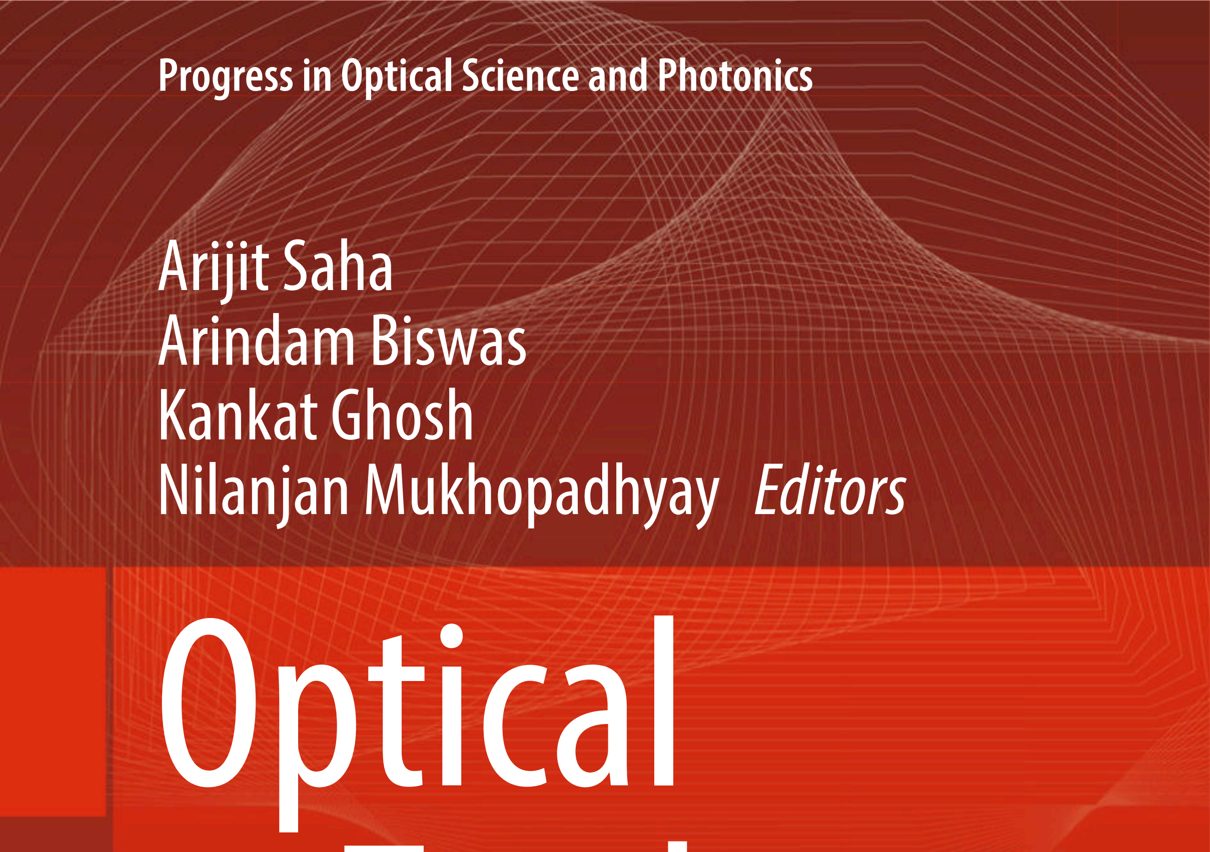
Progress in Optical Science and Photonics



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Arindam Biswas
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Optical to Terahertz Engineering

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The purpose of the series Progress in Optical Science and Photonics is to provide a forum to disseminate the latest research findings in various areas of Optics and its applications. The intended audience are physicists, electrical and electronic engineers, applied mathematicians, biomedical engineers, and advanced graduate students.

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Editors

Optical to Terahertz Engineering

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Preface

With the advancements in areas like optical communication, signal processing, imaging systems, etc. researchers, industry persons and end users are required to be familiarized with the progress in these sectors. In recent years, the almost unexplored domain of the THz range of electromagnetic spectrum has paved the way for terahertz technology. A wide range of applications using THz techniques such as terahertz time-domain spectroscopy (THz-TDS), biological, medical and pharmaceutical sciences, explosives inspection, Information and Communication Technology (ICT) sector and many more have the potential to be the technology of future. The present title "Optical to Terahertz Engineering" focuses on the recent developments in Optical and THz technology with an emphasis on their basic fundamentals. It illuminates on different materials required for THz and optical engineering, explains methodologies and challenges of imaging and secured communication in both THz and optical domains, and also discusses the applications of fiber optics in different domains. This book serves as a guide to THz and optical technology for new researchers in various fields. Many different disciplines, such as phase controllers for THz-Spectro-Polarimeters and photo-emission technology from heavily doped THz materials, involve the recent developments of THz technology. On the other hand, advancements and future prospects of Lithium Niobate-Based polarization phase modulator, photonic crystal fiber, Optical Code Multiple Access System, satellite image correction and thermal image processing emphasizes optical technologies. The focus of the current title mainly lies in the practical applications of THZ and optical engineering. Optical to Terahertz Engineering is an ideal book for a very vast audience from basic science to engineering and technology experts and learners.

