by Eric R. Mueller

Terahertz Radiation: Applications and Sources

Until recently, researchers did not extensively explore the material interactions occurring in the terahertz spectral region—the wavelengths that lie between 30 μm and 1 mm—in part because they lacked reliable sources of terahertz radiation. However, pressure to develop new terahertz sources arose from two dramatically different groups—ultrafast time-domain spectroscopists who wanted to work with longer wavelengths, and long-wavelength radio astronomers who wanted to work with shorter wavelengths. Today, with continuous-wave (CW) and pulsed sources readily available, investigators are pursuing potential terahertz-wavelength applications in many fields.

Bio and astro

Much of the recent interest in terahertz radiation stems from its ability to penetrate deep into many organic materials without the damage associated with ionizing radiation such as X-rays (albeit without the spatial resolution). Also, because terahertz radiation is readily absorbed by water, it can be used to distinguish between materials with varying water content—for example, fat versus lean meat. These properties lend themselves to applications in process and quality control as well as biomedical imaging. Tests are currently under way to determine whether terahertz tomographic imaging can augment or replace mammography, and some people have proposed terahertz imaging as a method of screening passengers for explosives at airports. All of these applications are still in the research phase, although TeraView (Cambridge, England), which is partially owned by Toshiba, has developed a technique for detecting the presence of cancerous cells that is currently in human trials.

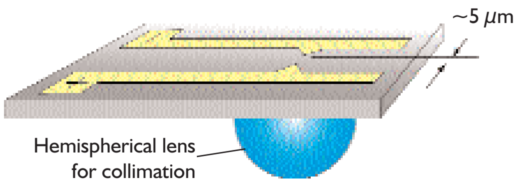


Figure 1. An electromagnetic wave is produced by this broadband short-pulse terahertz source when a dc bias is placed across the antenna and an ultrashort pump-laser pulse is focused in the gap.

Terahertz radiation can also help scientists understand the complex dynamics involved in condensed-matter physics and processes such as molecular recognition and protein folding.

CW terahertz technology has long interested astronomers because "approximately one-half of the total luminosity and 98% of the photons emitted since the Big Bang fall into the submillimeter and far-infrared," says Peter Siegel of the Jet Propulsion Laboratory (Pasadena, CA), and CW THz sources can be used to help study these photons.

One type of CW terahertz source is the optically pumped terahertz laser (OPTL). OPTL lasers are in use around the world, primarily for astronomy, environmental monitoring, and plasma diagnostics. A system installed at the Antarctic Submillimeter Telescope and Remote Observatory at the South Pole is the local oscillator for a THz receiver, which will be used to measure interstellar singly ionized nitrogen, H_2D^+, and carbon monoxide during the polar winter. Another system is slated for sub-Doppler terahertz astronomy use on the National Aeronautics and Space Administration's SOFIA airborne astronomical platform.

