixers typically have radiometric sensitivities (δT) near 0.05 K at 500 GHz and 0.5 K at 2500 GHz for a 1-s integration time and a 1-GHz predetection bandwidth. This is sufficient for detecting many naturally occurring thermal emission lines. Some improvement (typically 2×–4×) can be obtained with cooling of the detector as was demonstrated three decades ago by Weinreb and Kerr [87]. A wealth of papers have been published over the years describing many variations on the Schottky diode downconverter, including traditional waveguide-based and planar antenna/diode combinations ("mixtennas" [88]). The interested reader is referred to the many issues of this TRANSACTIONS and IEEE MTT-S conference papers for detailed designs and performance, as well as the texts by Kollberg [89] and Maas [90] and two nice, but older overview papers by Blaney [91] and Clifton [92].

2) Heterodyne Superconductor: High-sensitivity detectors must rely on cryogenic cooling for operation in the terahertz range. Several superconducting heterodyne detectors have been developed including those based on the Josephson effect [93], superconductor–semiconductor barriers (super-Schottky [94]), and bolometric devices [95]. However the superconducting



(a) (b)

Fig. 14. (a) 1200-GHz SIS tunnel junctions integrated on planar slot antenna circuit. (b) Current–voltage relationship and IF output signal for 77- and 300-K blackbody loads. Equivalent input receiver noise temperature is 650-K DSB at 1130 GHz (courtesy of A. Karpov [100]).

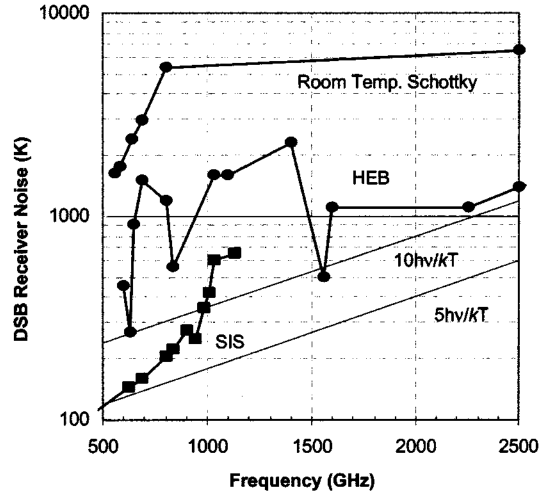
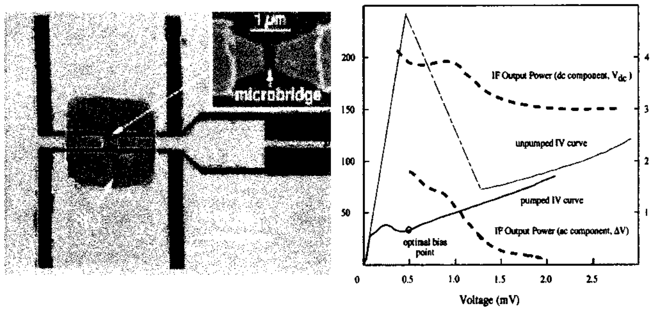


Fig. 15. Heterodyne receiver noise temperatures (SIS, HEB, and Schottky) versus frequency in the submillimeter range. SIS/HEB results can be found in the 11th and 12th International Space Terahertz Technology Conference and represent several receiver development groups and operating conditions (hence, the scatter). Schottky data are recent planar diode results from the University of Virginia, Charlottesville, and the JPL.

