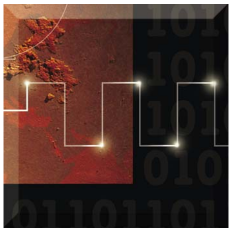

# Terahertz Waves for Communications and Sensing

*Michael J. Fitch and Robert Osiander*

The development of technology in the THz frequency band has seen rapid progress recently. Considered as an extension of the microwave and millimeter wave bands, the THz frequency offers greater communications bandwidth than is available at microwave frequencies. The development of sources and detectors for this frequency range has been driven by other applications such as spectroscopy, imaging, and impulse ranging. Only recently modulators and filters have been added to enable the development of communications applications. APL's contributions to date in THz research have been primarily in the areas of spectroscopy and imaging. This article gives an overview of THz technology for communications and sensing applications, with some discussion of the sources, detectors, and modulators needed for a practical THz communications system.

## INTRODUCTION

Until recently, the THz ($10^{12}$ Hz) region of the electromagnetic spectrum from about 100 GHz to 10 THz has been almost inaccessible because of the lack of efficient sources and detectors in this "THz gap." Beginning in the 1960s, the main interest in developing detectors in this frequency range was motivated by astrophysics, since the rotational spectra of some gases of astrophysical and environmental interest fall into this range. Known as millimeter wave and submillimeter wave astronomy (corresponding to the wavelengths), cryogenic detectors were used by observational astronomers to record spectra. Pioneering work in 1975 on picosecond photoconductivity in silicon[1,2] led to the development of photoconductive and electro-optic methods[3] to generate and detect radiation in the THz frequency range. Subsequently, interest in this frequency range rapidly increased, and today much effort is focused on the development of efficient sources, sensitive detectors, and suitable modulators in this range.

The electromagnetic spectrum is shown in Fig. 1. For the lower frequencies, including RFs for AM and FM radio as well as microwaves, the sources are based on electric generation governed by the classical transport of electrons. Most dielectric materials are transparent at these frequencies, allowing radio reception and cellular telephony indoors. The resolution of imaging applications such as radar is on the order of the wavelength and is typically limited to a few centimeters.

Higher frequencies in the spectrum encompass the optical regime, including IR radiation, visible light, and UV. Here, the light is generated by quantum transitions, which can generate very high intensities using lasers. Electromagnetic radiation in this regime typically propagates in free space according to the laws of

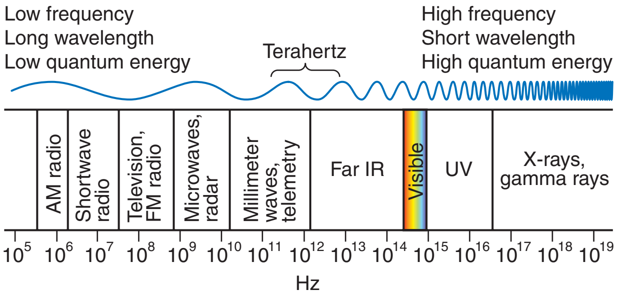

**Figure 1.** The electromagnetic spectrum.

geometrical optics. Many materials are opaque in this range, and optical radiation is strongly scattered by dust, fog, or grains in heterogeneous materials.

The THz regime is located between these two regions, and since it represents the transition between the electric and photonic sources, electromagnetic radiation in the THz range can be generated both ways. The development of modern microfabrication techniques, as well as the capability to fabricate structures on the order of the THz wavelength of a few 10s of micrometers in electronic and hybrid optoelectronic devices, was essential for the development of THz sources and receivers. Table 1 illustrates some of the parameters associated with electromagnetic radiation in the THz frequency range along with some standard laser lines. The wavelength of this radiation, which is on the order of a few hundred micrometers, determines the antenna size as well as propagation and imaging resolution. For example, the resolution that can be achieved in a diffraction-limited optical imaging setup is on the order of a wavelength.

