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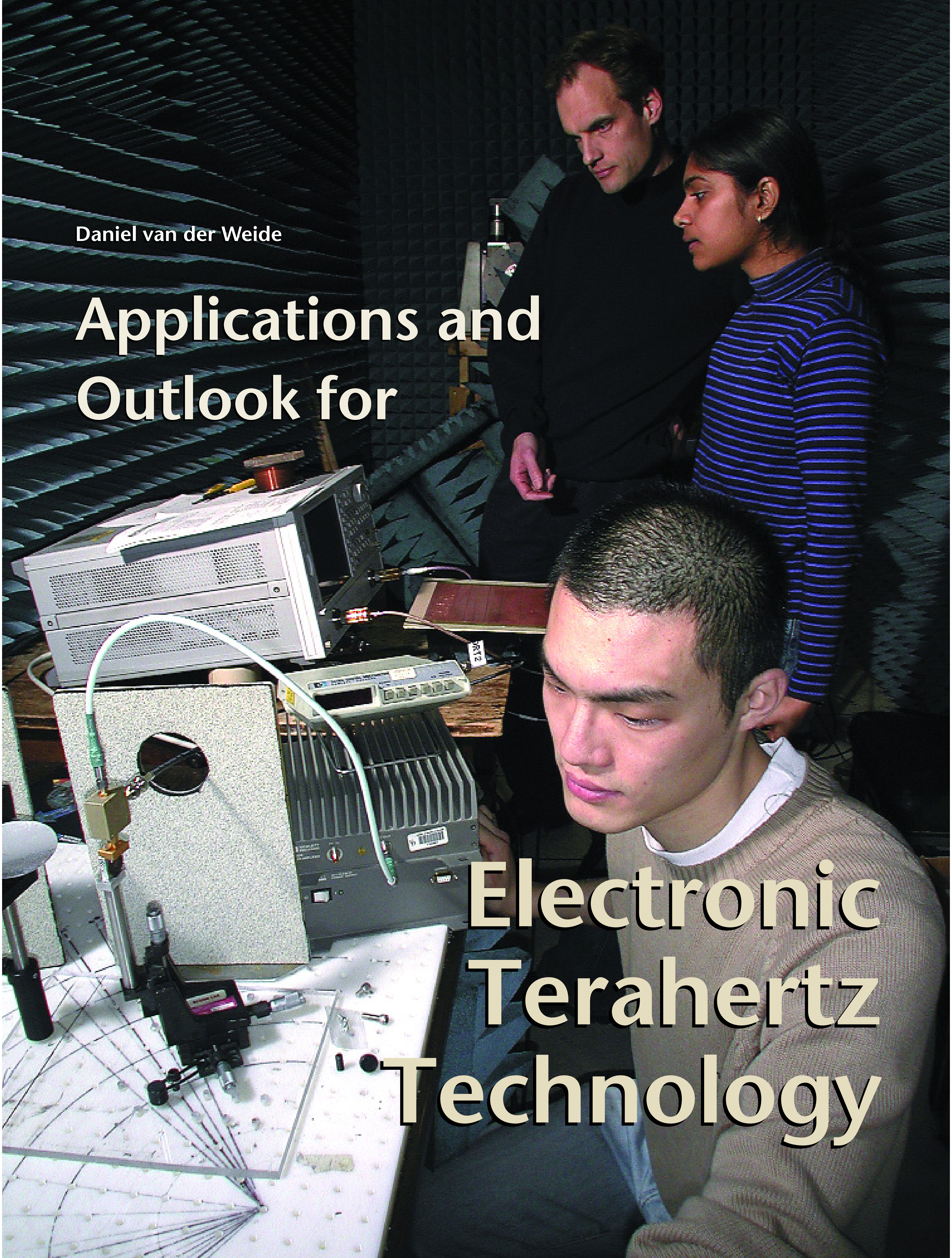
Applications and Outlook for Electronic Terahertz Technology



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A new field of spectroscopic imaging is opening up with the advent of terahertz technology, at the boundary between radio waves and light. Chemical and biological sensitivity, combined with quasi-optical propagation, offers exciting prospects for sensing and imaging.

