Proceedings of the 4th International Conference on Mathematical Physics and Computational Simulation
DOI: 10.54254/2753-8818/2026.34173

Terahertz Imaging Techniques: Status and Applications

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Abstract. Terahertz imaging has gone through extremely dramatic changes in the past 20 years, it has gradually stepped out of the unknown laboratory research stage and turned into a widely used characterization tool, which has been applied in industrial quality control, biomedical diagnosis, plant science and nanomaterial research. This review will comprehensively sort out the key technological progress that has promoted the development of this field, covering the evolution of optical fiber coupling terahertz time-domain spectroscopy (THz-TDS) systems, the commercialization process of portable instruments and the improvement of high-speed imaging structures. We will also focus on the representative applications that can reflect the unique advantages of terahertz radiation, including the non-destructive testing of composite materials, the three-dimensional distribution mapping of water in biological tissues and plants, and the diffraction limit breaking nanoscale imaging realized by scanning probe technology. In addition, we will discuss the remaining challenges and future development prospects of this field, including the possibility of further reducing the cost and expanding the application of terahertz technology in clinical and industrial fields in the future

Keywords: Terahertz imaging, time-domain spectroscopy, non-destructive testing, biomedical imaging, near-field microscopy, industrial quality control

1. Introduction

Terahertz imaging has gone through extremely dramatic changes in the past 20 years, it has gradually stepped out of the unknown laboratory research stage and turned into a widely used characterization tool, which has been applied in industrial quality control, biomedical diagnosis, plant science and nanomaterial research. This review will comprehensively sort out the key technological progress that has promoted the development of this field, covering the evolution of optical fiber coupling terahertz time-domain spectroscopy (THz-TDS) systems, the commercialization process of portable instruments and the improvement of high-speed imaging structures. We will also focus on the representative applications that can reflect the unique advantages of terahertz radiation, including the non-destructive testing of composite materials, the three-dimensional distribution mapping of water in biological tissues and plants, and the diffraction limit breaking nanoscale imaging realized by scanning probe technology. In addition, we will discuss the remaining challenges and future development prospects of this field, including the

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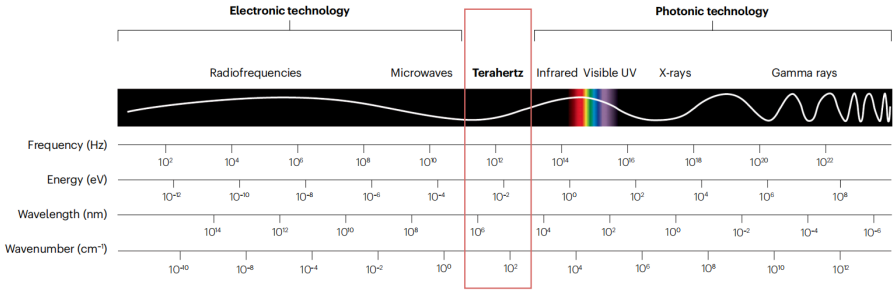

Figure 1. The electromagnetic spectrum highlighting the terahertz band [1]

This review will give an updated interpretation of the development of terahertz imaging [1-4], and focus on the technical progress based on time-domain spectroscopy imaging. We will first introduce the key hardware innovations that have expanded the application scope of terahertz imaging, including the development of optical fiber coupling systems and compact optical fiber laser instruments, then sort out the most influential applications of terahertz imaging in industry, biology and basic research fields. We will also introduce the recent progress of near-field terahertz imaging, this technology has pushed the spatial resolution far below the diffraction limit, and can realize the nanoscale characterization of materials, finally we will prospect the future development direction of this field.

2. Technological evolution of terahertz imaging systems

The earliest terahertz imaging systems were built on bulky titanium-doped sapphire femtosecond lasers, which directly limited the application of such systems to professional laboratory environments [3]. In the past 20 years, two key technological breakthroughs have completely changed the accessibility and flexibility of terahertz imaging systems.