Attenuation caused by scattering strongly increases when the particle size nears the wavelength of the radiation, which explains why THz radiation can propagate well in dust. The energy of a THz photon is on the order of a few milli-electronvolts, and as such is considered nonionizing radiation, with no proven impact on biological systems. This energy is equivalent to temperatures below 70 K, and so any semiconductor-based detector must usually be cryogenically cooled. The most available source for THz radiation, and the source for a lot of background noise in measurements at this frequency range, is thermal radiation. For example, the IR emission peak at human body temperature is at 10 $\mu$m (30 THz), with a high level of radiation in the lower THz range. Passive THz imaging can be used to detect the emission of hot objects just like passive IR imaging.

With sensing applications and short-range communications possible in the 10- to 100-m range, the technology and applications for THz waves are growing rapidly. Technology development focuses on sources, imaging arrays, and spectrometers to support applications in explosive and biochemical agent detection, mine detection, high-resolution through-the-wall imaging, etc. There are also a number of communications applications where THz waves will provide new capabilities.

## THz COMMUNICATION

The term "THz communication" can mean (1) effective data rates exceeding 1 Tbit/s (usually on an optical carrier) or (2) communication with a THz carrier wave, which is the focus of this article. Although ultimately greater bandwidths can be obtained at optical wavelengths with point-to-point optical communications (see the article in this issue by Boone et al.), a number of reasons make communications at THz frequencies very attractive, one being the availability of the frequency band and the communications bandwidth. Frequencies above 300 GHz are currently unallocated by the Federal Communications Commission, as shown in the U.S. Frequency Allocation chart (Fig. 2). THz communication is in the very early stages of development, with first data transmission in this frequency range recently reported.[4]

The obvious disadvantages of communications at THz frequencies arise from the strong absorption through the atmosphere (Fig. 3) caused by water vapor as well as the low efficiency and relatively low power available from currently available sources. For a 1-mW source and a detection sensitivity of 1 pW, the working dynamic range is 60 dB, which allows communications at a range of 500 m in an atmospheric transmission window with an attenuation of <100 dB/km.

Despite the strong atmospheric absorption and low source efficiency, there are possible communications applications for this frequency range. For satellite-to-satellite communications, atmospheric absorption is not a problem,

**Table 1. The THz regime in different units.**

| Frequency (THz) | Wavenumber (cm$^{-1}$) | Wavelength ($\mu$m) | Energy (meV) | Equivalent temperature (K) |
|---|---|---|---|---|
| 0.1 | 3.33 | 3000 | 0.41 | 5 |
| 1.0 | 33.3 | 300 | 4.1 | 50 |
| 10.0 | 333 | 30 | 41 | 500 |
| 29.7 | 990 | 10.1 (CO$_2$) | 123 | |
| 282.0 | 9,398 | 1.064 (Nd:YAG) | 1160 | |
| 474.0 | 15,797 | 0.633 (HeNe) | 1960 | |

Note: Energy and temperature are related by $E = k_B T$, where $k_B$ is Boltzmann's constant.

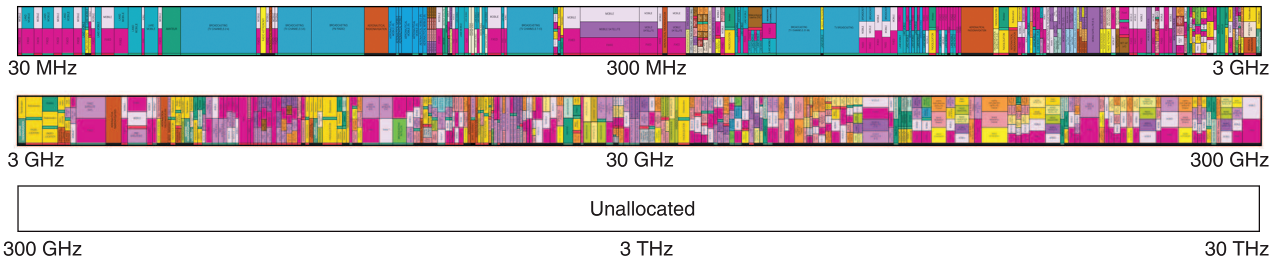

**Figure 2.** The regulated spectrum as designated by the U.S. Federal Communications Commission and the THz region, which is completely unallocated at the time of writing. (Source: http://www.ntia.doc.gov/osmhome/allochrt.pdf.)

