https://doi.org/10.21122/2227-1031-2024-23-2-91-104

UDC 378

# Nanoantenna Array for Terahertz Detection Application, Design and Scope

**S. V. Pande[1, 3], D. P. Patil[2], S. Gade[2]**

[1]PhD scholar, Sandip Institute of Technology & Research Centre (Trambak road Nashik, India),
[2]Sandip Institute of Engineering and Management (Trambak road Nashik, India),
[3]SVKM's NMIMS Mukesh Patel School of Technology Management & Engineering (Shirpur India)

**Abstract.** The development and implementation of a nanoantenna array for terahertz detection hold immense potential in advancing scientific research and innovation, proven by its ability to enhance terahertz signal reception, overcome limitations of conventional detection methods, and unlock new possibilities for numerous industries. However, concerns related to scalability, cost-effectiveness, and potential health hazards highlight the need for extensive research and regulation to ensure the safe and responsible deployment of this technology. In view of its remarkable highlights, the terahertz (THz) space of the electromagnetic range is wealthy in developing prospects in various applications, for example, remote correspondences, imaging, non-disastrous testing, security filtering, and process control. Terahertz waves are unmistakable for their non-ionizing radiation, further developed objective than microwaves, unprecedented reach ingestion, and ability to go through dielectric materials. This paper gives a brief overview of recent advances in THz antenna design for various applications and investigated possible challenges of these THz systems. We have also focus on terahertz sources and detectors as well as their applications and scope in different fields, different terahertz detection techniques, limitations of conventional terahertz detectors, design consideration parameters in the designing of nanoantenna, materials used for nanoantenna array designing, different fabrication techniques, parameters for evaluating performance and potential characteristics for nanoantenna array in tetrahertz detection.

**Keywords:** conventional detection methods, electromagnetic range, non-ionizing radiation, terahertz signal reception

**For citation**: Pande S. V., Patil D. P., Gade S. (2024) Nanoantenna Array for Terahertz Detection Application, Design and Scope. *Science and Technique*. 23 (2), 91–104. https://doi.org/10.21122/2227-1031-2024-23-2-91-104

# Наноантенная решетка для обнаружения терагерцового диапазона: применение, конструкция и область применения

**С. В. Панде[1, 3], Д. П. Патиль[2], С. Гаде[2]**

[1]Технологический институт и исследовательский центр Сандипа (Нашик, Республика Индия),
[2]Сандипский институт инженерии и менеджмента (Нашик, Республика Индия),
[3]Школа технологического менеджмента и инженерии Мукеша Пателя при Институте исследований управления Нарси Монджи Благотворительного фонда Шри Виле Парле Келавани Мандал (Ширпур, Республика Индия)

**Резюме.** Наноантенная решетка для обнаружения терагерцового диапазона обладает огромным потенциалом в продвижении научных исследований и инноваций, что подтверждается ее способностью улучшать прием терагерцового

---

**Адрес для переписки**
Дипак Пандуранг Патиль
"Дип Амрит", Плот № 46+47/3
Гаджанан Чоук,
Индранагри, Каматваде
Нашик, Индия
Пин код – 422008

**Address for correspondence**
Dipak Pandurang Patil
"DEEP AMRIT", Plot No 46+47/3
Gajanan Chowk,
Indranagri, Kamatwade
Nashik (MS), India
Pin Code – 422008

сигнала, преодолевать ограничения традиционных методов обнаружения и открывать новые возможности для многих отраслей. Однако проблемы, связанные с масштабируемостью, экономической эффективностью и потенциальными опасностями для здоровья, подчеркивают необходимость обширных исследований и регулирования для обеспечения безопасного и адекватного внедрения этой технологии. Благодаря своим прекрасным характеристикам терагерцовое (ТГц) пространство электромагнитного диапазона имеет благоприятные перспективы для развития различных приложений, например удаленной переписки, визуализации, неразрушающего контроля, защитной фильтрации и управления процессами. Терагерцовые волны безошибочно узнаваемы благодаря своему неионизирующему излучению, более развитой цели, чем у микроволн, беспрецедентной дальности проникновения и способности проходить через диэлектрические материалы. В данной статье дается краткий обзор последних достижений в разработке ТГц антенн для различных приложений и исследуются возможные проблемы, связанные с этими ТГц системами. Особое внимание уделено терагерцовым источникам и детекторам, а также их применению в различных областях, различным методам терагерцового обнаружения, ограничениям обычных терагерцовых детекторов, параметрам при проектировании наноантенны, материалам, используемым для проектирования наноантенной решетки, различным методам изготовления, параметрам, позволяющим оценить работоспособность и потенциальные характеристики наноантенной решетки при обнаружении в тетрагерцовом диапазоне.

**Ключевые слова:** обычные методы обнаружения, электромагнитный диапазон, неионизирующее излучение, прием терагерцового сигнала

**Для цитирования:** Панде, С. В. Наноантенная решетка для обнаружения терагерцового диапазона: применение, конструкция и область применения / С. В. Панде, Д. П. Патиль, С. Гаде // *Наука и техника.* 2024. Т. 23, № 2. С. 91–104. https://doi.org/10. 21122/2227-1031-2024-23-2-91-104

## Introduction

The topic of terahertz technology has emerged as a potential frontier with a wide variety of applications in today's fast evolving technological world. Between microwave and infrared wavelengths, terahertz waves, often called T-rays, generally have frequencies between 0.1 to 10 terahertz (THz) [1, 2]. This frequency range is ideal for many applications because to its special benefits, which include non-ionizing radiation, excellent spatial resolution, and material penetration.

Due to its capacity to improve terahertz system performance, Nanoantenna arrays have attracted a lot of interest in the field of terahertz detection. The exact control of electromagnetic waves at terahertz frequencies is made possible by these arrays [3], which are made up of subwavelength-sized antennas grouped in a regular manner. Nanoantenna arrays provide better sensitivity, selectivity, and spatial resolution by taking advantage of the collective behavior of nanoscale antennas, enabling groundbreaking developments in several fields.

## Basics of Terahertz Technology

The term “terahertz technology” refers to the study and use of electromagnetic waves in the 0.1–10 THz (1 THz = $10^{12}$ Hz) frequency range [3]. This frequency band is in the middle of the microwave and infrared spectrum. Terahertz waves have special characteristics that make them suited for a variety of uses in several industries. Terahertz waves stand apart from other parts of the electromagnetic spectrum thanks to a number of features. First off, terahertz vibrations are non-ionizing [4], which means they lack the energy to ionize atoms or molecules. They are safe for a variety of uses, such as security screening and medical imaging, thanks to this quality.

Terahertz waves may also penetrate a wide range of materials, including biological tissues as well as fabrics, plastics, paper, and ceramics [5]. This characteristic makes it possible to image structures that are not easily accessible using other types of radiation and to analyze items without causing any damage to them. Below Fig. 1 shows the placement of the THz wave in the spectrum.

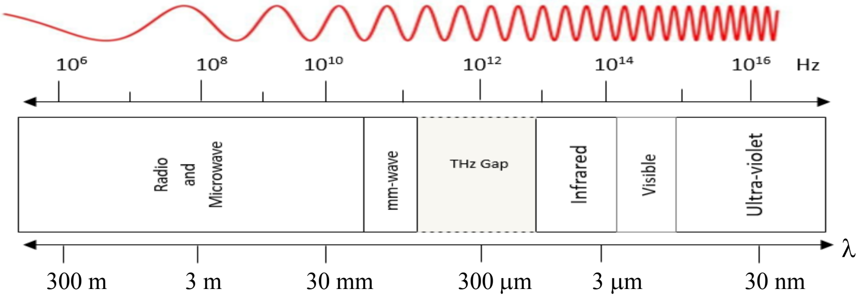


*Fig. 1.* Electromagnetic spectrum (correspond to frequency and wavelength)

Fig. 2 illustrates the terahertz region within the electromagnetic spectrum. THz radiation is classified into two types: broadband THz radiation and continuous wave THz radiation [7]. THz sources and detectors are listed below [8].