Interesting things happen at the boundaries: The terahertz (THz) regime, lying between electronics (0.1 THz) and photonics (30 THz, around the frequency of a CO_2 laser), is rich with emerging possibilities in sensing, imaging and communications, with unique applications in screening for weapons, explosives and biohazards, imaging of concealed objects, water content and skin, and (potentially) very broadband communications.

Many researchers with backgrounds in optics explore the regime by generating THz power with mode-locked femtosecond lasers driving photoconductive switches or nonlinear crystals, taking the "top-down" photon-energy approach to this regime. Those with backgrounds in electronics often work the energetic "bottom-up" angle by multiplying the frequency of microwave or millimeter-wave oscillators. Fundamental sources of THz power, such as backward-wave oscillators, free-electron and quantum cascade lasers, novel heterojunction diode and transistor circuits and—most recently—micromachined vacuum electronic devices, are now beginning to round out the THz toolset.

This set of sources is complemented by a growing set of detectors, coherent samplers and electo-optic sensors that measure the amplitude of the THz field, hence the real and imaginary components of dielectric response. If the source of THz is incoherent, thermal (bolometric) or Schottky mixer diodes are used. For example, atmospheric and space-based THz spectroscopy seeks out natural sources of radiation, such as the cosmic background or emission from molecular species, and takes advantage of cryogenic detector environments to sense weak photon energies.

In earth-bound applications, ambient temperatures are much higher; thermal detection of THz becomes much more difficult, so time-domain THz systems that can perform coherent generation and detection dominate the scene. These systems synchronize the detector with the emitter so that thermal noise power not related to the emitter's frequencies is largely ignored. The energy at a cryogenic temperature of 5 K corresponds to a 0.1 THz photon, while room temperature (300 K) corresponds to 6.25 THz. Between these two frequencies, the total thermal radiation from a 10-mm square blackbody (an ideal radiator, whose temperature is 300 K) is about 46 mW—overwhelming the submilliwatt powers of most THz sources—while at 5 K it is only 350 μW. Thus, thermal background strongly delineates space-based and cryogenic THz technology from its room-temperature counterparts. For this reason, detecting THz with room-temperature antennas requires a technique to limit the input noise power, such as coherent sampling of the THz wave.

Whether earth- or space-based, the frequency range bounded by these 5 and 300 K photon energies brackets the majority of THz systems and defines one of the least explored and most promising regions of the spectrum for a growing range of applications, primarily for sensing and spectrosopy, but perhaps ultimately for communications. Opportunities in sensing (such as detecting explosives or bioweapons), spectroscopic imaging for medical applications, and communications (for example, exploiting the unlicensed spectrum above 0.3 THz), could become significant and growing military and commercial markets for THz technology.

(*From top to bottom*): Author van der Weide and graduate students Rashmi Pahak and Min Choi explore both contact and free-space applications of THz technology in an anechoic chamber at the University of Wisconsin.

Its scientific applications have garnered the THz regime a growing share of articles, special journal issues and monographs, so there is little need for another comprehensive review. Even so, THz technology is still where the laser was in its infancy, a solution in search of a problem, especially a problem that could use large numbers of THz components! Applications for large numbers of components would build a viable market presence and feed back into further development in a manner analogous to the growth of the semiconductor laser market stimulated by laser printers and CDs.

At this crucial yet exciting time in the development of the field, it is important not only to look back at the progress to date but also to peer into the near future of where THz technology can go and what remains to be accomplished. So here I will focus on a few possibilities for using THz technology to address challenges of the next decade. While many of the examples here are drawn from research going on at the University of Wisconsin-Madison, they illustrate some of the potential for THz technology, and in particular, field-deployable electronic THz technology.

THz free-space propagation

The boundaries of the THz frequency range and the technologies associated with it have almost as many definitions as the number of laboratories pursuing THz studies. What unifies most researchers in THz technology is their work with quasi-optical propagation. Although important work has been done to probe and map THz frequencies on planar waveguides and circuits, the overwhelming majority of publications in the field discuss free-space propagation. This naturally involves both antennas borrowed from scaled-down microwave concepts and optics adapted from infrared and visible light.