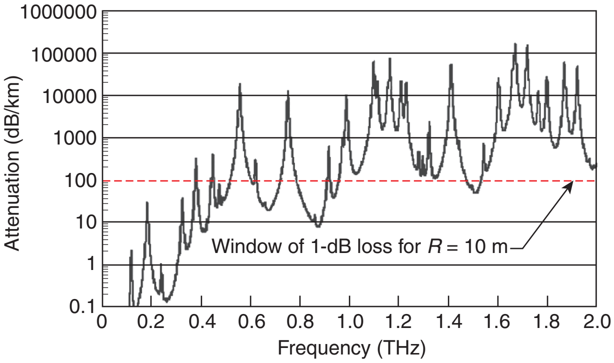

**Figure 3.** Atmospheric attenuation in the THz frequency range.

except for paths that graze the Earth's atmosphere. Here the advantages of using THz technology are the larger bandwidth and therefore higher transmission rate as compared to microwave communications, without having to switch to a different set of hardware such as lasers for optical communications. The all-electronic conversion from the THz carrier to microwave links will be straightforward. At the same time, the size of the antenna will be reduced, which favors smaller satellite systems.

Indoor wireless communications with THz may provide multiple data channels with gigabit per second or greater capacity. The data bandwidth would exceed wireless protocols such as IEEE 802.11b, and the propagation distance, though limited, would be competitive with line-of-sight IR.

One problem encountered in optical communications is attenuation caused by scattering and absorption by clouds, rain, dust, etc. In the Rayleigh scattering regime, the scattering cross section increases with shorter wavelengths as the 4th power of the inverse wavelength. This is the well-known explanation for the blue color of the sky and the redness of sunrise and sunset since the shorter blue wavelengths are scattered more strongly than the longer red. Consequently, THz and millimeter waves experience much less scattering loss caused by particulates than do optical wavelengths. Millimeter-band communications can be used as a backup to an optical link in case of rain or heavy clouds. Similarly, THz can be used for short distances if heavy particulates (smoke, dust) are present in the air.

Atmospheric transmission windows may allow application of THz for short-range tactical communication. In some cases, the limited transmission distance may be an advantage, considering the clutter and congestion of voice channels in combat zones. The beamlike properties of THz emission reduce the ability of distant adversaries to intercept these transmissions. The adversary may even lack the technological capability to detect, intercept, jam, or "spoof" a THz signal. In addition, atmospheric attenuation allows covert short-range communications, since these signals simply will not propagate to distant listening posts. Scenarios that might be of interest are platoon-level communications among individual soldiers if the THz communications gear can be made sufficiently small and light. THz navigational beacons would possess similar advantages in covertness (e.g., for insertion/extraction of special forces or rescue of downed pilots) and similar disadvantages of short range.

## TIME-DOMAIN THz GENERATION AND DETECTION

### Photoconductive and Electro-Optic THz Generation and Detection

Besides some maser or laser lines in the THz range, which could be used to generate coherent radiation in that frequency range, the only viable source for THz radiation before the mid-1970s was thermal and was typically used in Fourier transform IR spectrometers as a source for the far-IR (THz) spectrum. This changed in 1975, when D. H. Auston of Bell Labs demonstrated that a short laser pulse (on the order of 100 fs and with a wavelength above the bandgap) impinging on a biased semiconductor would create a picosecond current transient. This time-dependent current radiates classically in the far field and contains frequency components in the THz frequency range. This source for a THz pulse is called the "Auston switch,"[2] which has, together with the availability of femtosecond pulse laser sources, played a significant role in the growth of THz research and applications. Most commercial (electro-optic) THz systems use the Auston switch as a source, and a number of optimized semiconductor materials (e.g., radiation-damaged silicon on sapphire and low-temperature–grown GaAs[5]) have allowed extension of the range of available frequency components, determined by the THz pulse length, to include frequencies below 0.05 THz and over 4 THz.