### 1) Terahertz Sources

#### *A. Broadband sources:*

- Quantum cascade lasers,
- Surface Surge currents,
- Plasmon, phonon and coupled mode oscillation,
- Schottky diode,
- Photoconductive Switching;

#### *B. Continuous wave (CW) sources:*

- Backward wave oscillator,
- Quantum cascade lasers,
- Schottky multiplier chains.

Photoconductive switching. The generation of THz radiation using a femtosecond laser pulse is shown in Fig. 3.

1. Ranges from 0.1 to 10 THz
2. Wavelength: 3 to 0.3 mm
3. Wavenumber: 3.3 $cm^{-1}$ to 333.6 $cm^{-1}$
4. Energy: 0.41 to 41 meV

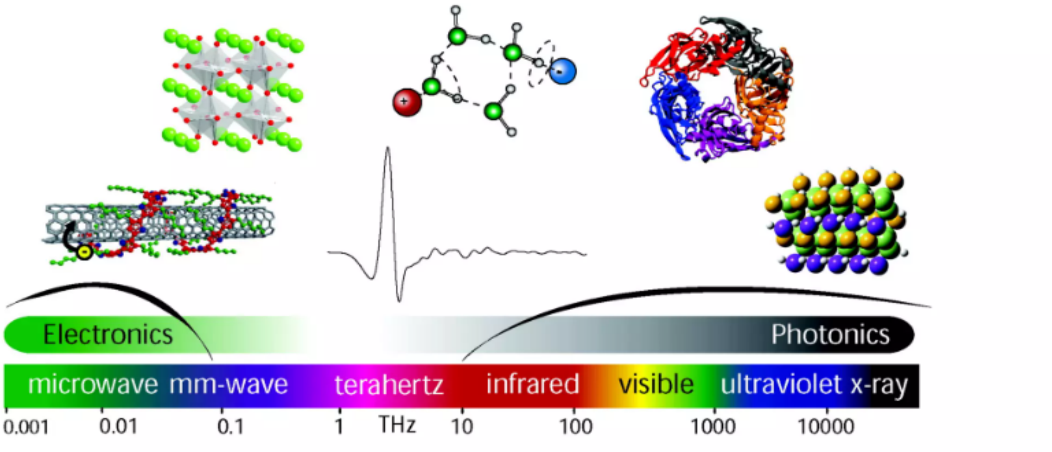


*Fig. 2.* Terahertz Radiation [6]

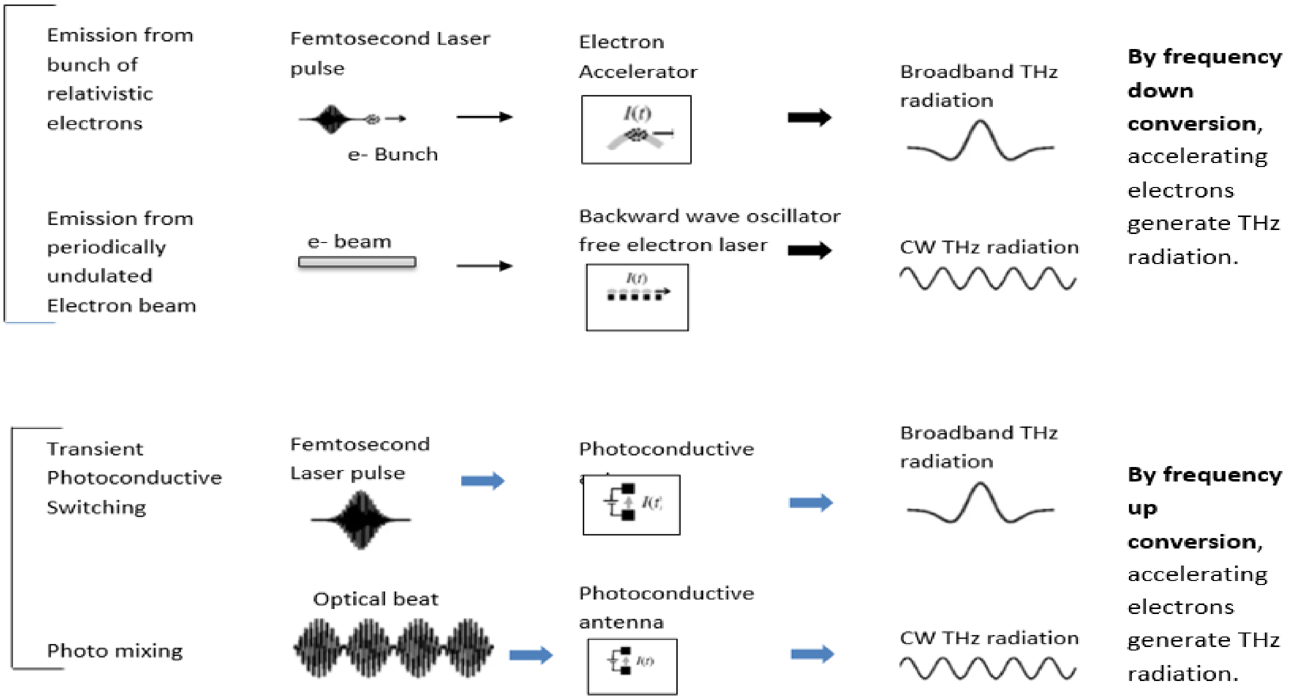


*Fig. 3.* Generation of THz radiation [5]

**2) Terahertz detectors –**

| Coherent | Semiconductor | Thermal |
|---|---|---|
| ❖ Homojunction devices, | ❖ Photoconductive switch, | ❖ Pyroelectric, |
| ❖ Quanum well infrared detectors; | ❖ Electro-optic detector; | ❖ Hot electron bolometer, |
| | | ❖ Photo-acoustic detector. |

Terahertz technology has a wide range of uses and is constantly developing new ones. Several applications such as imaging and sensing, characteristics of material. Security and surveillance, spectroscopy and Communication field are displayed in Fig. 4 and 5.