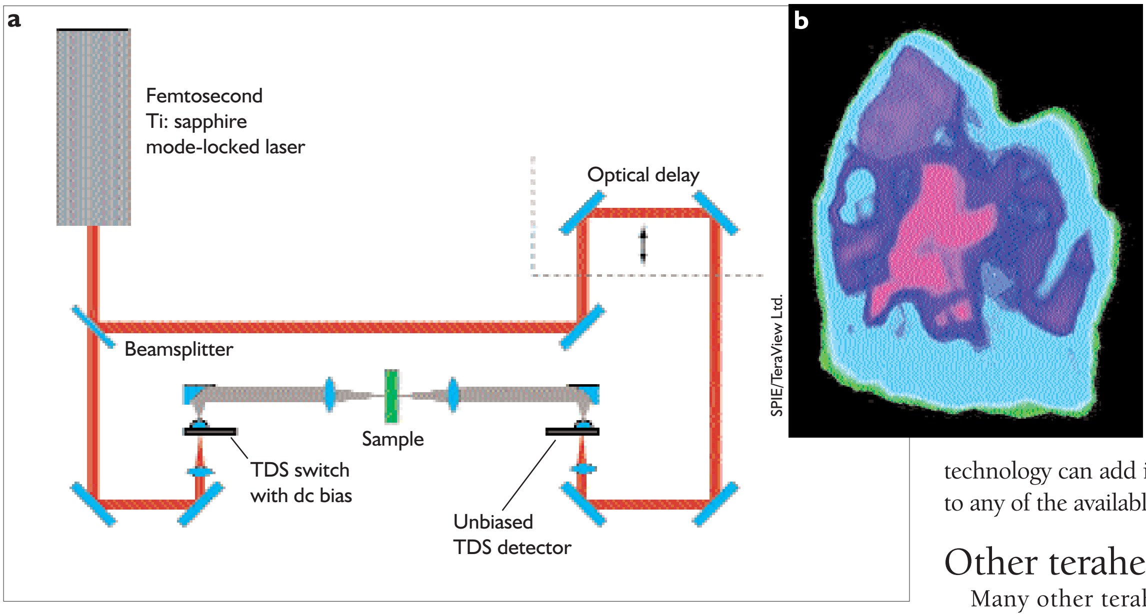
In 2004, a 2.5-THz laser will ride a Delta rocket into space aboard NASA's AURA satellite to measure the concentration and distribution of the hydroxyl radical (OH^-) in the stratosphere, a critical component in the ozone cycle. (Currently there are no global data for OH^- concentrations; only two spot measurements have been made using OPTL systems carried aboard high-altitude balloons.) The AURA system is less than 0.2 m^3, weighs less than 22 kg, and consumes 120 W of prime power. It works autonomously and is designed to operate in orbit for more than five years.

The emerging field of time domain spectroscopy (TDS) typically relies on a broadband short-pulse terahertz source (Figure 1). A split antenna is fabricated on a semiconductor substrate to create a switch. A dc bias is placed across the antenna, and an ultrashort pump-laser pulse ($<$100 fs) is focused in the gap in the antenna. The bias–laser pulse combination allows electrons to rapidly jump the gap, and the resulting current in the antenna produces a terahertz electromagnetic wave. This radiation is collected and collimated with an appropriate optical system to produce a beam.

This TDS switch puts out a train of pulses, whose repetition frequency is the same as that of the femtosecond pump laser. Pulse widths are on the order of 100 fs, with average powers of a few microwatts and a frequency spread of $>$500 GHz. The pulse bandwidth is typically centered at about 1 to 2 THz. The details of the spectrum can vary significantly, however, depending on the design of the switch and pump-laser power, pulse width, and configuration.

Figure 2a shows a typical TDS setup. The terahertz pulse is distorted by selective absorption as it passes through a sample, causing delays in its arrival time at the detector. The transmitted beam is then focused onto a detector, which is essentially identical to the emitter except that it is unbiased. By varying the time at which the sample pump pulse arrives at the detector, successive portions of the terahertz pulses can be detected and built into a complete image of the pulse in terms of its delay time, or time domain. The data are then processed by fast Fourier transform analysis in order to convert the delay time into the frequency of the terahertz signal that arrives at the detector.

The absorption characteristics of terahertz radiation vary greatly from material to material, and this property can be used to create images. In 1995, Binbin Hu and Martin Nuss at Lucent Technologies' Bell Laboratories created a terahertz imaging system using TDS and coined the term T-ray for these short, broadband terahertz



SPIE/TeraView Ltd.

Figure 2. In time domain spectroscopy, an image of the sample is built up based on selective absorption, which causes delays in arrival time at the detector (a). A typical result is this three-dimensional tomograph of a tooth, showing areas of decay (b).

pulses. The T-ray pulse is measured as it reflects from a sample. Because the pulse is so short, distance can be resolved by looking at the time of flight and then used to create a three-dimensional transparent reconstruction of various objects by measuring the time lapse between pulses reflected from different areas within the object (Figure 2b).