Semiconductor photoconductivity can also be used to detect the THz pulses in an arrangement called the "Grischkowsky antenna,"[2,6] shown in Fig. 4. A dipole antenna for the THz frequency range is patterned as a transmission line on an insulating semiconductor (GaAs in the figure). The antenna is gated on and off by a femtosecond laser pulse. Only when the laser pulse generates photo-carriers in the semiconductor does a current flow in the direction of the THz electric field. By scanning the time delay between the narrow gate laser pulse and the THz pulse, using a setup similar to the one shown in Fig. 5, the electric field of the THz wave can be measured as a function of time. Also known as "photoconductive antennas," such detectors have been used for time-domain spectroscopy (TDS; also called time-domain Fourier transform spectroscopy).[7,8]

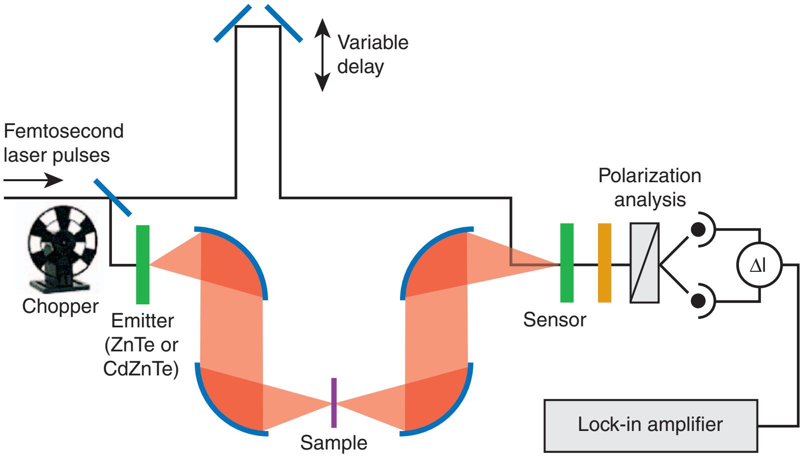

**Figure 5.** Schematic of a THz time-domain spectroscopy system. A 1-fs laser pulse pumps the emitter crystal and produces a pulse of THz radiation by a nonlinear optical process. A probe laser pulse is used for electro-optical detection in the sensor crystal. By scanning the relative delay between the two laser pulses, the THz waveform is measured directly in the time domain.

Another approach to generate picosecond THz pulses with femtosecond lasers uses nonlinear optics. Difference-frequency generation in a nonlinear optical crystal from the broad frequency spectrum of an ultrafast laser pulse generates a THz pulse with frequency components extending from 0.5 THz to more than 20 THz. This nonlinear optical process was studied and named "optical rectification" by Bass et al.[9] in 1962. Morris and Shen[10] realized that picosecond laser pulses could be used to generate far-IR light. The effect was observed by Auston and Glass[11] in 1972. Optical parametric oscillators and optical parametric amplifiers have been used to generate tunable IR radiation, and recent work[12] has extended this to the THz region. The capability to generate THz pulses with frequency components above 5 THz makes this approach very attractive for many sensor applications.

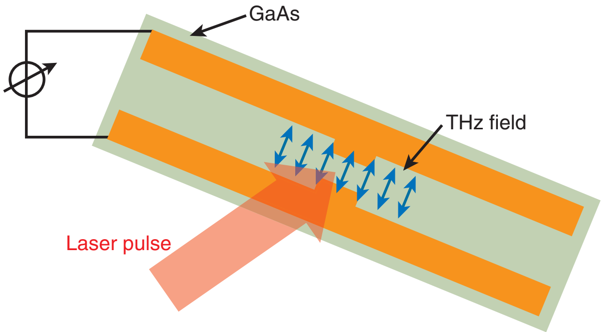

**Figure 4.** Grischkowsky antenna. The femtosecond laser pulse generates carriers in the GaAs substrate, which allow the THz field-induced currents to flow. Picosecond photoconductivity is the physical mechanism for operation of the device.