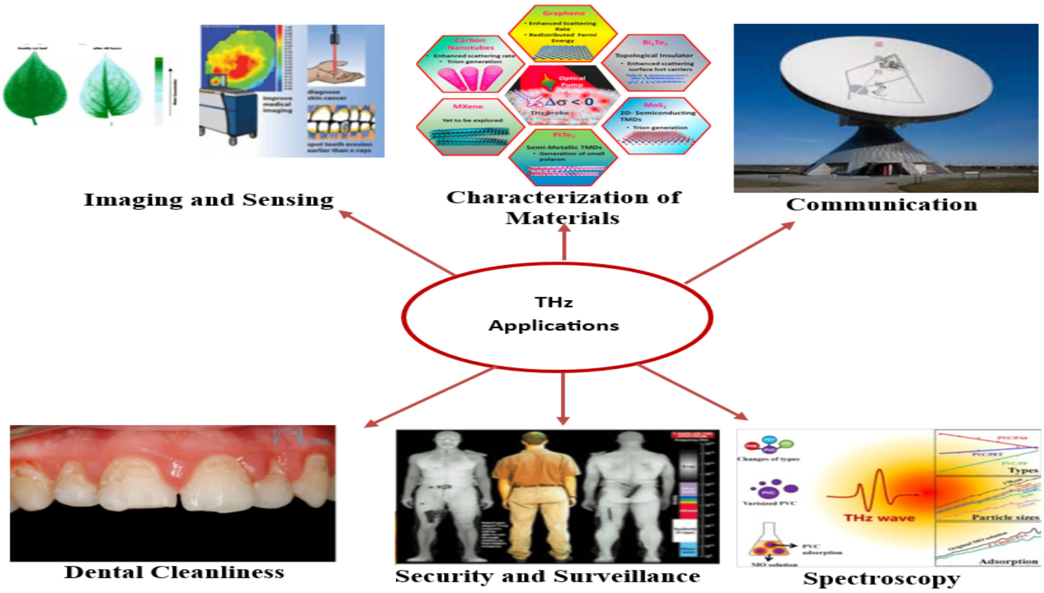


*Fig. 4.* Applications of THz waves in different fields

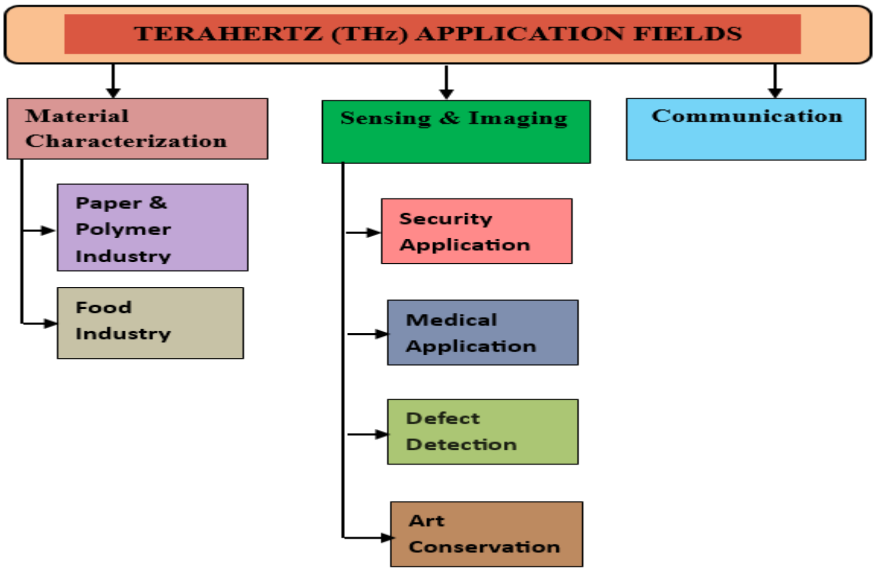


*Fig. 5.* THz Application Fields [6]

**1. Imaging and Sensing.** Terahertz waves have applications in imaging and sensing that provide important details about material characteristics including composition, thickness, and density. Terahertz images are also useful in biology. In the frequency, range of 1–3 THz Water is good observer of THz radiations. In the THz radiation is therefore capable of detecting differences in tissue water content and density [9]. Terahertz imaging, for instance, can also be used in the pharmaceutical sector to characterize tablet material or in the restoration of fine art to analyze hidden layers in paintings [10].

**2. Communication.** Because of its enormous bandwidth, terahertz waves have the potential to enable high-speed wireless communication systems [11]. The data rate of existing wireless system typically of 100 Mbps, is limited by the use of carrier wave below 5 GHz. High data rates are made possible by higher frequency carriers, and terahertz carrier waves enable data speeds of up to 1000 Gbps [12]. The benefit of terahertz communication is that it is immune to interference from other wireless technologies that use lower frequencies.

**3. Spectroscopy.** Terahertz spectroscopy enables the examination of atomic and molecular vibrations, revealing details about the structure and chemical make-up of materials. Environmental monitoring, security [13], and pharmaceutical research all benefit greatly from this.

**4. Characterization of Materials**. Semiconductors, superconductors, and other sophisticated materials may be characterized by using terahertz radiation to examine the electronic, vibrational, and magnetic characteristics of the materials [14].

**5. Security and Surveillance.** Terahertz waves may be applied to security screening tasks including finding narcotics, explosives, or concealed weapons. By detecting variations in terahertz wave transmission and reflection via various materials, terahertz imaging devices may locate items that are concealed [14]. Using terahertz systems, one can simultaneously perform imaging & spectroscopy. It has been shown that terahertz waves can penetrate materials such as paper, wood, plastic, ceramic etc. This allows them to reveal the presence of objects. There are several potential applications for this technology including identification of liquids in suspicious bottles, explosives in a mail envelope, detection of drugs.

**6. Dental Cleanliness.** Dental carries frequently knows as tooth rot is perhaps of the most widely recognized human problem. Carry on by delivering a subsurface sore in the veneer. If there is no macroscopically visible disintegration or even the formation of micro cavities at the toothe surface, the disease may spread to the dentine, the next tissue in the tooth layer. It is difficult to catch dental decay early because there are no obvious signs on the both surface. X ray one of the well-known methods for detecting decay, only reveal the issue when drilling and filling are the only options for preventing degradation.

Below Fig. 5 shows the applications of THz application fields.

Designing effective and dependable systems requires a thorough understanding of the principles of terahertz technology. We shall examine the nanoantenna arrays especially suited for terahertz detection in the further section of this paper. We are able to find answers to a variety of problems in industries ranging from telecommunications to healthcare by utilizing the special characteristics of terahertz waves.

## Introduction to Nanoantennas

In the realm of terahertz technology, nanoantennas are crucial, especially for the detection and control of terahertz waves. The diameters of these nanoscale-engineered antennas are often smaller than the wavelengths of the electromagnetic waves with which they interact. A wide range of applications in terahertz devices and systems are made possible by nanoantennas' efficient ability to link, emit, and modify terahertz radiation [15]. Enhancing the interaction between electromagnetic waves and materials at terahertz frequencies is the main goal of nanoantennas. The optical and electrical characteristics of the Nano antennas may be precisely adjusted to accomplish desired functionality by modifying their size, shape, and material composition. Nanoantennas allow for the targeted sensing and manipulation of terahertz waves by concentrating them into subwavelength zones, increasing the field intensity [16]. Several types of nanoantennas are commonly used in terahertz applications:

**1. Dipole Antennas.** Dipole antennas are made up of two conducting components, which are often shaped like straight rods or arms [17, 18] shown in Fig. 6. They are frequently used in terahertz technology because of how easy they are to make. Depending on the intended use, dipole antennas can be built as resonant or non-resonant structures.

**2. Loop Antennas.** A conductive loop or coil, which may have a circular, rectangular, or other shape, makes up a loop antenna [19] in Fig. 7. In terahertz systems that need a reduced footprint, loop antennas are frequently employed because of their tiny size. They have a high radiation efficiency and are capable of resonant behavior.

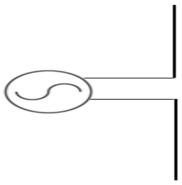
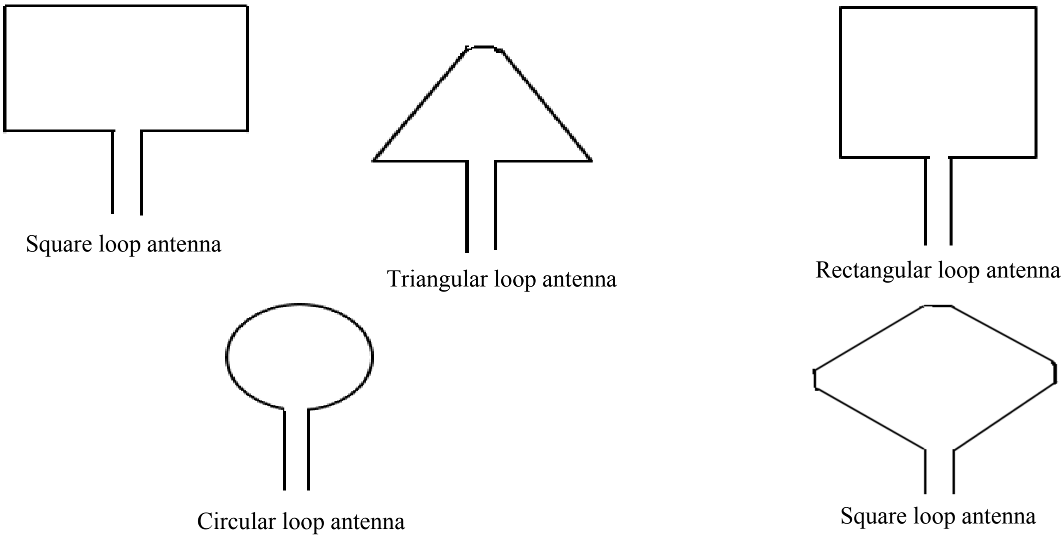


*Fig. 6.* Dipole antenna



Square loop antenna

Triangular loop antenna

Rectangular loop antenna

Circular loop antenna

Square loop antenna

*Fig. 7.* Types of loop antenna

**3. Patch Antennas.** These planar devices, which are generally made of a metallic patch and a dielectric substrate, operate as antennas [20, 21] shown in Fig. 8. Due to their simplicity of integration, compatibility with microfabrication methods, and customizable resonant qualities, they are commonly utilized in terahertz systems. Patch antennas are capable of achieving great radiation efficiency and directivity.

