Terahertz (THz) Technology: An Introduction and Research Update

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Within the electromagnetic spectrum (between DC and gamma rays) the last portion to be examined lies between millimeter waves and long-wave infrared. In terms of frequency, this region extends 3 decades, from roughly 300 GHz to about 300 THz. Other ranges may be referred to as "THz," but they vary only in the specific upper and lower boundaries. The key point to remember is that this range lies between what is commonly known as the highest "microwave" frequencies and the longest wavelengths of "lightwaves" in the infrared region.

THz Research History

The last gap in the spectrum was bridged in 1923, when Ernest Nichols and J.D. Tear finally completed their efforts to observe radiation in the THz range. Their work was a systematic approach, both upwards in frequency from the microwave region and downward from the infrared region.

Before this more-or-less official conclusion of the search, there were many significant contributions to THz-range understanding. Perhaps the most important was part of the scientific community's effort to characterize blackbody radiation versus temperature. In 1900, in Germany, Rubens and Kurlbaum applied earlier work Rubens had done in collaboration with Nichols, resulting in accurate experimental data at longer wavelengths than had been previously observed. Max Planck wrote the equation that would become Planck's Radiation Law on the same day that Rubens showed him those results.

Other experimental work in the THz region also made significant contributions. Initially, optical techniques of gratings, interference, refraction, etc. were only partially successful at THz frequencies, and radiometers were not very sensitive. As a result, much work was done to analyze data indirectly at harmonics that fell into the infrared range where measurements could readily be made. Intensive mathematical work was done to extract the fundamental frequency from the observed higher-order products. These manual techniques were used until the 1950s, when computers could finally perform a Fourier transform on the spectral data. Until then, however, THz research helped advance the ability to analyze measurements made using optical methods, including the famous Michelson interferometer.

Charactertics of the THz Region

There are several regions of transition in the electromagnetic spectrum. With increasing frequencies, EM radiation becomes more energetic, and the correspondingly shorter wavelengths cross various physical boundaries. As a result, different behaviors become apparent.

For example, at low frequencies, circuitry behaves very close to the idealized manner of DC. At a higher frequency, circuit dimensions become a significant percentage of a wavelength, and transmission line principles need to be applied. As we reach the microwave range, the higher electron transition energy levels result in more radiation, requiring a change in design techniques to minimize its effects. At higher frequencies yet, it is nearly impossible to fabricate circuits small enough, relative to wavelength, and we need to use electron beams, crystal structures, and other atomic-level and quantum phenomena to create and manipulate the EM waves. As we reach visible light, all generation and radiation involves quantum relationships, which are increasingly energetic and complex into the X-ray and gamma ray ranges.

Terrestrial propagation also changes with increasing frequency, from surface waves at the lowest frequencies, through ionospheric reflection and refraction, VHF/UHF line-of sight, microwaves affected by precipitation and foliage, atomic and molecular absorption at the higher mm-waves, etc. In this respect, THz radiation falls between microwaves and lightwaves. It experiences higher absorption by water vapor and dust than mm-waves, but can still pass through many materials that are opaque to lightwaves.

At THz frequencies, wavelengths are in the same order of magnitude as molecular-level structures. This size/wavelength convergence results in a unique set of behaviors that make THz technology very difficult to implement, but at the same time, creating opportunities for valuable new applications. With wavelengths in the same range as molecular structures, the THz spectrum is filled with absorption lines, fortunately, with some significant gaps between them. In theory, each type of molecule has a unique signature in the THz region that can be extracted using spectroscopic techniques, although the signal analysis is computationally intensive.

The large number of spectral absorption lines makes wide bandwidth communications difficult at THz frequencies. In the atmosphere, water vapor is the primary source of propagation losses, so outdoor communications links will rarely be practical. Indoors, over short distances, it appears practical for THz signals to support the transmission of bandwidths from 10s to 100s of GHz.

Generating THz signals with a useful power level is a significant problem to be solved. Conventional transistor oscillator and diode multiplier technology can reach into the lower end of the range, but not much beyond. Miniature backward-wave oscillators (BWOs) have been demonstrated, constructed using micromachining techniques. Quantum cascade lasers have generated several mW of power in the 5 THz range, but they require cooling to liquid nitrogen temperatures or below.

Current THz signal sources for research—including optical mixing, pulsed optics and mercury-arc broadband noise sources—do not deliver the necessary power levels for many potential applications. New quantum-level techniques will be needed to work with energy levels that are lower than those commonly used for related technologies in the IR and visible spectrum, such as solid state lasers. New materials structures will be needed—and are the subject of current research.

Detectors are perhaps the biggest problem to be solved. Photonic detectors are used in research, but they require cooling since the equivalent temperature of THz energy is <70K. Among electronic solutions, Schottky diode-based heterodyne detectors have reached 3 THz and beyond and, for the near future, will be the most important detector types for THz technology R&D.

Applications at THz Frequencies

THz applications are being explored agressively in a few areas that have the greatest potential for achieving entirely new capabilities. Medical imaging, security imaging and sensors, and very-high bandwidth communications are at the top of the list, with materials research and computing applications also receiving attention.

Currently, imaging applications are the leading area of research. THz waves (increasingly referred to as T-waves) offer new capabilities, due to their unique interaction with materials. In theory, they can penetrate somewhat like X-rays, but are not considered ionizing radiation, since the energy level is lower. They should be able to provide resolution as good or better than magnetic resonance imaging (MRI), possibly with simpler equipment.

THz waves are also at the lowest end of detectable thermal emissions, like infrared. The human body has a thermal emission peak at about 30 THz, so there is significant radiation in the THz region. This allows passive thermal imaging techniques to be applied, with the advantage that many materials (e.g., clothing) that are opaque at IR, are at least partially transparent in the THz range.

Active military research is underway to develop THz imaging. The initial investigations are attempting to develop imaging of explosive materials. Specific applications are security-related, such as detecting weapons and explosive devices, including the important task of land mine detection. If successful, these efforts will have a significant benefit for law enforcement and anti-terrorism, in addition to military use.

The same capabilities can be applied to medical imaging. Along with the ability to distinguish between different materials, a major reason for developing THz imaging is increased safety compared to X-rays. Because medical facilities offer a controlled environment, lower power is required than is needed for security or military imaging and materials identification. This may allow medical imaging to develop more quickly.

In addition to imaging, the molecular-scale wavelength makes it possible to examine material structures using THz time-domain spectroscopy. Military and security research has focused on identifying explosive materials, where proof-of-concept experiments have been successful and further development is underway.

With increasing demand for bandwidth, THz frequencies are being considered for short-range, high data rate applications. Some analyses predict that, within ten years, a user's wireless interconnections will require tens of Gbit/s data rates. Optical communications is one solution for that high rate, but THz waves are an alternative. Free-space optical transmission is a difficult problem for a flexible communications network. Because THz waves have a combination of optical and radio properties, they can be reflected and scattered more easily than lightwaves. Research is underway to develop low cost reflective/refractive materials that can distribute THz waves to randomly-located equipment in an indoor environment.

Summary

Terahertz technology has the potential to add new capabilities for imaging, communications, sensors and materials research. Although this frequency range seems to be a logical step above mm-waves and below infrared, that step is a big one. New types of electronic and photonic structures are needed to create better sources, detectors and modulators.

Despite the magnitude of the obstacles, the potential for valuable new applications is driving current research. Imaging applications are leading the way, but other applications in sensors and wide bandwidth communications and sensors are also being actively pursued.