This book has the potential to become a textbook for engineering and Post Graduate programs in science, and also for researchers. This title also serves the common public interest by presenting new methods of integration into society.

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Introduction to Terahertz Imaging Applications

Semanti Chakraborty and Kanik Palodhi

1 Introduction

Terahertz frequency domain is one of the most anticipated but largely unexplored regions of electromagnetic waves. As the name suggests, the frequency domain is generally considered to be between 0.1 THz and 10 THz, where $1\ \text{THz} = 10^{12}$ Hz corresponding to a wavelength range varying between 0.3 mm and 30 μm. Essentially, this domain is within high-frequency electronics close to the microwave region (~10 GHz/0.3 mm) and far-infrared optics ~100 THz/0.3 μm as shown in Fig. 1 [1–9]. Terahertz, therefore, closes the gap between these two mature technologies and provides the best of both worlds, so to speak, by making itself available to both communication and imaging [10–17].

One of the main reasons for the terahertz domain being unexplored is the unavailability of inexpensive generators or sources in this region. Terahertz domain corresponds to a photon energy of 4.1 meV which belongs to the energy range of thermal excitation regions of the semiconductor [18–22]. The traditional lasing option used in optics or novel use of different diodes in microwave regions owing to their bandgap cannot be used here as it is. This led to a technology gap known as the *terahertz gap*. In fact, before the coinage of the term terahertz/THz, it was often referred to as far-optics clustering it with far-infrared optics [23–25].

Despite the lack of suitable sources, some of the advantages of terahertz technologies are evident if interpolated from the proven principles (or technologies) in optics and microwave. One of the most advantageous aspects of this technology is that the terahertz probe beams are non-ionising and invisible to the eye [2, 22, 23]. Secondly, in this domain, using coherent detection techniques, the exact amplitude

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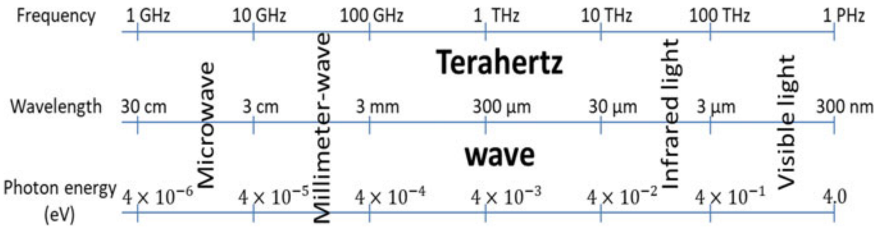


Fig. 1 Position of the terahertz wave in electromagnetic spectrum

and phase of the electric field can be determined leading to important applications in imaging, instrumentation and metrology [26–34]. During imaging, this technology also has the power to penetrate through layers of different materials including clothes [35–40]. Recently, body scanners developed using terahertz have been much talked about. It is a critical application in terms of security checking since prohibited items can be tracked, however, it is also ethically questionable as it leaves a trail of the human body together with its belongings. Apart from this, the interaction of terahertz waves (T waves) with matter can help investigate chemical compounds by applying spectroscopic techniques, which in turn, be of use in biomedical and pharmaceutical applications [41–55].

2 Instrumentation

In recent years, due to the advancement of technology, thanks to consistent efforts from both academia and industry, this domain is beginning to claim its rightful place closing the so-called ‘terahertz gap’. The most important aspect of THz technology that is propelling life-changing applications is the instrumentation containing different sources, detectors and other passive components. These are developed from emulating matured photonic and microwave technologies.

2.1 Sources

Currently, the available THz sources can be broadly classified into two groups depending upon their emission mode and operating frequency—continuous (CW) and pulsed (time-domain/TD) [8, 18–21]. Each category has different advantages and disadvantages prompting different usage. The CW sources developed using technologies pertaining to millimetre waves essentially scale up the frequencies and can reach up to the operating frequency of 5 THz in the case of backward-wave oscillators [22, 56]. A different approach can be used by applying the down-conversion principle commonly used in photonic waves. In this case, two sources differing in frequency can also be used to generate T-waves [22, 57]. Typically, CW sources are narrowband providing greater power compared to pulsed sources. They are more sensitive and are suitable for heterodyning applied to the communication of non-destructive testing applications.