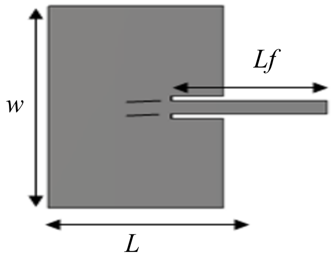


*Fig. 8.* Patch antenna

**4. Spiral Antennas.** Spiral antennas have conductive traces that are frequently etched or printed in the shape of spirals on a substrate [22] illustrated in Fig. 9. Spiral antennas are suited for terahertz applications that need broad frequency coverage and constrained physical area because of their broadband performance and small size.

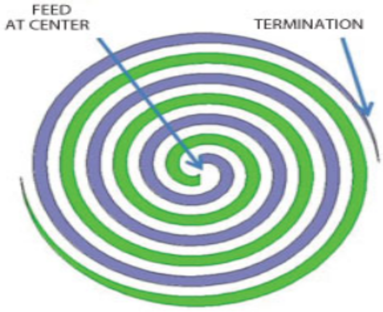


*Fig. 9.* Spiral antenna

Nanoimprinting, self-assembly processes, electron beam lithography, and other methods can all be used to create nanoantennas. Usually, they are constructed of metals like gold, silver, or copper, which have outstanding optical and conductivity qualities at terahertz frequencies. Nanoantennas can also benefit from the use of dielectric and semiconductor materials to improve performance or accomplish certain functionality [23].

In order to achieve the necessary electromagnetic response, size, shape, material qualities, and nanoantenna design must be carefully balanced [24]. To optimize the design parameters and forecast the behavior of nanoantennas, a variety of simulation tools are used, such as the finite element method (FEM) or finite-difference time-domain (FDTD) approaches.

The design considerations, manufacturing processes, and performance assessment of nanoantenna arrays especially suited for terahertz detection will be covered in the following chapters. We can improve the sensitivity, resolution [24], and selectivity of terahertz systems by utilizing the special qualities of nanoantennas, opening the door to groundbreaking applications in fields including security, medical imaging, and non-destructive testing.

## Terahertz Detection Techniques

For recording and analyzing terahertz waves in a variety of applications, terahertz detection methods are crucial. These methods make it possible to measure, image, and characterize terahertz radiation, giving vital information about the characteristics of materials and paving the way for the creation of terahertz-based gadgets and systems. There are several detecting methods used, and each has a special benefit and application.

Short terahertz wave pulses are sent and received via time-domain methods. These pulses interact with the target substance or item, which reveals details about its qualities. There are two popular time-domain methods:

In THz-TDS, a brief terahertz pulse is generated, and when it interacts with the sample, its time-domain waveform is measured. The terahertz absorption, refractive index, and other physical characteristics of the material may be ascertained by examining the amplitude and phase of the reflected or transmitted waveform. THz-TDS is frequently used in material characterization, pharmaceutical analysis, and quality control since it enables broadband measurements [25].

Electronic excitations in semiconductors have previously tracked application in lasers, electronics parts and PCs. At the same time, they comprise an astonishing body framework whose quantum properties might be changed for instance by nanostructure plan. Thus, THz spectroscopy on semiconductors is not only use for uncovering new mechanical possibilities of nanostructures but also use as key properties to control framework.  Many peculiarities have previously been inspected utilizing brief THz beats. The complicated permittivity or THz-retention coefficient and refractive list of unexcited, inborn semiconductors might be determined. Thz photons are consumed fundamentally by free transporters in doped or optically animated semiconductors.

TPI scans an object or sample using a terahertz pulse. A two-dimensional or three-dimensional picture of the target is produced using the measured reflected or transmitted pulses at various locations. TPI is used in applications for medical imaging [26], non-destructive testing, and security screening. The system is comprised of a laser-driven emitter, a beam-forming optics consisting of focused optics and mirrors, a sample holder, and an optical delay line, together with a laser-driven detector [27]. Terahertz pulse (THz) is measured with and without the sample using the difference absorption spectra approach. The sample's dispersion and absorption, as determined by the Fourier transformation. The phase and amplitude are both determined by Terahertz – Time domain spectra (THz-TDS). Fig. 10 depicts schematics diagram of Terahertz time domain Spectroscopy. Fig. 11 depicts schematic representation of terahertz time domain scanning and spectroscopic.

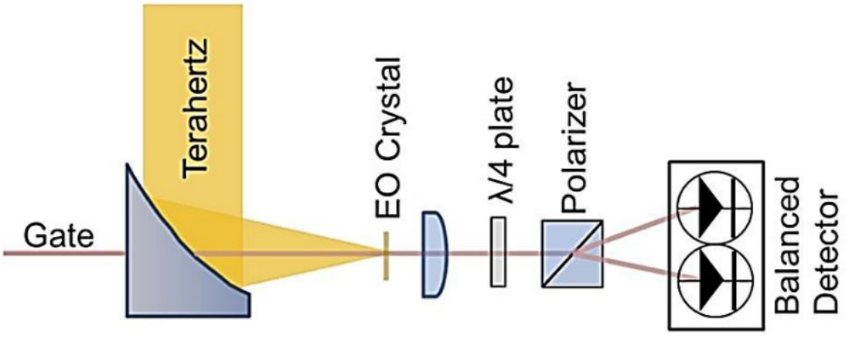


*Fig. 10.* Terahertz Time-Domain Spectroscopy (THz-TDS) [28]

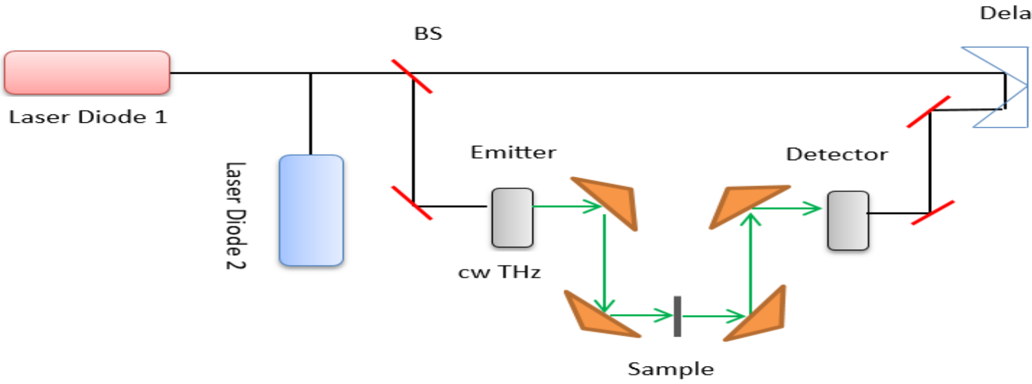


*Fig. 11.* Terahertz time domain scanning and spectroscopic [28]

Terahertz Pulsed Imaging is a pharmacological assessment device that uses very low power, extremely brief pulses of electrical energy at frequencies lower than ultraviolet (1 THz = 1012 Hz). It is completely risk free and harmless. It has already been demonstrated that terahertz spectroscopy is useful for distinguishing among the medications various polymorph structures. TIP is the subsequent stage in this cycle, where THz beats are utilized to picture an objective.