2.1. Fiber-coupled terahertz systems

The first important technical progress is that Picometrix (now Terametrix) launched the optical fiber pigtail type photoconductive antenna in 2001, this technology can flexibly place the terahertz transmitter and detector, and separate them from the optical platform where the laser system is located [2]. This flexible layout has created conditions for many new types of measurement experiments, including light scattering experiments, wavefront characterization and imaging detection of large or irregular samples. Early optical fiber coupling systems still used 800 nm titanium-sapphire lasers, matching with GaAs-based photoconductive antennas.

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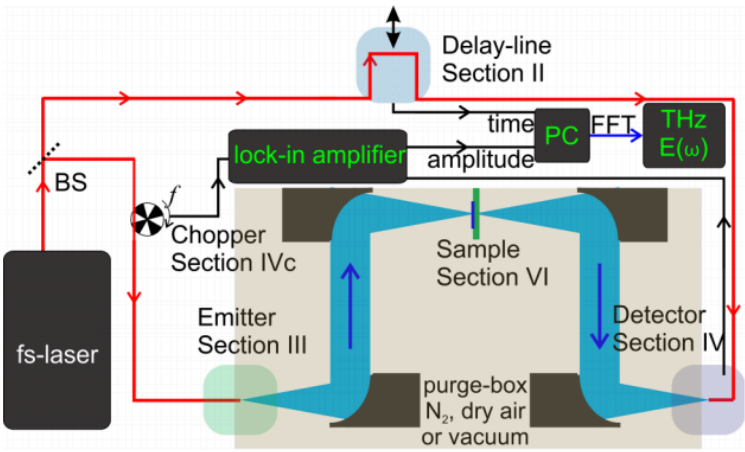

Figure 2. Simplified THz time-domain spectrometer (THz-TDS) [2]

The second transformative progress is the successful development of photoconductive antennas based on low-temperature growth InGaAs/AlInAs multiple quantum wells, such antennas can be pumped by 1.55 μm femtosecond fiber lasers. This technology has promoted the development of terahertz systems in the direction of compactness, stability and low cost, because erbium-doped fiber lasers are smaller, cheaper and more stable than titanium-sapphire lasers. The subsequent optimization of antenna design has increased the system bandwidth to more than 6 THz, and the dynamic range has exceeded 90 dB, which can meet the needs of a variety of imaging applications. At present, portable optical fiber-based THz-TDS systems have been commercialized by many manufacturers, which has greatly expanded the application scope of terahertz imaging technology beyond professional research laboratories.

2.2. Advances in imaging speed and architectures

Traditional terahertz imaging adopts the single-pixel detector raster scanning mode, this method can obtain high spectral resolution, but the acquisition time is very long, it usually takes several minutes to complete a two-dimensional image [5]. There are two main ways to solve the problem of slow imaging speed, one is computational imaging, the other is focal plane array camera.

Computational imaging includes compressed sensing, Fourier single-pixel imaging and ghost imaging, these methods can reconstruct images through a small number of measurement data, exchange the increase of computational complexity for the improvement of measurement speed. These technologies have realized video rate terahertz imaging with only a single-pixel detector, which is very suitable for applications that need both high spectral resolution and high-speed imaging.

Focal plane array cameras are developed based on microbolometers, CMOS detectors or photoconductive arrays, which provide another way to achieve high-speed imaging. Such arrays can collect complete images in parallel, and can realize video rate operation when matched with appropriate radiation sources. Although most terahertz cameras use narrowband continuous wave sources instead of broadband time-domain systems, they are very suitable for rapid large-area screening applications. Commercial terahertz cameras have been widely used at present, supporting security screening and industrial quality control and other scenarios.

The performance of terahertz systems has also been greatly improved in the past 20 years, the current advanced systems can achieve a bandwidth of more than 100 THz, the peak electric field

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strength can reach tens of megavolts per centimeter, and the average power can reach tens of milliwatts, these indicators have opened up new application fields for nonlinear terahertz spectroscopy and strong field physics research.

3. Applications of terahertz imaging

The technical progress mentioned above has made terahertz imaging applied in many practical fields, in this section we will select the most influential and representative applications in the past 20 years for key introduction.

3.1. Industrial quality control and non-destructive testing

Industrial application is one of the earliest commercial mature fields of terahertz imaging, it makes full use of the characteristics that terahertz radiation can penetrate most non-metallic materials and obtain the layered structure information with depth resolution [1, 2, 5]. One of the most successful commercial applications is the detection of automobile paint coating thickness, terahertz time-domain reflection measurement can accurately measure the thickness of multiple layers of paint at the same time with micron precision, which plays an important role in the quality control of automobile manufacturing process.