equivalent of the Schottky diode downconverter (in terms of widespread use below 1 THz) is the superconductor–insulator–superconductor (SIS) tunnel junction mixer. The current flow mechanism is based on the photon-assisted tunneling process discovered by Dayem and Martin [96] in the early 1960s. The first receivers using this effect were developed by groups at Bell Laboratories, Holmdel, NJ, and the California Institute of Technology, Pasadena [97], and at the University of California at Berkeley [98], and analyzed by Tucker [99] in the late 1970s. SIS mixers are widely used at frequencies from 100 to 700 GHz and very recently up to 1200 GHz [100] at observatories around the world and will soon be flown in space [12]. Like the Schottky diode downconverter, the SIS mixer (Fig. 14) relies on an extremely nonlinear I–V characteristic, in this case, created by the sharp onset of tunneling between the single-electron quasi-particles on either side of a thin superconducting gap. The tunneling process is nonclassical and the sensitivity limit (equivalent mixer noise temperature) is governed by the Heisenberg uncertainty principle $T_m = h\nu/2k$ [101]. In fact, the mixer conversion efficiency can actually become a gain under certain circumstances [102]–[104]. Sensitivities for the SIS mixers fall close to the quantum limit ($h\nu/2k \approx 0.05$ K/GHz) for frequencies up to several hundred gigahertz and are within a factor of ten of this limit up to 1 THz. Receiver noise temperatures (dominated by antenna, optics, and mixer mount losses) vary from less than 50 K at 100 GHz to over 500 K above 1 THz (Fig. 15). An additional advantage of the SIS mixers is the very modest LO power requirement compared to Schottky diodes; on the order of microwatts, rather than milliwatts, for a single device. SIS devices reach a natural frequency limit $f_{\rm cutoff}$ at approximately twice the superconducting energy gap $2\Delta \approx 3.5kT_c$ for ambient temperatures well below the critical temperature T_c [101]. This upper operating frequency is dependent upon the tunnel junction material composition $f_{\rm cutoff} \approx 146T_c$. For the most common SIS tunnel junctions, niobium–aluminum-oxide–niobium with $T_c = 9.3$ K, this frequency falls near 1350 GHz. Alternate materials such as niobium–nitride ($T_c = 16$ K) or high T_c superconductors based on YBCO ($T_c > 90$ K), have much higher operational frequency limits, but acceptable tunnel junctions have yet to be formed from these compounds. Since SIS devices have been around for less time than Schottky diodes, there have been significantly less circuit variations proposed, however a large number of submillimeter-wave systems have now been constructed and there are hundreds of papers on this subject. Two nice, but older review papers can be found in [105] and [106] and a general review of submillimeter-wave low-noise receivers with over 200 references was published more recently by Carlstrom and Zmuidzinas [107]. The reader may have to stray outside this TRANSACTIONS for many of the recent results, which tend to appear in physics and astronomy journals (e.g., *Applied Physics Letters* and the *Astrophysical Journal*) or in the applied superconductivity and NASA Space Terahertz Technology conference digests.

An alternative to terahertz SIS mixers that has received a great deal of attention in the last several years is the transition-edge or hot electron bolometer (HEB) mixer [108]. Unlike the InSb bolometers of [95], modern HEB mixers are based on extremely small microbridges of niobium, niobium–nitride, or niobium–titanium–nitride (and, recently, aluminum [109] and even YBCO [110]) that respond thermally to terahertz radiation (Fig. 16). These micrometer- and submicrometer-sized HEBs can operate at very high speeds through either fast phonon [111] or electron diffusion cooling [112]. For heterodyning, the bolometer has a voltage responsivity in the picosecond range, fast enough to track the IF up to several gigahertz. Depending on the dimensions and the composition of the material forming the microbridge and the cooling mechanism—electron–phonon into a superconducting bath or electron–electron diffusion into a normal metal—IF rolloffs of over 15 GHz can be obtained [113]. Since the bolometer is inherently a resistive device, its RF response is limited largely by the signal coupling antenna. HEB noise performance is dependent on the difference between the operating (bath) and the material critical temperature, as well as the sharpness of the transition between the superconducting and normal states of the bridge. Sensitivities are predicted to be only



(a) (b)

Fig. 16. (a) 2.5-THz niobium HEB twin-slot antenna mixer. (b) Current–voltage characteristics with and without LO power applied. Also shown is the dc ($V\mathrm{dc}$) and ac (ΔV) components of the IF output power (courtesy of [115] and [116]).

a few times higher than the quantum limit [113] and the required LO power is even lower than for SIS mixers, falling in the 1–100-nW range [113]. Excellent mixer performance has recently been achieved near 2.5 THz ($T_r = 1050$ K DSB, only ∼10× the quantum limit) [114]–[116] and operation above 5 THz has been reported [117]. The HEB has revolutionized broad-band terahertz detectors and has already been deployed at several observatories. HEB mixers are planned for operation on at least one space mission [12]. Some recent reviews of HEB mixing can be found in [113] and [118], but the field is advancing so quickly it is advisable to keep a close eye on the Space Terahertz Technology and Applied Superconductivity conference proceedings.