Optically pumped lasers

In its simplest embodiment, an OPTL system consists of a grating-tuned carbon dioxide pump laser and a far-infrared (FIR) gas cell mounted in a laser resonator. The pump beam enters the cell through an aperture in the high-reflecting resonator mirror. The pump laser is tuned to the appropriate absorption band, and lasing occurs. For several reasons, this is not as easy as it sounds. Both the absorption bandwidth of the vibrational energy state and the lasing bandwidth of its excited rotational states are quite narrow. Moreover, slight changes in the OPTL's pumping wavelength or changes in the cavity length itself can inhibit lasing, and feedback interaction between the pump laser and the terahertz laser can affect stability. Therefore, designers must pay careful attention to all of these things to achieve reliable performance.

In the past, research groups often built their own OPTLs, which were typically large and extremely difficult to use and maintain. Today, OPTL laser systems are smaller and more reliable turnkey systems. These improved systems stem from several developments, including permanently sealed, single-mode, frequency-stabilized, folded-cavity, radio-frequency-excited waveguide CO_2 lasers; sealed FIR gas cells that eliminate gas transport issues; and exquisitely stable passive resonator structures. The integration of these various improved laser technologies into a truly operator-friendly system has ensured ease of use.

Indeed, OPTLs can operate at many discrete frequencies, ranging from less than 300 GHz (1,000 μm) to more than 10 THz (30 μm). Different molecular gases each have their own spectrum of available lines. Sideband generation technology can add instantaneous tunability to any of the available OPTL laser lines.

Other terahertz sources

Many other terahertz source technologies have been investigated in the past four decades. Numerous groups worldwide are producing tunable CW terahertz radiation using photomixing of near-IR lasers. For example, Gerald Fraser's group at the National Institute of Standards and Technology is frequency mixing the output of a near-IR, fixed-frequency diode laser with that of a tunable Ti:sapphire laser in a low-temperature-grown gallium arsenide photomixer fabricated with the appropriate antenna pattern. This approach yields tens of nanowatts of tunable output with a spectral content governed by the spectral content of the near-IR laser.

Backward-wave oscillators (BWOs) are electron tubes that can be used to generate

TABLE 1. TECHNIQUES FOR GENERATING TERAHERTZ RADIATION

	Optically pumped terahertz lasers	Time domain spectroscopy	Backward wave oscillators	Direct multiplied sources	Frequency mixing
Average power	>100 mW[a]	~1 μW	10 mW	Milliwatts to microwatts (decreasing w/ increasing frequency)	Tens of nanowatts
Usable range	0.3–10 THz	~0.1–2 THz	0.1–1.5 THz	0.1–1 THz	0.3–10 THz
Tunability	Discrete lines[b]	N/A	200 GHz	~10–15% of center frequency	Continuous
Continuous wave/pulsed	CW or pulsed	Pulsed	CW	CW	CW
Turnkey systems available	Yes	Yes	No	Yes	No

[a] More than 1 W can be obtained at selected frequencies.
[b] Can be converted to tunable output using a Schottky-based sideband generator.

COMPANY	PRODUCT	WEB SITE
Coherent, Inc.	Optically pumped terahertz lasers, femtosecond laser sources for ultrafast switches	www.CoherentInc.com
Picometrics	Imaging system using ultrafast switch	www.picometrics.com
TeraView Ltd.	Imaging system using ultrafast switch	www.teraview.co.uk
Virginia Diodes, Inc.	Direct multiplier-based sources	www.virginiadiodes.com

tunable output at the long-wavelength end of the terahertz spectrum. To operate, however, they require a highly homogeneous magnetic field of approximately 10 kG.

Direct multiplied (DM) sources, such as those marketed by Virginia Diodes, Inc. (Charlottesville, VA), take millimeter-wave sources and directly multiply their output up to terahertz frequencies. DM sources with frequencies up to a little more than 1 THz and approximately 1 μW of output have been used as local oscillators for heterodyne receivers in select applications, most of which are in radio astronomy. However, they can produce substantially more output power at lower frequencies, and they are often well suited to applications requiring frequencies of less than 500 GHz.