Terahertz imaging is also widely used in the non-destructive testing of polymers, composites and ceramics, it can detect internal defects such as voids, delamination and inclusions that cannot be observed by ultrasonic and X-ray imaging and other non-destructive testing methods. In the pharmaceutical industry, terahertz imaging is used to characterize the coating thickness, porosity and chemical composition of tablets, which can realize the quality control of pharmaceutical products in the production process.

Another important industrial application is the non-contact electrical characterization of semiconductor materials and devices, terahertz imaging can map the carrier concentration and mobility of semiconductor wafers and graphene and other two-dimensional materials, providing important reference for the research and development of new generation electronic and optoelectronic devices. Different from traditional electrical characterization methods, terahertz imaging is non-contact and non-destructive, which is suitable for on-line quality control in semiconductor manufacturing.

3.2. Agricultural and plant science applications

The strong interaction between terahertz radiation and water has created new application directions in plant science and agriculture [6]. Terahertz imaging can quantify the moisture content in plant tissues with high spatial resolution, helping researchers to understand plant physiological processes and drought resistance mechanisms. A typical example is the three-dimensional mapping of moisture distribution in agave leaves, the results show that the highest moisture content is concentrated in the inner water storage tissue, which is related to the distribution of fructan with strong water retention capacity. This function is of great value for studying the drought resistance mechanism of desert plants and cultivating water-saving crop varieties.

3.3. Medical imaging applications

Biomedical imaging has always been a promising application direction of terahertz technology, it makes full use of the non-ionizing property of terahertz radiation and its sensitivity to moisture

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content and tissue composition. Many applications have shown good application prospects in preclinical and clinical research [1, 5].

One of the most mature biomedical applications is the evaluation of burn wound severity, terahertz imaging can distinguish deep partial-thickness burns and full-thickness burns by monitoring the dynamic changes of moisture content after injury, the moisture content at the wound will decrease transiently immediately after the burn, and then edema (moisture accumulation) will appear in the next few hours. The change degree of these indicators is related to the burn depth, which provides an objective and non-invasive burn evaluation method and helps to improve clinical decision-making and patient prognosis. This method has been verified effective in a variety of animal preclinical experiments, and is currently in the clinical transformation stage.

Another promising clinical application is the early diagnosis of diabetic foot, this is a common complication of diabetes, if it is not found early, it will lead to ulcer and even amputation. Diabetic foot is accompanied by the gradual dehydration of foot skin, this change can be detected with high sensitivity through terahertz imaging. A recent study involving 178 human subjects is the largest clinical terahertz imaging study so far, the results show that terahertz measurement of foot skin moisture content can find the early signs of diabetic foot before the appearance of symptoms, which is expected to realize early intervention and avoid the occurrence of complications.

Terahertz imaging also has good application prospects in ophthalmology, especially in the non-contact monitoring of corneal hydration. Corneal moisture content is an important indicator of eye health, terahertz measurement can detect the changes of corneal hydration related to keratoconus, Fuchs endothelial dystrophy and corneal transplant rejection and other diseases. Other biomedical applications under research include the detection of skin cancer, breast cancer, colon cancer and other tumors, terahertz imaging can distinguish cancer tissues and normal tissues according to the differences of moisture content and tissue structure.

3.4. Cultural heritage and archaeological applications

The characteristic that terahertz radiation can penetrate opaque materials has also been applied in cultural relic protection and archaeology [7]. Terahertz imaging can detect the hidden layers of paintings, find the internal defects of stone and ceramic artifacts, and analyze the structure of ancient documents without damage. Recent studies have combined terahertz tomography with robot positioning system and photogrammetry to analyze ancient pottery fragments, determine the thickness, porosity and composition of pottery, and provide clues for studying ancient manufacturing technology and trade routes.