Scientific curiosity has motivated a substantial amount of narrowband or continuous-wave (CW) work in the THz regime for space research and cosmology, where atmospheric absorption cannot interfere with observations. Back on earth, however, pressure-broadened absorption lines of water vapor place

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severe limitations on the distance many THz waves can propagate.

Although sending THz frequencies through gasses and measuring selective absorption have been important tools of molecular analytical chemistry, atmospheric absorption due to water vapor is a parasitic effect in THz sensing, imaging and communications: Water vapor absorption at 50% relative humidity at frequencies above 0.5 THz rises to between 0.1 and 10 dB/m in broad peaks that severely limit the distance of detectable propagation, effectively rendering the atmosphere black. This in turn limits stand-off distances when using > 0.5 THz frequencies for sensing and imaging the dielectric contrast of remote targets. It also challenges communications systems in which an attempt is made to use these frequencies for long distances. Conversely, THz communications within rooms or buildings will naturally be quite secure, and THz sensors will exhibit little interference with other systems or with each other. Water in living tissue limits depths of THz penetration to millimeters, a factor which circumscribes THz medical imaging to applications involving skin conditions and teeth.

So because of atmospheric limitations, it is largely impractical for systems doing spectroscopy or imaging above 0.5 THz (what we will call the "upper THz") to work beyond a meter or so of distance between emitter and detector without vacuum or a nitrogen purge. While this limits the range of applications mostly to laboratory studies and close-in spectroscopic imaging for industrial purposes, the majority of THz systems and results to date have been achieved in this upper THz regime.

THz optics

Since most applications for THz technology use free-space propagation, managing THz "light" is critical to success, especially because the power of THz sources is low, even though the dynamic range of THz systems can peak at 60 dB. Far-field imaging and sensing constitute the majority of current THz activity, though researchers have also employed near-field techniques such as using sharp, conductive probes as near-field antennas to localize THz energy, in some cases to submicrometer extents. It is also possible to generate and detect near-field THz light with subwavelength-sized crystals and excitation beams.

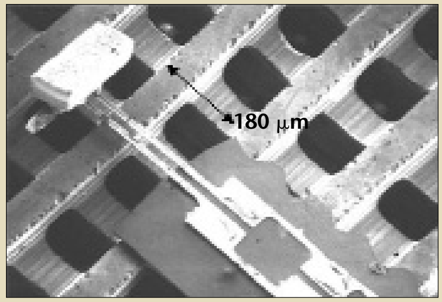

Figure 1. 500-GHz dipole antenna mounted on 500-GHz silicon photonic bandgap material. [From http://www.startiger.org/tech.htm, ESA's StarTiger Initiative and the StarTiger team.]

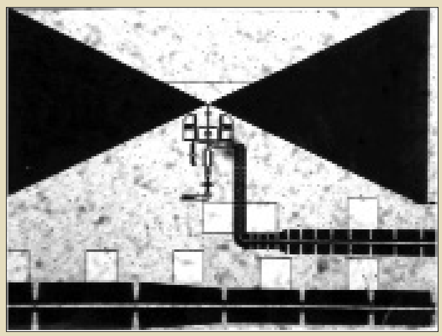

Figure 2. Broadband bowtie antenna integrated with a NLTL and sampling detector at the apex of the antenna.

Far-field optics in the visible spectrum are much larger than the wavelength of light; this is not true in most THz systems, and the situation is further complicated by the > 10:1 range of wavelengths common to pulsed THz technology. Transducing, guiding and focusing this broad range of wavelengths with high efficiency down to the diffraction limit is difficult: Metallic losses and modal dispersion in the source and detector substrates tend to attenuate the higher frequencies, while the limited spatial extent of reflective optics permits diffraction of longer wavelengths. New techniques, such as photonic bandgap structures (see Fig. 1) and ultrabroadband antennas (see Fig. 2), are being incorporated into THz systems to improve optical management. By controlling the dimensions of the THz beam (i.e., the antenna pattern), THz imaging and sensing systems will realize considerable gain, even with their current power limitations. This in turn will create new opportunities for greater stand-off distances in remote sensing.