3) Direct Detectors: Direct detectors are rapidly encroaching into the realm of heterodyne systems for applications that do not require ultrahigh spectral resolution. Room-temperature detectors have limited applications outside diagnostic measurements due to sensitivity constraints. Small-area GaAs Schottky diodes [119] used as antenna-coupled square-law detectors, conventional bolometers based on direct thermal absorption and change of resistivity (e.g., bismuth [120]), composite bolometers, which have the thermometer or readout integrated with the radiation absorber (bismuth [121] or tellurium [122]), microbolometers [123], which use an antenna to couple power to a small thermally absorbing region, Golay cells[4] based on thermal absorption in a gas-filled chamber and a detected change in volume via a displaced mirror in an optical amplifier, an acoustic bolometer,[5] which reads out the change in pressure of a heated air cell using a photoacoustic detector, and a fast calorimeter [124] based on single-mode heating of an absorber filled cavity, have all been used at terahertz frequencies. Calibration (mode matching) can be a serious problem for the antenna-coupled (small-area) detectors (diode and microbolometers), and response time is on the order of seconds for the calibrated, but poorer sensitivity (several microwatt level), acoustic bolometer and fast calorimeter. Cooled detectors take several forms, the most common commercial systems being helium-cooled silicon, germanium, or InSb composite bolometers,[6] [7] with response times on the microsecond scale. NEP is typically 10^{-13}W/$\sqrt{}$Hz for 4-K operation and improves greatly at millikelvin temperatures. Some traditional IR detectors also respond in the submillimeter, including pyroelectric [125], which change their dielectric constant as a function of temperature and direct photoconductors based on mechanically stressed gallium-doped germanium (Ge : Ga) [126] or even HgCdTe [127]. Noncommercial cooled bolometers of many forms have been used since the 1970s for spectroscopy and astronomical observations. Especially important are the transition edge bolometers [128] based on the change of state of a superconductor. An excellent review up to 1994 can be found in the paper by Richards [129]. Recent progress includes detectors and arrays based on bismuth-coated suspended micromachined silicon, doped to obtain the desired resistive temperature dependence [130], [131], absorber-backed neutron-transmutation-doped (NTD) germanium-on-silicon nitride "spider" bolometers [132], and superconductor–insulator–normal (SIN) metal tunnel junction composite bolometers [133]. NEPs for these devices are 10^{-17}–10^{-18} W/$\sqrt{}$Hz. The spider bolometer is expected to fly in space as part of the Spectral and Photometric Imaging REceiver (SPIRE) instrument on FIRST. SIS mixers also can, and have been, used as high-sensitivity detectors [134]. More recently, detectors based on the HEB mixer geometries (antenna coupled) working as hot electron superconducting transition edge sensors [135] have been proposed. These devices are predicted to have NEPs near 10^{-20} W/$\sqrt{}$Hz [136].

Before leaving the detector area, it is worth mentioning one other device that is catching quite a lot of attention, i.e., the quantum-dot single-photon detector developed by Komiyama [137], [138]. This detector (Fig. 17) uses a cold (50 mK) single electron transistor (SET) and quantum dot in a high magnetic field. Incident terahertz photons are coupled into the quantum dot via small dipole antennas. Within the quantum dot, an electron–hole pair created by the incident photon releases energy to the lattice, which causes a polarization between two closely coupled electron reservoirs. Electron tunneling occurs, causing a shift in the gate voltage of the SET. According to the authors, the detector has a sensitivity of 0.1 photons/s per 0.1 mm^2 detector area due to the photomultiplication effect where 10^6–10^{12} electrons per photon are generated. Single photon detection for signals in the range of 1.4–1.7 THz has been recorded. The equivalent NEP is on the order of 10^{-22} W/$\sqrt{}$Hz, more than 1000 times more sensitive than the best bolometric devices, but the speed of the detector is presently around 1 ms. The authors have hopes of taking advantage of the potential of new RF SET devices [139] that have intrinsic speeds near 10 GHz. Many other devices have been proposed as high-sensitivity detectors based on bolometric effects or photon counting [140] including some high T_c and even cooled semiconductor constructions [141]. Again, the author's advice is to keep a close eye on the aforementioned conferences to keep abreast of progress in this area.