Nonlinear optical crystals can also be used to detect THz pulses.[13–17] This detection method employs the electro-optic (Pockels) effect, where the polarization of light passing through a nonlinear crystal is rotated an amount proportional to an applied electrical field. When a femtosecond laser pulse and a THz pulse pass through the crystal at the same time, the polarization of the laser pulse is changed proportional to the electric field of the THz pulse. By scanning the relative time delay between the THz pulse and the femtosecond laser pulse, as with photoconductive antennas, the electric field of the THz pulse can be measured as a function of time. Electro-optic detection is also used in TDS and allows, in principle, a much wider frequency range to be covered. Since the electric field of the THz pulse for both detectors is measured as a function of time, the Fourier transform of the waveform gives amplitude and phase information, which is the basis of TDS (see the next section).

The application of photoconductive and electro-optic pulsed THz sources in communications is, in all likelihood, limited for the investigation of frequency responses and proof-of-principle experiments. Nevertheless, audio signal transmission using these approaches with a semiconductor modulator has just recently been demonstrated.[4]

An approach to generate THz emission from a semiconductor that is more applicable to communications is known as "photomixing." Mixing two continuous-wave lasers in a semiconductor material can drive a time-dependent current inside the semiconductor at the difference frequency, which then radiates classically at THz frequencies. In a common configuration, interdigitated electrodes coupled to a log-spiral antenna are used to increase efficiency.[18] Because of the limitations of carrier lifetime in the semiconductor, the process of photomixing is most efficient at 0.3–0.6 THz but drops significantly above 1.0 THz. Sources of this kind can be nearly as compact as the two lasers and provide a tunable continuous-wave THz source that can be modulated using the previously mentioned semiconductor modulators.

## Time-Domain Spectroscopy

Electro-optic and photoconductive THz sources and detectors have allowed compact and sensitive systems to be built for far-IR spectroscopy in the THz frequency range using TSD. The principle behind TDS is to determine the waveform of a THz pulse (the electric field as a function of time) and, using Fourier transformation, recover the frequency spectrum from the waveform. An important aspect of TDS is its high signal-to-noise ratio. Since it is a coherent detection method, other THz sources (e.g., thermal background radiation at THz frequencies) do not contribute to the signal at all.

Referring again to Fig. 5, THz pulses are generated with a femtosecond laser by nonlinear optical generation. A fraction of the original laser pulse is split off as the probe (gating) beam and is combined with the THz pulse in an electro-optical crystal. A combination of polarization optics and two photodiodes is used to measure the polarization shift, which is proportional to the THz electric field at the time of the laser pulse on the electro-optic crystal. A positioning stage or oscillating mirror is used to change the relative time delay between the THz pulse and the optical pulse, thus allowing measurement of the THz electric field as a function of time. The Fourier transform of the time-domain data corresponds to the frequency spectrum of the THz source and contains amplitude and phase information. Since electromagnetic radiation travels about 0.3 mm in 1 fs, recording the waveform of a picosecond THz pulse requires about 300 $\mu$m of travel.

One of the applications of THz TDS at APL is in the spectroscopic detection of explosives and bio-agents. The experimental setup uses GaSe crystals, which have a very high electro-optic coefficient (i.e., they are very efficient in generating and detecting THz) and a laser with a pulse length of 13 fs. The reason for using such incredibly short laser pulses is to generate a THz spectrum that extends from 1 THz to more than 20 THz, a frequency range in the far IR well known to be a fingerprint spectral region for many organic molecules. This can be applied to the detection and characterization of many compounds, including contraband drugs, chemical agents, and explosives. Researchers at APL and Rensselaer Polytechnic Institute (RPI) have recently demonstrated that THz TDS can be used to characterize intra- and inter-molecular vibrations in an entire class of explosives, including TNT.[19–22]

TDS has also been applied to absorption spectroscopy in the vapor phase. This phase-sensitive coherent detection technique even allows spectroscopy in hot environments such as flame chemistry,[23] where the high thermal backgrounds would completely swamp an incoherent detection system.