Electronic THz technologies

Although laboratory results from optoelectronic THz systems dominate the recent literature, field-deployable THz technologies for rugged, compact and ultimately low-cost screening and sensing will be based on electronics.

Narrowband/CW systems

There have always been fundamental trade-offs between the power, dynamic range and simplicity of continuous-wave (CW) or narrowband (< 10% fractional bandwidth) sources, amplifiers and detectors and their broadband counterparts. Both solid-state two-terminal sources [such as Gunn or impact avalanche and transit-time (IMPATT) diodes] and vacuum electronic tubes [such as klystrons, magnetrons and backward-wave oscillators (BWOs)] have continued their steady march toward higher power and higher frequencies over the past several decades. For applications in which the frequency of the desired effect (e.g., a gas absorption line) is known, these technologies are an attractive solution. They are usually deployed in situations in which absolute ranging and time gating is not needed and in which the complex (magnitude/phase) response is not required.

Their narrowband photonic counterparts, such as gas, lead-salt or—especially—quantum-cascade lasers, represent steadily improving technologies from the "top-down" angle. Another optoelectronic approach to generating tunable CW THz radiation is by frequency-mixing two lasers onto a nonlinear device and coupling out the difference frequency through an antenna.

Broadband pulsed systems

Outside of Fourier-transform infrared

(FTIR) spectrometers, which use interferometry to disperse a blackbody source, the most prevalent optoelectronic means for achieving broadband THz spectroscopy is time domain measurements using ultrafast mode-locked lasers and photoconductive switches or nonlinear crystals. The advantage of using synchronous, time-domain detection is three-fold: first, incoherent background noise is largely eliminated; second, the THz field amplitude rather than power is detected, enabling complex (real and imaginary) measurements of the sample's dielectric function; finally, time-gating can be employed to eliminate spurious reflections from the sample, thus minimizing the effects of standing waves.

In analogy to the pulsed optoelectronic approach, electronic pulses of a picosecond or even less can be generated from microwave sources using integrated circuits called nonlinear transmission lines (NLTLs). The NLTL, effectively a distributed-frequency multiplier, exhibits a wave-propagation velocity that depends on the amplitude of the signal propagating along it. For example, a diode-loaded NLTL might slow the portion of a voltage wave at zero volts to around half the speed of a part whose value is -8V, allowing the negative-voltage part to "catch up" to the slower one at zero volts, promoting the formation of a shock front. This is a steep voltage edge, the Fourier components of which might extend to the THz, depending on the design, construction and drive conditions of the NLTL.

When the output of this emitter NLTL is coupled to a broadband antenna, the pulse can be efficiently radiated into free space (see Fig. 2). Another NLTL that is driven synchronously with the emitter, but with a slight frequency offset, can serve as the strobe for a sampling detector, the operation of which is reciprocal to the emitter's: By using the short pulse of the detector NLTL to (very briefly) close a diode switch connected to another broadband antenna, a sample of the voltage present on the antenna's terminals is presented at the output of the switching detector. This small signal is amplified and presented on an oscilloscope or Fourier transformed by a spectrum analyzer to provide a low-frequency replica of the THz spectrum, much like a strobelight seems to slow down repetitive action so our eyes can follow it. Like the strobelight, the sampler delivers an equivalent-time voltage wave form to its output, the bandwidth of which—like that of our eyes—is limited. Thus, all the harmonic information contained in the original THz spectrum must be folded into the output bandwidth of the detector, which might be in the kHz to MHz range.

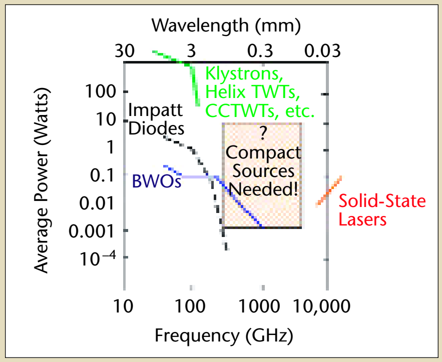

Figure 3. Trends in power of electronic and photonic sources vs. frequency. [Courtesy John Booske]. BWOs are backward-wave oscillators, TWTs are traveling wave tubes, CCTWTs are coupled-cavity TWTs and IMPATT stands for impact avalanche and transit-time.