[4]A submillimeter wave Golay cell with an NEP of 10^{-10}W/$\sqrt{}$Hz can be purchased from QMC Industries Ltd., Cardiff University, Cardiff, U.K. [Online]. Available: http://www.terahertz.co.uk

[5]TK TeraHertz Absolute Power Meter Systems, Thomas Keating Ltd., Billingshurst, West Sussex, U.K. [Online]. Available: http://qmwciworks.ph.qmw.ac.uk

[6]Semicalibrated units are available from Infrared Laboratories Inc., Tucson, AZ. [Online]. Available: http://www.irlabs.com

[7]Semicalibrated units are available from QMC Instruments Ltd., Cardiff University, Cardiff, U.K. [Online]. Available: http://www.terahertz.co.uk

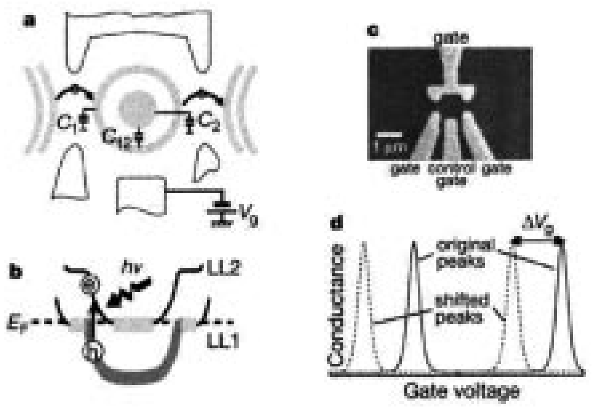


Fig. 17. Komiyama quantum-dot single-photon detector concept (courtesy of [137]).

B. Sources

Certainly the most difficult component to realize in the submillimeter-wave bands has been the terahertz source. There are several fundamental explanations for this. Traditional electronic solid-state sources based on semiconductors, i.e., oscillators and amplifiers, are limited by reactive parasitics or transit times that cause high-frequency rolloff, or they have simple resistive losses that tend to dominate the device impedance at these wavelengths. Tube sources suffer from simple physical scaling problems, metallic losses, and the need for extremely high fields (both magnetic and electric), as well as high current densities. Optical style sources, i.e., solid-state lasers, must operate at energy levels so low ($\sim$meV) they are comparable to that of the lattice phonons (relaxation energy of the crystal), although cryogenic cooling can mitigate this problem. More successful techniques for generating terahertz power have come from frequency conversion, either up from millimeter wavelengths, or down from the optical or IR. Many approaches have been tried with the most successful milliwatt sources to date being direct laser-to-laser (far-IR to submillimeter) pumping or reactive multiplication through our old standby the GaAs Schottky diode. For generating narrow-band microwatt or nanowatt power levels at terahertz frequencies, a variety of techniques have been demonstrated including optical mixing in nonlinear crystals [142], [143], photomixing (optical difference frequency mixing in a photoconductor coupled to an RF radiator) [144]–[147], picosecond laser pulsing [148], [149], laser sideband generation [150], [151], intersubband and quantum cascade lasing [152], [153], direct semiconductor oscillation with resonant tunneling diodes (RTDs) [154]–[156], direct lasing of gases [157], Josephson junction oscillations [158], and other techniques too numerous to mention. We can only take a brief scan of the more successful approaches and, again, the avid reader is relegated to the references for more details.