Another noteworthy use of time-domain techniques is impulse ranging. In one interesting study, 1/200th-scale models of aircraft (MiG-19 Fulcrum and F-117 Stealth) were used as targets for a THz pulse spanning from 0.1 to 2.0 THz.[24] The frequency scaling corresponds to conventional radar frequencies of 0.5–10.0 GHz. Results showed a lack of scattered field (within the signal-to-noise ratio) from the Stealth aircraft, testifying to successful faceted geometry of the aircraft, thus deflecting energy away from the detector.

## THz Imaging

A very important application and the focus of much research in THz is imaging using THz radiation. The capability of imaging through dielectrics with a resolution on the order of a few hundreds of micrometers has numerous applications. Many systems, such as the one at APL, are based on a photoconductive emitter, where THz imaging is performed with time-domain experimental setups simply by scanning an object through the focus of a single pixel. In the full image, each pixel has a complete time-domain waveform and a spectrum (with phase). Image acquisition times are typically 10s of minutes per frame. It has recently been shown that a large-aperture electro-optic crystal, in combination with a CCD camera, can take a full-field time-domain image.[25]

Researchers at APL and RPI have demonstrated the use of THz imaging for detecting buried antipersonnel mines to a depth of a few centimeters in slightly moist, granular soil.[26,27] Attenuation in sand is weaker than in soil, so greater detection depths should be possible for sand. Because TDS yields useful amplitude and phase information, it is possible to apply theoretical models developed for materials science to the problem of THz scattering and propagation in granular media. In particular, extraction of phase information can show the transition between Rayleigh scattering and multiple scattering in foams and ceramics[28] and in sand and soil.[29]

Although medical applications of THz imaging are limited by strong absorption in living tissue (attenuation coefficient = 220 cm$^{-1}$), studies have shown the ability to differentiate skin cancer (basal cell carcinoma) from healthy skin using this technique.[30] THz imaging has also been used to find defects in manufactured electronic chips[31] and in the sprayed-on foam insulation of the Space Shuttle's external fuel tank.[32]

A very different approach for THz imaging is passive imaging, where, similar to IR imaging, a detector array would detect the thermal radiation in the THz range. Since THz radiation, unlike IR radiation, can penetrate many low-loss dielectric materials such as paper, clothing, and cardboard, one of the major applications for THz waves is high-resolution imaging *through* dielectric material. Millimeter wave imaging arrays, such as the 94-GHz array by Trex Enterprises, have been developed. The StarTiger project (funded by the European Space Agency) has developed photonic bandgap structures as selective antennas that can form "two-color" images at two frequencies: 0.2 and 0.3 THz.[33] Although imaging through barriers can be done with millimeter wave systems, THz offers a greater spatial resolution and a smaller aperture. There are a number of security applications for this technology, such as through-the-wall imaging, luggage inspection, and detection at a distance of weapons or explosives (suicide bombers) hidden under clothing.

## DEVELOPMENT OF THz SOURCES, MODULATORS, AND DETECTORS FOR COMMUNICATION

The potential applications of THz communications will depend strongly on the availability of more efficient continuous-wave sources, coherent detectors, and modulators at this frequency range.

### Sources

Microwave sources followed by one or more stages of harmonic generation can reach frequencies of hundreds of gigahertz. Each stage of harmonic generation comes with an efficiency penalty, so at high frequencies the total available power and the efficiency are low and metal waveguides are lossy. To improve on waveguides, analogies of fiber-optics are being explored,[34] although long-distance transmission will be limited by the finite conductivity of metals and the absorption coefficient of dielectric materials. The tuning range of each harmonic generation chain (less important for communications applications than for spectroscopy applications) is usually limited to about a 20% bandwidth. The leader in commercial development today is Virginia Diodes, Inc. (Charlottesville, Virginia), which now offers sources based on microwave harmonic generation chains that reach 1.2 THz.