Lighting photoconductive semiconductors with beat close infrared laser energy creates and distinguishes THz beats in a cognizant way. Tablet coatings are cloudy to THz frequencies and do not disperse them altogether.

The behavior of materials or objects to terahertz radiation at certain frequencies is examined using frequency-domain methods. These methods frequently use continuous wave terahertz sources to determine the amplitude and phase of the terahertz signal. The two primary frequency-domain approaches are as follows:

1. Continuous Wave Terahertz Spectroscopy (CW-TDS);
2. Fourier Transform Infrared Spectroscopy (FTIR).

The limitations of conventional terahertz detectors and the particular benefits offered by nanoantenna-based systems led to the usage of nanoantenna arrays for terahertz detection. Nanoantenna arrays are perfect for terahertz applications because they provide high sensitivity, selectivity, and spatial resolution. The purpose of employing nanoantenna arrays in terahertz technology is examined in this paper. Conventional terahertz detectors including bolometers, photoconductive devices, and Schottky diodes have been extensively used for terahertz sensing and imaging [29]. The sensitivity, bandwidth, and integration capabilities of these detectors, however, are typically constrained. Here are a few important limitations:

**1. Low Sensitivity.** Conventional terahertz detectors frequently have low sensitivity, requiring the utilization of high-power terahertz sources or sophisticated amplification systems to generate adequate signal levels. This reduces the entire system's detecting range and sensitivity.

**2. Narrow Bandwidth.** Because many traditional detectors have restricted bandwidth, it is difficult to catch a wide variety of terahertz frequencies at the same time [30]. This can stymie applications requiring broad frequency coverage or spectroscopic research.

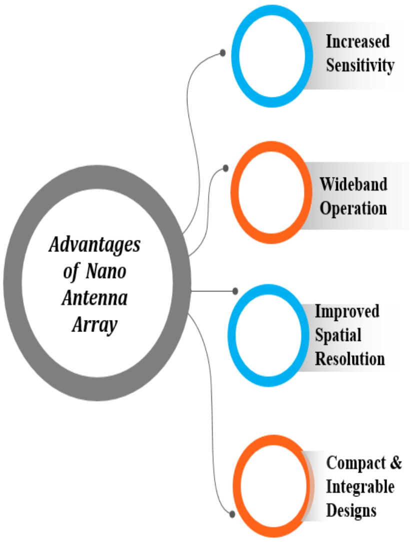
**3. Big and Elaborate Designs.** Because certain traditional detectors require elaborate cooling systems or external optics, they are big, costly, and difficult to integrate into small devices. This restricts their use in portable or tiny terahertz devices. Nanoantenna arrays outperform traditional terahertz detectors in various ways, solving the constraints outlined above and enabling substantial advances in terahertz technology:

*1. Increased Sensitivity.* Nanoantenna arrays may focus terahertz waves into subwavelength areas, significantly increasing local field strength. This higher field strength enhances terahertz detection sensitivity, allowing for the identification of weak signals and increasing the signal-to-noise ratio [31].

*2. Wideband Operation.* Nanoantenna arrays may span a wide frequency range by creating nanoantennas with specific resonant qualities. This enables the detection and manipulation of numerous terahertz frequencies at the same time, enabling broadband terahertz systems and spectroscopic investigation [32].

*3. Improved Spatial Resolution.* Nanoantenna arrays increase spatial resolution by confining terahertz waves into subwavelength areas [32]. This allows for high-resolution imaging and sensing, as well as the identification of small-scale features and the exact localization of terahertz sources.

*4. Compact and Integrable Designs.* Nanoantennas are small and easy to integrate with other components like microelectronic circuits or imaging systems. Because of their small size, nanoantennas may be easily integrated into portable or miniature terahertz devices, broadening the variety of conceivable applications [32].



The use of nanoantenna arrays in terahertz detection systems is a possible option for overcoming the limits of traditional detectors and unleashing new terahertz technological possibilities.

## Design Considerations for Nanoantenna Arrays

Nanoantenna arrays for terahertz detection need careful consideration of numerous characteristics, materials, and production procedures. These design factors are critical in influencing the performance and usefulness of nanoantenna arrays. This section brings into light crucial elements to consider throughout the design process.

When building nanoantenna arrays for terahertz detection, several aspects must be considered:

**1. Resonant Frequency.** The nanoantennas resonant frequency should match the intended terahertz frequency range of operation. The resonance frequency of nanoantennas may be controlled by adjusting their size, shape, and material qualities. By matching the resonance frequency, the incident terahertz waves may be efficiently coupled to the nanoantennas.

**2. Polarization.** Nanoantennas with specified polarization properties, such as linear, circular, or elliptical polarization, can be created. The polarization to be used is determined by the application requirements and the polarization state of the terahertz waves to be detected.

**3. Radiation Pattern.** The directionality and efficiency of the produced or received terahertz waves are determined by the radiation pattern of the nanoantenna arrays. Optimizing the radiation pattern ensures that terahertz signals are sent or received in the desired direction.

**4. Bandwidth.** The frequency range across which the nanoantenna arrays can efficiently couple with terahertz waves is defined by their bandwidth. Broadband nanoantenna designs are critical for applications requiring broad frequency coverage or spectroscopic analysis.

The materials used in nanoantennas are critical for obtaining high-performance terahertz detection:

**1. Metals.** Because of their outstanding conductivity and plasmonic features at terahertz frequencies, metals such as gold, silver, or copper are widely employed for nanoantennas. Plasmonic effects in metals can facilitate the interaction of terahertz waves with nanoantennas, resulting in higher sensitivity and field confinement [33].

**2. Semiconductors.** Certain semiconductor materials, such as gallium arsenide (GaAs) or indium phosphide (InP) [34], have advantageous terahertz detection capabilities. Semiconductors have the capacity to give tunability and integration, allowing for active control or modulation of terahertz signals.

**3. Dielectrics.** Dielectric materials, such as silicon dioxide (SiO2) or polymers, are used as substrates for nanoantenna manufacturing because of their low-loss qualities. Dielectrics can help nanoantenna arrays with structural support, insulation, and thermal stability.

The materials used are determined by the required qualities, production procedures, and compatibility with other terahertz system components.

Fabrication processes are critical in achieving nanoantenna arrays with exact dimensions and high-quality structures:

**1. Electron Beam Lithography (EBL).** EBL is a high-resolution process that employs a concentrated electron beam to selectively expose a resist material, enabling accurate patterning of nanoantennas. EBL is suited for fabricating nanoantenna arrays with subwavelength characteristics [35].

**2. Nanoimprint Lithography (NIL).** NIL includes mechanically pressing and heating a pattern from a mold onto a substrate. NIL provides a low-cost, high-throughput method for producing nanoantenna arrays [36].

**3. Self-Assembly Techniques.** Self-assembly methods use the intrinsic  characteristics of materials to produce ordered nanostructures spontaneously. Depending on the individual requirements and available resources, other manufacturing processes such as focused ion beam (FIB) milling, photolithography, or nano-scale 3D printing may be employed.

Nanoantenna array design for terahertz detection necessitates a thorough grasp of the necessary parameters, material qualities, and manufacturing procedures. Engineers and researchers may improve the performance and usefulness of nanoantenna arrays in terahertz applications by carefully examining these design elements.