1) Upconverters: By far the most common technique for producing small amounts of power at frequencies above 500 GHz is through nonlinear reactive multiplication of lower frequency oscillators. The field was actually better off 20 years ago when solid-state (Gunn and IMPATT diodes) and tube sources (carcinotrons, klystrons, and backward-wave oscillators) were more readily available at millimeter-wave frequencies. The demise of Cold War funding, advances in III–V monolithic microwave integrated circuit (MMIC) technology and the draw of enormous commercial markets in the communications bands below 100 GHz has left the field with few interested manufacturers of expensive custom-tailored high-frequency components. Although tube sources are still trickling out of the last commercial supply house in Istok, Russia, and small stockpiles of the original Varian-then-Litton-now-Filtronic high-frequency ($>$120 GHz) InP Gunn and Hughes-now-Boeing IMPATT devices can be found tucked away in the drawers of a few small millimeter-wave component companies, the most reasonable approach in the source area today is to multiply up from microwave frequencies (20–40 GHz). Although higher frequency (up to 200 GHz) Gunn, IMPATT, and TUNNETT devices are in development within university groups, especially by Eisele [159], they are not available commercially. Fortunately, commercially based W-band (75–110 GHz) InP MMIC power-amplifier chips have appeared [160] and promise to extend baseband frequency coverage up to at least 200 GHz within the very near future [161], [162]. At 100 GHz, power levels from waveguide-combined amplifiers of 300–400 mW are readily available [163] and there is a large effort underway to develop spatial power combined sources with many times this output level [164]–[166]. The amps can be driven by commercially available microwave oscillators [voltage-controlled oscillators (VCOs), dielectric-resonator oscillators (DROs)] and millimeter-wave upconverters.

The need for narrow-band compact solid-state terahertz sources is being driven, at least partially, by space applications such as FIRST/Herschel [167], which cannot fly bulky power-hungry lasers or short-lived very-heavy kilovolt-driven tube sources. In order to get from W-band to terahertz frequencies through solid-state upconversion, several octaves must be spanned. Despite no theoretical limitations [168], [169] and the best efforts of many researchers over many decades, comb generators and higher order multipliers ($>\times 4$) continue to provide extremely poor conversion efficiencies compared to doublers and triplers [170]. The most efficient terahertz sources are, therefore, composed of series chains of these lower order multipliers. Like the room-temperature downconverter technology, today's multiplied sources most commonly use planar (as opposed to whisker-contacted) GaAs Schottky barrier diodes mounted in single-mode waveguide, although the literature is replete with optically coupled circuits. Small electrical size and assembly constraints have led to some unusual and extremely low-loss device topologies [171], an example of which is shown in Fig. 18. An additional constraint for higher order multiplying (due to low overall efficiency) is the power-handling capacity of the first few stages of the chain, which can be beefed up by adding multiple devices in series to distribute the heat and increase the breakdown voltage [172]. Multiplier chains driven by amplified sources at 100 GHz have reached 1200 GHz with 75 μW at room temperature and over 250 μW when operated cold (120 K) [173]. Signals up to 2.7 tHz have been obtained with this technique [174] and the reported efficiencies and output power are improving monthly, driven by the instrument needs (and accompanying funding).

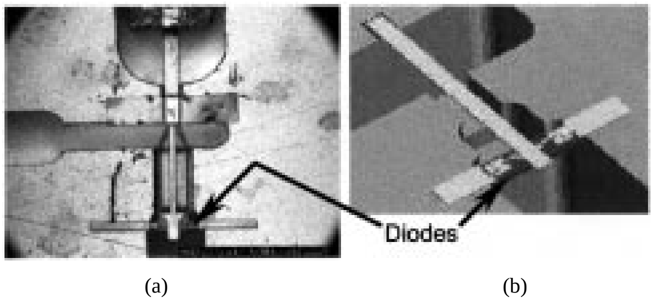


Fig. 18. Terahertz Schottky diode multiplier chips fabricated monolithically from GaAs. (a) 800-GHz balanced doubler with thin membrane frame mounted in waveguide block [171]. (b) 2400-GHz waveguide-mounted substrateless-doubler schematic (currently in process at the JPL) [167].