The pulsed/TD sources, on the other hand, are predominantly obtained from the conversion of optical signals to T-waves. By detecting the electromagnetic transient generated from a picosecond, laser pulse T-waves are generated. Since the short pulse is composed of multiple frequencies, it is typically applied to investigate spectral characteristics or ultrafast phenomena [57–62].

2.2 Detectors

THz detectors are usually categorised into three groups—thermionic, photoconductive antenna and electro-optic. Recent developments have made sure that accurate measurements of amplitude and phases can be done successfully using these techniques, particularly, photoconductive and electro-optic. Most of the commercially available THz systems, though only a few, have these types of detectors used [22, 23, 63–67].

2.3 Optics

Another important aspect of THz systems is the beam formation optics which is essential for higher throughput and diffraction-limited spot generation. This is challenging because (a) terahertz wavelengths cannot be treated as negligible compared to the size of the optical elements and (b) optical elements need to be achromatic over the entire THz region for flat phase response. This is generally achieved by using dispersionless substrate lenses made of highly resistive ($10^4\ \Omega$) silicon (refractive index $n = 3.42$) attached to the transmitter and receiver. Typically, the preferred design employs an aplanatic hyper hemispherical lens (a variant of hemispherical lens) which reduces aberrations such as astigmatism and increases effective aperture providing smooth collimation of the T-rays [2, 22, 68–73].

Another very important optical component is a parabolic mirror which is commonly used for beam traversal and focussing. This is typically used with a metal coating and has stringent specifications to be met [2]. Apart from beam coupling, recent developments have been made for beam engineering using traditional concepts of diffraction gratings, diffractive lenses, Fresnel lenses and similar components using spatial terahertz modulators or holograms [74–76]. These components can be made relatively cost-effectively using graphite, 3D-printed passive beam guides, high-density polyethylene (HDPE) and high-resistivity silicon [77–81]. In recent years, meta-materials have been developed for manipulating the beam using metasurface amplitude, phase and polarisation of the T-beam [82–85]. Some of the interesting applications of the use of metasurfaces are (a) vortex-beam generation [84], (b) novel components using polarisation conversion [86] and (c) polarisation-controlled superfocusing [87].

2.4 Signal Acquisition and Important Parameters

The signal acquisition process, here, is one of the most important aspects of the instrumentation. Traditionally, the delay in the generated pulse is scanned over the detecting pulse to measure the average photocurrent as a function of the delay. Essentially, this is a process of convolution of the temporal shape of the pulse with the generated waveform and this was previously achieved by a lock-in amplifier with a chopper wheel [23]. This process was not fast enough and was replaced by a scanning optical delay line as suggested by Hu and Nuss in their seminal paper [10]. The most common parameters employed to measure the performance of signal acquisition systems are dynamic range and signal-to-noise ratio (SNR). DR is defined as the difference between the maximum to minimum signal, whereas SNR provides a measure of the minimum detectable signal and sensitivity of the device.

Current measurement methods can have an SNR of 1000 or more for imaging applications. In the case of spectral imaging, a raster scan or a scanning mirror is used for a certain range of an area of the object under investigation. DR and SNR can be evaluated from the amplitude spectrum upon Fourier transform if spectroscopic data are analysed. Another important parameter for the spectroscopic system is spectral resolution given by twice the ratio of the velocity of light c and effective delay [2, 22, 88, 89]. The process of signal acquisition is automated by software, and even accessible spectral databases have been developed for comparison purposes.

2.5 Signal Processing

After the acquisition of the signal, image processing software is employed for the extraction of the amplitude and phase information. Different transform-based approaches such as Fourier, Hilbert or other approaches such as synthetic aperture imaging, reflectometry, etc. are quite popular for this purpose. Typical image processing operations, such as edge detection, histogram processing, etc. can also be performed. Recently, machine learning-based image processing techniques have also been successfully employed for different information [90].