## Performance Metrics and Evaluation

Evaluating the performance of nanoantenna arrays for terahertz detection is crucial to ensure their effectiveness and reliability. Several performance metrics and evaluation techniques are utilized to assess the functionality and efficiency of these arrays. This section discusses key performance metrics and evaluation methods commonly employed in the field. Key Performance Metrics for Nanoantenna Arrays:

**1. Radiation Efficiency.** The capacity of nanoantenna arrays to convert incident terahertz waves into radiated power is measured by radiation efficiency. It measures how well the arrays work at sending or receiving terahertz radiation. Better performance is indicated by a higher radiation efficiency. It can be expressed as:

$$\eta = Pr / Pi,$$

where $\eta$ – is radiation efficiency; $Pr$ is the radiated power by the antenna; $Pi$ is the input power to the antenna.

**2. Gain.** Compared to an isotropic radiator, gain is the amplification that the nanoantenna arrays produce when transmitting or receiving terahertz signals. It is computed as the difference between the power emitted equally in all directions and the power radiated in the intended direction. Signal strength improves with higher gain. It can be calculated using the equation:

$$G = (4\pi\eta A) / \lambda\hat{}2,$$

where $G$ is the antenna gain; $\eta$ is the radiation efficiency of the antenna; $A$ is the effective aperture area of the antenna; $\lambda$ is the wavelength of the terahertz wave.

**3. Bandwidth.** The range of terahertz frequencies across which nanoantenna arrays demonstrate effective coupling or radiation is referred to as their bandwidth. Applications that need spectroscopic analysis or extensive frequency coverage can be made possible by a greater bandwidth, which makes it possible to capture a wider variety of terahertz frequencies. The fractional bandwidth (FBW) can be calculated using the equation:

$$FBW = (f_{\max} - f_{\min}) / f_0,$$

where $FBW$ is the fractional bandwidth; $f_{\max}$ is the maximum frequency of operation; $f_{\min}$ is the minimum frequency of operation; $f_0$ is the resonant frequency of the nanoantenna array.

**4. Directivity**. The capacity of nanoantenna arrays to direct terahertz radiation in a particular direction is measured by directivity. The ratio between the highest radiation intensity in the chosen direction and the average radiation intensity in all directions is used to calculate it. Better concentration ability is indicated by higher directivity. The directivity ($D$) can be expressed as:

$$D = 4\pi(Prad - Ptotal),$$

where $D$ is the directivity; $Prad$ is the power radiated in the desired direction; $Ptotal$ is the total radiated power.

**5. Polarization Features.** Nanoantenna arrays may display certain polarization features, such as linear, circular, or elliptical polarization. The arrays polarization properties need to coincide with the polarization state of the terahertz waves. Essential variables to take into account are the level of polarization and the capacity to control polarization states.

**Performance Evaluation through Simulation and Measurement Methods.** Using simulation approaches, it is common practice to evaluate and enhance the performance of nanoantenna arrays.

**Finite Element Method (FEM)** is a numerical method for solving the partial differential equations governing the propagation of electromagnetic waves. It allows for the modeling and simulation of nanoantenna arrays, allowing for the examination of their electromagnetic characteristics and the optimization of design parameters.

**Finite-Difference Time-Domain (FDTD) method** is a computer technique for solving Maxwell's equations that discretizes both space and time. It is often used to investigate and simulate the interactions between terahertz radiation and nanoantenna arrays. FDTD contributes to the usability of nanoantenna arrays by showing how they behave in diverse settings. Measurement techniques are essential for proving the viability of nanoantenna arrays.

Finite Element Method (FEM) is for figuring out the amplitude and phase of terahertz waves that interact with nanoantenna arrays is called terahertz time-domain spectroscopy (THz-TDS) [37]. Investigations may evaluate the radiation efficacy, gain, and frequency responsiveness of the arrays using this technique.

Terahertz fields near nanoantenna arrays may be observed and mapped with high resolution using Near-Field Scanning Terahertz Microscopy (NSOM) techniques. This enables the observation and characterization of the field distribution, directivity, and polarization properties of the arrays. Engineers and scientists may thoroughly assess the performance of nanoantenna arrays and improve their designs to get the best functionality and efficiency by combining modeling and measurement methodologies. These assessment techniques aid in the verification of the theoretical models, direct the process of design optimization, and speed up the creation of high-performance terahertz detection systems.

## Applications of Nanoantenna Arrays in Terahertz Technology

Terahertz technology has found a wide range of uses for nanoantenna arrays, transforming multiple sectors and allowing breakthroughs in fields including security, medical imaging, and non-destructive testing shown in Fig. 12.

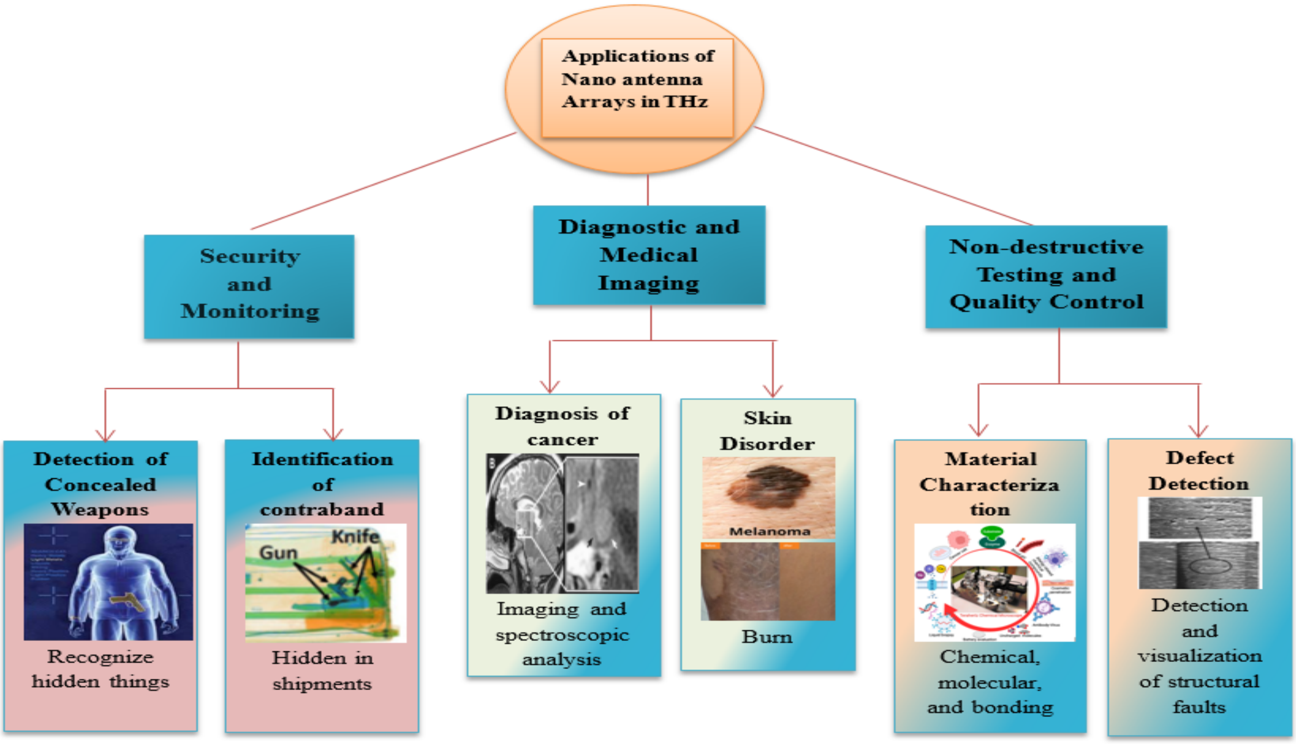


*Fig. 12.* Applications of Nanoantenna Arrays in THz

The primary application areas where nanoantenna arrays have had a substantial influence are explored in this section.