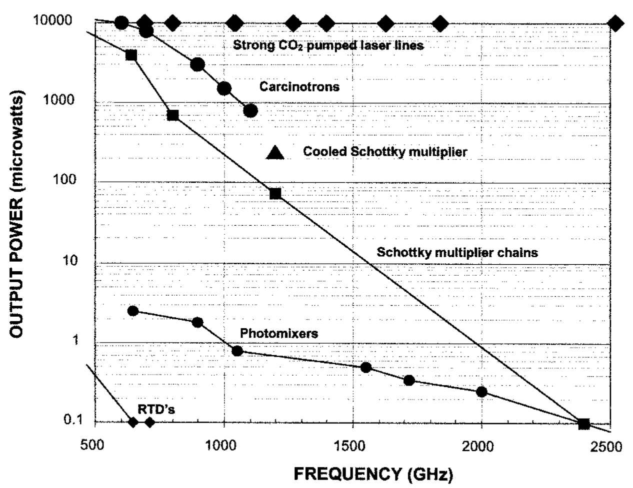


Fig. 19. Performance of some CW sources in the submillimeter-wave range. Data: Schottky varactor (JPL recent results), RTD [155], [156], Photomixer [52], [146], Carcinotron [Online]. Available: http://www.pi1.physik.uni-stuttgart.de/indexjs.html, Laser lines [185].

Fig. 19 shows the current state of affairs. All of the solid-state device-based sources, including amplifiers, multipliers, and oscillators (i.e., RTDs, TUNNETTs, Gunns) will, of course, benefit from spatial power-combining techniques [175], a field in and of itself. The literature, especially the IEEE MTT-S and NASA Space Terahertz Technology conferences, is filled with even more terahertz upconverter than downconverter designs, and the interested reader can scan them until they begin seeing double!

2) Tubes, Lasers, and Optical Downconverters: Although we cannot look very closely at other terahertz sources, a mention of the most likely contenders in this most important development area is certainly warranted. Despite their limited availability, terahertz tube sources [176] based on emission from bunched electrons spiraling about in strong magnetic fields (backward-wave tubes or carcinotrons) offer the most power and frequency tuning range at submillimeter wavelengths. Bench-top commercial units (as opposed to room-sized kilowatt clinotrons and gyrotrons [177]) extend to 1200 GHz[8] with mW levels of available power, although multimoding is a significant problem when coupling these sources to actual antennas (typical TE_{10}-mode coupled power can be 1/1000th or less of the total output power from the tube). The Russian tubes (the only ones still available) operate on 2–6 kV and ≈1-T fields that can be achieved by samarium cobalt permanent magnets. They are sweepable over ranges exceeding tens of gigahertz at kilohertz rates and can be phase locked [178] for high-stability applications. The tubes with magnet cost from $15 000–$75 000 each and have lifetimes of a few thousand hours at best. Despite the limitations, the tube concept is a slow one to die and there are currently several research groups trying to resurrect klystrons or other tube configurations [179] for terahertz operation by bringing in modern monolithic fabrication techniques and high-density cathode development [180]–[182]. Whether these efforts will yield successful terahertz oscillators remains to be seen.

The next most commonly used sources at terahertz frequencies are IR-pumped gas lasers such as those produced commercially by DEOS,[9] Edinburgh Instruments,[10] and MPB Technologies.[11] These are usually based on grating tuned CO_2 pump lasers (20–100 W) injected into low-pressure flowing-gas cavities that lase to produce the terahertz signals. Power levels of 1–20 mW are common depending on the chosen line, with one of the strongest being that of methanol at 2522.78 GHz. In the 500-GHz–3-THz regime, not all frequencies are covered by strong emission lines and some of the nastier gases are best left in their shipping containers under today's environmental safety policies! Nonetheless, laser sources have been in use for many years for spectroscopy and as terahertz LO sources in receivers. A fully sealed autonomous CO_2 pumped methanol laser has been space qualified and will fly on the EOS-MLS instrument in 2003 [19]. Total plug power for this system is only 120 W, with 20-W CO_2 output power and more than 30 mW of generated RF at 2523 GHz. Nice reviews can be found in [183]–[185]. The lasers are also used with harmonic generators to make sideband sources [151], [186] which have much more flexible tuning. While on the subject of laser sources, one cannot ignore the many laboratory efforts underway to develop direct semiconductor terahertz laser sources based on intersubband transitions and tailored quantum cascade laser devices, most notably by Capasso and Cho at Lucent Technologies [187], [188]. Most of these techniques will require cooling of the devices [189] and there is still a long way to go in extending out to terahertz frequencies, but there has been significant progress over the last several years and complex tailorable layers grown on an ever-expanding list of compound semiconductor materials hold hope for significant CW power sources in the not too distant future.