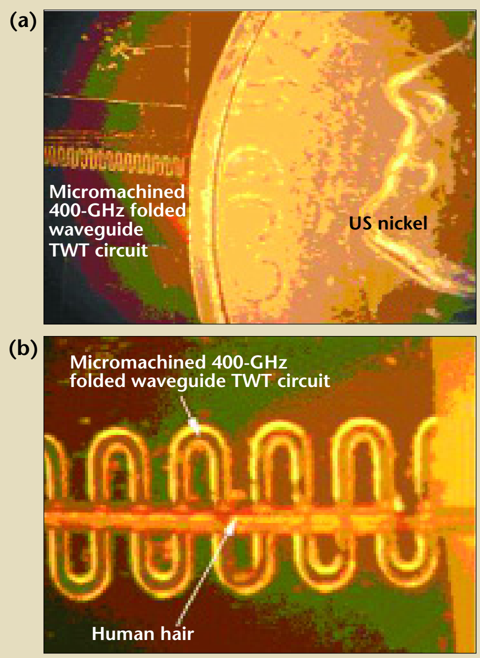

Figure 4. Folded waveguide (FWG) traveling wave tube (TWT) circuits compared to a U.S. nickel (a) and human hair (b). [Courtesy Sean Gallagher; fabricated at Argonne National Laboratory].

One of the issues for any coherent "equivalent-time" system, whether electronic or photonic, is the generation of the two phase-related signals to drive both emitter and detector so that their difference frequency (which forms the basis of the scaled-down THz spectrum) is low enough to measure with the output bandwidth of the detector. While we usually use two phase-locked microwave oscillators to do this in the laboratory, this approach is as bulky and expensive as any laser. We can, however, use the same NLTL designs that provide pulses in a new way, as small-signal delay (phase) modulators, scanning their bias voltages with a sawtooth wave in the same way one might scan the mirror of an optical interferometer. Thus, by splitting a single free-running microwave source and phase modulating one path with respect to the other, we can achieve the same results as by use of two sources, but in a much more compact and low-cost package, ultimately on the same integrated circuit. This phase modulation technique provides a clear path toward single-chip integration of broadband electronic THz systems.

Even though by working the "bottom-up" angle on THz spectroscopy the NLTL-based systems have not exceeded the 1-THz barrier by much, they show tremendous promise in lower-THz field-deployable sensor applications, where small size and relatively low power are of concern. These systems have been used with synchronized microwave sources in the laboratory to measure useful spectra on a variety of samples, including photonic bandgaps, gasses, explosive materials and even a simulant of anthrax, *B. cereus.*

Broadband amplifiers

One of the most prominent gaps in the

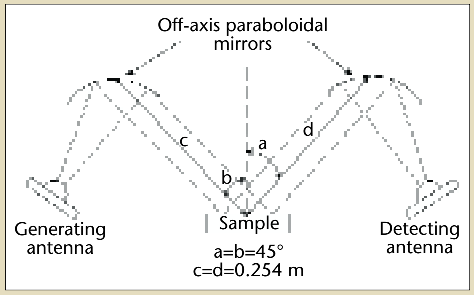

Figure 5. Reflection measurement setup. [Courtesy Min Choi.]

