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Terahertz Technology

Fundamentals and Applications

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Preface

The lack of reliable, high-power, room-temperature terahertz sources and efficient detectors in the past several decades has caused the researchers do not extensively explore the material interactions related to the terahertz spectral region that was once dubbed. However the recent progress in developing of new terahertz continuous-wave and pulsed sources along with user-friendly detectors advent the terahertz-wavelength applications in many fields. For realization of the full potential of THz applications, wide-bandwidth, highly efficient sources and detectors must be developed. Historically, the fields of astronomy and chemistry have been a driving force for developing sources and detectors in the terahertz regime. Even though the applications of terahertz have yet to be used widely, much research is being directed toward the development of terahertz sources and detectors, particularly for applications in medical imaging and security scanning systems.

The electromagnetic waves at frequencies in the region of the electromagnetic spectrum between 300 GHz 3×10^{11} Hz) and 3 THz (3×10^{12} Hz), corresponding to the submillimeter wavelength range between 1 mm (high-frequency edge of the microwave band) and 100 mm (long-wavelength edge of far-infrared light) is called terahertz radiation. This radiation can pass through clothing, paper, wood, masonry, plastic, ceramics and penetrates fog and clouds, but this not apply to metal or water. Terahertz radiation is emitted as a part of the black body radiation from anything with temperatures greater than about 10 K where observations at these frequencies are important for characterizing the 10–20 K cold dust in the interstellar medium.

The generation and detection of radiation in the terahertz range is resistant to the commonly employed techniques in the neighboring microwave and infrared frequency bands where the use of solid state devices has been hampered for the reasons of transit time of charge carriers being larger than the time of one oscillation period of terahertz radiation, and the energy of radiation quanta being substantially smaller than the thermal energy at room temperature and even liquid nitrogen temperature.

Generally there are two types of methods to generate and detect THz signal. There are optical method such as Austin switch, Photomixing, Optically pumped THz lasers and electronic method including Quantum Cascade Lasers, Gunn diodes, Schottky diode frequency multipliers and so on. The THz radiation and detection based on the two-dimensional electron gases (2DEG) oscillation of the field-effect transistor are drawing much attention for its ability to provide frequency–voltage tunable, compact and room temperature workable THz source and detectors. The reported results show that the gated FET with high mobility and smaller channel length results in good performance of the THz radiation source and detector. For example silicon nanowire MOS transistor (SNFET) shows great potential in the future for THz integrated circuit applications.

Today for coherent generation and detection of wideband THz radiation, photoconducting dipole antennas and electro-optic (EO) materials are used in particular for THz spectroscopy and imaging systems. While conventional photoconducting dipole antennas have superior sensitivity, there exists bandwidth limitation and a speed versus sensitivity trade-off. Although the 60 THz detection at low-temperature GaAs photoconducting dipole antennas has been reported, non existing high signal-to-noise ratios and having high-frequency roll-off may limit their use in mid-IR spectroscopic applications. In addition, the low-temperature signal magnitude for GaAs was less than that of reported using ZnTe. EO crystals of ZnTe have shown high-frequency performance up to 30 THz, and the organic crystal DAST has shown performance up to 20 THz. However, both of these EO crystals exhibit wide gaps in their frequency responses that are due to absorption from lattice vibrations and to a phase mismatch between the THz beam and the probe beam in the EO sensor.

Quantum structures, fabricated by molecular beam epitaxy (MBE) can be used for the generation and detection of THz radiation. The THz QCL (quantum cascade laser) as a compact generator also THz quantum well infrared detectors (QWIPs) or heterojunction interfacial work function internal photoemission detectors (HEIWIPs) as detectors are developed which can be engineered by varying the widths of the wells/barriers and the doping profile. Alternatively, one can rely on the properties of carriers along the structure layers for detection of THz radiation using the excitation of plasma waves or non-uniform electron heating in a two-dimensional electron gas.

Some of the viable sources of terahertz radiation are: the gyrotron, the backward wave oscillator, far infrared laser, quantum cascade laser, free electron laser, synchrotron light sources, photomixing sources, single-cycle sources and optical rectification. Among species of terahertz sources, the optically pumped terahertz laser (OPTL) system may be preferable because of its operational simplicity, high signal-to-noise ratio, and ability to use conventional, room temperature detectors. OPTL is in use around the world, primarily for astronomy, environmental monitoring, and plasma diagnostics. Short-pulse terahertz systems are used in time-domain spectroscopy to understand biological processes and to create two or three-dimensional images. The choice of a terahertz source will determine the type

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	~1 μW	10 mW	mW–μW (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	N/A	200 GHz	~10–15% of center frequency	Continues
Continues wave/pulsed	CW or pulsed	Pulsed	CW	CW	CW
Turnkey systems available	Yes	Yes	No	Yes	Yes

of detection scheme required. Table 1 shows some of the techniques for generating terahertz radiation.