One cannot leave sources without mentioning today's most commercially successful technique for generating terahertz energy—downconversion from the optical regime. Two principal methods have been exploited to produce both narrow- and broad-band energy. The first, photomixing [144], [145],

[8]Tubes are distributed in the U.S. by Insight Products, Brighton, MA, or by ELVA-1, St. Petersburg, Russia. [Online]. Available: http://www.elva-1.spb.ru/

[9]DeMaria Optical Systems, New Haven, CT. [Online]. Available: http://www.deoslaser.com

[10]Edinburgh Instruments, Livingston, U.K. [Online]. Available: http://www.edinst.com

[11]MPB Technologies, Montréal, QC, Canada. [Online]. Available: http://www.mpb-technologies.ca/index.html

[190], uses offset-frequency-locked CW lasers focused onto a small area of an appropriate photoconductor (one with a very short <1-ps carrier lifetime e.g., LTG GaAs) to generate carriers between closely spaced (<1 μm) electrodes (source and drain) printed on the semiconductor. The laser induced photocarriers short the gap producing a photocurrent, which is modulated at the laser difference frequency. This current is coupled to an RF circuit or antenna that couples out or radiates the terahertz energy. The resulting power is narrow-band, phase lockable, and readily tuned over the full terahertz band by slightly shifting the optical frequency of one of the two lasers. Both 780–820 nm Ti : sapphire and 850-nm distributed Bragg reflector (DBR) semiconductor lasers have been used to match the bandgap of the LTG GaAs. Simple optical-fiber coupling to the photoconductor has also been employed [191] and work on new materials (erbium–arsenide-doped LTG GaAs) that would enable operation in the optical fiber band (1.3–1.55 μm) is on-going [192]. Typical optical to terahertz conversion efficiencies are below 10^{-5} for a single device [191] and reported output power falls from ≈1 μW at 1 THz to below 0.1 μW at 3 THz, even with the newer distributed or traveling-wave photomixer designs [146]. However, cooling, arraying, and new materials hold great promise for these photomixers, and modest improvements will open up applications both in radiometry (as broadly tunable LO sources) and communications [52]. A second and perhaps the most widely employed optical technique for producing terahertz energy (although broad-band) is based on using a short pulse (femtosecond) optical laser [193]–[195] (argon-laser-pumped Ti : sapphire laser) to illuminate a gap between closely spaced electrodes on a photoconductor (e.g., silicon-on-sapphire or LTG GaAs) generating carriers, which are then accelerated in an applied field (<100 V). The resulting current surge, which is coupled to an RF antenna, has frequency components that reflect the pulse duration, i.e., terahertz rates. The same terahertz output spectrum can be obtained by applying short laser pulses to a crystal with a large second-order susceptibility χ^2 (field-induced polarization) like zinc telluride [60]. Since the higher order susceptibility terms are indicative of nonlinear response, mixing occurs, producing a time-varying polarization with a frequency-response representative of the pulse length, i.e., terahertz oscillation. These techniques are the basis for the T-ray systems [59], [60] described previously. As with the photomixers, RF power may be radiated by antennas printed on the photoconductor or crystal, and typically have frequency content from 0.2 to 2 THz or higher depending on the laser pulse parameters. Average power levels over the entire spectrum are very low (nanowatts to microwatts) and pulse energies tend to be in the femtojoule to nanojoule range [60]. Fiber coupled systems have been developed [59] and continual improvements are being made to these RF generators in order to increase the signal-to-noise of the T-ray imagers. Finally, it is worth mentioning one last pulsed laser technique that shows promise for high levels of terahertz output power. The technique [196], [197] uses a Q-switched Nd : YAG laser to illuminate a large $LiNbO_3$ sample causing optical parametric oscillation via the crystal χ^2 and polariton mode scattering. The parametric process creates a near-IR photon close in wavelength to that of the Nd : YAG pump and a terahertz difference photon. A prism coupler is used to extract the terahertz power and tuning can be accomplished by simply changing the incident angle of the Nd : YAG laser. The system is shown in Fig. 20 and pulsed power output (linewidth ≈15 GHz) is reported to be as high as 3 mW at 1.8 THz.