Vacuum tube technologies developed for radio and microwave applications have been extended to the THz frequency range using micromachining techniques. Among the most successful tubes is the backward wave oscillator (BWO), so named because the direction of radiation amplification is opposite to the direction in which the electron beam travels. The disadvantages of BWOs include the need for a large external magnetic field, for a highly stable high-voltage power supply, and, since it cannot be directly modulated, for a separate high-speed THz modulator or mixer.

Another THz source developed recently is the quantum cascade laser (QCL). QCLs require a rather sophisticated fabrication process of multiple quantum wells. Electrons cascade from localized states in wells, and as they fall from one well to the next, a THz photon is emitted. Lasing action is achieved with a large number of quantum wells, along with suitable feedback. A device lasing at 4.4 THz has achieved 4-mW continuous-wave output power at an operating temperature of 48 K.[35] Recently, continuous-wave operation of two devices—one lasing at 3.2 THz up to a temperature of 93 K[36] and the other at 2.9 THz up to 70 K[37]—was reported. The advantages of QCLs include narrow linewidth, reasonable power (in milliwatts), and compact size. Active development aims to reduce the disadvantages: the need for cooling at or near liquid nitrogen temperatures, limited tuning range, limited device lifetime (hundreds of hours), and high unit costs. QCLs can operate in pulsed mode, allowing the possibility of modulating the output by directly modulating the injection current.

### Modulators

For future applications in THz communications and surveillance, components such as modulators, phase-shifters, attenuators, and polarizers will be needed. A liquid-crystal phase shifter has been demonstrated.[38] It is difficult to adapt conventional electro-optic modulators because material birefringence is low in the THz regime. Modulation of a near-IR optical beam by a THz signal has also been reported[39] in an undoped double quantum well structure. Semiconductor modulators of THz have been demonstrated,[40,41] but operate only at cryogenic temperatures. A room-temperature modulator based on electrically driving the density of a 2-D electron gas was able to achieve a modulation depth of 3%.[42] Although this depth is relatively small, it was sufficient to encode an audio signal.[4] Higher modulation depths should be possible with either higher electron densities or by stacking devices in series. A THz transistor[43,44] has also recently been reported. Clearly, rapid progress is expected in THz devices.

### Detectors

Heterodyne receivers based on GaAs Schottky diodes have been developed for applications in the frequency range from 100 GHz to over 3 THz.[45–47] The high sensitivity, large spectral resolution, and large instantaneous bandwidth of these receivers have been used for a variety of scientific applications, including radio astronomy and chemical spectroscopy. It appears that Schottky devices will continue to play a critical role at THz frequencies for the foreseeable future, although a number of effects degrade diode performance as the frequency approaches 1 THz. One of the most important effects is the increase in the series resistance of a given diode with frequency caused by the skin effect, which constrains the current to flow along the edge of the chip substrate. Also, at THz frequencies the inertia of the electrons adds an inductive element to the circuit model, and dielectric relaxation adds a capacitive element. Note that a frequency of 1 THz requires charges to be moving on a timescale of 1 ps.

In competition with antenna-coupled Schottky diodes[48] is the nonlinear transmission line.[49,50] Another candidate could be diode systems based on metal-oxide metal diodes, which have shown some success from 90 GHz up to 30 THz.[51,52]

An excellent overview on THz technology in general is given in a review article by Siegel.[53]

## CONCLUSIONS

The development of technology to generate and detect THz radiation has seen incredible growth within the last 5 years, in part because of the great promise it holds for security applications such as high-resolution imaging and spectroscopy of, for example, bio-agents or explosives. For these applications, much of the progress has been made using optically based techniques such as electro-optic generation or photomixing. Electric sources and receivers are now available for frequencies up to 1 or 2 THz, as are modulators that should allow communications in the THz frequency band to experience rapid progress. Even though the propagation length is limited, THz offers advantages (small wavelength, high bandwidth, ability to penetrate dielectrics) in some areas over millimeter waves and optical free-space communications. Development of better THz sources, detectors, and modulators is progressing, which will enable a practical THz communications system.

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