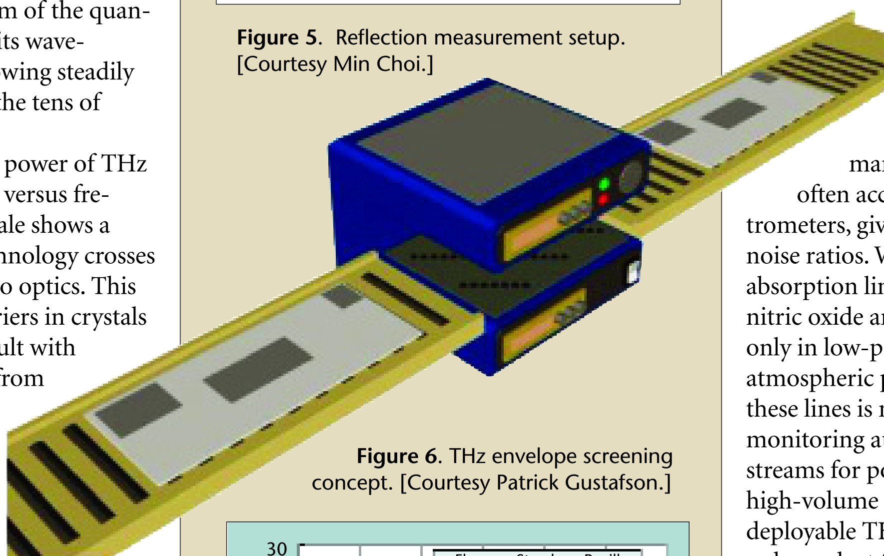

Figure 6. THz envelope screening concept. [Courtesy Patrick Gustafson.]

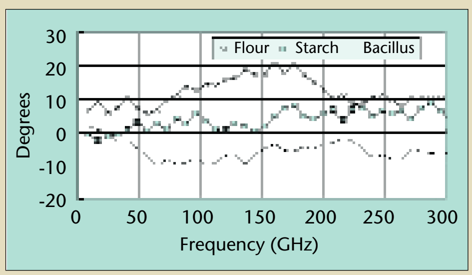

Figure 7. Phase of transmission through envelopes containing flour, starch and spore of *B. cereus*, all normalized to same phase at the fundamental frequency of ~ 8 GHz. [From Choi *et al.*]

THz toolkit is the lack of suitable broadband and high-power amplifiers. While both broadband and narrowband tunable sources have proliferated, the quest to find the analogy of a broadband laser's gain medium in the THz has been largely fruitless. Outside of gas lasers, in the "top-down" world, the most promising candidate for approaching the THz is the gain medium of the quantum cascade laser; yet its wavelengths—although growing steadily longer—still hover in the tens of micrometers.

Plotting the output power of THz sources and amplifiers versus frequency on a log-log scale shows a V-shaped trend, as technology crosses over from electronics to optics. This is because moving carriers in crystals gets increasingly difficult with high frequency, while from the visible working toward the THz, inverting carrier populations becomes harder as level separations approach a few times kT.

One promising approach to addressing the gap in power versus frequency around 0.5 THz is being pursued at the University of Wisconsin: micromachined traveling wave tube amplifiers. The microwave versions of these beam-wave interaction devices have been used successfully in both space and terrestrial applications for over 40 years. They still represent the best combination of high power, broad bandwidth and reliability for mission-critical applications such as satellite communications.

Most TWTs in the microwave range are built with helical waveguides that serve to slow an electromagnetic wave down so that it interacts with an electron beam. Energy flows from the electron beam to the wave, pumping the wave, depleting the beam and inducing "beam bunching" that further enhances the efficiency of beam-wave energy transfer. As wavelengths shrink below a few millimeters, however, building a helix is much less practical, while the planar projection of a helix, a folded (rectangular) waveguide (FWG), becomes very attractive for micromachining. By etching or building up a FWG with a beam hole running through its center, we have realized structures that promise to be useful broadband THz amplifiers. We have recently demonstrated a 10x scale model of the structure in Fig. 4 as a feedback oscillator running at over 40 GHz.

Applications

Of the many applications for THz technology that have been pursued or suggested, a few have the potential to address markets in which sales of over 100 units or systems per year might be possible.