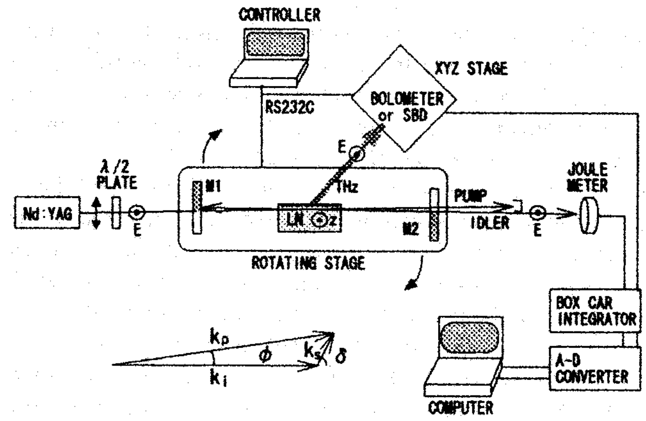


Fig. 20. Terahertz generator based on laser illumination of a lithium–niobate crystal (courtesy of [196], American Institute of Physics).

V. Future Applications and Concluding Remarks

It is clear that terahertz technology is just beginning to come of age and many applications yet to be realized lie in wait. The most pressing component technology development remains in the area of terahertz sources, just as it did in 1963 [8] and 1985 [1]. However, advances on several fronts in the solid-state device and laser pumped photoconductor areas are pushing hard at this bottleneck and it should not be too many more years before we will have sufficient power to do heterodyne imaging, radar, or communications with terahertz signals. The sensor side has progressed remarkably, and near quantum limited receivers up to 1 THz are becoming widespread. Beyond 1 THz, direct detectors are grabbing territory at an alarming rate and the promise of single photon counters in the submillimeter may usurp some quantum limited optical applications. Unless sources make some quick progress, direct detectors rather than heterodyne systems will likely dominate the terahertz regime in the near term, especially for space and low-background signals. As 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 terahertz frequencies. On the instrument side, we are just beginning to see emerging systems. A terahertz network analyzer is commercially available [198], near-field antenna measurements have been performed at 640 GHz,[12] a recently demonstrated millimeter-wave near field microscope technique [199] promises micrometer resolution terahertz 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 terahertz wavelengths for the

[12]SWAS, MIRO, and MLS all used customized near-field ranges to measure large antenna beam patterns at 470, 557, and 640 GHz, respectively.

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. There is already an enormous program (by submillimeter standards) with nine research partners, recently started in Europe to evaluate and coordinate findings on the biological aspects of terahertz radiation and terahertz imaging.[13] Even in the spectroscopy area, commercial instruments are on the near horizon. High-resolution FTS systems like FASSST may see use in military systems as chemical agent detectors and a substantial Multidisciplinary University Research Institute (MURI) program[14] promises to help open up biomedical applications for this technology in the U.S. 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 predicts that submillimeter systems will complement near-IR and optical sensors for interferometric measurements in the search for extraterrestrial life, although the case has yet to be made. All of these exciting applications and countless undiscovered ones remain in wait while terahertz technology enters adulthood—*diu venturus erat et ibi est multus labor faci*—it has been a long time coming and there is still much work to be done.

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[13]This program, known as "Terahertz-Bridge" (terahertz radiation in biological research, investigation on diagnostics and study of potential genotoxic effects), already has nine university and industry partners investigating a wide range of terahertz applications and effects in the bio area. [Online]. Available: http://www.frascati.enea.it/THz-BRIDGE

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