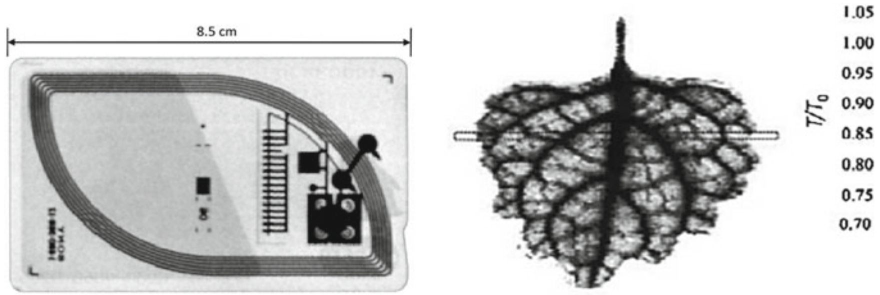
3 Imaging

The first instance of THz images was reported by Hartwick et al. in 1976 using an optically pumped THz laser [91]. Then, in their seminal paper, Hu and Nuss presented the idea of THz imaging using a femtosecond laser in 1995 [10]. As described in the introduction, THz waves offer unique capabilities of penetrating through non-polar and non-metallic objects such as paper, plastics, ceramics, clothes, etc. which makes it suitable for imaging and spectroscopy used in industrial imaging such as non-destructive evaluation (NDE) [7, 92], material characterisation [93, 94], medical diagnostics [9, 12], cultural heritage objects such as paintings, etc. [95, 96]. Absorption of THz waves in water is very high which is of great importance for imaging of organic materials or medical imaging [97–99]. Apart from metal and water, most other materials have a unique signature in the spectral domain (~THz). This can be combined with the THz imaging setup for the detection of special reagents such as explosives, medicines, etc. [14, 100].

In Fig. 2, it can be seen that three objects, (a) a smart card, (b) a coleus leaf and (c) a razor, partially covered by a polythene sheet have been imaged using THz imagers. Clearly, the THz waves have penetrated non-metallic materials and have been reflected from the metals. For organic samples, the water molecules have absorbed the T waves, therefore, it appears dark in the regions where water is present.

3.1 Imaging with Continuous-Wave (CW) THz Waves

Many of the initial systems in THz domain were based on the principle of CW operations. Typically, photomixers, THz parametric oscillators (TPO), backward wave oscillators, QCLs, etc. are used as sources with a frequency of operation close to 0.5 THz, and heterodyne detectors are used as receivers. The instrumentation of



(a) (b)

Fig. 2 Examples of THz images—**a** THz transmission image of a contactless smart card embedded with a metallic circuit [101]; **b** THz image of a Coleus leaf where the grayscale is correlated with water content, with darker shade indicating more water [69]

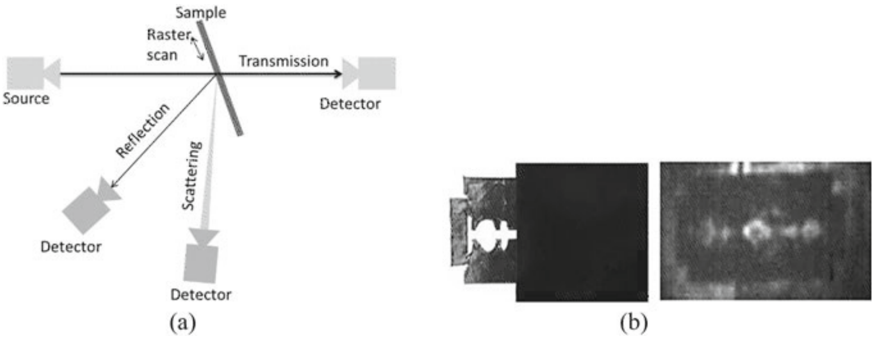


Fig. 3 **a** Scheme of CW operations using raster scan; **b** Scaled razor blade covered by a black polyethylene sheet—a photograph and a THz image using 2.52 THz, 10 mW radiation from a gas laser with a microbolometer detector. In the THz image, the covered part of the blade is clearly visible [102]

the CW imaging systems is very critical to the specific needs of the application. For example, for higher sensitivity, cryogenic detectors could be required or for moving objects, high frame rates of the detectors may be necessary. There are numerous applications such as body scanners, non-destructive testing units, etc. which have been developed based on this principle.

Raster scan, as shown in Fig. 3a, is the most commonly used scheme for CW operations [2, 103]. Here, the THz wave from the source passes through the sample, and depending upon the application, the reflected/scattered or the transmitted beams are recorded. An example of a typical security system is shown in Fig. 3b, where the two images of a razor blade, partially covered by a black polythene sheet, are shown. The first one, the photograph, could not reveal the covered part, whereas in case of THz imaging, the covered parts are visible.

3.2 *Imaging with THz Pulses*

CW operation, as described in the previous section, has to be designed for specific purposes and lacks flexibility. The THz pulsed system, essentially, THz time-domain spectroscopy can be designed to be flexible, compact and cost-effective. In addition, by measuring - (a) the diminished amplitude of the sub-picosecond pulses after passing through the object and (b) the phase change of the pulse, crucial information can be extracted about the samples [2, 22]. In fact, recent commercial instruments from Teraview or Picometrix Inc. have already developed these techniques [104].