In addition, physicists in Italy, Switzerland, the United States, and the United Kingdom have recently demonstrated quantum-cascade semiconductor lasers operating at wavelengths in the 4.4-THz regime. These lasers are made from 1,500 alternating layers (or stages) of gallium arsenide and aluminum gallium arsenide and have produced 2 mW of peak power (20 nW average power), and advances in output power and operating wavelength continue at a rapid pace. Applying a potential across the device causes electrons to cascade through each stage, emitting photons along the way. The photon wavelength is determined by the thickness of the stages. These lasers currently work best at only a few kelvins, but in the future they could become an important source of commercial terahertz systems.

Table 1 compares some of the techniques for generating terahertz radiation. At present, only the OPTL, TDS, and DM systems are commercially available as turnkey systems. However, many researchers assemble TDS systems in the laboratory using readily available laser sources, and DM sources are often procured from a number of research organizations and at least one commercial source. The availability and operation of BWOs at terahertz frequencies are somewhat problematic, but several groups use lower-frequency (<500-GHz) BWOs for device characterization.

The choice of a terahertz source will determine the type of detection scheme required. Sources with submilliwatt output power complicate detection and often necessitate the use of liquid-helium-cooled bolometers or similar devices. Short-pulse terahertz devices often need gated detection using a TDS switch.

For time-domain spectroscopy, or where an overall snapshot of the spectral characteristics of a sample in the terahertz region is important, TDS technology may be the optimal choice. For a more precise, higher-resolution look, consider the OPTL system, using either discrete frequencies or tunable sideband generation technology. Many applications do not need the complete terahertz spectrum of a sample but merely need to identify one or two characteristic features. In these cases, the OPTL system may be preferable to the TDS system because of its operational simplicity, high signal-to-noise ratio, and ability to use conventional, room-temperature detectors.

Although the practical application of terahertz radiation is in its infancy, the recent availability of reliable sources in the 0.3- to 5-THz range may have a wide-ranging impact on science, industry, and medicine. Short-pulse terahertz systems are used in time-domain spectroscopy to understand biological processes and to create two- and three-dimensional images. CW OPTL systems have been used extensively in aerospace and astronomical applications, primarily for remote sensing, and may find new uses as terahertz applications mature.

Further reading

Arnone, D. D.; et al. Application of terahertz (THz) technology to medical imaging. In *Proc. SPIE Terahertz Spectroscopy Applications II*; International Society for Optical Engineering: Bellingham, WA, 1999; pp. 209–219.

Köhler, R.; Tredicucci, A.; Beltram, F.; Beere, H. E.; Linfield, E. H.; Davies, A. G.; Ritchie, D. A.; Iotti, R. C.; Rossi, F. Terahertz semiconductor-heterostructure laser. *Nature* **2002**, *417*, 156.

Mueller, E. R.; Fontanella, J.; Henschke, R. Stabilized, Integrated, Far-Infrared Laser System for NASA/Goddard Space Flight Center. 11th International Symposium on Space Terahertz Technology, Ann Arbor, MI, May 1–3, 2000. Available at http://www.coherentinc.com/downloads/NASA-Goddard.pdf.

Mueller, E. R.; Waldman, J. Power and Spatial Mode Measurements of Sideband Generated, Spatially Filtered, Submillimeter Radiation. *IEEE MTT* **1994**, *42* (10), 1891.

Rochat, M.; Ajili, L.; Willenberg, H.; Faist, J.; Beere, H.; Davies, G.; Linfield, E.; Ritchie, D. Low-threshold terahertz quantum-cascade lasers. *Appl. Phys. Lett.* **2002**, *81*, 1381.

Siegel, P. H. Terahertz Technology. *IEEE MTT* **2002**, *50* (3), 910.

Williams, B. S.; Callebaut, H.; Kumar, S.; Hu, Q.; Reno, J. L. 3.4-THz quantum cascade laser based on LO-phonon scattering for depopulation. *Appl. Phys. Lett.* **2003**, *82*, 1015.

BIOGRAPHY

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