**1. Security and Monitoring.** Because they improve the capabilities for threat detection and identification, nanoantenna arrays have proven to be beneficial in security and surveillance applications. A few noteworthy uses are:

Terahertz radiation has the potential to penetrate clothing and other materials, making it feasible to discover unlawful or concealed goods. Nanoantenna arrays make it simpler to find and recognize hidden things because to their high sensitivity and spatial resolution.

Nanoantenna arrays may be used by terahertz imaging systems to detect illegal substances that are hidden in shipments or luggage. The enhanced sensitivity and imaging capabilities of nanoantenna arrays allow for more accurate detection and labeling of illicit products.

**2. Diagnostic and Medical Imaging.** The potential for medical imaging and diagnostics have been broadened by non-invasive, high-resolution nanoantenna arrays. Such uses in the healthcare industry include:

Because malignant tissues absorb terahertz energy differently than healthy cells, terahertz waves may be able to distinguish between the two. Nanoantenna arrays provide accurate imaging and spectroscopic analysis, which help with the early identification and characterization of malignancies.

Nanoantenna arrays in terahertz imaging devices can deliver accurate information on skin issues including melanoma, burns, or infections. High-resolution imaging capabilities of nanoantenna arrays enable accurate skin disease diagnosis and monitoring.

**3. Nondestructive Testing and Quality Control.** Nanoantenna arrays are crucial for non-destructive testing and quality control of materials because they may reveal details about a material's composition, structural integrity, and defects. Here are a few examples:

- **Material Characterization.** Terahertz spectroscopy and nanoantenna arrays make it possible to investigate the chemical, molecular, and bonding states of materials. This aids in the material's characterization, quality assurance, and impurity or pollutant identification.
- **Defect Detection.** Nanoantenna arrays used in terahertz imaging systems may find flaws or concealed damage in a variety of materials, such as composites, ceramics, or electronic parts. They enable the detection and visualization of structural faults, such as fractures or delaminations, because to their improved sensitivity and spatial resolution.

These application fields just scratch the surface of the numerous opportunities that nanoantenna arrays in terahertz technology afford. Nanoantenna arrays are anticipated to find increasingly more varied uses as this field of study and development advances, fostering developments in industries including telecommunications, environmental monitoring, and semiconductor characterization.

We shall dig more into the design concepts, manufacturing methods, and particular application concerns for nanoantenna arrays in terahertz detection in the subsequent sections of this paper.

## CONCLUSION

This paper presents design concepts, manufacturing methods, performance evaluation , particular application concerns for nanoantenna arrays in terahertz detection.

**1. Terahertz Technology:**

- Terahertz waves occupy the frequency range between microwaves and infrared radiation.
- Terahertz waves possess unique properties, such as non-ionizing nature and ability to penetrate various materials.
- Terahertz technology finds applications in imaging, communication, spectroscopy, material characterization, and security.

**2. Nanoantennas:**

- Nanoantennas are engineered at the nanoscale to efficiently couple, radiate, and manipulate terahertz waves.
- Different types of nanoantennas, such as dipole antennas, loop antennas, patch antennas, and spiral antennas, are commonly used in terahertz applications.

- Nanoantennas can be fabricated using techniques like electron beam lithography, nanoimprint lithography, or self-assembly processes.
- Materials like metals (gold, silver, copper), semiconductors (GaAs, InP), and dielectrics are used for nanoantenna fabrication.

**3. Design Considerations:**

- Design parameters, such as resonant frequency, polarization, radiation pattern, and bandwidth, need to be considered for efficient nanoantenna array design.
- Materials selection plays a crucial role in achieving desired performance characteristics.
- Fabrication techniques, including electron beam lithography, nanoimprint lithography, and self-assembly, are employed for nanoantenna array fabrication.

**4. Performance Evaluation:**

- Performance metrics like radiation efficiency, gain, bandwidth, directivity, and polarization characteristics are used to assess nanoantenna array performance.
- Simulation techniques, such as finite element method (FEM) and finite-difference time-domain (FDTD), aid in performance evaluation.
- Experimental techniques like terahertz time-domain spectroscopy (THz-TDS) and near-field scanning terahertz microscopy (NSOM) are employed for measurement and validation.

**5. Applications:**

- Nanoantenna arrays find applications in security and surveillance, medical imaging and diagnostics, non-destructive testing, and quality control.
- They enable concealed weapons detection, contraband identification, cancer detection, skin disease diagnosis, material characterization, and defect detection, among others.

### Compliance with Ethical Standards

1. Disclosure of potential conflicts of interest.
   There is no conflict of interest.
2. Research involving human participants and/or
   Animals.
   For this type of study formal consent is not required.
3. Informed consent.
   Informed consent was obtained from all individual participants included in the study.

### Acknowledgement

I would like to thank, my guide Dr. Dipak P Patil Principal & Professor of Sandip Institute of Engineering and Management Nashik for his constant support, inspiration, and insightful advice throughout this entire project. It would have been challenging to complete this research without his support and guidance.

### REFERENCES

1. Adak S., Tripathi L. N. (2019) Nanoantenna Enhanced Terahertz Interaction of Biomolecules. *Analyst*, 144 (21), 6172–6192. https://doi.org/10.1039/c9an00798a.
2. Al Hadi R., Grzyb J., Heinemann B. Pfeiffer U.R. (2013) A Terahertz Detector Array in a SiGe HBT Technology. *IEEE Journal of Solid-State Circuits*, 48 (9), 2002–2010. https://doi.org/10.1109/jssc.2013.2265493.
3. Bareib M., Tiwari B. N., Hochmeister A., Jegert G., Zschieschang U., Klauk H., Fabel B., Scarpa G., Koblmuller G., Bernstein G. H., Porod W. (2011) Nanoantenna Array For Terahertz Detection. *IEEE Transactions on Microwave Theory and Techniques*, 59 (10), 2751–2757. https://doi.org/10.1109/tmtt.2011.2160200.
4. Boppel S., Lisauskas A., Mundt M., Seliuta D., Minkevicius L., Kasalynas I., Valusis G., Mittendorff M., Winnerl S., Krozer V., Roskos, H. G. (2012) CMOS Integrated Antenna-Coupled Field-Effect Transistors for the Detection of Radiation From 0.2 to 4.3 THz. *IEEE Transactions on Microwave Theory and Techniques*, 60 (12), 3834–3843. https://doi.org/10.1109/tmtt.2012.2221732.
5. Cai Y., Brener I., Lopata J., Wynn J., Pfeiffer L., Stark J. B., Wu Q., Zhang X. C., Federici J. F. (1998) Coherent Terahertz Radiation Detection: Direct Comparison Between Free-Space Electro-Optic Sampling and Antenna Detection. *Applied Physics Letters*, 73 (4), 444–446. https://doi.org/10.1063/1.121894.
6. Malhotra I., Jha K. R., Singh G. (2018) Terahertz Antenna Technology for Imaging Applications: a Technical Review. *International Journal of Microwave and Wireless Technologies*, 10 (3), 271–290.
7. Yun-Shik Lee (2009) *Principles of Terahertz Science and Technology*. New York, Springer. 66. https://doi.org/10.1007/978-0-387-09540-0.
8. Sizov F., Rogalski A. (2010) THz Detectors. *Progress in Quantum Electronics*, 34 (5), 278–347. https://doi.org/10.1016/j.pquantelec.2010.06.002.
9. Hu B. B., Nuss M. C. (1995) Imaging With Terahertz Waves. *Optics Letters*, 20 (16), 1716–1718. https://doi.org/10.1364/ol.20.001716.
10. Taday P. F., Pepper M., Arnone D. D. (2022) Selected Applications of Terahertz Pulses in Medicine and Industry. *Applied Science*, 12 (12), 1–18. https://doi.org/10.3390/app12126169.