The next generation of detection systems will be multi-modal which will be used for both imaging and detection. The absorption characteristics of terahertz radiation vary greatly from material to material, and this property can be used to create images. Different materials absorb different frequencies by molecules vibrating against each other. Because of some materials being hard to identify this can be used for detection. For example a white powder may be a narcotic or remnants of explosive material, or it may simply be talcum powder or sugar. One of the ways to identify this type of materials is to consider using the absorption property of electro-magnetic energy. For instance, the measured spectrum of Semtex-H plastic explosive at a distance of a metre allows for rapid and reliable identification.

Although terahertz radiation has the potential to revolutionize certain aspects of medical imaging, the problem is the lack of practical detection technology. It is worth to mention that the scientists have developed a detector based on a carbon nanotube transistor that can sense small numbers of terahertz photons. A component known as a two-dimensional electron gas (2DEG) absorbs THz radiation. A single electron carbon nanotube transistor which acts as a switch is laid on top of the 2DEG. By absorption of the terahertz tradition through the 2DEG the transistor voltage will be switched. Experimental and theoretical results clearly indicate that nanometer transistors are promising candidates for a new class of efficient THz detectors. Also the properties of magneto-plasmons in the two-dimensional electron system can be applied for detection of terahertz radiations. For instance, InGaAs/InAlAs Field Effect Transistors in quantizing magnetic field was used for the terahertz radiation detection. The detection is accomplished based on the rectification of the terahertz radiation by plasma waves.

Heterodyne detectors are the most common terahertz detectors although nowadays focuses have been made toward implementation of direct detectors in particular for applications that do not require ultra-high spectral resolution. Some of the most important direct THz detectors are: GaAs–Schottky diodes, conventional bolometers, composite bolometers, microbolometers, hot electron bolometer detector, Golay cells, an acoustic bolometer and finally a fast calorimeter.

A broadband terahertz detector can be realized based on the following idea: if terahertz radiations can be generated from light then it can also be converted back to light. Remember that in the world of optics, there is a range of high-speed, sensitive detectors that can operate at room temperature. For an example a detector was introduced that can detect terahertz radiations indirectly by detecting the light generated when the DAST crystal is exposed to terahertz radiation.

For terahertz time domain spectroscopy (THz-TDS), conventional detectors such as bolometers are not suitable because they can only measure the total energy of a terahertz pulse, rather than its electrical field over time. Instead the following two methods are applied: photoconductive sampling and electro-optical sampling. In both of these methods an ultrashort laser pulse is fed to the detector along with simultaneously applying a terahertz pulse. As a result of this, depending upon whether the detection pulse with the electric field of the THz pulse being high or low, the detector will produce a different electrical signal.

Ultimately, the terahertz detection is possible using both passive and active methods. The passive detectors are effective due to the temperature difference between human body and environment. While the active detectors are cheap but require high power sources. For this reason they are yet to be used with full potential.

Among the most important applications of the terahertz technological under development we mention the followings: medical imaging (terahertz radiation is able to penetrate deep into many organic materials without causing any damage associated with ionizing radiation such as X-rays and can also be used as a cancer detector), security (terahertz radiation can be used in surveillance such as security screening, uncovering concealed weapons, non-destructive detection of narcotics or stimulants in mail, remotely), communications (space and satellite communications), and industrial applications (quality, sensing, monitoring, and process control). Finally as far as the scientific research is concerned we can briefly name: chemistry and biochemistry measurements, study of the complex dynamics involving condensed-matter in high magnetic fields physics, molecular recognition and protein folding, submillimetre astronomy, and detection of murals hidden beneath coats of plaster or paint.

In this book we have only briefly concentrated on the ever expanding world of terahertz where the scope of potential and actual applications cannot be underestimated. Our primary interest lies on the detection and generation of terahertz radiation using optoelectronic quantum devices. In the first chapter of this book, we review the terahertz technology and its associated scientific achievements as important as is in today's world. In the second chapter, the terahertz and infrared quantum photodetectors is studied where its importance is emphasized. Finally, in the third chapter the terahertz and infrared sources based on quantum cascade lasers along with fresh ideas will be analyzed and discussed.

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