Gas spectroscopy/sensing

An intriguing aspect of broadband THz sensors would be their multivalent capability for sensing multiple gas species with one system. While mid- and near-infrared sensors are usually employed for gas sensing and spectroscopy, rotational lines of molecules with a permanent dipole moment are often accessible to THz spectrometers, given sufficient signal-to-noise ratios. We have measured absorption lines of species such as nitric oxide and carbonyl sulfide, but only in low-pressure tubes where atmospheric pressure broadening of these lines is nonexistent. The idea of monitoring automotive exhaust gas streams for pollution is an intriguing high-volume application for field-deployable THz technology, but will only work at frequencies far from the ubiquitous water-vapor absorption lines that dominate the spectra. This challenge is compounded by the ~ 400 K temperature of exhaust gas, which further enhances thermal background.

Security

The heightened sense of vulnerability to concealed threats—whether nonmetallic weapons, explosives or even biological agents such as anthrax—has motivated a wide-ranging response from the scientific community. THz technology, with its ability to "see through" many types of enclosures (and to distinguish metal from plastics) is a promising candidate to address the problem of detecting such concealed threats.

Laboratories around the world including ours have measured a variety of targets both in transmission and in reflection (see Fig. 5) to map out potential routes to field-deployable sensing systems for concealed weapons, whether on people or in packages and envelopes. The ability to penetrate envelopes and see useful dielectric contrast with THz radiation may enable rapid screening and identification of suspicious contents (Fig. 6).

Weapons

We have made several reflection measurements of metallic and non-metallic targets in our laboratory, and have observed predictably high contrast against a skin background. In particular, we have taken small quantities of energetic materials, such as plastic explosives and TNT, and measured them against both reflecting and absorbing backgrounds at the focus of a broadband electronic THz reflectometer. The patterns of reflection versus frequency give rise to signatures that are remarkably specific to the chemical composition of the target, even though the target's morphology and position is varied. While more fundamental work is ongoing to understand the response of organic crystals such as these in the low-THz regime, the results provide intriguing motivation to push for a new type of screening system that would operate in tandem with existing x-ray and metal-detecting screeners.

Biological agents

To examine the contents of envelopes with an eye toward distinguishing common powders from potentially dangerous ones, we prepared samples of sugar, starch, flour and talcum powder, and used our electronic THz system on them in both reflection and transmission. Additional transmission measurements were done through envelopes with the same four powders and with *B. cereus*, a close relative of *B. anthracis*, or anthrax.

While the magnitude of transmission from 8-300 GHz showed interesting patterns for all powders, the phase signal (Fig. 7) was most conclusive, demonstrating the value of a broadband system to accurately discriminate the spores from other powders. The negative dispersion exhibited in this measurement is readily distinguished, and may be due to the particular water content and size of the spores.

The outlook for THz technology—especially for field-deployable systems that can be compact and even battery-operated—is bright. While optoelectronic THz technology is more refined, in part because of a larger number of practitioners, electronic THz technology will catch up as more high-volume applications are pursued. To summarize many of the application areas and the suitability of different THz regimes to address them, it is useful to tabulate the application areas and indicate whether the application has been pursued or is a possibility (see Table 1.)

Regardless of the technology, the terahertz field is an exciting and growing one with both scientific and economic potential. Lying at the boundary between electronics and optics, it also finds itself at the boundary between scientific curiosity and widespread application. Interesting things can happen at the boundaries!

Application Area	Lower THz (< 0.5 THz)	Upper THz (> 0.5 THz)
Space (low atmospheric absorption)		
• Spectroscopy/sensing	X	X
• Imaging (e.g., cosmic background)	X	X
• Communications	?	?
Laboratory (~ 1 m propagation distance)		
• Spectroscopy	X	X
• Imaging (e.g., near- and far-field)	X	X
• Communications	X	?
Industrial (~ 1 m propagation distance)		
• Spectroscopy	X	X
• Sensing (e.g., moisture)	X	X
• Imaging (e.g., near- and far-field)	X	X
• Communications	?	?
Medical (< 1 m propagation distance)		
• Imaging (e.g., skin, teeth)	X	X
Government/Security		
• Sensing (e.g., screening) at > 1 m stand-off	X	?
• Imaging (e.g., locating weapons)	X	?
• Communications	X	?

Table 1. Demonstrated (X) and potential (?) applications of THz technology both below and above 0.5 THz.

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