11. Akyildiz I. F., Jornet J. M., Han C. (2014) Terahertz Band: Next Frontier for Wireless Communications. *Physical Communication*, 12, 16–32. https://doi.org/10.1016/j.phycom.2014.01.006.
12. Dhillon S. S., Vitiello M. S., Linfield E. H., Davies A. G., Hoffmann M. C., [et.al.] (2017) The 2017 Terahertz Science and Technology Roadmap. *Journal of Physics D: Applied Physics*, 50 (4), 043001. https://doi.org/10.1088/1361-6463/50/4/043001.
13. Huang S., Deng H., Wei X., Zhang J. (2023) Progress in the Application of Terahertz Time-Domain Spectroscopy for Pharmaceutical Analyses. *Front Bioeng Biotechnology,* 11, 1219042. https://doi.org/10.3389/fbioe.2023.1219042.
14. Hou H., Liu Z., Teng J., Palacios T., Chua S. J. (2016) A Sub-terahertz Broadband Detector Based on a GaN High-Electron-Mobility Transistor with Nanoantennas. *Applied Physics Express*, 10 (1), 014101. https://doi.org/10.7567/apex.10.014101.
15. Lepeshov S., Gorodetsky A., Krasnok A., Rafailov E., Belov P. (2017) Enhancement of Terahertz Photoconductive Antenna Operation by Optical Nanoantennas. *Laser & Photonics Reviews*, 11 (1), 1600199. https://doi.org/10.1002/lpor.201600199.
16. Peter F., Winnerl S., Nitsche S., Dreyhaupt A., Schneider H., Helm M. (2007) Coherent Terahertz Detection with a Large-Area Photoconductive Antenna. *Applied Physics Letters*, 91 (8), 081109. https://doi.org/10.1063/1.2772783.
17. Jepsen P. U., Jacobsen R. H., Keiding S. R. (1996) Generation and Detection of Terahertz Pulses From Biased Semiconductor Antennas. *Journal of the Optical Society of America B,* 13 (11), 2424–2436. https://doi.org/10.1007/978-1-4615-5897-2_142.
18. Mitrofanov O., Brener I., Luk T. S., Reno J. L. (2015) Photoconductive Terahertz Near-Field Detector with a Hybrid Nanoantenna Array Cavity. *ACS Photonics*, 2 (12), 1763–1768. https://doi.org/10.1021/acsphotonics.5b00475.
19. McKinley A., White T. P, Catchpole K. (2013) Theory of the Circular Closed Loop Antenna in the Terahertz, Infrared, and Optical Regions. *Journal of Applied Physics*, 114 (4), 044317. https://doi.org/10.1063/1.4816619.
20. Choudhury B., Sonde A. R., Jha R. M., Choudhury B., Sonde A. R., Jha R. M. (2016). Terahertz Antenna Technology for Space Applications. *Springer Briefs in Electrical and Computer Engineering*. Springer, Singapore, 3–33. https://doi.org/10.1007/978-981-287-799-4_1.
21. Samanta D., Karthikeyan M. P., Banerjee A., Inokawa H. (2021) Tunable Graphene Nanopatch Antenna Design for On-chip Integrated Terahertz Detector Arrays with Potential Application in Cancer Imaging. *Nanomedicine*, 16 (12), 1035–1047. https://doi.org/10.2217/nnm-2020-0386.
22. Suzuki M., Tonouchi M. (2005) Fe-Implanted InGaAs Photoconductive Terahertz Detectors Triggered by 1.56 μm Femtosecond Optical Pulses. *Applied Physics Letters*, 86 (16), 163504. https://doi.org/10.1063/1.1901817.
23. Hasan M.R., Helles O. G. (2021) Dielectric Optical Nanoantennas. *Nanotechnology*, 32 (20), 202001. https://doi.org/10.1088/ 1361-6528/abdceb.
24. Bragas A. V., Maier S. A., Boggiano H. D., Grinblat G., Berté R., de S. Menezes L., Cortés E. (2023) Nanomechanics with Plasmonic Nanoantennas: Ultrafast and Local Exchange Between Electromagnetic and Mechanical Energy. *Journal of the Optical Society of America B*, 40 (5), 1196–1211. https://doi.org/10.1364/JOSAB.482384.
25. Neu J., Schmuttenmaer C. A. (2018) Tutorial: An Introduction to Terahertz Time-Domain Spectroscopy (THz-TDS). *Journal of Applied Physics,* 124, 231101. https://doi.org/10.1063/1.5047659.
26. D’Arco A., Fabrizio M. D., Dolci V., Petrarca M., Lupi S. (2020) THz Pulsed Imaging in Biomedical Applications. *Condensed Matter,* 5 (2), 25. https://doi.org/10.3390/condmat5020025.
27. Sun Y., Sy M. Y., Wang Y. X. J., Ahuja A. T., Zhang Y. T., Pickwell-MacPherson E. (2011) A Promising Diagnostic Method: Terahertz Pulsed Imaging and Spectroscopy. *World Journal of Radiology,* 3 (3), 55–65. https://doi.org/10.4329/wjr.v3.i3.55.
28. Fischer B. M., Hoffmann M., Helm H., Wilk R., Rutz F., Ostmann T. K., Koch M., Jepsen P. U. (2005) Terahertz Time-Domain Spectroscopy and Imaging of Artificial RNA. *Optics Express*, 13 (14), 5205–5215. https://doi.org/10.1364/OPEX.13.005205.
29. Liu Yu, Liu Hao, Tang Meiqiong, Huang Jiaoqi, Liu Wei, Dong Jinying, Chen Xueping, Fu Weiling, Zhang Yang (2019) The Medical Application of Terahertz Technology in Non-Invasive Detection of Cells and Tissues: Opportunities and Challenges. *RSC Advances*, 9, 9354–9363. https://doi.org/10.1039/C8RA10605C.
30. Li C., Zhang Y., Hirakawa K. (2023) Terahertz Detectors Using Microelectromechanical System Resonators. *Sensors,* 23 (13), 5938. https://doi.org/10.3390/s23135938.
31. Fu X., Liu Y., Chen Q., Fu Y., Cui T. J. (2022) Applications of Terahertz Spectroscopy in the Detection and Recognition of Substances *Frontiers in Physics,* 10, 869537. https://doi.org/10.3389/fphy.2022.869537.
32. Chen X., Lindley-Hatcher H., Stantchev R. I., Wang J., Li K., Hernandez Serrano A., Taylor Z. D., Castro-Camus E., Pickwell-MacPherson E. (2022) Terahertz (THz) Biophotonics Technology: Instrumentation, Techniques, and Biomedical Applications. *Chemical Physics Reviews*, 3, 011311. https://doi.org/10.1063/5.0068979.
33. Piccoli R., Rovere A., Toma A., Morandotti R., Razzari L. (2017) Terahertz Nanoantennas for Enhanced Spectroscopy. *Terahertz Spectroscopy - A Cutting Edge Technology*. https://doi.org/10.5772/66349.
34. Anwar R. S., Ning H., Mao L. (2018) Recent Advancements in Surface Plasmon Polaritons-Plasmonics in Subwavelength Structures at Microwave and Terahertz Regime *Digital Communications and Networks*, 4 (4), 244–257. https://doi.org/10.1016/j.dcan.2017.08.004.
35. Božanić M., Sinha S. (2019) Emerging Transistor Technologies Capable of Terahertz Amplification: A Way to Re-Engineer Terahertz Radar Sensors *Sensors,* 19 (11), 2454. https://doi.org/10.3390/s19112454.
36. Parinaz Emami (2015) *Electron Beam Lithography for nano-antenna Fabrication* [thesis]. Master of Science University of Missouri-Columbia. Available at: https://mospace.umsystem.edu/xmlui/handle/10355/50185.
37. Koch M., Mittleman D. M., Ornik J., Camus E. C. (2023) Terahertz Time-Domain Spectroscopy. *Nature Reviews Methods Primers*, 3, 48. https://doi.org/10.1038/s43586-023-00232-z.

Received: 07.08.2023
Accepted: 10.10.2023