4. Near-field terahertz imaging: breaking the diffraction limit

One of the most exciting progress in terahertz imaging in the past 20 years is the emergence of near-field technology that breaks the diffraction limit, this technology can achieve nanoscale spatial resolution far lower than the terahertz radiation wavelength. The 1999 review introduced the early research of aperture type near-field terahertz imaging, this method used sub-wavelength apertures to achieve about 100 μm spatial resolution. Since then, apertureless scattering scanning near-field optical microscopy (s-SNOM) has become the mainstream method of terahertz nanoscale imaging [8].

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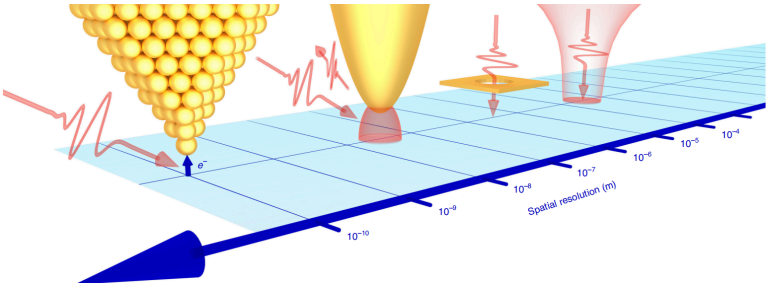

Figure 3. Zooming in on surfaces with terahertz microscopy [8]

In THz s-SNOM (Figure 3), terahertz radiation is focused on a sharp metal tip, the lightning rod effect enhances and limits the radiation to the tip apex. The scattered radiation carries the information of the local dielectric properties of the sample, the spatial resolution is determined by the tip radius, usually 10–100 nm, not by the incident radiation wavelength. This technology has promoted the revolutionary research of nanomaterials, including the first observation of gate-tunable plasmons in graphene, and opened up the field of terahertz nanophotonics.

Researchers have developed a variety of improved terahertz near-field microscopy technologies in recent years. Terahertz emission nanoscopy uses near-infrared pulses to excite terahertz emission in the sample, and the tip couples the emission to the far field, the nonlinear characteristics of terahertz generation process make this method have higher resolution than traditional s-SNOM. Time-resolved pump-probe s-SNOM combines nanoscale spatial resolution and femtosecond time resolution, which can be used to study the ultrafast dynamic process of nanomaterials.

The highest spatial resolution of terahertz imaging has been achieved by terahertz scanning tunneling microscopy (THz-STM), this technology combines the atomic-scale spatial resolution of scanning tunneling microscopy and femtosecond time resolution. In THz-STM, terahertz pulses act as ultrafast bias at the tunneling junction, which can measure the ultrafast dynamic process of single molecules and atomic-scale structures with sub-picosecond time resolution. This technology has created new research opportunities for the study of ultrafast dynamics in condensed matter systems with unprecedented spatial and temporal resolution.

5. Conclusions and future outlook

Terahertz imaging has made remarkable progress in the past 20 years, it has developed from a laboratory exploratory technology to a widely used characterization tool, and has been applied in many fields. The development of optical fiber coupling systems and compact optical fiber laser instruments has played a key role in promoting the popularization of terahertz technology, making it accessible to more users. The application of terahertz imaging in industrial quality control has been fully commercialized, and the biomedical application is rapidly moving towards clinical transformation. Near-field terahertz imaging technology has pushed the spatial resolution to the atomic scale, which can realize unprecedented research on nanomaterials and their dynamic processes.

Although the field has made great progress, terahertz imaging still needs to solve some problems to achieve large-scale popularization and application. The cost of terahertz systems is still higher than that of competing technologies, which limits its application in cost-sensitive markets. The development of terahertz systems based on low-cost monolithic semiconductor mode-locked lasers is expected to significantly reduce the system cost in the next few years, and is likely to open up

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new mass market applications. Further improving the imaging speed, especially the hyperspectral time-domain imaging speed, will also play an important role in expanding the application scope.

In the future, terahertz imaging will continue to expand to new application fields, from on-line industrial quality control to clinical diagnosis and basic material science research. The combination of non-ionizing radiation, depth-resolved imaging ability and unique spectral contrast makes terahertz imaging a powerful tool with great potential. With the continuous progress of technology and the reduction of cost, terahertz imaging will become an increasingly important characterization tool in many disciplines in the next few decades.

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